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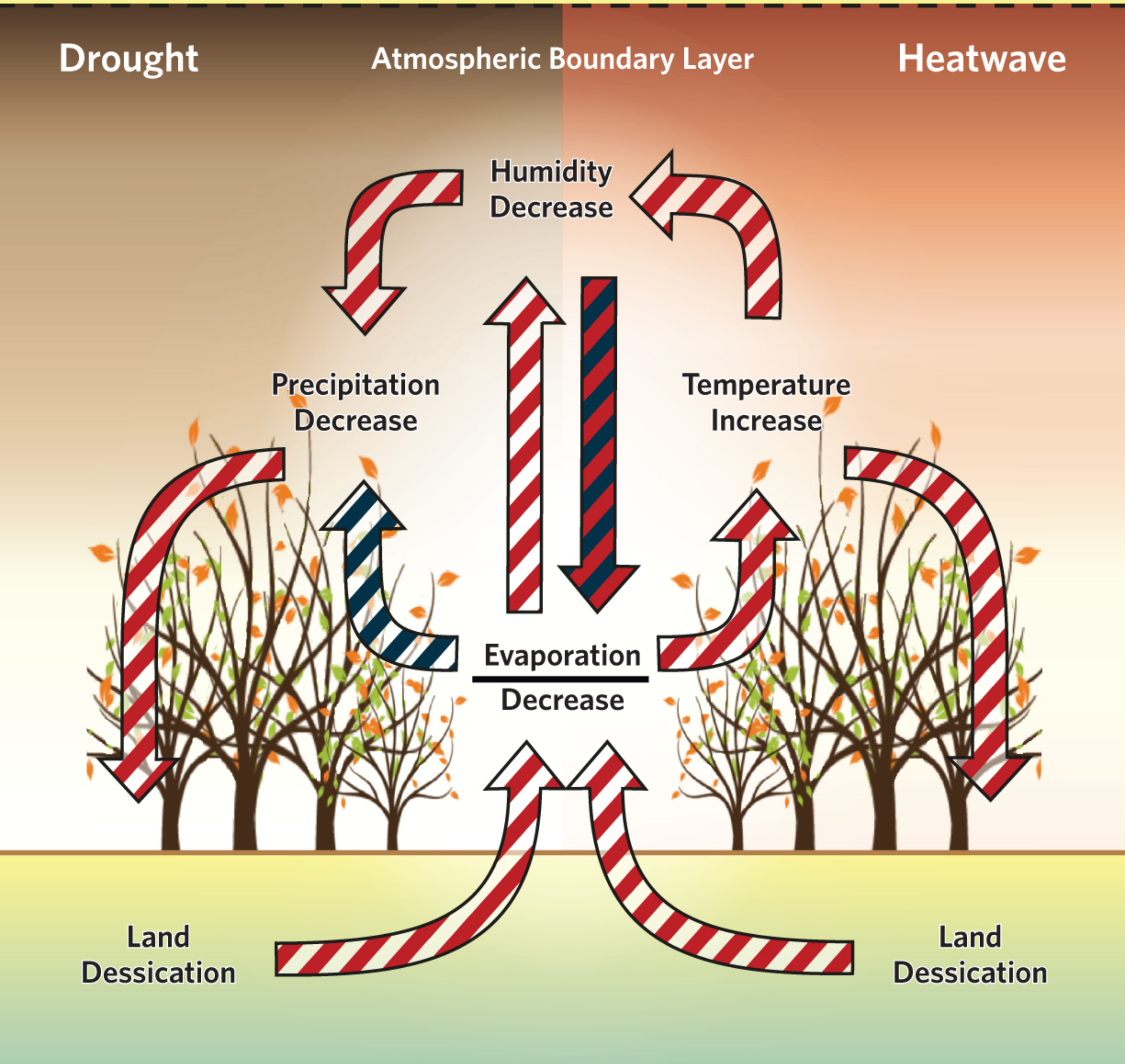

VOLUME 1436, SPECIAL ISSUE
JANUARY 2019

Climate Sciences

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report Executive Summary

Cities and the communities who live in them are significantly impacted by climate shifts in both means and extremes. These are already affecting the New York metropolitan region and will increasingly do so in the coming decades. Following the Metro East Coast Study (MEC), NPCC1, and NPCC2, the New York City Panel on Climate Change 2019 Report (NPCC3)[a] provides co-generated[b] tools and methods for implementing region-wide resilience strategies.

As the city follows flexible adaptation pathways[c] to respond to the increasing risks posed by climate change, these tools and methods can be used to observe, project, and map climate extremes; monitor risks and responses; and engage with communities to develop effective policies and programs (Fig. ES.1).

This information is especially important at "transformation points" in the adaptation process when large changes in the structure and function of physical, ecological, and social systems of the city are undertaken. The city's portfolio approach to resilience includes a range of policies, social programs, engineering projects, and ecosystem-based solutions.

[a]The MEC study was published in 2001; the first NPCC Report was published in 2010 (NPCC1); and the second NPCC Report was published in 2015 (NPCC2).

[b]Co-generation is defined by the NPCC as an interactive process by which stakeholders and scientists work together to produce climate change information that is targeted to decision-making needs.

[c]The term flexible adaptation pathways describes an overall approach to developing effective climate change adaptation strategies for a region under conditions of increasing risk. Flexible adaptation pathways are not fixed; they are ones in which adaptations are defined in terms of acceptable risk levels and re-evaluated over time, rather than using an approach that sets inflexible standards for adaptation early in the process (NPCC, 2010).

Spatial and temporal scales

The tools and methods developed for the NPCC 2019 Report are for use by the entire metropolitan region over long-term, medium-term, and short-term time frames.

- The spatial domain of the NPCC 2019 Report is the New York metropolitan region, consisting of 31 counties across New York State, New Jersey, and Connecticut. This is important because many critical infrastructure systems extend far beyond the city's five boroughs. Regionally coordinated approaches can help to scale up climate change resilience and lessen widespread vulnerability.
- Climate change is an ongoing challenge that affects long-term (2080s, 2100, and beyond), medium-term (2050s), and short-term (2020s) decision-making. The three time horizons are useful in framing climate risk information and indicators used to guide adaptation planning and implementation.

Because climate change is projected to continue for the foreseeable future, the NPCC3 considers, for the first time, potential changes in climate in New York City (NYC) beyond 2100. For example, rising sea levels are expected to persist for centuries.

Climate observations and projections

NPCC3 analyzes how recent climate trends compare to the projections that the NPCC made in 2015. The goal is to understand how well what the New York metropolitan region is experiencing tracks the projections.

- Increasing observed annual temperature and precipitation trends between 2010 and 2017 fell largely within the NPCC 2015 projected range of temperature and precipitation changes for the 2020s time period

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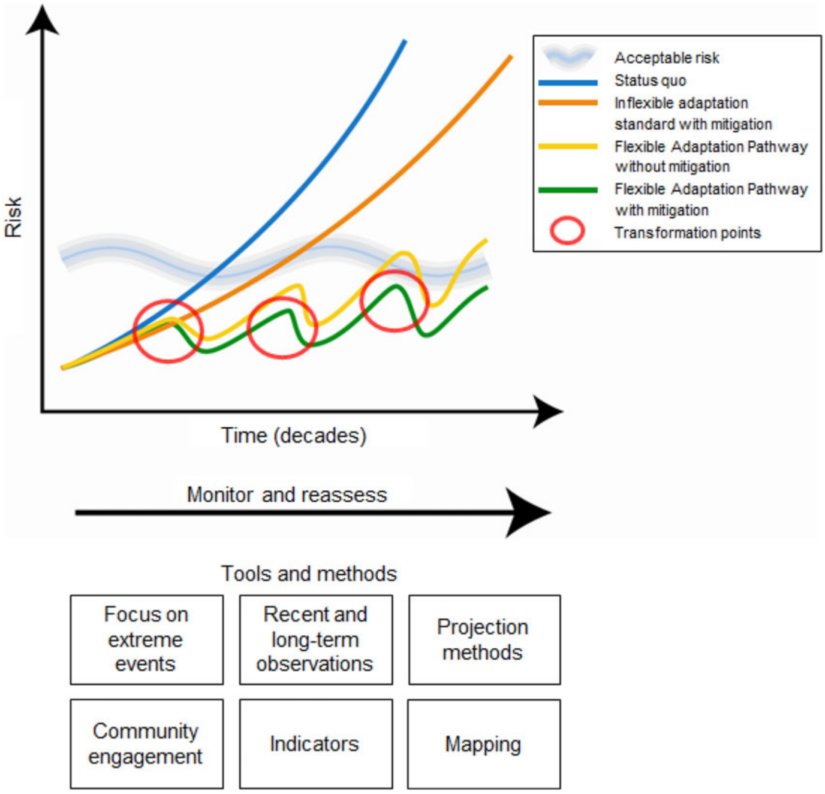

Figure ES.1. Tools and methods for implementing flexible adaptation pathways and transformation points presented in the NPCC 2019 Report.

encompassing the years 2010–2039 (Fig. ES.2a and ES.2b).

- However, these comparisons should be viewed with caution because of the role that natural variation plays on small spatial and short temporal scales.

[Correction added on June 12, 2019, after first online publication: In the bullet point above, "short timescales" was changed to "small spatial and short temporal scales."]

Projections of Record

Based on climate analyses, regional and global trends, and a review of scientific literature, NPCC3 confirms the NPCC2 2015 projections of temperature, precipitation, sea level rise, and coastal flooding for use in resiliency planning for the city and region.

New methods for extreme temperatures, heavy downpours, and droughts

Projected increases in the frequencies and intensities of extreme events pose particular challenges to New York City. The climate extremes considered in NPCC3 are extreme heat and humidity, heavy downpours, droughts, extreme winds, and cold snaps, as well as sea level rise and coastal flooding.

NPCC3 develops and tests new methods for observations and projections of extreme events to be used in resilience planning for the region. They utilize expanded observations, bias correction, and regional climate models (RCMs).

Extreme heat

NPCC3 analysis of extreme heat builds on NPCC2 projections for temperature extremes by expanding the number of reference weather stations and concentrating on the summer months.

- Decadal trends in annual average daily maximum summer temperatures in June, July, and August vary spatially across the city (Fig. ES.3). Central Park has experienced an increasing trend of 0.2 °F per decade from 1900 to 2013. Since 1970, annual average daily maximum summer temperatures have been rising

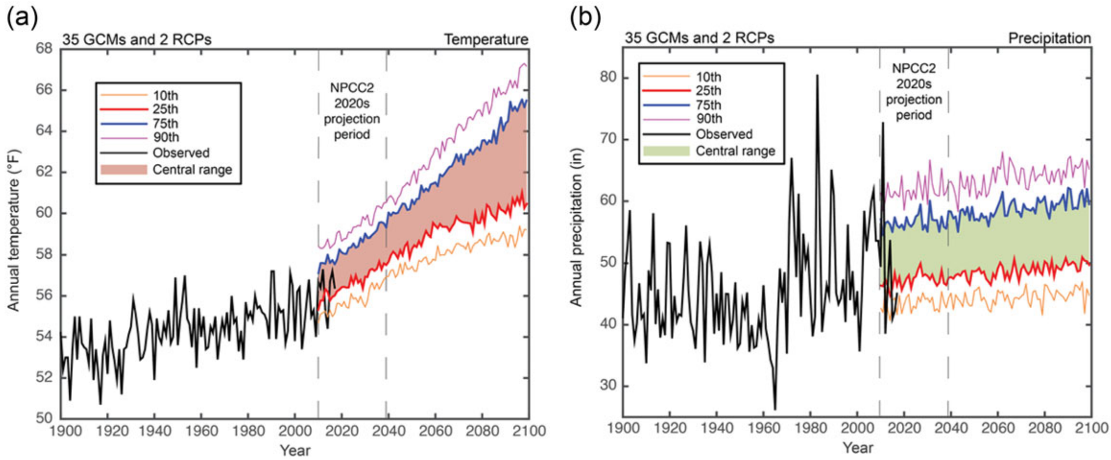

Figure ES.2. Observations at Central Park (1900–2017) compared to the 2020s (2010–2039) timeslice of NPCC2 projected changes for (a) average annual temperature and (b) average annual precipitation. Colored lines represent the 10th, 25th, 75th, and 90th percentiles of model projections across RCPs 4.5 and 8.5 for 35 GCMs. Shading shows the central range of projections between the 25th and 75th percentiles. Vertical dotted lines represent the range of the 2020s time slice from 2010 to 2039. Observed data are from the United States Historical Climatology Network (USHCN) and climate projections are from the Coupled Model Intercomparison Project Phase 5 (CMIP5). *Note:* These comparisons should be viewed with caution because of the role that natural variation plays on small spatial and short temporal scales.

[Correction added on June 12, 2019, after first online publication: In the last sentence of the legend for Figure ES.2, "in the short term" was changed to "on small spatial and short temporal scales."]

at rates of 0.5 °F per decade at JFK airport, and 0.7 °F per decade at LaGuardia airport.

- New projection methods for extreme heat events were developed and tested for the New York metropolitan region for use in future assessments of the NPCC. The new methods utilize bias correction, a method that adjusts the mean and variance of global climate model (GCM) results to match a representative set of observations from the region, and high-resolution RCMs to represent the spatial variation of future projections across the city.

Heavy downpours

NPCC3 analysis of heavy downpours and urban flooding builds on NPCC2 projections for daily extreme rainfall by more closely examining past and present rainfall across New York City and across

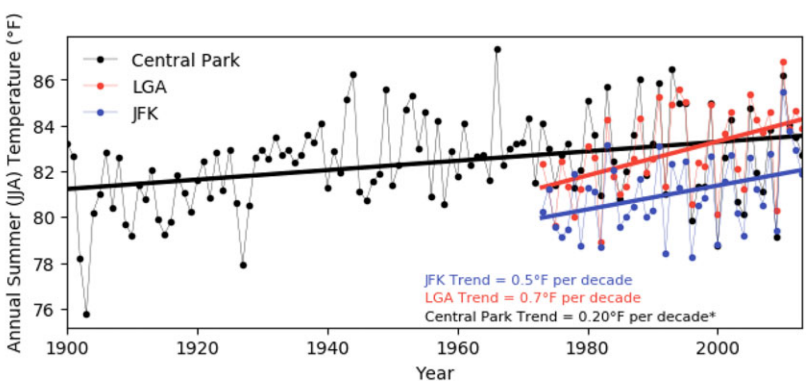

Figure ES.3. Annual average daily maximum summer temperatures (June, July, and August) at Central Park from 1900 to 2013, LGA Airport from 1970 to 2013, and JFK Airport from 1970 to 2013. Solid lines represent linear trend for each station. Station records were obtained from the U.S. Historical Climatology Network (USHCN) Version 2.5. *Central Park trend is significant at 0.01 level, while LGA and JFK trends are positive but not significant, possibly due to shorter record length.

Table ES.1. Comparison of NPCC2 daily extreme rainfall projections (1 inch, 2 inches, and 4 inches) for the 2020s time slice (2010–2039) to observed values at Central Park (2011–2017) and baseline values (1971–2000)

Heavy rainfall days	Baseline values (1971–2000)	NPCC2 2020s low estimate (10th percentile)	NPCC2 2020s middle range (25th–75th percentile)	NPCC2 2020s high estimate (90th percentile)	Observed values (2011–2017)
Number of days ≥1 inch	13	13	14–15	16	14.1
Number of days ≥2 inches	3	3	3–4	5	2.7
Number of days ≥4 inches	0.3	0.2	0.3–0.4	0.5	0.4

NOTE: These comparisons should be viewed with caution because of the role that natural variation plays on small spatial and short temporal scales.

[Correction added on June 12, 2019, after first online publication: In the note below Table ES.1, "in the short term" was changed to "on small spatial and short temporal scales."]

timescales. Heavy downpours are defined as rarely occurring rainfall at less than daily timescales that can produce urban flooding.

- Heavy downpours on the daily timescale are for the most part tracking the NPCC2 projected values for daily extreme rainfall in the region (Table ES.1). These comparisons should be viewed with caution because of the role that natural variation plays on small spatial and short temporal scales.

  [Correction added on June 12, 2019, after first online publication: In the bullet point above, "in the short term" was changed to "on small spatial and short temporal scales."]
- In the New York metropolitan region, extratropical cyclones (e.g., nor'easters) cause the greatest number of extreme daily precipitation events in each month of the year, compared to tropical cyclones (e.g., hurricanes) and non-cyclone rain events.
- Baseline data of urban flooding based on complaint calls indicate substantial spatial variation across NYC from 2004 to 2015 (Fig. ES.4). Separate sewers occur generally in the locations of higher flood complaints, avoiding combined overflows.

Droughts

NPCC3 uses tree-ring analysis to understand the long-term occurrence of drought in the New York

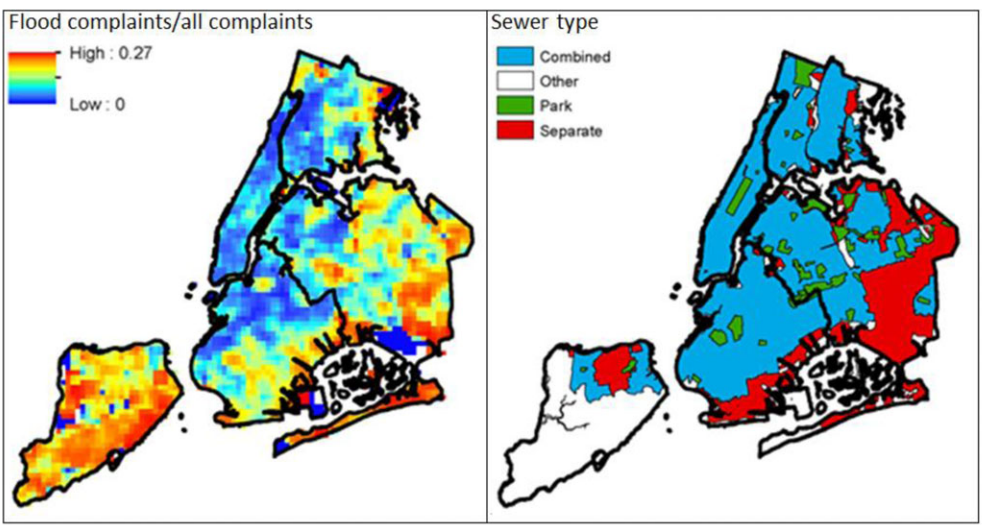

Figure ES.4. Flood reports to 311 for the period 2004–2015. Left panel: Flood reports to 311, normalized by all 311 reports. Units are in flood reports per any report in 0.5 mi^2. Right panel: NYC sewer type. Adapted from Smith and Rodriguez (2017).

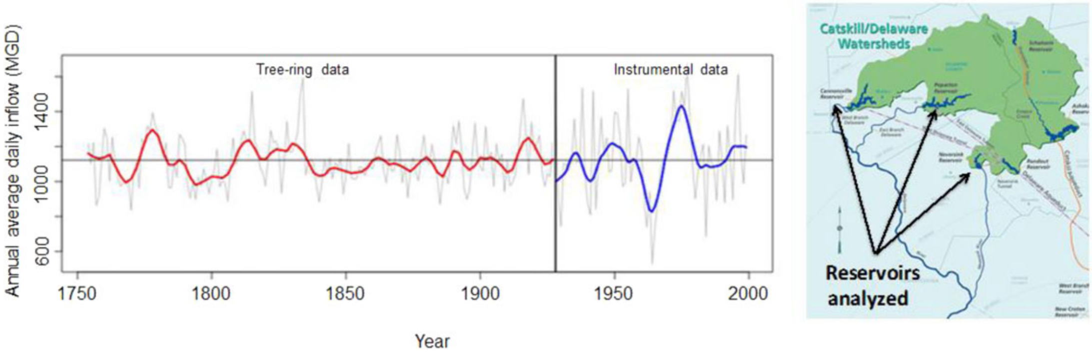

Figure ES.5. Reconstruction of combined annual average daily inflow from eight tree-ring chronologies in the Pepacton, Cannonsville, and Neversink Reservoirs from 1750 to 2000.

metropolitan region. Since tree growth is dependent on climate and since each tree-ring represents a season of growth, tree-ring measurements provide information on hydrological indicators over a tree's life span that can be used to understand long-term variations in climate.

- Analysis based on tree rings since 1750 shows that 8 five-year or longer droughts have occurred in the New York City watershed region over this 250-year period (Fig. ES.5).

Warming winters

NPCC3 analyzes trends in the number of days below freezing (a day where minimum temperatures reach less than or equal to 32 °F) in a year and in the number of cold days (a day with minimum temperatures less than or equal to the 10th percentile of daily minimum temperature of a given year) between 1900 and 2017 at the Central Park weather station.

- Days below freezing temperatures decreased at a rate of roughly 1.9 days per decade, with about 22 fewer days below freezing per year in 2017 than in 1900.
- The 10th percentile threshold for cold days was 24.1 °F from the entire 1900–2017 record. The number of cold days decreased about 1.5 days per decade, with about 17 fewer cold days per year in 2017 than in 1900.

New sea level rise scenario for long-term high-end risk awareness

Recent observations and modeling suggest the possibility of greater global mean sea level rise late in this century than previously anticipated, particularly under high greenhouse gas emission scenarios, due to rapid ice melt in the Antarctic.

To raise awareness of this emerging high-end risk, NPCC3 developed a new sea level rise Antarctic Rapid Ice Melt (ARIM) Scenario, which includes the possibility of Antarctic ice sheet destabilization later this century under continued warming at high greenhouse gas emissions rates. The ARIM Scenario represents a low-probability, upper-end case for the late 21st century.

This scenario is associated with high uncertainty due to incomplete knowledge about ice loss processes and atmosphere, ocean, and ice sheet interactions, and how fast these processes and interactions may proceed. Nevertheless, because of the potentially severe consequences of such a low-probability upper-end outcome, city planners should be aware of this growing risk.

- Sea level at The Battery has been rising at a rate of 0.11 inches per year since 1850.
- Sea level rise in New York City is higher than the global average because of the region's ongoing land subsidence in response to retreat of ice age glaciers and warmer ocean waters nearby.
- Recent evidence has shown that Antarctica is increasingly contributing to global sea level changes, indicating a need to better understand how this could amplify future sea level rise projections.
- The new upper-end, low-probability NPCC3 ARIM Scenario projects 6.75 ft in the 2080s and 9.5 ft of sea level rise by 2100. This projection takes into account the latest developments in ice sheet behavior and supplements the current

Table ES.2. New York City sea level rise projections relative to 2000–2004, including the NPCC2 2015 projections of record for planning and the new Antarctic Rapid Ice Melt (ARIM) scenario for risk awareness

	NPCC2 2015 sea level rise projections[a]			NPCC3 ARIM scenario[b]
	Current projections of record for planning			Growing awareness of long-term risk
Baseline (2000–2004) 0″	Low estimate (10th percentile)	Middle range (25th–75th percentile)	High estimate (90th percentile)	ARIM scenario
2020s	0.17 ft	0.33–0.67 ft	0.83 ft	–
2050s	0.67 ft	0.92–1.75 ft	2.5 ft	–
2080s	1.08 ft	1.50–3.25 ft	4.83 ft	6.75 ft
2100	1.25 ft	1.83–4.17 ft	6.25 ft	9.5 ft

[a]The 10th, 25th–75th, and 90th percentile projections are from NPCC2 (2015); they are based on six components that include global and local factors. This report confirms the use of the NPCC (2015) sea level rise projections for decision-making.
[b]ARIM represents a new, physically plausible upper-end, low-probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from recent modeling of ice sheet–ocean behavior. However, uncertainties remain regarding ice sheet processes and atmosphere, ocean, and ice sheet interactions.

NPCC 2015 projections used by the city for planning (Table ES.2).

- Although many future global sea level rise projections end in 2100, the longevity of atmospheric CO_2 commits the planet to higher temperatures and sea levels long after reduction and stabilization of greenhouse gas emissions. Sea level in the New York metropolitan region is projected to continue to rise well beyond 2100.

Coastal flooding

Rising sea levels will result in coastal flooding, one of the most dangerous and damaging natural hazards that societies face. Extreme water levels are increasing globally, mainly driven by rise in mean sea levels. To inform decision-making in the region, NPCC3 analyzes sea level rise effects on monthly tidal flooding, uses of a broadened set of sea level rise scenarios including the Antarctic Rapid Ice Melt (ARIM) scenario, and examines the latest science on extreme winds.

- If the city experiences high-end (NPCC2 2015 90th percentile) sea level rise, monthly tidal flooding will begin to affect neighborhoods around Jamaica Bay by the 2050s and many other areas by the 2080s.
- A new approach for mapping monthly tidal flooding through mean monthly high water (MMHW) provides a broadened perspective on future flood risk, and serves as a useful indicator of when areas may begin to be affected by recurring "sunny-day" flood events due to sea level rise.

Mapping climate risk

This report continues the use of the NPCC2 2015 projections for the 100-year flood map, and presents two new coastal flood maps illustrating potential mean sea level and monthly tidal flooding. New coastal floodplains have been added to each map to illustrate the upper-end, low-probability ARIM scenario.

Two new data products have yielded significant advancements in the mapping methodology and results: a new LiDAR data set (2017) for NYC and a more accurate digital elevation model (DEM) used to depict baseline topography.

- NPCC3 mapped 100-year (1% annual) recurrence-interval flooding associated with sea level rise for the 90th percentile scenario (NPCC 2015) and the ARIM scenario (Fig. ES.6).

Community-based assessments of adaptation and equity

Vulnerability to climate change in New York City varies across social groups, economic levels, and neighborhoods. Spatial analysis of vulnerability can aid in the targeting of adaptation resources. There is broad recognition of the need to involve local communities earlier and more often into adaptation decision-making.

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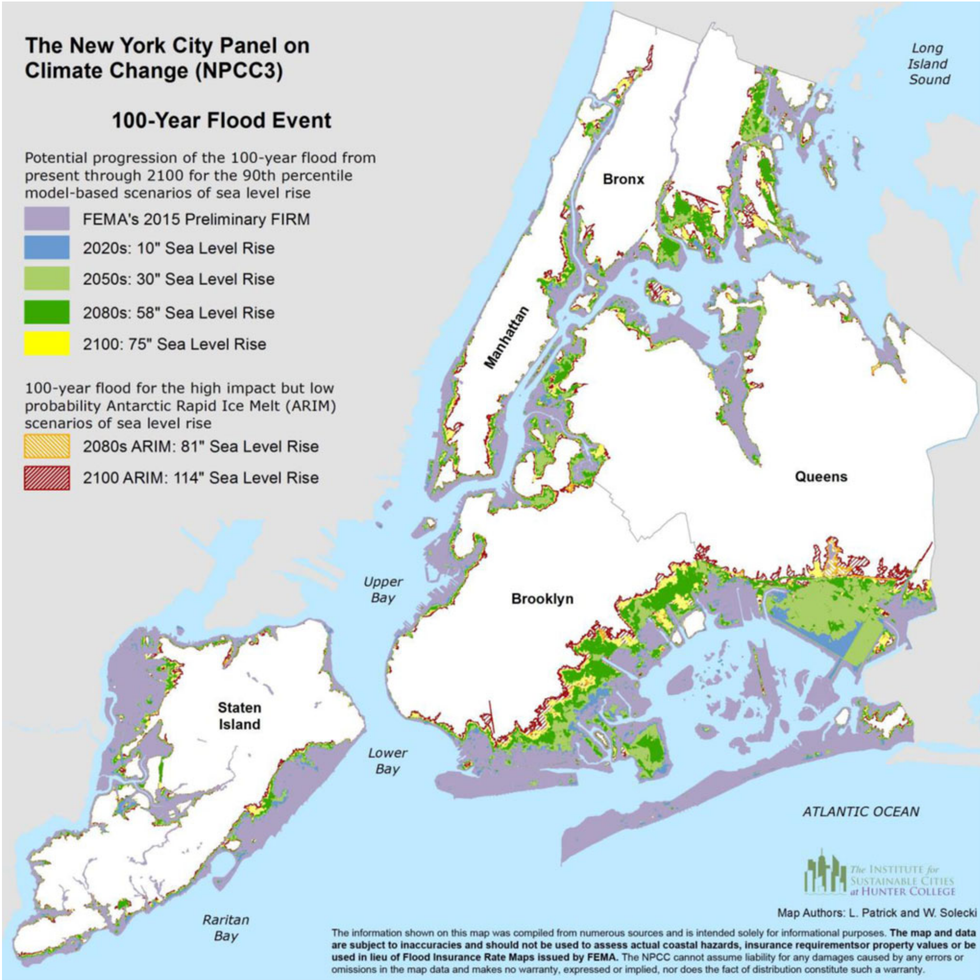

Figure ES.6. Potential progression of the 100-year floodplain from present through 2100 for the 90th percentile model-based projections and the ARIM scenario of sea level rise. *Note:* The areas delineated on this map do not represent precise flood boundaries but rather illustrate distinct areas of interest: (1) Areas currently subject to flooding that will continue to be subject to flooding in the future; (2) Areas that do not currently flood but are expected to potentially experience flooding in the future; and (3) Areas that do not currently flood and are unlikely to do so in the timeline of the climate projection scenarios (end of the current century). All spatial data contain uncertainty and error; as a result NPCC maps should be considered as representations of current and potential future conditions. The case of ARIM, a higher-impact but lower-probability sea level rise scenario, is included to raise awareness, but not for planning purposes.

- Social vulnerability to climate change hazards is unequally distributed across NYC; high levels of social vulnerability are consistently found in areas with lower incomes and higher shares of African American and Hispanic residents (Fig. ES.7).
- Collaboratively produced case studies (northern Manhattan; Hunts Point, South Bronx; and Sunset Park, Brooklyn) demonstrate that high levels of social vulnerability to climate change overlap with disproportionate exposure to environmental pollution, health stressors, and gentrification pressures.
- Communities are involved in many forms of adaptation planning (e.g., traditional government-led, inclusive, nongovernmental), but express a desire for deeper engagement with the city via use of fully collaborative, co-production planning approaches.
- Recognizing this importance, New York City has made community engagement a central component of the OneNYC planning process

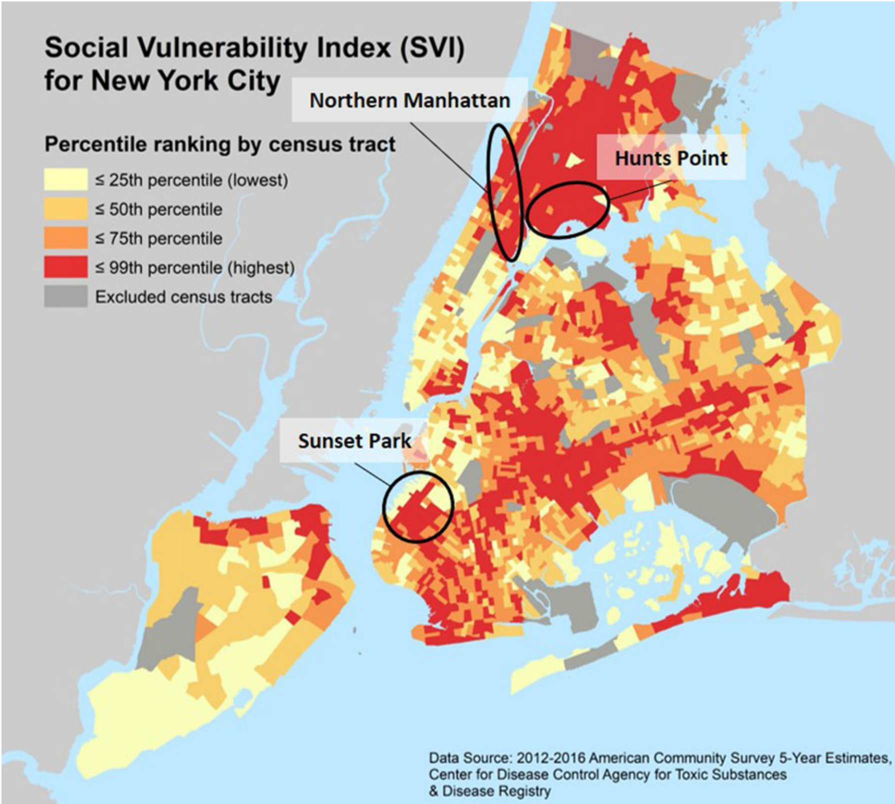

Figure ES.7. Social Vulnerability Index (SVI) for New York City. The SVI utilizes 15 indicators categorized into four themes: socioeconomic status, household composition and disability, minority status and language, and housing and transportation. NPCC3 community case study neighborhoods are circled. (Map constructed by NPCC3 Community-Based Adaptation Workgroup.)

and will continue to prioritize it using fully collaborative adaptation approaches.

- Cross-city analysis reveals that New York and other cities in the Northeast are incorporating equity in their adaptation planning, but largely emphasize distributional equity in these efforts.

Resilience strategies for critical infrastructure

NPCC3 analyzes dependencies and interdependencies among infrastructure systems to examine how climate change will exacerbate the risks associated with these connections. The infrastructure sectors covered are energy (electricity), transportation, telecommunications, and water/waste/sewer. It also examines risks to energy infrastructure in the context of two sectors on which communities strongly depend, hospitals and housing (Box ES.1).

Vulnerabilities, dependencies, and interdependencies

- Critical infrastructure in the New York metropolitan region has underlying vulnerabilities that are not directly related to climate change, which affect the region's resilience or ability to withstand climate change stresses. Examples include age, deterioration, construction or maintenance flaws, and usage exceeding capacity. All of these indicate potential vulnerabilities for New York City that can interact with climate risks.
- Critical infrastructure is directly vulnerable to climate change risk factors, such as extreme heat, heavy downpours, sea level rise, and coastal storms, depending on their location.
- Interdependent infrastructures create vulnerabilities that can develop into cascading impacts. These include water, energy,

Box ES.1. Community-based infrastructure dependencies and resilience strategies

Hospitals. NYC's 62 hospitals are dependent on transportation, power, and water, especially in emergencies. Many hospitals are in locations at risk of flooding. Hospital Row is an area along the East River in Manhattan, between East 23rd to 34th Streets and First Avenue, where three at-risk hospitals are situated. The vulnerability of these facilities to climate-related extreme events is shown by the impacts that Hurricane Sandy had on them in 2012. Five acute-care hospitals shut down in NYC due to Hurricane Sandy, and there were substantial delays in returning to normal functioning. Adaptation planning with consideration of hospital capacity and lifeline infrastructure in vulnerable areas will be essential for minimizing costs and damages to health institutions during and after future extreme weather events.

NYC Housing Authority (NYCHA). During Hurricane Sandy, infrastructure service outages affected hundreds of buildings and thousands of residents. The infrastructure systems of these residential buildings sustained significant damage—residents endured loss of electricity, elevators, heat, and hot water. NYCHA housing in Coney Island, Brooklyn, for example, sustained significant damage from sand and saltwater infiltration, while damage to other NYCHA housing was mostly the result of flooding. NYCHA's challenges during Hurricane Sandy have underscored the dependence of NYCHA infrastructure systems for heat, hot water, elevators, trash compacting, and other functions on grid-connected electrical power. Incorporating distributed energy resources into the power systems of apartment complexes in neighborhoods vulnerable to sea level rise, storm surge, and heat waves is one way to rethink and adjust the mix of energy sources, access to power during emergencies, and carbon emissions.

transportation, and information technology (IT) systems.

Insurance and finance

- Economic losses from hurricanes and floods have significantly increased in past decades and are likely to increase further in the future from more intense hurricanes and higher sea level rise.
- Insurance can be a catalyst for infrastructure resilience by encouraging investment in adaptation measures prior to a disaster through a reduction in premiums to reflect lower claim payments.
- Financing mechanisms for enhancing the resilence of NYC's infrastructure need to draw from diverse sources, in particular with respect to local, state, and federal agencies, and the private sector.

Links to mitigation

- Mitigation and adaptation strategies for critical infrastructure need to be coordinated to amplify synergies, avoid trade-offs, and to ensure equity.
- New construction and major renovation of infrastructure in the public and private sectors offer major opportunities to reduce CO_2 emissions and transition to lower-carbon, greener-energy feedstocks that can be coupled with initiatives to reduce water and waste footprints in the built environment.

Indicators and monitoring

Figure ES.8 depicts the operational components of the proposed New York City Climate Change Resilience Indicators and Monitoring (NYCLIM) system. These components include data collection agencies and processing centers, and online repositories of climate change adaptation databases that are equipped with references, resources, topical categories, and key words.

The proposed system includes community–stakeholder partnerships that inform decision makers and contribute to prudent, equitable, and scientifically sound climate change policy. The system would also be robust and flexible enough to incorporate ongoing research and new knowledge, the potential for indicators to change, and for new indicators to be developed.

An initial set of indicators for the energy and transportation sectors was co-generated in concert with practitioners from several city and regional agencies. NPCC3 further explores how indicators may track interdependencies among infrastructure systems.

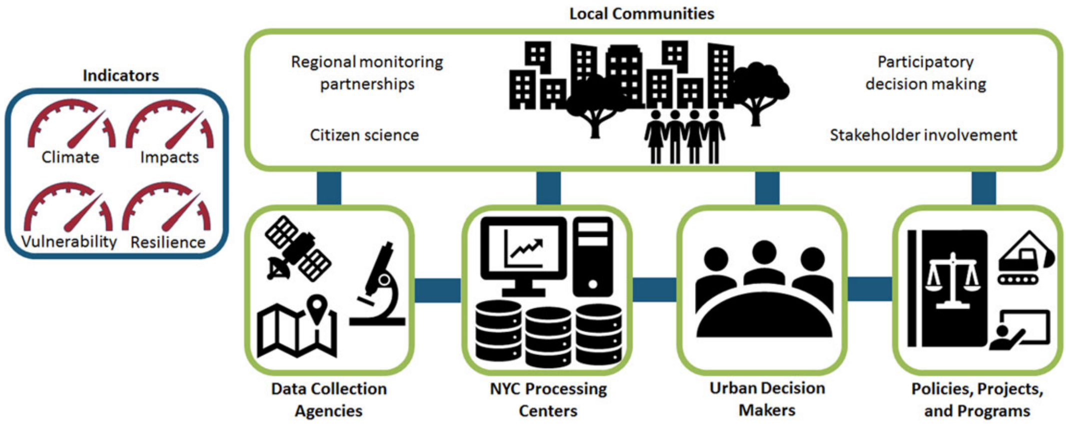

Figure ES.8. Prototype structure and functions of the proposed New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM). The proposed system tracks four types of indicators from data collection agencies, processing centers, urban decision makers, and policies, projects, and programs. The proposed NYCLIM system is co-generated by scientists, practitioners, and local communities to determine which indicators should be tracked over time to provide the most useful information for planning and preparing for climate change in New York City.

Indicator and monitoring system

- A centralized, coordinated indicators and monitoring system is essential for a comprehensive, city-wide risk assessment of trends in climate and impacts and course correction toward climate change adaptation and resiliency goals and targets. Damage to energy assets from extreme storms like Hurricanes Irene and Sandy is an example of the types of indicators that can be tracked in the proposed NYCLIM system (Fig. ES.9).
- To detect trends and differences across sectors and to allow for effective comparisons, spatial and temporal scales of indicators need to be consistent and comparable.

Infrastructure system indicators

- Illustrative indicators for energy sector transmission and distribution under extreme heat and humidity include reduction in transmission due to sag in overhead power lines, complaint and fire department emergency calls, and power outages and brownouts.
- A set of preliminary, decision-support indicators for the transportation sector have been

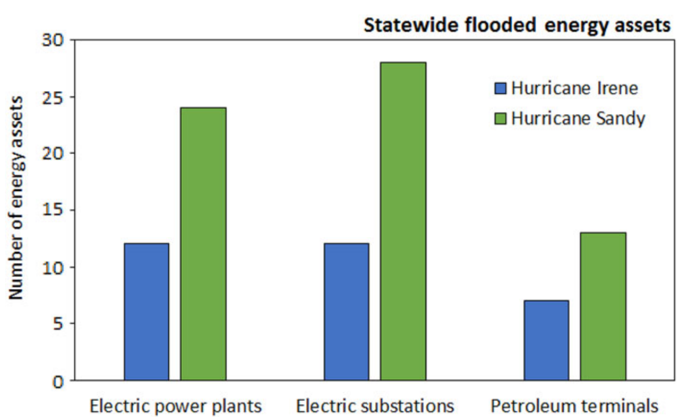

Figure ES.9. Comparative damages to energy assets in flooded areas in New York (statewide) during Hurricanes Irene (2011) and Sandy (2012). *Source:* Data from U.S. DOE (2013).

identified as being critical to the city's adaptive responses to promote resilience.

Financial indicators[d]

- The city's credit rating was stable through Hurricane Sandy (2012) despite major damages.
- As credit rating agencies incorporate climate change into their risk analyses, indicators such as coastal flood heights and number of vulnerable properties in the flood plain can be included in NYCLIM for tracking and evaluation.

Conclusions and recommendations

Understanding climate change in cities is important because of the dramatic growth in urban populations and thus vulnerability, as well as the emerging role of cities as first responders to climate change. Since 2008, the New York Panel on Climate Change (NPCC) has analyzed climate trends, developed projections, explored key impacts, and advised on response strategies. Charting a future course for the NPCC ensures that NYC continues to play its role as a climate change leader for other cities, not only in the United States but around the world.

Overall NPCC3 Report recommendations

- The City should establish a pilot climate indicators and monitoring system (NYCLIM).
- The City should task the NPCC to coordinate with other regional organizations, such as the Consortium for Climate Risk in the Urban Northeast (CCRUN), to conduct integrated climate assessments for the New York metropolitan region on a regular basis. These assessments should encourage the participation of a wide range of city and regional agencies and communities, and a full range of systems and sectors.
- As the City complies with Local Law 42 of 2012, the next generation of projections should incorporate updated methods and analyses, such as presented in the NPCC 2019 Report.
- The City and the NPCC should host a climate summit once every mayoral term in order to bring together the key groups working on climate change around the New York metropolitan region: scientists, practitioners, decision makers, and stakeholders. The climate summits will provide opportunities for inclusive discussion on flexible adaptation pathways to achieve climate resilience in the region.

[d]Financial indicators were developed in collaboration with the NYC Comptroller's Office. Adoption of financial indicators would require NYC Office of Management and Budget and Bond Council review.

Data Sources

Figure ES.2.
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Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report Chapter 1: Introduction

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Keywords: NPCC 2019; climate change; New York; metropolitan region; risk assessment

While urban areas like New York City and its surrounding metropolitan region are key drivers of climate change through emissions of greenhouse gases, cities are also significantly impacted by climate shifts, both chronic changes and extreme events. These are already affecting the New York metropolitan region, including the five boroughs of New York City through higher temperatures, more intense precipitation, and higher sea levels, and will increasingly do so in the coming decades.

The City of New York has embarked on a flexible adaptation pathway (i.e., strategies that can evolve through time as climate risk assessment, evaluation of adaptation strategies, and monitoring continues) to respond to climate change challenges. This entails significant programs to develop resilience in communities and critical infrastructure to observed and projected changes in temperature, precipitation, and sea level.

The first NPCC Report laid out the risk management framing for the city and region via flexible adaptation pathways (Rosenzweig and Solecki, 2010). The second New York City Panel on Climate Change Report (NPCC2) developed the "climate projections of record" that are currently being used by the City of New York in its resilience programs (Rosenzweig and Solecki, 2015).

The NPCC3 2019 Report co-generates new tools and methods for the next generation of climate risk assessments and implementation of region-wide resilience. *Co-generation* is an interactive process by which stakeholders and scientists work together to produce climate change information that is targeted to decision-making needs. These tools and methods can be used to observe, project, and map climate extremes; monitor risks and responses; and engage with communities to develop effective programs (Fig. 1.1). They are especially important at "transformation points" in the adaptation process when large changes in the structure and function of physical, ecological, and social systems of the city and region are undertaken.

Stakeholder interactions and co-generation

Engagement with stakeholders and users of climate information has been emphasized throughout the NPCC process from the beginning in 2008. NPCC3 members interacted with a variety of stakeholders, including members of city government agencies, infrastructure managers, and communities to "co-generate" the information that is presented in this report. These interactions included communicating over email, phone calls, and in-person meetings or workshops, as well as discussing relevant science needs that decision makers have from the start, and reviewing draft report text, figures, and data. Throughout this process, NPCC3 scientists responded to and incorporated stakeholder feedback into the final NPCC3 Report.

doi: 10.1111/nyas.14004

Ann. N.Y. Acad. Sci. 1439 (2019) 22–29

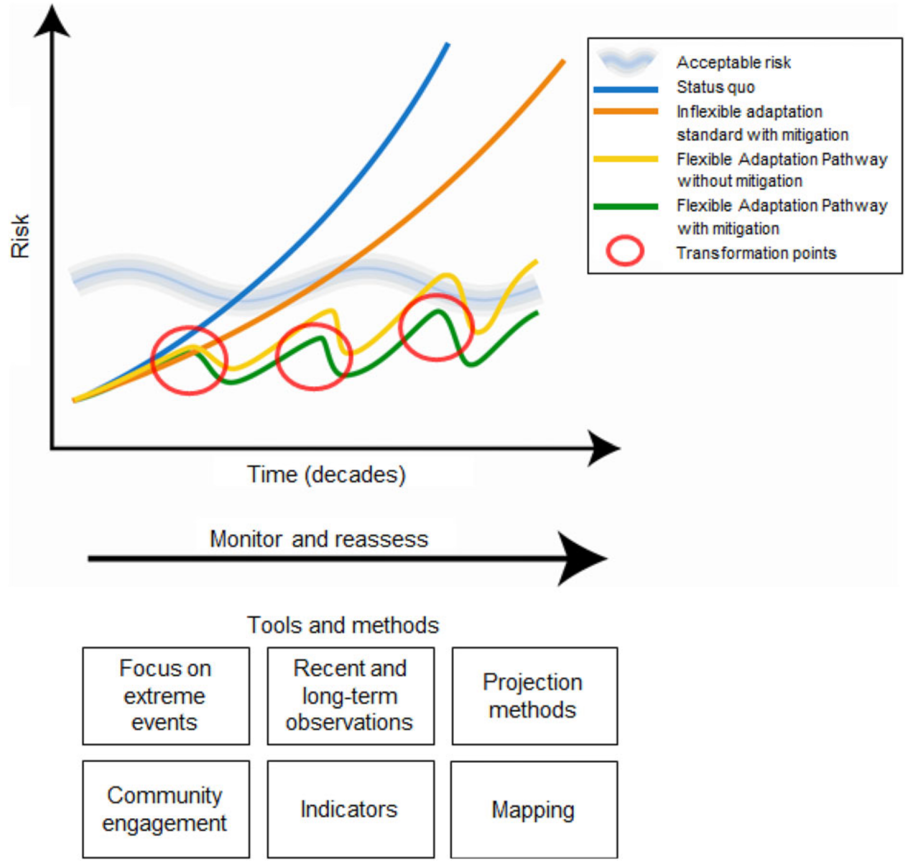

Figure 1.1. Tools and methods for implementing Flexible Adaptation Pathways and Transformation Points discussed in the NPCC 2019 Report.

To integrate feedback from community members, NPCC3 scientists interacted with community groups from three neighborhoods in the city: Sunset Park in Brooklyn, Harlem in northern Manhattan, and Hunts Point in the Bronx. In addition, the members of the work group engaged with city agencies to understand their interactions with community members in responding to the risks of climate change and environmental justice. The specific interactions that NPCC3 members had with community stakeholders are discussed in greater detail in Chapter 6, Community-Based Assessments of Adaptation and Equity.

In the development of the proposed New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM) outlined in this report, NPCC3 engaged in a range of stakeholder interactions. This included meetings with individual infrastructure managers that took place over the phone, in-person, and over email, workshops with members of the New York City Climate Change Adaptation Task Force (CCATF), and reviews of NPCC3 proposed indicators by relevant New York City government agencies and infrastructure managers. The interactions that took place between the NPCC3, the city, and infrastructure stakeholders are discussed in detail in Chapter 7, Resilience Strategies for Critical Infrastructures and Their Interdependencies, and in Chapter 8, Indicators and Monitoring.

Key concepts

Several key concepts undergird the work of NPCC3, which focuses on the development of tools and methods for flexible adaptation pathways and integration of climate science and policy. These include1 adaptation, flexible adaptation pathways, impacts,

Box 1.1. Key definitions

Adaptation: The process of adjustment to actual or expected climate change and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.
Flexible adaptation pathways: A sequence of adaptation strategies that policymakers, stakeholders, and experts develop and implement that evolve as knowledge of climate change progresses.
Impacts: Effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences or outcomes. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.
Resilience: The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.
Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability or likelihood of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. In this report, the term risk is often used to refer to the potential, when the outcome is uncertain, for adverse consequences on lives, livelihoods, health, ecosystems and species, economic, social and cultural assets, services (including environmental services), and infrastructure.
Transformation: A change in the fundamental attributes of natural and human systems; the trajectory taken over time to meet different goals for greenhouse gas (GHG) emissions, atmospheric concentrations, or global mean surface temperature change that implies a set of economic, technological, and behavioral changes. This can encompass changes in the way energy and infrastructure are used and produced, natural resources are managed, and institutions are set up in the pace and direction of technological change.
Uncertainty: Uncertainty denotes a state of incomplete knowledge that results from lack of information, natural variability in the measured phenomenon, instrumental and modeling errors, and/or from disagreement about what is known or knowable (IPCC, 2013). See Box 1.2 for information on sources of uncertainty in climate projections.

Source: IPCC, 2014; Rosenzweig and Solecki, 2010; Rosenzweig and Solecki 2015.

resilience, risk, and transformation. For definitions of these concepts, see Box 1.1.

Organizational structure for responding to climate change

The structure of the New York City response to developing resilience to climate change is shown in Figure 1.2. Collaboration with communities is essential to the design and implementation of resilience programs and can help ensure that measures take local context into account. Recognizing this importance, New York City has made community engagement a central component of the OneNYC planning process and will continue to prioritize it through the use of fully collaborative adaptation planning approaches.

Spatial and temporal scales

The tools and methods developed for the NPCC3 2019 Report are for use by the metropolitan region over long-term, medium-term, and short-term timeframes. The spatial domain of the NPCC3 Report is the entire New York metropolitan region, consisting of 31 counties across New York State, New Jersey, and Connecticut (Fig. 1.3). This is important because many of the critical infrastructure systems extend far beyond the five boroughs. Further, regionally coordinated approaches to climate change resilience can help in scaling up adaptation and lessening widespread vulnerability.

Those responsible for developing resilience strategies for communities and critical infrastructure across the region need to understand how

Figure 1.2. Organizational structure of the New York City response to developing resilience to climate.

climate is projected to change in the short (2020s), medium (2050s), and long term (2080s, 2100, and beyond), because planning horizons often differ depending on type of activities and assets. The 2020s, 2050s, and 2080s timeframes are embedded in the NYC Climate Resilience Design Guidelines, which are based on NPCC2 projections (NYC ORR, 2018). These timeframes are also included in the NPCC adaptation framework steps to call out the explicit decision pathways relevant to these short-, medium-, and long-term periods (Fig. 1.4). Because climate change is a very long-term process, NPCC3 has begun to research potential changes in climate in the New York metropolitan region beyond 2100, especially regarding sea level rise.

Observations and projections

NPCC3 analyzes how recent temperature and precipitation trends (from 2010 to 2017) compare to the projections that NPCC made in 2015 for the New York metropolitan region. The goal is to understand how well what the New York metropolitan region is experiencing tracks the projections. The analysis finds that observed annual temperatures and precipitation increases are tracking the projections. These comparisons should be viewed with caution because of the role that natural variation plays in the short term.

Climate extremes

NPCC3 has a special focus on six climate extremes: extreme heat and humidity, heavy downpours, droughts, sea level rise and coastal flooding, extreme winds, and cold snaps. The city and region is already experiencing changes in some of these, and changes in some are predicted to occur in the future. These climate extremes are covered in various chapters throughout the NPCC3 Report (Table 1.1).

Uncertainty

Box 1.2. Sources of uncertainty in climate projections

Uncertainty regarding factors affecting the Earth radiative balance, such as future concentrations of GHGs and aerosols (particularly black carbon) and land use changes. Future concentrations will depend on population and economic growth, technology, and biogeochemical feedbacks (e.g., methane release from permafrost in a warming Arctic). Multiple representative concentration pathways are used to explore possible futures.

Sensitivity of the climate system to changes in GHGs and other "forcing" agents. Climate models are used to explore how much warming may occur for a given change in radiatively important agents. The direct temperature effects of increasing CO_2 are well understood, but models differ in their feedbacks (such as changes in clouds, water vapor, and ice with warming) that determine just how much warming ultimately will occur. A set of climate models is used to sample the range of such outcomes.

Regional and local changes that may differ from global and continental averages. Climate model results can be statistically or dynamically downscaled, but some processes may not be captured by existing techniques. Examples include changes in land–sea breezes and the urban heat island effect. In statistical downscaling approaches, results are sensitive to the method of adjusting the model output to represent the observed mean and variability of the weather in the target domain. Dynamical downscaling results depend on the high-resolution, regional model in use and global model used to provide boundary conditions.

Natural variability that is largely unpredictable over the long time ranges addressed in this report, especially in mid-latitude areas such as the New York metropolitan region. Even as increasing GHG concentrations gradually shift weather and climate, random elements will remain important, especially for extreme events and over short time periods. Chaos theory has demonstrated that natural variability can be driven by small initial variations that amplify thereafter. Other sources of natural variability include the El Niño Southern Oscillation (ENSO) and solar cycles.

Observations include uncertainties as well. These matter when comparing model projections to baseline conditions or when developing downscaling and model bias correction schemes. Sources of observational uncertainty include poor location of weather stations, instrument errors, and errors involved in data processing and maintenance.

Contents of the NPCC3 Report

The NPCC3 2019 Report consists of three sections: Urban Climate Science, Community Resilience and Critical Infrastructure, and Charting Adaptation Pathways.

The four chapters of the *Urban Climate Science* section focus on climate extremes (Chapter 2), sea level rise (Chapter 3), coastal flooding (Chapter 4), and mapping (Chapter 5). Chapter 2, entitled New Methods for Assessing Extreme Temperatures, Heavy Downpours, and Drought, develops and tests new methods for observations and projections to be used in resilience planning for the region. Using expanded observations, bias correction, and regional climate models, these methods provide quantitative analyses for heat and cold extremes, heavy downpours, and drought. They are available for developing the next full set of NPCC projections.

The heat section expands the number of weather stations from the one (Central Park) in NPCC2 to three (Central Park, LaGuardia, and JFK) in NPCC3 enabling a more spatially disaggregated analysis across the city. It develops new methods for projections of heat wave characteristics including heat wave frequency, heat wave duration, maximum temperature during a heat wave, and humidity, and analyzes observed trends in heavy downpours and long-term records of droughts in the region.

In Chapter 3, the NPCC3 reaffirms the NPCC2 2015 sea level rise projections as the basis of decision making in the region. For late in the century, new developments suggest the possibility of greater global mean sea level rise than previously anticipated, particularly under high greenhouse gas emission scenarios. To take these high-end risks into account, NPCC developed a new SLR scenario, Antarctic Rapid Ice Melt (ARIM) for the 2080s and 2100, which includes the possibility of Antarctic Ice Sheet destabilization. This scenario is associated with high uncertainty due to lack of knowledge about ice loss processes and atmosphere, ocean, and ice-sheets interactions. ARIM represents an upper-end, low-probability case for the late 21st century.

Since it may not be possible to find solutions to keep rising seas out of all neighborhoods, a shift of paradigm is needed to consider living with higher sea levels and more frequent and intense coastal flooding.

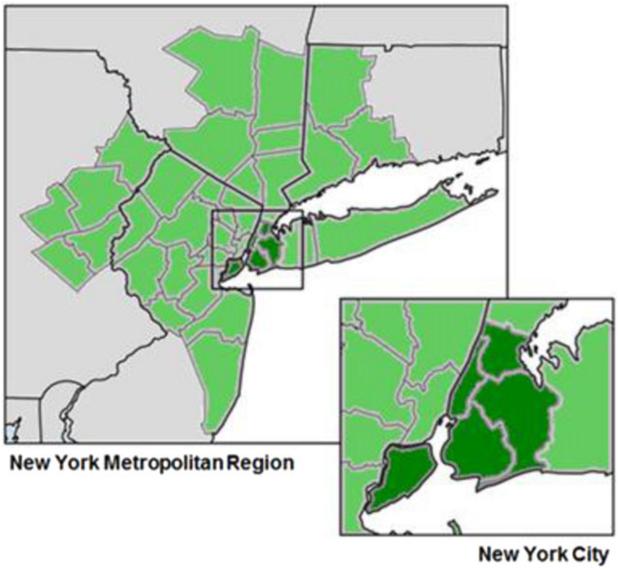

Figure 1.3. The New York metropolitan region is the spatial domain of NPCC3 (as in Rosenzweig and Solecki, 2001).

Coastal flooding is one of the most dangerous and damaging natural hazards that societies face. Extreme water levels are increasing globally, mainly driven by rises in mean sea level. In Chapter 4, Coastal Flooding, NPCC3 continues to use FEMA's 1% annual chance floodplain as a baseline extreme flood hazard. New to this chapter is a review of the latest science, a dynamic model-based analysis of monthly tidal flooding, a broadened set of sea level rise scenarios including the ARIM scenario,

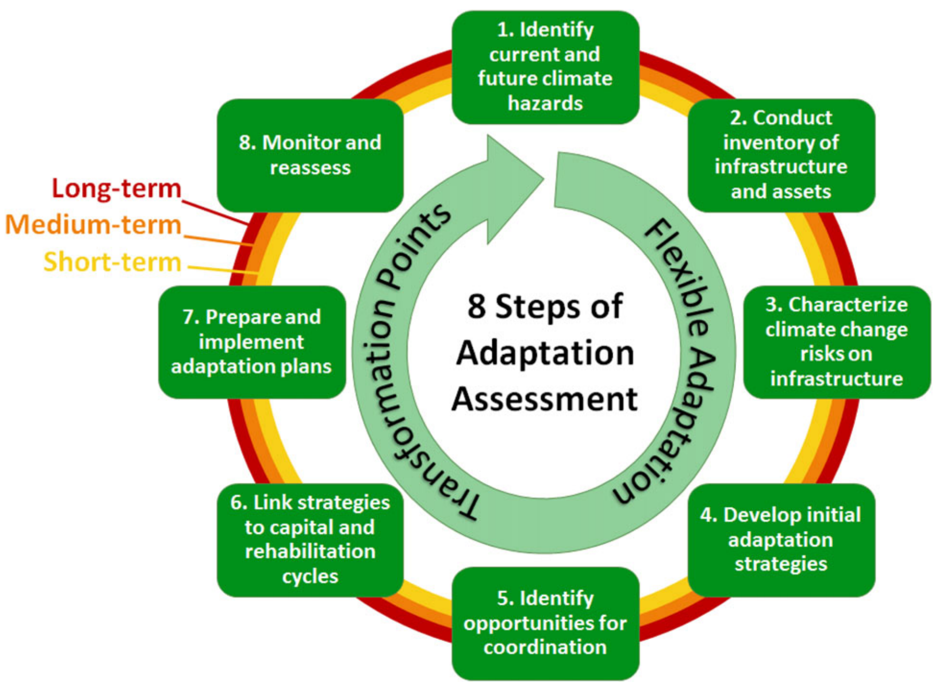

Figure 1.4. Adaptation steps across long-term (2080s, 2100, and beyond), medium-term (2050s), and short-term (2020s) time frames (modified from Adaptation Steps diagram in the NPCC 2010 Report, Rosenzweig & Solecki, 2010).

Table 1.1. Six climate extremes and the NPCC3 chapters in which these are considered

Climate extreme	Chapter 3: Extreme temperatures, heavy downpours, and drought	Chapter 4: Sea level rise	Chapter 5: Coastal flooding	Chapter 6: Community-based assessments of adaptation and equity	Chapter 7: Critical infrastructure systems	Chapter 8: Indicators and monitoring
Extreme heat and humidity	X			X	X	X
Heavy downpours	X				X	
Drought	X				X	
Sea level rise and coastal flooding		X	X	X	X	X
Extreme winds			X		X	
Cold snaps	X				X	X

and sensitivity analyses that show how differing methods affect results.

Since it may not be possible to find solutions to keep rising seas out of all neighborhoods, a shift of paradigm is needed to consider living with higher sea levels and more frequent and intense coastal flooding.

Chapter 5, Mapping Climate Risk, focuses on the analysis and presentation of spatial climate risk information. The chapter focuses primarily on flood risk and presents new coastal inundation and flooding maps associated with the ARIM scenario utilizing a new LiDAR dataset for New York City and an improved digital elevation model used to depict baseline topography. The new LiDAR data, collected in 2017, are an update from the 2010 dataset and capture recent areas of changed shoreline. The information includes empirical or observed data and model projections. However, all spatial data involve uncertainty and error.

The second section of the NPCC3 Report, *Community Resilience and Critical Infrastructure*, consists of two chapters, Community-based Assessments of Adaptation and Equity (Chapter 6) and Resilience Strategies for Critical Infrastructures and Their Interdependencies (Chapter 7). Chapter 6 analyzes vulnerability to climate change in the New York metropolitan region and how it varies across social groups, economic levels, and neighborhoods. It considers how spatial analysis can provide guidance on the location of socially vulnerable neighborhoods and can aid in the targeting of adaptation resources. The chapter presents variables or indicators to assess and track spatial patterns of vulnerability at the neighborhood level; case studies of community adaptation in three socially vulnerable neighborhoods: northern Manhattan, Sunset Park, and Hunts Point; and ways to incorporate equity into adaptation planning at the city level.

Climate change poses many challenges to infrastructure in New York City. Chapter 7, Resilience Strategies for Critical Infrastructures and Their Interdependencies, builds upon earlier NPCC work on climate change and critical infrastructure systems and provides new directions, updates, and considerations. Heat waves, heavy downpours, and droughts are added as additional variables posing a threat to infrastructure. NPCC3 analyzes dependencies and interdependencies among infrastructure systems to examine how climate change will exacerbate the risks associated with these connections. It also examines risks to infrastructure in the context of two communities that depend on them: hospitals and housing. Two case studies on hospitals in Manhattan and the NYC Housing Authority are presented, as well as the role of insurance and finance in preparing for the impacts of climate change on infrastructure systems. Given the importance of both mitigation and adaptation to responding to climate change, the chapter explores synergies and trade-offs between them.

The third section, *Charting Adaptation Pathways*, addresses the need for indicators and monitoring of climate changes and responses, and provides perspectives on the work of the NPCC since its inception in 2008. Chapter 8, Indicators and

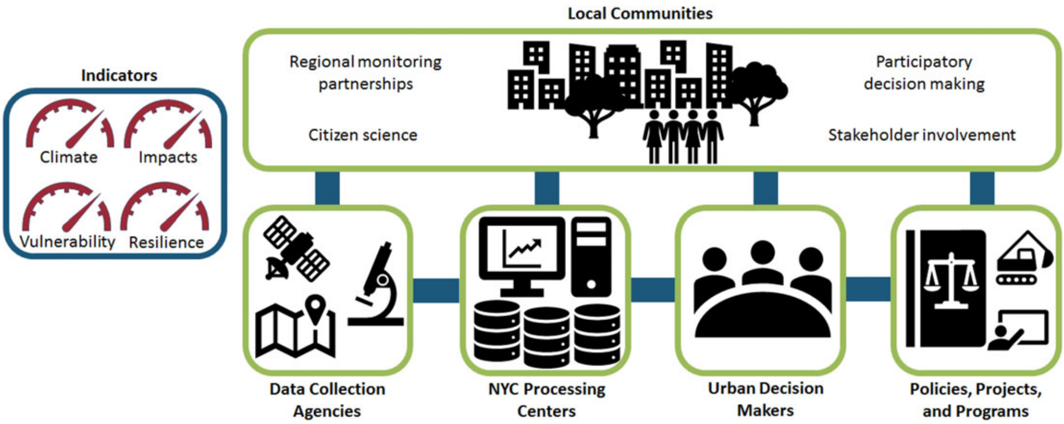

Figure 1.5. Prototype structure and functions of the proposed New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM). The proposed system tracks four types of indicators from data collection agencies; processing centers; urban decision makers; and policies, projects, and programs. The proposed NYCLIM system is co-generated by scientists, practitioners, and local communities to determine which indicators should be tracked over time to provide the most useful information for planning and preparing for climate change in New York City.

Monitoring, has advanced this crucial area by proposing a New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM) (Fig. 1.5). The chapter presents an initial set of indicators for variables to be tracked in the NYCLIM and explores how indicators may track interdependencies among infrastructure systems, with a particular focus on the energy and transportation sectors.

Chapter 9, Perspectives on a City in a Changing Climate, frames the third report of the New York City Panel on Climate Change (NPCC3) in the context of the role of cities in responding to climate change and the history of how New York City, in particular, has addressed climate change since the Metro East Coast Assessment that began in the 1990s and the founding of the NPCC in 2008 (Rosenzweig and Solecki, 2001; Rosenzweig and Solecki, 2010; Rosenzweig and Solecki, 2015). It explores ways that NPCC's role as a knowledge provider to the city and region can continue to assess vulnerability, impacts, and adaptation; monitor climate change; evaluate effectiveness of resilience measures; and serve as a convener for groups and stakeholders addressing climate change challenges in the New York metropolitan region.

Conclusions and recommendations from the entire NPCC3 Report are presented in Chapter 10.

Acknowledgments

We thank Danielle Manley for her dedicated work as program manager of NPCC3, and Daniel Bader for his work finalizing the NPCC3 report.

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Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report Chapter 2: New Methods for Assessing Extreme Temperatures, Heavy Downpours, and Drought

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Keywords: regional climate; extreme events; downscaling; heat waves; inland flooding; water resources

Contents

2.1 Introduction

This New York City Panel on Climate Change (NPCC3) chapter builds on the projections developed by the second New York City Panel on Climate Change (NPCC2) (Horton *et al.*, 2015). It confirms NPCC2 projections as those of record for the City of New York, presents new methodology related to climate extremes, and describes new methods for developing the next generation of climate projections for the New York metropolitan region. These may be used by the City of New York as it continues to develop flexible adaptation pathways to cope with climate change. The main topics of the climate science chapter are:

(1) Comparison of observed temperature and precipitation trends to NPCC2 2015 projections.
(2) New methodology for analysis of historical and future projections of heatwaves, humidity, and cold snaps.
(3) Improved characterization of observed heavy downpours.
(4) Characterization of observed drought using paleoclimate data.
(5) Suggested methods for next-generation climate risk information.

The focus of NPCC3 is on high-risk events involving extreme temperatures, extreme precipitation, and drought. Current trends are presented using historical climate records of high temperature, cold snaps, humidity, and extreme precipitation for the New York metropolitan region. The geographical span of the New York metropolitan region considered here includes, in addition to New York City, adjacent sections of New Jersey such as Newark, Jersey City and Elizabeth, as well as other nearby locations in New York such as Yonkers and Long Island. Historical records of droughts in the Delaware watershed region are also examined. Each climate extreme is analyzed for detection of current trends, and future projections

[Correction added on June 12, 2019, after first online publication: In the author list, the eighth author's name was changed from "Luis Rivera" to "Lea Rivera."]

doi: 10.1111/nyas.14007

are updated for high-temperature extremes as a test of new methods that could be utilized by NPCC4.

These represent finer temporal and spatial resolutions that may be of practical use to key stakeholders in New York City for planning purposes and/or emergency responses. They include local projections of extreme heat and demonstrate the role of the heterogeneous landscape of the city in each process (e.g., how the urban heat island (UHI) affects city neighborhoods differently). Each section of the chapter presents definitions, baselines, methods, and projections, along with uncertainties and recommendations for future work.

2.2 NPCC3 approach

As in NPCC2, NPCC3 makes use of definitions, measurements, baselines, and scenarios to represent how the probabilities of climate events may change in the future. Here, the focus is on extreme events. For most climate hazards, the definitions of extremes are consistent with the NPCC2, specifically for extreme heat, cold spells, and precipitation.

NPCC3 confirms the temperature and precipitation projections of NPCC2 as those of record for use in planning. Based on emerging science, NPCC3 introduces a new methodology for analyzing heat and precipitation extremes that could be used for developing future projections of record in NPCC4.

In NPCC2, temperature analyses included projections of average temperature changes and changes in heat waves and hot days. NPCC3 explores new methodologies for downscaling heat extremes and introduces new metrics to analyze historical and projected humidity. For precipitation, NPCC2 developed quantitative projections for average rainfall and daily maximum rainfall events, and NPCC3 introduces a methodology for quantifying projections for sub-daily heavy downpour rain events.

In addition, NPCC3 examined how current observations of temperature and precipitation changes compare to projected changes from NPCC2 into the 2020s time slice, which encompassed the time period from 2010 to 2039. Figure 2.1 shows the results of this analysis and demonstrates that observations from 2010 to 2017—the period for which both observed data and NPCC2 projections are available to compare—have been largely consistent with projected changes in average conditions for both temperature (Fig. 2.1a) and precipitation (Fig. 2.1b). However, these comparisons should be viewed with caution because of the role that natural variation plays in the short term.

As NPCC3 shifts from a focus on average conditions to extremes, the baselines in some cases vary according to the relevance of the period for the extreme event researched and the period for which data are available. To the extent possible, consistency with NPCC2 is maintained. For example, the baseline for heat waves is 1971–2000, which is the same as NPCC2. However, NPCC3 uses summer months for extreme heat events (June, July, and August) for three reference weather stations, while NPCC2 used the whole year with one reference weather station.

NPCC3 uses bias-corrected statistical downscaling and develops future projections for extreme heat based on summer seasons only and includes high-resolution dynamical downscaling at 1 km for selected time slices. Summer humidity is included in the projections as a new heat-related variable. The section of extreme temperatures closes with a short view of cold spells and winter extremes.

The section on urban flooding makes use of shorter, more detailed records of satellite and radar data to demonstrate the spatial distribution of these extreme events at sub-hourly time resolution.

For droughts, a much longer precipitation record based on tree rings is used to capture decadal variations in the New York City watershed region, and reconstructions of inflows to reservoirs are used to understand how frequently extreme droughts have occurred in the past.

To create the new extreme event projections, bias-corrected statistical downscaling is used (see Section 2.3). In the Appendix, we provide an example of dynamic downscaling, a method that can capture the role of the urban built environment in magnifying heat events and mitigating flooding events.

Model outputs from the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor *et al.*, 2012) are used for projections of extreme heat. Methods for calculating future projections are consistent with NPCC2 but are updated to account for climate model biases in simulating the distribution of temperature (National Climate Assessment; Walsh *et al.*, 2014). Results are provided in 30-year intervals centered on the 2020s, 2050s, and 2080s as defined by NPCC2. The ensemble of CMIP5 results includes two representative concentration pathways (RCPs) (see Box 2.1).

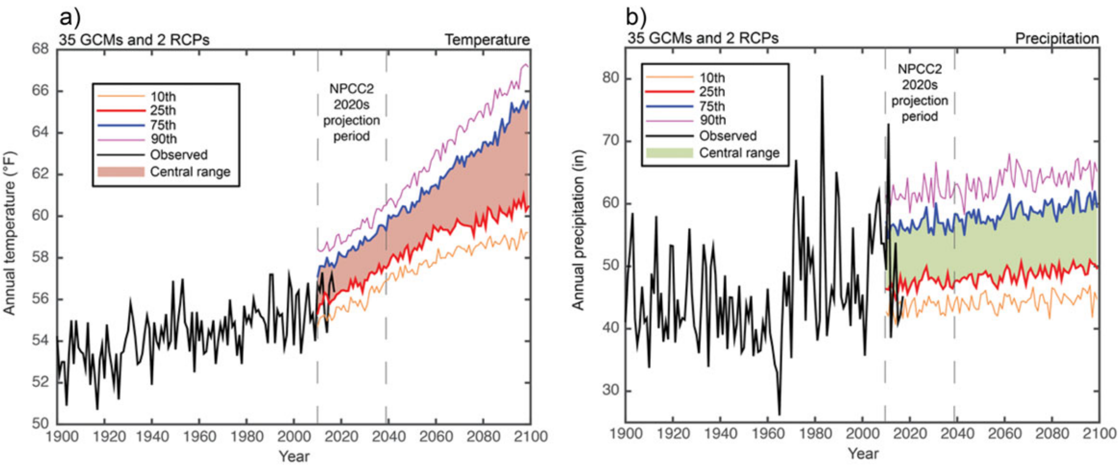

Figure 2.1. Observations at Central Park (1900–2017) compared to the 2020s (2010–2039) time slice of NPCC2 projected changes for (a) average annual temperature and (b) average annual precipitation. Colored lines represent the 10th, 25th, 75th, and 90th percentiles of model projections across RCPs 4.5 and 8.5 for 35 GCMs. Shading shows the central range of projections between the 25th and 75th percentiles. Vertical dotted lines represent the range of the 2020s time slice from 2010 to 2039. Observed data are from the United States Historical Climatology Network (USHCN), and climate projections are from the Coupled Model Intercomparison Project Phase 5 (CMIP5).
Note: These comparisons should be viewed with caution because of the role that natural variation plays in the short term.

2.3. Extreme temperature and humidity

Summer (defined as the months of June, July, and August) temperatures are expected to increase in New York City throughout the 21st century (Horton *et al.*, 2015), leading to more frequent and intense extreme heat events known as heat waves. Here, we follow the definition of heat waves according to the National Weather Service (NWS), that is, an interval of 3 (or more) consecutive days with temperatures of at least 90 °F (32.22 °C).

Heat waves affect a wide range of human activities. These effects include increasing energy demand (Schaeffer *et al.*, 2012; Sailor, 2001; Santamouris, 2014) and mortality (Knowlton *et al.*, 2007; Luber and McGeehin, 2008; Anderson and Bell, 2010; Rosenthal *et al.*, 2014). Moreover, higher temperatures associated with urbanization, a phenomenon called the Urban Heat Island (UHI) (Oke, 1982), exacerbate the impacts of extreme heat events (Li and Bou-Zeid, 2013; Ramamurthy and Bou-Zeid, 2016; Ramamurthy *et al.*, 2017; Ortiz *et al.*, 2018).

New York City, being the most populated urban area in the United States with over 8 million people (U.S. Census Bureau, 2018), has a large human and economic incentive to understand and mitigate the negative impacts of these events now and in the future.

Extreme heat projections have primarily been developed on global (Meehl and Tebaldi, 2004) or continental scales (Gao *et al.*, 2012), with less work focusing on local urban projections that require accounting for finer-scale processes and feedbacks that may affect the occurrence and characteristics of high-temperature events. An example of these processes is the soil moisture-heat wave feedback, wherein dry soil conditions may amplify heat waves by reducing available moisture for evaporative cooling (Seneviratne *et al.*, 2006; Lorenz *et al.*, 2010; Fischer *et al.*, 2007). Cities may amplify these feedbacks by reducing exposed soil area, greatly reducing the capacity for water retention near the land surface (Li and Bou-Zeid, 2013; Ramamurthy and Bou-Zeid, 2016; Ramamurthy *et al.*, 2017).

Other relevant city-scale processes include waste heat from buildings and transportation (Taha, 1997; Ichinose *et al.*, 1999; Offerle *et al.*, 2005), lower surface reflectivity of built surfaces (Taha *et al.*, 1988; Morini *et al.*, 2016; Ramamurthy *et al.*, 2015) and increased heat storage in buildings and built structures (Oke *et al.*, 1981; Arnfield and Grimmond, 1998).

Humidity content of the atmosphere can play an adverse role in how humans react to high heat conditions (Davis *et al.*, 2016; Hass *et al.*, 2016).

As air becomes more saturated with water vapor, the human body becomes less able to shed excess heat through evaporative cooling of perspiration. This can lead to exacerbation of high-temperature impacts such as fatigue and heat exhaustion.

This section presents extreme heat and specific humidity projections for New York City using new methods, accounting where possible for urban effects via statistical processing of global climate model (GCM) simulation data. This statistical processing, or downscaling, is necessary because global models have, in general, very coarse spatial resolution (>100 km^2) and are thus not able to resolve coastlines, topography, and land cover.

The downscaling technique used by NPCC3 is *histogram matching*. It aims to adjust the model representations of observed climate by correcting their *mean* and *variance* to match a representative set of observations in the target domain (see Appendix 2.B). This differs from the bias adjustment procedure of NPCC2 that combined GCM results with station records to downscale the projections to the New York metropolitan region using the "delta method" (Horton *et al.*, 2015), where mean monthly projected changes are applied to daily observations.

In NPCC3, as in NPCC2, the climate projections are based on multiple climate models, driven by two RCPs—RCP4.5 (referred to as medium emissions) and RCP8.5 (referred to as high emissions) (see Box 2.1). The aim of this approach is to capture the uncertainties emerging from the range of model results as well as those related to the impacts of future industrial activity, energy use, and technology on greenhouse gases (GHGs), aerosol emissions, and land use change. For consistency, NPCC3 uses the same baseline period as the NPCC2 (1971–2000). Definitions and methods are detailed in Table 2.1.

Box 2.1. Definitions and terms

Climate change

Climate change refers to a significant change in the state of the climate that can be identified from changes in the average state or the variability of weather and that persists for an extended time period, typically decades to centuries or longer. Climate change can refer to the effects of (1) persistent anthropogenic or human-caused changes in the composition of the atmosphere and/or land use, or (2) natural processes such as volcanic eruptions and Earth's orbital variations (IPCC, 2013).

Global climate models (GCMs)

A GCM is a mathematical representation of the behavior of the Earth's climate system over time that can be used to estimate its sensitivity to atmospheric concentrations of greenhouse gases (GHGs), aerosols, and land use change. Each model simulates physical exchanges among the ocean, atmosphere, land, and ice.

Representative concentration pathways (RCPs)

RCPs are sets of trajectories of concentrations of GHGs, aerosols, and land-use changes developed for climate models as a basis for long-term and near-term climate-modeling experiments (Moss *et al.*, 2010). RCPs describe different climate futures based on different amounts of climate forcings. These data are used as inputs to GCMs to project the effects of these drivers on future climate. The NPCC uses sets of GCM simulations driven by two RCPs, known as 4.5 and 8.5. The set of GCM simulations driven by RCP 4.5 is defined here as a medium-emissions scenario, and that by RCP 8.5 as a high-emissions scenario.

Climate change risk information

On the basis of the selection of the RCPs and GCM simulations, local climate change information is developed for key climate variables—temperature, precipitation, and associated extreme events. These results and projections reflect a range of potential outcomes for the New York metropolitan region.

Climate hazard

A climate hazard is a weather or climate state such as a heat wave, flood, high wind, heavy rain, ice, snow, or drought that can cause harm and damage to people, property, infrastructure, land, and ecosystems. Climate hazards can be expressed in quantified measures, such as flood height in feet, wind speed in miles per hour, and inches of rain, ice, or snowfall that are reached or exceeded in a given period of time.

Uncertainty

Uncertainty denotes a state of incomplete knowledge that results from lack of information, natural variability in the measured phenomenon, instrumental and modeling errors, and/or from disagreement about what is known or knowable (IPCC, 2013).

Table 2.1. Methods for heat extremes used in NPCC2 and NPCC3

Methods	NPCC2 (2015)	NPCC3 (2018)
Definition of heat wave	• Three or more consecutive days at or above 90 °F	• Three or more consecutive days at or above 90 °F
Metrics	• Number of heat waves per year • Duration of heat wave (number of days average heat wave lasts) • Total days at or above 90 °F per year • Total days at or above 100 °F per year	• Number of heat waves per year • Duration of heat wave (number of days average heat wave lasts) • Average maximum temperature during heat wave (heat wave intensity) • Total days above 90 °F per year • Total days above 100 °F per year • Annual mean specific humidity
Baseline years	1971–2000	1971–2000
Baseline reference locations	Central Park	Central Park (extreme heat) LaGuardia Airport (extreme heat, humidity) JFK Airport (extreme heat)
Baseline values	• 2 heat waves per year • 4 days in duration • 18 days at or above 90 °F • 0.4 days at or above 100 °F	• 1.1 heat waves per year • 4 days in duration • 94.2 °F maximum temperature • 9.6 days above 90 °F • 0.27 days above 100 °F • 0.0123 kg_{vapor}/kg_{air} mean specific humidity
Future time slices	• 2020s (2010–2039) • 2050s (2040–2069) • 2080s (2070–2099)	• 2020s (2010–2039) • 2050s (2040–2069) • 2080s (2070–2099)
Methodology	• 2 RCPs (4.5 and 8.5) • 35 GCMs • 10th, 25th, 75th, and 90th percentiles[c] across both RCPs and 35 GCM outputs • Delta method used for GCM bias correction	• 2 RCPs (4.5 and 8.5) • 26[a] GCMs • 10th, 25th, 75th, and 90th percentiles across both RCPs and 26 GCM outputs • GCM mean and variance bias correction to temperature station records[b].

[a]NPCC3 uses a smaller GCM ensemble than the 35-model ensemble used in NPCC2 because not all GCMs provide specific humidity as a standard output.
[b]Bias correction is performed on GCM data in order to improve how representative a single grid box is to local New York City conditions.
[c]The Xth percentile is defined as the value that X percent of the outcomes are the same or lower than.

2.3.1 *Observed trends in summer heat waves*

Historical trends of daily maximum summer temperature in New York were analyzed using Central Park weather station, John F. Kennedy (JFK), and LaGuardia Airports during June, July, and August (Fig. 2.2). Central Park has the longest historical record, dating back to 1900, where the average annual daily maximum summer temperature has been rising at an average of 0.2 °F per decade from 1900 to 2013. JFK and LaGuardia weather stations go back to 1970, where average annual daily maximum summer temperatures have been increasing at a rate of 0.5 °F per decade and 0.7 °F per decade, respectively.

The distance between these weather stations provide insights into processes that affect temperatures near the surface, such as sea breezes[a] and the UHI. Sea breeze effects appear in stations located close to Long Island's southern shore (e.g., JFK), with lower

[a]Sea breezes form due to temperature differences between the air over land and ocean and are a feature of New York City coastal areas (Haurwitz, 1947; Childs and Raman, 2005).

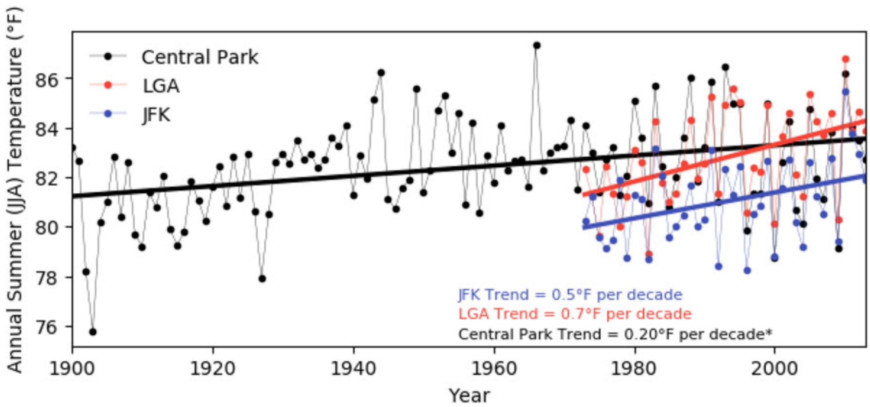

Figure 2.2. Annual average daily maximum summer temperatures. (June, July, August) in Central Park from 1900 to 2013, LaGuardia (LGA) airport from 1970 to 2013, and John F. Kennedy (JFK) airport from 1970 to 2013. Solid lines represent linear trends for each station. Station records were obtained from the U.S. Historical Climatology Network (USHCN) Version 2.5 (Menne *et al.*, 2013). *Central Park trend is significant at 0.01 level, while LGA and JFK trends are positive but not significant, possibly due to shorter record length.

daily maximum temperatures compared to their in-land counterparts (Fig. 2.2).

Sea breeze impacts on temperatures show that geospatial heterogeneity of the urban landscape plays a role in near-surface temperatures, and therefore impact occurrences of extreme heat. The weather station located at JFK, which experiences afternoon sea breezes, has a mean summer maximum temperature of 80.6 °F, whereas the other stations have a mean value of 82.7 °F, which is 2.1 °F higher. This is consistent with climatological studies (e.g., Gedzelman *et al.*, 2003) of the UHI in the region, which have found that afternoon summer sea breezes may shift the center of the urban heat island west and north, toward New Jersey and The Bronx.

2.3.2 New methods for projected changes in heat waves

This section describes new methods and results for NPCC3 projected changes in heat waves. Projections are presented in two formats:

- Graphical time series: Results shown as a time series are further broken out into the two RCP scenarios used in NPCC3 (see Fig. 2.3). These include a medium-emissions scenario (RCP4.5) (Thomson *et al.*, 2011) and a high-emissions scenario (RCP8.5) (Riahi *et al.*, 2011).
- Time slices table: Results are summarized for the 10th, 25th, 75th, and 90th percentile of climate model outcomes across both RCP 4.5 and 8.5 scenarios in Table 2.2, averaged by 30-year time slices centered around the 2020s (2010–2039), 2050s (2040–2069), and 2080s (2070–2099) decades.

2.3.2.1 Heat wave frequency, duration, and intensity. Heat wave characteristics considered here are their frequency (events/year), mean event duration (number of days/event), and intensity (average maximum temperature/heat wave). NPCC2 had previously analyzed frequency and mean event duration; heat wave intensity is a new metric in NPCC3. While a new methodology is tested here that is different from NPCC2, NPCC3 confirms the use of NPCC2 projections as the projections of record for New York City to plan for extreme heat. The new methodologies presented in NPCC3 could be used in developing new projections of record in NPCC4.

Using a composite observed temperature record derived by averaging the daily maximum temperature over the three New York City stations, results from 26 GCMs were bias corrected in order to project distributions of heat waves for the NPCC3 time slices following the methods of Piani *et al.* (2010) and Hawkins *et al.* (2013). (See Appendix 2.C for detailed methods.) The mean and standard deviation of a given variable were used to adjust the model distribution against the target observed distribution. For each GCM, the closest

Table 2.2. Results from new projection methods for future assessments of heat wave across 52-member ensemble (26 models, RCPs 4.5 and 8.5) for New York City

		10th percentile	25th percentile	75th percentile	90th percentile
Heat waves per year (average number	2020s	1	2	4	5
of events per year)	2050s	2	3	5	6
Baseline[a] 1.1	2080s	2	3	5	7
Mean heat wave duration (average	2020s	3	4	6	8
heat wave length in days)	2050s	4	5	9	13
Baseline 4	2080s	4	6	15	27
Mean heat wave intensity (average	2020s	91.8	92.5	94.5	95.7
maximum temperature during	2050s	92.6	93.5	95.4	96.5
heat wave event in °F)	2080s	93.2	94.2	97.1	99.1
Baseline 94.2 °F					
Days above 90 °F (average number	2020s	6	11	25	34
of days per year)	2050s	15	24	46	56
Baseline 9.6	2080s	24	35	63	75
Days above 100 °F (average number	2020s	0	0	0	2
of days per year)	2050s	0	0	4	8
Baseline 0.27	2080s	0	1	13	27

[a]Baseline refers to 1971–2000 average characteristics for Central Park, LaGuardia, and JFK.
Note: NPCC3 confirms the temperature projections of NPCC2 as those of record that should be used for planning.

land grid point was selected, as was done in NPCC2, and the distribution of maximum daily temperature at this point was bias corrected against the city's composite maximum temperatures. This method is referred to as a "single-point" bias correction.

The previous NPCC2 approach may have resulted in a bias toward slightly cooler projected extreme temperatures compared to those projected using the NPCC3 bias-correction methods, particularly toward the warmer periods in the 2080s time slice. These changes may be due to the correction to the variance that, at least partially, addresses the fact that GCM grid boxes near coasts may include water.

NPCC3 analysis of the bias-corrected single-point projections shows overall increase across all heat wave metrics throughout the 21st century (Fig. 2.3). To highlight the sensitivity to emission scenarios, we present the response to medium-emission and high-emission scenarios separately. In Table 2.2, the projections are based on the distribution of multimodel results showing the 10th, 25th, 75th, and 90th percentile outcomes across both RCP scenarios, as was done in NPCC2.

Mean daily maximum temperature (Fig. 2.3a) shows a nearly linear trend in the high-emissions scenario (RCP8.5), whereas the rate of change in the medium-emissions scenario (RCP4.5) slows after 2040.

The number of heat waves per year (Fig. 2.3b) shows far less deviation between the two emissions scenarios. Both scenarios increase at a pace of about one additional yearly event every 20 years until 2060, where growth slows down considerably. This may be due to consecutive events coalescing into very long heat waves, which becomes more likely as heat waves increase in length and frequency. It is also an artifact of the definition of heat wave used, which establishes an unchanging temperature threshold through the entire century. As mean temperatures increase, meeting the 90 °F on consecutive days becomes more likely. Uncertainty in projections as described by confidence intervals increase over time, with a spread of 1 event in the first half of the century that grows to a spread of about two events by end of century.

Mean event duration projections (Fig. 2.3c) are similar across the scenarios in the first half of the century, growing by around 2 days per 20-year period. However, the high-emissions scenario projections show accelerated growth in the latter half of the century, as well as more spread in the model ensemble, with an uncertainty band spanning about 10 days, compared to about 2 days

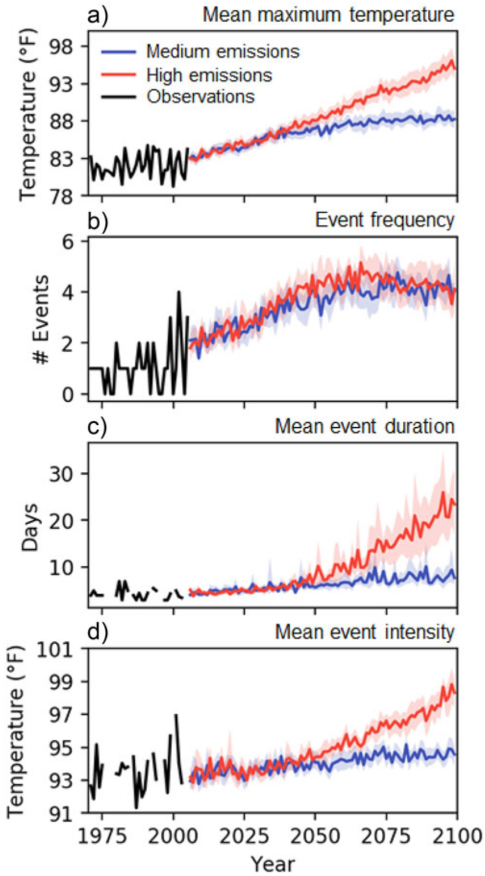

Figure 2.3. Results from new bias-corrected projections for future assessments of (a) mean daily maximum temperature, (b) event frequency, (c) mean event duration, and (d) mean event intensity compared to the 1971–2000 base period. Solid lines represent the multimodel mean of a 26 global climate model ensemble, while shaded bands show 95% confidence intervals. Black lines indicate observations from three GHCN stations—Central Park, JFK, and LaGuardia—between 1971 and 2000.

in the first half. This accelerated increase in event duration may explain the stabilization of event frequency projections in Figure 2.3(b), as events may aggregate into longer heat waves.

Mean intensity, defined as the mean of event maximum temperatures, shows large interannual variation (Fig. 2.3d), with projected values that increase from about 93 °F early in the century, to 95–98 °F by the end of the century. Confidence interval bands increase slightly throughout by end of century, reaching an ensemble spread of about 1 °F.

2.3.2.2 New methods for warm day analyses. Additional key metrics of extreme heat explored are number of days above 90 and 100 °F in the summer season (Table 2.2). Projected days above 90 °F are expected to become more likely as summer temperatures increase. By the 2080s, projections show 24 (10th percentile) to 75 (90th percentile) days above 90 °F compared to the 1971–2000 baseline (10 days).[b]

2.3.3 Methods for assessing trends in humidity

The humidity content of the atmosphere can play an adverse role in how humans react to high heat conditions (Davis *et al.*, 2016; Hass *et al.*, 2016). We present projections of daily mean specific humidity based on a 26 multimodel ensemble, across medium- and high-emissions scenarios, as in Section 2.3.2. For each model, the land grid point closest to New York City is used. Due to a lack of specific humidity records from all weather stations, GCM humidity was bias corrected based on LaGuardia Airport only. In addition, the 1971–2000 baseline for specific humidity is based only on the LaGuardia Airport weather station. Humidity is a new metric being considered by the NPCC3.

Results show an increase between the 2020s and 2080s time slices of around 9% at each period's 10th percentile, while changes in the 90th percentile represent a 16% increase (Table 2.3). The uncertainty in these projections as characterized by the model ensemble 95% confidence bands (Fig. 2.4) is relatively large. Increases in specific humidity combined with increasing temperatures might lead to higher heat index (see Box 2.2), which has major consequences for human health and is a driver of peak energy demand for space cooling, as air conditioning systems remove sensible (temperature-related) and latent (moisture-related) heat from buildings. To assess combined air moisture and temperature impacts, concurrent hourly values must be used, rather than daily outputs from the model ensemble.

[b]Although warm days can occur outside of the traditional summer months, here we only consider June, July, and August, as extreme heat days are more likely to occur during this period.

Table 2.3. Specific humidity projections across the 52-member ensemble (26 models, RCPs 4.5 and 8.5) for New York City

		Baseline	10th percentile	25th percentile	75th percentile	90th percentile
Mean specific humidity (kg_{vapor}/kg_{air})	2020s	0.0123	0.0115	0.0119	0.0127	0.0131
	2050s	0.0123	0.0122	0.0126	0.0138	0.0146
	2080s	0.0123	0.0125	0.0130	0.0149	0.0164

NOTE: Baseline period for humidity is 1971–2000 at the LaGuardia Airport weather station.

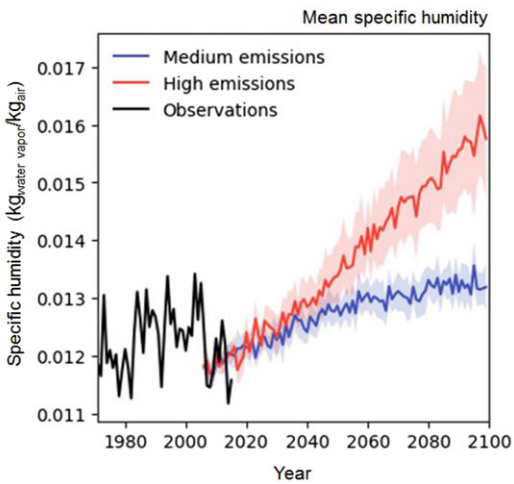

Figure 2.4. Specific humidity projections from the bias-corrected 26-member global climate model ensemble and across the medium (RCP4.5) and high (RCP8.5) emissions scenarios compared to the 1971–2000 baseline period at the LaGuardia Airport weather station. Shaded bands represent 95% confidence intervals across the ensemble. Specific humidity refers to the amount of water vapor in the atmosphere and combined with increasing temperatures can lead to a higher heat index.

Box 2.2. Key humidity definitions

Specific humidity: A measure of the amount of water in the atmosphere; the mass fraction of water vapor per unit mass of moist air.
Absolute humidity: Mass of air per unit volume of moist air.
Relative humidity: The ratio of water vapor pressure to the saturation vapor pressure. It measures how saturated with water vapor the atmosphere is. As air becomes more saturated with water vapor, it becomes more difficult for the human body to shed excess heat through evaporative cooling of perspiration.
Heat index: A measure of the combined effects of temperature and relative humidity. It is defined by the National Weather Service.

See Appendix 2.C of this chapter for an expanded discussion of how climate change is projected to impact the heat index. NPCC3 recommends further testing of this methodology for the development of new projections of record in NPCC4.

2.3.4 Cold snaps

NPCC3 confirms the analysis of NPCC2 days with minimum temperatures below 32 °F as the projections of record for New York City planning. NPCC3 further examines historical extreme cold events, using two measures of extreme cold (Boyle, 1986; de Vries *et al.*, 2012; Chen *et al.*, 2013; Peterson *et al.*, 2008; Efthymiadis *et al.*, 2011):

- A *day below freezing* occurs whenever minimum temperature is equal to or less than 32 °F
- A *cold day* occurs whenever its minimum temperature is equal to or less than the 10th percentile of daily minimum temperature of a given year.

Other definitions vary, including the use of standard deviations (Vavrus *et al.*, 2006). Cold spell changes have been reported on regional scales (e.g., Europe, de Vries *et al.*, 2012; China, Zhang *et al.*, 2017; Northeast United States, Thibeault and Seth, 2014) and for global scales (Vavrus *et al.*, 2006; Konrad, 1996) using GCM ensembles and long-term climate records. In most cases, cold days have shown decreases, and notably in Northern latitudes, it has been found that accelerated decreases of cold spells outpace increases in summer maxima (Thibeault and Seth, 2014).

We used data from Central Park to establish a benchmark for cold spells. The 10th percentile threshold for cold days at this station was computed from the entire 1900–2017 record, with a value of 24.08 °F. In general, cold days per year decreased

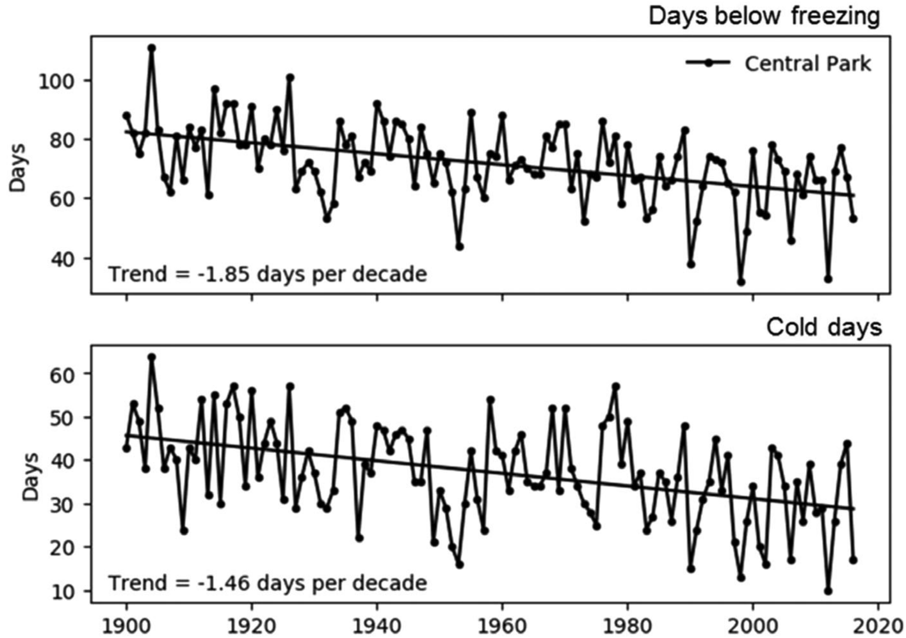

Figure 2.5. Observed annual number of cold days at Central Park Station (1900–2017). Solid straight lines represent the linear trend in days below freezing temperatures (top) and cold days (bottom). A day below freezing occurs whenever minimum temperature is equal to or less than 32 °F. A cold day occurs whenever its minimum temperature is equal to or less than the 10th percentile of daily minimum temperature of a given year. Station records obtained from the U.S. Historical Climatology Network (USHCN). Both trends are significant at the 0.001 level.

by 1.46 days every decade between 1900 and 2017, while days below freezing temperatures decreased at a rate of 1.85 days per decade (Fig. 2.5). This results in recent years having, on average, about 22 fewer days below freezing and 17 fewer cold days than in 1900. The rate of change of these trends is slightly lower than those reported for the entire Northeast by Thibeault and Seth (2014).

For the case of New York City, the attribution of these rapid decreases of cold spells may be a combined effect of global warming and urbanization. Urbanization leads to the UHI effect, which tends to have a larger effect in the winter.

2.3.5 Polar vortex and extreme cold events

The impact of global warming on climate implies an overall decrease in the number of cold extremes, while the number of warm extremes increases (Horton *et al.*, 2015). However, recent persistent winter events of record cold weather in the Northeast United States and in other Northern Hemisphere regions raise concern of a possible connection to climate change.

Both the science community (Screen *et al.*, 2015) as well as the public (Lyons *et al.*, 2018) have been engaged in research and discussion about cold air outbreaks associated with the Polar Vortex. An aspect of these discussions is the connection between the gradual disappearance of Arctic sea ice due to the polar amplification of global warming, the increase in atmospheric "blocking" events, and the slowing down and deepening of the wavy circulation in the midlatitudes (Screen and Simmonds, 2010; Overland *et al.*, 2015). With the increase in amplitude and slowdown of atmospheric waves, cold air can flow down from the Arctic deep into the midlatitudes, and *vice versa*, warm air flows north. This creates protracted deviations from normal conditions in either place.

In early January of 2014, a large cold air mass moved from Canada into the northern Great Plains states and made its way slowly to the Northeast. The unusual cold weather in the eastern half of the United States did not abate until April. At the same time, other areas in the Northern Hemisphere experienced record warm winter weather.

Shorter events similar to this have happened since, as was the case during winter months in 2017–2018 and 2019. These events were connected to stratospheric warming, where the low-pressure vortex that is usually centered on the North Pole moves equatorward. This change in circulation is communicated down to the troposphere and results in anomalous weather situations during the winter season (Kretschmer *et al.*, 2018; Screen *et al.*, 2018).

There has been much debate whether such events are linked to the gradual melting of sea ice in the Arctic, and it appears that the answer is that there is a link (Overland *et al.*, 2015; Screen *et al.*, 2018). This was shown in climate models (Zhang *et al.*, 2018) and is consistent with the observation that polar vortex events are on the rise (Kretschmer *et al.*, 2018).

There is, however, no evidence that cold air outbreaks in the United States have increased as a result of this or other phenomena (Screen *et al.*, 2015). The increase in polar vortex events was found to influence surface weather in Siberia, where a significant cooling of the average winter weather has been detected, in contrast with the observed warming elsewhere around the globe (Kretschmer *et al.*, 2018; Zhang *et al.*, 2018).

2.3.6 Summary and future research directions for extreme temperature and humidity

New methodologies for projections of heat wave characteristics for the New York metropolitan region were tested in NPCC3 using bias-corrected climate model projections. For the early part of the century (2020s), these results are consistent with those of NPCC2. In the later part of the century (2050s and 2080s), the NPCC3 results display the potential for more intense heat events with longer durations.

Results show large changes across all heat wave metrics throughout the 21st century. The high-emissions scenario (RCP8.5) projects, in many cases, several times larger effects than the medium-emissions scenario. The uncertainty of the projections increases through time.

The new NPCC3 methods include humidity, which is projected to increase by more than 30% from baseline values. These increases in atmospheric humidity with extreme temperatures are likely to have large societal implications reflected in public health and energy demands.

NPCC3 confirms the NPCC2 projections for heat waves, hot days, and cold days as those of record for New York City in planning for the impacts of climate change and recommends the incorporation of the new methodologies into revised projections of record in NPCC4.

Future work in projecting extreme heat and humidity for the NPCC should be directed to incorporating the spatial distribution of these extreme heat events to account for coastal influence and UHI effects (e.g., sea breeze effects). This may require using regional climate models (RCMs) to dynamically downscale projections to finer spatial scales within the New York metropolitan region. Carrying this out for an ensemble of GCMs and RCMs will require large computational efforts. New methods may be needed to account for uncertainties in dynamic downscaling. See Appendix 2.C for an example of the possible approach, utilizing one GCM and one RCM for two time slices, as a potential guide for new research directions in NPCC4.

2.4 Heavy downpours and urban flooding

NPCC2 projected quantitative changes in daily extreme rainfall amounts for 1 inch, 2 inches, and 4 inches (Table 2.4). NPCC2 also included a qualitative projection in relation to extreme rainfall, stating that heavy downpours in the New York metropolitan region are very likely to increase by the 2080s (Horton *et al.*, 2015).

NPCC3 does not provide new projections for heavy rainfall and confirms the NPCC2 projections as those of record for city planning and adaptation. It provides new analyses of the dynamics of heavy rainfall events in the New York metropolitan region recommended for use in developing new projections of record in NPCC4.

NPCC3 focuses on observed annual rainfall (see Section 2.2) and observed heavy rainfall days in recent years compared to the NPCC2 2020s time slice projections. NPCC3 also analyzes the types of storm systems associated with heavy rainfall events, and the regional drivers of historical flash flooding events. This section also conducts a trend analysis of sub-daily heavy precipitation events at the 1-, 3-, 6-, and 24-h duration. Finally, this section explores ways to illustrate the spatial variation of urban flooding events. It is recommended that this work serve as a foundation for new projections of record

Table 2.4. NPCC2 projected changes in heavy rainfall days (Horton *et al.*, 2015)[a]

Heavy rainfall days	Baseline (1971–2000)	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
2020s				
Number of days rainfall ≥1 inch	13	13	14–15	16
Number of days rainfall ≥2 inches	3	3	3–4	5
Number of days rainfall ≥4 inches	0.3	0.2	0.3–0.4	0.5
2050s				
Number of days rainfall ≥1 inch	13	13	14–16	17
Number of days rainfall ≥2 inches	3	3	4–4	5
Number of days rainfall ≥4 inches	0.3	0.3	0.3–0.4	0.5
2080s				
Number of days rainfall ≥1 inch	13	14	15–17	18
Number of days rainfall ≥2 inches	3	3	4–5	5
Number of days rainfall ≥4 inches	0.3	0.2	0.3–0.5	0.7

[a]Projections are based on 35 GCMs and two RCPs. Baseline data are for the 1971–2000 base period. Projections show the low estimate (10th percentile), middle range (25th–75th percentile), and high estimate (90th percentile) 30-year mean values from model-based outcomes.

NOTE: NPCC3 confirms the use of these NPCC2 projections as those of record for city policy and planning purposes.

for heavy rainfall that are to be developed in NPCC4.

NPCC3 analyses of heavy downpours build on NPCC2 projections for daily extreme rainfall by more closely examining the past and present rainfall across New York City and across timescales. Additionally, NPCC3 includes observations of urban flooding (definition in Table 2.5), in New York City and surrounding areas. NPCC3 refocuses discussion from daily extreme rainfall to sub-daily "heavy downpours," defined as rarely occurring rainfall at less than daily timescales that can produce urban flooding. NPCC3 lays the groundwork for a new set of future projections in NPCC4 using these metrics.

Extreme rainfall is defined as a rainfall amount that is a rare event, that is, one that approaches the end of the probability distribution of all events. In NPCC2, daily extreme rainfall in the current climate was represented by the number of occurrences of rainfall above 1 inch, 2 inches, or 4 inches per day at the Central Park weather station in New York City.

Extreme rainfall measured at Central Park has significant year-to-year variation such that no statistically significant trends in extreme rainfall can be identified (Horton *et al.*, 2015). (A statistically significant trend indicates that this trend in extreme rainfall would be unlikely to occur by chance). NPCC2 did note that the heaviest 1% of daily rainfalls have increased by approximately 70% between 1958 and 2011 in the Northeast (Horton *et al.*, 2015). NPCC2 used the observed measurements as a baseline (Horton *et al.*, 2015) for projections of extreme rainfall (Table 2.6; Horton *et al.*, 2015).

2.4.1 Extreme rainfall and heavy downpours

This section focuses on extreme rainfall by describing the approaches to heavy downpours in NPCC2 and NPCC3, studying regional drivers of daily and sub-daily heavy rainfall, providing a revised historical analysis of heavy rainfall across New York City, and summarizing new research projecting future changes in heavy downpours in the region.

2.4.1.1 Extreme daily rainfall and links to tropical and extratropical cyclones. NPCC2 results included projections for extreme rainfall in the 2020s (2010–2039), 2050s (2040-2069), and 2080s (2070–2099) compared to the baseline (1971–2000) at Central Park. Data for the first 8 years of the 2020s time slice can now be compared to projections—as has been done above with climate averages in Section 2.2. However, several caveats should be kept in mind. First, the fewer years of data, the more likely that year-to-year variations will outweigh any longer-term climatic trends in data. Second, if there is a substantial climatic trend in rainfall extremes, the first 8 years of a 30-year

Table 2.5. NPCC3 rainfall and urban flooding definitions

Term	Definition
Daily extreme rainfall	Rainfall depths at the high end of the rainfall probability distribution; defined as the number of days per year that exceed 1 inch, 2 inches, and 4 inches of rainfall averaged across New York City
Heavy downpours	Rainfall at 1-, 3-, 6-, and 24-h durations that may cause urban flooding; for statistical analyses, annual maximum values are used heavy rainfall intensities may differ across New York City rain gauges.
Days of known flooding	Urban flooding identified by experts (emergency managers and National Weather Service) through either New York City Hazard Mitigation Reports or the National Centers for Environmental Information (NCEI) Storm Events Database.
Urban flooding	Surface flooding of an urban (generally over 20% impervious) area. Urban flooding is caused by rain falling faster than local conveyance systems (sewers or streams) can transmit it. When available, streamflow data from small urban streams in the New York City metropolitan region are used as a proxy for New York City urban flooding data sets.

time slice may look substantially different than the last 8 years of the time slice.

Table 2.7 shows the 2020s (defined as 2010–2039) extreme daily rainfall projections from NPCC2 compared to actual rainfall data from 2011 to 2017 and the baseline values from 1970 to 2003. The first observed 8 years of the 2020s time slice show that observed heavy daily rainfall totals have fallen within the low- to middle-range estimate of the projected amounts.

NPCC3 provides supplemental information by conducting a benchmark analysis on the seasonal characteristics governing daily precipitation extremes in the recent historical record, as well as an overview of recent studies of precipitation extremes that have occurred since NPCC2.

The primary large weather systems that affect New York City are cyclones. Cyclones refer to low-pressure regions where air converges and causes uplift. Cyclones can include extratropical cyclones, caused by mid-latitude weather fronts (e.g., Nor'Easters) and tropical cyclones, which originate in the tropical oceans (e.g., hurricanes). The tracks for both types of cyclones are used to associate extreme precipitation with storms.

The precipitation data used in this section are daily weather station data from JFK, LaGuardia, and Newark International Airports available from the Integrated Surface Database (Smith *et al.*, 2011). The

Table 2.6. NPCC2 daily extreme rainfall analyses (from Horton *et al.*, 2015)

Extreme precipitation methods	NPCC2 (2015)
Definitions	• Individual days per year with rainfall at or above 1 inch • Individual days per year with rainfall at or above 2 inches • Individual days per year with rainfall at or above 4 inches
Metric	• Number of days per year with rainfall reaching at or above daily rainfall total
Baseline years	1971–2000
Baseline values	• 13 days (1 inch) • 3 days (2 inches) • 0.3 days (4 inches)
Future time slices	30-year time slices for • 2020s (2010–2039) • 2050s (2040–2069) • 2080s (2070–2099)
Methodology	• 2 RCPs (4.5 and 8.5) • 35 GCMs • 10th, 25th, 75th, and 90th percentiles across both RCPs and 35 GCM outputs

Table 2.7. Comparison of NPCC2 daily extreme rainfall projections for the 2020s time slice (2010–2039) to observed values at Central Park (2011–2017) and baseline values (1971–2000)

Heavy rainfall days	Baseline values (1971–2000)	NPCC2 2020s low estimate (10th percentile)	NPCC2 2020s middle range (25th–75th percentile)	NPCC2 2020s high estimate (90th percentile)	Observed values (2011–2017)
Number of days ≥1 inch	13	13	14–15	16	14.1
Number of days ≥2 inches	3	3	3–4	5	2.7
Number of days ≥4 inches	0.3	0.2	0.3–0.4	0.5	0.4

NOTE: These comparisons should be viewed with caution because of the role that natural variation plays in the short term.

extremes are defined as 24-h precipitation for the top 1% of days for the record, per station, which translates to 138 days per site. The baseline period used, 1979–2016, was selected based on the availability of satellite-era gridded sea-level pressure (SLP) reanalysis data (Dee *et al.*, 2011). SLP fields are used to track extratropical cyclone centers via the numerical algorithm of Bauer *et al.* (2016). Cyclone association is calculated by checking if a cyclone center is within 1000 km of New York City on the date of the precipitation event. However, all cyclones that ended up being associated with a precipitation extreme passed within 500 km of New York City. Additional details of the analysis method are in Towey *et al.* (2018).

Daily (24-h) precipitation extremes during the 1979–2016 period occurred most often in August, but more than one event occurred in each month of the year. For events in winter months, the precipitation more likely fell as snow, but the snow water equivalent is used for this analysis.

Figure 2.6 summarizes the annual cycle for extreme 24-h precipitation events. Extratropical

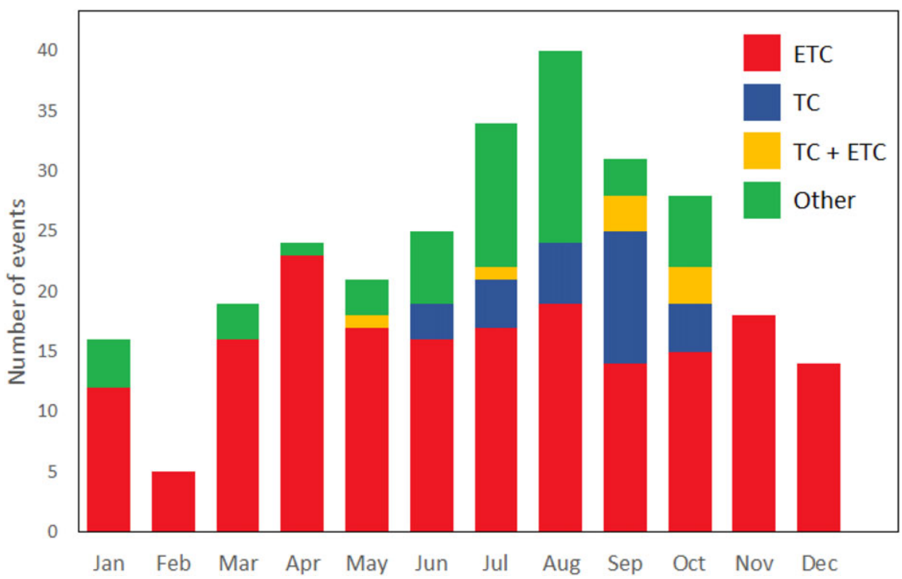

Figure 2.6. Total number of extreme 24-h precipitation events at three New York metropolitan region airports (JFK, LaGuardia, and Newark) per month from 1979 to 2016 correlated with storm type. If more than one airport measured a precipitation extreme on the same date, then that event is only counted once in this figure. ETC refers to extra-tropical cyclones and TC to tropical cyclones; TC + ETC are hybrid storms that display characteristics of both types. Cyclones are identified using Modeling, Analysis, and Prediction (MAP) Climatology of Midlatitude Storm Area (MCMS; Bauer *et al.*, 2016). Tropical cyclones are distinguished by the presence of HURicane DATabase tracks. "Other" refers to high precipitation events differing from tropical and extratropical cyclones that may be related to small-scale storms.

cyclones cause the largest number of extreme 24-h precipitation events in each month of the year. Tropical cyclone and non-cyclone events tend to occur in summer and early fall. Other events may simply be related to small-scale storms. These types of storms are likely to drop all their precipitation in a short time period and be associated with shorter-term heavy rainfall. They are the focus of the remainder of this section. For a more detailed analysis of extreme rainfall and cyclones, see Appendix 2.D.

2.4.1.2 Regional outlook on heavy rainfall at sub-daily scales. Building upon the daily rainfall extremes analysis in NPCC2, NPCC3 also reviews methods to examine heavy downpours that often drive urban flooding, with analysis of sub-daily events occurring at 1- to 6-h timescales (Smith *et al.*, 2013). Rainfall that drives urban and flash flooding in the Northeast is typically temporally and spatially concentrated and is most often caused by thunderstorms (Fig. 2.7; Smith and Smith, 2015).

Regarding projections, NPCC2 included a qualitative projection that downpours are "very likely" to increase by the 2080s. NPCC3 does not update this prediction but does establish heavy downpours as an additional quantitative variable to be included in projections in NPCC4.

Since NPCC2 there have been a few new studies using GCM projections of precipitation extremes in the Northeast United States. The results from these studies are consistent with the NPCC2 Report in that they project an increase in precipitation, both in terms of the mean and extremes for the region (Ning *et al.*, 2015). These precipitation changes are expected to occur in both winter and summer seasons (Fan *et al.*, 2014).

However, the uncertainty in these precipitation projections is much larger than the uncertainty in the modeled temperature projections. One reason for the uncertainty is the presence of modes of natural variability, such as the North Atlantic Oscillation,[c] that affect precipitation in the New York metropolitan region. These can have strong interannual impacts on the location and the types of cyclones that generate at least half of the strong precipitation events for the region (see, e.g., Hall and Booth, 2017). Additionally, the issue of characterizing and projecting Northeast U.S. precipitation extremes and their relationship to natural climate variability has been found to be more complicated than understanding the cyclone tracks (Ning and Bradley, 2014).

Recent studies have projected future rainfall intensity–duration–frequency (IDF) curves for New York State. These project future rainfall extremes for durations longer than 1 h using a set of downscaled GCMs and RCMs (Castellano and DeGaetano, 2015; DeGaetano and Castellano, 2017; Castellano and DeGaetano, 2017). Future IDF curves were developed by using change factors calculated as change in rainfall between past observations and downscaled climate model projections of future rainfall. These projections, which can be found online at http://ny-idf-projections.nrcc.cornell.edu/, are more certain for rainfall durations of more than 24-h than for those under 24 hours. These are peer-reviewed, local, sub-daily rainfall projections available for New York City, used in development of the New York City Climate Resiliency Design Guidelines (http://www.nyc.gov/resiliency).

2.4.1.3 Heavy downpours: past trends and baselines. For NPCC3, historical trends in heavy downpours were analyzed using hourly data from multiple New York City area NOAA rain gauges at Central Park, LaGuardia Airport, JFK Airport, and Newark Airport. This analysis allows for an investigation of trends in short-duration heavy downpours. Heavy downpours, defined as the annual maximum hourly, 3-hourly, 6-hourly, and daily rainfall depths were analyzed for change points. Change points indicate that the median rainfall depth has significantly changed in that year, while trends indicate a gradual and continuous shift in medians throughout the time-period (see Fig. 2.8 for examples). Methods for determining trends in extreme rainfall included the nonparametric Pettitt Test (Pettitt, 1979), nonparametric Mann-Kendall Test (Mann, 1945; Kendall, 1975), and Sen's Slope (Sen, 1968).

Historic trends in heavy downpours are difficult to establish. The natural annual variation in rainfall maxima is generally more significant than trends over time, so that few statistically significant change

[c] The North Atlantic Oscillation, or NAO, is a fluctuation in sea-level atmospheric pressure between the Icelandic Low and Azores High. It influences climate patterns in the Northern Hemisphere.

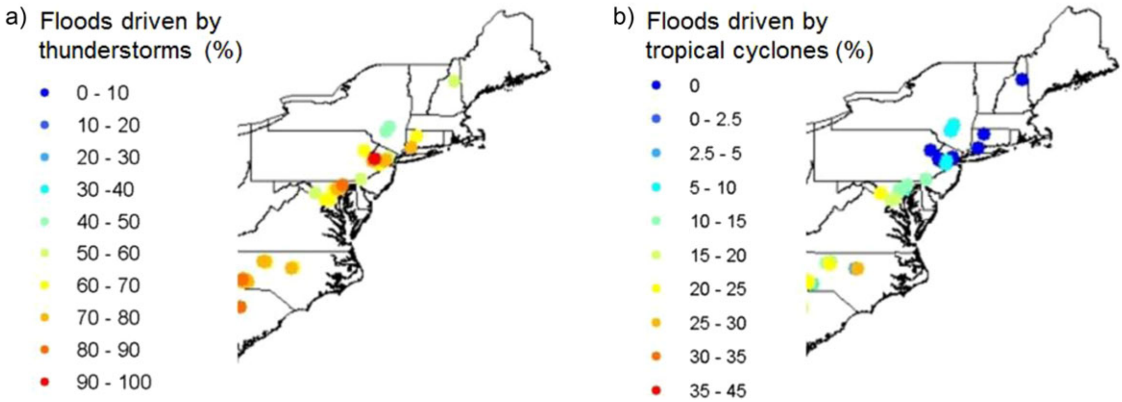

Figure 2.7. Proportion of recent flash flood events (streamflow >92 $ft^3/s/mi^2$ or 1 $m^3/s/km^2$) on small (<5.8 mi^2 or 15 km^2) USGS gauged streams in the Northeastern United States caused by (A) thunderstorms and (B) tropical cyclones. (Adapted from Smith and Smith, 2015). Thunderstorms are distinguished by the presence of lightning flashes, while tropical cyclones are distinguished by the presence of HURicane DATabase tracks. Data are for the entire period of record for each stream gauge, generally from the mid-1980s to 2015.

points or trends can be found in the rainfall record (see Appendix 2.D for specific results).

Statistical results indicate that change points can be detected at the Central Park rain gauge in the mid-1960s at the 3- to 24-h timescale for annual maximum rainfall. Change points can also be detected at the Newark Airport rain gauge in 1971 for 1- and 24-h annual maximum rainfall. These change points may represent a meteorological regime shift associated with the wetter years after the mid-1960s drought, or they may represent changes in recording. After accounting for change points, few rainfall records exhibit statistically significant trends in annual maxima. The only significant trend is for the 3-h annual maximum rainfall depth at the JFK Airport rain gauge (Fig. 2.8). Across rain gauges and timescales, it appears that there may have been an upward shift in extreme rainfall in the late 1960s to early 1970s, but that there has been no consistent trend in heavy downpours across the city.

In order to define current baseline and spatial variation for heavy downpours in New York City,

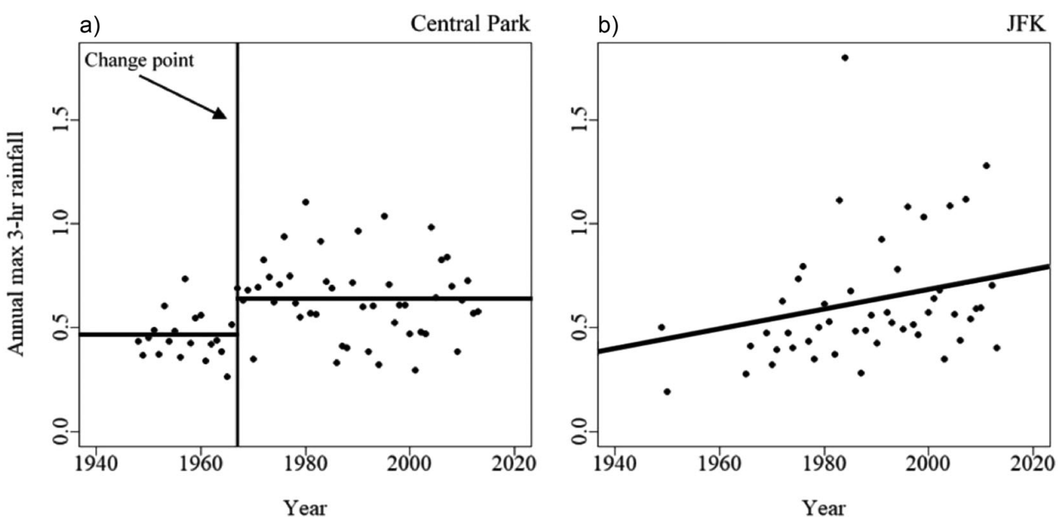

Figure 2.8. Annual maximum 3-h rainfall (in) at Central Park (a) and JFK (b) rain gauges. Central Park displays a change point, a change in median rainfall depth, in 1967 (vertical line), and JFK displays an increasing trend.

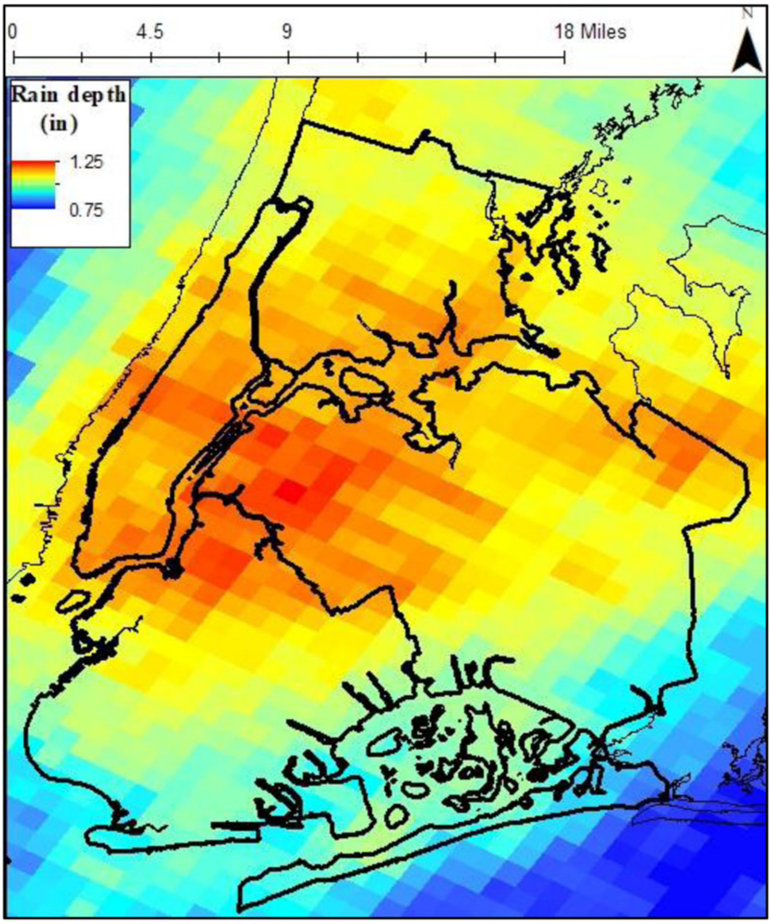

Figure 2.9. **Daily average rainfall for days of known flooding (2001–2015). Rainfall data from Staten Island are missing due to a blocked radar band. Image adapted from Smith and Rodriguez (2017).**

a high-resolution rainfall dataset for 1 km^2 and 15-min intervals was developed using warm season rainfall from 2001 to 2015 for the Fort Dix, NJ (KDIX) SR-88D (Weather Surveillance Radar, 1988 Doppler) radar in Mount Holly, New Jersey operated by the NWS (see Appendix 2.D for details of methods).

Baseline data for heavy downpours in New York City indicate a spatial variation in rainfall depth (Fig. 2.9). Days of known flooding (from Hazard Mitigation Reports and National Centers of Environmental Information (NCEI)) vary in rainfall depth between 0.9 and 1.25 inches across New York City. Rainfall on flooding days is at a maximum (1.25 inches) over the geographic center of the city (North Brooklyn and Northwest Queens), while some areas of high rainfall extend to the northeast. This region of high rainfall rates can be related to the urban impact on convective rainfall with higher rainfall within the city center. Figure 2.10 shows average maximum rainfall rates on days of known flooding at sub-daily timescales.

2.4.1.4 Heavy downpour projections. Predicting and understanding heavy downpours in New York City is difficult, and the science is not yet available to accurately project future heavy rainfall at 1- to 6-h timescales. Short-duration heavy downpours are likely more sensitive to atmospheric conditions than longer-duration extreme rainfall, and results from longer-duration studies are not directly applicable to shorter-duration rainfall (Westra *et al.*, 2014). Additionally, heavy downpours can vary spatially across the city, and therefore rainfall

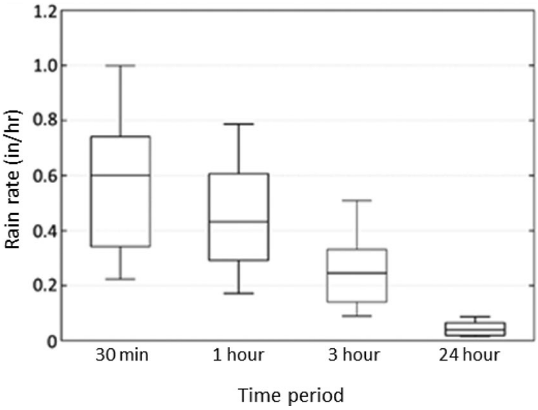

Figure 2.10. Boxplot for NYC-averaged max rainfall rates over 30 min, 1-, 3-, and 24-h for the 86 days of known flooding (2001–2015). Staten Island is excluded due to a blocked radar band. Whiskers represent the 10th and 90th percentiles, the box represents the 25th and 75th percentiles, and the line represents the median. Image from Smith and Rodriguez (2017).

results from Central Park may not be applicable across all five boroughs. Finally, when using rainfall projections for design purposes such as in the New York City Climate Resiliency Design Guidelines (NYC Mayor's Office of Recovery and Resiliency, 2018), it is important to recognize that smaller areas can experience higher rainfall rates than larger areas. This is often solved using Area Reduction Factors, which scale rainfall intensity by the areal extent of coverage (e.g. Wright *et al.*, 2013).

Urban impacts. Heavy downpours in New York City and other cities are affected by several physical processes including urban modification of rainfall and interactions with the land–sea boundary. Patterns of urban modification of rainfall have been found in Chicago (Changnon, 1968), Cleveland (Huff and Changnon, 1973), St. Louis (Changnon, 1979), San Antonio and Dallas (Shepherd *et al.*, 2002), Houston (Burian and Shepherd, 2005), Indianapolis (Niyogi *et al.*, 2011), Atlanta (Wright *et al.*, 2012; McLeod *et al.*, 2017), Baltimore (Smith *et al.*, 2012), and Charlotte (Wright *et al.*, 2013).

Urban areas can change rainfall patterns through UHI effects, urban-induced roughness (i.e., buildings interrupting air flow), and aerosols caused by pollution (Shepherd, 2005; Shepherd, 2013). These effects influence the path and development of thunderstorms, resulting in different rainfall patterns depending on the atmospheric setting. Generally, a weak UHI increases rainfall over city centers, while strong UHIs increase rainfall around the urban fringe, particularly downwind of urban areas (Bornstein and LeRoy, 1990; Shepherd, 2013). Short-duration heavy rainfall that produces flooding in urban areas is typically driven by warm-season thunderstorms with the most extreme rain rates occurring in the evening (Ntelekos *et al.*, 2007). These storms are also the most influenced by urbanization (Smith *et al.*, 2013).

A handful of studies have attempted to understand the spatial patterns of observed extreme rainfall in New York City as it is affected by urbanization. Bornstein and LeRoy (1990) investigated the impacts of the city on paths of thunderstorms. They found that the UHI can cause convection, or lifting of air, while the city roughness (buildings and structures) can induce divergence, or the separation of air; together these result in rainfall minima within the city and rainfall maxima surrounding and downwind of the city, especially on days with a strong UHI (Bornstein and LeRoy, 1990).

Yeung *et al.*, 2011, used high-resolution radar rainfall fields from the Fort Dix, NJ radar and Weather Research and Forecasting modeled storm events to investigate the role of urban areas on convective storm tracks in the greater New York City region. The results showed an increased number of days exceeding 1 inch of rainfall over New York City (on average, 9 days per summer season).

Recently, 1-h, 4 km^2 multisensor Stage IV rainfall data (Lin and Mitchell, 2005) were used to classify rainfall in New York City down to 1-h events (Hamidi *et al.*, 2017). The results showed that rainfall extremes have substantially higher rainfall rates at a 1-h scale in summer, and that summer extreme rainfall is more localized and associated with frontal systems than is winter extreme rainfall. Furthermore, Queens is most likely, and Staten Island is least likely, to experience high-intensity large areal extent 1-h summertime precipitation extremes (Hamidi *et al.*, 2017).

Land–sea boundary effects. The land–sea boundary also plays an important role in storm development and spatial patterns of extreme rainfall. The sea breeze can cause air to converge at low levels, thus creating uplift for thunderstorms (Weckwerth, 2000) and producing strong convection (Wilson and Megenhardt, 1997). In regions with both urbanization and land–sea boundaries to the east, the land–sea boundary tends to increase convergence, provide a source of moisture for thunderstorms, and increase rainfall intensity (Ryu *et al.*, 2016). It is difficult, however, to disentangle the effects of sea breezes and the urban influence, as urbanization can affect the location of sea-breeze fronts (Carter *et al.*, 2012). Furthermore, New York City's location with its multiple water bodies creates an array of different sea breeze fronts across the city (Colle *et al.*, 2003; Novak and Colle, 2006). In the case of New York City, where the sea breeze generally is located to the southeast of the urban center, cooler air tends to stabilize the lower layers of incoming thunderstorms, generally causing them to weaken as they cross the city center (D. Rind, personal communication).

2.4.1.5 Effects of climate change on heavy downpours. Climate change is likely to influence the complex dynamics of urban and sea breeze–modified heavy downpours. Heavy downpours are closely tied to the amount of available moisture in the air, which is in turn influenced by air temperature. As the climate warms, the Clausius–Clapeyron relationship indicates that a warmer atmosphere can have higher ratios of water vapor to air at saturation; this is likely to increase rates of heavy downpours with climate change (Trenberth *et al.*, 2003).

However, increases of rainfall intensity with temperature have been observed at much higher ratios than predicted by the Clausius–Clapeyron equation, especially for sub-daily extreme rainfall (Westra *et al.*, 2014). It has also been projected that there will be more convective storms over the Northeast United States during the later 21st century (Li and Colle, 2016), which will additionally increase heavy downpours and flooding.

Interactions between these complex mechanisms are difficult to predict, but some paths forward have been proposed (Arnbjerg-Nielsen *et al.*, 2013). These include a determination of the storm types that drive extreme rainfall in New York City (Figs. 2.6 and 2.7). This will help to clarify a path forward and should be considered in future work of the NPCC.

2.4.2 Urban flooding

Increases in extreme rainfall are expected to increase urban flooding because an increase in water volume should increase flood peaks (Ashley *et al.*, 2005; Melillo *et al.*, 2014). At national and regional scales, however, the ability to detect this trend is difficult. Several studies have examined streamflow records for a connection between high-flow events and climate change at national and regional scales. While some studies have found significant trends in high-flow streamflow (Groisman *et al.*, 2001a; Groisman *et al.*, 2001b; Juckem *et al.*, 2008; Sagarika *et al.*, 2014), others have not (Douglas *et al.*, 2000; McCabe and Wolock, 2002; Small *et al.*, 2006; Villarini *et al.*, 2009; Hirsch and Ryberg, 2011).

These studies typically analyze watersheds that are undisturbed, but a few regional studies have attempted to discern changes in the urban flood record with climate change (Yang *et al.*, 2013 in Milwaukee; Rouge and Cai, 2014 in Chicago). Yang notes that for changes in flood response it is difficult to disentangle signals of "large-scale climate change, regional climate change induced by urbanization, and contrasting runoff generation mechanisms associated with land surface properties."

Urban flooding was not covered in NPCC2. Here, NPCC3 establishes current baselines and past trends in urban flooding for New York City and the surrounding area. These can be used in the next generation of projections for urban flooding that will be derived from quantitative projections of heavy downpours to be developed by NPCC4.

2.4.2.1 Urban flooding past trends and baselines. In order to investigate trends, streamflow data for flash flooding in small watersheds near New York City was used as a proxy (see Appendix 2.E). Annual peak streamflows in several small (less than 15 km^2) watersheds in the U.S. Census-designated New York City urban region were analyzed for change points and statistically significant trends, similarly to the heavy downpour rainfall data.

Trends in urban flooding are difficult to establish via this flash flooding proxy (for full results see Appendix 2.D). One New York City–region stream record, for the Mahwah River near Suffern, NY, has a statistically significant change point in 1967, which is similar to the change point in rainfall extremes (see Section 2.4.1.3). A different stream, Jumping Brook near Neptune City, NJ, has a statistically significant negative trend in annual peaks. Changes in annual peaks vary across the 14 streams with both increasing and decreasing change points and trends.

These changes are likely to be less representative of climate change (which would show more consistent patterns across the streams) and are more representative of a direct human impact on flash flooding. Nearly all the streams are highly managed through regulations, upstream diversions, and channel modifications. These urbanization effects, including the effects of impervious surfaces (Leopold, 1968), are likely to have larger impacts on the frequency and intensity of flash floods than does climate change (e.g., Yang *et al.*, 2013; Rouge and Cai, 2014).

Futhermore, the combination of urbanization and climate change requires flooding and stormwater management to be assessed in a nonstationary framework—that is a framework in which historic flood and runoff occurrence is not strictly relied upon to predict the probability of future flooding events (Milly *et al.*, 2008). This appears to be particularly evident with compound flooding (flooding caused by the combination of heavy downpours and storm surge) occurrence. Research has shown the number of compound flooding events in New York City to be increasing as weather patterns shift and sea levels rise, to cause larger precipitation amounts and more storm surge (Wahl *et al.*, 2015).

Urban flooding baselines and variation across the city were analyzed using 311 flood report data (https://data.cityofnewyork.us/Social-Services/311-Service-Requests-from-2010-to-Present/erm2-nwe9). Typically, urban flooding is detected as a quick rise in stream depth or flow over a certain threshold (as used in Appendix 2.D). However, within the limits of New York City, there are no small stream channels to use for flood analyses. A major source of flood data is the 311 database, which records citizen phone calls to report street or highway flooding.

These 311 flood calls are biased due to two major issues. First, population density differences across the city make floods much more likely to be seen and reported in dense areas of the city. Second, different communities may report flooding at different rates due to perceptions of the likelihood of a response to their reports. These differences in reporting can also be observed in other types of 311 calls; for example, noise complaints, broken street lights, and other reports are also geographically biased.

This underlying bias of all types of 311 reports was used to correct the bias in flooding 311 reports. The number of 311 flood calls within a 1 km^2 area around a point was divided by the number of all 311 calls within the same area (Fig. 2.11). This allows for a distinction of how often floods are reported as compared to other 311 issues.

Additionally, the New York City 2019 Hazard Mitigation Plan with its annual updates and flood reports from the National Climatic Data Center (https://www.ncdc.noaa.gov/stormevents/) were used to define days of known flooding. These reports are generated by experts (NWS staff and emergency managers), which can make them more accurate. However, standards in reporting have changed over time, and event reporting has increased in more recent years.

Baseline data based on 311 calls for urban flooding indicate substantial spatial variation across New York City from 2004 to 2015 (Fig. 2.11). Flooding appears to occur most often in areas near the coast and areas without combined sewers: Staten Island, Jamaica Bay, and eastern Queens. The flooding pattern has been analyzed in comparison to rainfall and other potential factors, including elevation, impervious surfaces, and population density, to determine the drivers of flooding in New York City (Smith and Rodriguez, 2017). Results indicate that high groundwater tables influence flooding along the coast, while intense 1-h to 1-day rainfalls cause flooding farther inland. Flooding in Staten Island is primarily caused by wintertime extratropical cyclones (Smith and Rodriguez, 2017).

Results from the 311 data indicate that differences in flooding across the city are likely related to rainfall patterns, proximity to the coast, impervious coverage, and differing sewer coverage. The New York City 2019 Hazard Mitigation Plan additionally includes irregular topography, soil infiltration rate, and soil storage capacity as factors that influence flooding location. Figure 2.11 indicates the similar patterns between flood occurrence and sewer type, including: combined sewers, which collect both sewage and stormwater into one system; separate sewers, which have separate systems for sewage and stormwater; parks, which do not require sewers; and other, which includes any other means of stormwater conveyance, including direct drainage into local waterways.

2.4.3. Future research on heavy downpours and urban flooding

Improved projections of future heavy downpours and urban flooding in New York City will require

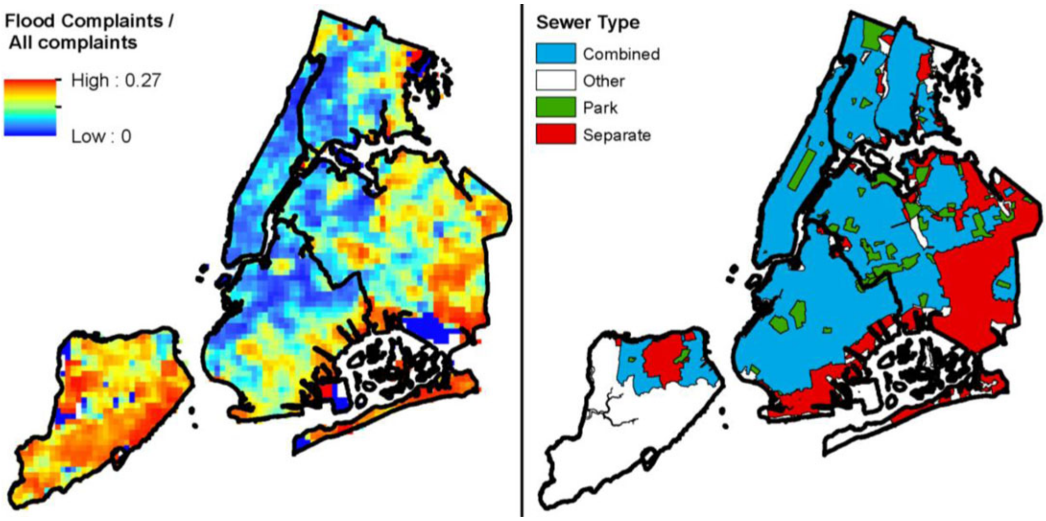

Figure 2.11. Flood observations based on 311 calls for the period 2004–2015. Left panel: Flood observations based on 311 calls, normalized by all 311 observations. Units are in flood observations per all observations in 1 km^2; Right panel: New York City sewer type. Image from Smith and Rodriguez (2017).

substantially more research. Potential areas of future research include:

Heavy downpours

- *Analysis of natural climate variability.* A more complete characterization is needed of present-day variability in storms and flooding. Because the New York metropolitan region experiences such large shifts in temperatures due to the annual cycle as well as large year-to-year variability per season, it is often difficult to determine the strength of the signal of climate change relative to the noise of natural climate variability. Quantifying this relationship for different precipitation metrics would help decision-makers prioritize hazard-specific responses to the projected changes.
- *Precipitation downscaling.* Results from GCMs can be dynamically downscaled, in which the outputs from the GCMs are used to force higher-resolution RCMs centered around the area of interest. The RCMs should include urban features related to the New York metropolitan region, such as its large proportion of impervious surface, tall buildings, and location near the sea. The proposed future methods for extreme heat events could be used as a basis for projecting heavy downpours as well. However, research in this area should evaluate how well RCMs can be used in conjunction with GCMs for projections of heavy downpours and urban flooding.
- Given that daily precipitation maxima are associated primarily with extra-tropical cyclones, research could assess whether there has been any convergence in global climate model projections on future storm track changes relevant to New York City.

Urban flooding

- *Urban flood modeling.* While projecting future heavy downpours is a task that requires substantially more research, modeling urban flooding in New York City may be developed in the near future. Several open-source academic models exist or are in development (e.g., Downer and Ogden, 2004; Goodrich *et al.*, 2010; Sanders *et al.*, 2008), and commercial urban flood models (MIKE SHE, InfoWorks ICM) are available as well. Utilization of such models will allow for understanding more clearly the relationships between rainfall intensity, duration, and frequency, and their effects on urban flooding in the region. These models could be used to assess current and future flood risks as heavy downpour projections become available.[d]

- *Increased urban flood observations.* It is difficult to determine urban flood risk in New York City and to validate urban flood models due to lack of data. Urban flooding is typically measured by depth of streamflow in small catchment streams, but this is difficult in New York City because its surface streams have been buried. Recent advances in environmental sensing using microcontrollers may indicate a path forward for urban flood data collection. In recent years, there have also been substantial efforts to identify flood risk outside the typical streamflow methods through citizen science reporting (Cheung *et al.*, 2016; Poser and Dransch, 2010).

2.5 Droughts

NPCC1 reported the potential future changes in droughts for the city using the 12-month average Palmer Drought Severity Index (PDSI) (NPCC, 2010). It was projected that the frequency of drought will approximately double by the 2050s and will be five times greater by the 2080s. This NPCC3 report focuses on drought indices developed for the city's major reservoir system using paleoclimate data.

The drought of record in the New York metropolitan region is the one that occurred in the early to mid-1960s (Namias, 1966). It stands as a warning of the potential vulnerability of New York City to severe water shortages. Many of the operating rules governing water management for the region depend largely on performance testing using the 1960s drought as the standard (Kolesar and Serio, 2011, Devineni *et al.*, 2013, Ravindranath *et al.*, 2016).

Since reliable observed streamflow data in the region often date back only to the 1950s, this section addresses questions as to the longer-term drought risk including the characterization of drought duration, severity and return period through paleoclimate data analyses.

Hydrologic reconstructions of streamflow from tree-rings spanning the past several centuries can provide a more complete picture of the range of variability at the decadal or longer time scales. Other paleoclimate studies using pollen assemblages suggest drought conditions from ~800 to 1300 AD as well (Pederson *et al.*, 2005).

These paleoclimate studies can place the short instrumental record into a more long-term perspective. Previous work (Devineni *et al.*, 2013, Woodhouse *et al.*, 2006, Nowak *et al.*, 2012; Stockton and Jacoby, 1976) have demonstrated the utility of paleo climate streamflow reconstructions in providing a more objective evaluation of operating rules for reservoir systems. Consequently, for NPCC3, we developed reconstructions of the Pepacton, Cannonsville, and Neversink (PCN) reservoir inflows (Fig. 2.12) using tree-ring chronologies in the upper Delaware River basin.[e] We used these extended reservoir inflow records to develop long-term drought profiles on duration, severity and return periods under different water demand thresholds. Table 2.8 provides key definitions for terms used to discuss drought throughout this section.

2.5.1 Methods of analysis

This section briefly presents the methodology employed for reconstructing reservoir inflow and for deriving drought indicators. Data description and technical details of the model structure are provided in Appendix 2.E. Full details of the methods can be found in Devineni *et al.* (2013).

2.5.1.1 Reservoir inflow reconstructions. We developed the PCN reservoir inflow reconstructions using a statistical regression model. Instrumental data (i.e., inflows for the three reservoirs during the observation period since 1928) were provided by the New York City Department of Environmental Protection. Tree-ring width measurements that represent paleoclimate data for the Delaware watershed date back to 1754. These are available from the Tree Ring Laboratory at the Lamont-Doherty Earth Observatory (LDEO).

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[d]See the following website for information about the Town & Gown: Citywide Stormwater Resiliency study: https://www1.nyc.gov/assets/ddc/downloads/town-and-gown/active-rfps/CitywideStormwaterResiliencyStudy T+GRFP.pdf

[e]While this NPCC report uses the Delaware River Basin as a drought proxy for the New York metropolitan region, the city measures and monitors water supply availability on a whole-system basis including the Delaware, Catskill and the Croton systems.

Table 2.8. NPCC3 drought definitions

Term	Definition
Reservoir inflow	Streamflow (amount of water) coming into reservoirs.
Reconstruction	Estimate of streamflow for past period using trees proven to be good estimators of observed streamflow during the period of gauged record. This is typically developed using statistical models that capture the relationship between tree growth index and the observed streamflow record during the overlapping period. This statistical model is applied to the prior period.
Cumulative deficit	Accumulated water deficit over an *n*-year period. Deficit for each year is defined as the difference between water demand (reservoir releases) and water supply (reservoir inflows).

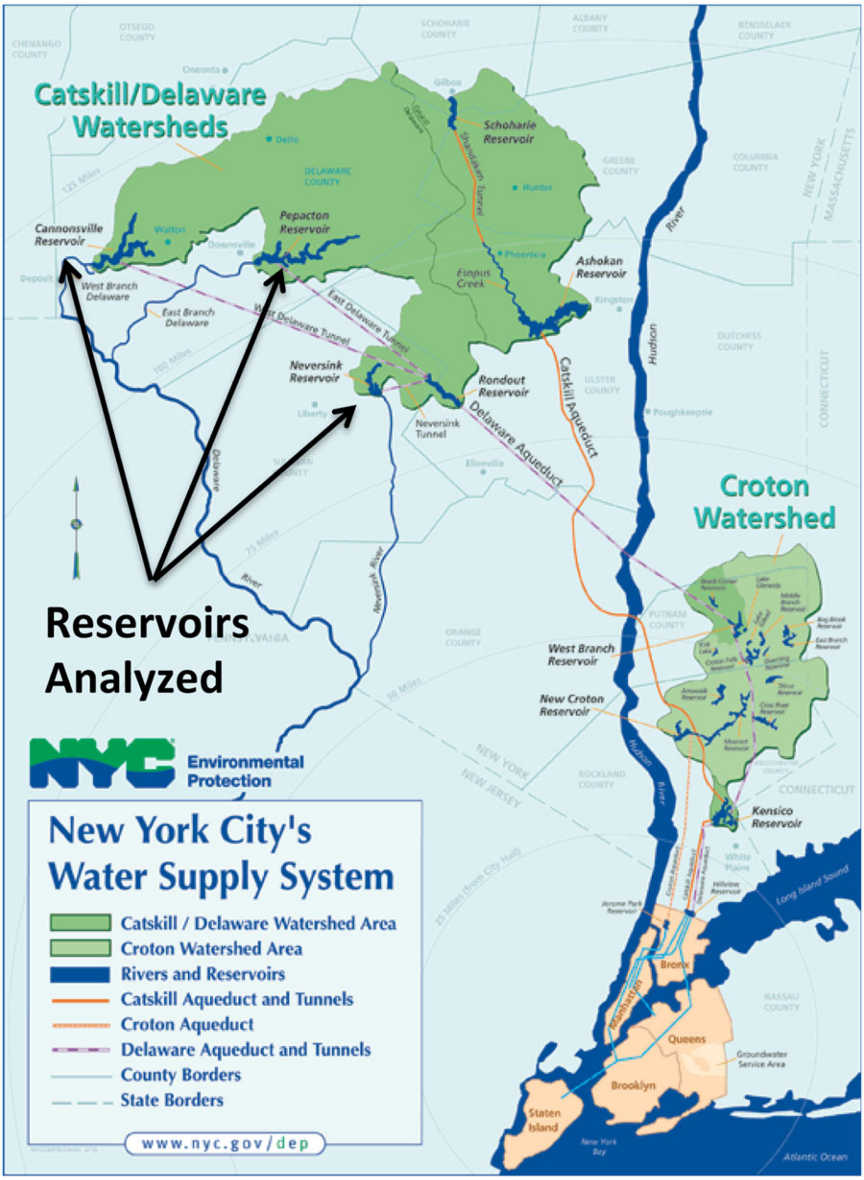

Figure 2.12. New York City's Water supply system. The Cannonsville, Pepacton, and Neversink reservoirs of the Delaware Watershed are analyzed by NPCC3 using long-term drought records from tree-ring data. *Source: NYCDEP.*

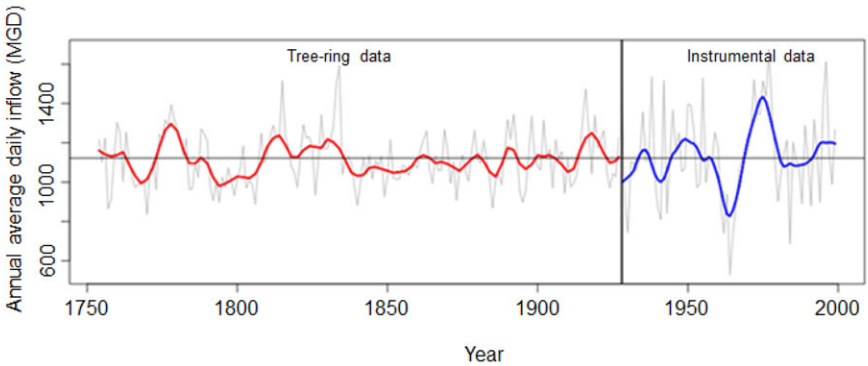

Figure 2.13. Reconstruction of combined annual average daily inflow from eight tree-ring chronologies in the Pepacton, Cannonsville, and Neversink reservoirs, which supply approximately 50% of the New York City water supply (DRBC 2018). Since tree growth is dependent on climate and since each tree-ring represents a season of growth, tree-ring measurements provide information on hydrological indicators over a tree's life span that can be used to understand variations in climate.

Given data from the three reservoirs and eight local tree-ring chronologies as predictor variables, the statistical model provides regression equations for each reservoir that are used to reconstruct the streamflow. The period over which the reconstruction was done is 1754–1927. The resulting outputs are simulations of annual average daily streamflow from 1754 to 2000 for the three reservoirs.

2.5.1.2 Drought indicators. We constructed a drought index to characterize the regional drought with explicit consideration of water demand. We developed the drought index on instrumental streamflow data first to gain an understanding of the observed drought risk since 1928. Then, we applied it to the reservoir inflows reconstructed from the tree-ring data.

2.5.2 Results

This section presents the results of the streamflow reconstructions and drought analyses for the instrumental period and the paleo-reconstructed period.

2.5.2.1 Combined inflows from tree-ring data and incidence of observed drought. The general trends of combined reservoir inflow from tree-ring data from 1754 to 2000 are shown in Figure 2.13. While the 1960s drought is the most severe in the extended record, the tree-ring analysis show that there were regimes with less severe but longer drought durations (e.g., 1830–1860, 1790–1810).

By examining this historical record, we found that there are at least eight incidences of historical drought lasting 5 consecutive years or longer occurring in the region since 1750 (Table 2.9). Six of these occurred in the paleo record period, and two were observed in the instrumental period. This indicates there is a potential for persistent drought in the New York metropolitan region in the future.

Table 2.9. **Incidence of historical drought of at least 5 consecutive years in the New York metropolitan region in the paleo record (1754–1927) and the instrumental record (1928–1999)**

Drought duration	Years
Paleo record	
10 years	1764–1773
11 years	1791–1801
5 years	1803–1807
9 years	1852–1860
6 years	1883–1888
5 years	1909–1913
Instrumental record	
5 years	1929–1933
7 years	1961–1967

2.5.3 Summary and future work

Long-term drought risk for the New York City water supply system is developed based on tree-ring reconstructions for PCN reservoir inflows. The streamflow reconstructions reveal droughts with a longer duration than the 7-year major drought seen in the instrumental period (1961–1967). If the variability of streamflow as seen from the long paleoclimate tree-ring record (246 years) were to continue into the future, increases in regional water demand due to population increase and climate change could affect the duration of droughts. This is important from a drought risk and planning perspective.

Hydrologic reconstructions provide a more complete picture of how streamflows have varied in the New York metropolitan region water supply area. However, longer-term water planning decisions should also be informed by climate scenarios, such as the New York City Panel on Climate Change (Moody and Brown, 2012; Steinschneider and Brown, 2012; NAS, 2018; Rosenzweig and Solecki, 2018).

Given current understanding of seasonal to interannual climate variability, and of climate change, NPCC4 could develop an approach for regularly updating the drought estimates using climate observations and models tuned to prediction at different timescales. Consequently, future work should involve drought risk characterization and modeling that embraces paleo-reconstructions, climate model hindcasts utilizing such metrics as PDSI, observed trends, and near-term and longer-term projections in a rigorous way to understand climate risk and formulate management and adaptation strategies at decision-relevant scales.

2.6 Conclusions and recommendations

NPCC3 confirms the use of NPCC2 projections as those of record for decision-making in the City of New York. It analyzed how recent climate trends compare to the projections for the region. Further, it has begun to develop and test new methods for observations and projections to be used in resilience planning. Using expanded observations, bias correction, and RCMs, these methods can provide quantitative analyses for heat extremes, heavy downpours, and droughts. They are available for developing the next full set of NPCC projections.

Based on these and other methods, the next generation of global and RCM outputs will be used in upcoming NPCC assessments to create a new unified set of projections for decision making in the New York metropolitan region. The methods tested by NPCC3 utilizing GCM and RCM ensembles and scenarios will enable the updated identification of climate change "hotspots" of vulnerability at finer spatial scales within the city and across the region.

However, GCMs may not yet be able to simulate the forcings required for RCMs to model some finer-scale extreme events such as convective thunderstorms.

Key findings

Observations and projections

- Observed annual temperature and precipitation trends between 2010 and 2017 fell largely within the NPCC2 projected range for the 2020s time period. [These comparisons should be viewed with caution because of the role that natural variation plays in the short term.]
- Observations of increasing heavy rainfall between 2011 and 2017 fell largely within the NPCC2 projected range 2020s time period. [These comparisons should be viewed with caution because of the role that natural variation plays in the short term.]
- NPCC3 confirms the use of the NPCC2 2015 projections for decision-making by the city and region.

Extreme heat

- Increasing decadal trends in annual daily average maximum summer temperatures in June, July, and August varied across the city. Central Park has experienced an increasing trend of 0.2 °F per decade from 1900 to 2013. Since 1970, JFK average annual daily maximum summer temperatures have been rising at a rate of 0.5 °F per decade, and LaGuardia at 0.7 °F per decade.
- New projection methods for extreme heat events were developed and tested for the New York metropolitan region. The test includes bias correction, a method that adjusts the mean and variance of GCM results to match a representative set of observations from the region, and high-resolution regional climate modeling.

Heavy downpours

- New studies support NPCC2 projected increases in precipitation, in terms of the mean and extremes for the region. These precipitation changes are expected to occur in both the winter and summer seasons. However, uncertainty in these precipitation projections is larger than the uncertainty in temperature projections.
- A change point in sub-daily heavy rainfall events can be detected at the Central Park rain gauge in the mid-1960s for the annual maxima of 3-hourly rainfall; the only significant trend

found was for 3-h annual maximum rainfall depth at the JFK rain gauge.

- Extratropical cyclones cause the largest number of extreme 24-h precipitation events in New York City in every month out of the year.
- Rainfall that drives urban and flash flooding in the Northeast is typically temporally and spatially concentrated and is most often caused by thunderstorms.
- Days of known flooding vary spatially across New York City in rainfall depth between 0.9 and 1.25 inches. Rainfall on flooding days is at a maximum (1.25 inches) over the geographic center of the city (North Brooklyn and Northwest Queens).
- Urban flooding appears to occur most often in areas near the coast and areas without combined sewers: Staten Island, Jamaica Bay, and eastern Queens. Results from 311 call data indicate that differences in flooding across the city are likely related to rainfall patterns, proximity to the coast, impervious surfaces, and differing sewer coverage.
- The groundwork for future projections was established by refocusing the discussion from daily to sub-daily rainfall extremes.

Droughts

- While there has not been a major drought since the 1960s in the New York metropolitan region, analysis based on tree-rings from about the last 250 years shows that 10-year or longer droughts have occurred. Thus, the possibility of future droughts should be considered in planning.

Recommendations for research

- Future NPCC research can improve the utility of quantitative heat wave projections by working with the New York City Department of Health and Mental Hygiene and the National Weather Service (NWS). Together these groups can investigate how best to evaluate need for future revisions of heat advisory criteria that consider changing combined effects of temperature and humidity (i.e., heat index).
- Relevant research areas include examination of thresholds of heat and humidity effects on human health, and strategies to design interventions that will be effective in New York City's hotter climate.
- Research is needed to determine benchmarks for sub-hourly extreme precipitation and associated flooding events using satellite data and rain gauges at Central Park, LaGuardia, JFK, and Newark. Using these benchmarks, researchers should aim to improve sub-hourly extreme precipitation projections that consider urban meteorological effects and identify neighborhoods likely to be flooded.
- Improved characterization is needed of likely large-scale conditions that may lead to extreme drought based on further tree-ring analysis in the region.

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Appendix 2.A. NPCC3 Global Climate Models

Table 2.A.1. Global climate models used in NPCC3 ensemble for extreme heat and humidity

Center	Model
Commonwealth Scientific and Industrial Research Organization—Bureau of Meteorology (Australia)	ACCESS1-0
	ACCESS1-3
Canadian Centre for Climate Modeling and Analysis (Canada)	CanESM2
National Center for Atmospheric Research (USA)	CCSM4
Centro Euro-Mediterraneo per i Cambiamenti Climatici (Italy)	CMCC-CM
	CMCC-CMS
Centre National de Recherches Méteorologiques/Centre Eurorpéen de Rechercheet Formation Avencée en Calcul Scientifique (France)	CNRM-CM5
Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence (Australia)	CSIRO-Mk3-6-0
NOAA Geophysical Fluid Dynamics Laboratory (USA)	GFDL-ESM2G
	GFDL-ESM2M
NASA Goddard Institute for Space Studies (USA)	GISS-CM3
	GISS-E2-H
	GISS-E2-R
Met Office Hadley Centre (UK)	HadGEM2-AO
	HadGEM2-CC
	HadGEM2-ES
Institut Pierre-Simon Laplace (France)	IPSL-CM5A-LR
	IPSL-CM5A-MR
	IPSL-CM5B-LR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute/National Institute for Environmental Studies/Japan Agency for Marine-Earth Science and Technology (Japan)	MIROC-ESM
	MIROC-ESM-CHEM
	MIROC5
Max Planck Institute for Technology (Germany)	MPI-ESM-LR
	MPI-ESM-MR
Meteorological Research Institute (Japan)	MRI-CGCM3
Institute for Numerical Mathematics (Russia)	INM-CM4

Appendix 2.B. NPCC3 Bias Correction Methods for Heat Waves

The bias correction technique corrects for both differences in model mean and standard deviation using a linear model, or:

$$T_{BC} = \overline{T}_{Obs,REF} + \frac{\sigma_{Obs,REF}}{\sigma_{GCM,REF}} \left(T_{GCM,RAW}(t) - \overline{T}_{GCM,REF}\right)$$

TBC refers to the bias-corrected temperature record. In the equation, T refers to the temperature records, and σ refers to the standard deviation of temperatures. Subscripts *Obs* and *GCM* refer to observations and climate model data, respectively, while *REF* and *RAW* refer to the reference (2006–2015) and entire projection periods (2006–2099), respectively. The over bar (–) marker denotes use of the average for the specified dataset and time period. The calculation of the bias correction is performed by weighting the difference between the observed reference and total period data by the ratio of the observed to climate model standard deviations, and adding the "weighted difference" to the observations to produce a time series.

The mean values of the four urban stations are used as observations for the training period of 2006–2015 for each model of the ensemble. The correction is then carried on for the three 30-year periods of interest (2020s, 2050s, and 2080s). The bias-corrected distributions are presented in Figure 2.B.1 for the complete ensemble of GCM daily maximum temperatures, which shows the bias-corrected distributions are much closer to the observations.

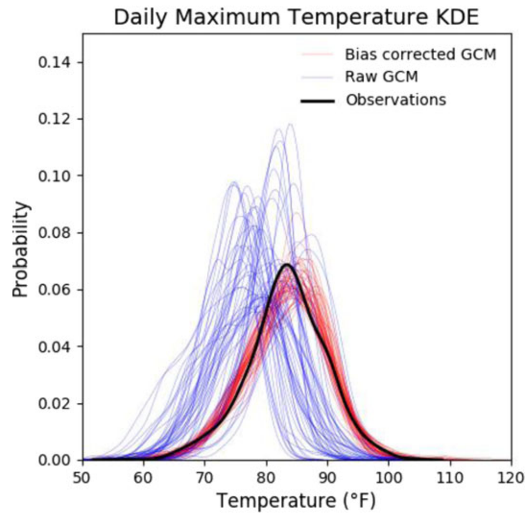

Figure 2.B.1. Sample of bias-corrected GCM distributions for maximum temperatures for the training period of 2006–2015. KDE refers to a Kernel Density Estimate, a representation of the probability of occurrence of a given value in the data set.

Appendix 2.C. Potential New Methods for NPCC4 Extreme Heat Projections

The output from GCMs can be dynamically downscaled, in which GCM outputs are used to drive high-resolution RCMs. This approach has led to development of regional, or limited area models (Dickinson *et al.*, 1989; Giorgi *et al.*, 1993; Skamarock *et al.*, 2008). This is a potential method for the next generation of NPCC climate change projections for New York City for use in adaptation planning and implementation. It can be a useful approach because GCMs used for quantifying future changes currently do not have adequate resolution to realistically simulate many extreme weather events, such as extreme heat, tropical storms, rapidly deepening nor'easters, severe convective storms, and heavy rainfall. Since these models are often run at 100–300 km grid spacing, much of the uncertainty originates from not properly resolving atmospheric dynamics for this weather. Further, GCM physics have large uncertainties at coarse resolution, since they do not resolve finer-scale processes such as the UHI and sea breezes. See Tables 2.C.1 and 2.C.2 for details.

Dynamical downscaling uses output from GCMs as initial and boundary conditions for high-resolution model run centered on the region of interest. In order to resolve clouds and urban-specific processes (e.g., anthropogenic heat and radiation blocking), this will require resolutions

Table 2.C.1. Summary of approach used for regional climate model simulations

Simulation approach	
Regional Climate Model	Weather Research and Forecasting (WRF) model version 3.8
Initial and boundary conditions	Community Earth System Model version 1 (CESM1)
Baseline years	2006–2010
Simulation period	June 1st to August 31st
Scenarios	RCP4.5 (medium emissions) RCP8.5 (high emissions)

Table 2.C.2. **Physics options used in WRF simulations**

Parameterization	Reference
Convection	Kain-Fritsch (Kain, 2004)
Microphysics	WSM6 (Hong and Lim, 2006, p. 6)
Boundary Layer	Mellow-Yamada-Janjic (Nakanishi and Niino, 2006)
Land Surface	Noah land surface model (Tewari *et al.*, 2004)
Urban Physics	BEP (Martilli *et al.*, 2002)
	BEM (Salamanca *et al.*, 2010)
	Cooling Tower (Gutiérrez *et al.*, 2015b)
	Urban Drag Coefficient (Gutiérrez *et al.*, 2015a)

around 4-km grid spacing or less; however, most current downscaling simulations use ∼20-km grid spacing. To address uncertainties in dynamically downscaled simulations, multi-simulation ensembles are employing varying boundary conditions, physics parameterizations, and grid spacing should be employed. Examples of this ensemble approach include the North American Regional Climate Change Assessment Program (NARCCAP; Mearns *et al.*, 2009) for the contiguous United States at 50 km resolution.

Another approach is using pseudo-global warming (PGW; Kimura and Kitoh, 2007). In the PGW approach, the ensemble mean monthly temperature changes from the GCMs are added to the historical reanalysis data, which in turn is used for initial conditions (ICs)/boundary conditions (BCs) for the future high-resolution regional domain runs. This approach is cheaper, since separate runs are not needed for each GCM, but this approach does not include any large-scale flow changes in the future from the GCM, since only temperature perturbations are added.

2.C.1 High-resolution dynamical downscaling

To test the approach for the New York metropolitan region, GCM projections are downscaled using an urbanized version of the Weather Research and Forecast Model (WRF; Skamarock *et al.*, 2008) developed and maintained by the National Center for Atmospheric Research (NCAR). Model physics are based on Gutiérrez *et al.* (2015a; Gutiérrez *et al.* (2015b)) and are summarized in Table 2.C.2. In contrast to GCMs, dynamical downscaling is performed by embedding, or nesting, models of higher spatial complexity within each other. In this case, three domains (one parent, two nested) are used, with horizontal grid spacing of 9, 3, and 1 km (Fig. 2.C.1). The high-resolution domain covers the New York metropolitan region with results presented for New York City.

Urban parameterizations require use of urban canopy parameters, such as urban land use, building

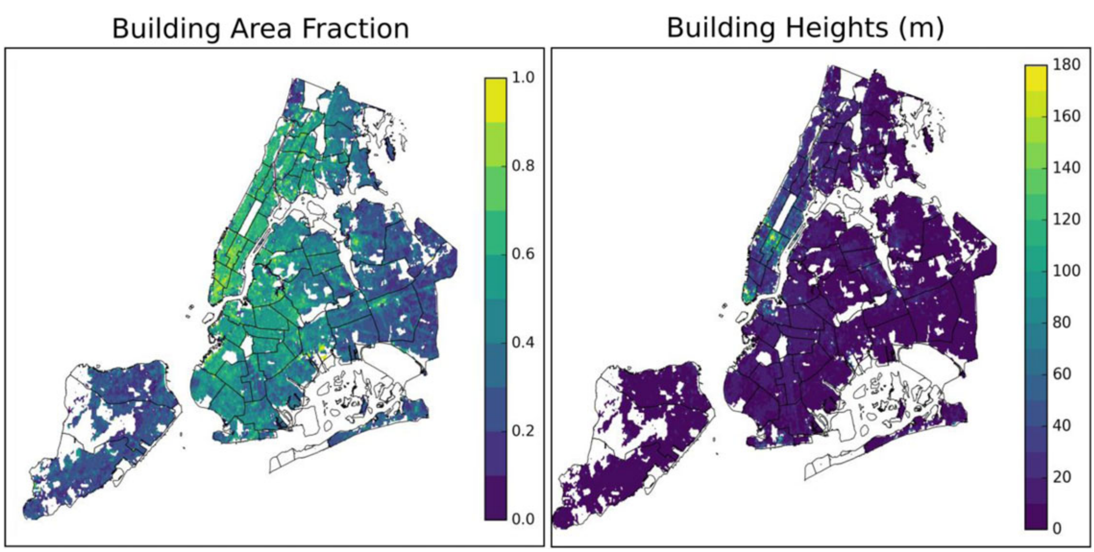

Figure 2.C.1. **Urban canopy parameters for NYC derived from PLUTO. These parameters are used to calculate interactions between the atmosphere and buildings.**

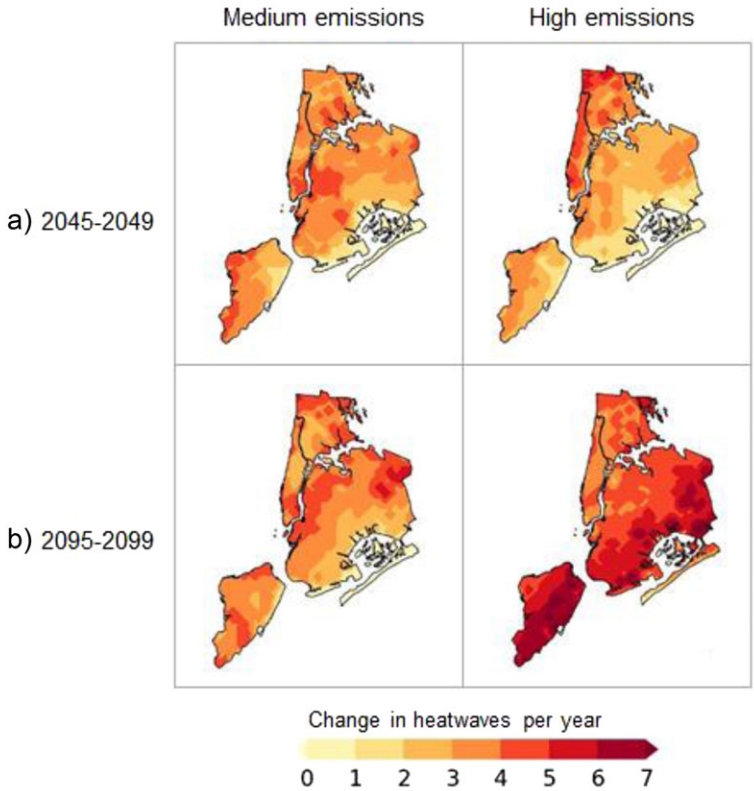

Figure 2.C.2. Median projections of event frequency for New York City.

plant area fraction (Fig. 2.C.1, left), and building heights (Fig. 2.C.1, right) to represent energy and momentum exchanges between the atmosphere and built environment (Fig. 2.C.1). These parameters have been derived from the Property Land Use Tax-lot Output (PLUTO) (NYC Open Data. Primary Land Use Tax Lot Output (PLUTO). https://data.cityofnewyork.us/City-Government/Primary-Land-Use-Tax-Lot-Output-PLUTO-/xuk2-nczf/data.) made publicly available since 2013.

Model initial and boundary conditions are taken from a bias-corrected Community Earth System Model (CESM) data set provided by NCAR (Bruyère *et al.*, 2015), which corrects biases in the intra-annual variation for all meteorological variables using ERA-Interim Reanalysis. The bias correction technique follows the work from Holland *et al.* (2010) as applied by Bruyère *et al.* (2014). The correction method separates the GCM and reanalysis signal into a seasonally varying term and a perturbation term (containing the model's climate signal). The seasonal mean is the corrected mean using the reanalysis's historical seasonally varying mean, while keeping the model's climate perturbation. This method was found by Bruyère *et al.* (2014) to produce more realistic patterns of wind shear and tropical cyclone generation for the historic period. The projection ensemble is summarized in Table 2.C.1. Correcting all model variables was shown to decrease CESM1 cold temperature biases when used as input to a regional model. Finally, three time periods are selected[f]: historical (2006–2010), mid-century (2045–2049), and end of century (2095–2099).

2.C.2 RCM results

Spatial variation of heat wave changes is shown for two time slices (2045–2049 and 2095–2099;

[f] Current computational power limits high-resolution RCM simulations to relatively time slices compared to those presented at the GCM level. However, the authors feel that the added spatial granularity provide significant value.

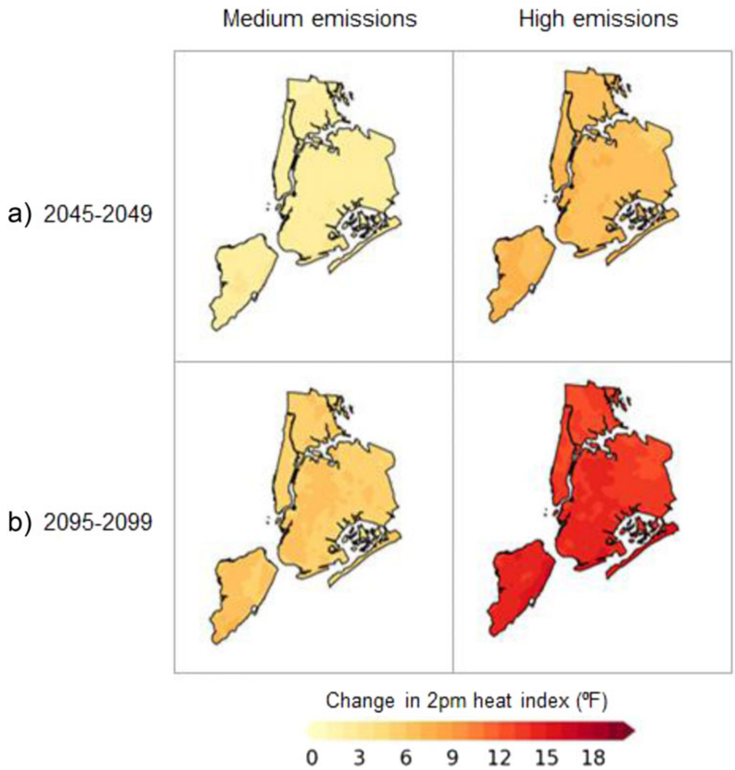

Figure 2.C.3. Median 2 pm afternoon heat index for 2045–2049 and 2095–2099 periods compared to the 2006–2010 baseline.

Fig. 2.C.2) for a typical year (i.e., median values). In general, sea breeze fronts, which typically develop in the afternoon due to land-ocean air temperature differences, play a crucial role in determining projected changes by moderating high temperatures near the coast.

The RCM simulations show that the number of heat waves per year is projected to stabilize after 2045 in the medium-emissions scenario. This stabilization occurs because the land surface warms more than the ocean and this differential warming causes sea breezes to moderate the number of heat waves that take place. This is similar to current conditions in which sea breeze circulations prevent parts of Brooklyn and Queens from experiencing as many and as severe heat waves as parts of Manhattan and the Bronx. Projections for Manhattan and The Bronx, however, show increases in heat waves by two to four events per year for both time periods.

In the high-emissions scenario (RCP8.5), the sea breeze is weakened due to increased ocean air temperatures, leading to Brooklyn and Queens experiencing higher event frequencies of between five and seven additional events per year. This is even greater than projected heatwave increases in Manhattan and The Bronx of four to six events. Larger increases near the coast may also be due to historically lower temperatures due to the local sea breeze.

The heat index (Rothfusz, 1990), combining temperature and relative humidity, is often used as a metric of how heat affects humans. Projections show that the heat index is expected to increase with time across projections, with end of century changes ranging between 6 and 8 °F in medium-emissions scenario to 12–16 °F in high-emissions scenario (Fig. 2.C.3). Changes in heat index are, in general, slightly larger over Manhattan and the northern part of Brooklyn in all scenarios and time slices except in end-of-century high-emissions scenario, where a similar pattern as that observed in event frequency projections emerges, with heat index increasing at a faster rate toward the coast.

Although multimodel high-resolution ensembles were not used in this study due to computational cost, changes in internal model variability across time slices and emissions scenarios are explored.

Table 2.D.1. Association of daily precipitation extremes at New York metropolitan region airports from 1979 to 2016

Storm type	JFK Airport station	LaGuardia Airport station	Newark Airport station
Extratropical cyclones	92, 4, 7.4%	92, 3, 7.3%	96, 5, 7.9%
Tropical cyclone	19, 4, 30.3%	17, 3, 27%	13, 5, 24%
Noncyclone	23	26	24

Note: When three values are given, the first is the number of isolated cyclones, the second is the number of extratropical plus tropical cyclones that occurred, the final number is the percentage of cyclone that pass within 500 km of New York City that caused extreme precipitation at the given station.

Sources of uncertainty in urban modeling may include:

- Representation of urban environment: Although this study uses relatively high-resolution urban canopy parameters, building-atmosphere interactions are heavily parameterized, depending on values averaged over grid points.
- Limited domain size: Due to computational limitations, high-resolution urban climate models run on a relatively small domain. Local conditions, in particular heat waves, are impacted by large scale synoptic processes that may occur thousands of miles away from New York City. Any uncertainties in the input model will be carried over in boundary and initial conditions used in these simulations.

Appendix 2.D. Methods of Extreme Rainfall Analyses

Table 2.D.1 summarizes the results of the extratropical and tropical cyclone associated analysis. If neither type of cyclone was associated with the precipitation event, the event is labeled noncyclone. In addition to identifying the total number of cyclone-associated events, we calculate the percentage of cyclones that cause extremes. To do this, we divide the number of cyclones associated with a precipitation extreme by the total number of cyclones that pass within 500 km of New York City. For extratropical cyclones, 7.5% of the storms caused a precipitation extreme. For tropical cyclones, the number is much higher, at 30%. This probabilistic calculation cannot be made for noncyclones, because the storm-type for those events is not known. At least some of those events are most likely associated with are quasi-linear convective systems (Lombardo and Colle, 2012), which are sometimes grouped with frontal systems (Kunkel *et al.*, 2011). The dominant cause of extreme daily rainfall events for all airport stations out of these storm types is extratropical cyclones.

Radar was processed with the Hydro-NEXRAD algorithms (Seo *et al.*, 2011) and corrected with

Table 2.D.2. Statistical analyses of rainfall data in New York City region

Parameter		CP	LGA	EWR	JFK
Hourly record	Time period	1948–2013	1948–2013	1948–2013	Hourly record
One hour	Change point	–	–	1971 (+35%)**	One hour
	Trend	–	–	–	
Three hours	Change point	1967 (+42%)**	–	–	Three hours
	Trend	–	–	0.2 mm/year**	
Six hours	Change point	1966 (+34%)**	–	–	Six hours
	Trend	–	–	–	
Daily	Change point	1965 (+17%)**	–	1971 (+30%)**	Daily
	Trend	–	–	–	
Daily record	Time period	1869–2017	1940–2017	1893–2017	Daily record

Note: Rainfall gauges located at Central Park, LaGuardia Airport, Newark Airport, and JFK Airport. Statistics are for 1-, 3-, 6-h, and daily annual rainfall maxima. Change points are shown in year and (change in averages), while trends are shown in Sen's Slope.
**A value is significant at a 5% level.
*A value is significant at a 10% level.

Table 2.D.3. Statistical analyses of streamflow data in the U.S. census New York City urban region

USGS gauge ID	Location	Time frame	Number of years	Change point	Trend (cfs/year)	Notes
01374654	Carmel, NY	1996–2012	17	–	–	Regulated flow
01374930	Baldwin Place, NY	1996–2016	21	2011 (–38%)*	–	Occasional regulation
01381400	Morristown, NJ	1996–2015	20	–	–	Diversion upstream
01387450	Suffern, NY	1959–1998	40		–	
		2001–2015	15	1967 (+154%)**		Well withdrawals upstream
01392210	Passaic, NJ	1977–1999	21	–	–	
01399670	Whitehouse Station, NJ	1978–2015	37	–	14.09*	Occasional regulations and upstream releases
01401650	Belle Mead, NJ	1991–2015	25	–	–	Some irrigation regulation in summer
01403150	Martinsville, NJ	1980–2015	35	–	3.84*	
01403400	Seeley Mills, NJ	1967–2015	49	–	–	Temporarily moved 1969–1979
01403535	Watchung, NJ	1980–2015	36	–	–	
01403540	Watchung, NJ	1973–2015	43	–	–	Occasional regulation, channel modified in 1991 and 1997
01407290	Marlboro, NJ	1980–2015	35	1999 (–25%)*	–	
01407705	Neptune City, NJ	1967–2014	48	–	–	Diversion upstream, a portion is regulated
01407760	Neptune City, NJ	1967–2016	50	–	–7.47**	Upstream diversion water supply and golf courses

NOTE: Statistics are for annual peak (maximum) in instantaneous streamflow. Change points are shown in year and (change in averages), while trends are shown in Sen's Slope.
**A value is significant at a 5% level.
*A value is significant at a 10% level.

a daily multiplicative bias (as in Smith *et al.*, 2012) using rain gauges from the National Oceanic and Atmospheric Administration Meteorological Assimilation Data Ingest system (NOAA MADIS, https://madis.ncep.noaa.gov).

Methods for determining trends in extreme rainfall and proxy-stream flash flooding included the nonparametric Pettitt Test (Pettitt, 1979), nonparametric Mann-Kendall Test (Mann, 1945, Kendall, 1975), and Sen's Slope (Sen, 1968). Complete results from these analyses are shown in Tables 2.D.2 and 2.D.3.

Appendix 2.E. Methods of Tree Ring Analysis and Drought Analysis

The PCN reservoir inflows were developed using a Bayesian regression model. Given data from three streamflow gages and eight local tree-ring chronologies (that date back to 1754) as predictor variables, the Bayesian model provides regression equations for each reservoir that are used to hindcast the streamflow. Annual average daily streamflow (June–May) was assumed to follow a lognormal distribution. The Bayesian regression models used to produce this partially pooled reconstruction explain around 60% of the streamflow variance and validate best against withheld data. The posterior probability distributions of the reconstructed combined reservoir inflow from the Bayesian regression model during the period 1754–2000 are shown in Figure 2.13. The record period common to all selected trees determined the time span of the reconstructions. The reconstructions of the combined reservoir inflow are presented as time series composed of the

Table 2.E.1. Summary of the probability of exceedances and the return periods of the droughts for four different demand levels

		Demand			
		950 MGD $D^* = 6$ $S^* = 1000$ MGD	1000 MGD $D^* = 6$ $S^* = 1300$ MGD	1050 MGD $D^* = 6$ $S^* = 1600$ MGD	1100 MGD $D^* = 7$ $S^* = 1900$ MGD
Exceedance probability	$P(S > S^*)$	0.03	0.04	0.45	0.95
	$P(D > D^* \cap S > S^*)$	0.006	0.028	0.40	0.94
Return period	Severity	33 years	25 years	2.2 years	1 years
	Joint	166 years	36 years	2.5 years	1 year

median of the posterior distribution for each year, as the reconstructions for each year are estimates of the posterior distribution of the annual average daily inflow for those years. The record of observed PCN combined inflow data is shown using the 11-year low-pass filtered values (blue color line during the instrumental period (1928–2000)). Similar low-pass filtered values are also shown for the median inflows (red color line) during the reconstruction period to visualize the general trend in the data.

2.E.1. Drought index (methods)

We developed the drought index to capture the effect of drought over multiple years. The index is based on the sequent peak algorithm (Loucks *et al.*, 1981). It quantifies the water reservoir drawdown for meeting the demand. The steps for the computation are as follows:

$$\text{Deficit}_t = \max(\text{Deficit}_{t-1} + D_t - S_t, 0),$$

$$\text{where Deficit}_{t=0} = 0$$

$$\text{Severity} = \max_t(\text{Deficit}_t; t = 1 : n - \text{years}).$$

where Deficit_t refers to the accumulated annual deficit, D_t refers to the annual water demand, S_t refers to the annual water supply and n is the total number of years under considerations. The maximum accumulated deficit estimated over the n-year period is defined as the Severity of the drought. It measures the potential impact of multiyear droughts (Etienne *et al.*, 2016).

2.E.2. Drought profile based on the reconstructed reservoir inflow data

The demand-specific drought index is applied to the simulations of the reconstructed PCN combined

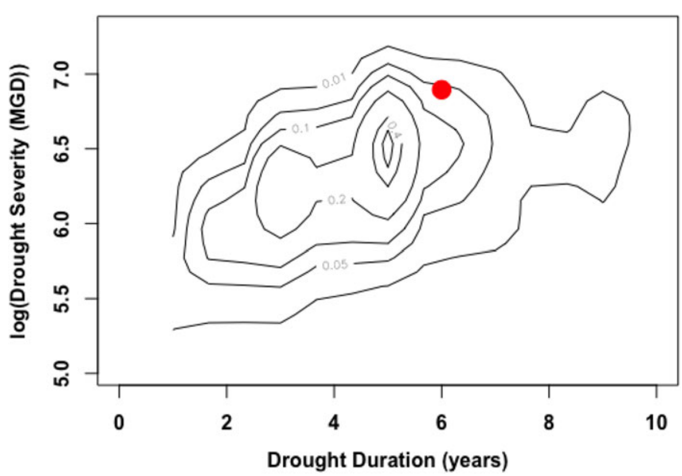

Figure 2.E.1. The joint drought profile for a demand of 950 MGD annual average daily outflow. The contour plot shows the joint probability distribution of drought duration and severity. The drought of the record (1960s drought of 6 years and 1000 MGD cumulative deficit) is shown as a red circle on the contour plot.

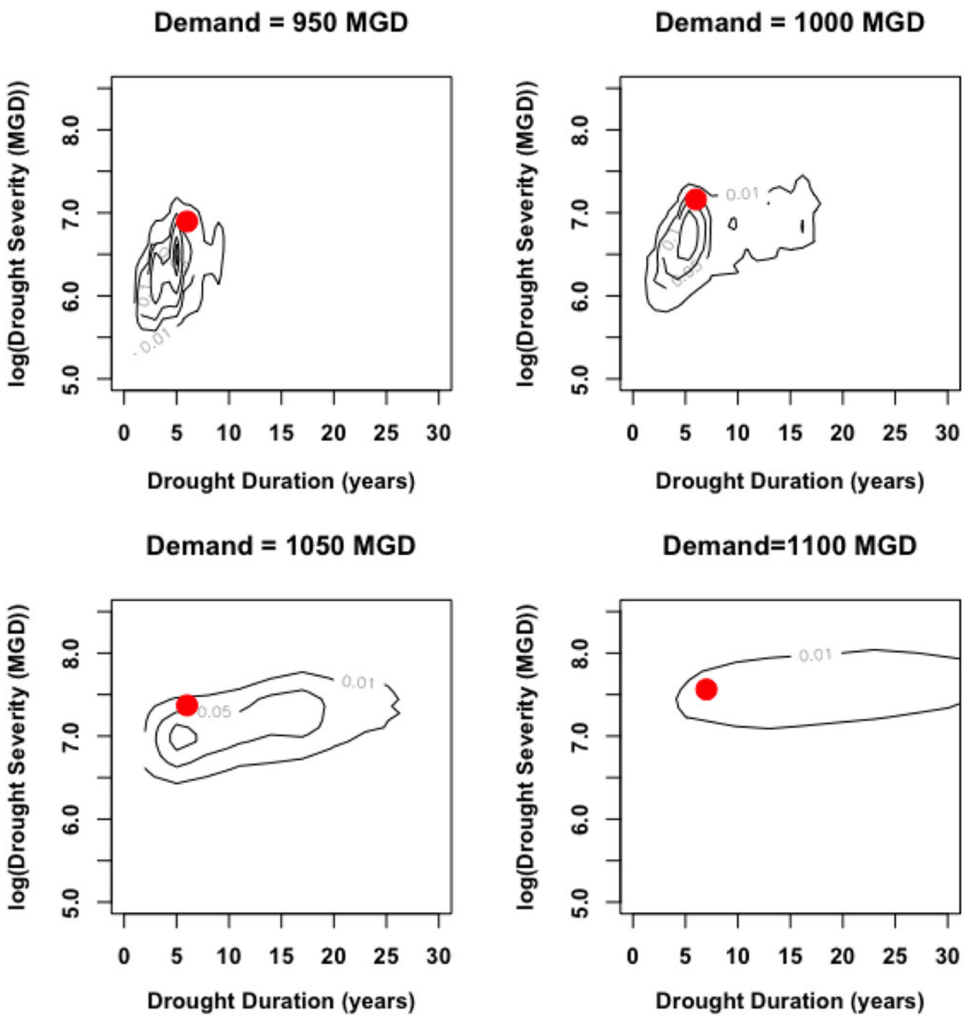

Figure 2.E.2. The joint drought profile for varying demands.

inflows with a demand threshold of 950 million gallons per day (MGD) of annual average daily flow to develop the long-term drought risk profile. Figure 2.E.1 presents the joint probability distribution of the drought duration and severity as seen from the paleo records. The worst drought event in the instrumental period (the 1960s drought of 6 years and a cumulative deficit of 1000 MGD) is shown as a red circle in the figure. It is evident from the paleo streamflow data that the drought of the record, the 1960s drought, is still an extreme event relative to a long-term drought risk profile. The probability of exceedance of the 6-year drought duration is $P(\text{Duration} > 6) = 0.06$, an approximate average return period of 16 years if drought length is of concern. The probability of exceedance of the 1000 MGD cumulative deficit (drought severity) is $P(\text{Severity} > 1000\ \text{MGD}) = 0.03$, an approximately average return period of 33 years if drought severity is of concern. However, if combined variables of duration and severity are of interest, the probability of joint exceedance $P(\text{Duration} > 6 \cap \text{Severity} > 1000) = 0.006$, an approximate average return period of 166 years. Hence, while a drought of a 6-year length occurs more frequently than the drought of a 1000 MGD severity, the recurrence of the joint drought as worse as the 1960s is anomalous.

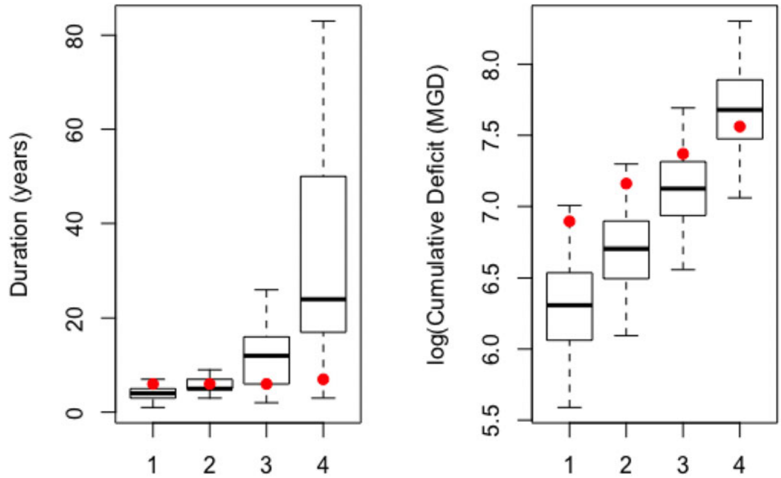

Figure 2.E.3. The distributions of drought duration and severity for varying demands.

2.E.3. Drought profile based on the reconstructed reservoir inflow data and changing demand

It is important to note that the drought stress is always relative to the demand of the region. The above analysis is shown for a demand of 950 MGD of annual average daily flow as a benchmark water demand. We have chosen this threshold given this is the average PCN combined reservoir release (including diversions to New York City, conservation, and directed releases) for the last 5 years (USGS, 2018). To investigate the effect of water demand on drought stress, we have applied the drought index for four different thresholds, 950 MGD, 1000 MGD, 1050 MGD and 1100 MGD. Any average demand greater than 1100 MGD will exceed the average combined reservoir inflow.

The joint probability distributions of drought duration and drought severity (long-term drought profiles) for various water demand levels is shown in Figure 2.E.2. We observe from these distributions that the drought duration is changing at a rate faster than the drought severity with increasing demand. As the water demand of the region increases, from a

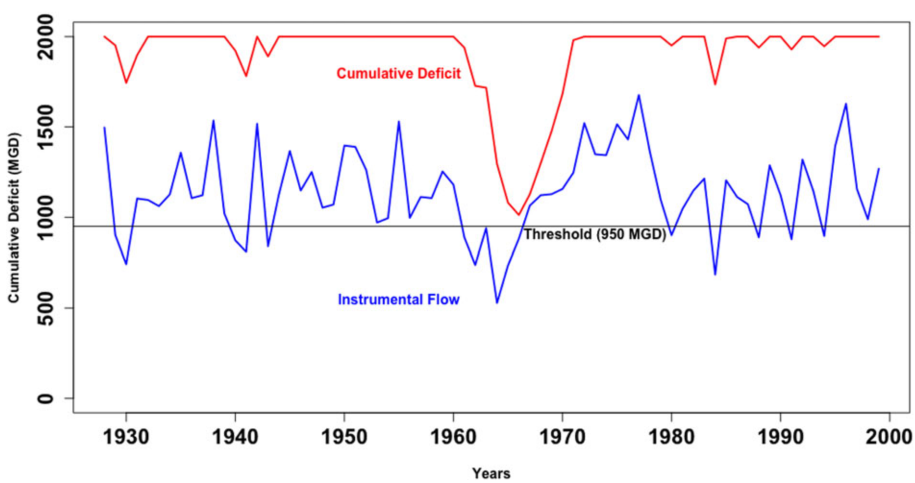

Figure 2.E.4. Annual average daily inflows and cumulative deficit (drawdown) of the combined Pepacton, Cannonsville, and Neversink (PCN) reservoir during the instrumental period (1928–2000). The blue line shows the observed PCN reservoir combined inflow. The red line (inverted) indicates the cumulative deficit.

long-term planning perspective, the critical metric to focus on will be the length of drought. Drought stress is experienced in terms of its persistence. This can also be seen from Figure 2.E.3, which shows the individual distributions for each of these thresholds along with the drought of the record from the instrumental period.

The streamflow reconstructions reveal droughts with a longer duration than the duration of the drought seen in the instrumental period (1960s drought). Joint distributions of duration and severity are developed for various demand levels to get a better perspective of the long-term drought profile. Based on a demand level that matches the average reservoir releases for the last 5 years, the worst drought of the record in the instrumental period is 6-year drought with a 1000 MGD cumulative deficit. This event has a joint return period of 166 years when contextualized with the long-term drought profile. However, the drought stress is very sensitive to regional water demand. A marginal increase in the demand from the 950 MGD level will lead to droughts that are longer and more severe, and their joint occurrence becomes more frequent. A comparison of duration versus severity metrics indicates that the rate of change with respect to demand levels is much faster for the drought duration.

2.E.4. Observed droughts

For the period of 1928–2000, annual average daily inflows and cumulative reservoir deficit was calculated based on a total demand of 950 MGD of annual average daily flow (Fig. 2.E.4). Note that 950 MGD is approximately the average reservoirs' release for the recent 5 years.

In the decade of the 1960s, the reservoirs had extensive drawdown, making it the worst drought of the instrumental period. The observed duration of the drought is 6 years, from 1961 to 1967. The severity of the drought, measured as the cumulative deficit, is approximately 1000 MGD. The recovery period of this drought is 5 years. While there are other periods with small to moderate droughts, there is no other period in the instrumental record that has a drought as severe as the 1960s drought.

Table 2.E.1 summarizes the individual and joint probability of exceedances and return periods of the drought duration and severity. Evidently, they are very sensitive to the demand. While the droughts stress for a demand level consistent with the water releases for the past 5 years is moderate, the drought stress is more likely and reoccurs more frequently for a marginal increase in the demand levels.

Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report Chapter 3: Sea Level Rise

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Contents

Introduction

The New York City Panel on Climate Change (NPCC, 2015) sea level rise projections provide the current scientific basis for New York City scientific decision making and planning, as reflected in, for example, the City's Climate Resiliency Design Guidelines. However, since the IPCC (2013) and NPCC (2015) reports, recent observations show mounting glacier and ice sheet losses leading to rising sea levels. Furthermore, new developments in modeling interactions between oceans, atmosphere, and ice sheets suggest the possibility of a significantly higher global mean sea level rise (GMSLR) by 2100 than previously anticipated, particularly under elevated greenhouse gas emission scenarios.

Because of the potentially serious adverse consequences of soaring sea levels to people and infrastructure in low-lying neighborhoods of New York City, we introduce a new high-impact sea level rise scenario, Antarctic Rapid Ice Melt (ARIM), which includes the possibility of Antarctic Ice Sheet destabilization. An earlier "Rapid Ice Melt Scenario" (NPCC, 2010) assumed a late 21st century rate of high-end sea level rise of ~0.39–0.47 in. per decade, based on paleo-sea level data after the last Ice Age. ARIM represents a new, physically plausible upper-end, low probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from improved modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections.

We briefly summarize key processes that control sea level rise on global to local scales, observed trends, and risks the city faces due to current and ongoing sea level rise. We also briefly recap the NPCC (2015) sea level rise projections for comparison with ARIM. To set the stage for ARIM, we review recent trends in land ice losses (Section 3.5) that reinforce the need to consider such an upper-end scenario. A more detailed discussion of these trends and technical details of the ARIM scenario are provided in Appendix 3.A.

3.1. *Key processes*

Multiple physical processes govern sea level rise on global to local scales. These include: (1) ocean density changes (involving temperature and salinity); (2) changes in ocean currents and circulation patterns; (3) ice mass losses from glaciers, ice caps, and ice sheets; (4) redistribution of ocean water in response to changes in the Earth's gravitation, rotation, and deformation caused by current ice mass losses (collectively referred to as "fingerprints"); (5) past ice mass losses (i.e., glacial isostatic adjustments, GIA[a]); (6) other vertical land movements

[a]Glacial isostatic adjustment (GIA) refers to Earth's lithospheric responses to the addition or removal of ice masses, which affect land elevation (either subsidence or uplift).

doi: 10.1111/nyas.14006

caused by ongoing tectonic activity, sediment compaction due to loading, and subsurface extraction of water, oil, gas; and (7) changes in land water storage, for example, in dams or from groundwater mining. Thermal expansion along with losses of ice from mountain glaciers and small ice caps have historically been the major contributors to observed mean global sea level rise, but in recent decades, shrinking ice sheets have played a growing role and dominate in the higher scenarios for future GMSLR (Slangen *et al.*, 2017, 2016; Kopp *et al.*, 2014; Church *et al.*, 2013, IPCC AR5).

These processes interact in ways that differ from place to place, such that for any given locality the sum of the components for local sea level rise may deviate significantly from the global mean. New York City lies in a region that experiences higher than average sea level rise due to enhanced thermal expansion, mounting ice losses from the Antarctic Ice Sheet, and GIA.

An additional possible factor is changes in ocean circulation. A major oceanic circulation system, the Atlantic Meridional Overturning Circulation (AMOC), could slow down due to decreased North Atlantic salinity resulting from Greenland ice losses, increased precipitation and northern river freshwater inflow, and sea ice attrition. The resulting heat build-up due to a weakened North Atlantic circulation would increase thermal expansion and redistribute water mass shoreward especially in the mid-Atlantic region, including New York City (Krasting *et al.*, 2016; Yin and Goddard, 2013; Yin *et al.*, 2010; 2009).

While a regional sea level acceleration "hotspot" has been observed in tide gauge records along the Atlantic coast from Cape Cod to Cape Hatteras (including New York City) since the early 1990s (Sallenger *et al.*, 2012; Boon, 2012), it is more likely that this hotspot reflects high interannual to multidecadal ocean variability than a shift in ocean circulation (Kopp, 2013; Valle-Levinson *et al.*, 2017). Attribution of the hotspot to a weaker Gulf Stream and slowdown of the AMOC (Rahmstorf *et al.*, 2015; Yin and Goddard, 2013) has not yet been substantiated (Böning *et al.*, 2016; Watson *et al.*, 2016) and is thus premature. However, this process could become important in the future (e.g., Section 3.4.2).

In addition—perhaps counterintuitively, given the great distance between Antarctica and New York City—ice losses from Antarctica are amplified along the mid-Atlantic coast by the gravitational responses to this change. As the mass of the ice sheet shrinks, its gravitational attraction weakens, and water congregates farther from it. This, as well as continued GIA-related land subsidence, leads to a higher than average local sea level rise. On the other hand, gravitational effects from more nearby ice losses on Greenland and northern hemisphere glaciers mean that these ice losses raise local sea levels less than the global average. The net effect of all these processes drives New York City sea level rise above the global average (e.g., Carson *et al.*, 2016; Slangen *et al.*, 2014; Kopp *et al.*, 2014.; Horton *et al.*, 2015a).

3.2 Observations and trends in sea level

Sea level rise represents one of the most momentous consequences of climate change, potentially affecting hundreds of millions of people worldwide. In recent decades, melting ice sheets and glaciers account for over half of the total observed current rise (Dieng *et al.*, 2017; Rietbroek *et al.*, 2016), a fraction likely to increase with continued global warming (see Sections 3.4.1, 3.5, and 3.6). This section briefly reviews current global and local/regional trends in sea level rise, to provide context for future sea level changes, discussed in later sections.

3.2.1 Global mean sea level rise. Tide gauge-based reconstructions of GMSLR between 1900 and 1990 range between 0.04 and 0.08 in./year (1 and 2 mm/year) (Dangendorf *et al.*, 2017; Jevrejeva *et al.*, 2017; 2014; Hay *et al.*, 2015; Church *et al.*, 2013; Church and White, 2011). Between 1993 and 2017, satellite altimetry shows an average GMSLR of around 0.12 in./year (3 mm/year),[b] after accounting for satellite instrumental drift that affected the earlier TOPEX/Poseidon mission between 1993 and 1998 (Watson *et al.*, 2015; Dieng *et al.*, 2017;

More inclusively, GIA refers not only to still ongoing viscous responses to ice removal following the last ice age, but also to elastic responses to recent ice melting.

[b]Most recent updated trends: 3.1 ± 0.4 mm/year; seasonal trends removed (http://sealevel.colorado.edu (posted 2/23/18; accessed 5/18/18); and 3.32 ± 0.5 mm/year, GIA-corrected (https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html posted 3/26/18; accessed 5/18/18).

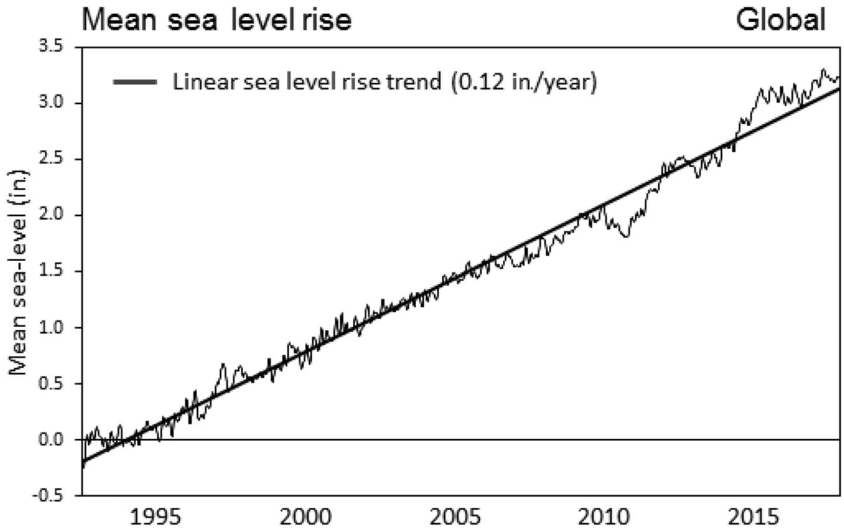

Figure 3.1. Global mean sea level rise during the satellite era, 1993–2018 (AVISO, France; posted March 26, 2018).

Beckley *et al.*, 2017). After further accounting for the effects of the 1991 Mt. Pinatubo volcanic eruption and of strong El Niño–Southern Oscillation events, these revised estimates show clear acceleration of the sea level record, attributable to accelerated ice sheet mass loss (Chen *et al.*, 2017; Dieng *et al.*, 2017; Nerem *et al.*, 2018; Fig. 3.1). Glaciers, ice caps, and ice sheets combined have raised ocean levels by 0.01 in./year (0.31 mm/year) between 1992 and 1996, increasing to 0.07 in./year (1.85 mm/year) between 2012 and 2016 (Bamber *et al.*, 2018).

Furthermore, GMSLR since the late-19th century has greatly exceeded the range of variability seen over the last three millennia (Kopp *et al.*, 2016; Gehrels and Woodworth, 2013). These results imply two stages of global mean sea level acceleration: the first between late 19th and early 20th century to around 1990, which may in part reflect natural climate cycles, and the second from the 1990s to the present. Since 1970, anthropogenic factors may account for over 70% of the rise (Slangen *et al.*, 2016).

3.2.2 Local and regional sea level rise. The local or relative[c] sea level rise in New York City has averaged 0.11 in./year from 1850 to 2017 as measured by The Battery tide gauge, nearly double the 1900–1990 mean global rate (Fig. 3.2; NOAA, 2017). Local GIA-related subsidence, which accounts for roughly half of the observed relative sea level rise (Engelhart *et al.*, 2011; Engelhart and Horton, 2012), is a key reason why New York City's rate of sea level rise is so high. As elsewhere, the historic New York City trend has increased markedly relative to the previous millennium (Kemp *et al.*, 2017).

3.2.3. Observed sea level rise since NPCC 2015. Sea level rise has been tracked over time by the NPCC using data from both tide gauges and satellite altimetry. (For more information on tide gauges, see the NOAA Tides & Currents[d] website; for satellite altimetry, see NASA Jason[e] and AVISO/CNEs[f] websites). New observations from these sources are included in updated analyses of sea level rise trends in each NPCC report and are included in reference to any new projected values.

NPCC 2019 extends the observed record for sea level rise from NPCC 2015. In addition, NPCC 2019 analyzed how the trends in recent sea level rise compare in general to the projected changes in sea level from NPCC 2015 into the 2020s timeslice, which encompasses the time period from 2020 to 2029.

[c]Relative sea level rise is that measured locally by instruments such as tide gauges. It can differ considerably from global mean sea level rise for any combination of the reasons given in Section 3.1.

[d]https://tidesandcurrents.noaa.gov/
[e]https://sealevel.nasa.gov/missions/jason-3
[f]https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html

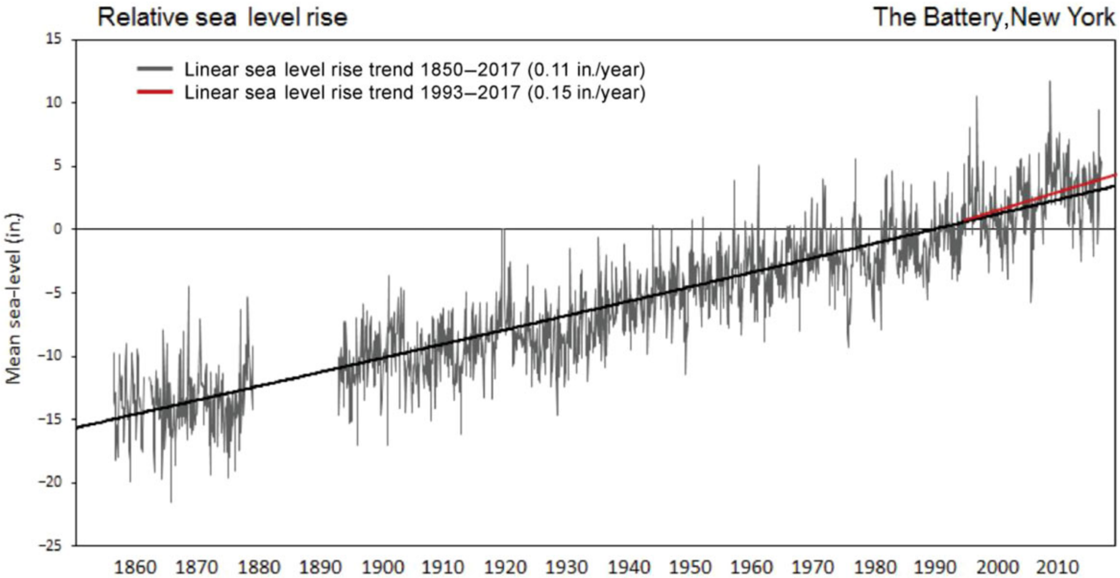

Figure 3.2. Historic sea level rise 1850–2017 in New York City at The Battery (NOAA, 2017). Black trend line shows an increasing trend from 1850 to 2017, while the red trend line shows a slightly higher trend from 1993 to 2017, which may reflect the apparent recent acceleration seen in the global sea level rise record.

Figure 3.3 shows the observed trend in sea level rise at The Battery in New York City from 1900 through 2017 compared to the NPCC 2015 projections. While NPCC3 cannot yet compare analytically projected to observed values from NPCC 2015 through 2017–2018 since we have not yet entered the onset of the 2020s time slice, nevertheless, the most recent observed trends show that sea level at The Battery has continued its upward rise since the previous NPCC report. A more comprehensive, comparative

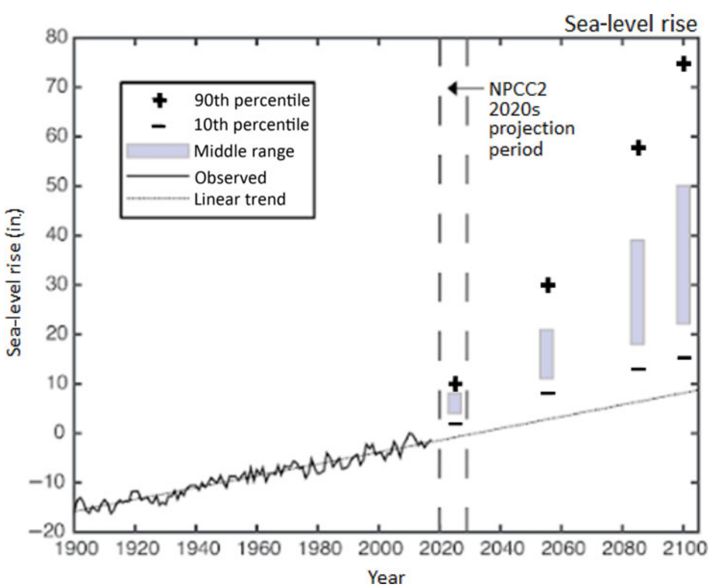

Figure 3.3. Observed sea level rise at The Battery in New York City from 1900 through 2017 compared with projected changes in sea level rise from the NPCC 2015 Report in the 2020s.

analysis will be part of the next NPCC report when a greater overlap will exist between the observed trend time period and projected values from NPCC 2015. However, such comparisons should be viewed with caution because of the role of natural variability in the short term.

3.3 Current risks: role of sea level rise

New York City is part of a metropolitan region (population 23.7 million[g]) that covers three adjacent states—Connecticut, New York, and New Jersey. Long-term sea level rise, as well as episodic coastal flooding, poses a high risk to the population, housing, and many essential New York City infrastructure facilities that line the 520 miles (837 km) of the city's waterfront. These include three major international airports, shipping infrastructure, segments of commuter and intercity bus and rail transit systems, many subway, tunnel, and bridge entrances, nearly all city wastewater treatment plants (WWTPs), oil tanks and refineries, most power plants, and telecommunication networks.

The combined effects of New York City sea level rise (18 in., 45.7 cm between 1856 and 2017; Fig. 3.2, NOAA, 2017) and changes in storm climate variability (Orton *et al.*, 2016; Lin *et al.*, 2016; Reed *et al.*, 2015; Talke *et al.*, 2014; and Wahl *et al.*, 2017) have increased the impact of coastal flood hazards (see also, Chapter 5: Mapping Climate Risk). Due to historic growth patterns and high-density shoreline development, a significant population resides within areas exposed to coastal hazards. The above-average water levels during strong hurricanes or hybrid storms, such as Sandy (Oct., 2012), Donna (Sept., 1960), Irene (Aug., 2011), and the unnamed 1788 and 1821 hurricanes, as well as "nor'easters" (e.g., Dec, 1992) resulted in substantial coastal flooding (Section 3.2.1).

The location of property and key infrastructure near the shore or within the FEMA 1%-annual-chance floodplain places them at increased risk to ongoing and future sea level rise, in the absence of protective structures, such as levees, or other adaptation strategies. For example, storm surges occurring on top of higher sea level can damage wastewater treatment facilities, causing combined sewer overflows and pollution of waterways (NYC Hazard Mitigation Plan 2014). Acutely aware of this hazard, especially following Hurricane Sandy, the New York City Department of Environmental Protection has taken steps to increase resiliency and minimize potential damages. Buildings damaged by severe coastal erosion, prolonged saltwater exposure, and/or tidal flooding in low-lying areas require costly retro-fitting or even eventual relocation. In addition to high coastal storm floods and heavy rain, rising sea level is currently causing sewer surcharge and flooding streets farther away from the coast. The probability of blocked outfalls caused by poor drainage and additional backflow increases with elevated coastal storm surge superimposed on rising sea levels.

[g]U.S. Census, 2017. U.S. Census Bureau Metropolitan Population Estimates July 1, 2016—Release Date: March 23, 2017.

3.3.1 Increasing coastal flooding. Historical sea level rise in New York City (Fig. 3.2) has intensified the effects of coastal storm floods (Talke *et al.*, 2014). In the lowest lying neighborhoods, flooding now occurs at times of high astronomical tides (tidal flooding), even in the absence of active storms. The frequency of such so-called "nuisance flooding" at The Battery has more than doubled since the 1950s (Sweet and Park, 2014; Strauss *et al.*, 2016). Sea level rise alone will increase the severity and occurrence of New York City coastal storm-driven flooding, irrespective of changes in storm characteristics (Buchanan *et al.*, 2017; Lin *et al.*, 2016; Orton *et al.*, 2016; Reed *et al.*, 2015; Talke *et al.*, 2014; Kemp and Horton, 2013). Further discussion on historic, current, and future flood risks is given in Chapter 4: Coastal Flooding.

3.3.2 Land inundation. The Mississippi Delta and Chesapeake Bay are examples of areas already experiencing permanent land inundation due to high rates of relative sea level rise from land subsidence superimposed on global sea level rise. The Chesapeake Bay area has the highest rates of relative sea level rise on the East Coast, due to GIA and groundwater withdrawal (Eggleston and Pope, 2013), which has led to the shrinkage or loss of several small islands (Gornitz, 2013). The high relative sea level rise has led to increased tidal flooding in places such as Norfolk, Virginia (see also discussion of tidal flooding in Chapter 4).

Although New York City is not at immediate risk of extensive land inundation, the regions currently experiencing inundation provide a preview of potential permanent land loss due to sea level rise facing some New York City neighborhoods under the ARIM scenario in the later years of the 21st century (see Chapter 5, Fig. 5.1). The first areas that could be affected include low-lying city neighborhoods that will experience frequent tidal flooding and, in a few cases, permanent inundation by the 2050s and especially the 2080s (e.g., compare Fig. 5.1 with Figs. 5.2 and 4.4). (Note: Because the ARIM scenario shown in these figures is based on data with high associated uncertainties, it should be regarded as suggestive of areas that might become inundated and should therefore not be used for planning purposes. See further discussion and disclaimer in Chapter 4: Coastal Flooding, and Chapter 5: Mapping Climate Risk).

3.3.3 Effects on salt marshes and natural wave attenuation. Studies show that intertidal salt marshes and particularly their substrate play an important role in attenuating storm waves as they break on shore (Marsooli *et al.*, 2017), although they may not lessen high storm water levels, or reduce flooding if deep shipping channels are present (Orton *et al.*, 2015).

Many New York City salt marshes, including in Jamaica Bay, have receded historically and have become increasingly ponded, with enlarging tidal inlets and pools (Hartig *et al.*, 2002). In addition to historic sea level rise, other stressors have led to attrition of local salt marshes, such as channelization, shoreline development and armoring with engineered structures, excess nitrogen nutrient loading from nearby sewage treatment plants, and inadequate sediment supply (e.g., Hartig *et al.*, 2002). As a result, salt marshes at the shoreline edge are converting to tidal mudflats. The National Park Service, in conjunction with the U.S. Army Corps of Engineers, is engaged in restoration efforts at several Jamaica Bay salt marshes (e.g., Elders Point Marsh, Yellow Bar Hassock, and Rulers Bar).

Rising sea levels lead to longer periods of salt marsh submergence during high tides. Salt marsh vegetation zones can gradually shift landward, but may not find space, due to urban development (i.e., "coastal squeeze") or too steep a rise in inland topography. Wetlands will drown in place wherever rates of accretion cannot keep pace with sea level rise, and/or if sediment supplies are insufficient. However, as noted above, sea level rise is just one of many environmental factors that contribute to New York City saltmarsh losses.

3.3.4 Effects of saltwater intrusion on New York City. Sea level rise, in addition to climate change, can alter the flow of saltwater and propagation of tide and storm surge up streams, in estuaries such as the Hudson River, and into coastal lagoons. The mean location of the salt front pushes upstream as a result. Hydroclimate also influences the position of the saltwater front in the Hudson River. A decrease in precipitation reduces streamflow, which allows the salt front to migrate further upstream (and vice-versa); higher temperatures increase evaporation and decrease freshwater runoff, also forcing an upstream migration of the salt front (Buonaiuto *et al.*, 2011).

Salt front migration up the Hudson River (and the Delaware River Basin; Chapter 2, Climate Science) during severe droughts and/or higher sea levels could adversely impact the emergency New York City drinking water supply from the Hudson River at the Chelsea Pumping Station.

Sea level rise will also increase the salinity of brackish water in the estuary and lagoons, also affecting inflow of seawater to sewers and WWTPs located along the saltwater-dominated coastline and thereby lessen infiltration efficiency. In addition, higher water levels will reduce the capacity of WWTP effluents to drain by gravity and pumping (see also Chapter 4, Coastal Flooding). Although less urgent today, salinization accompanying sea level rise may become a major issue for drainage systems and warrants further investigation. Structures not designed for exposure to repetitive and lengthening saltwater exposure would also face more frequent and higher repair or replacement costs (Solecki *et al.*, 2015).

3.3.5 Increased beach erosion. Sea level rise, in conjunction with higher waves and/or water levels during intense storms, such as Hurricane Sandy in 2012, is likely to exacerbate ongoing coastal erosion, particularly of exposed, ocean-facing shorelines. This can disrupt sediment transport and undermine natural landforms, like beaches and salt marshes offering protective features, with associated land loss and environmental degradation. In urban areas, coastal erosion and flooding can severely damage structures, and if unchecked, can undermine foundations, ultimately leading to building collapse, as shown during Hurricane Sandy for the New Jersey and New York regions (Hatzikyriakou *et al.*, 2016; Hatzikyriakou and Lin, 2018).

An integrated approach for managing high erosion risks includes upgrading major structural protections, such as seawalls, revetments, bulkheads, groins, etc., as well as implementing beach nourishment and living shorelines. Continual erosion of the city's sandy beaches requires periodic nourishment with sand dredged from offshore (New York City, 2014). Potential coastal restoration projects by the U.S. Army Corps of Engineers are in review for Coney Island and the Rockaways (USACE, 2016a, 2016b). Coastal erosion risks can also be mitigated by the limitation of high-density development in high-erosion hazard zones.

Three current "erosion hotspot" neighborhoods (south shore of Staten Island, Coney Island, and Rockaway Peninsula) have been designated Coastal Erosion Hazard Areas (CEHA), for which new construction or land use change requires special permits from the New York State Department of Environmental Conservation (NYC, 2014).

3.4 Future sea level rise

As atmospheric greenhouse gases continue to accumulate, and temperatures climb, sea level is expected to rise in the future at accelerating rates. Climate scientists look ahead by using computer-generated coupled global atmospheric-oceanographic models that are based on known laws of physics that govern our climate. Section 3.4.1 briefly reviews the sea level rise projections of the Intergovernmental Panel on Climate Change (IPCC, 2013), and several newer reports that suggest a higher future global sea level than that in the IPCC report. The sea level rise projections for New York City developed by NPCC (2015), which are reaffirmed for use as the basis of New York City resiliency planning, are described in Section 3.4.2.

3.4.1 Global mean sea level rise projections. The IPCC AR5 (Church *et al.*, 2013) projects future climate changes for a set of four representative concentration pathway (RCP) scenarios, which represent different trajectories of greenhouse gas emissions, aerosols, and land use/land cover (Moss *et al.*, 2010). They range from a high greenhouse gas emission "business-as-usual" scenario (RCP8.5) to one involving strong mitigation efforts (RCP2.6). Driven by the RCPs, a suite of coupled atmospheric and oceanographic global climate models (AOGCMs) numerically simulate physical interactions between the atmosphere, ocean, continents, and sea ice, in order to project future trends in climate variables including temperature, precipitation, and sea level rise. AOGCMs directly compute changes in ocean density (temperature and salinity) and circulation patterns. Temperature and precipitation projections from AOGCMs are used to drive separate numerical models to estimate surface mass balance[h] of glaciers and ice sheets. Models that include both dynamic ice flow and surface mass balance driven by climate projections (i.e., temperature, precipitation) estimate future changes in discharge of ice past the grounding line[i] and calving rates of icebergs. The individual components are then summed to obtain global sea level.

An alternative approach to projecting GMSLR, the semiempirical approach, makes projections of future sea level rise based on the assumption that the statistical relationship that existed between past temperatures and rates of sea level change will continue into the future. Thus, the future trajectory of sea level rise remains closely linked to that of increasing global temperature (e.g., Moore *et al.*, 2013; Rahmstorf *et al.*, 2012, Rahmstorf, S., 2007; Kopp *et al.*, 2016). However, this assumption may no longer hold if processes that were minor contributors to past sea level change, such as ice sheet dynamics, become major contributors in the future.

IPCC (2013) projects a "likely"[j] GMSLR by 2100 of 0.9–2.0 ft for RCP2.6, 1.2–2.3 ft for RCP4.5, and 1.7–3.2 ft for RCP8.5 relative to a 1986–2005 baseline, and notes the potential for collapse of marine-based parts of the Antarctic Ice Sheet to contribute another several tenths of a meter (Church *et al.*, 2013), IPCC, 2013, Chapter 13, Table 13.5). An earlier assessment (Pfeffer *et al.*, 2008) suggested that 6.6 ft was a physically plausible upper bound to GMSLR, a level adopted by the Third National Climate Assessment for its highest sea level rise scenario

[h]Surface mass balance (glacier, ice sheet) is the net balance between snow accumulation and losses due to surface melting and runoff.

[i]Dynamic ice flow refers to the discharge of ice flowing past the grounding line, which defines the boundary between a land-based glacier and attached floating ice.

[j]The "likely" range of sea level rise represents a probability of approximately two-thirds (Church *et al.*, 2013).

(Parris *et al.*, 2012). However, this upper bound was subsequently criticized (Miller *et al.*, 2013) for failing to fully represent uncertainty regarding Antarctica (Bamber and Aspinall, 2013), thermal expansion (Sriver *et al.*, 2012), and land water storage (IPCC, 2013).

Since IPCC (2013), new observations from the Greenland and Antarctic Ice Sheets (e.g., Rignot *et al.*, 2014), progress in ice sheet–ice shelf–ocean modeling (e.g., Joughin *et al.*, 2014), and expert assessments (Horton *et al.*, 2014; Bamber and Aspinall, 2013) have reaffirmed the physical plausibility of sea level rise well in excess of the IPCC (2013) "likely" range (Jevrejeva *et al.*, 2014; Kopp *et al.*, 2014; Slangen *et al.*, 2017). Newly recognized mechanisms for ice-shelf instability further emphasize the plausibility of high-end outcomes, especially beyond 2100 in high-emission futures (Pollard *et al.*, 2015; DeConto and Pollard, 2016; Kopp *et al.*, 2017; Le Bars *et al.*, 2017; Wong *et al.*, 2017; see also, Section 3.4.2).

Based on these findings, the Fourth National Climate Assessment recommended a suite of GMSLR scenarios for the period 2000–2100 that range between a "low" scenario of 1.0 ft to a physically plausible "extreme" scenario of 8.2 ft by 2100 (Sweet *et al.*, 2017). Sweet *et al.* (2017) additionally describe methods for adapting these projections to regional scales, as illustrated for New York City in in Section 3.4.2. and Appendix 3.A.

Although many future global sea level rise projections end in 2100, the longevity of atmospheric CO_2 commits us to higher temperatures and sea level long after reduction of stabilization of greenhouse gas emissions. Ending further emissions by midcentury would allow some of the anthropogenic CO_2 and temperature to slowly diminish after several decades, with gradual dissipation of the balance. It would take centuries to millennia to reach a new equilibrium state. In the interim, sea level will continue to rise well beyond 2100, because of the continued climate warming and slow heat penetration into the deep ocean (Clark *et al.*, 2016; Mengel *et al.*, 2016; Golledge *et al.*, 2015).

3.4.2 Current New York City sea level rise projections. In its second report, the NPCC (2015) developed a multicomponent methodology for projecting future sea level rise for New York City (Horton *et al.*, 2015a). Components include oceanographic changes (thermal expansion, dynamic ocean height), ice mass losses with associated gravitational and glacial isostatic adjustments, and anthropogenic land water storage change, for an ensemble of 24 CMIP global climate models and two climate change scenarios (RCP4.5, RCP8.5), as well as literature review and expert judgment. Sea level rise, relative to the 2000–2004 base period, was calculated for the 10th, 25th, 75th, and 90th percentiles from a model-based distribution and estimated ranges from the literature.

Table 3.1. New York City sea level rise projections[a] for the 2020s, 2050s, and 2100, relative to 2000–2004, (NPCC, 2015)

Sea level rise baseline (2000–2004)	Low estimate (10th percentile)	Middle range (25th–75th percentile)	High estimate (90th percentile)
2020s	+2 in.	+4–8 in.	+10 in.
2050s	+8 in.	+11–21 in.	+30 in.
2080s	+13 in.	+18–39 in.	+58 in.
2100	+15 in.	+22–50 in.	+75 in.

[a]Based on 24 GCMs and two representative concentration pathways, RCP 4.5 and 8.5. Shown are the low-estimate (10th percentile), middle range (25th–75th percentile), and high-estimate (90th percentile).

NPCC (2015) assumed that all uncertainties were perfectly correlated so that, for example, the 90th percentile projection combined the 90th percentile values for each of the different terms. While this could lead to overly high estimates, NPCC (2015) offered some leeway in case the individual component projections—consistent with most sea level rise projections in recent decades—would later be found to underestimate the extreme tail of the distribution.

NPCC (2015) projects a mid-range (25th–75th percentile) sea level rise of 11–21 in. (0.28–0.53 m) at The Battery by the 2050s and 18–39 in. (0.46–0.99 m) by the 2080s, relative to a 2000–2004 baseline. High-end estimates (90th percentile) reach 30 in. (0.76 m) by the 2050s, 58 in. (1.47 m) by the 2080s, and 75 in. (1.91 m) by 2100 (Table 3.1). Appendix 3.B illustrates how recent observed trends in sea level rise from 1900 to 2017 compare to these projected changes from NPCC (2015).

The results of a similar study by Kopp *et al.* (2014), which did not assume perfect correlation of uncertainties, and applied a hybrid approach to ice sheets that blended NPCC (Horton *et al.*, 2015a) and IPCC methodologies, are shown in Appendix

Table 3.A.1. Results from a more recent study (Kopp *et al.*, 2017), incorporating Antarctic ice-sheet projections from DeConto and Pollard (2016), and projections based on these studies, are also shown in Appendix Table 3.A.1. Appendix Table 3.A.2 places these projections in the context of the local sea level rise scenarios developed by Sweet *et al.* (2017) for the Fourth National Climate Assessment (see Appendix 3.A for more details).

As mentioned in Section 3.1, sea level rise in New York City is expected to exceed global mean values (NPCC, 2015; Carson *et al.*, 2016; Kopp *et al.*, 2014; Love *et al.*, 2016). This arises primarily because of GIA-related subsidence, far-field effects of Antarctic ice loss, and above-average ocean dynamic height due to projected slowdown of the AMOC with continued ocean freshening and Greenland ice losses (Yin and Goddard, 2013; Yin *et al.*, 2010; 2009). Enhanced warming in the western Atlantic relative to the Pacific Ocean may also elevate steric sea level rise along the East Coast, particularly for high carbon emission scenarios (Krasting *et al.*, 2016). Although gravitational effects associated with proximity to Greenland and northern hemisphere glaciers will partially reduce sea level rise, the combined effect of all contributing factors will result in higher than average sea level rise for New York City (Sweet *et al.*, 2017; Love *et al.*, 2016).

It should be re-emphasized that the NPCC (2015) sea level rise projections represent the current scientific foundation for New York City decision making and planning. However, recent observed trends in land ice mass losses and advances in ice–ocean–atmosphere interactions raise the possibility of higher future sea levels than previously assumed (Section 3.5). Furthermore, NPCC (2015) sea level rise estimates lie within the 10–90% probability range. They do not provide sea level rise values with a lower than 10% probability of occurrence by 2100 (i.e., the very large sea level increases that lie in the upper 10% tail of the sea level rise probability distribution).

Nevertheless, consideration of such high-end sea level rise outcomes is of great importance for effective long-term decision making. Focusing on the central range may lead to underestimation of the future risks, especially in the light of science that suggests that high-end scenarios may become more probable under high-emissions scenarios than thought a few years ago.

A new upper-end, low-probability sea level rise scenario, introduced in Section 3.6, is designed to address the concerns of stakeholders interested in long-term planning, who may need to examine credible scenarios at the extreme upper tail of the distribution. The ARIM scenario provides one physically plausible, low-probability scenario (i.e., one with significantly less than 10% likelihood of occurrence by 2100) for considering the consequences of very unlikely, yet high-impact outcomes. For example, many public or private sector decision makers may need to examine future risks to the city over much longer time periods, for example, infrastructure lifespans, than those which generally interest many New Yorker City homeowners—namely, risks that play out over longer timescales than those of an average 30-year home mortgage.

Furthermore, sea level rise scenarios with a less than 10% chance of occurring by 2100 may become much more likely after 2100, especially if greenhouse gas emissions are not eventually reduced (see Sections 3.6 and 3.7). However, stakeholders using ARIM should also bear in mind that scientific understanding of processes affecting sea level rise will evolve over time, especially for such low-probability, high-impact eventualities.

3.5 Recent land ice losses and implications for future sea level rise

Recent observations of land ice mass losses and advances in ice sheet–ocean–atmosphere modeling suggest the physical possibility of higher sea levels by 2100 than previously assumed (reviewed in Sweet *et al.*, 2017; Slangen *et al.*, 2017, and briefly in this section), particularly under high-emission futures (Kopp *et al.*, 2017). Although it is premature to assign a probability to such extreme outcomes, in view of the potential for widespread infrastructure and societal impacts from a high-impact sea level rise in major coastal urban centers, such as New York City (e.g., Hauer *et al.*, 2016), we follow the example of the Fourth National Climate Assessment in proposing a new upper-end sea level rise scenario that includes the possibility of Antarctic Ice Sheet destabilization (Section 3.6).

Therefore, as a supplement to the current NPCC (2015) sea level rise projections (Table 3.1), the new scenario provides a physically plausible upper-end, low-probability alternate scenario for late 21st century New York City sea level rise. The ARIM scenario follows the same logic as used by the Fourth National Climate Assessment, namely, it is based on a number of lines of evidence (including, but not limited to, Deconto and Pollard, 2016) that 8.2 ft GMSL rise represents a physically plausible upper-end projection for 2100. It presents a scenario for sea level rise over space and time that is consistent with 8.2 ft (Sweet *et al.*, 2017). It resembles that of Kopp *et al.* (2017), which makes a set of assumptions similar to that of NPCC (2015) except with respect to ice sheets.

In the new scenario, the NPCC (2015) estimate of the Antarctic contribution is replaced by one taking an approach to ice sheet dynamics that incorporates findings from more recent studies. Values for the other components contain minor updates which have minimal impact in the current context (see discussion in Section 3.6). To justify the reason for this high impact, uncertain probability future, a brief summary of recent changes in land ice masses, with emphasis on the Antarctic Ice Sheet, is presented below. Additional information is furnished in Appendix 3.B.

3.5.1 Changes in land ice masses.

Glaciers. The observed rapid worldwide recession of mountain glaciers, especially in recent decades, demonstrates a high sensitivity to the recent global warming trend and probable response to continued future climate change. Glacier retreat has increased substantially since the 2000s, equivalent to a sea level rise of 0.02–0.03 in./year—around a fifth of the current global sea level trend (Marzeion *et al.*, 2017). By 2100, glaciers could contribute between 4 and 8 in. to sea level rise relative to the 2000s (Appendix Table 3.B.1).

Greenland Ice Sheet. Since the 2000s, Greenland contributed between 0.02 and 0.04 in./year to global sea level rise, of which 40% comes from surface melting and runoff; the balance comes from calving and responses to thinning of ice tongues/shelves (Appendix Table 3.B.2; Bamber *et al.*, 2018; Tedesco *et al.*, 2017; Forsberg *et al.*, 2017; van den Broecke *et al.*, 2016; Kjeldsen *et al.*, 2015). Greenland's growing contribution to sea level rise stems from sensitivity to both atmospheric and ocean warming (Appendix 3.B).

By 2100, Greenland is projected to add between 4 and 6.7 in. to sea level rise, from both surface melting and ice discharge, across the four IPCC RCP scenarios (Fürst *et al.*, 2015). Higher sea level is possible because parts of the Greenland Ice Sheet, like Antarctica, are also potentially vulnerable to a marine ice sheet instability (MISI) (Fig. 3.5) along several deeply buried subglacial valleys with possible marine outlets (Morligham *et al.*, 2014). Some of these lie, in part, on reverse slopes[k] that extend far inland. Furthermore, a temperature rise of only 1.8–7.2 degrees Fahrenheit could initiate irreversible melting of the Greenland Ice Sheet (Church *et al.*, 2013; Robinson *et al.*, 2012).

Antarctic Ice Sheet. Recent evidence has shown that Antarctica is increasingly contributing to global sea level changes, illustrating a need to better understand how this could amplify future sea level rise projections (Fig. 3.4). Since 2012, ice losses from Antarctica have tripled, increasing sea levels by 0.12 in. in that time frame (Shepherd *et al.*, 2018).

Appendix Table 3.B.3 shows that Antarctic ice losses exceed gains and that loss rates have been generally increasing since the 1990s (IMBIE TEAM, 2018). Furthermore, concerns are growing over the future stability of the West Antarctic Ice Sheet (WAIS). Melting of all marine-based WAIS ice[l] would elevate global-mean sea level by up to about 10 ft (Bamber *et al.*, 2009). Much of WAIS is grounded (i.e., rests on bedrock) below sea level and lies on reverse slopes. The MISI hypothesis proposes that an ice stream or glacier grounded on a reverse slope is inherently unstable, because it will accelerate across the grounding line, stretch, thin, and discharge more ice until the bed slope levels out (Fig. 3.5). Grounding lines of a number of WAIS glaciers have retreated in recent decades and attached ice shelves have thinned. While it remains unclear that an ongoing MISI process (Joughin *et al.*, 2014; Rignot *et al.*, 2014) could produce catastrophic collapse this century, 21st century warming could trigger such a reaction over several centuries or longer. Parts of East Antarctica are also potentially vulnerable to ocean warming (Appendix 3.B).

DeConto and Pollard (2016) presented an ice sheet/ice-shelf model which includes MISI, hydrofracturing, and ice-cliff collapse instabilities (MICI). These processes could accelerate ice mass

[k] One that tilts toward the center of the ice sheet.
[l] Where the base of the ice sheet rests on bedrock below sea level.

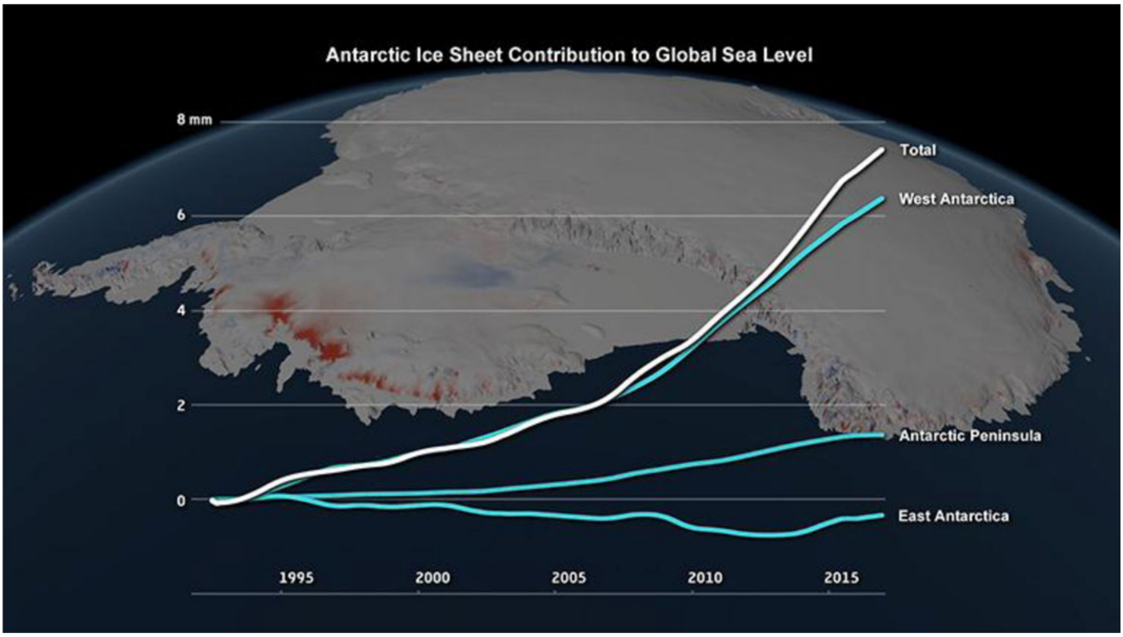

Figure 3.4. Cumulative Antarctic Ice Sheet mass change and contribution to sea level rise 1990–2017. *Source*: Shepherd *et al.*, 2018 and NASA Planetary Visions, 2018.

losses as explained further in Appendix 3.B (see also, Pollard *et al.*, 2015).

In simulations assuming continued high greenhouse gas emission rates, these mechanisms could initiate ice-shelf break-up starting after mid-century (DeConto and Pollard, 2016). By century's end, in their model, Antarctica alone could contribute a median of 2.3 ft of sea level rise, with 5th–95th

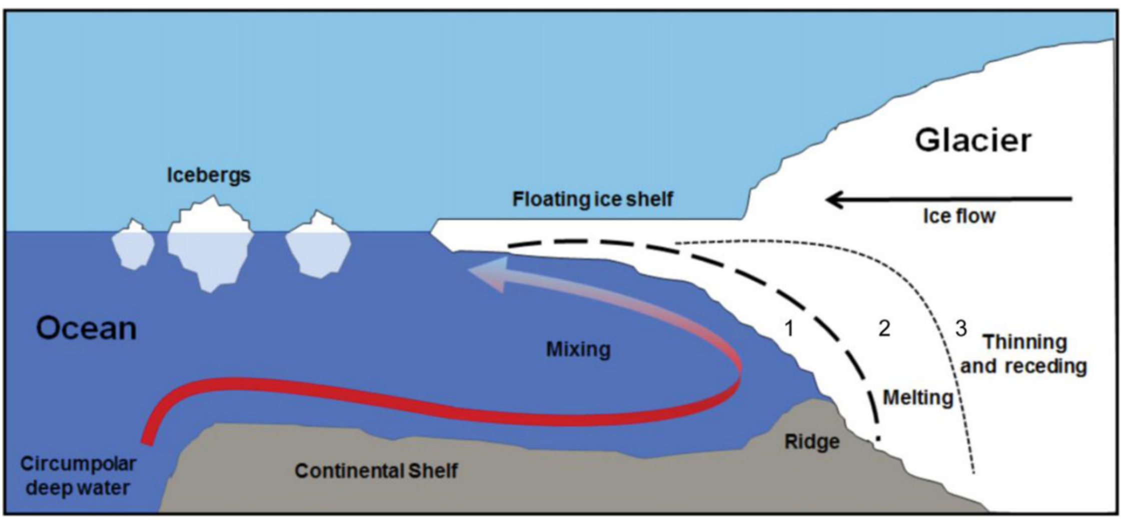

Figure 3.5. Marine ice sheet instability (MISI) on Antarctica: (1) ice stream or glacier is grounded on a bedrock ridge on the continental shelf; (2) warm circumpolar deep water flows into cavity beneath the ice shelf and melts the base of the glacier at the grounding line; (3) the grounding line continues to retreat beyond the ridge further downslope, causing the ice shelf to thin and the glacier to accelerate forward (Modified from Bethan Davies, AntarcticGlaciers.org).

percentile range of 0.7–5.2 ft. Such high rates would result in collapse of the WAIS and some parts of the East Antarctica Ice Sheet within a few hundred years, potentially contributing over 49 ft to global mean-sea level rise by 2500.

Inasmuch as the DeConto and Pollard (2016) model limits the maximum ice-cliff retreat rate, even higher rates than they project could be theoretically possible. While including several generally not previously modeled processes which could play an important future role in Antarctic ice mass losses, especially in higher emissions scenarios, the DeConto and Pollard (2016) paper represents just one study and remains to be confirmed by further observations or modeling.

By comparison, another study, which did not include hydrofracturing and ice-cliff collapse, found instead Antarctica would contribute, at most (95th percentile), around 1 ft by 2100 and 2.4 ft by 2200 (Ritz *et al.*, 2015) but for a moderate rather than high emission scenario.

The divergence among different models underscores the deep uncertainty surrounding high-end sea level rise projections for late in this century and beyond 2100. Given the potential consequences of the high-end projections, this divergence emphasizes the importance of considering extreme outcomes, even though the scientific community has not yet come to agreement on how probable they are.

3.6 Development of ARIM—a new upper-end sea level rise scenario for New York City

The NPCC (2015) sea level projections form the scientific basis for climate change adaptation guidelines in New York City at this time, and are plausible distributions that explicitly take into account multiple factors. New research developments illustrate the desirability of considering updating the New York City sea level rise projections in future NPCC assessments. Recent ice sheet trends and improved understanding of ice sheet–ocean–atmosphere interactions raise the prospects of higher sea levels than previously assumed (Sweet *et al.*, 2017; Slangen *et al.*, 2017). The sum of all ice mass losses (Appendix 3.B, Tables 3.B.1–3) constitutes half or more of total sea level rise in recent decades, a proportion likely to increase throughout this century (Nerem *et al.*, 2018; Dieng *et al.*, 2017; Rietbroek *et al.*, 2016). Gaining an improved understanding of potential upper limits to GMSLR by 2100 is therefore an important scientific objective to aid in critical and long-lived infrastructure decisions.

As discussed by Sweet *et al.* (2017), an increasing body of evidence—including observational evidence of marine ice-shelf instability in parts of the Antarctic Peninsula, further indications of potential MISI on the WAIS, consideration of previously omitted ice sheet dynamic processes, and revised estimates of “maximum physically plausible” sea level rise—argues that 8.2 ft represents an unknown-probability, yet physically plausible “extreme” GMSLR projection for the 21st century (see also, Hansen *et al.*, 2016).

This suggests that using a single probability distribution to represent such extreme outcomes inadequately expresses the current incomplete state of the science for Antarctic ice melt (see Kopp *et al.*, 2017, for further discussion). One workaround is to employ multiple probability distributions; but such an approach can be challenging for the users of projections. Accordingly, rather than producing an entire supplemental distribution, we instead provide a new, alternate upper-end, low-probability scenario, herein referred to as the ARIM scenario.

The ARIM scenario offers an alternate plausible upper-end sea level rise projection for 21st century rise for New York City, based on recent advances in understanding of ice sheet behavior, particularly that of Antarctica, in order to prepare for possible high-impact situations. For the ARIM scenario, there are multiple plausible alternative distributions that exhibit limited convergence (Horton *et al.*, 2018).

Following Sweet *et al.* (2017), we generate this upper-end scenario by filtering a set of probabilistic projections to isolate a subset consistent with 98.4 ± 5.9 in. (250 ± 15 cm) (i.e., between 92.5 and 104 in. (235 and 265 cm) of GMSLR between 2000 and 2100). Whereas Sweet *et al.* (2017) filtered the probabilistic projections of Kopp *et al.* (2014), we instead use a set of projections from Kopp *et al.* (2017) that employs the Kopp *et al.* (2014) sea level rise projection framework, but substitutes the Antarctic ice-sheet projections of DeConto and Pollard (2016). As described above (Section 3.5), the DeConto and Pollard (2016) model simulates the MISI, hydrofracturing, and ice-cliff fracturing

Table 3.2. New York City sea level rise projections, including the new Antarctic Rapid Ice Melt (ARIM) scenario, relative to 2000–2004 (in feet)

	NPCC2 2015 sea level rise projections[a] Projections of record for planning			NPCC3 ARIM scenario[b] Growing awareness of long-term risk
Baseline (2000–2004) 0"	Low estimate (10th percentile)	Middle range (25–75th percentile)	High estimate (90th percentile)	ARIM scenario[a]
2020s	0.17 ft	0.33–0.67 ft	0.83 ft	–
2050s	0.67 ft	0.92–1.75 ft	2.5 ft	–
2080s	1.08 ft	1.50–3.25 ft	4.83 ft	6.75 ft
2100	1.25 ft	1.83–4.17 ft	6.25 ft	9.5 ft

[a]The 10th, 25th–75th, and 90th percentile projections are taken from NPCC2 (2015); the six sea level rise components upon which they are based include global and local factors (see Section 3.4.2 and NPCC (2015)). Use of NPCC2 sea level rise projections is confirmed for decision making at this time. The ARIM scenario is based on DeConto and Pollard (2016), Kopp *et al.* (2014; 2017) and informed expert judgments with regard to maximum plausible ice loss rates from Antarctica (see above and Sweet *et al.*, 2017). See this section and Appendix 3.B for full ARIM scenario and explanation.
[b]ARIM represents a new, physically plausible upper-end, low probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from recent modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections. In the 2020s and 2050s, the ARIM scenario does not lie outside the pre-existing NPCC 2015 range and therefore NPCC 2015 results apply to these two earlier time slices. The ARIM scenario contains uncertainties stemming from incomplete knowledge of ice-sheet processes and atmosphere, ocean, and ice–sheet interactions.

instabilities. The other components are projected as in Kopp *et al.* (2014).

For each of the RCP 2.6, 4.5, and 8.5 emission scenarios, the projections include (1) global-climate-model-driven projections of global mean thermal expansion, regional dynamic sea level, and glacier mass changes; (2) Greenland Ice Sheet projections based on structured expert judgment (SEJ) and the IPCC's AR5 assessment; (3) global mean land-water-storage changes based on the historical relationships between population, groundwater withdrawal, and dam construction; (4) a geophysical model of the gravitational, rotational, and deformational "static-equilibrium" ("fingerprint") effects of mass redistribution from the polar ice sheets and 18 glacial regions; and (5) geologically driven relative sea level change (at The Battery, due exclusively to GIA) based on analysis of tide-gauge observations.

To make ARIM projections consistent with the 2000–2004 baseline in NPCC (2015), instead of the 1991–2009 baseline used by Kopp *et al.* (2014) and Sweet *et al.* (2017), 0.8 in. (2 cm) was added to the projections. This amount corresponds to the observed difference between the two period averages in the New York City Battery tide gauge record.

The ARIM scenario can be thought of as a modification of Sweet *et al.* (2017), in which the physical basis of the relationship between late 21st-century global mean sea level and relative sea level over time comes from Kopp *et al.* (2017), rather than Kopp *et al.* (2014).

In the 2020s and 2050s, the ARIM scenario does not lie outside the pre-existing NPCC (2015) 10th–90th percentile scenario range (Table 3.2). This is because the ARIM scenario is constructed to be consistent with a 98.4 in. (250 cm) GMSL rise over the 21st century. To generate such an extreme outcome requires a substantial destabilization of marine-based parts of the Antarctic Ice Sheet, but physical modeling results (DeConto and Pollard, 2016; Kopp *et al.*, 2017; Le Bars *et al.*, 2017; Wong *et al.*, 2017) indicate that this destabilization is highly unlikely to emerge until the second half of the century, and only then under high emission scenarios. Relative sea level trends that lie within the mid-range of projections over the next few decades would therefore not exclude more possibly extreme outcomes later in the century.

Furthermore, sea level rise will not slow or reverse quickly even following deep emission reductions. Almost all scenarios suggest that sea level will continue to rise for centuries. Although ARIM ends at

2100, it provides insights into the large sea level rises that may occur beyond 2100.

Inclusion of nonlinear acceleration of ice-mass loss is an advance from Sweet *et al.* (2017), who filtered projections (Kopp *et al.*, 2014) that assumed a simple linear acceleration of Antarctic mass losses over the century and therefore showed a strong correlation between early- and late-century sea level rise. The possibility of nonlinear accelerations causes the ARIM projections consistent with 98.4 in. (2.5 m) of GMSL rise to be somewhat lower than the "Extreme" projections of Sweet *et al.* (2017), particularly earlier in the century (Appendix Table 3.A.3).

Differences between the ARIM Scenario and NPCC (2015) for the 2020s and 2050s arise from slightly different treatments of the non-ice sheet components, in addition to differences in treatment of ice sheets. Many stakeholders focus on the 2050s because that is, for their particular purposes, a rational near-term to medium-term planning horizon. This is before the ARIM scenario diverges significantly from NPCC (2015) projections and before the consequences of the differing greenhouse gas concentration pathways (RCPs) become significant (see the Appendix 3.B for fuller treatment of the ARIM scenario).

Although it is not currently possible to make a strong statement about the probability of the ARIM scenario, we have high confidence that it is more likely under high-end emission scenarios (e.g., RCP 8.5) and is implausible under the lowest emission scenarios (e.g., RCP2.6). Averting the ARIM scenario is thus another benefit that will accrue from greenhouse gas mitigation efforts. To summarize, the sea level rise scenarios presented in NPCC (2015) are still appropriate for New York City and are currently used in resiliency planning, especially for the 2020s and 2050s.

Because the ARIM scenario is in part based on a new, still preliminary and controversial model, a probability assignment would not be very meaningful. Stakeholders can obtain some indication of the potential range of outcomes for the 2080s and 2100 by keeping both ARIM and NPCC (2015) projections in mind.

One important consequence of an upper-end sea level rise scenario, such as ARIM, is not only the increased frequency of coastal flooding, but also the progressive expansion of the floodplain over time with sea level rise for both 100-year floods and monthly tidal flooding (although obviously to difference extents and frequencies) (e.g., Figs. 5.2 and 5.3). Another consequence, absent additional defensive measures, is the potential inundation due to the elevated sea level of low-lying neighborhoods by the end of the century that had previously experienced frequent tidal flooding. For example, a comparison of Figure 5.2 with Figure 4.4 (tidal flooding) suggests that many of the locations that could undergo monthly tidal flooding by the 2050s and 2080s in areas surrounding Jamaica Bay and Coney Island under the 90th percentile sea level rise projection (NPCC, 2015), shown in light and dark green, respectively, (Fig. 4.4), might face permanent sea level rise by 2100 under the ARIM sea level rise scenario, with current shoreline elevations (see Fig. 5.1 in Chapter 5: Mapping Climate Risk).

In addition to the Jamaica Bay and Coney Island areas, other potentially affected areas include portions of Staten Island, edges of the lower Manhattan waterfront, Red Hook, along the Gowanus Canal in Brooklyn, along Newton Creek in Brooklyn and Queens, and Pelham Bay in the Bronx.

3.6.1 Expert elicitation on the Antarctic contribution. Two separate workshops[m] were held on SEJ of ice sheets, a form of expert elicitation, in part as a supplement to the development of the ARIM scenario. SEJ elicits and combines individual expert judgments into outcome probability distributions, in this case, on various aspects of future contributions of the Antarctic and Greenland ice sheets to sea level rise (e.g., Bamber and Aspinall 2013). The performance of each expert on a set of calibration questions regarding uncertainties for ice sheet variables with known values is used to weight their judgments on the unknown quantities regarding future ice sheet behavior.

This approach has been used in the estimation of variables related to nuclear reactor safety, volcanology, ecology, and aeronautics/aerospace applications. Based on past experience, performance-weighting generally yields predictions with improved statistical accuracy as compared

[m]Elicitations conducted with support from Resources for the Future, Rutgers University, Princeton University, European Research Council grant number 684188, and the NYC Office of Recovery and Resiliency (ORR).

to individual predictions, and smaller associated uncertainties as compared to unweighted estimates (Oppenheimer *et al.*, 2016).

Twenty-two ice sheet experts assembled at two separate workshops, one in Washington, D.C. in January 2018, composed of North Americans, and the other, in London in February 2018, of Europeans. Experts were asked to estimate accumulation, runoff, and discharge for the Greenland, West Antarctic, and East Antarctic ice sheets under two warming scenarios.

The low scenario reached 2.7°F (1.5 °C) in the 2050s and 3.6°F (2.0 °C) in 2100, stabilizing thereafter; the high scenario reached 3.6°F (2.0 °C) in 2050 and 9.0°F (5 °C) in 2100, stabilizing thereafter. Each expert evaluated 5%, 50%, and 95% probability values for these contributory processes and quantified the dependence between these processes. North American and European experts were asked identical questions.

Estimates from the two groups were then combined to produce performance weighted (i.e., calibrated) and unweighted distributions. The experts' performance-weighted estimates for the Antarctic contribution to GMSLR between 2000 and 2100 was a median of 0.7 ft (21 cm) (5th–95th percentile range of –0.4 to 4.3 ft (–11 to 132 cm)) under the high scenario and 0.3 ft (9 cm) (–0.3 to 1.7 ft (–8 to 53 cm)) under the low scenario.

These estimates were combined with the projections for non-ice sheet components developed using the Kopp *et al.* (2014) framework to examine their implications for total GMSLR. In particular, they combined the low scenario estimate projections with a 3.6°F scenario developed by Rasmussen *et al.* (2018) and the high scenario estimate with RCP8.5.

Localizing these GMSL projections for New York City indicates that the judgment of this group of experts in early 2018 aligns reasonably well with the NPCC2 projections at the 50th, 75th, and 90th percentiles, and that the ARIM scenario has about a 3% chance of being realized by 2100 in a high-emissions future, but close to zero probability a low-emissions future.

3.7. Conclusions and recommendations

3.7.1 Findings. Consistent with other studies (e.g., Carson *et al.*, 2016; Kopp *et al.*, 2014; Tebaldi *et al.*, 2012; Sweet *et al.*, 2017, Horton *et al.*, 2011), projected sea level rise from NPCC (2015) and the new ARIM scenario suggest that sea level trends for New York City will likely exceed the global average. This arises because of processes that will affect the region's sea level change, such as enhanced thermal expansion, dynamic oceanographic changes, mounting ice losses from glaciers and ice sheets and their associated "fingerprints," as well as ongoing glacial isostatic adjustments. This would pose mounting hazards to substantial segments of the region's coastal population, infrastructure, and other built and natural assets in low-lying areas.

Sea level rise alone stands to increase the frequency and intensity of coastal flooding over time, as shown in Chapter 4. New York City sea level rise is expected to accelerate as the century progresses and could reach almost 9.5 ft. by 2100 in the new ARIM scenario, although this large estimate has a deeply uncertain probability and appears implausible under low-emission futures.

Recent increasing ice mass losses in Greenland and Antarctica, advances in modeling ice sheet–ocean–atmosphere interactions, as well as a potential for marine ice-shelf instability in West Antarctica, raise the prospects of higher sea levels than previously assumed. A growing awareness therefore exists for the need to consider high impact, low probability scenarios in coastal risk management, particularly when planning for long-lived infrastructure development (e.g., Wahl *et al.*, 2017; Sweet *et al.*, 2017). This new perspective also informs the need to supplement the NPCC (2015) sea level rise projections with an alternative, extreme scenario.

The ARIM scenario is constructed following an approach used for the Fourth National Climate Assessment and adopts the magnitude of the "extreme" GMSLR scenario developed for it (Sweet *et al.*, 2017). Its construction leverages the probabilistic projections of Kopp *et al.* (2014, 2017) and the Antarctic ice-sheet projections of DeConto and Pollard (2016), which includes improved models of ice dynamic processes.

Because the scenario uses information from the physical model of Deconto and Pollard (2016), it takes into account the possibility that considerably different and potentially destabilizing processes of Antarctic Ice Sheet mass loss will gain in importance in the second half of this century than those occurring in the first half, which differ little from previous results. Therefore, the ARIM projections, presented for the 2080s and 2100 in Table 3.2, are most applicable in late 21st century, at higher-end emission scenarios, such as RCP 8.5.

The implications of substantial economic and societal consequences to major coastal urban centers, such as New York City (e.g., Hauer *et al.*, 2016, Xian *et al.*, 2018), underscore the need to consider the possibility of such revised upper-end scenarios in coastal risk management. Therefore, the next NPCC report should continue to monitor new findings and update the latest trends in sea level rise from the various contributing components, especially those from the major ice sheets. In particular, the panel should periodically reassess the processes that could potentially destabilize the WAIS. Development of the next-generation sea level rise scenarios, including the latest CMIP climate model results, would form an important part of future research.

3.7.2 Beyond 2100. Because of the longevity of atmospheric CO_2, temperatures and sea level will continue to rise even after stabilization or reduction in greenhouse gas emissions. With total cessation of further anthropogenic CO_2 emissions by mid-century, CO_2 and atmospheric temperatures would slowly begin to decrease after several decades. But most of the CO_2 would still remain in the atmosphere and take centuries to millennia to slowly dissipate. This, and slow heat penetration into the deep ocean, would cause sea level to continue rising well beyond 2100 due to thermal expansion alone (Clark *et al.*, 2016; Mengel *et al.*, 2016; Golledge *et al.*, 2015).

Furthermore, during this extended period of sustained warmth, the losses of ice on Greenland and Antarctica will continue and could become quite substantial. Clark *et al.* warn that the Greenland Ice Sheet could be totally deglaciated within 2500–6000 years at higher emission scenarios (Greenland stores the equivalent of ∼23 ft, ∼7 m of GMSLR). Even greater losses are potentially possible if contributions from the WAIS are added. For both the NPCC 2015 projections and the ARIM scenario, much higher sea levels can be expected beyond 2100 than those projected for 2100.

3.7.3 Recommendations. NPCC3 therefore makes the following recommendations for research to address sea level rise in the New York metropolitan region:

- The NPCC should continue to monitor and periodically update trends in sea level rise, trends in glacier and ice sheet mass losses, and processes leading to destabilization of the WAIS.
- Further research into sea level change for the next several centuries, to 2200 and 2300, should be explored, in light of the sea level rise commitment on longer timescales.
- The consequences of long-term sea level rise scenarios on coastal flooding, including those stemming from low-probability, high-end scenarios, should also be examined.

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Appendix 3.A. NPCC3 sea level rise methods and projections

Introduction

Appendix 3.A presents the results of a study by Kopp *et al.* (2014) compared with those of the NPCC (2015) 10th-90th percentile range, as shown in Appendix Table 3.A.1.[n] Results of a study by Kopp *et al.* (2014) are similar to NPCC (2015), but do not assume perfect correlation of uncertainties. Appendix Table 3.A.1 also shows sea level rise projections from a more recent study (Kopp *et al.*, 2017), incorporating Antarctic ice-sheet projections from DeConto and Pollard (2016). Appendix Table 3.A.2 places these projections in the context of the local sea level rise scenarios developed by Sweet *et al.* (2017) for the Fourth National Climate Assessment.

As discussed in Section 3.6, the extreme scenario of Sweet *et al.* (2017) was developed using the same method as the ARIM scenario, except that in Sweet *et al.*, the underlying projections filtered were those from Kopp *et al.* (2014) rather than those of Kopp *et al.* (2017) that also incorporated data from DeConto and Pollard (2016) ice models (Appendix Table 3.A.2). Appendix Table 3.A.3 compares the filtered sea level rise projections for ARIM with those from Sweet *et al.* (2017). In addition to the median local projections consistent with 2.5 m of GMSL rise by 2100, Appendix Table 3.A.3 also

Table 3.A.1. Probabilistic New York City sea level rise projections (Kopp *et al.*, 2014, 2017) compared to the NPCC (2015) projections (10th–90th percentile range), m relative to 2000–2004 baseline

	NPCC (2015)	Kopp *et al.* (2014)			Kopp *et al.* (2017), DP 16		
	10th–90th percentile	RCP 2.6	RCP 4.5	RCP 8.5	RCP 2.6	RCP 4.5	RCP 8.5
2020s	0.05–0.25	0.11–0.26	0.12–0.25	0.09–0.29	0.08–0.27	0.09–0.26	0.06–0.29
2050s	0.20–0.76	0.22–0.58	0.25–0.60	0.26–0.66	0.19–0.62	0.25–0.66	0.30–0.75
2080s	0.33–1.47	0.28–0.89	0.35–0.99	0.44–1.19	0.30–0.96	0.51–1.30	0.80–1.87
2100	0.38–1.91	0.31–1.03	0.40–1.18	0.52–1.49	0.35–1.12	0.67–1.69	1.13–2.65

Table 3.A.2. Fourth National Climate Assessment sea level rise projections for New York City (Sweet *et al.*, 2017), m relative to 2000–2004 baseline

	Low	Intermediate-low	Intermediate	Intermediate-high	High	Extreme
2020s	0.15	0.18	0.26	0.34	0.42	0.42
2050s	0.30	0.37	0.60	0.84	1.10	1.27
2080s	0.44	0.55	1.07	1.55	2.14	2.60
2100	0.48	0.63	1.32	1.99	2.81	3.44

[n]Data from Kopp et al. (2014) have been recalculated to conform to time slices and baseline period used in NPCC (2015), to facilitate comparison between the studies. See Appendix IIB (NPCC, 2015) and Kopp et al. (2014) for additional technical details describing similarities and differences in assumptions, methodology, and data sources.

Table 3.A.3. Filtered sea level rise projections used to generate the ARIM scenario and the extreme scenario of Sweet *et al.* (2017), m relative to 2000–2004 baseline

	ARIM (10th–90th %)		Sweet *et al.* (2017) (17th–83rd %)	
	Median	Range	Median	Range
2020s	0.20	0.10–0.29	0.42	0.23–0.46
2050s	0.74	0.58–0.89	1.27	0.85–1.34
2080s	2.07	1.79–2.31	2.60	1.94–2.71
2100	2.90	2.56–3.19	3.4	2.64–3.58

shows the 10th-90th percentile range of the filtered projections (for ARIM)[o] and the 17th–83rd percentile range for Sweet *et al.* (2017); Sweet *et al.* (2017) labeled the latter as the "low" and "high" variants, respectively. As shown in this paper, the assumption by Sweet *et al.* (2017) of linear changes in ice-sheet mass loss rates makes their extreme scenario exhibit unrealistically high projections in the 2020s and 2050s, whereas during this time period, the ARIM scenario values lie below those of the NPCC's (2015) 90th percentile projections. By the 2080s, however, the median ARIM projection lies within the range of the extreme scenario, as defined by Sweet *et al.* (2017); By 2100, the median ARIM projection lags the median of the extreme scenario, as defined by Sweet *et al.* (2017) by only about one decade.

Appendix 3.B. Cryosphere trends

Appendix 3.B summarizes recent observations that show mounting glacier and ice sheet losses contributing to sea level rise. In addition to observations, progress in modeling ocean–atmosphere–ice sheet interactions raises the possibility of a significantly higher global mean sea level rise by 2100 than previously projected, particularly for elevated greenhouse gas emission scenarios. These new developments, as well as serious socioeconomic impacts of rising sea levels in large urban centers, such as New York City, indicate the need to consider updated high-end scenarios in long-term coastal risk management decisions. The new Antarctic Rapid Ice Melt Scenario (ARIM), which includes the possibility of Antarctic Ice Sheet destabilization, represents a physically plausible upper-end, low probability late 21st century sea level rise scenario for New York City. Not meant to replace NPCC (2015), which still forms the scientific basis for the city's climate change adaptation efforts, ARIM instead offers an alternate plausible extreme late 21st century sea level rise scenario, based on recent progress in modeling ice sheet processes, particularly for Antarctica.

The following section summarizes recent increasing trends in ice mass losses from glacier and ice sheets that have added to sea level rise in recent decades, with emphasis on Antarctica, as well as several processes that may potentially lead to destabilization of the West Antarctic Ice Sheet (WAIS). These new findings reinforce the need for an extreme scenario, such as ARIM.

Changes in glaciers and ice caps

Glaciers, ice caps, and ice sheets are large masses of ice formed by compaction and recrystallization of snow that gradually flow downslope under the pull of gravity. Mountain glaciers respond relatively fast to climate variability, making them particularly important barometers of local to regional climate change. Rising air temperatures have led to increased surface melting and runoff on mountain glaciers and the Greenland Ice Sheet. Warmer ocean water entering fjords of Greenland, Arctic, and Alaskan glaciers penetrates beneath floating ice tongues and melts them from below. A similar process has also begun to affect many Antarctic ice shelves. As ice tongues or shelves thin, they weaken and break off large pieces of ice. The glaciers feeding the ice shelves begin to accelerate, stretch, and thin, increasing the discharge rate across the grounding line and calving of icebergs, ultimately contributing to sea level rise.

Mountain glaciers respond relatively fast to even minor climate fluctuations. Therefore, their observed rapid worldwide recession, especially in recent decades, demonstrates a high sensitivity to the recent global warming trend and probable response to continued future climate change. Glaciers hold enough ice to elevate the world's oceans by 0.35–0.41 m (1.3 ft), if all melted and the water spread out uniformly (Grinsted, 2013; IPCC, 2013). Glacier retreat has increased substantially since ~2000, equivalent to a sea level rise of

[o]Those that that are consistent with 2.5 m of global mean sea level rise (i.e., that lie between 235 and 265 cm).

Table 3.B.1. Future sea level rise due to glaciers and small ice caps, m, 2010–2100, after Slangen *et al.* (2017)[a]

Sea level rise	RCP 2.6	RCP 4.5	RCP 8.5	Reference
	0.09 ± 0.3	0.12 ± 0.03	0.18 ± 0.03	Huss and Hock, 2015
	0.12 ± 0.03	0.13 ± 0.03	0.18 ± 0.04	Marzeion *et al*, 2012, updated
		0.16 ± 0.04	0.22 ± 0.4	Radić *et al.*, 2014, updated
		0.15 ± 0.04	0.21 ± 0.04	Slangen and van de Wal (2011), updated

[a]Includes peripheral glaciers. The last three sources listed in this table have been updated by Slangen *et al.* (2017).

0.4–0.8 mm/year—around a fifth of the current global sea level trend (Marzeion *et al.*, 2017; Bamber *et al.*, 2018). The range of estimates results from differences in instrumentation, data sources, averaging techniques, and uncertainties in extrapolating from limited spatial coverage. Nevertheless, while individual glaciers may show net growth, most glaciers have consistently retreated over the past century, and particularly within the two last decades.

Glacier ice mass losses exceeded the contributions of Greenland and Antarctica combined between 1993 and 2010 (IPCC, 2013, Table 13.1), although the ice sheets' share has grown significantly since then (e.g., Nerem *et al.*, 2018; Dieng *et al.*, 2017; Rietbroek *et al.*, 2016; Bamber *et al.*, 2018). Glacier contributions to sea level rise will continue to increase for the next several decades at least, but will decline in the long run, as the total glacier ice mass, if all melted, would raise global-mean sea level by less than half a meter (Grinsted, 2013). By 2100, glaciers could contribute between 0.1 and 0.2 m to sea level rise (Table 3.B.1).

Greenland Ice Sheet

The sensitivity of Greenland's marine-terminating, or tidewater glaciers, to both atmospheric and ocean warming accounts for their growing contribution to sea level rise. Greenland sea level rise, 2000–2100, including surface melting and ice discharge, is projected to range between 0.01 and 0.17 m, across the

Table 3.B.2. Recent observed Greenland Ice Sheet contributions to sea level rise, mm/year

Greenland Ice Sheet	Method(s)	Reference
	1980s–present	
–0.09 ± 0.23 (1992–1996)	Multiple	Bamber *et al.* (2018)
0.33 ± 0.08 (1993–2010)	Multiple	IPCC (2013)
0.39 ± 0.14 (1992–2011)	Multiple	Shepherd *et al.* (2012)
0.20 ± 0.11 (1983–2003)	Geodesy; laser altimetry	Kjeldsen *et al.* (2015)
0.47 ± 0.23 (1991–2015)	GRACE; mass budget model	van den Broeke *et al.* (2016)
	Post–2000	
0.63 ± 0.17 (2005–2010)	Multiple	IPCC (2013)
0.58 ± 0.10 (2000–2011)	Multiple	Shepherd *et al.* (2012)
0.68 ± 0.05 (2003–2009)	Laser altimetry	Csatho *et al.* (2014)
0.68 ± 0.08 (2000–2012)	Landsat 7 Enhanced Thematic Mapper+ and Terra ASTER	Enderlin *et al.* (2014)
0.42 ± 0.09 (2000–2005)	Landsat 7 Enhanced Thematic Mapper+ and Terra ASTER	Enderlin *et al.* (2014)
0.73 ± 0.05 (2005–2009)	Landsat 7 Enhanced Thematic Mapper+ and Terra ASTER	Enderlin *et al.* (2014)
1.04 ± 0.14 (2009–2012)	Landsat 7 Enhanced Thematic Mapper+ and Terra ASTER	Enderlin *et al.* (2014)
0.77 ± 0.16 (2003–2013)	GRACE gravimetry	Velicogna *et al.* (2014)
0.40 ± 0.04 (2003–2009)	Laser altimetry	Helm *et al.* (2014)
1.03 ± 0.07 (2011–2014)	Radar altimetry	Helm *et al.* (2014)
0.51 ± 0.05 (2003–2010)	Geodesy; laser altimetry	Kjeldsen *et al.* (2015)
0.65 ± 0.24 (2000–2011)	GRACE; mass budget model	van den Broeke *et al.* (2016)
0.72 ± 0.07 (2002–2015)	GRACE gravimetry	Forsberg *et al.* (2017)
0.74 ± 0.07 (2003–2017)	GRACE gravimetry	Tedesco *et al.* (2017)
0.69 ± 0.04 (2012–2016)	Multiple	Bamber *et al.* (2018)

Table 3.B.3. Recent observed Antarctic Ice Sheet contributions to sea level rise, mm/year

Antarctic Ice Sheet	Method(s)	Reference
0.20 ± 0.15 (1992–2011)	Multiple	Shepherd *et al.*, 2012
0.22 ± 0.10 (2005–2010)	Multiple	Shepherd *et al.*, 2012
0.27 (0.37–0.16) 1993–2010	Multiple	IPCC, 2013
0.41 (0.61–0.20) 2005–2010	Multiple	IPCC, 2013
0.31 ± 0.06 (2003–2012)	GRACE; GPS	Sasgen *et al.*, 2013
0.44 ± 0.13 (2010–2013)	Radar altimetry	McMillan *et al.*, 2014
0.18 ± 0.12 (2003–2013)		Velicogna *et al.*, 2014
0.25 ± 0.03 (2003–2014)	GRACE gravimetry	Harig and Simons, 2015
–0.31 ± 0.17 (1992–2001)	Radar, laser altimetry	Zwally *et al.*, 2015
–0.23 ± 0.07 (2003–2008)	Radar, laser altimetry	Zwally *et al.*, 2015
0.30 ± 0.15 (1992–2017)	Multiple	IMBIE Team, 2018
0.20 ± 0.15 (2002–2007)	Multiple	IMBIE Team, 2018
0.60 ± 0.12 (2012–2017)	Multiple	IMBIE Team, 2018
0.53 ± 0.07 (2012–2016)	Multiple	Bamber *et al.*, 2018

four IPCC RCP scenarios (Fürst *et al.*, 2015). Surface melting is expected to dominate future ice losses, because ice discharge will diminish once tidewater glaciers retreat upslope.

Greenland Ice Sheet mass loss rates have more than doubled over the past quarter century (Bamber *et al.*, 2018; Khan *et al.*, 2015). Ice losses, however, vary considerably, both spatially and temporally. Since ∼2000, Greenland contributed between 0.4 and 1.0 mm/year to sea level rise, of which over half comes from calving and basal melting of ice tongues/shelves (discharge); the balance comes from surface melting and runoff (Table 3.B.2, and recent references therein). Mass gains in Greenland's interior are offset by greater peripheral losses that have spread northeastward and northwestward since 2003 (Kjeldsen, *et al.*, 2015; Khan *et al*, 2014). Lowering of Greenland Ice Sheet surface albedo (surface reflectivity) due to expansion of summer meltwater pool area, along with airborne soot, dust, and exposed bare soil, amplifies surface melting in a positive feedback loop (Tedesco *et al.*, 2016).

Greenland's tidewater glaciers are highly sensitive to both atmospheric and ocean warming. Erosion of subglacial ice by warmer ocean water thins the ice tongues and initiates grounding line retreat, with consequent increased ice mass losses. Projected Greenland sea level rise, 2000–2100, including surface melting and ice discharge, is expected to range between 0.01 and 0.17 m, across the four RCP scenarios (Fürst *et al.*, 2015). Surface melting is expected to dominate future ice losses, because ice discharge will diminish once tidewater glaciers retreat upslope.

Parts of the Greenland Ice Sheet could potentially undergo a marine ice sheet instability (MISI) (see Antarctic Ice Sheet, below), because of several deeply buried subglacial valleys with potential marine outlets (Morligham *et al.*, 2014). The Northeast Greenland ice stream (NEGIS) drainage system, parts of which lie on a reverse slope,[p] extends deep into the heart of Greenland. The once-stable Zachariae ice stream, a branch of NEGIS, began to retreat in the early 2000s (Khan *et al.*, 2014). Several other glaciers, including fast-retreating Jakobshavn Isbrae, Helheim, and Kangerdlugssuaq glaciers, also lie on reverse slopes.

Antarctic Ice Sheet

Antarctic ice losses have been increasing since the 1990s and now mostly exceed gains (Appendix Table 3.B.3; IMBIE Team, 2018; Bamber *et al.*, 2018). However, future climate changes could potentially lead to destabilization of the WAIS. Melting of all marine-based WAIS ice[q] would raise global-mean sea level by up to about 3 m (Bamber *et al.*, 2009). Much of WAIS is "grounded" (i.e., rests on bedrock) below sea level and lies on reverse slopes, which makes it vulnerable to a MISI (Fig. 3.5). Fast-flowing glaciers in the Amundsen Sea sector, such as Pine Island, Thwaites, Smith, Kohler, Pope, and Haynes Glaciers, drain a third of the WAIS. Their grounding lines have retreated within the last few decades and abutting ice shelves have thinned. Grounding

[p]One that tilts toward the center of the ice sheet.
[q]Where the base of the ice sheet rests on bedrock below sea level.

lines of Pine Island and Thwaites Glaciers approach sections with reverse slope. Although an ongoing MISI process (Joughin *et al.*, 2014; Rignot *et al.*, 2014) may not cause catastrophic collapse this century, projected 21st century warming could trigger such a reaction over the next several centuries or longer. Parts of East Antarctica are also potentially vulnerable to ocean warming, for example, Totten Glacier (with a volume equivalent to around 3.5–3.9 m of sea level rise, if all melted, Rintoul *et al.*, 2016; Li *et al.*, 2015) and the Wilkes Basin (which holds a comparable volume of potentially unstable ice; Greenbaum *et al.*, 2015; Mengel and Levermann, 2014).

DeConto and Pollard (2016) presented an ice sheet/ice-shelf model which includes MISI, hydrofracturing, and ice-cliff collapse instabilities (MICI), which could accelerate ice mass losses (Pollard *et al.*, 2015). Hydrofracturing begins with downward propagation of small surface cracks under meltwater pressure and further expansion upon freezing. The enlarging crevasses weaken ice until it eventually splits. Additionally, stresses on thick ice cliffs and unbuttressed (unsupported) ice shelves induce grounding line fractures. While intact ice shelves slow the advance of ice steams at the grounding line, heavily fractured ice shelves are more subject to rapid disintegration. This in turn causes glaciers and ice streams to accelerate across the grounding line and discharge more ice.

At continued high greenhouse gas emission rates, these mechanisms could initiate ice-shelf break-up starting after mid-century and add up to 1.6 m (5.2 ft) to sea level rise for Antarctica alone by 2100 (DeConto and Pollard, 2016). Such high rates would result in collapse of the WAIS and some parts of the East Antarctica Ice Sheet within a few hundred years, potentially contributing over 15 m (49 ft) to global mean sea level rise by 2500. Inasmuch as this model limits the maximum ice-cliff retreat rate, even higher rates could be theoretically possible. Although DeConto and Pollard (2016) include several generally not previously modeled processes, which could become more important in Antarctic ice mass losses, especially in higher emissions scenarios, their paper represents just one study that remains to be confirmed by further observations or modeling.

Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report Chapter 4: Coastal Flooding

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Contents

Introduction

Coastal flooding from storm surge is one of the most dangerous and damaging natural hazards that societies face. It was responsible for half of all hurricane-related mortalities in the United States from 1963 to 2012, far more than any other factor (Rappaport, 2014). Coastal extreme water levels are increasing globally, mainly driven by rises in mean sea level (MSL; e.g., Marcos *et al.*, 2015; Marcos and Woodworth, 2017; Menéndez and Woodworth, 2010). Sea level rise is also causing rapid increases in the annual number of shallow "nuisance floods" for low-lying neighborhoods (e.g., Strauss *et al.*, 2016; Sweet and Marra, 2014).

The objectives of this chapter are to review the latest knowledge on New York City flood risk from storms and tides, and to evaluate how climate change will affect this risk between now and the end of the century. Methods used by NPCC (2015) for assessing storm-driven extreme floods are generally repeated here, including the use of the Federal Emergency Management Agency (FEMA, 2013) baseline flood hazards (e.g., the 100-year flood[a]) and the methods for adding sea level rise and mapping the resulting hazard (Horton *et al.*, 2015b; Patrick *et al.*, 2015). New advancements include an innovative analysis of monthly tidal flooding based on a dynamic model, a broadened set of sea level rise scenarios supplemented with the Antarctic Rapid Ice Melt (ARIM) scenario (see Chapter 3), and sensitivity analyses that show how differing methods would affect our results. Wind is a primary factor for coastal storm surge, and a brief review is given in Appendix 4.A, with the latest scientific knowledge on what drives extreme wind events in the New York City area and how they may change in the future.

4.1. Key processes

Coastal storms have historically flooded New York City's lowest lying neighborhoods many times, and even a water level 5 ft below that of record-setting Hurricane Sandy is sufficient to begin flooding several neighborhoods (Fig. 4.1). The worst four known coastal floods were all caused by tropical cyclones (1788, 1821, 1960, and 2012), whereas the fifth worst was caused by an extratropical cyclone in 1992 (Orton *et al.*, 2016b). Sandy in 2012 was a "hybrid" storm type, in that it was transitioning from a tropical to an extratropical cyclone while approaching landfall. It generated the highest recorded water level at New York Harbor in at least 300 years, due to sustained strong easterly winds and a storm surge maximum coinciding with high tide (Colle *et al.*, 2015; Orton *et al.*, 2016b).

Wind is the primary factor governing storm surge, through its speed and the distance over which it blows, the wind fetch. The height and timing of high tide relative to the peak storm surge is also an

[a]The coastal flood that has a 1/100 or 1% chance of occurring in each year.

doi: 10.1111/nyas.14011

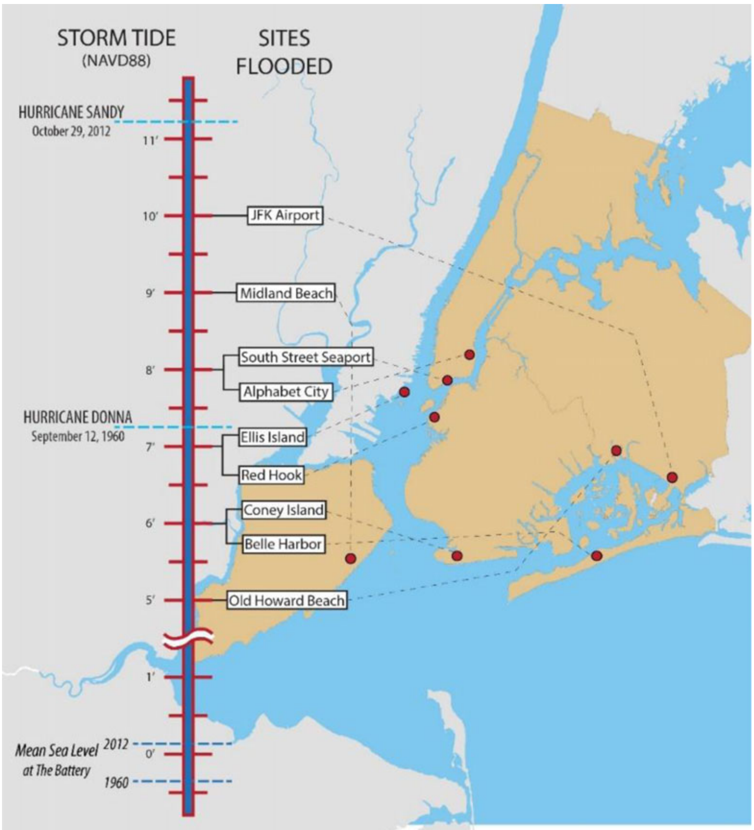

Figure 4.1. Vertical scale bar illustrating approximate breach elevations for the water level (in feet) that floods various New York City locations and neighborhoods. Hurricanes Sandy and Donna peak water levels are shown for comparison. Water levels are assumed spatially constant. Breach, or critical, elevations estimated using a 1-ft resolution 2010 LIDAR-based DEM, with static mapping (Patrick *et al.*, 2015) and 0.5-ft vertical increments of water level.

important factor for New York City coastal flooding (e.g., Colle *et al.*, 2015; Colle *et al.*, 2008; Georgas *et al.*, 2014; Kemp and Horton, 2013). Storm tide can be defined as the combination of tide level and storm surge, measured as a value above a given year's MSL. The total water level is the storm tide plus MSL and can be measured with respect to the geodetic North American Vertical Datum of 1988 (NAVD88). In addition to storm surge and tide, waves can also raise water levels at some coastal neighborhoods of New York City (e.g., Van Verseveld *et al.*, 2015), and are incorporated into FEMA's "base flood elevation" (FEMA, 2013).

This section hereafter refers to storm tide and total water level (called "still water elevation" by FEMA), neither of which includes the oscillations caused by waves. Rainfall typically has a negligible effect on storm-maximum coastal and estuarine water levels surrounding New York City (Orton *et al.*, 2012), though it can directly cause street and neighborhood flooding (e.g., NYC-DEP, 2010).

Of the top 22 known historical storm tide events in New York City history, 15 have been caused by extratropical cyclones, which impact the region far more often than hurricanes (Booth *et al.*, 2015; Catalano and Broccoli, 2018). However, extratropical cyclones appear to have a lower maximum storm tide potential because their maximum wind speeds (based on observations) are much lower than those for hurricanes or hybrids (Orton *et al.* 2016b). In storm tide data going back to 1844 (Talke *et al.*, 2014) and news reports back to the 1700s (Orton *et al.*, 2016b), no extratropical cyclone-driven storm tide has exceeded 7.2 ft MSL and the 1000-year return period extratropical storm tide was recently estimated to be only 8.5 ft MSL (Orton *et al.*, 2016b).

Table 4.1. Comparison of storm tides (in feet)[a] at various return periods (in years) for The Battery, New York City, from various studies and sources

		Return period			
		1	10	100	500
Study	Study type				
FEMA (2007)	Model		6.4	8.6	10.8
Lin *et al.* (2012)[b]	Model			6.7	10.2
FEMA (2013)	Model		7.0	11.3	14.8
Lopeman *et al.* (2015)	Historical Monte Carlo		6.5	11.1	
Nadal-Caraballo *et al.* (2016)	Historical Monte Carlo		6.1	8.0	
Cialone *et al.* (2015)	Model	4.7	7.5	11.2	14.9
Buchanan *et al.* (2016)	Historical	4.7	6.1	8.4	10.7
Orton *et al.* (2016b)	Model		6.4	8.9	12.8
NOAA (2017)	Historical	4.0	6.1	8.0	
Range over studies		4.0–4.7	6.1–7.5	6.7–11.3	10.2–14.9

[a]Values are given in feet above any given year's mean sea level (MSL).
[b]Lin *et al.* (2012) analyzed only tropical cyclones based on the period 1980–2000, and is included for comparison to the longer 100- and 500-year return period storm tides.

For comparison, Sandy's storm tide was 11.1 ft MSL (relative to the 2012 MSL).

Climate change is an increasingly important factor for storm-driven floods and "sunny-day" nuisance floods worldwide. It has increased the height of New York City coastal floods by causing sea levels to rise (Kemp and Horton, 2013; Talke *et al.*, 2014), and this effect is expected to worsen in future decades (e.g., Garner *et al.*, 2017; Orton *et al.*, 2015). Although intensities of tropical and perhaps extratropical cyclones are expected to strengthen in this region, cyclone track changes are difficult to project, and studies have shown mixed results for the effects on New York City storm tides. Uncertainty in this area of research is still high (Garner *et al.*, 2017; Lin *et al.*, 2012; Roberts *et al.*, 2016).

4.2. Current coastal flood risks: observations and trends

"Present-day" flood risk studies typically use past storm events or analysis of their characteristics to represent the present-day hazard, assuming no change to storm climatology. Several academic and governmental studies have found 100-year storm tide estimates in New York City ranging from 6.7 to 11.3 ft (Table 4.1). FEMA's standard map products show contours of the 100- and 500-year return period flood zones, among other metrics, and these return periods have been a common focus of past NPCC flood mapping assessments of sea level rise impacts (Orton *et al.*, 2015; Patrick *et al.*, 2015). These can be referred to as the 1% and 0.2% annual chance floods, respectively, corresponding to the percentage chance of each occurring in a given year. The most recent FEMA (2013) estimates of 100- and 500-year floods are 11.3 and 14.8 ft NAVD88, respectively, and are presently used for planning and building codes but not for insurance purposes because of a successful appeal by New York City (FEMA, 2016).

One source of differences between studies in Table 4.1 involves the use of historical storm tide data versus model-based data. Model-based studies can include synthetic tropical cyclones that have never occurred, with the goal of representing all possible events and surge–tide combinations beyond those observed in the limited historical record (Lin *et al.*, 2014).

Additional reasons for differences can include the particular choice of models, probability distributions, and probabilistic frameworks used to derive storm sets (see discussion in Orton *et al.*, 2016b; Wahl *et al.*, 2017). The Monte Carlo approaches of Lopeman *et al.* (2015) and Nadal-Caraballo *et al.* (2016) are based on historical storm tide data, but also show strong differences for the 100-year event, likely due to their use of different methods for synthesizing water-level time series from storm surge and tide data. Considering the very wide range of storm tide estimates at all return periods shown in Table 4.1, flood hazard assessments should be

Figure 4.2. Nuisance flooding occurs several times per year due to spring tides with small storm surges (e.g., 1–2 ft), (left) on Rockaway Peninsula and (right) in Hamilton Beach. Photos are from 9:49 am dated 9/10/2018 (credit: Jeanne DuPont) and 11:06 am dated 10/8/2017 (credit: Nathan Kensinger), respectively. The Rockaway Peninsula location frequently floods from saltwater coming up through sewers and rain that will not drain through sewers blocked by high sea levels.

evaluated using comparisons of both observed and model-based estimates (Orton *et al.*, 2016b).

Coastal flooding for the New York City region has already been worsened by sea level rise. For example, Sandy's peak water level rose higher, and its return period decreased by a factor of three because of the historic sea level rise of 1.64 ft between 1800 and 2000 (Lin *et al.*, 2016). An early sign of sea level rise readily experienced by the public is an increasing frequency of nuisance flooding, which increased substantially in the United States between 1950 and 2013 (Sweet and Marra, 2014; Sweet *et al.*, 2014). Strauss *et al.* (2016) attribute two-thirds of U.S. nuisance flood days since 1950 to global warming.[b]

Nationwide, the number of such flood days has increased by over 80% for the period 1985–2014 relative to 1955–1984. In New York City, the total number of flood days has grown from 32 to 63 over these two 30-year periods. Thirty-four of the 63 flood days can be linked to anthropogenic sea level rise over the study period (Strauss *et al.*, 2016).[c]

The increasing incidence of coastal flooding creates a growing public inconvenience because of potential damages to low-lying infrastructure and private homes, which would face more frequent street, driveway, and basement flooding without adaptive measures. Already affected New York City areas include several neighborhoods around Jamaica Bay, including parts of Old Howard Beach (Fig. 4.1) and nearby Hamilton Beach, Broad Channel, and Rockaway Peninsula (Fig. 4.2).

New York City flood risk may also have risen due to climate change–related influences on storms (e.g., intensity, frequency, or storm track), as well as changes in the water flow behavior in New York Harbor caused by dredging of ship channels and filling of wetlands. The latter has been shown to have raised the 100-year flood for the Jamaica Bay region of New York City by 1.44 ft since the late 1800s (Orton *et al.*, 2016a). Since the mid-1800s, the 10-year flood height at The Battery has risen by 2.36 $\pm$ 0.82 ft, 1.44 ft of this resulting from sea level rise and the remaining 0.92 ft from other sources, such as storm changes or anthropogenic harbor modifications (Talke *et al.*, 2014).

Studies of historical data have not found significant evidence in this region for larger storm tides due to the effect of climate change on storms (e.g., Marcos and Woodworth, 2017; Wahl and Chambers, 2016). Moreover, no quantitative evidence has been presented demonstrating that Hurricane Sandy was intensified or its storm tide was increased or made more likely by climate change (Lackmann, 2015; Mattingly *et al.*, 2015). Sandy had hybrid cyclone characteristics as it

[b]Sea level rise due to increasing global temperature. Not considered are land subsidence (GIA, subsurface fluid extraction), spatial fingerprints of land–ice mass change, or ocean dynamics.

[c]The "nuisance flood" level at The Battery in New York City is 26 inches (0.65 m) above Mean Higher-High Water (MHHW; Sweet *et al.*, 2014).

approached the region and therefore represents a relatively complex case study (Galarneau *et al.*, 2013; Zambon *et al.*, 2014).

4.3. Future coastal flood risk under climate projections

In this section, we assess how sea level rise will affect storm-driven and tidally driven coastal flooding over the 21st century. The assessment and mapping of storm-driven floods with the NPCC (2015) high-estimate (90th percentile) scenarios conservatively[d] captures the possible future extreme event contribution to coastal flood risk (Horton *et al.*, 2015b; Patrick *et al.*, 2015). These results are repeated here, as they are now being used for planning purposes by New York City (e.g., NYC-DCP, 2018a, 2018b, 2018c).

The assessment of tidal flooding is an important advancement over NPCC (2015), as more frequently recurring nuisance floods are one of the earliest manifestations of sea level rise and can be a more important driver of flood adaptation (Moftakhari *et al.*, 2017; Sweet and Park, 2014). The water levels and flood mapping of ARIM, a higher impact, lower probability sea level rise scenario, are included for both storm- and tide-driven flooding to raise awareness, but not for planning purposes.

Static mapping approaches simply superimpose sea level rise on water levels for various return period floods and extrapolate ("bathtub") the water level horizontally over the floodplain (Patrick *et al.*, 2015). On the other hand, dynamic flood modeling explicitly accounts for all the forces acting on the water and the resulting water movement, yet is computationally expensive (Orton *et al.*, 2015). Static mapping is used here for the storm-driven flood assessment, and a hybrid dynamic/static approach is used for tidally driven flooding, as described and discussed below.

All flood mapping in this report uses the static approach to project water levels onto inland flood zones, and these static mapping methods are given in Chapter 5 of this report. The flood hazard assessments and mapping assume no future changes in the shoreline due to either coastal erosion or coastal flood protection, for example, and therefore may over- or underestimate flood area. New York City is implementing a $20 billion adaptation plan developed after Hurricane Sandy (City of New York, 2013). Moreover, recent work has demonstrated that while extreme water levels around the United Kingdom have increased due to sea level rise, this has not led to a corresponding increase in coastal flooding, due to improved coastal protection measures, forecasts, and emergency planning (Haigh and Nicholls, 2017; Stevens *et al.*, 2016).

[d]Conservative from an adaptation perspective, that is, erring on the side of a high-risk bias and therefore leading to a more risk-averse response.

4.3.1 Future storm tide flooding. NPCC (2015) research compared the results of static and dynamic flood modeling of sea level rise using FEMA (2013) storm tide scenarios as a present-day baseline, and found that they were similar for most locations. Differences were usually within ±0.5 ft, and therefore using static mapping leads to a relatively small additional uncertainty compared to the large uncertainty in storm tide probabilities and sea level rise projections (Orton *et al.*, 2015).

Section 4.3.2 uses dynamic modeling to address possible changes to tides with sea level rise, and shows these are also relatively small. Due to these findings and the high expense of performing hundreds of storm simulations for each sea level rise scenario, here we utilize static methods to assess future storm-driven flooding.

We also follow NPCC (2015) precedent by not including the possible effects of storm climatology changes on flooding, but this is partially addressed with a sensitivity analysis (see "Sensitivity tests" section). Studies have shown that atmospheric warming will likely intensify tropical cyclones in the future (Emanuel, 2005; Garner *et al.*, 2017; Knutson *et al.*, 2010; Lin *et al.*, 2012). However, changes in storm tracks could offset the intensity increase, resulting in little change in storm tides at The Battery (Garner *et al.*, 2017).

Most studies suggest there will be a future decrease in the frequency of extratropical cyclones over the North Atlantic (Bengtsson *et al.*, 2006; Chang, 2013; Zappa *et al.*, 2013), although little decrease near the coast (Colle *et al.*, 2013). Some studies have shown an increase in intensity for extratropical cyclones over the next 100 years (Marciano *et al.*, 2015; Michaelis *et al.*, 2017) resulting from additional condensational heating in a warmer

Table 4.2. Water levels (feet NAVD88) for (top) 100-year floods and (bottom) 500-year floods at The Battery for NPCC (2015) (10th–90th percentiles) and ARIM sea level rise scenarios, using static superposition (with unchanged storm climatology)

	NPCC2 2015 Coastal flooding projections Current projections of record for planning				NPCC3 ARIM scenario Growing awareness of long-term risk
	Time horizon	Low estimate (10th percentile)	Middle range (25th–75th percentile)	High estimate (90th percentile)	ARIM scenario
100-year flood	2020s	11.5 ft	11.6 to 12.0 ft	12.1 ft	–
	2050s	12.0 ft	12.2 to 13.0 ft	13.8 ft	–
	2080s	12.4 ft	12.8 to 14.5 ft	16.1 ft	18.0 ft
	2100	12.5 ft	13.1 to 15.5 ft	17.6 ft	20.7 ft
500-year flood	2020s	15.0 ft	15.1 to 15.5 ft	15.6 ft	–
	2050s	15.5 ft	15.7 to 16.5 ft	17.3 ft	–
	2080s	15.9 ft	16.3 to 18.0 ft	19.6 ft	21.5 ft
	2100	16.0 ft	16.6 to 19.0 ft	21.1 ft	24.2 ft

Notes: The baseline 100- and 500-year water levels are 11.3 and 14.8 ft, respectively (FEMA, 2013; Horton *et al.*, 2015b). ARIM represents a new, physically plausible upper end, low probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from improved modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections.

(and more moist) climate; however, not all models agree with this change (Seiler and Zwiers, 2016).

There is currently little understanding of how hybrid storms like Sandy will change in the future, and more work is needed looking at tropical and extratropical cyclone changes as well.

Methods. The NPCC (2015) coastal flood scenarios took the FEMA (2013) study as a baseline, focused only on the 90th percentile sea level rise scenario, and used static methods for the primary map and flood-level products (Horton *et al.*, 2015b; Patrick *et al.*, 2015). Those results are now being used for planning purposes by New York City (e.g., NYC-DCP, 2018a, 2018b, 2018c). The sea level rise projections were based on an ensemble of 24 global climate models and two emissions scenarios (RCP4.5 and RCP8.5), along with literature review and expert judgement (see Chapter 3) to reflect uncertainty in future emissions as well as in the ocean, cryosphere, and climate system. The sea level rise projections were presented for the 10th, 25th, 75th, and 90th percentiles, for the 2020s, 2050s, 2080s, and 2100 (Table 3.1).

We keep the same static flood scenario approach, superimposing the percentiles of sea level rise on the 100- and 500-year storm tide of the FEMA (2013) baseline. In addition, we expand the calculation to include this report's new upper-end ARIM projections that are available for the 2080s and 2100 (see Chapter 3, Section 3.6, Table 3.2).

Results. Results for 100- and 500-year flood water levels for a range of sea level rise scenarios and time horizons are shown in Table 4.2. For example, the 100-year water level for the 2080s ranges from 12.4 to 16.1 ft NAVD88 for the 10th–90th percentile sea level rise scenarios. This rises to 18.0 ft NAVD88 in the ARIM scenario.

Table 4.3 shows estimated future return periods for the baseline 100- and 500-year floods of 11.3 and 14.8 ft NAVD88, respectively. Today's 100-year flood will become more frequent, occurring on average every 28–71 years in the 2050s, and every 8–59 years in the 2080s (90th and 10th percentiles). If the ARIM projection is reached at 2100, today's 500-year flood of 14.8 ft will have a return period below 5 years. Results for a full range of return periods are plotted in Appendix 4.B, Figure 4.B.1.

A 100-year flood map with the 90th percentile and ARIM sea level rise scenarios, for the Jamaica Bay and Coney Island areas of the city, is shown in Figure 4.3. A similar city-wide map is presented in Chapter 5 of this report (Mapping Climate Risk), but here we zoom in on this localized region due to its having a significant proportion of the city's total floodplain area. The maps clearly illustrate the expansion of the area at risk of flooding for each

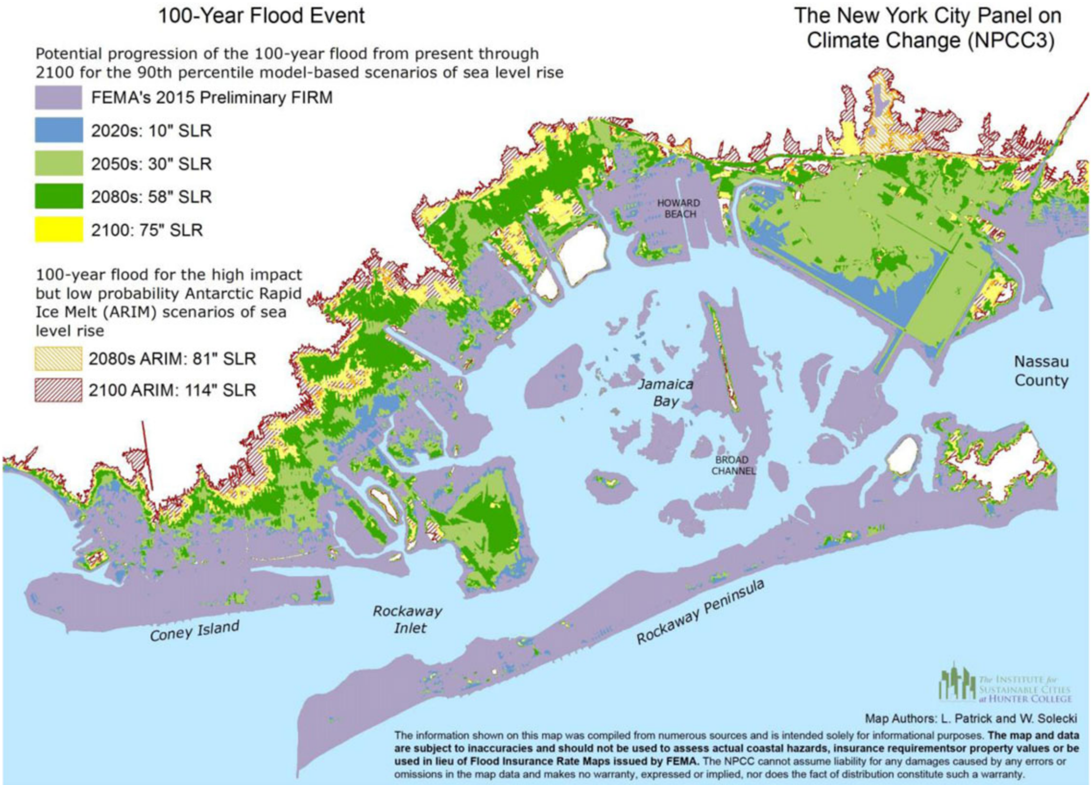

Figure 4.3. **Expansion of the 100-year return period floodplain over time in the Jamaica Bay and Coney Island areas of New York City for the NPCC (2015) 90th percentile sea level rise and ARIM scenarios. Results assume no future changes in the shoreline due to either coastal erosion or coastal flood protection, for example, and therefore may over- or underestimate flood area.**
Note: ARIM represents a new, physically plausible upper end, low probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from recent modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections. It is included to raise awareness but not for planning purposes.

mapped sea level rise scenario, progressing into the future. However, only Tables 4.2 and 4.3 show the range of uncertainty across the sea level rise projections. The 100-year flood baseline of FEMA (2013) covers a similar area to that which was flooded during Hurricane Sandy (Orton *et al.*, 2015), and this is compared with future tidal flooding at the end of Section 4.3.2.

Sensitivity tests. Detailed analyses of the sensitivity of these results to three key underlying assumptions are given below. First, we evaluate the sensitivity to assumptions on future emissions, which can cause large differences in sea level rise projections. Second, the choice of superimposing a single sea level rise percentile is analyzed, as for certain applications it may be more appropriate to incorporate the full probability distribution of projected sea level rise through mathematical convolution[e] (Lin *et al.*, 2016; Lin and Shullman, 2017; Ruckert *et al.*, 2017). In the third sensitivity test, we examine the possible influence of changing storm characteristics due to climate change, for which there remains substantial uncertainty.

The results presented in Tables 4.2 and 4.3 are based on NPCC (2015) sea level rise projections (Chapter 3, Section 3.4.2) that combine projections for both the lower emission RCP4.5 and higher emission RCP8.5 pathways (Horton *et al.*, 2015a, 2015b). Applying a higher emission scenario would result in higher projected flood levels. For example, applying the 90th percentile sea level rise for an

[e] A convolution is an integral that expresses the amount of overlap of one distribution as it is shifted over another. It therefore "blends" one distribution with the other.

Table 4.3. Future return periods (in years) for today's 100-year flood of 11.3 ft (top), and 500-year flood of 14.8 ft (bottom), for the NPCC (2015) sea level rise projections

		NPCC2 2015 coastal flooding projections Current projections of record for planning			NPCC3 ARIM scenario Growing awareness of long-term risk
	Time horizon	Low estimate (10th percentile)	Middle range (25th–75th percentile)	High estimate (90th percentile)	ARIM scenario
100-year flood	2020s	93 years	85–71 years	66 years	–
	2050s	71 years	64–42 years	28 years	–
	2080s	59 years	47–19 years	8 years	<5 years
	2100	54 years	40–11 years	<5 years	1 day
500-year flood	2020s	457 years	429–374 years	346 years	–
	2050s	374 years	332–228 years	161 years	–
	2080s	304 years	255–112 years	53 years	19 years
	2100	282 years	219–72 years	25 years	<5 years

NOTES: The FEMA (2013) baseline flood exceedance curve data do not extend to lower return periods than 5 years (therefore, "<5" is designated), but tidal flood modeling with sea level rise helps estimate a return period of 1 day for one case. The ARIM scenario is shown to raise awareness of potential long-term risk. ARIM represents a new, physically plausible upper-end, low-probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from improved modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections.

RCP8.5 projection (Kopp *et al.*, 2017) that considers rapid ice melt (DeConto and Pollard, 2016) leads to an estimated 100-year flood by the 2080s that is 2.4 ft higher than that based on the NPCC (2015) 90th percentile sea level rise projection (16.1 ft). On the other hand, applying a lower emission scenario would result in lower projected flood levels. Estimated flood levels based on the considered percentiles of RCP8.5, RCP4.5, and RCP2.6 sea level rise projections from Kopp *et al.* (2017) are shown in Figures 4.B.2–4.B.4, respectively.

The alternative approach of combining a full sea level rise distribution with the storm tide distribution through convolution leads to a 100-year flood in the 2080s of 16.7 ft (for the case where the RCP 8.5 sea level rise distribution (Kopp *et al.*, 2017) is applied to the FEMA baseline). This approach estimates the "expected" flood level (integrating all sea level rise percentiles; Lin *et al.*, 2016), but, in this case, the estimated flood level is slightly above the result from superposition with the 50th percentile of the same sea level rise distribution.

Results for various sea level rise distributions are compared in Figures 4.B.2–4.B.4. In the cases where the sea level rise distribution is broader (i.e., the sea level rise projection less certain) such as with the high emissions scenarios for 2100, the result of incorporating the full sea level rise distribution can be well above the result from superposition with the 50th percentile. Future projections of the effect of sea level rise on coastal floods may incorporate full sea level rise distributions, in addition to superposition with specific percentiles, to provide a more integrated account of the uncertainties in sea level rise projections.

Finally, the above results neglect climate-driven changes to storms, which could also increase future flood risk. To test sensitivity to changing tropical cyclones, we estimated future tropical cyclone storm tide probabilities using storm projections based on four IPCC (2007) climate models (Lin *et al.*, 2012). Results show a weighted average increase of 3.4/7.3% in the 100-/500-year storm tides in the 2080s, relative to the assessment considering only sea level rise and no storm changes. Additional details of this analysis are given in Figure 4.B.5.

Results using these climate models suggest that tropical cyclone changes will lead to slightly higher storm tides, yet similar studies elsewhere using IPCC (2013) climate models found no changes in tropical (Garner *et al.*, 2017) and extratropical cyclone (Roberts *et al.*, 2015) storm tides. The spread among different climate models in these studies is often large, and some models indicate that surges could possibly get significantly worse (Lin *et al.*, 2012). Therefore, further research on this topic should be undertaken. One potentially important additional factor that needs more study is the possible correlation between future sea level rise and storm changes (Little *et al.*, 2015).

4.3.2 Future monthly tidal flooding. Tides are far more predictable than storm surges, and modeling their potential flooding therefore requires a much smaller number of simulations and computational expense than storms. As a result, we use dynamic model simulations with sea level projections to quantify the future evolution of tides, though we subsequently use static mapping to map these water levels onto topography. Presently, monthly tidal flooding threatens the lowest lying streets in a few city neighborhoods (e.g., Hamilton Beach).

NPCC has not previously evaluated how sea level rise will affect tidally driven nuisance flooding. However, regular tidal flooding can lead to a tipping point in the advancement of impacts, hypothesized to occur at a threshold of perhaps ∼30 nuisance floods per year (Sweet and Park, 2014). As a result, the city has become interested in seeing projections of future tidal flooding (see Chapter 3 for description of flooding impacts).

Methods. An innovation here is that we map monthly tidal flooding, which can be a useful threshold indicator of repeated flooding that is sufficient to trigger large-scale adaptation investments. Specifically, we model and map the Mean Monthly High Water (MMHW), which is the average of all monthly maxima in predicted astronomical tide levels. MMHW is not a standard tidal datum used by NOAA, such as MSL or MHHW. It is typically exceeded by observed water levels about 25–35 times per year at New York City, based on examination of observed water levels at The Battery, Kings Point, and Jamaica Bay (Inwood, Long Island), closely approximating the aforementioned tipping point of 30 floods per year (Sweet and Park, 2014).

Three-dimensional dynamic simulations of tides are performed using the Stevens Institute of Technology Estuarine and Coastal Ocean Model using the New York Harbor Observing and Prediction System (NYHOPS) operational model setup and grid (Georgas and Blumberg, 2010; Orton *et al.*, 2016b). Simulations cover a 35-day period beginning August 1, 2015, under tide and streamflow forcing (no wind). Modeled water-level time series at all model grid cells are subjected to tidal harmonic analysis (Pawlowicz *et al.*, 2002) to create 19-year tide time series that capture all the periodicities therein, and monthly maxima are computed and averaged.

Resulting tide datum estimates are bias-corrected using observation-based estimates from several sites around New York City (the mean magnitude of model bias for MMHW was only 1 inch). The biases for this zero sea level rise case are then applied to all results for six sea level rise scenarios.

This approach for modeling tides with sea level rise was used recently by this chapter's lead author in studies of Long Island Sound and Jamaica Bay (Fischbach *et al.*, 2018; Kemp *et al.*, 2017). Static mapping methods for using these dynamically modeled estuary tide data to map monthly tidal floodplains are described in Chapter 5 (Mapping Climate Risk).

Results and discussion. Figure 4.4 presents the map of monthly tidal flooding for the Jamaica Bay area of New York City, based on six projections of 90th percentile and low-probability ARIM sea level rise. A similar citywide monthly tidal flood map is presented in the Mapping Climate Risk chapter (Chapter 5). Under the conservative 90th percentile sea level rise scenario, monthly tidal flooding by the 2050s is moderately widespread, including large swaths of low-lying areas like Rockaway Peninsula. At 2100 under this 90th percentile scenario, flooding is very widespread across all neighborhoods around the bay and includes portions of John F. Kennedy Airport (Fig. 4.4, top right). In the more extreme ARIM scenario, the flooding is extremely widespread at 2100.

The new concept of a monthly tidal flood datum MMHW is presented here as a useful metric of chronic flooding. Mapping the effect of sea level rise on monthly tidal flooding (MMHW) has several advantages compared with mapping daily tidal flooding (MHHW), which has become common practice (e.g., Climate Central, 2018; NYC-DCP, 2018b).

Depending on location around New York City, MMHW exceeds MHHW by 0.6–1.0 ft (Fig. 4.B.6), and therefore is a substantially higher metric of tidal flooding, reaching a larger area of the city sooner as sea level rises. While MHHW is exceeded hundreds of times per year, MMHW has only 25–35 exceedances per year, and is more useful as a threshold indicator for when sea level rise will first affect neighborhood habitability and require adaptation (e.g., elevated seawalls).

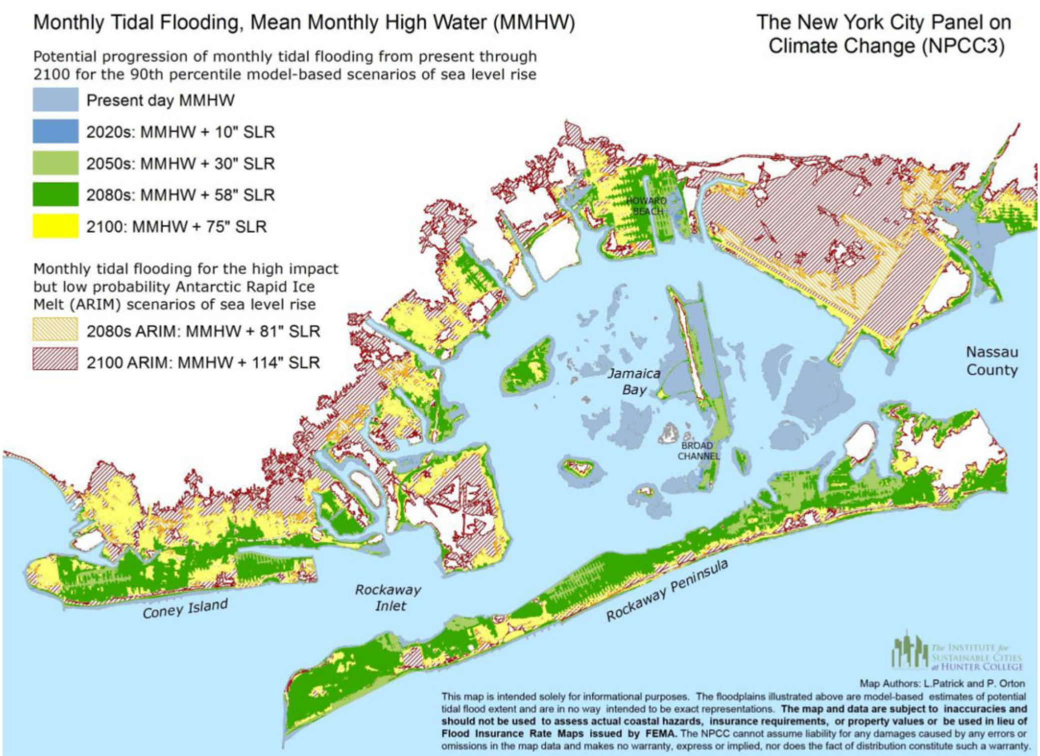

Figure 4.4. Expansion of area affected by monthly tidal flooding for Jamaica Bay and Coney Island areas of New York City for NPCC (2015) 90th percentile sea level rise and ARIM scenarios. Results assume no future changes in the shoreline due to either coastal erosion or coastal flood protection, for example, and therefore may over- or underestimate flood area.
Note: ARIM represents a new, physically plausible upper end, low-probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from recent modeling of ice sheet–ocean behavior to supplement the current (NPCC, 2015) sea level rise projections. It is included to raise awareness but not for planning purposes.

Monthly tidal flooding is already occurring on some low-lying streets of New York City, and citizen observations with time-stamped photographs are helping validate the modeling and mapping (e.g., Fig. 4.2). Moreover, mapping the relatively frequent and observable monthly tidal flooding may be more helpful than mapping the rare 100-year flood, for communicating flood risk and its advancement with sea level rise.

A comparison of dynamic modeling results to simple superposition of tides and sea level rise (Fig. 4.B.7) demonstrates that the difference is relatively small around New York Harbor and moderate for western Long Island Sound (southeast Bronx and northern Queens), adding about 2% and 7% of the amount of sea level rise to MMHW levels, respectively. Similar to previous results where dynamic and static storm tide modeling were compared (Orton *et al.*, 2015), the differences between them here are within ±0.5 ft. Using the 90th percentile 2100 sea level rise (6.25 ft) as an example, the additional increase in monthly high tides at The Battery is 0.15 ft, and at western Long Island Sound is 0.45 ft (Fig. 4.B.7). That is, sea level rise adds 6.25 ft, while the dynamic response of the tides adds another 0.15–0.45 ft to MMHW.

The ARIM sea level rise at 2100 has a very low probability, significantly less than 10%, but provides insights into the impacts of extreme sea level rise that may occur in centuries beyond 2100 (see Chapter 3, Sea Level Rise). In the long term, sea level rise could eventually raise tidal flooding to levels even more severe than those that occurred during Hurricane Sandy. For example, with the ARIM scenario of 9.5 ft of sea level rise at 2100, even the daily maximum tidal water levels are worse than the maximum water levels during Sandy (Fig. 4.B.8).

4.4 Conclusions and recommendations

In this update to the NPCC (2015) coastal flood projections for New York City, NPCC3 has reviewed key processes, summarized historical trends and present-day flood hazards, and assessed how sea level rise will affect storm- and tide-driven future flooding.

A combined dynamic/static analysis shows that monthly flooding will not be a widespread problem until the 2050s or later, but by late in the century it could impact most of the neighborhoods immediately surrounding Jamaica Bay, as well as several other low-lying neighborhoods of the city. Areas particularly susceptible to this monthly tidal flooding include Rockaway Peninsula, Howard Beach, and Coney Island and areas immediately to the north. Under the new ARIM scenarios, sea level rise by the end of this century could raise daily tidal flooding to levels even more severe than that which occurred during Hurricane Sandy.

A static assessment of storm-driven flooding shows how extreme events such as the 100- and 500-year floods will rise with a variety of sea level rise projections, ranging from 10th to 90th percentiles for the 2020s, 2050s, 2080s, and 2100 and including the ARIM scenarios for the 2080s and 2100. Assumptions on future emissions pathways are shown to cause large differences in the sea level rise projections, and as a result, the flood projections. Moderate differences can also arise from differing methods for combining probabilities of storm tides and sea level rise.

An improved understanding of present and future flood risk should be helpful to New York City for optimal long-term planning. NPCC3 therefore makes the following recommendations for continued research to address coastal flooding risks in the New York metropolitan region:

Recommendations for research

- Given the wide range of estimates of storm tide at different return periods, continued research is needed on flood hazards in the New York metropolitan region, including investigations of historical or sedimentary archives, flood modeling, storm modeling, and analyses of how and why the range of hazard assessments differ.
- There remains substantial uncertainty regarding the potential influences of future changes to tropical, extratropical, and hybrid cyclones, and more research should be conducted into future changes to each of these storm types.

Acknowledgments

P. Orton is supported by a NOAA's Regional Integrated Sciences and Assessments (RISA) program (Award NA10OAR4310212). N. Lin and B. Colle are supported by the United States Army Corps of Engineers (USACE) Climate Preparedness and Resilience Program, with administrative support from Oak Ridge Institute for Science and Education (ORISE). The Figure 4.1 map was a collaborative effort with New York City Department of City Planning (Jonathan Goldman, Mary Kimball).

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Appendix 4.A. Extreme winds and possible future trends

None of the chapters in this report specifically address the related topic of extreme wind events and how they may change across the region in the future, so here we briefly review the latest science on this related topic. Extreme winds at New York City and the New York Bight are associated with nearby extratropical cyclones, cold and warm fronts, convective storms, and tropical cyclones (tropical storms and hurricanes). High winds during the cool season can be separated in pre-cold frontal (PRF), post-cold frontal (POF), and strong pressure gradients near a coastal northeast winter storm (NEC).

Layer and Colle (2015) showed that NECs and PRFs peak in December, while POFs peak in January and February. During the warm season, there can be severe small-scale convective wind gusts (Colle *et al.*, 2012), quasi-linear convective systems and squall lines (Lombardo and Colle, 2010), and tropical cyclones undergoing extratropical transition such as Sandy (2012; Colle *et al.*, 2015) and Floyd (1999; Colle, 2003).

With regard to extratropical cyclones, most studies suggest there will be a future decrease in their frequency over the North Atlantic (Bengtsson *et al.*, 2006; Chang, 2013; Zappa *et al.*, 2013), although little decrease near the coast (Colle *et al.*, 2013). Some studies have found that there will be an increase in intensity for extratropical cyclones over the next 100 years over the northern Atlantic (Marciano *et al.*, 2015; Michaelis *et al.*, 2017) resulting from additional condensational heating in a warmer (and more moist) climate; however, not all models agree with this change (Seiler and Zwiers, 2016). Extratropical cyclones that cause wind extremes tend to follow a preferred track (Booth *et al.*, 2015), and climate models suggest that there has been an increase in the occurrence of strongly intensifying cyclones along this preferred track (Colle *et al.*, 2013). However, these two studies were not focused on the exact same types of storms, and so more work is needed.

Future trends in tropical cyclones, squall lines, and convective systems are even less certain because climate models cannot resolve convective storm events. Therefore, statistical approaches have been attempted by using future changes in the ambient conditions from CMIP5 models to predict future convective storm changes. For example, Li and Colle (2015) showed that there will be a 50–80% increase in the number of convective storm days for the New York region by the end of the century, from which one can infer a significant increase in the number of convective wind gusts. However, higher resolution models will need to be used in future studies to confirm these results.

Several studies have shown that atmospheric warming will likely intensify tropical cyclones in the future (Emanuel, 2005; Garner *et al.*, 2017; Knutson *et al.*, 2010; Lin *et al.*, 2012). There is currently little understanding of how hybrid storms like Sandy will change in the future, and more work is needed to examine both tropical and extratropical cyclone changes.

Appendix 4.B. Coastal flooding supplemental figures

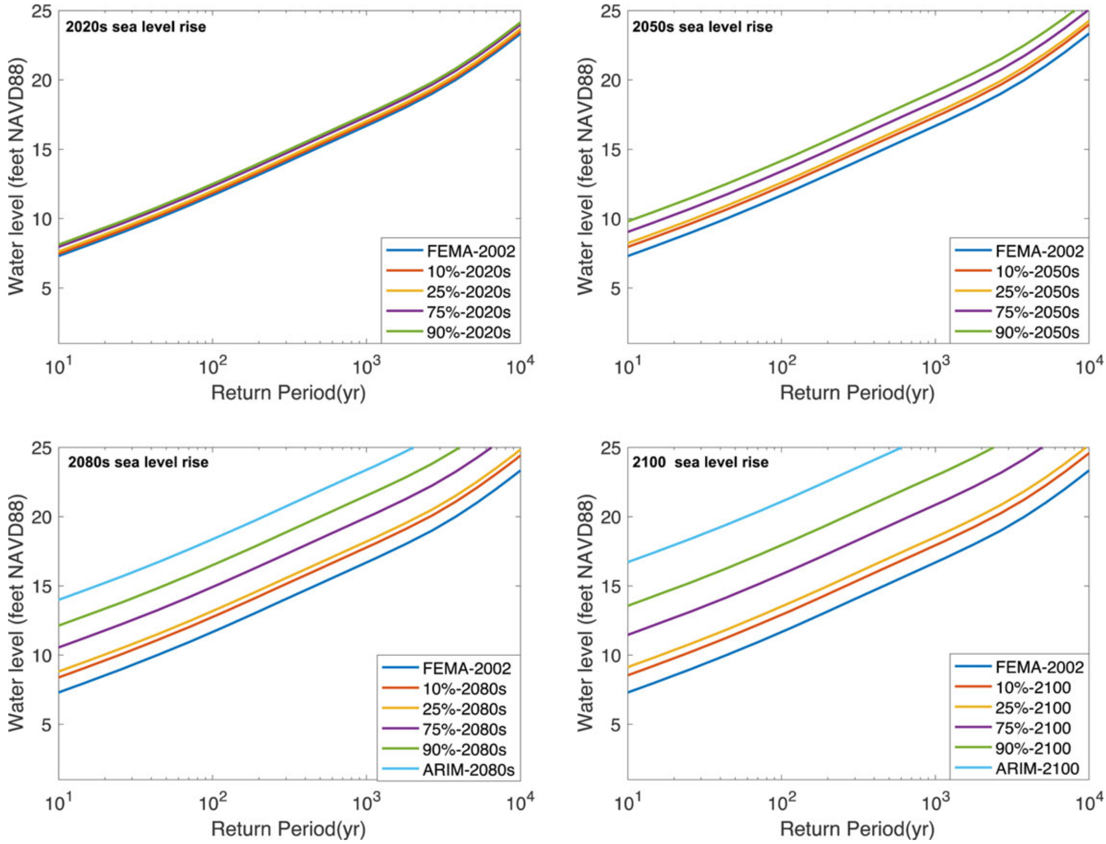

Figure 4.B.1. Estimated flood return periods based on FEMA (2013) storm tide probability distribution ("2002" baseline, i.e., 2000–2004 mean sea level) and NPCC (2015) and ARIM sea level rise scenarios. Particular percentiles (%) of the NPCC sea level rise are considered. Top left: sea level rise for the 2020s; top right: sea level rise for the 2050s; bottom left: sea level rise for the 2080s; bottom right: sea level rise for 2100. Results for 100- and 500-year flood levels are presented in Table 4.2.

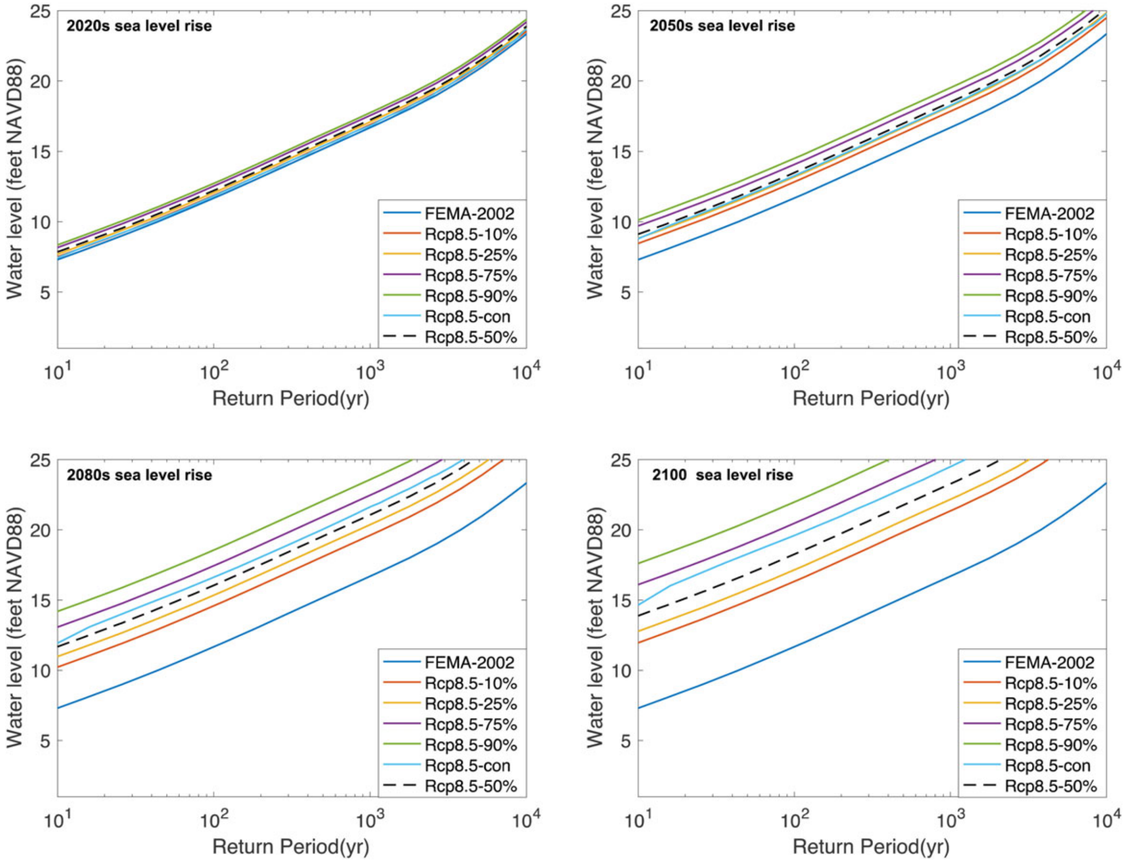

Figure 4.B.2. Estimated flood return periods based on FEMA (2013) storm tide probability distribution ("2002" baseline, i.e., 2000–2004 mean sea level) and RCP8.5 sea level rise probability distribution of Kopp *et al.* (2017). In addition to estimates based on superposition of particular percentiles (%) of the sea level rise to the storm tide return levels, estimates based on convolution with the full distribution of sea level rise ("con") are also shown.

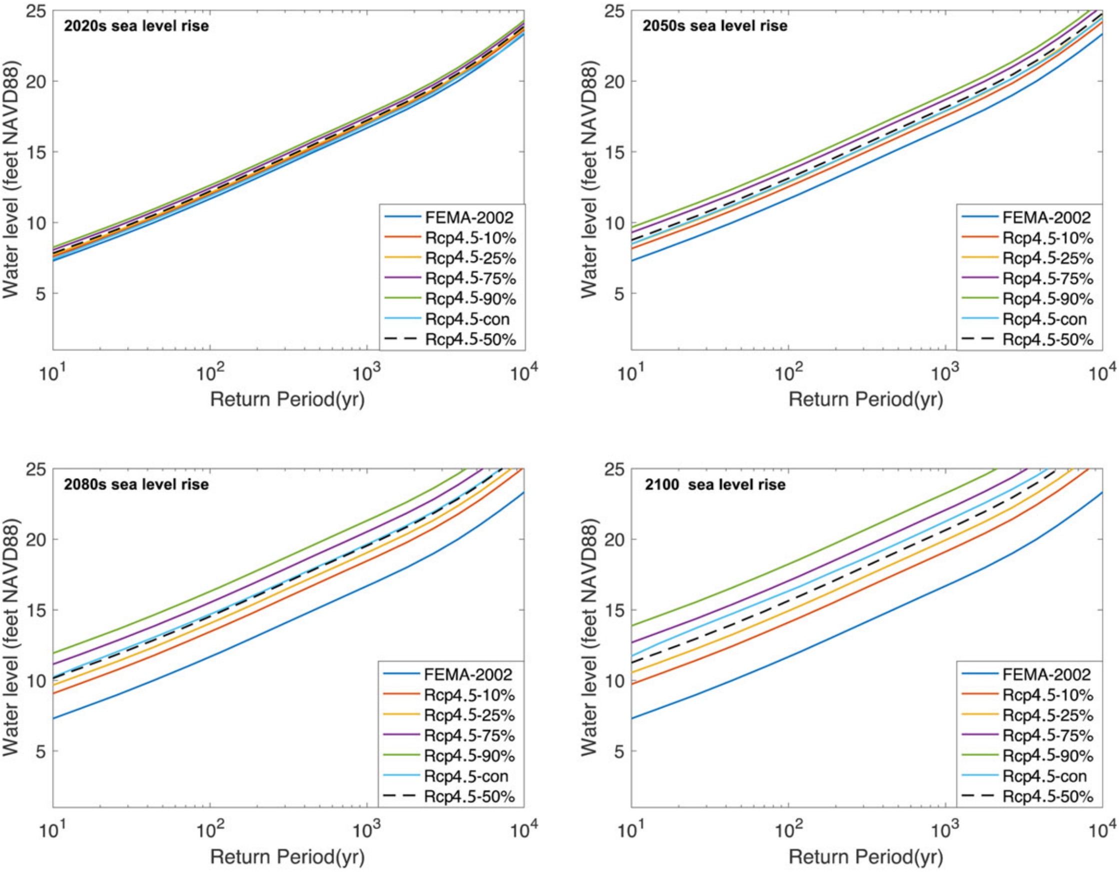

Figure 4.B.3. Same as Figure 4.B.2 but using the RCP4.5 sea level rise probabilities of Kopp *et al.* (2017).

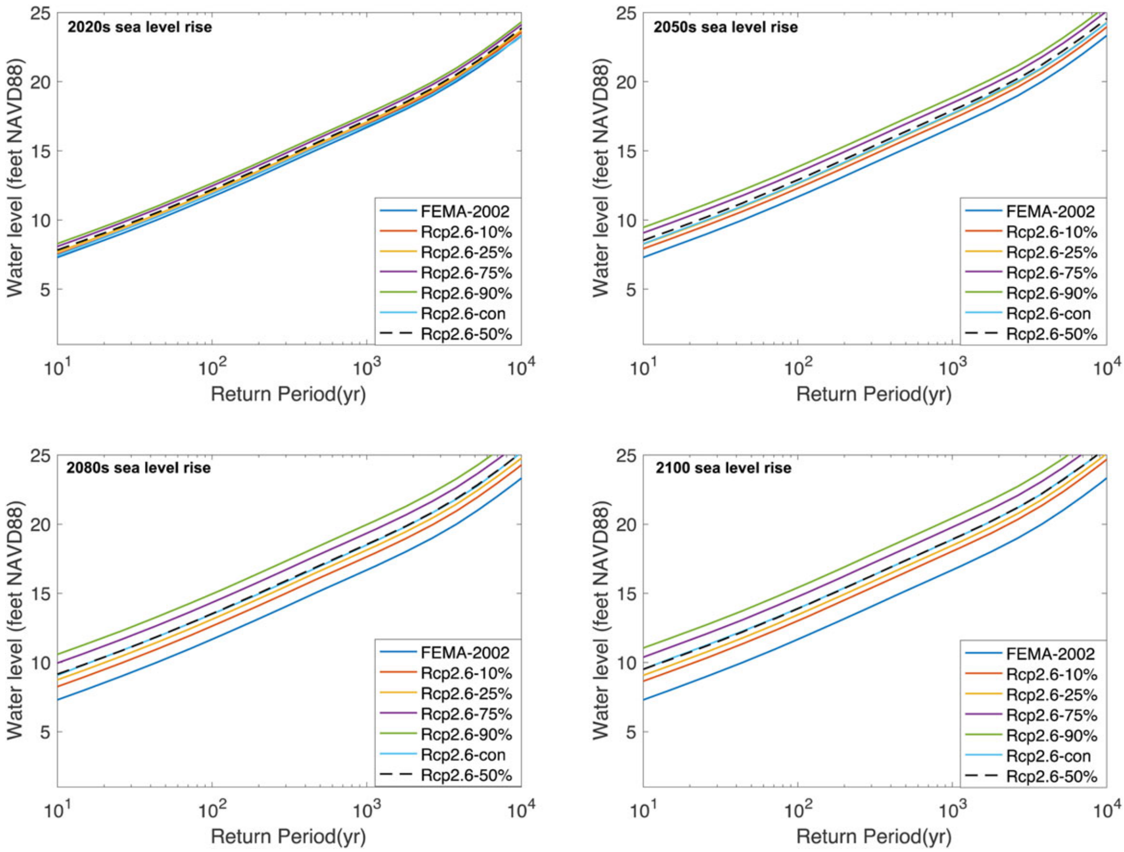

Figure 4.B.4. Same as Figure 4.B.2 but using the RCP2.6 sea level rise probabilities of Kopp *et al.* (2017).

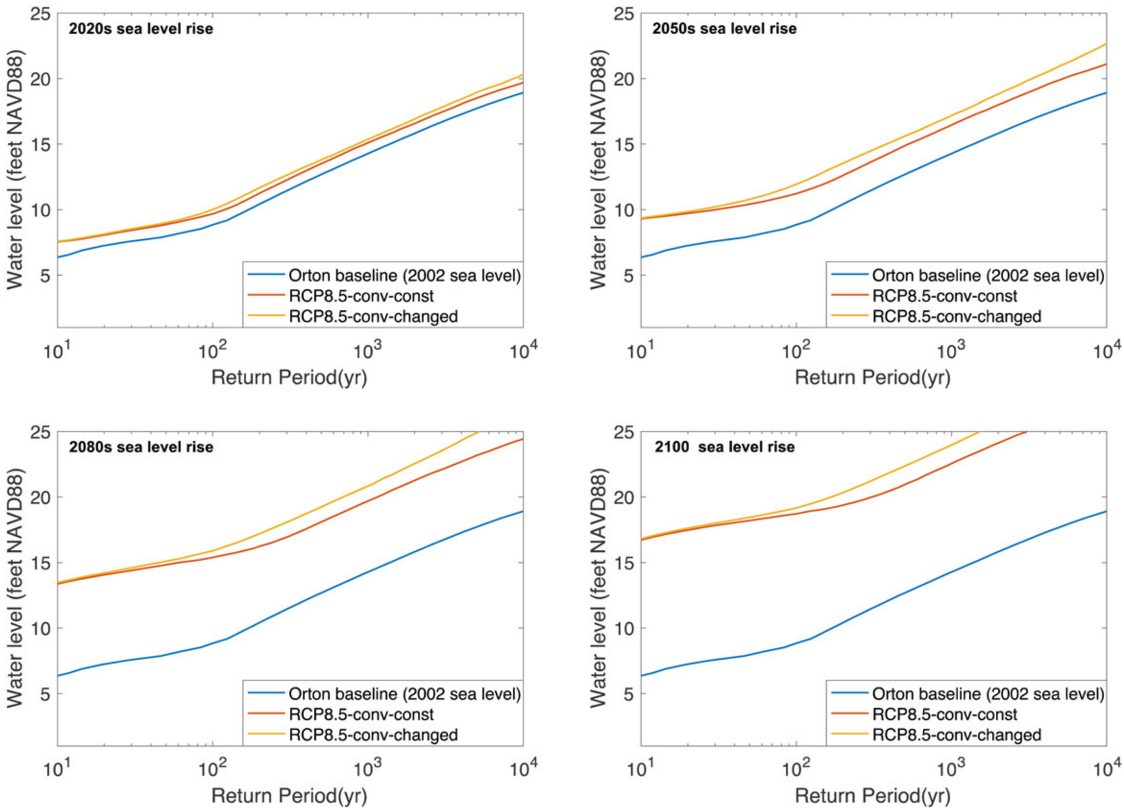

Figure 4.B.5. Estimated water-level return periods based on the storm tide probability distribution of Orton *et al.* (2016b) and RCP8.5 sea level rise probabilities of Kopp *et al.* (2017), with (changed) and without (constant) considering tropical cyclone changes (Lin *et al.*, 2012). The effect of tropical cyclone changes is estimated as a weighted average based on four IPCC (2007) climate model projections in Lin *et al.* (2012). Orton *et al.* (2016b) is used as the storm tide baseline in this analysis of the effect of tropical cyclone changes, as it depicts more appropriate relative contributions of tropical cyclones and extratropical cyclones to the surge probabilities than the FEMA baseline.

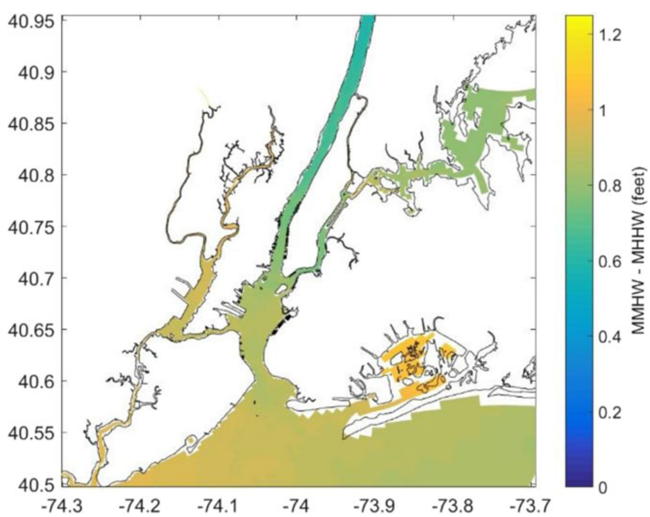

Figure 4.B.6. Map (versus longitude, latitude) showing the difference between present-day tidal MMHW (monthly maximum) and MHHW (daily maximum) water levels.

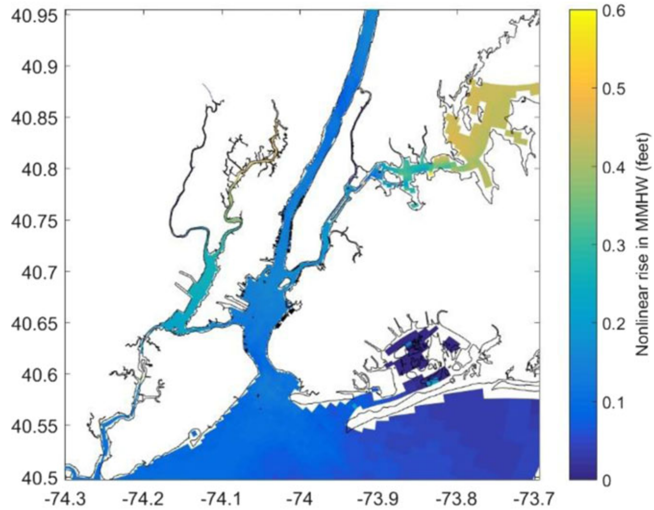

Figure 4.B.7. Map (versus longitude, latitude) showing the difference between the water levels for the dynamic and static superposition approaches for the 90th percentile SLR in 2100 (after NPCC, 2015). In the dynamic approach, nonlinear effects are captured with modeling.

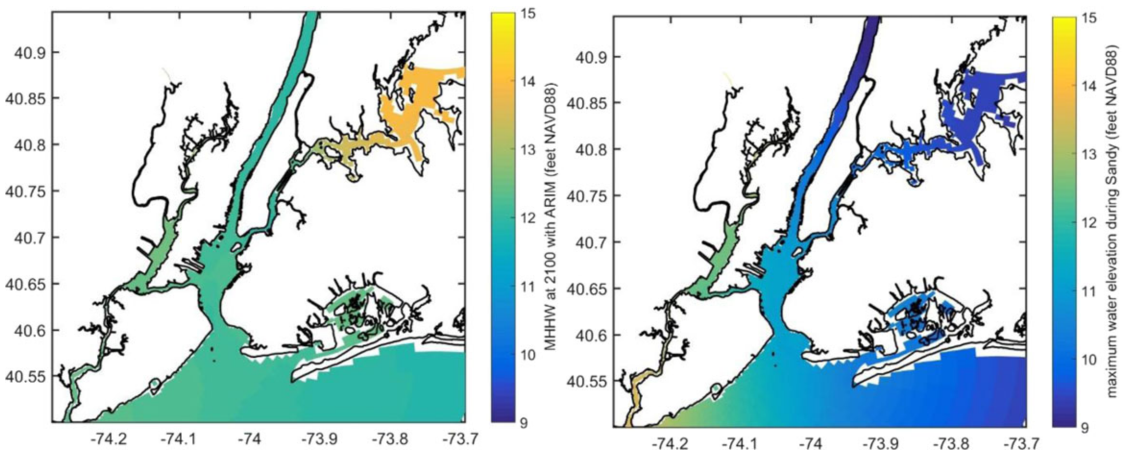

Figure 4.B.8. Comparison of (left) MHHW water levels under the ARIM sea level rise scenario at 2100, with (right) Hurricane Sandy water levels. These are raw model results, and the model is not gridded over land. As a result, no overland flooding is shown.

Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report Chapter 5: Mapping Climate Risk

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Contents

5.1 Introduction

The mapping work of the NPCC is focused on illustrating spatial climate risk information to inform policy makers, stakeholders, and the public of the distribution of climate risk across the landscape of New York City. Flood risk, overall, has been the primary focus of climate risk, based on a variety of approaches including global climate models, semiempirical studies, literature surveys, expert-opinion, and historic tide gauge and more recently, satellite observations of sea level rise. Maps of potential future flood extents are used to visualize coastal flooding extents at the neighborhood scale and to assess the progression of citywide flood risk throughout the 21st century. The NPCC maps were developed as a tool to illustrate our present understanding of the potential futures for which we need to prepare.

This chapter reviews the background, methodology, and limitations of the NPCC3 (and NPCC2) mapping approach and features new citywide maps of mean sea level rise, monthly tidal flooding, and 100-year return period flooding under a high-end scenario of sea level rise. It concludes with a discussion of future mapping efforts and next steps that the NPCC could consider.

NPCC mapping history

The 2010 and 2015 NPCC reports featured citywide maps of current and projected future risk to extreme coastal flood events, specifically the 100-year flood.[a] These maps were displayed as standalone products and presented in the context of New York City jurisdictional boundaries, management areas, and critical infrastructure in order to highlight the need for interagency and interjurisdictional coordination in the development of adaptation strategies.

The NPCC chose to focus on the 100-year flood instead of sea level rise inundation or hurricane storm surge scenarios for two primary reasons: (1) the 100-year flood is used as the current critical benchmark for major land use, flood insurance, and policy decisions and therefore meaningful for decision makers and (2) as a theoretical value, the 100-year flood can be used to approximate potential flooding events, irrespective of the storm event with which they are associated.

The 2010 report featured 100-year flood maps based on two sets of sea level rise projections: 90th percentile model-based projections of sea level rise and semiempirical high-end "Rapid Ice Melt" projections of sea level rise, based on the average rate of sea level rise over the approximately 10,000-year period following the end of the last Ice Age. This scenario was intended to provide a rough simulation of what might occur with future accelerated rates of ice melt from the Greenland and West Antarctic ice sheets.

However, the record surge brought by Hurricane Sandy emphasized the need in follow-up research

[a]A map of the 100-year flood, also referred to as the 1-in-100 year flood or the 1% annual chance flood, identifies all locations that have a 1% chance of flooding in any given year. It is a statistical construct representing many possible flood events, not one particular event (Galloway *et al.*, 2006).

doi: 10.1111/nyas.14015

to look beyond the 100-year flood to assess more upper end future flood possibilities. Though flood insurance is not required for structures located in the 500-year floodplain, knowledge of the potential extent of this floodplain in the future can serve to guide long-term efforts for planning and resiliency and allow for protection of critical infrastructure and essential facilities. For this reason, in the subsequent 2015 report, the NPCC2 chose to feature maps of both the current and potential future 100- and 500-year floodplains based on the 90th percentile model-based sea level rise projections.

NPCC3 mapping

In line with previous reports, the NPCC3 has created a map of the current and future 100-year flood based on 90th percentile model-based projections of sea level rise. However, this work also includes two new floodplains developed from high-impact, low-probability Antarctic Rapid Ice Melt (ARIM) sea level rise projections (see Chapter 3, for a discussion of the new ARIM scenario).

In addition, the NPCC3 has expanded its scope of mapping work beyond the 100-year and 500-year flood events to consider other types of coastal flood risk. Maps showing the expansion of land exposed to monthly tidal flooding and mean sea level rise over time were developed to illustrate areas increasingly impacted by frequent flooding, as well as areas that could become permanently submerged due to future sea level rise. Monthly tidal flood mapping is useful for planning, in that it is a useful threshold indicator of repeated flooding that is sufficient to trigger large-scale adaptation investments.

Mean sea level rise mapping also depicts land that could potentially be submerged in the future under a given sea level rise scenario. Submerged refers to areas of the coastline that are underwater at all times, and not just subject to flooding during high tides and coastal storm events.

Two new data products have yielded significant advancements in the NPCC3 mapping methodology and results: a new LiDAR data set for New York City and a hydro-enforced digital elevation model (DEM) used to depict baseline topography. The new LiDAR data set, collected in 2017, is an update from the 2010 data set and captures recent areas of enhanced coastal protection. The hydro-enforced DEM is an improvement upon the bare-earth DEM used in previous reports in that it removes artificial obstructions to water flow by accounting for culverts and other devices that allow water to flow beneath structures. A bare-earth DEM is unable to capture these structures resulting in artificial floodplain boundaries. These two data products have improved the accuracy of the mapping methodology, resulting in more conservative floodplain extents.

Each of the NPCC flood maps are meant to illustrate three distinct areas of interest worthy of further study: (1) areas currently subject to flooding that will continue to be subject to flooding in the future; (2) areas that are not currently subject to flooding but are expected to potentially experience flooding in the future; and (3) areas that do not currently flood and are unlikely to do so within the timeframe of the climate projection scenarios (end of the current century). In this way, the NPCC has established a framework by which to evaluate future flood scenarios.

All spatial data involve uncertainty and error. As a result, NPCC flood maps should be considered only as a representation of current and potential future conditions and never understood to be actual reality or predicted reality.[b]

Background

Many studies have produced maps of coastlines at risk of future sea level rise scenarios. Their purpose was to illustrate the impacts of accelerated sea level rise on coastal lands and to estimate the spatial extent of areas at risk of inundation. In many of these efforts, projections of sea level rise were added to topographic contours, orthometric datums, or tidal datums to map land that could be inundated or eroded by rising seas, and to delineate potential future coastlines within the continental United States.

However, many of these studies were limited in that they only evaluated sea level rise inundation and did not account for specific flood events; they did not connect their analyses with designated flood hazard metrics, nor did they evaluate populations or infrastructure at risk (Titus and Richman, 2001; Mazria and Kershner, 2007; Poulter and

[b]NPCC maps, unless otherwise noted, do not take into account future coastal protection measures or other changes in shoreline elevations that may reduce the extent of future flooding.

Halpin, 2007; Gesch, 2009; Li *et al.*, 2009; Cooper *et al.*, 2005; Gornitz *et al.*, 2002). Although high-resolution LiDAR (light detection and ranging) elevation data were used in a few studies (Larsen *et al.*, 2004; Poulter and Halpin, 2007; Titus and Wang, 2008; Gesch, 2009), the majority of elevation data sets used in these studies were of coarse resolution providing limited accuracy.

Projections of sea level rise have been added to specific flood events using the SLOSH (Sea, Lake and Overland Surges from Hurricanes) model, which estimates storm surge heights from hurricanes, to assess vulnerability within future sea level rise enhanced storm surge zones. See Wu *et al.* (2002); Kleinosky *et al.* (2006); Rygel *et al.* (2006) for examples of SLOSH application in other locations contexts.

These studies could be particularly useful in areas of the New York City coastline where higher topography or protective infrastructure limits sea level effects to increased height and extent of storm surge events. This is especially relevant in those waterfront areas of the city where high bulkheads have been built and as a result local flooding will initially be associated with storm surge as opposed to gradual sea level rise and increase of tidal water reach.

In addition to mapping future sea level rise scenarios, a few studies have evaluated sea level rise enhanced storm surge zones under future scenarios of population growth to assess potential emerging areas of community vulnerability (Wu *et al.*, 2002; Kleinosky *et al.*, 2006).

Data and imagery about sea level rise and coastal flood events have become increasingly accessible via online web mapping tools. Sea level rise mappers and viewers such as NOAA Digital Coast's Sea Level Rise Viewer and Coastal Flood Exposure Mapper (https://coast.noaa.gov/digitalcoast/tools/slr; and https://coast.noaa.gov/digitalcoast/tools/flood-exposure.html), Climate Central's Surging Seas Risk Zone Map (https://ss2.climatecentral.org), and NYC's Flood Hazard Mapper (https://www.nyc.gov/floodhazardmapper) visualize community-level impacts from coastal flooding or sea level rise and allow for the assessment of flood risk.

These tools enable the user to select various scenarios of sea level rise or coastal flood elevation at multiple scales, even down to the street level. Though the NPCC does not plan to develop a web mapping tool itself, the shapefiles developed for each of the floodplains have been and will continue to be made available to the public through NYC's Open Data portal.

Methodology and limitations

This section reviews the flood mapping methodology and limitations and describes the intended use of the maps.

Data sets used for mapping. The following data sets were used to develop the NPCC3 flood maps:

1. High-estimate (90th percentile) value projections of sea level rise elevations for the 2020s, 2050s, 2080s, and 2100 developed by NPCC2.
   - 2020s, 10 inches; 2050s, 30 inches; 2080s, 58 inches; 2100, 75 inches
   - Completed: December 2013
2. High-impact, low-probability ARIM projections of sea level rise elevations for the 2080s and 2100 developed by NPCC3.
   - 2080s, 81 inches; 2100, 114 inches
   - Completed: February 2018
3. Mean monthly high water (MMHW) tidal elevations based on the six projections of 90th-percentile and low-probability ARIM sea level rise.
   - Modeled using the New York Harbor Observation and Prediction System (NYHOPS)
   - Vertical datum: NAVD88
   - Completed: October 2018
4. Preliminary 2015 FIRMs derived from the FEMA 2013 Preliminary Flood Insurance Study for the City of New York, NY.
   - FEMA's best available flood maps for New York City
   - Flood extent and base flood elevation (BFE) information (relative to the North American Vertical Datum of 1988 (NAVD88)) for the 100-year floodplain
   - Release date: December 5, 2013
5. Hydro-enforced DEM for New York City
   - Surface developed from LiDAR data collected in May 2017 over New York City
   - Nominal pulse spacing of LiDAR: 0.35 m
   - Density: average 8 pulses/m^2
   - Non-vegetated vertical accuracy: 2.9 inches (7.4 cm)
   - Horizontal datum: North American 1983 (NAD83, 2011)

- Vertical datum: NAVD88 (GEOID012B)
- Release date: October 2018

The hydro-enforced DEM used in the NPCC3 flood map process was developed from LiDAR data collected in the spring of 2017 by Quantum Spatial, Inc. The non-vegetated vertical accuracy of the DEM was reported as 2.9 inches (7.4 cm) with 95% confidence (Quantum Spatial, 2017), a significant improvement over the 2010 DEM vertical accuracy of 3.7 inches (9.5 cm). The 90th percentile sea level rise projections of 10 inches (25.4 cm) for the 2020s, 30 inches (76.2 cm) for the 2050s, 58 inches (145.3 cm) for the 2080s, and 75 inches (190.5 cm) for 2100, and the ARIM projections of 81 inches (205.7 cm) for the 2080s and 114 inches (289.6 cm) for 2100 all exceed the 95% error bounds of the elevation data. Thus, the vertical accuracy of the underlying elevation data is sufficient to support the mapped sea level rise increments.

Methods. All NPCC3 map products were developed using spatial processing techniques in ESRI's ArcGIS software. The hydro-enforced DEM data set for New York City provided foundational topographic data upon which to model future floodplain extent. All floodplains were created using a static "bathtub" coastal flood-modeling technique that assumes floodwaters will continue to move landward until they reach an equivalent topographic elevation (see NPCC2; Rosenzweig and Solecki, 2015). Baseline flood elevation data sets were specific to the map being created.

The map of the potential progression of mean sea level over time did not reference a baseline flood elevation data set but instead directly referenced the hydro-enforced DEM to delineate flood extent. In the DEM, all cells at or below a given mean sea level elevation were flagged as flooded, capturing low elevation areas both along the coast and in the interior of the city. The interior areas of low elevation not connected to the ocean were removed and the low elevation coastal areas were retained to represent the mean sea level floodplain.

The future monthly tidal flood map was developed using a baseline data set of modeled tidal water elevations combined with projections of future mean sea level. Tides were modeled along the New York City coastline using the Stevens Institute of Technology Estuarine and Coastal Ocean Model on the NYHOPS model domain (Georgas and Blumberg, 2010; Orton *et al.*, 2016). Static flood mapping was used to extrapolate the tidal flood elevations from the coastline to the interior to approximate flood extent (Patrick *et al.*, 2015).

Future 100-year floodplains were developed using a baseline data set of FEMA's 2015 Preliminary FIRM BFE values combined with projections of sea level rise. The combined values were extrapolated from the coastline landward until reaching a topographic contour of equivalent elevation.

One distinguishing aspect of the NPCC 100-year flood maps as compared to some storm surge and sea level rise maps is the integration of base flood elevation data into their future flood projections. Many sea level rise and storm surge mapping methodologies use one spatially constant flood elevation as their baseline and simply add elevation to represent inundation.

For example, Cooper *et al.* (2005) considered the 100-year flood in their analysis of the impacts of sea level rise on New Jersey. They used FEMA's 100-year base flood elevation for Atlantic City (9.5 ft), added projections of sea level rise elevation, and applied that new value to the entire New Jersey coastline by mapping the corresponding topographic contour. However, the complex coastal configuration around New York City causes large spatial variations in tides and storm surge (Orton *et al.*, 2012), resulting in large changes in BFE values over small horizontal alongshore distances.

Change in flood elevation values should also be incorporated, such that the inland shape and extent of the flood zone reflects the changing base flood elevation values nearer to shore. The NPCC approach incorporates these lateral variations in flood elevation values by assuming that landward values of floodwater elevation are likely to be more similar to neighboring flood-elevation values and less similar to more distant values. This unique approach to flood modeling is creative but also simplistic in that it makes broad assumptions about the movement of floodwaters.

The across-shore variation in flood elevation is a complex process best quantified via a combination of high-resolution but computationally intensive hydrodynamic and wave modeling. This modeling accounts for the effects of soils, vegetation, surface permeability, topography, existing structural and nonstructural flood protections, friction, and other factors that affect the movement of floodwaters and result in local variations in flooding extent.

When the use of hydrodynamic and wave transformation modeling is not available to develop future flood projections, many assumptions, sometimes *ad hoc*, have to be made in the GIS-based NPCC methodology concerning storm surge movement and wave action, and connectivity to the open ocean. In addition, numerous sources of error and uncertainties exist in data sets that are foundational to the future flood maps. For example, the NPCC sea level rise projections, the modeled BFE values developed by FEMA, and the underlying topographic data set each have their own margin of error that is difficult to quantify and present visually on the NPCC flood maps.

The flood maps of future conditions developed by the NPCC are useful for presenting such data. A great advantage of these maps is that they are not specific to a given storm and instead present surge scenarios that could occur in tropical storm, hurricane, or nor'easter conditions, thereby broadening their applicability (see Chapter 4, Coastal Flooding). Maps that approximate future flood zone extents are critical to decision and policy makers as well as the public to prepare for floods of increased elevation, extent, and duration. Also, local and regional stakeholders and policy makers consider these NPCC maps in the development of their climate change adaptation plans and strategies. Thus, NPCC maps can complement and add value to ongoing citywide resiliency efforts.

5.2 Mean sea level

Mean sea level (specifically local MSL) is a term that describes the average elevation of the surface of the ocean, relatively to land elevations. We know that mean sea level is rising globally but at rates that vary regionally. In New York City, the historic rate of sea level rise has averaged 0.12 inches per year, a rise imperceptible to the naked eye but documented through measurements at local tide gauges (see Chapter 3, Sea Level Rise).

Unlike abrupt flooding events brought about by tides or storm surge, the rise of mean sea level is a gradual encroachment of the ocean upon shorelines. With the exception of areas of storm-induced coastal erosion, many neighborhoods in New York City that experience coastal flood events become high and dry again once waters recede. For this reason, the idea of permanent submersion remains an abstraction. Therefore, it is important to map the potential progression of mean sea level throughout the 21st century in order to emphasize the potential for current coastlines to become submerged in the future.

The significance of mean sea level in the context of sea level rise is that it marks the final stage of a sequence of progressively frequent and intense flooding as lands transition from lying above to lying below mean sea level. In this sequence, as sea levels rise, lands that were once beyond the reach of coastal flooding become vulnerable to extreme and infrequent coastal flood events such as the 1000-year and 500-year storm. As sea levels continue to rise, these same lands grow increasingly vulnerable to flooding during less extreme events, such as the 100-year storm flood, then monthly high tide[c] flooding, and eventually daily high tides. If sea level continues to rise, these lands fall below mean sea level, at which point they are wetted by tides more often than they are dry.

The map presented in Fig. 5.1 depicts the coastal areas potentially subject to submersion under 90th percentile model-based scenarios of sea level rise over time and upper-end, low-probability ARIM scenario sea level rise toward the end of the 21st century.

According to the 90th percentile model-based projections of sea level rise shown in Figure 5.1, areas more likely to experience submersion later in this century include low-lying wetlands, such as the marshes and Broad Channel neighborhood of Jamaica Bay; Saw Mill Creek, and Old Place Creek parks in western Staten Island; and Flushing Meadows Park in Queens. Areas bordering waterways such as the Gowanus Canal in Brooklyn, Newton Creek in Brooklyn and Queens, and Pelham Bay in the Bronx may also become submerged.

Also of note are areas of the Coney Island Peninsula protected from the Atlantic yet flooded from the north through Sheepshead Bay and the Coney Island Creek. Bayside neighborhoods of the Rockaway Peninsula such as Somerville and Edgemere

[c] King tides, or the Proxigean Spring Tide, refer to the very highest naturally occurring tides.

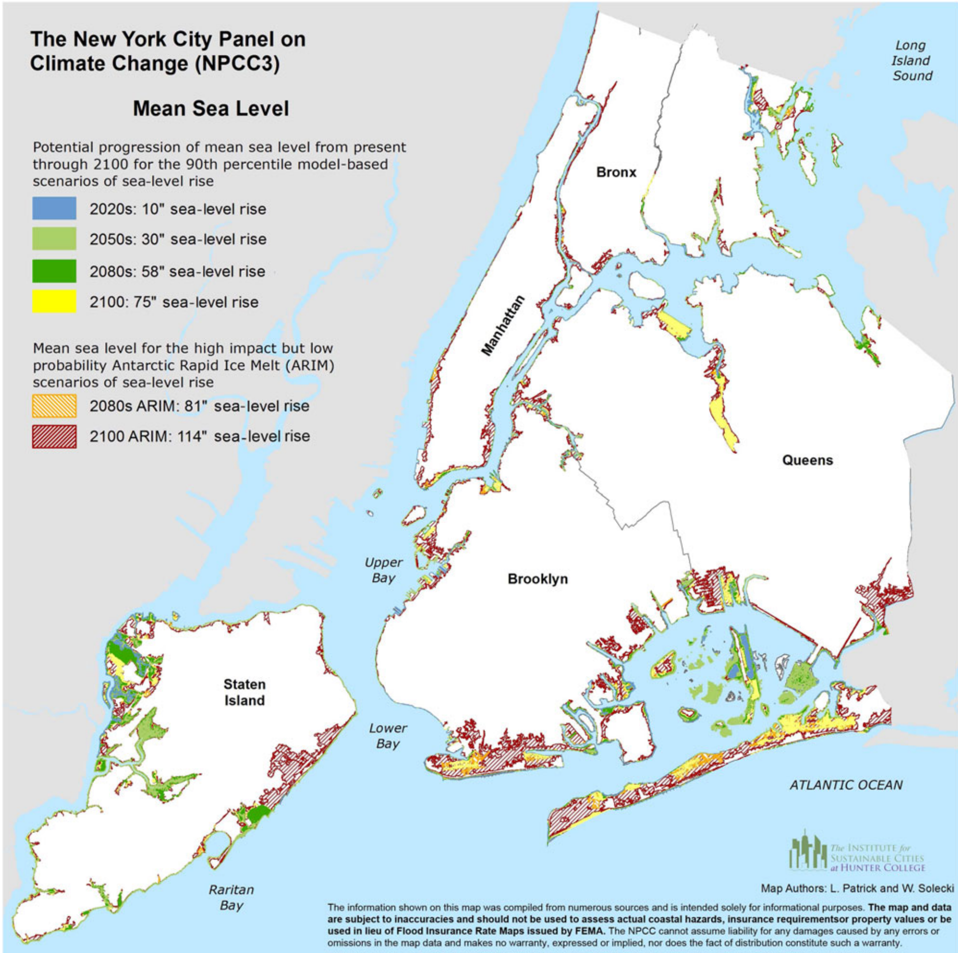

Figure 5.1. Potential progression of mean sea level from present through 2100 for 90th percentile model-based scenario and the ARIM scenario of sea level rise. NOTE: The 90th percentile sea level rise projections from NPCC (2015) remain the scientific basis for New York City resiliency planning programs. Furthermore, the areas delineated on this map do not represent precise flood boundaries, but rather illustrate distinct areas of interest: (1) Areas that are not currently below mean sea level but may become submerged in the future; and (2) Areas that are not currently below mean sea level and are unlikely to become submerged in the timeline of the climate projection scenarios (end of the current century).

may also become submerged along with parts of the Navy Yard and Red Hook in Brooklyn and LaGuardia Airport in Queens.

The low-probability, high-impact ARIM scenario shows further encroachment of sea level late in the 21st century into most of the Rockaway Peninsula and Coney Island up through Gravesend, the eastern coast of Staten Island, and the Howard Beach and Rosedale neighborhoods in Queens, among other areas. Although the ARIM scenario is an upper-end estimate of sea level rise, it is important to acknowledge the potential for an expanded mean sea level floodplain within the next 100 years.

5.3 Monthly tidal flooding

In contrast to the often-indiscernible long-term change of mean sea level, tides can be perceived and experienced daily along most coastlines. The term "tides" refers to the rise and fall of sea levels due to the combined effects of the gravitational forces exerted by the moon, sun, and Earth. In New York City, semi-diurnal tides produce two high waters and two low waters each day, with an average tidal range[d] of 5.06 ft (1.54 m). Spring tides exceed the

[d]The average tidal range refers to the difference in height between high and low waters.

average tidal range producing very high and very low tides during the full and new moons. Often the highest tide on one of the two spring tides is substantially higher than the other, controlled by the distance between Earth and the Moon that varies through the Moon's orbit. The significance of tidal flooding in the context of sea level rise is that the frequency of tidal flooding on streets is a metric of interruption of commerce and the necessity of adaptation.

NPCC3 uses dynamic model simulations with sea level projections to quantify the future evolution of tides (see Chapter 4, Coastal Flooding), though we use static mapping to map these water levels onto topography. Tides are far more predictable than storm surges because they are caused by the gravitational pull of the moon and the sun, and thus modeling their potential flooding requires a much smaller number of simulations and computational resources. Presently, monthly tidal flooding threatens the lowest properties in a few city neighborhoods (e.g., Howard Beach in Jamaica Bay). The NPCC has not previously evaluated how sea level rise will affect this tidally driven "sunny-day" nuisance flooding.

Mean monthly high water (MMHW) is a new metric defined as the average of all monthly maxima in predicted astronomical tide levels. Here, three-dimensional dynamic simulations of tides are performed using the Stevens Institute of Technology Estuarine and Coastal Ocean Model using the New York Harbor Observing and Prediction System (NYHOPS) operational model setup and grid (Georgas and Blumberg, 2010; Orton *et al.*, 2016).

Simulations cover a 35-day period beginning August 1, 2015, under tide and streamflow forcing (no wind). Modeled water-level time series at all model grid cells are subjected to tidal harmonic analysis (Pawlowicz *et al.*, 2002) to create 19-year tide time series that capture all the periodicities therein, and monthly maxima are computed and averaged (see Section 4.3.2 for a full discussion of tidal modeling).

The modeled MMHW data are mapped to illustrate potential future monthly sunny-day tidal flooding. MMHW is typically exceeded by observed water levels about 25–35 times per year in New York City, based on examination of observed water levels at The Battery, Kings Point, and Jamaica Bay (Inwood).[e]

Alternatively, the mean higher high water tidal (MHHW) datum is commonly used with static flood mapping to evaluate future flooding due to sea level rise (e.g., Climate Central, 2018; NYC-DCP, 2018). However, MHHW represents flooding that occurs far more frequently—hundreds of times per year—and is therefore less meaningful as a threshold indicator of livability (for more discussion, see Chapter 4, Coastal Flooding).

Figure 5.2 presents the map of monthly tidal flooding for New York City, based on projections of 90th-percentile and ARIM sea level rise. Under the 90th percentile sea level rise scenario, monthly tidal flooding by the 2050s will become moderately widespread, and by 2100 very widespread across many waterfront and coastal neighborhoods. In the more extreme ARIM scenario, at 2100 the flooding is extremely widespread.

One important consequence of an upper-end sea level rise scenario such as ARIM is a rapid advancement from sunny-day tidal flooding to complete loss of land to the ocean. Although New York City is not at immediate risk of extensive land inundation, some neighborhoods may face permanent land loss in 2100 under the ARIM scenario.

For example, a comparison of Figure 5.1 with Figure 5.2 suggests that some of the areas that could undergo monthly tidal flooding by the 2050s under the 90th percentile sea level rise projection (NPCC, 2015), shown in light green, respectively, might face permanent inundation by the 2080s if the latter half of the century begins to follow the ARIM sea level rise scenario, in the absence of additional coastal protection measures. Areas colored yellow (2100 90th percentile) often obscure those with orange hatching (2080s ARIM), as these two sea level scenarios are nearly equal (75 versus 81 inches).

Areas that would be permanently inundated in the 2080s of the ARIM scenario include portions of Rockaway Peninsula, Howard Beach, Coney Island, Red Hook, and Staten Island, as well as edges of lower Manhattan waterfront, the Gowanus Canal

[e] Sweet and Park (2014) associated approximately 30 floods per year as a tipping point for property abandonment.

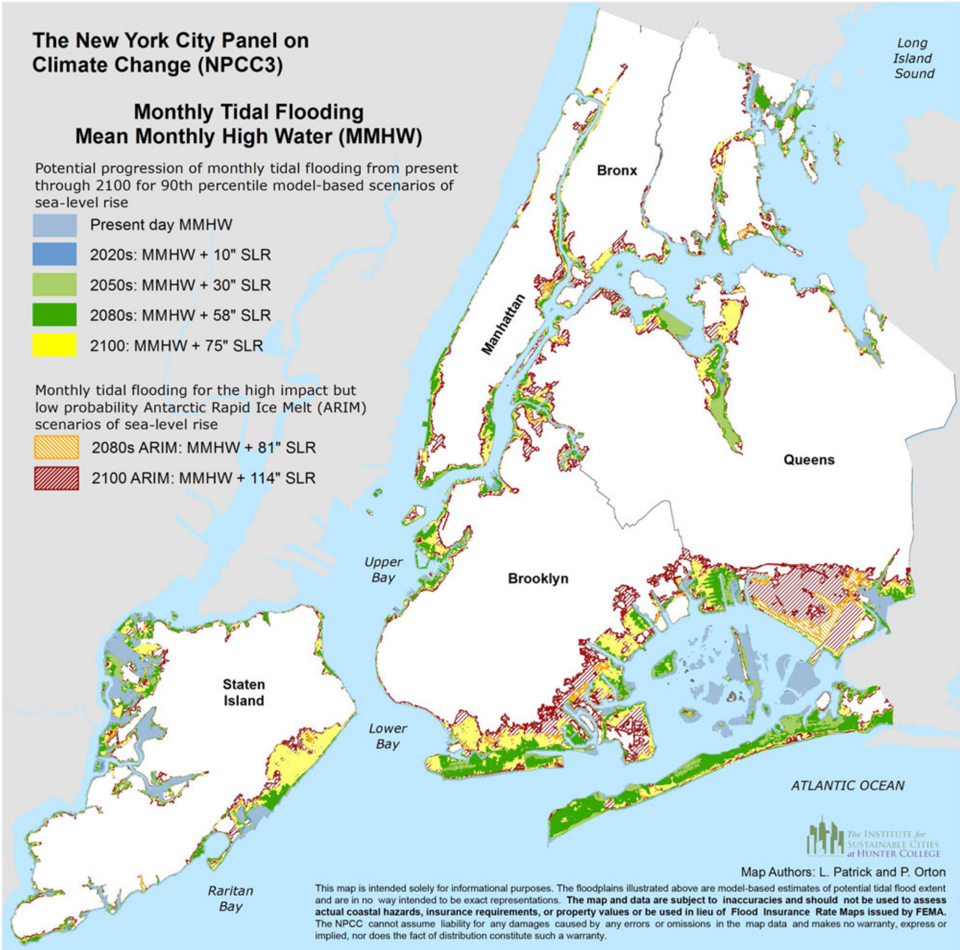

Figure 5.2. Potential progression of MMHW flooding from present through 2100 for 90th percentile model-based scenarios and the ARIM scenarios of sea level rise. Note: The areas delineated on this map do not represent precise flood boundaries but rather illustrate distinct areas of interest: (1) Areas currently subject to flooding that will continue to be subject to flooding in the future; (2) Areas that do not currently flood but are expected to potentially experience flooding in the future; and (3) Areas that do not currently flood and are unlikely to do so in the timeline of the climate projection scenarios (end of the current century).

in Brooklyn and Newtown Creek in Brooklyn and Queens, and Pelham Bay in the Bronx. Because Figure 5.1 is based on data with high associated uncertainties, it should be regarded as suggestive of areas that might become inundated and should therefore not be used for planning purposes. See the further discussion in Chapter 3, Sea Level Rise.

5.4 One hundred-year flood

While tidal flooding is frequently experienced in coastal communities, the 100-year flood is a higher-impact but lower-frequency event. The 100-year flood is based on statistical analysis of historical data and encompasses all locations that have a 1% or higher chance of being flooded in any given year. It can be a misleading term, in that neighborhoods situated within the current 100-year floodplain could be flooded 2 years in a row, or not flooded at all in 150 years. Regardless, the 100-year flood zone is an important benchmark in that it is considered a high-risk flooding area and subject to special building codes, insurance requirements, and environmental regulations.

The significance of the 100-year flood in the context of sea level rise is threefold: (1) neighborhoods not previously vulnerable to the 100-year flood will grow increasingly vulnerable as sea level rises, (2) neighborhoods currently within today's 100-year floodplain will experience higher 100-year flood elevations during future floods, and (3) neighborhoods currently within today's 100-year floodplain will experience such flooding much more frequently (in other words, the return period of the 100-year flood will become shorter).

Significant attention in NPCC3 mapping has been given to improved presentation and understanding of future flood events and how sea level rise projections may alter the spatial extent of the FEMA 100-year floodplain. A key question not considered in previous NPCC reports is what are the flood extents for the 2080s and 2100 under the ARIM scenario of sea level rise (see Chapter 3, Sea Level Rise, for discussion of the ARIM projections). The map presented in Figure 5.3 illustrates the potential landward progression of the 100-year floodplain from its current extent though the year 2100 for both 90th percentile and upper-end ARIM scenarios of sea level rise. The maps show a growing area of the city susceptible to future possible extreme events.

It is important to understand that these maps reflect the current coastline of New York City and do not account for planned or potential future coastal protection features. Site-specific projects to restore wetlands and fortify shorelines are in progress and under development, and these natured-based and hard-engineering approaches may serve to reduce the extent and elevation of the 100-year flood (see Chapter 9, Perspectives).

5.5 Moving forward

The NPCC has been mapping climate risk information for 10 years. Future NPCC mapping includes several next steps.

Incorporating confidence intervals into modeled results

Several data and process limitations are embedded in sea level rise maps. Inherent uncertainty is present in the flood extent shapefiles used to delineate future flood events. NPCC flood shapefiles contain numerous sources of potential error as a result of the data sets and methodologies used in their development: errors in the topographic elevation data, sea level rise projections, and FEMA model outputs all contribute to this uncertainty and limit the accuracy of the shapefiles. The population, facilities, and infrastructure within the future flood zones are defined as "flooded" by the shapefile extents.

Though not quantified, the uncertainty of future flood areas is lower near the coastline and greater near the inland boundaries of the flood extents. It is possible that small changes to the flood-extent boundary could result in large changes to the populations defined as "flooded." For this reason, future work should consider using flood data that incorporate confidence intervals in the analysis. Visualizing this uncertainty is a challenge to be addressed.

Mapping synergistic flood properties

Although current mapping only considers the impacts of storm surge flooding events, future work might consider how the cumulative effect of storm surges combined with intense rainfall flooding might impact the movement, timing, and drainage of floodwaters. Though coastal flooding dominates in NYC, fluvial and urban street flooding occurs during intense rainfall events resulting in overflows in residential and municipal drainage systems. Coastal flooding may reach greater extents and take longer to recede with storm drains already overfull. For these reasons, a storm event that brings both heavy precipitation and high surge is potentially worthy of inclusion in risk mapping.

Climate risk indicator mapping

The NPCC has proposed a robust climate risk indicator and monitoring system (see Chapter 8). Mapping of these indicators will be an essential component of an effective monitoring system. Indicator mapping should address climate risks, impacts, vulnerabilities, and adaptation effectiveness. Several issues need to be considered when developing climate risk indicator maps. These include the spatial extent of the data (e.g., does the data set cover NYC, and could it be expanded beyond the borders of the five boroughs) and the longitudinal extent of the data set (e.g., has it been collected in the past, and can it be easily and consistently collected in the future). Other considerations include whether the data are cost effective to collect; whether collection can be sustained (e.g., collection is not likely to suffer budget cuts); whether the data illustrate the concept/concern in question (e.g., the data define a specific climate metric today, and this climate metric will continue to be relevant in the future); and whether the data can be mapped

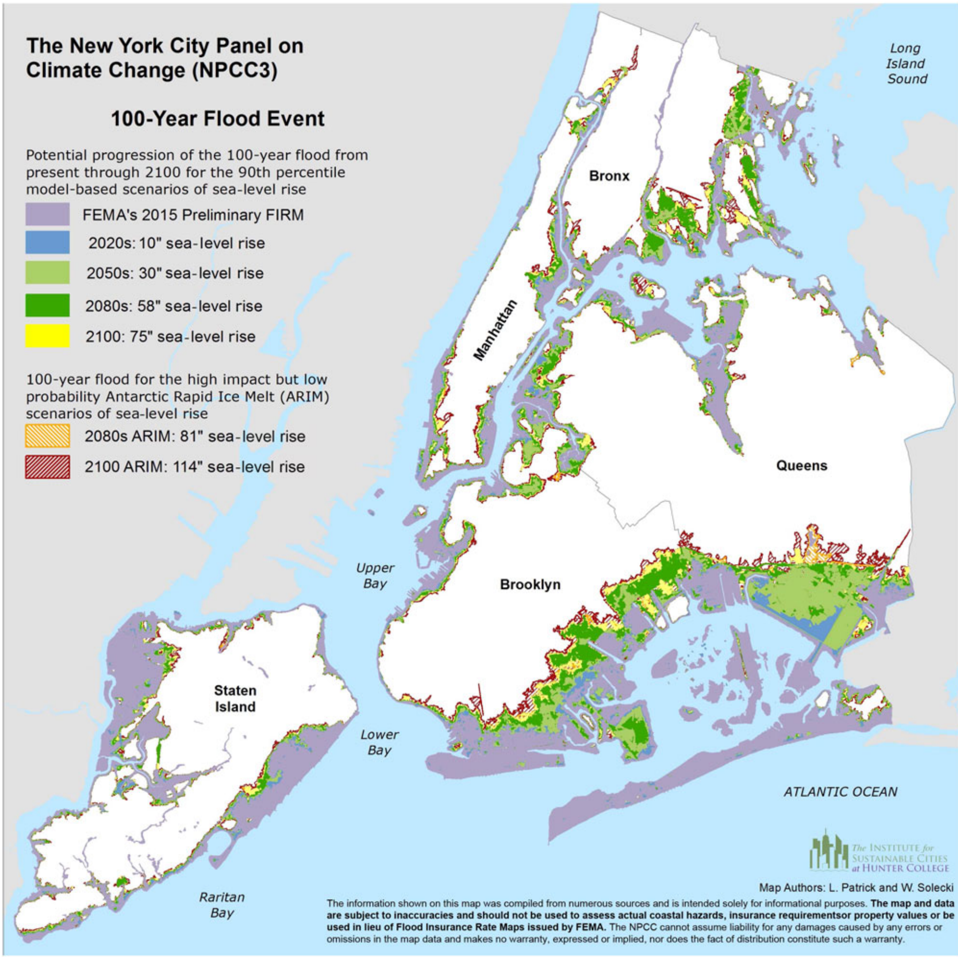

Figure 5.3. **Potential progression of the 100-year floodplain from present through 2100 for the 90th percentile model-based scenarios and the ARIM scenarios of sea level rise. Note: The areas delineated on this map do not represent precise flood boundaries but rather illustrate distinct areas of interest: (1) Areas currently subject to flooding that will continue to be subject to flooding in the future; (2) Areas that do not currently flood but are expected to potentially experience flooding in the future; and (3) Areas that do not currently flood and are unlikely to do so in the timeline of the climate projection scenarios (end of the current century).**

without methodological issues (e.g., data will not be distorted due to map projection; levels of uncertainty and error can be communicated).

Acknowledgments

We thank the City of New York for providing new LIDAR data for the maps in this chapter.

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Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report Chapter 6: Community-Based Assessments of Adaptation and Equity

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Contents

6.1. Introduction

There is a widespread awareness that the uneven distribution of climate change impacts combined with preexisting social and economic challenges makes some communities more vulnerable than others (Reckien *et al.*, 2018; IPCC, 2014; Leichenko *et al.*, 2011). There is also growing recognition of the need for inclusion of community perspectives, viewpoints, and exigencies into adaptation decision making and planning (Chu *et al.*, 2016).

The concept of equity relates to climate change adaptation through inequalities in climate change impacts and vulnerabilities, as well as through uneven involvement in adaptation planning. It recognizes that disparities in health outcomes, inequities in living conditions, and lack of political power place low-income communities and many communities of color at greater risk and limit their capacity to adapt. The NPCC3 Workgroup on Community-Based Assessment of Adaptation and Equity (CBA Workgroup) explored how equity concerns can be incorporated into climate change vulnerability assessments and community adaptation planning in New York City.

The CBA Workgroup's explicit focus on equity in vulnerability and adaptation is a new contribution to the NPCC. While prior New York State research by Leichenko *et al.* (2011) identified a need for consideration of equity and environmental justice in the analysis of state-wide climate impacts, vulnerabilities, and adaptation, the formation of the CBA Workgroup within the NPCC3 reflects the city's recognition of and strong commitment to these issues.

The CBA Workgroup tasks included assessing social vulnerability patterns and identifying indicators to track social vulnerability at the neighborhood level (see Chapter 8, Indicators and Monitoring), conducting case studies of community adaptation in socially vulnerable neighborhoods, and identifying effective practices for incorporating equity into adaptation planning at the city level. These tasks were accomplished through:

1. **Investigation of spatial patterns of social vulnerability to climate change stressors in New York City.** This entailed compilation, review, and assessment of recent vulnerability mapping studies conducted in New York City and elsewhere in the United States. The aim of this review was to identify spatial patterns of vulnerability to climate change stresses across neighborhoods and communities and to provide guidance on methods and indicators that

doi: 10.1111/nyas.14009

can be used to monitor and track neighborhood vulnerability over time.[a]

2. **Case studies in socially and economically disadvantaged communities**. Case studies of climate change vulnerability and adaptation were undertaken in collaboration with three community-based organizations (CBOs)—WE ACT for Environmental Justice in Harlem, THE POINT CDC in Hunts Point, and UPROSE in Sunset Park. These CBOs are situated predominantly in neighborhoods whose residents are often low-income or people of color who have been excluded from opportunity and resources. All of these CBOs have mobilized to develop climate adaptation plans for their communities.
3. **Examination of community-based adaptation planning efforts.** For each case study community, we collaborated with CBOs and New York City planners to explore how community group perspectives and input are incorporated into the development and implementation of community-based adaptation plans.
4. **Analysis of current practices for incorporating equity**. This task was achieved via comparative investigation of how New York City and other cities in the northeastern United States incorporate principles of equity into community adaptation planning.

Relying on long-established conventions and practices within the field of environmental justice and emerging practices for community-based vulnerability analysis, the CBA Workgroup adopted a collaborative co-production model for assessing vulnerability and equitable adaptation (Deas *et al.*, 2017; Sarzynski 2015; Lemos and Morehouse, 2005; Cole and Foster 2001). This approach involved meeting at the outset with CBOs from the targeted study neighborhoods and including them as full participating members and contributors to the CBA Workgroup. Given that the broad mandate of the CBA Workgroup was to examine ways in which equity is incorporated into climate adaptation planning, partnering with local communities helped ensure that the work process and product adhere to the principles of environmental justice.

[a]Except where noted, our examination of social vulnerability to climate change stressors is intended to reflect vulnerability to all six types of stressors identified in NPCC 2019 Chapters 2, 3, and 4, including those associated with (1) extreme heat and humidity; (2) heavy downpours; (3) drought; (4) sea level rise and coastal flooding; (5) extreme winds; and (6) cold snaps.

6.2. Framing equity in the climate change context

Research on climate change has drawn attention to numerous inequalities associated with mitigation, vulnerability, and adaptation. These include the uneven distribution of greenhouse gas emissions and mitigation responsibility; differential vulnerability to climate stressors across regions, communities, and social groups; and intergenerational equity in terms of who should bear the cost of impacts and mitigation efforts (Parks and Roberts, 2010; Paalova and Adger, 2006; Kasperson and Dow, 1991). The equity dimensions of adaptation also highlight differences in capacity to respond to climate stresses and recover from climate shocks, and the possibility of uneven benefits and burdens linked to adaptation efforts (Klein *et al.*, 2014; Smit and Wandel, 2006).

At the urban scale, the research points to the disproportionate risks from climate change impacts in low-income communities, the existence of economic and social factors that may undermine or limit community adaptive capacity, the importance of including a diversity of community voices and perspectives in adaptation planning efforts, and the need for equitable allocation of adaptation resources (Reckien *et al.*, 2018; Deas *et al.*, 2017; Anguelovski *et al.*, 2016; Chu *et al.*, 2016; NAACP, 2015; Schlosberg and Collins, 2014; Bulkeley *et al.*, 2014; Ross and Berkes, 2014).

While there is increasing recognition of equity issues in urban adaptation planning, there remains a need for a more systematic framework for urban adaptation and equity analysis. Ideally, such a framework would serve as a template for cities that wish to incorporate fully equity considerations into adaptation planning. In proposing such a framework, this chapter draws on the climate change adaptation, mitigation, and environmental justice literatures (Reckien *et al.*, 2018; Foster, 2017; Schlosberg and Collins, 2014; McDermott *et al.*, 2013; Leichenko *et al.*, 2011; Cole and Foster, 2001). In particular, the chapter builds upon the equity framework developed by McDermott *et al.* (2013) for application to payments for ecosystem services. As suggested by McDermott *et al.* (2013), our approach incorporates three elements: distributional, contextual, and procedural equity (see Box 6.1).

Box 6.1: Three dimensions of equity in adaptation (based on McDermott *et al.*, 2013)

Distributive equity	Emphasizes disparities across social groups, neighborhoods, and communities in vulnerability, adaptive capacity, and the outcomes of adaptation actions
Contextual equity	Emphasizes social, economic, and political factors and processes that contribute to uneven vulnerability and shape adaptive capacity
Procedural equity	Emphasizes the extent and robustness of public and community participation in adaptation planning and decision making

Distributional equity emphasizes the uneven environmental burdens and benefits across groups and neighborhoods (Foster, 2017). The literature on environmental justice, for example, has brought attention to racial and ethnic disparities in the distribution of polluting facilities and other environmental hazards and the lack of environmental amenities such as green spaces in low-income and minority communities (Coburn *et al.*, 2006; Cole and Foster, 2001; Fothergill *et al.*, 1999; U.S. EPA, 1992).

Within the climate change literature, elements of distributional equity include recognition of inequalities in social vulnerability to climate change; inequalities in the capacity to adapt or influence mitigation of climate change; inequalities in benefits associated with adaptation policies; and inequalities and unintended consequences of adaptation and mitigation efforts (McDermott *et al.*, 2013; Leichenko *et al.*, 2011).

Distributional equity in both the environmental justice and climate adaptation literatures brings attention to the distribution of costs and benefits of policy initiatives on various populations. Rooted in principles of equality and social welfare, efforts to incorporate distributive equity are often needs based (McDermott *et al.*, 2013). As such, these approaches directly target the least advantaged communities and most at-risk community members in standard-setting and adaptation planning.

While the notion of *contextual equity*, as proposed by McDermott *et al.* (2013), is a relatively recent addition to climate change adaptation discussions, its essential elements are well recognized in the climate vulnerability and environmental justice literatures, both of which emphasize social "root causes" of vulnerability, including the influence of structural racism (Ribot, 2014; Cole and Foster, 2001). Social context (and history) is important to understanding existing disparities and to adequate assessment of social impacts at different stages of the planning process (i.e., preplanning, planning, action development, implementation, and evaluation/feedbacks on outcomes) (Sarzynski, 2015; O'Brien *et al.*, 2007).

Contextual equity draws attention to factors that contribute to social vulnerabilities and recognizes that differences in power and access can prevent some communities from receiving resources or from participating in the decision-making process (Fraser, 2009). Consideration of contextual equity entails recognition of the "uneven playing field" that is created for some communities as a result of pre-existing economic, social, and political inequalities (McDermott *et al.*, 2013). A contextual equity approach suggests that recognition of socioeconomic conditions and existing injustices is critical for designing community-based adaptation strategies (Schlosberg *et al.*, 2017).

Within the environmental justice and climate change literatures, *procedural equity* is typically defined as the representation and inclusion of affected individuals, communities, and groups in environmental and adaptation priority-setting and decision making. With respect to climate change impacts, this includes decisions about adaptation strategies and actions, as well as emergency preparedness and emergency response in relation to climate-related risks. Efforts to achieve procedural equity most often require explicit mechanisms to ensure participation of affected actors in policy and planning decisions (Chu *et al.*, 2016; Schlosberg, 2013; Leichenko *et al.*, 2011).

Traditional efforts to include groups historically deprived of resources in environmental and adaptation decision-making processes include public hearings and meetings, citizen advisory councils, and citizen panels (Sarzynski, 2015). However, the climate change community is also paying increased attention to the need for greater inclusion of affected groups in the climate assessment process. Co-production of adaptation entails collaboration between researchers, policy makers, and affected groups in the identification of critical risks and vulnerabilities, formulation of adaptation options, and selection and implementation of response strategies (Cornell *et al.*, 2013; Kirchhoff *et al.*, 2013; Rosenzweig *et al.*, 2011).

This type of collaborative engagement of affected communities in all phases of adaptation planning and implementation has been identified by the environmental justice community as a critical need in the New York region (NYCEJA, 2018; NYCEJA, 2016; Sandy Regional Assembly, 2013). More generally, co-production approaches are considered vital for identification of sustainable adaptation pathways (Eisenhauer, 2016) and for fostering of equitable and sustainable cities (Rosenzweig *et al.*, 2018; Iaione, 2016; Foster and Iaione, 2016).

The remainder of the chapter is structured along these three dimensions of equity. Distributional equity is captured in Section 6.3's examination of spatial vulnerability patterns and indicators, where the primary emphasis is on measurement and tracking of spatial inequalities in vulnerability and capacity to adapt to climate change stressors. Contextual equity is highlighted in Section 6.4 through three case studies of socially vulnerable communities, in which we examine how climate stressors overlap with social and economic barriers and disadvantages, as well as legacy environmental justice issues. In Section 6.5, the concept of procedural equity is employed to examine community involvement in local adaptation planning efforts in New York City. In Section 6.6, we employ all three equity dimensions in a comparative examination of adaptation efforts in five cities in the Northeast of the United States.

6.3. Spatial analysis

Vulnerability to climate change is defined as the susceptibility of a given population, system, or place to harm from exposure to climate-related shocks and stresses (IPCC, 2012). Social vulnerability analysis, which has been extensively developed in the hazard and climate change literatures, describes the relationship between social characteristics and biophysical vulnerability to climate change stressors and other environmental hazards, as well as the distribution of tangible and intangible impacts on particular subpopulations or communities (Cutter and Finch, 2008; Adger, 2006; Cutter *et al.*, 2000).

In addition to measuring vulnerability to climate stressors, social vulnerability analysis increasingly is used to measure vulnerability to toxic and hazardous facility siting and to determine environmental justice areas based on indicators that track proximity and exposure to a variety of pollution sources (Foster, 2017; Sadd *et al.*, 2011).

A similar literature identifies social and biophysical factors that contribute to community climate change and disaster resilience (Leichenko *et al.*, 2015; Cutter *et al.*, 2014). Social factors that have been found to contribute to resilience include, for example, economic vitality and diversity; quality of housing and infrastructure; institutional, governance, and civic capacities; presence of strong social networks; and availability of health insurance. Biophysical factors include the presence of natural flood buffers and pervious surfaces, availability of locally sourced food supplies, adequacy of local water supplies, and location outside of low-elevation coastal zones (Cutter *et al.*, 2014; Leichenko, 2011).

Social vulnerability analysis focuses on demographic and socioeconomic factors that increase or attenuate the effects of climate change or other hazard events on a local population. Factors that are often found in the literature include socioeconomic status (wealth or poverty); education; age; access and functional needs; gender; race and ethnicity (Cutter *et al.*, 2009) (see Appendix 6.A).

Through the creation of empirical metrics and indicators of social vulnerability, researchers capture a wide array of factors that shape the susceptibility of certain populations and communities to harm from environmental hazard events and the ability to recover following these events (Tate, 2012; Cutter *et al.*, 2003).

Consideration of distributional equity is foundational to all types of social vulnerability analysis, where the goal is to document the uneven distribution of vulnerabilities to climate shocks and stress across neighborhoods, communities, and regions. Vulnerability analysis is often explicitly designed to help identify "hot spots" for needs-based targeting of resources and policies to communities that are most at risk (de Sherbinin, 2014; Dunning and Durden, 2011).

In the following discussion, we describe methodological approaches used for social vulnerability analysis and mapping in New York City and elsewhere. We examine vulnerability mapping applications conducted by nonprofit organizations, academic institutions, and governmental agencies. We also provide recommendations for spatial vulnerability tracking at the neighborhood level.

6.3.1 Vulnerability mapping

Vulnerability mapping is a widely used approach for assessment of the spatial patterns related to climate change risks and for allocation of resources to at risk communities (de Sherbinin, 2014). Mapping of social vulnerability patterns provides a comparative, cross-sectional overview of vulnerability levels across various parts of a study area (e.g., comparing counties, census tracts, or block groups) (see Box 6.2).

The two most prevalent frameworks for social vulnerability mapping applications in the United States are the Social Vulnerability Index (SoVI), a product of the Hazards and Vulnerability Research Institute at the University of South Carolina (Cutter *et al.*, 2003), and the Social Vulnerability Index (SVI), a product of the U.S. Centers for Disease Control (CDC) (Flanagan *et al.*, 2011). SoVI and SVI are widely used by state and local government agencies to document spatial patterns of vulnerability to climate stressors for the purpose of targeting resources to those areas with the greatest needs (HVRI, 2018a; CDC SVI, 2018).

These and related approaches are intended to capture social conditions that influence vulnerability to a range of climate stressors. Importantly, these efforts emphasize general vulnerability to climate stresses, and can also be designed to capture population exposure to specific climate stresses such as heat or coastal flooding.

All the approaches to vulnerability mapping rely on selected indicators of social vulnerability. Table 6.1, based on Cutter *et al.* (2009), classifies common social vulnerability indicators into general categories used in different studies. These categories include socioeconomic status, gender, race and/or ethnicity, age, housing tenure, employment, occupation, family structure, education, population growth, access to medical services, access and functional needs populations, and social dependence.

Box 6.2: Definition of census spatial units (U.S. Census Bureau, 2018; NYC DCP, 2018b)

County or statistically equivalent entity	Primary legal divisions of most states
Census tracts	Subdivisions of a county or equivalent entity. Tracts generally have a population size between 1200 and 8000 people. The spatial extents of tracts vary widely depending on the density of settlement
Census blocks	Subdivisions which form the building block of all other geographic units tabulated by the U.S. Census such as tracts, places, and American Indian Reservations
Community district (CD)	New York City is organized into 59 CDs. Each CD is represented by a Community Board, composed of volunteer community members appointed by the Borough President, who assist neighborhood residents and advise on neighborhood and citywide planning and service issues
Public use microdata areas (PUMAs)	Statistical geographic areas defined for the dissemination of public use microdata sample (PUMS) data. PUMAs are aggregated from census tracts and have a minimum population of 100,000. They are used to approximate populations of CDs or combinations of CDs. There are 59 CDs in New York City but only 55 NYC PUMAs
Neighborhood tabulation areas (NTAs)	Aggregations of census tracts that are subsets of New York City's 55 PUMAs with a minimum population of 15,000. NTA boundaries and their associated names may not represent neighborhoods

While generalized social vulnerability maps such as SoVI and SVI are not intended to document physical exposure to specific climate change stressors,

Table 6.1. Indicators of vulnerability (based on Cutter *et al.*, 2009)

Concept or characteristic	Proxy variable	Effect on social vulnerability
Socioeconomic status	% poverty	Increases
	Per capita income	High-decreases; low-increases
Gender	% female-headed households	Increases
Race and/or ethnicity	% African Americans	Increases
	% Hispanics	Increases
Age	% elderly	Increases
	% under 18	Increases
Housing tenure (ownership)	% renters	Increases
	% homeowners	Decreases
Employment	% unemployed	Increases
Occupation	% agricultural workers	Increases
	% low-skilled service jobs	Increases
Family structure	% single-parent households	Increases
	Large family	Increases
Education	% less than high school	Increases
Population growth	Rapid growth	Increases
Access to medical services	Higher density of medical establishments and services	Decreases
Access and functional needs populations	Homeless, tourists, transients, nursing home residents	Increases
Social dependence	% social security recipients	Increases

many studies combine social vulnerability maps with other maps displaying exposure to specific climate stressors such as coastal flooding (e.g., U.S. Climate Resilience Toolkit, 2018; Martinich *et al.*, 2013). The resulting “overlay” maps help to pinpoint intersections between social and biophysical vulnerabilities (O’Brien *et al.*, 2004).

6.3.1.1 SoVI applications. The current edition of the SoVI (2010–2014) is constructed using a set of 29 socio-demographic variables related to age, education, employment, income, health, household structure, housing, language barriers, poverty, race/ethnicity, and transportation access (see Table 6.2 and Appendix 6.A). Data sources for SoVI variables generally come from the most recently available U.S. Census (last completed in 2010), and the annual and 5-year updates from the American Community Survey (ACS).

The SoVI index employs principal component analysis (PCA), which is a statistical technique that reduces a large set of variables into a smaller set of aggregated factors (Tate, 2012). Cardinality (+) or (–) is assigned to component loadings. Positive loadings are associated with increased vulnerability and negative loadings with decreased vulnerability. The equally weighted components are added together to create a numerical social vulnerability value for each spatial unit (county, census tract, etc.).

The SoVI approach is widely used for social vulnerability mapping throughout the United States. Examples include applications in the Southeastern U.S. (OXFAM, 2009), California (Cooley *et al.*, 2012), New Jersey (Pflicke *et al.*, 2015), and a number of studies in New York City (Nature Conservancy, 2013; de Sherbinin and Bardy, 2015). These efforts involve employing some or all of the variables in the SoVI and utilizing PCA to tabulate the social vulnerability scores. Key differences among SoVI-like vulnerability indices lie in the number and type of variables included, the spatial unit of analysis, inclusion of data sources other than the U.S. Census, and areas of study.

In some cases, the selection of variables for inclusion may be influenced by the type of climate stressor that the researcher wishes to examine. For example, Cooley *et al.* (2012) use the SoVI method, but

Table 6.2. **The SoVI index**

Index name and author(s)	Data and geography	Number of indicators and methodology	References
Social Vulnerability Index (SoVI) to environmental hazards Cutter *et al.* from the Hazard Vulnerability Research Institute (HVRI) at the University of South Carolina	Data for the latest edition from U.S. Census (2010) and American Community Survey (2010–2014). Data can be used to compare and visualize social vulnerability patterns at different scalar levels (i.e., county, tract, and block group) in the United States. Other data sources: Geographic Names and Information System (GNIS); model-based Small Area Health Insurance Estimates from U.S. Census Bureau Editions of SoVI SoVI 2010–2014 latest edition uses same 29 indicators as SoVI 2006–10 SoVI 2006–2010 edition used 29 indicators SoVI 2000 modified edition used 32 indicators SoVI 2000 original edition used 42 indicators	29 indicators Principal component analysis (PCA) is a data reduction technique used to synthesize socioeconomic variables and assign cardinality to component loadings (+) or (–); positive loadings are associated with increased vulnerability and negative with decreased vulnerability; after cardinalities are determined, components are added together to create numerical social vulnerability score. Equal weighting is applied for all variables	Cutter *et al.* (2003) http://artsandsciences.sc.edu/geog/hvri/sovi%C2%AE-0 (website)

select indicators that are intended to capture social vulnerability to extreme heat, coastal flooding, wild fires, and air quality (see Appendix 6.A). Another source of differences is whether the variables reflect portions of the population within given characteristics in a block or tract or the density of households or individuals with those characteristics.

Methods used to combine individual factors into an index (e.g., with or without weights, etc.) are another source of variations. Social vulnerability patterns identified in the applications reflect the specific combinations of variables and scale used to create each index.

The New York City studies were used to illustrate how the SoVI approach has been applied to examine distributional vulnerabilities to climate change–related coastal flood risk at the neighborhood level (see Table 6.3). These include the Nature Conservancy Mapping Portal (2013) and a study by de Sherbinin and Bardy (2015). Each of these studies follows the prescribed SoVI framework by Cutter *et al.* (2003) with modifications of variable selection in some instances.

The Nature Conservancy analysis of social vulnerability to flooding and sea level rise in New York City utilized 27 variables from the SoVI 2006 to 2010 edition, excluding two variables due to lack of data availability (Nature Conservancy, 2013). The results demonstrate that medium and high levels of social vulnerability are concentrated in census tracts located in northern Manhattan, the South Bronx, the Lower East side, western and southern Brooklyn, north-central Queens (e.g., Flushing), and the Rockaways. Census tracts in our three case study areas (northern Manhattan; Sunset Park, Brooklyn; and Hunts Point, Bronx) display medium or high levels of vulnerability according to this analysis (see Figs. 6.1 and 6.2). Results of the de Sherbinin and Bardy (2015) analysis reveal similar distributions of social vulnerability to climate stressors (flooding) across city neighborhoods. They examined spatial vulnerabilities across block groups using the general

Table 6.3. Selected examples of SoVI-based indexing and mapping in New York metropolitan region

Index name	Data and geography	Number of indicators and methodology	Climate stressors and other environmental hazards	References
The Nature Conservancy Coastal Resilience Mapping Portal (2013)	Data from U.S. Census (2010) and American Community Survey (2006–10). Tract level for New York City, Hudson Valley, and Long Island	27 indicators (from the SoVI 2006 to 2010 edition) Principal component analysis (PCA)	Coastal flooding and sea level rise	Nature Conservancy (2013)
Social vulnerability to floods in two coastal megacities: New York City and Mumbai (2015)	Data from U.S. Census (2010) and American Community Survey (2006–2010) Block group level for New York City	21 indicators (reduced from SoVI 2006 to 2010 edition's 32 indicators to 21 due to data availability) Principal component analysis (PCA)	Coastal flooding	de Sherbinin and Bardy (2015)

SoVI approach but reduced the number of variables to 21 (variables that were not available at the block group level were excluded from the analysis).

While patterns of social vulnerability largely overlap across the two SoVI-based New York City studies, a key difference among them stems from the unit of analysis. In the visualizations in Figures 6.1 and 6.2, the finer spatial detail provided by the block group analysis in de Sherbinin and Bardy (2015) appears to reveal greater concentrations of highly vulnerable block groups in some areas than are apparent from the census tract results in the Nature Conservancy (2013) analysis.

In the cases of northern Manhattan and the South Bronx, for example, the tract visualization indicates that this area has medium vulnerability with small pockets of high vulnerability. In contrast, the two block group visualizations both reveal large concentrations of high vulnerability block groups within these "medium" vulnerability tracts. These areas of high vulnerability are not well captured in the tract-level analysis. While these results are contingent on how the data are classified in the visualization, they nonetheless reveal important differences between block group and census tract-level results.

6.3.1.2 SVI applications. The Center for Disease Control Agency of Toxic Substances and Disease Registry (CDC ATSDR) has its own social vulnerability framework and indexing methodology based on the work of Flanagan *et al.* (2011). The SVI utilizes 15 indicators, which are categorized into four themes: socioeconomic status, household composition and disability, minority status and language, and housing and transportation (see Table 6.4 and Appendix 6.A).

The CDC ATSDR employs a percentile ranking methodology, which entails calculation of the proportion of scores in a distribution that a specific score is greater than or equal to, for all census tracts. It then generates percentile rankings for the 15 individual indicator variables. Theme rankings are calculated by summing the percentiles for the variables comprising each theme and ordering the summed percentiles for each theme to determine the theme-specific percentile ranking. Tract ranking is determined by combining the sums for each theme, ordering the tracts, and calculating the overall percentile ranking for each tract. The SVI index has been estimated for all census tracts in the United States (CDC SVI, 2016).

The SVI index is widely used by governmental agencies, particularly public health departments (CDC SVI, 2018). A notable example is the application of the SVI index for the City of Seattle and King County by their Department of Public Health Division of Emergency Preparedness (SVI Seattle-King County, 2013) (see Appendix 6.A). The SVI for Seattle was created by ranking each tract according to its level of vulnerability in comparison

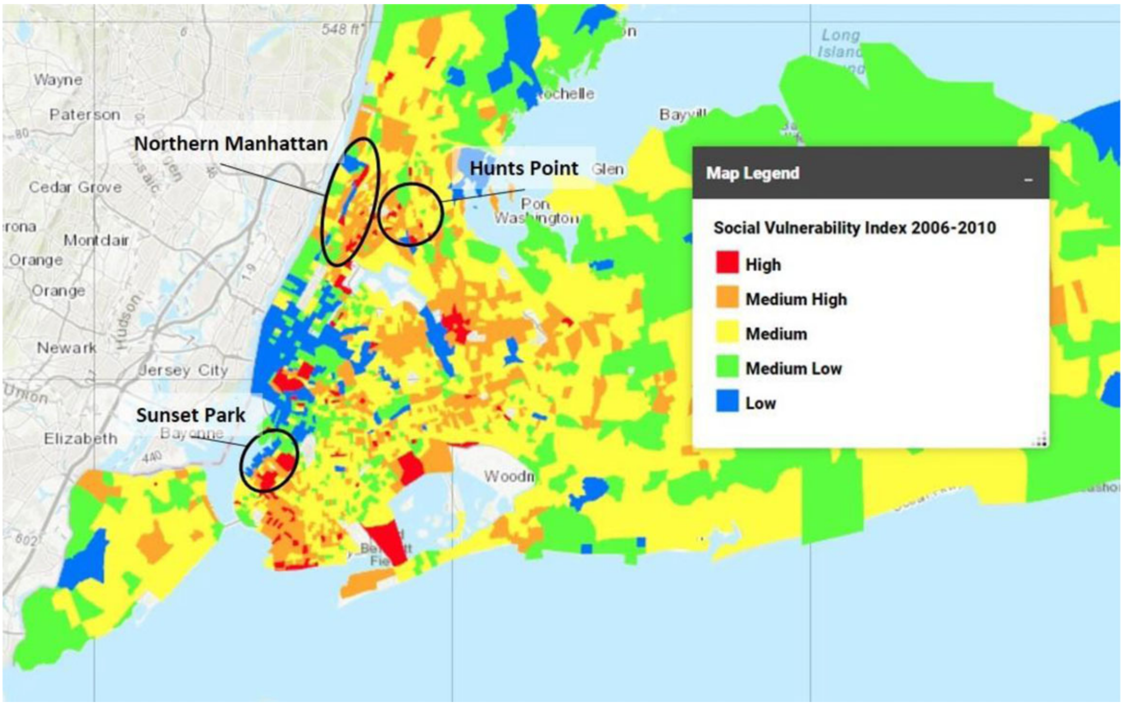

Figure 6.1. Social vulnerability index (SoVI) by the Nature Conservancy at census tract level (Nature Conservancy, 2013). Note: NPCC3 community case study neighborhoods are circled.

to the average across (1) the state of Washington, (2) the Urban Area Security Initiatives (UASI), (3) King County, and (4) Emergency Management Regions.

Other examples include the Dartmouth Flood Observatory overlay of flooding data onto the social vulnerability map for the City of Houston, which was constructed from the CDC SVI online mapping application. This usage of CDC SVI was picked up by several media outlets covering the postflooding period in Houston following Hurricane Harvey (Deaton, 2017; Misra, 2017) (see Appendix 6.A).

In contrast to SoVI applications that display some flexibility in choice of variables to include in the analysis, SVI applications generally include the same 15 variables and generally utilize percentile rankings. As such, the SVI results are more directly comparable across different applications. Because tract-level data for the SVI can be directly downloaded from the CDC website, the SVI can be rapidly deployed following a disaster event, as was done after Hurricane Harvey (see Appendix 6.A).

While a general SVI analysis has not been conducted for New York City, the CDC SVI (2016) model provides statewide vulnerability estimates for New York State. These results, which entail comparison of all census tracts in New York State, reveal high and medium vulnerability in many of the same areas of New York City that were identified by SoVI analyses (see Fig. 6.3). As with the SoVI studies, the New York State SVI indicates medium or high levels of general social vulnerability in all three of our case study areas.

The consistency of the findings between SoVI and SVI reflects the underlying commonalities in the variables used to document social vulnerability in both indices. These results also support our selection of vulnerable communities for the chapter's case studies.

6.3.1.3 Other social vulnerability mapping applications. In addition to SoVI- and SVI-based studies, there are many other types of vulnerability mapping applications that use different methods of variable selection and index compilation (see Table 6.5). Three examples include a climate vulnerability assessment for the City of Boston by the Resiliency Office (Martin, 2015), a social

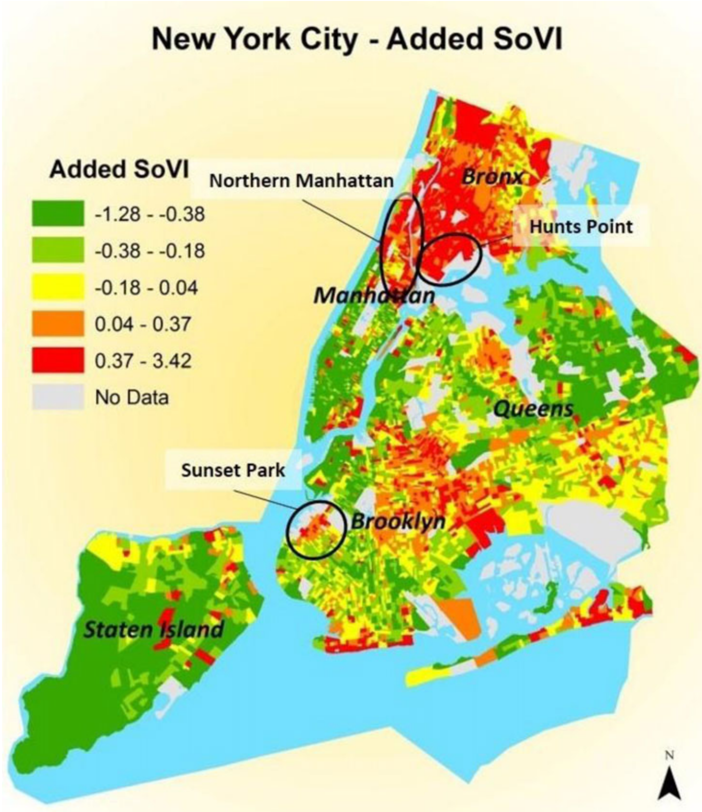

Figure 6.2. Social vulnerability to floods in New York City at census block group level using a modified SOVI in which component scores are equally weighted, added together, and averaged (de Sherbinin and Bardy, 2015).
NOTE: NPCC3 community case study neighborhoods are circled.

vulnerability assessment for the City of New York (Reckien, 2018), and the Heat Vulnerability Index by the New York City Department of Health and Mental Hygiene (City of New York, 2017b).

The social vulnerability mapping application by Martin (2015) utilizes 12 indicators, which were derived via correlation analysis based on an original set of 63 attributes assessed to be linked to social vulnerability. These 12 indicators include children, people with disabilities, older adults, people with chronic and acute medical illness, social isolation, people with low-to-no income, people of color, people with limited English proficiency, people with less than high school education, renters, women, and those lacking a vehicle. Using these variables, Martin (2015) created 12 separate vulnerability indicator maps, each of which is intended to reveal hotspots of social vulnerability for particular indicators at the tract and neighborhood levels (see Fig. 6.4).

Reckien (2018) conducted a comprehensive comparison of different statistical approaches for social vulnerability assessment in New York City. The study used a base set of 10 variables including: total population, female population, African American population, Asian population, Hispanic population, population under 10 years old, population over 65, population living in poverty, population with access to a car, and single-person households. The study compares a range of different approaches to index construction. These approaches include additive normalization without weighting, additive normalization with weighting, and PCA. The study finds that results tend to vary depending on how the indices are constructed. In general, weighted additive approaches may suggest higher levels of social vulnerability throughout the city than PCA approaches. Using a combination of these approaches, Reckien (2018) was able to isolate hotspots that showed consistently high levels of

Table 6.4. The SVI index

Index name and source	Data and geography	Number of indicators and methodology	References
Social Vulnerability Index (SVI) to climate stressors and other environmental hazards (2016) Center for Disease Control Agency for Toxic Substances and Disease Registry (CDC ATSDR)	Data for the latest edition (2016) came from U.S. Census 2010 and American Community Survey (2012–2016). Tract level in the United States	15 indicators Percentile ranking values range from 0 to 1, with higher values indicating greater vulnerability. For each tract, CDC ATSDR generated percentile rank (1) for 15 individual variables, (2) for four theme domains, and (3) for overall position. Theme domain ranking involves summing percentiles for variables constituting each theme and ordering summed percentiles. Overall, tract ranking involves summing the sums for each theme and ordering the tracts	Flanagan *et al.* (2011) https://svi.cdc.gov/Documents/Data/2014_SVI_Data/SVI2014Documentation.pdf (methodology) https://svi.cdc.gov/map.aspx (interactive map)

vulnerability across the methods. Each of our three case study neighborhoods is revealed as a hotspot on this composite map (see Fig. 6.5).

In contrast to most of the SoVI and SVI applications discussed above, the Heat Vulnerability Index, launched in 2015 by the New York City Department of Health and Mental Hygiene and Columbia University, focuses on a single climate stressor. The index, based on a case study of heat vulnerability in New York City by Madrigano *et al.* (2015), is intended to help identify neighborhoods that are most at risk to adverse health effects during extreme heat events.

The index includes two environmental factors (daytime summer surface temperature and distribution of greenspace) and two social factors (poverty as measured by the percent of people receiving public assistance and race as measured by the percent of non-Hispanic blacks residing in the community). Each of these factors has been shown to be associated with increased risk for heat-related death in New York City (Madrigano *et al.*, 2015). The values for each neighborhood are used to assign a score from 1 (lowest risk) to 5 (highest risk). The index serves as a tool to identify communities that are vulnerable to heat extremes and to assist in guiding the allocation of adaptation and mitigation resources (e.g., outreach efforts, planting street trees) to different areas (see Fig. 6.6).

6.3.2 Assessment of vulnerability mapping approaches and recommendations

Despite the widespread usage of social vulnerability analysis and the SoVI and SVI, there are limitations of vulnerability indices for application to policy and planning decisions (Preston *et al.*, 2011; Schmidtlein *et al.*, 2008). For example, social vulnerability scores, which are employed to map and visualize patterns of social vulnerability, only provide a relative indicator of vulnerability in comparison to other areas.

In other words, a low vulnerability score simply means that one area has relatively lower social vulnerability than areas with higher scores; a low vulnerability score does not ensure that an area is resilient to climate shocks, nor does it imply that all of the residents of that area have low vulnerability. Other limitations, such as the lack of attention to underlying social vulnerability drivers, are inherent to this approach (Rufat *et al.*, 2015). Researchers are continuing to seek ways to improve social vulnerability methodologies, for example through uncertainty and sensitivity analysis (Tate, 2013).

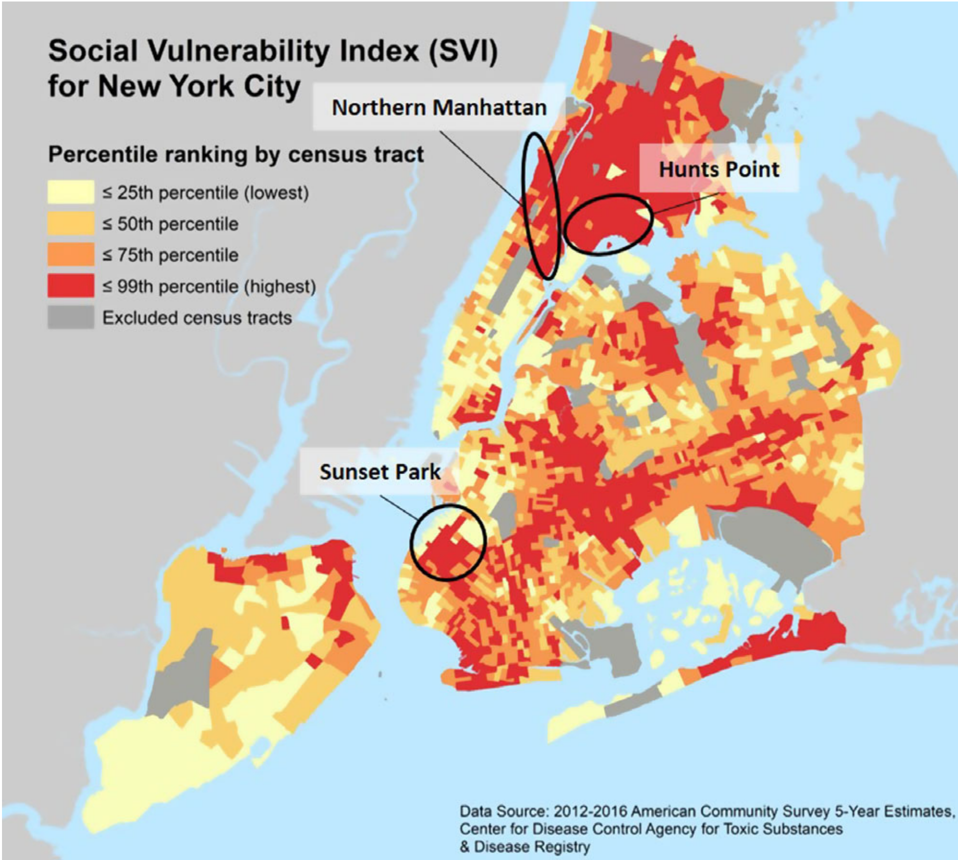

Figure 6.3. SVI New York State application displaying results for New York City (map constructed by the CBA Workgroup). The SVI utilizes 15 indicators, which are categorized into four themes: socioeconomic status, household composition and disability, minority status and language, and housing and transportation.
NOTE: NPCC3 community case study neighborhoods are circled.

Social vulnerability analysis provides useful information on spatial patterns via comparison of different communities or neighborhoods. However, this type of aggregated, composite vulnerability index has more limited utility for tracking how vulnerability changes over time in a particular community or geographic area. The numerical score values for individual tracts are not directly comparable over time because the scores for each time period are calculated relative to other tracts during that time period. In addition, the scores do not provide clear guidance on which components of social vulnerability have contributed to changes in score values. For these reasons, tracking of changes in social vulnerability over time can be better accomplished through the use of single variable indicators.

As the above review suggests, there are many options for documenting and tracking spatial vulnerability in New York City. Both SoVI and SVI have been empirically validated and replicated and are widely used throughout the United States (Bakkensen *et al.*, 2017; Myers *et al.*, 2008; Cutter and Emrich, 2006). Creation of social vulnerability maps based on either method would aid in the identification of census tracts with high levels of social vulnerability to all types of climate stressors including heat and floods.

Either method would require updates on a regular basis as new ACS and Census data are released. These updates could potentially be incorporated into future NPCC assessments. In conjunction with updates based on new data releases, they would also need to be regularly evaluated based on "ground truthing" in local communities to ensure that mapping results reflect conditions perceived by local residents (Schmidtlein *et al.*, 2008; O'Brien *et al.*, 2004).

Table 6.5. Other social vulnerability indexes and applications

Index name	Data and geography	Number of indicators and methodology	Climate stressors and other environmental hazards	References
Social Determinants of Vulnerability Framework: Climate Vulnerability Assessment for the City of Boston (2016)	Data from U.S. Census 2010, American Community Survey (2008–2012), and SimplyMap Easy Analytic Software. Census tract level for City of Boston	12 indicators Correlation analysis and mapping of hotspots	Environmental hazards (non-specific)	Martin (2015)
Heat Vulnerability Index (2017)	Data from U.S. Census (2010), American Community Survey, New York City Department of Parks and Recreation, U.S. Geological Survey. Community district for New York	Four indicators (two environmental and two social) Additive normalization approach	Heat	City of New York (2017b); Madrigano *et al.* (2015)
Social vulnerability index for New York City (2018)	Data from U.S. Census 2010 and American Community Survey (2006–2010). Census tract level	10 indicators Compared indices using: (1) additive normalization with weighting; (2) additive normalization with no weighting; (3) principal component analysis (PCA)	Flooding and heat	Reckien (2018)

As an alternative or supplement to construction of vulnerability indices, the city may also consider tracking of specific indicators of neighborhood vulnerability over time. Use of specific indicators would permit documentation of changes over time (see Chapter 8, Indicators and Monitoring) and ensure continual needs-based targeting of adaptation efforts as part of the proposed pilot New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM). While many factors contribute to social vulnerability of specific households or groups, the above approaches permit identification of variables that are widely found to be indicative of social vulnerability.

The proposed variables (see Table 6.6), all of which were found to contribute to social vulnerability in the studies reviewed above, are intended to provide a starting point for vulnerability tracking for climate stressors in New York City and may be supplemented with additional indicators that are viewed as relevant by the city or by particular communities:

- Access and functional needs populations
- Educational attainment
- English fluency
- Female-headed household
- Foreign-born population
- Income
- Older adults over 65
- Poverty
- Race/ethnicity
- Rent burden

These proposed indicators, which are updated annually by the ACS at the census tract level, would allow for the tracking of factors that are widely thought to contribute to social vulnerability

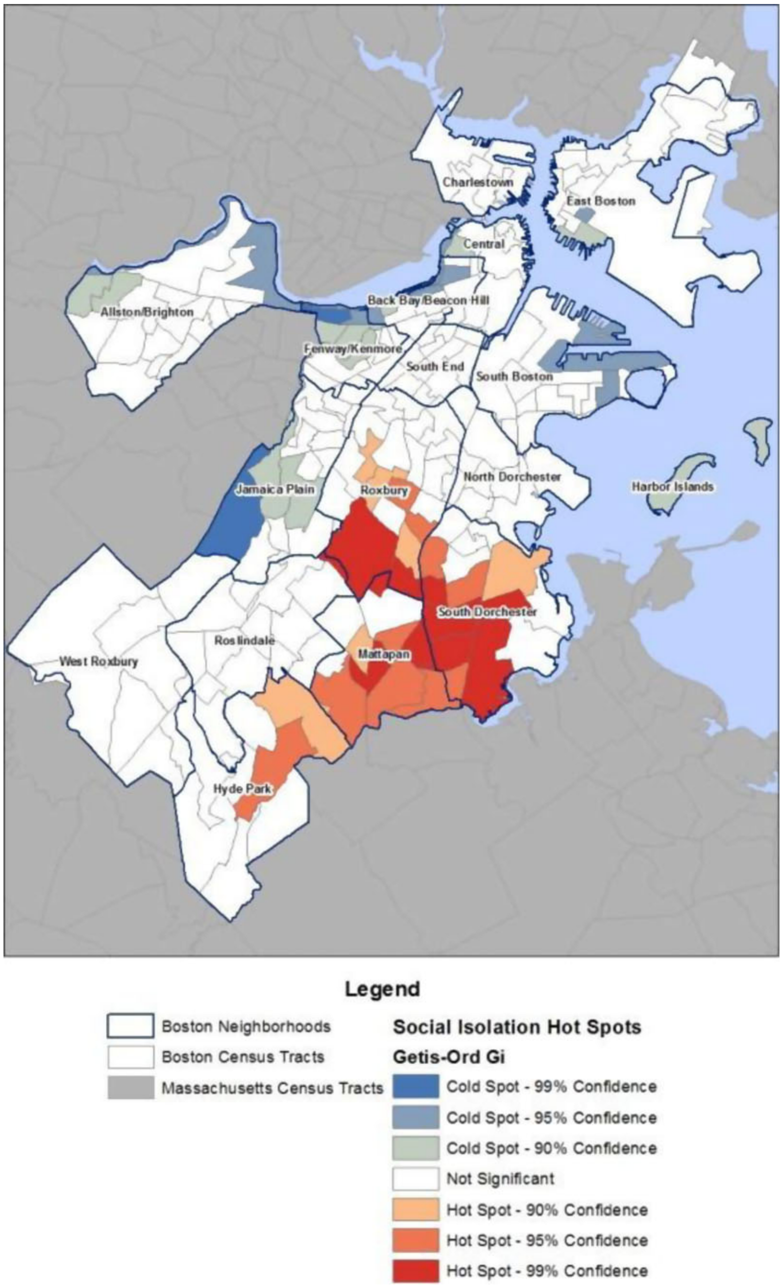

Figure 6.4. Illustration of single variable indicator (social isolation) map showing hotspots in the City of Boston (Martin, 2015).

and spatial differences or inequalities in vulnerability. The indicators are intended to capture demographic, economic, housing, and educational disparities across neighborhoods. They also capture access and functional needs populations and older populations who are especially at risk to climate extremes (Kinney *et al.*, 2015).

One important consideration with respect to tracking is the unit of analysis. While block groups provide fine-scale details on the locations of socially

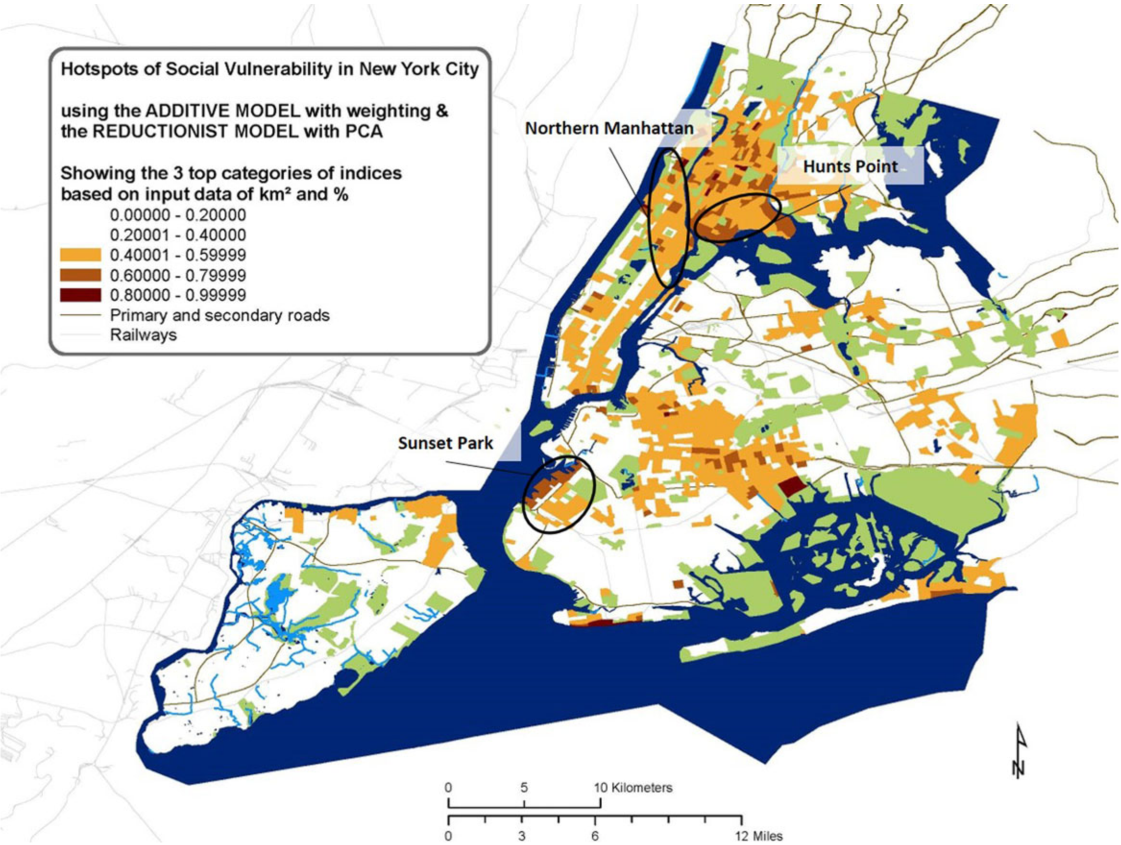

Figure 6.5. Map of vulnerability hotspots in New York City (Reckien, 2018).
NOTE: NPCC3 community case study neighborhoods are circled.

vulnerable populations, these data are not consistently available for all block groups in the city.

Because tract-level data are available on a consistent basis, and because the City uses aggregated tract-level data to determine administrative boundaries (e.g., community districts (CDs), neighborhood tabulation areas), we propose tracking at this more aggregated level. We suggest that the tracking process should be supplemented, as needed, using city health data sources (e.g., NYC Environment and Health Data Portal) to ensure accurate documentation of access and functional needs populations.

Additional city-specific health-related variables related to climate change might include, for example, population lacking air conditioning, population lacking health insurance, population living with chronic health conditions, population with asthma, and population dependent on electric medical equipment (Kinney *et al.*, 2015; McArdle, 2013).

Social vulnerability mapping provides important information about distributional inequalities in susceptibility to harm as a result of climate change, and how these inequalities vary across New York City communities. This information can serve as a useful tool for needs-based targeting of adaptation resources. However, social vulnerability mapping does not illuminate why certain neighborhoods are more vulnerable than others.

To effectively address, or to reduce, social vulnerability to climate change, it is necessary to understand the factors that shape the vulnerability of a particular neighborhood or community. As will be discussed in the next section, equitable climate change adaptation planning requires a contextual assessment and analysis of inequity in vulnerability to climate change impacts.

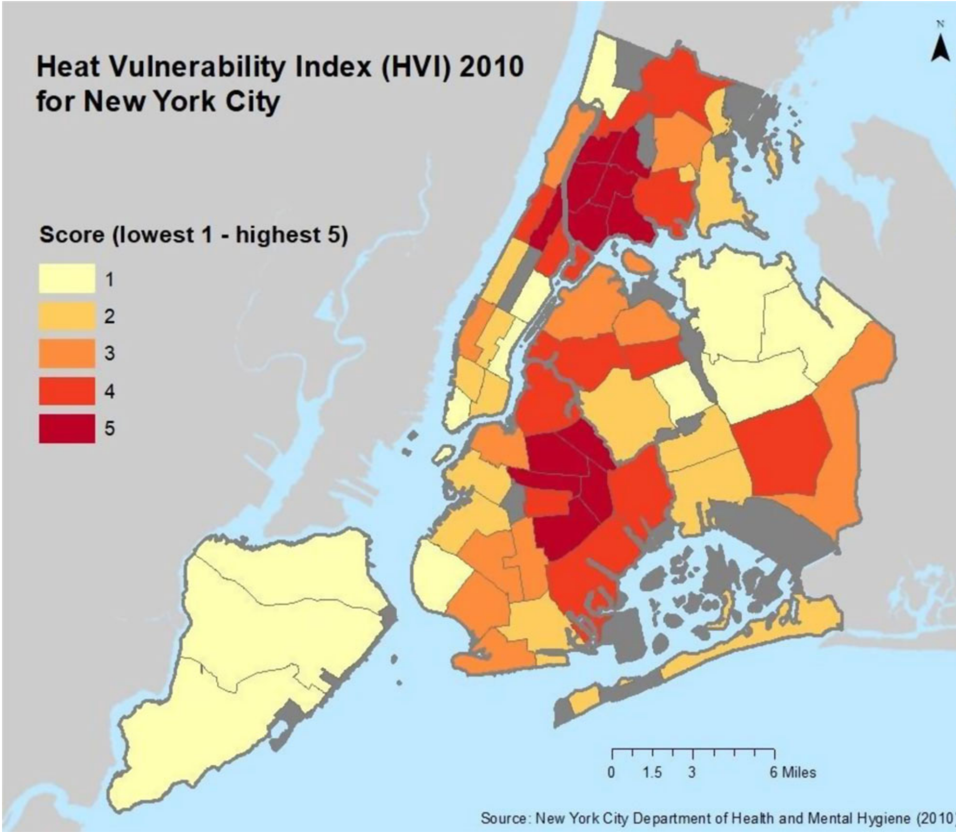

Figure 6.6. Heat Vulnerability Index for New York City based on data from NYC DOHMH (2015).

6.4. Community case studies

In this section, we conduct a contextual equity analysis via case studies of socially vulnerable communities. This type of qualitative case study research and the community inputs we sought and received is a critical supplement to analysis of distributive equity. It is necessary to validate spatial patterns of vulnerability and to explain why certain communities are more vulnerable to environmental and climate extremes than others. The results of the SoVI, SVI, and other social vulnerability analyses played an important role in the selection of our case study communities.

A core tenet of the environmental justice movement is that environmentally overburdened communities should "speak for themselves" with regard to the ways that they suffer the injustice of disproportionate hazard exposure (Bullard and Alston, 1990). As such, the very concept of environmental injustice (or inequality) is rooted in the idea of contextual equity. Scholars have articulated and analyzed the theory of environmental injustice "from the ground up," investigating and listening to (as well as capturing the voices of) communities as a window into economic and social factors and dynamics rendering those communities vulnerable to disproportionate hazard exposure (Cole and Foster, 2001; Foster, 2017).

Following this approach to the issue of climate justice and equity, the CBA Workgroup conducted case studies of three environmental justice communities in New York City: northern Manhattan; Sunset Park, Brooklyn; and Hunts Point, the Bronx in order to better understand the interaction between environmental and climate stressors and social and economic disadvantages. We collaborated with major CBOs in these neighborhoods to capture the different contexts in which the communities face climate and other risks.

Table 6.6. Initial proposed list of vulnerability indicators for NYCLIM

Vulnerability factor	Potential social indicators	Census data source
Access and functional needs populations	Percent of civilian non-institutionalized population with a disability	ACS 2012–2016 DP02
Educational attainment	Percent population with bachelor's degree or higher	U.S. Census 2010 S1501 ACS 2012–2016 SF1501
	Percent population over 25 years old with no high school degree	U.S. Census 2010 S1501 ACS 2012–2016 SF1501
English fluency	Percent population 5 years or over who speak English less than "very well"	ACS 2012–2016 DP02
Female-headed household	Percent of female-headed households	U.S. Census 2010 QT-P11 ACS 2012–2016 S1101
Foreign-born population	Percent of foreign-born population	ACS 2012–2016 B05002
Income	Median household income	ACS 2012–2016 DP03
	Percent of households receiving public assistance income	ACS 2012–2016 B19057
Older adults over 65	Percent population over 65 years old	U.S. Census 2010 DP-1 ACS 2012–2016 DP05
Poverty	Percent of population living below poverty level	ACS 2012–2016 S1701
Race/ethnicity	Percent of nonwhite population	U.S. Census 2010 DP-1 ACS 2012–2016 DP05
Rent burden	Percent of occupied units paying 35% or more of household income on rent	ACS 2012–2016 DP04

These CBOs, all of which are engaged with their communities in the development of climate action plans, include WE ACT (West Harlem, northern Manhattan), UPROSE (Sunset Park, Brooklyn), and THE POINT CDC (Hunts Point, South Bronx).

In addition to interviewing representatives from each of these CBOs, the CBA Workgroup also interviewed city officials, reviewed policy and planning documents from both the city and the CBOs, and collected relevant demographic and health data from city agencies and public sources. CBO representatives also provided feedback and comments on earlier drafts of this chapter, which were incorporated into subsequent drafts.

The CBA Workgroup selected these case study communities for three primary reasons. The first reason is that these communities in many ways exemplify and are representative of the social vulnerability that characterizes many of New York City's neighborhoods. As researchers at NYU's Furman Center found in their 2017 "State of New York City's Housing and Neighborhoods" report, low-income New Yorkers of different races and ethnicities tend to live in certain areas of the city and under significantly different conditions than do most others (Austensen *et al.*, 2017).

Low-income New Yorkers, especially those who are non-Hispanic black and Hispanic, live in neighborhoods with more violence, poorer quality schools and housing conditions, fewer college graduates, and lower rates of employment. Low-income non-Hispanic blacks and Hispanics tend to be concentrated in the Bronx, northern Manhattan, and northern Brooklyn. Low-income Asian residents are more concentrated in southern Brooklyn, parts of Queens, and the Lower East Side of Manhattan. Low-income whites are concentrated in southern and northwest parts of Brooklyn (Austensen *et al.*, 2017).

The second reason we chose these communities and CBOs is their engagement in climate change. In addition to having a history of environmental justice activism, they are each deeply engaged in climate adaptation, mitigation, and resilience projects. Importantly, the CBOs have been given support by foundations, such as the Kresge Foundation, that help fund community-based climate efforts in socially marginalized or vulnerable neighborhoods. Northern Manhattan, Sunset Park, and Hunts Point thus represent a selected sample of communities that reflect the ways social vulnerability manifests in New York City and that have a long history of advocacy for environmental and climate justice. These communities have also been highlighted in the City of New York's OneNYC Plan (City of New York, 2015).

The third reason we chose these case study communities is their social vulnerability. These three neighborhoods were identified from the indices reviewed in Section 6.3. Those results, which are indicative of distributional inequalities across city neighborhoods, show that these are appropriate case study areas for further investigation of contextual and procedural equity related to climate change.

The case studies provide contextual information about these predominantly racial and ethnic minority, low-income communities and the critical climate and non-climate stressors that concern them. The CBA Workgroup collaborated with CBO representatives to document climate stressors and equity issues to gain a better and more complete picture of vulnerability concerns in these communities. We also investigated their interactions with the city's climate mitigation and adaptation efforts as a lens into assessing the issue of procedural equity, which is the subject of Section 6.5.

In addition to interviewing each CBO to learn about the historical and current vulnerability of these communities to environmental pollution and climate change, we also captured their demographic and social profiles using publicly available data (see Appendix 6.A). Current socio-demographic data about the study areas were collected and described at the CD level from the New York City Department of City Planning (NYC DCP, 2018a). Census data for CDs come from the 2000 U.S. Census, 2010 U.S. Census, and the latest 2012–2016 ACS. Public use microdata areas can be used to approximate data for the CDs.

6.4.1 Northern Manhattan (Harlem, Washington Heights, Inwood)

The geographic area for the northern Manhattan case study consists of the northern portion of New York City's Borough of Manhattan. It includes the following neighborhoods: Hamilton Heights, Manhattanville, and West Harlem (Manhattan CD 9); Central Harlem (Manhattan CD 10); East Harlem (Manhattan CD 11); and Washington Heights, Inwood, and Marble Hill (Manhattan CD 12) (see Fig. 6.7). The Hudson River, located west of the study area, and the Harlem River, east of the study area, separate the island of Manhattan from New Jersey and the Bronx, respectively. Northern Manhattan has an estimated area of 8.1 sq miles. It had a population of over 600,000 people in 2016 and a population density of approximately 74,950 people per sq mile.

Northern Manhattan is home to many educational and health-related institutions including Columbia University, City University of New York, St. Luke's–Roosevelt Hospital, Harlem Center for Health Promotion and Disease Prevention, Harlem Hospital Center, and Columbia Medical Center. It also contains major transportation infrastructure including the Henry Hudson Parkway, Broadway/Amsterdam, heavily traveled north–south truck routes, Harlem River Bridge, six north–south subway lines, and numerous MTA bus routes.

This area is characterized by very heavy traffic density, experiencing twice the rate of miles traveled than the rest of New York City. While the average annual amount of vehicle miles for cars and trucks traveled per square kilometer in New York City is 23 million miles, it is almost 47 million miles in Washington Heights, 40 million miles in Central Harlem, and 60 million miles in East Harlem (NYC DOHMH, 2018). These are indicators of emissions from automobile exhaust, brake wear, and tire wear.

Northern Manhattan is also host to multiple polluting or hazardous sources including MTA bus depots, the North River Wastewater Treatment Plant, and the closed 135th Street Marine Waste Transfer Station. Harlem is home to a number of public housing (NYCHA) buildings and also the disproportionate siting of environmentally hazardous land uses, which have been a source of many community complaints about air pollution (Sze, 2006).

Given the area's history as a manufacturing and industrial center, some communities in northern Manhattan, particularly Harlem, have long been characterized as experiencing disproportionate exposure to waste, pesticides, toxic products, and other environmental hazards (Sze, 2006; Brown *et al.*, 2003).

This heavy exposure has contributed to poor air quality in the neighborhood, among other health stressors (Brown *et al.*, 2003). Asthma rates in 2005

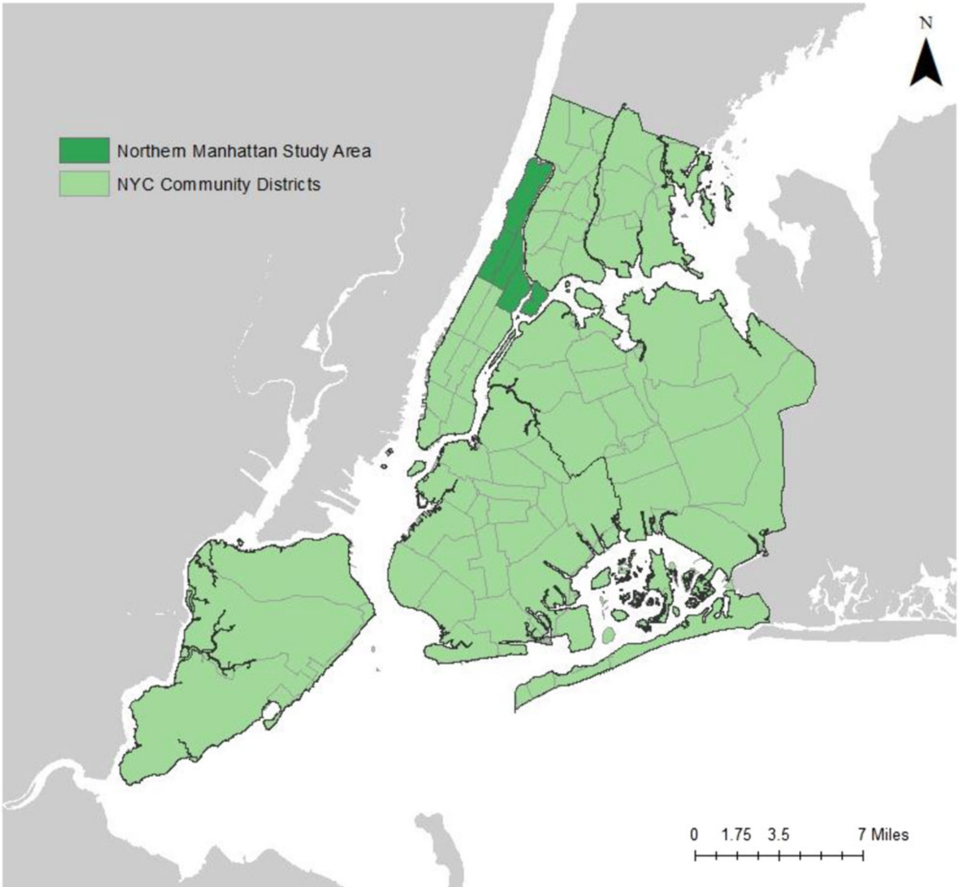

Figure 6.7. Northern Manhattan case study region.

were four times the national average and some studies have found that at least one in four children in Central Harlem has asthma (Corburn *et al.*, 2006; Nicholas *et al.*, 2005; Diaz *et al.*, 2000). When compared to the city as a whole, Central and East Harlem, in particular, have worse air pollution, higher asthma hospitalizations and emergency visits among children and adults, and worse health outcomes overall (Corburn *et al.*, 2006). In Central and East Harlem, asthma emergency visits in 2014 for children 5–14 years old average 638 and 631 per 10,000 residents, respectively. These rates are significantly higher than those for Manhattan (304) and New York City overall (260) (NYC DOHMH, 2018).

Similarly, asthma hospitalization rates in people over 15 years old are disproportionately higher for this area with rates of 44 and 48 per 10,000 residents, respectively in Central and East Harlem, which are more than twice the rates of Manhattan (17) and NYC (22) (NYC DOHMH, 2018). Many emergency room visits are attributable to exposure to fine particulates (PM2.5). In Central and East Harlem, PM2.5 emergency visits were 137 and 147 per 100,000 residents for adults and 291 and 299 for children—again, much higher than PM2.5 ER visits for Manhattan (46 for adults and 144 for children) or New York City as a whole (45 for adults and 107 for children) (NYC DOHMH, 2018).

Many northern Manhattan communities are socially and economically fragile. More than 20% of northern Manhattan residents live at or below the poverty line. They live in poor housing stock often with exposure to lead paint and elevated indoor pollution rates (Corburn *et al.*, 2006). In Central Harlem and Washington Heights in 2011, fewer homes and structures were rated in good or excellent shape (60% and 50%, respectively), as compared to those in Manhattan (80%) and New York City overall (75%) (NYC DOHMH, 2018).

Likewise, only about 37% of renter occupied homes in Central Harlem and 34% in Washington Heights reported no maintenance deficiencies, compared to 48% in Manhattan and 44% in New York City as a whole (NYC DOHMH, 2018). Homes in Washington Heights (26%), Central and East Harlem (28% and 31%, respectively) report maintenance deficiencies at twice the rate for Manhattan (14%) and New York City overall (15%) (NYC DOHMH, 2018).

Notwithstanding the long history of struggle against environmental injustice, zoning, and other land-use changes in recent years, scholars and community activists are increasingly concerned about the threat of displacement and gentrification in Harlem and other parts of northern Manhattan (Savitch-Lew, 2018; Morse, 2017; Checker, 2011). As higher-earning individuals are being drawn into core cities, the price of housing is rising and putting pressure on the affordability of its neighborhoods for many longtime residents (Goldstein, 2017). Many low-income minority communities in northern Manhattan are now undergoing changing demographics, with many residents moving away and more affluent residents moving in (Zanoni, 2011).

Even though other regions of New York were influenced by three decades of gentrification, upper Manhattan did not experience much of it until the end of the 20th century (Outka, 2016). Between 2000 and 2016, northern Manhattan gained over 60,000 people, an increase of 11.4% as compared to an increase of 6.4% for the Borough of Manhattan and 6.6% citywide. White and Asian populations increased by more than 90%, while black population decreased by 10%. The Hispanic population had a modest increase of less than 3%.

Despite this overall growth in the region, some neighborhoods including Washington Heights and Inwood both experienced population declines of 15,554 and 2341, respectively, with increasing numbers of less affluent residents leaving these areas since 2000. Community Board 12 Chair, Pamela Palanque-North, attributes the decline of low-income populations to the lack of affordable housing options in Washington Heights (DNAinfo, 2012). Table 6.7 shows a list of indicators that are relevant to community vulnerability to climate change and compares data for those indicators in northern Manhattan with that of the Borough of Manhattan and the city as a whole.

As these broad trends suggest, many neighborhoods in northern Manhattan are experiencing a high degree of what some researchers term "ethnic churning"—large percentage shifts in the demographics of the area that can render some of these communities vulnerable to weakening social ties or social capital (Betancur, 2011; Sadd *et al.*, 1999). Researchers have found that ethnic churning, more generally, can leave communities vulnerable to hazardous facility siting and other environmental inequities due to frayed social ties.

On the other hand, areas richer in social capital are better able to resist such siting, regardless of their level of other political and economic assets (Balzarini and Shlay, 2018; Cutter *et al.*, 2014; Pastor and Manuel, 2001). While ethnic churning may not have left northern Manhattan communities vulnerable to hazardous waste facility siting, frayed social ties can threaten their ability to adapt and survive extreme weather events such as heat waves (Klinenberg, 2015).

Other non-climate stressors that contribute to community vulnerability in northern Manhattan communities include rising energy costs, lack of access to healthy and affordable food choices, quality health care, affordable and equitable transit, and safe and quality housing.

In addition to traditional environmental pollution and poor air quality conditions, there are significant climate stressors in the neighborhood. Chief among these is exposure to heat waves due to the urban heat island effect and the lack of adequate air conditioning in many homes (Vant-Hull *et al.* 2018).

In Washington Heights in 2013, for instance, only 73% of adults over the age of 65 reported having air conditioning in their home, a lower rate than Manhattan (88%) and New York City overall (87%) (NYC DOMH, 2018). Heat stress emergency visits per 100,000 residents were higher in Washington Heights (12), Central Harlem, (18) and East Harlem (13), than in Manhattan (8) and New York City overall (9) (NYC DOHMH, 2018).

Some neighborhoods near the Hudson and East Rivers are located within the 100-year floodplain and are also at risk to sea level rise and storm surge (see Chapter 3, Sea Level Rise; and

Table 6.7. Socioeconomic characteristics of northern Manhattan, with climate change vulnerability implications, compared with the Borough of Manhattan and New York City (NYC DCP, 2018a)

Indicators	Northern Manhattan	Manhattan	New York City
Foreign-born population	34.4%	28.9%	37.2%
Limited English proficiency	24.2%	15.6%	23.0%
Educational attainment or residents aged 25+ with bachelor's degree or higher	35.6%	60.4%	36.2%
Median household income ($2016)	$40,917	$75,513	$55,191
Unemployment rate	11.0%	6.9%	8.6%
Poverty measure (authors' calculation based on residents who have income below the NYCgov* poverty threshold)	21.6%	13.9%	20.3%
Renter-occupied housing units	89.3%	76.9%	68.0%
Rent burden (households spending more than 35% of income on rent	42.7%	37.1%	44.6%
Access and functional needs populations	12.1%	9.9%	10.5%
Population over 65	11.5%	14.4%	13.0%

*The NYCgov poverty measure is a metric that was developed by the Poverty Research Unit of the Mayor's Office for Economic Opportunity in order to capture poverty in the city more accurately than the federal measure (City of New York, 2018a).

Chapter 4, Coastal Flooding). Almost 95% of the East Harlem area and 64% of the Central Harlem area are located within the hurricane evacuation zone; this is substantially larger than the area for the rest of Manhattan (49%) and New York City overall (47%) (NYC DOHMH, 2018).

6.4.2 Sunset Park, Brooklyn

Sunset Park is a waterfront neighborhood located in the western part of Brooklyn (Fig. 6.8). It has an area of approximately 3.7 square miles. Sunset Park is a community with more than 150,000 residents with a population density of approximately 40,880 people per sq mile. It is bordered by the neighborhoods of Park Slope and Greenwood Heights to the north and Bay Bridge to the south. It is roughly bound by 15th Street to the north; Fort Hamilton Parkway, 37th Street, and 8th Ave to the east; 65th Street to the south; and Upper New York Bay. The Gowanus Expressway/Interstate I-278 divides the neighborhood into two distinct areas: the industrial waterfront and the upland residential community.

Sunset Park is home to one of the last industrial working waterfronts in New York City. Dominant economic activities are anchored in manufacturing, wholesale trade, and construction. Sunset Park is also home to a critical assemblage of city-owned waterfront properties such as the South Brooklyn Marine Terminal, Bush Terminal Industrial Campus, Brooklyn Meat Market, and the Brooklyn Army Terminal (NYC SIRR, 2013). The waterfront hosts automobile shops, active industrial and polluting facilities, brownfield sites, and defunct factories (NYC DCP, 2011).

Sunset Park is also home to multiple rail and highway networks including the Bay Ridge Channel, Cross Harbor barge service, Bay Ridge Rail Line, and the Gowanus Expressway. The area is characterized by high traffic density, with about 26 million annual vehicle miles traveled per square kilometer (NYC DOHMH, 2018). Heavy congestion and a high volume of truck traffic on the Gowanus Expressway and on the waterfront contribute to the poor air quality in neighborhood.

A predominantly Hispanic and Asian immigrant community, the area is also undergoing some demographic change as the number of Hispanics and non-Hispanic Blacks is decreasing slightly, while Asian and White populations are increasing sharply. This demographic change is happening alongside the transition from an industrial to a service economy, which creates job insecurity in a community with relatively low levels of formal education and high levels of limited English proficiency (see Table 6.8).

Although Sunset Park retains some of its manufacturing sectors, it has experienced a gradual decline in industrial activities and related jobs over

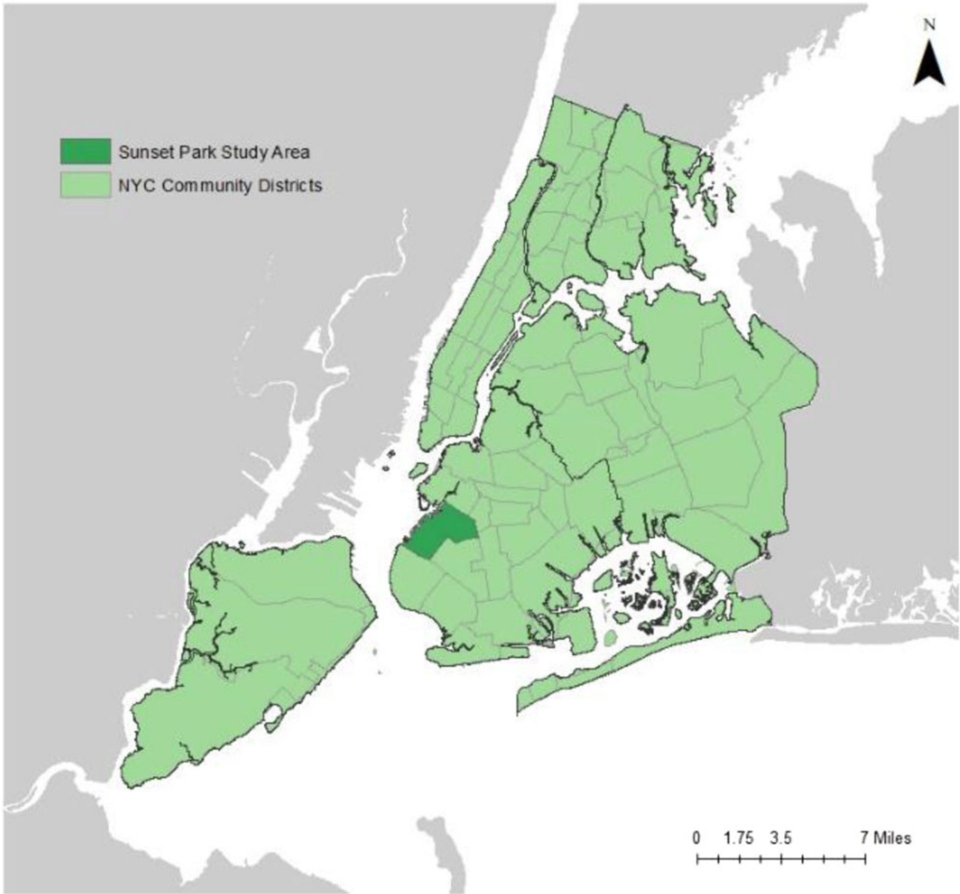

Figure 6.8. Sunset Park, Brooklyn case study region.

the past several decades (Hum, 2014). The increased presence of commercial development in the area often means a higher share of unskilled, low-wage jobs in the service sector, as compared to skilled industrial jobs that historically offered a higher wage (Hum, 2014).

The commercialization of Sunset Park is widely perceived by residents as catering to middle- and upper-middle-class clientele and is becoming increasingly inaccessible to the area's low-income residents. Similar to the socio-demographic shifts in northern Manhattan, these changes are indicative of a larger gentrification of the area, as "young white professionals" and "creative-class members" who cannot afford other areas in the city are settling in once-dilapidated sections of the community (Hum, 2014).

Some also point to the additional development pressure resulting from rezoning of the area as a driver for gentrification (Sze and Yeampierre, 2018; Amar, 2017; Warerkar, 2017; Hum, 2014). As Sunset Park benefits from the environmental cleanup of its industrial legacy and the City's efforts to redevelop the waterfront, it is likely that the area will continue to attract additional newcomers, putting pressure on existing residents who face rising housing costs (Sze and Yeampierre, 2018).

At the same time that cost of living and rents are rising, low-income residents in the neighborhood often live with poor housing conditions. Housing quality for low-income tenants is a big, and very public, concern in Sunset Park, as indicated through media coverage. In a 2015 survey, 58% of renter-occupied homes in the area reported at least one maintenance defect (e.g., water leaks, cracks and holes, inadequate heating, presence of mice or rats, toilet breakdowns, and peeling paint) (NYC DOHMH, 2018).

Table 6.8. Socioeconomic characteristics of Sunset Park, Brooklyn, with climate change vulnerability implications, compared with the Borough of Brooklyn and New York City (NYC DCP, 2018a)

Indicators	Sunset Park	Brooklyn	New York City
Foreign-born population	47.8%	37.2%	37.2%
Limited English proficiency	48.6%	23.1%	23.0%
Educational attainment or residents age 25+ with bachelor's degree or higher	26.2%	34.1%	36.2%
Median household income ($2016)	$48,232	$50,640	$55,191
Unemployment rate	7.7%	9.0%	8.6%
Poverty measure (residents who have income below the NYCgov poverty threshold)*	29.4%	20.5%	20.3%
Renter-occupied housing units	73.9%	70.6%	68.0%
Rent burden (households spending more than 35% of income on rent)	51.7%	45.7%	44.6%
Access and functional needs populations	8.6%	10.1%	10.5%
Population over 65	8.9%	12.2%	13.0%

*The NYCgov poverty measure is a metric that was developed by the Poverty Research Unit of the Mayor's Office for Economic Opportunity in order to capture poverty in the city more accurately than the federal measure (City of New York, 2018a).

Sunset Park's waterfront location and the presence of numerous power plants, waste stations, and other industrial sites render the neighborhood vulnerable to both the direct impacts of sea level rise and higher storm surge as well as indirect industrial-contaminated flooding. The area, located next to New York Harbor, is home to electrical generators operated by New York Power Authority, diesel-powered electric generators owned by Con Edison, turbine units belonging to Eastern Generation, the Hamilton Avenue Marine Transfer Station, a commercial waste station, a recycling facility, a garage for garbage trucks, the Owls Head Wastewater Treatment Plant, and other numerous brownfields and nonoperational industrial buildings.

Sunset Park is also located within a combined sewer district in New York City, which implies that during flooding events, sanitary and storm waters will be intermingled (NYC SIRR, 2013).

The low-lying neighborhood is particularly vulnerable to flooding (see Chapter 3, Sea Level Rise; and Chapter 4, Coastal Flooding). Over 33% of the Sunset Park area is located within hurricane evacuation zones (NYC DOHMH, 2018). This risk carries with it the potential that surging storm water could spread toxins from the many nearby industrial sites. During Hurricane Sandy, Sunset Park's waterfront was heavily flooded and chemical-contaminated water was pushed into residential areas (Madrigano *et al.*, 2018; Bautista *et al.* 2015).

Another climate-related stressor is heat, as hot summers can worsen the effects of air pollution and impact low-income residents without adequate air conditioning. In a citywide 2015 survey, 69% of adults aged 65 and over reported air conditioning in the home in 2013, which was lower than Brooklyn's overall 86.7% and New York City's overall 87.7% (NYC DOHMH, 2018). About 4.5 per 100,000 Sunset Park residents were admitted for heat stress hospitalization in 2013; higher than Brooklyn's rate of 3 and New York City's overall rate of 2 per 100,000 residents (NYC DOHMH, 2018).

Moreover, the area is perceived by residents as lacking sufficient greenspace to help mitigate the effects of heat exposure. Only 26% of Sunset Park's area is estimated to have vegetative cover (i.e., trees and grass), which is comparable to the amount of greenspace in Brooklyn but about 10% lower than that average amount of green space in New York City (NYC DOHMH, 2018).

6.4.3 Hunts Point, South Bronx

Hunts Point (Fig. 6.9) is located in the South Bronx. It occupies approximately 4.4. sq miles. As of 2016, Hunts Point had a population of more than 160,000 people with a population density of approximately 36,663 people per sq mile. It is home to the NYC Food Distribution Center (FDC) and its related infrastructure.

The 329-acre FDC facility occupies nearly half of the Hunts Point Peninsula in the South Bronx.

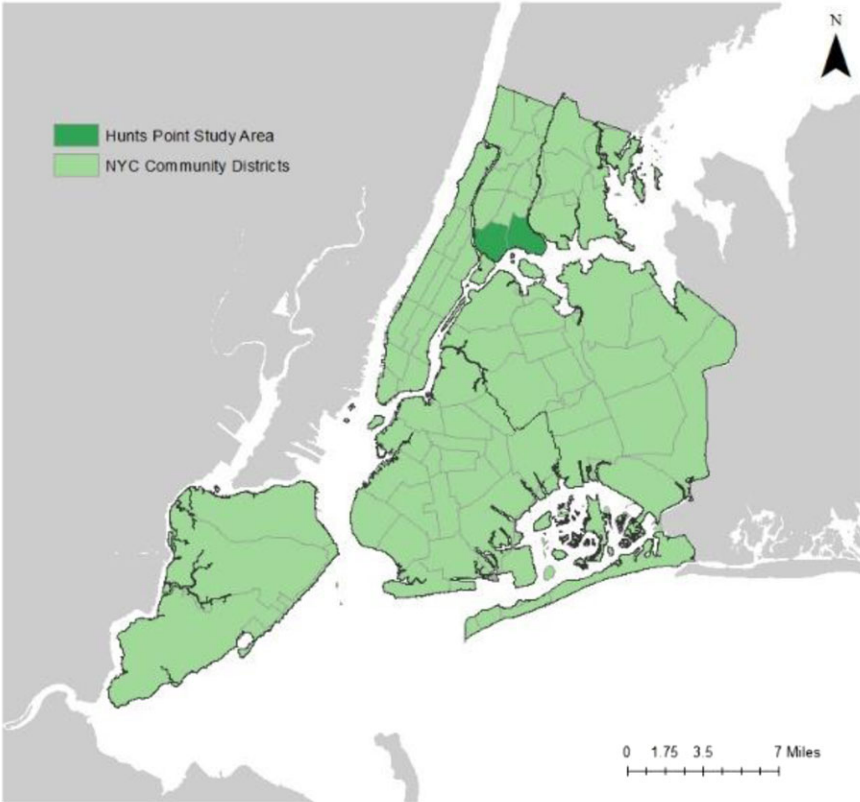

Figure 6.9. Hunts Point, South Bronx case study region.

It is owned and operated by the New York City Economic Development Corporation (NYCEDC) with an annual revenue of more than $3 billion (NYC SIRR, 2013). It employs about 7000 people (NYC Food Policy, 2014). The FDC, consisting of the Hunts Point Terminal Produce Market, the Cooperative Meat Market, and the New Fulton Fish Market, provides food and produce for 23 million people regionally, and supplies 60% of New York residents' fruit and vegetable consumption (NYC Food Policy, 2014).

Activities at the FDC involve more than 10,000 truck trips per day. In addition to the FDC, Hunts Point also contains nine waste transfer stations (WTS) that contribute to the truck traffic in the neighborhood (New York Environment Report, 2015). Although there are numerous expressways in the South Bronx and Hunts Point, there are no direct access routes from the highways to the industrial areas.

Air pollution is one of the most pressing environmental issues in Hunts Point given vehicle and truck traffic serving the FDC and industrial facilities and spilling over into residential streets (Corburn *et al.*, 2006). Exposure to fine particulate matter (PM 2.5) is elevated in the area compared to the Bronx and NYC overall; average rates in 2016 are 8.3 mcg per cubic meter in the area versus 7.8 overall in the Bronx and 7.5 overall in NYC (NYC DOHMH, 2018).

For adults in Hunts Point, the attributable asthma emergency department visit rate was 138 per 100,000, more than twice the rate for the Bronx (67) and citywide (45) (NYC DOHMH, 2018). For children, however, exposure to PM 2.5 is highly elevated compared with the rest of the Bronx and NYC (251 per 100,000 in Hunts Point-Mott Haven, compared with the Bronx 128 and NYC 107) (NYC DOHMH, 2018).

Hunts Point is predominantly made up of Hispanics and non-Hispanic Blacks. Residents have suffered from a high rate of poverty and the prevalence of asthma among all age groups (see Table 6.9). The Department of Health Bureau of Biometrics and Health Statistics reported that the Bronx has the

Table 6.9. Socioeconomic characteristics of Hunts Point-Mott Haven, with climate change vulnerability implications, compared with the Borough of the Bronx and New York City (NYC DCP, 2018a)

Indicators	Hunts Point-Mott Haven	the Bronx	New York City
Foreign-born population	29.6%	34.9%	37.2%
Limited English proficiency	32.6%	26.0%	23.0%
Educational attainment, or residents age 25+ with bachelor's degree or higher	9.8%	19.1%	36.2%
Median household income ($2016)	$23,131	$35,302	$55,191
Unemployment rate	12.2%	12.7%	8.6%
Poverty measure (residents who have income below the NYCgov poverty threshold)*	29.3%	25.0%	20.3%
Renter-occupied housing units	92.4%	80.9%	68.0%
Rent burden (households spending more than 35% of income on rent)	48.6%	50.6%	44.6%
Access and functional needs populations	14.0%	13.8%	10.5%
Population over 65	8.2%	11.3%	13.0%

*The NYCgov poverty measure is a metric that was developed by the Poverty Research Unit of the Mayor's Office for Economic Opportunity in order to capture poverty in the city more accurately than the federal measure (City of New York, 2018a).

highest age-adjusted asthma death rate (43 deaths per million) among all counties in the state. In 2013, Hunts Point-Longwood had the third-highest asthma hospitalization rate among children 5–14, more than twice the city rate (88 per 100,000 for Hunts Point; 72 for the Bronx; and 36 for NYC) (NYC DOHMH, 2018).

Similarly, the rate of asthma emergency room visits in 2014 for people aged 15 and over is elevated (340 per 10,000 residents) compared to the Bronx overall (224) and New York City (115) (NYC DOHMH, 2018). The rate of adult hospitalizations for asthma in Hunts Point is also twice the citywide rate (592 per 100,000 adults for Hunts Point-Longwood; 482 for the Bronx; 260 for NYC) (NYC DOHMH, 2018). A study by New York University also found that children in the South Bronx are twice as likely to attend a school near a highway as compared to other children in New York City (New York University Wagner ICIS, 2006).

As in other low-income communities, the housing stock in Hunts Point is old and fragile. Less than 50% of homes and structures in 2011 were rated as good or excellent, lower than those that rated similarly in the Bronx (58%) and New York City (75%) (NYC DOHMH, 2018). For example, the rate of homes with cracks, holes, and leaks has been higher there than in the Bronx and citywide. Nearly, one-third of homes (30%) reported three or more maintenance deficiencies (NYC DOHMH, 2018). Homes in this area had more sources of indoor allergens and pollutants that can exacerbate asthma than the rest of the Bronx and NYC (Corburn *et al.*, 2006). In 2014, as many as 40% of residents, for instance, reported the presence of cockroaches and rats in their building, higher than the reporting rates of the Bronx and New York City overall (NYC DOHMH, 2018)

Surrounded by the East River on two sides and the Bronx River on the third, Hunts Point is highly vulnerable to flooding. Approximately 93 acres of the site, or 28%, lies within the 100-year floodplain (NYC SIRR, 2013) (see Chapter 3, Sea Level Rise; and Chapter 4, Coastal Flooding). Over 70% of the Hunts Point-Mott Haven Area is located within a hurricane evacuation zone (NYC DOHMH, 2018).

Much like the other communities studied, climate change can exacerbate existing environmental risks in Hunts Point. The coastline has a history of heavy industrialization that contaminated the land around factories and rendered it unusable. In addition, the Hunts Point neighborhood also has numerous auto-mechanic shops and other auto-related infrastructure. Extreme precipitation events, sea level rise, and flooding can spread industrial chemical pollutants into residential areas. While the Hunts Point FDC was spared the worst inundation when Hurricane Sandy hit in 2012, residents and city officials are concerned about the impacts of future extreme weather

Table 6.10. Summary of social, economic, climate, and other environmental stressors and needs identified by CBOs in the three case study communities

Communities	Northern Manhattan	Sunset Park, Brooklyn	Hunts Point, Bronx
Social and economic stressors			
Aging housing stock	X	X	X
Decrease in manufacturing jobs	–	X	–
Energy cost burdens	X	–	–
Increase in commercial presence	X	X	–
Health disparities	X	–	X
High number of foreign-born residents	–	X	–
High rate of poverty	X	X	X
Lack of affordable housing options	X	X	X
Rising cost of living	X	X	–
Unemployment	X	–	–
Climate stressors			
Rising average temperatures	X	X	X
Growing number of heat waves and hot days	X	X	X
Changing patterns of precipitation and inland flooding	X	X	X
Sea level rise	X	X	X
Coastal flooding from storm surge and sea level rise	X	X	X
Extreme hurricane winds	X	X	X
Drought	–	–	–
Cold snaps	–	–	–
Other environmental stressors			
Air pollution	X	X	X
High truck traffic	X	X	X
Storm water runoff	X	X	X
Community needs			
Access to healthcare services	X	–	–
Access to healthy food and lifestyle programs	–	–	X
Access to the waterfront	X	X	–
Access to affordable housing	X	X	X
Access to public health facilities	–	–	X
Access to greenspace	X	X	X
Improved disaster preparedness and evacuation planning	X	X	X
Protection of local employment	–	X	X

events on the food supply system (NYC SIRR, 2013).

Hunts Point is also vulnerable to the impacts of the urban heat island effect. The neighborhood has limited green space and cooling facilities. Only 16% of the area has vegetative cover including trees and grass, which is much lower than the overall Bronx coverage (36%) and New York City coverage (35%) (NYC DOHMH, 2018). The effects of extreme heat are worsened by excessive truck exhaust. In 2013, heat stress hospitalizations were 3.5 per 100,000 residents, compared with the citywide rate of 2.4 per 100,000 residents.

6.4.4 Summary of contextual equity concerns in case study communities

In the last two decades, New York City has become a more expensive, less affordable place to live (Yager, 2015). Communities in northern Manhattan, Sunset Park, and Hunts Point are all confronting the challenge of gentrification and/or displacement (Austensen *et al.*, 2015). In particular, CBOs identified numerous concerns related to changing social and economic conditions, including, concern about the rising cost of living, increased rents, and lack of affordable housing options (see Table 6.10) (Austensen *et al.*, 2015).

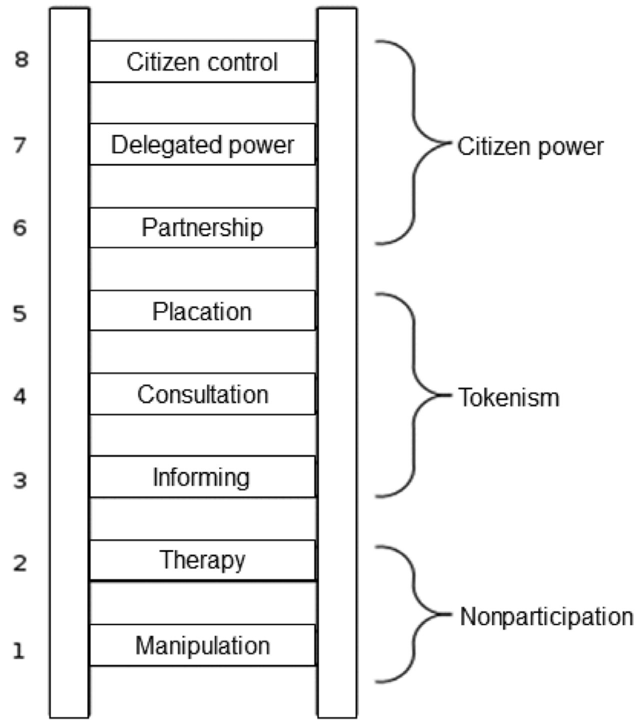

Figure 6.10. Eight rungs on the ladder of citizen participation (Arnstein, 1969).

In addition, the processes of deindustrialization and commercialization create great uncertainty regarding job opportunities. At the same time, there is an increased presence of commercial development in these areas, offering unskilled jobs in the service sector (as compared to skilled manufacturing and industrial jobs). These jobs do not allow existing residents to meet increases in the cost of living, particularly of housing.

New commercial activities typically cater to middle- and upper-middle-class clientele and are generally not accessible to low-income residents (Adams, 2016; Gonzalez, 2016). The growth of the commercial sector also contributes to conflicts over land use and planning. Vacant warehouses and buildings are being bought by private developers, which threatens to transform working-class neighborhoods into unaffordable upscale enclaves. Residents and community activists are actively fighting to preserve their manufacturing zoning and job opportunities (Fainstein, 2011; Sze and Yeampierre, 2018; Checker, 2011).

The neighborhoods of northern Manhattan, Sunset Park, and Hunts Point are hotspots of environmental pollution (see Table 6.10). They are disproportionately burdened with numerous hazardous and polluting industrial facilities and related activities (e.g., garbage processing centers, power plants, WTS, bus depots, and heavy traffic).

In all three neighborhoods, many industrial facilities or former industrial sites are located on the waterfront, which make them vulnerable to extreme flooding and heavy storm surges (Fainstein, 2011; Bautista *et al.*, 2015). These neighborhoods and their residents are concerned about having adequate emergency preparedness capacity and evacuation centers during natural disasters (NYCEJA, 2018).

Low-income residents bear the health consequences of living in proximity to these toxic sites. There is significant concern regarding toxic chemicals on the waterfront being displaced into residential areas. On the other hand, many young children and adults suffer from asthma and other respiratory illnesses, which can be exacerbated by worsened air quality during extreme heat events. Due to a lack of quality recreational green space, the more vulnerable residents, such as the elderly and children, are at risk of heat-related illnesses.

In order to address the unique ways and contexts in which communities are both ecologically and socially vulnerable, the CBOs on the CBA Workgroup emphasized that their communities lack some of the basic goods and services that are important to fostering resilient communities. A shortage of affordable and quality housing stock, lack of adequate health care and public health facilities, lack of access to healthy food and green spaces undermine these communities' ability to face and adapt to the environmental and climate stressors present in their communities. Expanding their access to these basic social and environmental goods should be a critical part of adaptation planning in socially vulnerable communities.

The CBOs also emphasized the importance of early and meaningful engagement with public officials in all phases of development planning in their communities, including adaptation planning and implementation. Each of the CBOs has engaged, often extensively, in adaptation planning in their communities and with their residents. The challenge is how to align these planning efforts with the city's adaptation planning processes. As we will discuss in Section 6.5, robust community engagement is a critical element of procedural equity in climate change adaptation.

6.5. Procedural equity

This section describes how each of the three case study communities engage in, and are included in, local adaptation planning efforts. Based on relevant literature, interviews with representatives from each of the CBOs, and conversations with City officials, we examine these efforts through the lens of procedural equity that draws upon Arnstein's (1969) widely used "ladder" of public participation (see Fig. 6.10). This study offered a typology or hierarchy of participation that illustrates the range of potential public engagement in official decision-making processes. The ladder depicts various levels of engagement ranging from nonparticipation (manipulation and power) to tokenism (informing, consultation, placation) to citizen empowerment (partnership, delegated power, and citizen control).

Arnstein (1969) argues that if restricted to the first two levels, participation will not change the *status quo* or result in meaningful engagement. The metaphor of the ladder also suggests a ranking of the levels. The higher levels are preferable to the lower, and the ultimate goal of participation is the achievement of decision-making power for citizens.

We also build upon recent work by Sarzynski (2015) who has developed a typology specific to public participation in climate adaptation planning. Based on the work of Dietz and Stern (2008), Sarzynski (2015) suggests a typology to categorize the different levels of public participation in climate change adaptation in cities (see Box 6.3).

6.5.1 Community-based adaptation initiatives and projects

Most of the community-based adaptation efforts of our three partner CBOs fit into the categories of inclusive planning, nongovernmental planning, and nongovernmental provision. Each CBO is simultaneously participating in city-initiated and city-led planning and adaptation efforts, in parallel with its own internal grassroots efforts in the communities. These parallel efforts suggest opportunities in the future for more partnerships or co-production of adaptation planning that would involve these communities earlier and more substantively in the process of designing resilience plans.

These opportunities could result in more efficient planning processes that incorporate community knowledge and expertise at the design stage, addressing early on the unique ways that different communities are vulnerable. This could increase the capacity of city planning processes to be more adaptive to local conditions and vulnerabilities.

6.5.1.1 WE ACT for environmental justice (WE ACT) and northern Manhattan. WE ACT began its advocacy work in 1988 by opposing the North River Wastewater Treatment Plant and protesting the exclusion of vulnerable populations and communities from local and state decision-making processes. Starting in 1990, WE ACT became increasingly active in addressing air pollution and environmental health concerns, including children and youth exposure to lead in northern Manhattan communities. WE ACT is now one of the leading environmental justice organizations in New York City and nationwide. Its mission is to educate, empower, and mobilize residents of northern Manhattan regarding environmental issues that affect their health and quality of life.

Box 6.3: Types of public participation in climate adaptation planning (based on Sarzynski (2015))

Traditional government-led climate planning: The most common form of climate adaptation planning and action; participation tends to be limited in duration, intensity and influence; and to pursue instrumental goals; common formats include public consultation workshops, citizen engagement, public comments on draft plans or proposed rules (one-way information exchange).
Inclusive planning: A government-led process that emphasizes intensive public consultation and recognizes that public participation can help improve the quality and legitimacy of government plans; common formats include selecting experienced nongovernmental actors to be part of steering committees, consulting with community emergency responders; creating citizen advisory committees or task forces.
Nongovernmental planning: A nongovernmental organization-led climate adaptation planning effort with minimal government involvement; aims to pursue a broader scope of participants and intrinsic goals; common formats include scenario-based stakeholder engagement (often led by university researchers) and consultation with community participants.
Nongovernmental provision: These include community self-help and community-based initiatives to adapt to locally important climate risks; can also be private business led; nongovernmental led actions reveal private and nonprofit sector capacity for urban climate governance.
Partnerships: These involve the formation of public-private partnerships (PPPs), often government led but have also been led by NGOs; a downside of PPPs is that they may result in loss of public accountability and transparency or lead to private-sector favoritism; degree of private citizen involvement tends to be minimal.
Co-production: A process that involves both government and community participants intensely and substantively in adaptation planning and implementation; differs from partnership approach due to explicit involvement of civil society and individual citizens in provision of urban climate governance; can include community-based adaptation targeting low-income communities, community action planning, and scenario-based stakeholder engagement.

WE ACT engages in a number of community adaptation projects that include elements of both nongovernmental and inclusive planning (Table 6.11). Chief among its efforts is the Northern Manhattan Climate Action Plan (NMCA), a community-produced climate adaptation plan. WE ACT served as the community broker in the planning process of the NMCA, which closely followed the template of nongovernmental planning. Its role entailed convening public residents, scientists, and other stakeholders to engage in a broad but locally adapted planning process.

WE ACT also directly participates in the city's Solarize NYC program, again as a community broker, to convene and engage residents and other stakeholders. In this city-initiated project, which relies on principles of inclusive planning, WE ACT facilitated community engagement in the city's efforts to promote group purchasing of solar power. In addition, WE ACT participates in the Healthy and Sustainable Public Housing Initiative. Working in partnership with NYCHA, this project entailed outreach to residents of public housing and organization of a series of workshops to solicit feedback on environmental issues affecting community residents.

6.5.1.2 UPROSE and Sunset Park. The United Puerto Rican Organization of Sunset Park (UPROSE) is one of Brooklyn's oldest Latino social service agencies and CBOs. It was incorporated in 1966 and originally intended to serve the then-predominantly Puerto Rican neighborhood. As Sunset Park experienced significant demographic change in recent decades, UPROSE has extended its outreach to other Spanish-speaking populations and to the Chinese population in the community. UPROSE serves as an advocacy organization for a variety of environmental justice and public health issues including waterfront redevelopment, cleanup and remediation of local brownfields, transportation access, public and open spaces, air quality, and educational and youth empowerment campaigns. Its primary mission is to promote sustainability and climate change resiliency in Sunset Park.

UPROSE's climate adaptation efforts generally fit into the category of nongovernmental planning and nongovernmental provision (see Table 6.12). These efforts include establishment of the Sunset Park Climate Justice Center, the Be a Block Captain program, and the Climate Justice Youth Summit. Each of these efforts involves engagement of residents and/or local businesses and young people in community

Table 6.11. Selected northern Manhattan community mitigation and adaptation projects

Current WE ACT projects	Description	Community engagement	References
Northern Manhattan Climate Action Plan (NMCA)	Result of a community-based planning process held from January through July of 2015: included residents from Central Harlem, East Harlem, Washington Heights, and West Harlem Four themes: energy democracy, emergency preparedness, social hubs, and public participation	Seven public workshops, hundreds of community members, meetings with partners and city agencies. NPCC3 members provided climate projections and interacted with community members at workshops	https://www.weact.org/campaigns/nmca/
Solar Uptown Now! (part of Solarize NYC)	Campaign to enable northern Manhattan community members to purchase solar as a group. Project helps customers choose solar installers that offer competitive, transparent pricing Partnership with Solar One, the Urban Homesteading Assistance Board, and Sustainable CUNY	Provided option to purchase solar power as a group, with objective of reducing cost of solar installation for all participants	https://solaruptownnow.org/landing/
Healthy and Sustainable Public Housing	Work with residents of NYCHA's Dyckman Houses to improve their homes and community well-being	Series of workshops with residents living in NYCHA buildings to solicit feedback on how to address environmental issues faced by the community	https://www.weact.org/dyckman/3

adaptation planning, emergency preparedness, and training in community organizing.

6.5.1.3 THE POINT CDC and Hunts Point. THE POINT Community Development Corporation (CDC), founded in 1994, is a nonprofit organization of the South Bronx. The organization is dedicated to youth development and the cultural and economic revitalization of Hunts Point. It is also an advocacy group for environmental and

Table 6.12. Selected Sunset Park community adaptation projects

Current UPROSE projects	Description	Community engagement	References
Sunset Park Climate Justice Center	Designed to create, implement, and manage community climate adaptation and resiliency planning	Gathers community members, residents, and local business leaders to participate in the planning process	https://www.uprose.org/climate-justice/
Block Captains	Recruits and trains local residents to volunteer as block captains to implement climate resiliency strategies	Takes inventories of neighborhood vulnerability and coordinates climate adaptability workshops	https://www.uprose.org/climate-justice/
Climate Justice Youth Summit	Organizes and trains young people of color to hone their engagement, social justice, and leadership skills	Hosts a 2-day annual event where young people from NYC gather to learn about environmental justice issues in their communities	https://www.uprose.org/youth-summit-2017/

Table 6.13. Selected Hunts Point community adaptation projects

Current THE POINT CDC projects	Description	Community engagement	References
Hunts Point Lifelines	Part of the Energy Resiliency Project to provide 11.6 MW of "resilient" energy generation capacity for the Hunts Point peninsula led by NYCEDC in partnership with the Mayor's Office of Recovery and Resiliency (ORR), local stakeholders, and the THE POINT CDC	Formed an advisory working group, neighborhood outreach team; held four public meetings and a community workshop	https://www.nycedc.com/project/hunts-point-resiliency-implementation
Be a Buddy NYC	The city is launching a 2-year, multistakeholder pilot to promote community cohesion. Through partnerships with community-based organizations, Be A Buddy NYC will develop and test strategies for protecting at-risk New Yorkers from the health impacts of extreme heat in the South Bronx, Central Brooklyn, and northern Manhattan	A community-led preparedness model that promotes social cohesion	https://www1.nyc.gov/assets/orr/pdf/Cool_Neighborhoods_NYC_Report_FINAL.pdf
South Bronx Community Resiliency Agency	Engage local communities in creating a comprehensive climate resilience agenda that will strengthen the physical and social resilience of the South Bronx Significant and Industrial Area (SMIA); enable THE POINT CDC to influence the next phases of Hunts Point Resiliency	Coordination with local residents and neighborhoods (e.g., Port Morris, Soundview, Mott Haven, and Longwood)	https://thepoint.org/community-development/reenvisioning/

climate justice issues in the South Bronx. THE POINT CDC engages in both nongovernmental and inclusive forms of community adaptation planning (see Table 6.13).

Specifically, its South Bronx Community Resiliency Agenda (SBCRA), which can be categorized as a nongovernmental planning effort, is engaging local communities in the creation of a comprehensive resilience plan. The SBCRA's goals are to strengthen the local capacity for community-led resilience planning and ultimately to strengthen the physical and social resilience of the South Bronx Significant Maritime and Industrial Area (SMIA) and surrounding neighborhoods (Port Morris, Soundview, Mott Haven, and Longwood).

In terms of inclusive planning, THE POINT CDC is working with the city, as a local stakeholder, with the New York City Economic Development Corporation (NYCEDC) and the Mayor's Office of Recovery and Resilience to implement a $45 million Hunts Point Lifelines project to improve coastal resilience of the region.

The Hunts Point Lifeline was developed from the Rebuild by Design competition which was funded through the Housing and Urban Development (HUD) Community Development Block Grant Disaster Recovery (CDBG-DR). It includes two feasibility studies for energy resilience and flood risk reduction, as well as a conceptual design for a resilient energy pilot project (see Table 6.13).

THE POINT CDC is also one of the three implementing partners for the city's Be a Buddy program, a climate adaptation initiative to promote community cohesion and develop and test strategies for protecting at-risk residents from health impacts of extreme heat in the South Bronx.

6.5.2 Community perspectives on procedural equity in adaptation planning

Even for those communities sought out for their input and engagement in city-led adaptation and resilience-building processes, there is a perception that existing city outreach efforts are conducted in good faith but may miss some of the ways these communities are uniquely vulnerable. In particular, these CBOs perceive that they are asked for their input and engagement often after critical decisions have been made, leaving little room for these groups and their communities to meaningfully shape development to meet their needs. In other words, these communities reported that they are often approached after policies and designs have been selected.

Some examples that the CBOs offered to support this viewpoint are recent resilience-building initiatives and development decisions that prioritize market-oriented development and ignore the equity implications of these efforts. The Hunts Point Lifelines Resiliency Project, for example, involved a year-long community engagement process that identified flood risk and resilient energy as priority areas. This process was described by the CBO as very structured and rigid, with little room left for community inputs and creative ideas. While the project is making headway toward a more economically viable coastline, community members expressed concern that the city's concept of resilience was overly focused on coastal protection and renewable energy to the exclusion of social concerns such as gentrification and displacement.

Similarly, in Sunset Park, the CBO expressed heightened concern that development and resilience projects initiated or approved by the city could potentially lead to or accelerate displacement of local residents. Specifically, the CBO pointed to the mayor's plan for a Made In NYC campus to bring back manufacturing to the waterfront. Not only did community members express that there was a lack of communication about this initiative, but they also indicated that there was a lack of engagement in the visioning process about development of the waterfront in ways that do not lead to or accelerate displacement of residents (Santore, 2017). The CBO expressed interest in linking the Made in NYC campus to a community-led regenerative energy hub project. However, the CBO also expressed concern that the city's rezoning proposals to accommodate commercial development would limit possibilities for such a project.

Thus, one consistent area of concern for each of these communities, but particularly in northern Manhattan and Sunset Park, is that city climate adaptation and resilience projects will contribute to the out-migration of long-term residents and the weakening of social networks and social capital, both necessary for creating resilient communities. Each CBO expressed a strong desire for city officials and initiatives to actively support residents through cooperative practices that build up social capital and therefore preserve vulnerable neighborhoods through equitable development practices. As Schlosberg *et al.* (2017, pp. 422–423) observe, in planning for climate adaptation, "local community groups . . . do not operate in a risk management or simple resilience framework," but rather "focus more on . . . basic needs and capabilities of every day."

Adaptation and resilience planning might entail a stronger focus on community development (e.g., building schools, safer streets, and greening space) in order to reduce the potential of displacing longtime residents and be more responsive to the social sustainability of these communities.

For instance, WE ACT has engaged in extensive climate action planning with deep community engagement and a collaborative process of identifying vulnerabilities and adaptation needs. Out of that process has emerged a focus on critical infrastructure required for emergency preparedness and resilience—including a community microgrid, neighborhood and senior facilities, cooling centers, grocery stores/food, and refrigeration for medication in an emergency.

WE ACT is also focused on energy democracy—the shift from centralized, corporate fossil fuel–generated energy to energy generated and governed by communities and that supports local economies, energy security, and the health and well-being of the people within those communities. Given this extensive planning and engagement process in place in northern Manhattan, the city could leverage these efforts to implement adaptation and resilience projects that account for both contextual and procedural equity.

The current inclusion of these CBOs and their communities in city planning processes is noted as a positive aspect of the city's approach to procedural equity. However, when asked about areas in which the city can facilitate vulnerability reduction and resilience, each partner CBO expressed some frustration with the level of participation and engagement with city agencies and staff on environmental and climate planning. As referenced earlier, there is a palpable feeling among the CBOs that the city could be a model for more meaningful and empowering inclusion of vulnerable communities (NYCEJA, 2016; NYCEJA, 2018).

In particular, each CBO expressed interest in a more fully collaborative, co-production model of equitable adaptation and resilience planning in which city officials work side by side with CBOs (and other actors) at the outset to design and implement climate adaptation and resilience planning. This model could, for example, improve the quality of planning processes focused at the neighborhood level by better incorporating the unique ways in which specific communities are both ecologically and socially vulnerable, as discussed above.

As Sarzynski (2015) has noted, the co-production or co-creation model of urban climate adaptation is underway in many countries around the world as a way to more deeply involve civil society and citizens in the provision of adaptation and resilience strategies.

Consider one prominent example from Europe to illustrate what this co-production model might resemble. In 2016, the City of Vejle, Denmark launched Europe's first Resilience Strategy, with support from the 100 Resilient Cities Program of the Rockefeller Foundation (100RC). The strategy envisions more than 100 city-wide projects or initiatives over the course of 4 years and three neighborhoods that will be used as "laboratories" for experimenting with different resilience projects. The city's strategy was produced through a process of "co-creation" that required collaboration between citizens and the municipality, including workshops where residents were invited to shape and build 3D models of what a resilient Vejle would look like, as well as to inject their priorities and concerns into the city's strategy.

Involving the community early on and inviting their broad input at the conception of a city's resilience strategy increase the chances that neighborhood participation will drive climate adaptation planning. Thus, these plans will reflect community needs and address their unique vulnerabilities (Rockefeller Foundation, 2016).

6.6. Cross-city analysis

In this section, we shift from a community-level analysis to consideration of how equity is being incorporated in urban adaptation planning at the city level in the Northeast. This cross-city analysis provides a window into how New York City and other nearby cities are incorporating principles of distributive, procedural, and contextual equity into community adaptation planning.

Many cities throughout the United States and elsewhere have recognized the importance of incorporating equity into adaptation planning. In this section, we explore how New York and other cities in the Northeast of the United States incorporate the three dimensions of equity—distributional, contextual, and procedural—in the design and implementation of climate adaptation strategies.

Information for this section is based on a review of each city's plans and targeted interviews conducted by the CBA Workgroup (see Appendix 6.B). These interviews were conducted with city officials in charge of adaptation planning and with representatives of CBOs in each city. The interview questions were focused on the issue of equitable adaptation, particularly seeking to capture the extent of community involvement during the planning and implementation process.

In addition to New York, we analyzed adaptation plans and planning processes in Boston, Baltimore, Philadelphia, and Newark (see Table 6.14). The goals of this review were to provide an overview of how equity is understood and incorporated into adaptation planning efforts in each city. The review also provided information on adaptation decision making and governance in each city as well as the stakeholders involved.

6.6.1 Adaptation planning in northeast cities

All five cities are engaged in a number of different types of climate adaptation planning. In some cases, these efforts are designed as standalone city plans that target climate change preparedness (e.g., Climate Ready Boston, Baltimore Climate Action Plan). In other cases, planning for the impacts of climate change is incorporated into larger sustainability planning efforts (e.g., OneNYC, Resilient Boston, Newark Sustainability Action Plan). Two of the

Table 6.14. Selected city adaptation and policy plans

City	Population	Plan
New York City	8.623 million	OneNYC: The Plan for a Strong and Just City (2015); OneNYC Progress Reports (2016, 2017, and 2018)
		New York City Panel on Climate Change (NPCC) Report: Building the Knowledge Base for Climate Resiliency (2015)
		New York City Panel on Climate Change Report (NPCC): Building a Risk Management Response (2010)
		New York City Special Initiative on Recovery and Resiliency (NYC SIRR) (2013)
Boston	685,094	Greenovate Boston: Climate Action Plan Update (2014)
		Climate Ready Boston (2016)
		Resilient Boston: An Equitable and Connected City (2017)
Baltimore	611,458	Baltimore Climate Action Plan (CAP) (2013)
		City of Baltimore: Disaster Preparedness and Planning Project, A Combined All-Hazards Mitigation and Climate Adaptation Plan (2013)
		The Baltimore Sustainability Plan (2018) (Final Draft)
Newark	285,154	The City of Newark: Sustainability Action Plan (2013) (currently being updated)
Philadelphia	1.581 million	Growing Stronger: Toward a Climate-Ready Philadelphia (2015)
		Greenworks: A Vision for a Sustainable Philadelphia (2016)

cities—Boston and New York—are participants in the Rockefeller 100 Resilient Cities project; Boston's adaptation plans were developed in collaboration with the Rockefeller program. Several of the cities are also members of the C40 and ICLEI networks.

Each of these cities is also engaged in a number of specific projects that entail community-based climate change adaptation planning. These projects are initiated and managed through a variety of different agencies in each city, including the offices of planning, sustainability, emergency management, housing, and health. The projects generally emphasize specific types of adaptation actions such as post-disaster recovery, heat warnings and/or reduction of the effects of extreme heat, and flood protection. All of the cities participated in adaptation projects funded by the Kresge Foundation that entailed collaboration between cities and communities in the design of community-based adaptation projects. Table 6.15 outlines these initiatives across the five cities.

Each of the cities incorporates, to some degree, recognition of equity in both their citywide and community-based adaptation planning efforts. The goal of the CBA Workgroup's analysis was to determine whether there are lessons, insights, and/or effective practices that could be gleaned from each of these city's efforts to incorporate equity into adaptation planning. More specifically, the focus was on extracting from these cities' plans and planning processes whether and how each dimension of equity manifests and is operationalized.

6.6.1.1 Distributional equity in city adaptation planning. Each of the cities studied intentionally and explicitly adheres to the principle of distributional equity in its adaptation planning documents and program descriptions (see Tables 6.15 and 6.16). They do so, first, by targeting their programs and initiatives toward disadvantaged and socially vulnerable neighborhoods and populations. A number of these plans and programs entail documenting vulnerability to climate change stressors at the neighborhood level.

The 2016 Climate Ready Boston and the 2015 Climate-Ready Philadelphia plans, for example, both use spatial indicators of neighborhood vulnerability in order to document the locations of socially vulnerable populations as a part of their climate assessment processes (Boston Department of the Environment, 2016; Philadelphia Office of Sustainability and ICF International, 2015).

New York's Cool Neighborhood program and the City of Baltimore's plan target socially vulnerable populations in an effort to identify neighborhoods that are likely to be disproportionately exposed to extreme heat (City of New York, 2017b; Baltimore Office of Sustainability, 2013b).

In addition to utilizing social vulnerability mapping tools to identify vulnerable populations,

Table 6.15. Selected city adaptation projects and initiatives

Project/initiative name	Description	Municipal agencies in charge and/or nongovernmental organizations involved
New York City		
Hurricane Sandy Houses of Worship & Charitable Organization Recovery Task Force (2017)	Established by Mayor de Blasio to better understand the role of faith-based organizations, nonprofit organizations, and other community-based organizations in Hurricane Sandy recovery efforts. http://www1.nyc.gov/assets/orr/images/content/header/Hurricane-Sandy-Recovery-Task-Force-Report-April-2017.pdf	New York City Council; Mayor's Office of Recovery and Resiliency; NYC Office of Emergency Management
NYC Flood Hazard Mapper (2017)	Online interactive mapping product that provides a comprehensive overview of the extent of existing and future coastal flooding. https://www.floodhelpny.org/	NYC Department of City Planning
NYC CoolRoofs (2009)	Citywide initiative that provides local job-seekers with training and work experience installing energy-saving reflective rooftops. Also supports the City's goal to reduce carbon emissions 80% by 2050 (80 × 50). Has short-term focus on communities with highest heat-related health risks. https://www1.nyc.gov/nycbusiness/article/nyc-coolroofs	NYC Department of Small Business Services; Mayor's Office of Sustainability; Mayor's Office of Recovery and Resiliency; Sustainability South Bronx
NYC Solar Partnership (made up of two programs, Solarize NYC and Shared Solar NYC (2016))	Solarize NYC program: short-term, local, community-led initiative that connects communities with solar installers. Designed to reduce barriers for communities that have historically had limited access to solar by providing informal resources and offerings at discounted pricing Shared Solar NYC program: designed to connect interested customers (e.g., renters and homeowners) with community-shared solar systems. https://www.nycedc.com/program/nyc-solar-partnership	Sustainable CUNY of the City University of New York; New York City Economic Development Corporation; Mayor's Office of Sustainability
NYC Resilient Neighborhoods (2013)	Place-based planning initiative to identify neighborhood-specific strategies, including zoning and land-use changes. Focus on preparedness and resilience in communities located in floodplains. http://www1.nyc.gov/site/planning/plans/resilient-neighborhoods.page	NYC Department of City Planning; Mayor's Office of Recovery and Resiliency; Housing Recovery Operations; NYC Department of Environmental Protection
Cool Neighborhoods Program (2017)	Designed to curb effect of extreme heat in neighborhoods identified as vulnerable to heat-related health risks. Heat Vulnerability Index (2017) used to identify high-risk neighborhoods. http://www1.nyc.gov/assets/orr/pdf/Cool_Neighborhoods_NYC_Report_FINAL.pdf	Mayor's Office of Recovery and Resiliency; NYC Department of Parks & Recreation; NYC Department of Health; NYC Department of Small Business Services; NYC Office of Emergency Management: Columbia University; members of nonprofit and private sectors

Continued

Table 6.15. ***Continued***

Project/initiative name	Description	Municipal agencies in charge and/or nongovernmental organizations involved
Boston		
Climate Ready Boston (2016)	Ongoing initiative to help neighborhoods and communities plan for future climate change impacts and develop resilient solutions Targets communities that have highest flood risks and high concentrations of vulnerable residents and critical infrastructure (e.g., East Boston, Charlestown, South Boston). https://www.boston.gov/departments/environment/climate-ready-boston	Boston Environment Department; Boston Planning and Development Agency; Massachusetts Office of Coastal Zone Management; the Barr Foundation
Climate Ready Boston Map Explorer (2017)	Mapping tool to explore risks of flooding and extreme heat and how these risks intersect with social factors. https://www.boston.gov/departments/environment/climate-ready-boston-map-explorer	Boston Environment Department
Moakley Park Vision Plan (2018)	Vision plan for Moakley Park in South Boston (60 acres) to serve as coastal protection site and prevent future flooding of nearby homes. https://www.boston.gov/departments/parks-and-recreation/moakley-park-vision-plan	Boston Parks and Recreation Department
Baltimore		
"Every Story Counts" Campaign (2017)	Initiative that seeks to promote equity and inclusion in building a more sustainable and resilient Baltimore. http://www.baltimoresustainability.org/every-story-counts/	Baltimore Office of Sustainability 2016
Code Red Heat Alert Plan (2011)	Multiagency-coordinated approach to provide cooling relief to vulnerable populations in the city during a heat crisis. https://health.baltimorecity.gov/coderedinfo	Baltimore City Department of Health
Baltimore Green Network Vision (2018)	Vision plan that promotes urban resilience through land-use equity to increase urban green infrastructure and amenities in underinvested neighborhoods (draft plan under review). http://greennetwork.Civicomment.org/	Baltimore Department of Planning
Newark		
Cumulative Impact Ordinance and Zoning Amendments (2016)	Legislation passed by the City Council of Newark that considers environmental justice implications in land use and zoning regulations, aiming to reduce health disparities in low-income residents and people of color. https://newark.legistar.com/LegislationDetail.aspx?ID=2770971&GUID=D0C566D0-463A-482D-A4AC-78884351DA79&FullText=1	Newark Department of Planning and Zoning

Continued

Table 6.15. *Continued*

Project/initiative name	Description	Municipal agencies in charge and/or nongovernmental organizations involved
Prepared Together (2018)	Initiative that contains series of impact volunteering projects to build community resilience via green infrastructure and disaster preparedness education and outreach. Projects include Sustainable Stormwater Stewards, Newark Tree Count, and Extreme Weather Event Preparedness. https://www.newarknj.gov/card/prepared-together	Newark Office of Sustainability; Environmental Commission; municipal departments; Newark community members
Philadelphia		
Greenworks Equity Index (2018)	Program to identify underserved communities affected by disproportionate impacts of environmental stressors as well as build community adaptive capacity and climate resiliency. https://beta.phila.gov/departments/office-of-sustainability/greenworks/greenworks-equity-index/	Philadelphia Office of Sustainability
Ready Philadelphia (2017)	Program that guides residents to create emergency plans for extreme weather events on the block level. https://beta.phila.gov/departments/oem/programs/readyphiladelphia/	Philadelphia Office of Emergency Management
Greenworks Dashboard (2017)	Visualization tool that allows users to view data about Greenworks sustainability visions (e.g., food and drinking water, health, outdoor and indoor air quality, clean and efficient energy). https://cityofphiladelphia.github.io/greenworks-dashboard/	Philadelphia Office of Sustainability; Office of Open Data and Digital Transformation

and specifically disproportionate exposure to climate stressors and other environmental hazards, many of these cities also seek to address distributional inequities in the provision of environmental amenities. These cities specifically target the provision of green infrastructure to socially vulnerable neighborhoods. Efforts to develop green flood protection, stormwater management, and waterfront parks are particularly evident in Boston, New York, and Philadelphia. Additionally, Newark is making efforts to pilot these types of projects in some of its historically vulnerable communities.

Along with programs intended to reduce disproportionate exposure and vulnerability to climate stressors, all of the cities have programs in place to enhance local environmental quality in disadvantaged neighborhoods. These programs also emphasize improvement of baseline environmental conditions through programs designed, for example, to improve air quality, remediate brownfields, or enhance access to public transportation and solar energy.

6.6.1.2 Contextual equity in city adaptation planning. Contextual equity is acknowledged in several ways in all of the cities' adaptation planning efforts. All of the cities studied acknowledge in their planning documents and efforts the legacy of structural racism and the ways that it shapes current social, economic, political, and environmental disparities in low-income and minority communities and populations. In some cases, it is a core principle guiding a city's effort.

Most of the cities incorporate attention to equity in their hiring practices via commitment to maintaining a diverse workforce in city agencies. Less common practices include direct linkage of adaptation plans to broader inequalities, designing co-benefits for low-income and minority residents,

Table 6.16. Programs and activities in northeastern U.S. cities, intended to address distributive equity (identified based on review of planning documents)

Program areas	Baltimore	Boston	Newark	New York City	Philadelphia
Air quality	X	–	X	X	X
Affordability of flood insurance	–	–	–	X	–
Brownfield remediation	X	X	–	X	–
Building community capacity	X	X	–	X	X
Community land trust	X	–	X	–	–
Community vulnerability assessment	X	X	–	X	X
Energy retrofitting	X	–	–	X	X
Equitable access to recycling	–	–	–	X	X
Equitable access to solar energy	X	X	–	X	X
Equitable access to transportation	X	–	–	–	–
Green infrastructure	X	X	X	X	X
Toxic hotspots	–	–	–	X	–
Indoor health hazards	X	–	X	X	–
Youth and school programs	X	X	–	–	–

Note: Distributive equity emphasizes disparities across social groups, neighborhoods, and communities in vulnerability, adaptive capacity, and the outcomes of adaptation actions.

and the hiring of equity consultants for training of city staff.

One example of how contextual equity is manifested in adaptation planning is through the use of vulnerability assessments that go beyond indices and indicators to capture the unique ways that historical legacies and contemporary social and economic processes shape the vulnerability of particular neighborhoods.

Thus, for example, New York City engages in neighborhood vulnerability assessments, employing the case study method to identify the social issues that affect people at the neighborhood level, and consults with community resilience focus groups to structure the case studies. As is evident in this report, case studies can be useful in understanding the dynamics underlying neighborhood vulnerability and in gaining better insights into how adaptation planning can produce co-benefits for vulnerable populations.

6.6.1.3 Procedural equity in city adaptation planning. All of the city plans recognize the need for procedural equity in adaptation planning (see Table 6.17). These efforts reflect elements of both traditional and inclusive planning. The most common ways that cities engage with communities in adaptation planning are through community meetings and inclusion of community representatives and organizations as part of advisory boards. Four of the five cities engage in both of these practices. Three of the cities conduct public forums and workshops. Less-common approaches to procedural equity include youth convening and avoidance of overly technical language, both of which are practiced only by Baltimore.

There is evidence of many strong collaborative relationships between city officials engaged in adaptation planning and CBOs in cities like New York, Boston, and Newark. In some cities, based on our interviews with city officials and CBO representatives, we were able to identify public engagement processes that resemble higher levels on Arnstein's ladder of citizen participation (see Fig. 6.10 in Section 6.5) and even those that resemble Sarzynki's co-production model (see Box 6.3 in Section 6.5). In each of these cases, capacity—both the city's and that of the CBO—turns out to be a significant variable.

In particular, established or relatively well-resourced (e.g., foundation supported) CBOs are able to not only engage in their own adaptation planning processes, but also, when given the chance, they substantively and substantially shape their city's plan and implementation. They can help the city design adaptation plans and projects that do not duplicate existing community-based efforts, but rather leverage them.

Table 6.17. Activities and programs in northeastern U.S. cities intended to address procedural equity (identified based on the review of planning documents)

Program areas	Baltimore	Boston	Newark	New York City	Philadelphia
Avoidance of overly technical language	X	–	–	–	–
Community representatives and organizations on advisory boards	X	X	X	X	–
Community meetings	X	X	–	X	X
Public, telephone, and online surveys	X	–	–	X	X
Public forums and workshops	X	X	–	X	–
Youth convening	X	–	–	–	–

NOTE: Procedural equity emphasizes the extent and robustness of public and community participation in adaptation planning and decision making.

In some instances, as is the case in one city we studied, CBOs can have significant influence in crafting plans where the city itself is consistently strapped for resources and funding. CBOs and communities play a watchdog roll, functioning in some areas not covered in city programs.

6.6.2 *Summary and insights on effective practices for equitable adaptation planning*

Our examination of adaptation plans and practices in northeastern cities provided a number of insights on how equity can be incorporated into adaptation planning. Every city recognizes that all three types of equity are an important component of adaptation planning. In practice, however, the cities largely emphasized distributional equity in these efforts, through documentation of the locations of socially vulnerable neighborhoods and targeting of adaptation projects and initiatives toward disadvantaged and socially vulnerable communities.

While the cities recognize the importance of contextual equity, specific strategies to address underlying drivers of such inequalities are relatively limited. Most city efforts to address contextual inequalities focus on ensuring diversity in hiring practices.

Regarding procedural equity, there is evidence of collaboration and co-production in some city-based adaptation efforts. However, efforts to incorporate procedural equity more typically followed traditional planning or blend elements of traditional and inclusive planning.

All of the cities display elements of effective practices for incorporating distributional equity in their adaptation planning. While elements of contextual and procedural equity are also evident in some of these efforts, incorporation of all three elements of equity into community adaptation planning is still an aspiration for all of the cities. Incorporation of all three equity elements represents an important goal for ensuring equity in future community-based adaptation planning efforts.

6.7. Conclusions and recommendations

This chapter explored equity in community-based adaptation planning in New York City. The chapter adopted an equity framework that incorporated three key dimensions of equity, including distributional, contextual, and procedural equity. Distributional equity emphasizes disparities across social groups, neighborhoods, and communities in vulnerability, adaptive capacity, and outcomes of adaptation actions. Contextual equity considers how social, economic, and political factors and processes contribute to vulnerability and shape adaptive capacity. Procedural equity emphasizes the extent and robustness of public and community participation in adaptation planning and decision making.

Key Findings

- A framework for equitable adaptation to climate change requires incorporation of distributional, contextual, and procedural equity in adaptation planning.
- Social vulnerability to climate change stressors is unequally distributed across New York City; high levels of social vulnerability are consistently found in areas with lower incomes and higher shares of African-American and Hispanic residents.
- Collaboratively produced case studies (northern Manhattan; Hunts Point, South Bronx;

Sunset Park, Brooklyn) demonstrate that high levels of social vulnerability to climate change overlap with disproportionate exposure to environmental pollution, health stressors, and gentrification pressures.
- New York City communities are involved in many forms of adaptation planning (e.g., traditional government led, inclusive, nongovernmental) but express a desire for deeper engagement with the city via use of fully collaborative, co-production planning approaches.
- Cross-city analysis reveals that New York and other cities in the Northeast are incorporating all three forms of equity in their adaptation planning, but largely emphasize distributional equity in these efforts.

Recommendations for New York City

- There should be future tracking of social vulnerability through the proposed New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM); this tracking may be accomplished using index-based methods such as SoVI or SVI, through individual variables, or via a combination of approaches.
- All forms of equity should be reflected in climate adaptation efforts, particularly if resilience planning is focused at the neighborhood level.
- Local communities should be involved earlier and more often in order to understand local context and ensure procedural equity in climate adaptation planning.
- City officials should work side by side with communities at the outset to codesign and coimplement neighborhood-based climate adaptation projects.
- Climate change adaptation projects should contain a stronger focus on community development to reduce the potential of displacing longtime residents and to promote the social sustainability of local communities.

Recommendations for Research

This examination of equity in climate change adaptation planning revealed several areas where further investigation is warranted. While this chapter focused primarily on adaptation planning efforts and specific projects, there is a need for further attention to, and analysis of, equity issues surrounding the implementation of adaptation plans. This includes recognition of equity issues associated with decisions about how projects are selected and implemented as well as equity issues that may arise from the unintended consequences of these efforts.

There is also a need to consider the equity consequences of city- and region-wide adaptation planning efforts. Large-scale barriers, flood control measures, and other projects will have differential effects across neighborhoods and communities, and will require community input in all phases of planning. All three forms of equity identified in this chapter should be taken into account when planning the types of large-scale adaptations that may ultimately be needed to prepare New York City for climate change.

- There is a need for further investigation of optimal methods to track both social vulnerability to climate change and resilience at the community scale.
- There is a need for further investigation of the use of co-production planning models in the climate context and their adaptability to NYC.
- There is a need for further investigation of the equity impacts of climate change adaptation projects, including both community-specific projects and city- and region-wide efforts, such as proposed regional storm surge barriers.
- There is a need for further investigation of potential linkages and synergies between adaptation and mitigation planning and community equity.

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Appendix 6.A

Social indicators used in SoVI and SVI

Table 6.A.1. Twenty-nine social indicators used in SoVI 2010–2014 (HVRI, 2018b)

Indicators in Social Vulnerability Index (SoVI) 2010–2014
1. Percent Asian
2. Percent African-American
3. Percent Hispanic
4. Percent Native American
5. Percent population under 5 years or 65 and over
6. Percent children living in married couple families
7. Median age
8. Percent households receiving Social Security benefits
9. Percent poverty
10. Percent households earning over $200,000 annually
11. Per capita income
12. Percent speaking English as a second language with limited English proficiency
13. Percent female
14. Percent female headed households
15. Nursing home residents per capita
16. Hospitals per capita (county-level only)
17. Percent of population without health insurance (county-level only)
18. Percent with less than 12th grade education
19. Percent civilian unemployment
20. People per unit
21. Percent renters
22. Median housing value
23. Median gross rent
24. Percent mobile homes
25. Percent employment in extractive industries
26. Percent employment in service industry
27. Percent female participation in labor force
28. Percent of housing units with no car
29. Percent of unoccupied housing units

Table 6.A.2. Selected examples of SoVI-based indexing and mapping

Index name	Data and geography	Number of indicators and methodology	Risks and hazards	References
Social Vulnerability Mapping of the Southeastern States in the United States (2009) for OXFAM	Data from U.S. Census (2000) and American Community Survey (2005–2009). County level for 13 U.S. southeastern states	32 indicators (from an outdated SoVI 2000 modified edition); Principal component analysis (PCA)	Environmental hazards focusing on climate-related hazards (i.e., drought, flooding, hurricane-force winds, and sea level rise)	OFXAM (2009) and Emrich and Cutter (2011)
Social Vulnerability to Climate Change in California (2012)	Data from U.S. Census (2000) and American Community Survey (2005–2009). Tract level for the state of California	19 indicators (reduced from SoVI 2000 modified edition's 32 to 19 indicators based on the Project Advisory Committee); Principal component analysis (PCA)	Environmental hazards focusing on climate-related hazards (i.e., extreme heat, wildfire risk, coastal flooding from sea level rise, and air quality)	Cooley et al. (2012)
Social Vulnerability Index for the State of New Jersey (2015)	Data from U.S. Census (2010) and American Community Survey (2006–2010). Tract level for New Jersey	30 indicators (29 indicators came from the SoVI 2006–2010 edition and 1 non-SoVI indicator); Principal component analysis (PCA)	Environmental hazards focusing on climate-related hazards (i.e., flooding)	Pflicke et al. (2015)

Table 6.A.3. The 15 social indicators used in the SVI (Flanagan et al., 2011)

Indicators in Social Vulnerability Index (SVI)
Socioeconomic status
1. Persons below poverty
2. Civilians (age 16+) unemployed
3. Per capita income
4. Persons (age 25+) with no high school diploma
Household Composition and Disability
1. Persons aged 65 or older
2. Persons aged 17 or younger
3. Civilian with a disability
4. Single-parent household
Minority Status and Language
1. Minority (all persons except white, non-Hispanic)
2. Persons (age 5+) speaking English "less than well"
Housing and Transportation
1. Multiunit housing (10+ units)
2. Mobile homes
3. Crowding (household level, more people than rooms estimate)
4. Households with no vehicle
5. Persons in institutionalized group quarters

Table 6.A.4. Selected examples of SVI-based indexing and mapping

Index name	Data and geography	Number of indicators and methodology	Risks and hazards	References
Social Vulnerability Index (SVI) for Seattle and King County (2013)	Data from U.S. Census 2010 and American Community Survey (2006–2010). Census tract level for Seattle and King County	15 indicators Percentile ranking	Environmental hazards	SVI Seattle-King County (2013)
Social Vulnerability Index (SVI) for the City of Washington, North Carolina (2015)	Data from U.S. Census 2010. Block group level for Washington, North Carolina	12 indicators (three indicators excluded due to lack of available data at block group level) Percentile ranking	Environmental hazards focusing on climate-related hazards (e.g., flooding and sea level rise)	Berke et al. (2015)
Media outlets referencing the Center for Disease Control Social Vulnerability Index (CDC SVI) in post-Houston flood (2017)	Data from U.S. Census (2010) and American Community Survey (2010–2014). Tract level in New York State and New York City	15 indicators Percentile ranking	Environmental hazards	Misra (2017) and Deaton (2017)

NOTE: Demographic and social profiles of case study communities. Northern Manhattan consists of Hamilton Heights, Manhattanville, and West Harlem (Manhattan CD 9 / PUMA 3802); Central Harlem (Manhattan CD 10 / PUMA 3803); East Harlem (Manhattan CD 11 / PUMA 3804); and Washington Heights, Inwood, and Marble Hill (Manhattan CD 12 / PUMA 3801). Sunset Park consists of Sunset Park and Windsor Terrace (Brooklyn CD 7 / PUMA 4012). Hunts Point consists of Melrose, Mott-Haven, Port Morris (Bronx CD 1), and Hunts Point and Longwood (Bronx CD 2); PUMA 3710 approximately represents Bronx CD 1 and 2. Demographic data were collected from the New York City Department of City Planning. Data came from the 2012 to 2016 American Community Survey 5-Year Estimates.

Table 6.A.5. Demographic makeup of northern Manhattan (NYC DCP, 2018)

Northern Manhattan	Northern Manhattan estimate 2016	Northern Manhattan growth/decline between 2000 and 2016	Northern Manhattan estimate percent (%) 2016	Manhattan estimate percent (%) 2016	New York City estimate percent (%) 2016
Total population	607,096	11.4%	100.0%	100.0%	100.0%
White non-Hispanic	112,330	90.9%	18.5%	47.1%	32.3%
Black non-Hispanic	159,073	−10.2%	26.2%	12.6%	22.2%
Asian and Pacific Islander non-Hispanic	30,336	113.9%	5.0%	11.7%	13.6%
Other non-Hispanic	3537	14.4%	0.6%	0.5%	1.1%
Two or more race non-Hispanic	11,666	20.8%	1.9%	2.2%	1.8%
Hispanic origin	290,154	2.9%	47.8%	25.9%	29.0%

Table 6.A.6. Demographic makeup of Sunset Park, Brooklyn (NYC DCP, 2018)

Sunset Park	Sunset Park estimate 2016	Sunset Park growth/decline between 2000 and 2016	Sunset Park estimate percent (%) 2016	Brooklyn estimate percent (%) 2016	New York city estimate percent (%) 2016
Total population	151,258	26.0%	100.0%	100.0%	100.0%
White non-Hispanic	33,714	23.2%	22.3%	35.8%	32.3%
Black non-Hispanic	3917	−6.8%	2.6%	30.9%	22.2%
Asian and Pacific Islander non-Hispanic	48,965	134.2%	32.4%	11.6%	13.6%
Other non-Hispanic	632	−31.7%	0.4%	0.6%	1.1%
Two or more race non-Hispanic	1754	−47.2%	1.2%	1.7%	1.8%
Hispanic origin	62,276	−1.7%	41.2%	19.4%	29.0%

Table 6.A.7. Demographic makeup of Hunts Point-Mott Haven, South Bronx (NYC DCP, 2018)

Hunts Point-Mott Haven	Hunts Point-Mott Haven estimate 2016	Hunts Point-Mott Haven growth/decline between 2000 and 2016	Hunts Point-Mott Haven estimate percent (%) 2016	Bronx estimate percent (%) 2016	New York City estimate percent (%) 2016
Total population	161,319	25.1%	100.0%	100.0%	100.0%
White non-Hispanic	2567	52.9%	1.6%	9.6%	32.3%
Black non-Hispanic	45,438	45.2%	28.2%	29.5%	22.2%
Asian and Pacific Islander non-Hispanic	1298	107.0%	0.8%	3.6%	13.6%
Other non-Hispanic	1182	102.7%	0.7%	0.9%	1.1%
Two or more race non-Hispanic	842	−22.8%	0.5%	1.0%	1.8%
Hispanic origin	109,992	17.4%	68.2%	55.4%	29.0%

Appendix 6.B

Interview Guide for Cross-City Analysis

1. On the Community Engagement Process

This set of questions is designed to explore the experience of initiating and carrying out the engagement process between city officials, researchers, and community representatives.

- Who initiated the community engagement process? How? Why?
- Did you reach out to, or engage, the community in connection with a project or proposal?
    - If so, did the project envision a collaborative relationship with the community in shaping the project, or was the project already in place before the community engagement process was initiated?
- What were the guiding principles or goals/objectives for community engagement?
    - Equity? Inclusion? Participation? Collaboration?
- What did the community engagement process entail?
    - What were the outreach strategies? How did the participants become involved?
    - What were the meeting formats? Workshops? Meetings? What were their goals/objectives? What were the outcomes?
- What were the community representatives' concerns regarding climate change impacts/stressors? Did they mention other non-climate stressors, specifically those related to social or economic vulnerabilities?
- How did community feedback and local knowledge get integrated or taken into consideration on this particular project or other projects?
- Were there other institutions or entities (from civil society, nonprofit sector, universities or other researchers, private sector, or government) that you involved in the community engagement process?
    - If so, how and why did you choose particular institutions or entities to get involved with the community in the project/process?
    - What were their respective roles in the community engagement process or in the project overall?
- What is your assessment of the success of the community engagement process? Are there things you could or would have done differently? Why?

2. On the Collaborative Community-based Adaptation Framework

This set of questions is designed to solicit feedback and opinion on a set of protocols for community engagement in adaptation and resiliency planning that takes collaboration and equity into consideration

- What are, or should be, the criteria for measuring community-led adaptation efforts?
    - Inclusion? Equity? Participation? Collaboration? Efficiency? Effectiveness?
    - Is there a framework that you already use for guidance?
- Based on your experience, what is the best entry point for local governments and other public officials to engage with communities on climate resiliency efforts?
- Do you have any thoughts on how best to create a good process for collaboration that engages communities at the beginning of the planning process for resiliency?
- Do you think it would be useful to have a set of protocols for this kind of collaborative community engagement process with equity as a strong component?

Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report Chapter 7: Resilience Strategies for Critical Infrastructures and Their Interdependencies

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Contents

7.1 Introduction

Climate change poses many challenges to infrastructure in New York City. This chapter builds upon the work on climate change and critical infrastructure systems presented in the first and second New York Panel on Climate Change (NPCC) reports (NPCC, 2010, 2015), and provides new directions, updates, and considerations. Key concepts and definitions for resilience and vulnerability are found in Box 7.1. NPCC (2010) covered infrastructure by inventorying selected New York City facilities and their vulnerability to climate change. Vulnerabilities were described primarily in terms of outages and other disruptions, and covered a wide range of climate hazards, with a particular focus on exposure to sea level rise. NPCC2 (2015) did not have a separate chapter titled infrastructure, and infrastructure dimensions were distributed throughout the report.

In addition to building upon the previous work of the NPCC, many other New York City efforts are integrated in this chapter and others such as *PlaNYC* (City of New York, 2013), *OneNYC* (City of New York, 2015), the *1.5 Celsius Aligning NYC with the Paris Climate Agreement* report (City of New York, September, 2017), the NYC Mayor's Office of Recovery & Resiliency *Climate Resiliency Design Guidelines* (NYC Mayor's ORR, April 2018) summarized in Box 7.2, and the NYC Office of the Mayor *Mayor's Management Report* (2017, 2018). New York State reports particularly following Hurricane Sandy (e.g., NYS, 2013) and U.S. Department of Homeland Security (DHS) reports (U.S. DHS, 2013, 2015) are also key sources.

The goals of this chapter on critical infrastructures are to:

- Place climate change challenges in the context of current infrastructure usage and condition in New York City as these characteristics contribute to infrastructure vulnerability
- Provide insights on dependency and interdependency among NYC's infrastructure systems
- Present case studies of how infrastructure and climate change intersect at the community level
- Explore insurance and finance issues related to infrastructure resiliency in the face of climate change

doi: 10.1111/nyas.14010

Box 7.1. Resilience and vulnerability in the context of infrastructure

Resilience: Resilience is a core concept throughout the infrastructure and climate change theme. Resilience generally refers to the ability of systems, whether networked, interdependent, or independent, to return to some state after experiencing a disturbance and/or adopting processes that promote those readjustments. That state can either be the state prior to the disturbance or to a different state that can resist adverse effects of disturbances (Vale, 2014), resist change altogether, or prepare, respond, and recover from disturbances (NYC Mayor's Office of Recovery and Resiliency (ORR) 2018 Climate Resiliency Design Guidelines; City of New York, 2013). Resilience is often associated with vulnerability.
Vulnerability: A review of the concept of vulnerability by Adger (2006: 268) defined vulnerability in the context of changing conditions or threats as "the state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt" referencing both processes and outcomes. For infrastructure, aspects of vulnerability emphasized in this chapter are: its initial condition and its usage relative to its capacity, both of which influence the extent to which infrastructure is exposed to a threat and can resist or adapt to it maintaining at least its initial functions (Gallopín, 2006; Farmani and Butler, 2013; Zimmerman, 2016).

- Link resiliency to mitigation of greenhouse gas (GHG) emissions as well as to adaptation

This chapter focuses on infrastructure categories, typically referred to as "lifelines," for example, energy, transportation, telecommunications, water, and waste and sewers, that are considered "essential to the operation of most critical infrastructure sectors" (U.S. DHS, 2013: 17) and social infrastructure. Dependencies and interdependencies among infrastructures are another dimension addressed in addition to the individual sectors, and are defined in Box 7.3.

Selected infrastructure properties that create potential vulnerabilities for infrastructure in the context of climate change are described in Box 7.4.

This chapter on critical infrastructures is closely linked to Chapter 8, Indicators and Monitoring, and provides additional detailed references for that chapter. This chapter sets forth vulnerabilities of the critical infrastructure systems in New York City to key climate extremes, and Chapter 8 describes how to track those vulnerabilities and proposes the creation of the New York Climate Resiliency Indicators and Monitoring System to do so.

In Section 7.2, infrastructure issues are examined with regard to the climate variables that are described in Chapters 2–4: (1) extreme heat, (2) cold snaps, (3) heavy downpours, (4) drought, (5) sea level rise and coastal flooding, and (6) extreme winds. This list of variables updates those that were identified in NPCC1 (NPCC, 2010). The impacts identified in this chapter provide the basis for and are directly linked to the infrastructure indicators and metrics in Chapter 8. In Section 7.3, key infrastructure vulnerabilities are addressed, first for individual infrastructures, with and without

Box 7.2. NYC design guidelines for climate resiliency

NYC Climate Resiliency Design Guidelines: In April 2017, the NYC Mayor's ORR released a draft of its "Climate Resiliency Design Guidelines," which was finalized in 2018 (NYC Mayor's ORR, 2018). The Guidelines' purpose is to provide guidance on "how to use the range of climate projections in design" in order to promote resilience (NYC Mayor's ORR, 2018: 5) across the useful life of a facility in light of three climate elements: heat, precipitation, and sea level rise. The Guidelines indicate the need to coordinate with other guidance in connection with special funding and other requirements and considerations (NYC Mayor's ORR, 2018). Procedures are provided to select climate data, analyze risk, consider uncertainty, conduct sensitivity analyses, and identify and analyze design-related interventions depending on what the particular facility is, its useful life, and where it is located.

Box 7.3. Infrastructure dependencies and interdependencies

The concept of dependencies and interdependencies among infrastructure sectors and between infrastructure and the economy and society was identified by Rinaldi *et al.* (2001), expanded in subsequent literature, and has increasingly been drawing the attention of infrastructure managers, infrastructure finance organizations, and disaster management agencies. Infrastructure interdependencies may not always have appeared to be a direct component of climate-related infrastructure concerns; however, the focus on interdependencies is emerging in the examples, scenarios, and guidelines being used to connect climate and infrastructure.

According to Rinaldi *et al.* (2001), dependencies refer to a one-way relationship where one type of infrastructure depends on another but the reverse does not occur. Interdependencies connote at least a bi-directional relationship and can have a more complex structure when numerous infrastructure systems are involved. These concepts have since been carried forward into policy and planning documents, for example, into the sector-specific plans developed by the U.S. DHS for infrastructure (U.S. DHS, 2013; U.S. DHS, 2015). These documents and subsequent work have articulated various types of such interconnections involving, for example, spatial proximity, functional dependency, and information control, and the interconnections have formal properties that involve flows of people, goods, and information applicable to many infrastructure sectors (Rinaldi *et al.*, 2001; U.S. DHS, 2015). These different types of interdependencies often occur simultaneously.

The effects of these interconnections on system operations include what happens system-wide when a particular node (infrastructure component) or link (infrastructure route) upon which other systems rely becomes disabled. This partially explains why extreme events are a useful perspective for identifying infrastructure vulnerabilities. Metrics exist to characterize these relationships (which are addressed in Chapter 8: Indicators and Monitoring). Concepts and models for interdependencies have been developed and applied across a number of lifeline sectors, potentially applicable to climate change (Zimmerman *et al.*, 2016, 2017, 2018; Zimmerman *et al.*, 2017 and numerous references therein).

Interdependencies have typically started with electric power, since it is used by practically all sectors either directly or indirectly, and electric power in turn relies on those other sectors. Electricity is used by the transportation sector for road-based systems to power lights, signals, and fuel pumps, and for rail-based systems to power signals, switches, and third rails and catenary lines to power trains (Zimmerman and Restrepo, 2009). Energy is vital to the water sector for the operation of pumps for those portions of the water supply system not operating by gravity and for intermittent pumping operations to dewater equipment that is flooded. Transportation in turn enables workers and supplies to be transported to facilities and services that are critical components of electric power and other infrastructures. Water is needed for power production and other processing functions, where they occur, as well as providing water for worker consumption. Telecommunications connect with all critical infrastructures for purposes of detecting system states and anomalies, controlling and managing infrastructure systems, and communication of information to deploy resources, and in turn relies on other infrastructure, particularly electric power, to function.

climate change in Sections 7.3.1 and 7.3.2 and then for infrastructure dependencies and interdependencies with and without climate change, respectively, in Sections 7.3.3 and 7.3.4.

In Section 7.4, social infrastructure and related community issues are presented for two case studies that illustrate how infrastructure interfaces with communities, providing a model or benchmark for other cases. New finance and insurance mechanisms that have emerged to reduce vulnerability are introduced in Section 7.5. Section 7.6 briefly links infrastructure strategies to mitigation. In Section 7.7, conclusions and recommendations are presented that synthesize some of the major findings and suggest new directions.

Appendices present background information for selected New York City infrastructure sectors (Appendix 7.A), a compendium of adaptation measures (Appendix 7.B), acknowledging the need to balance risk, cost, and uncertainty in implementation decisions, and the progress toward NYC's commitment to reduce GHG emissions 80% by 2050 (Appendix 7.C). The section on adaptation reflects part of a trend toward innovative urban transformation emerging as a new direction for infrastructure adaptation (Solecki *et al.*, 2018).

Box 7.4. Selected infrastructure properties

Condition: The condition of infrastructure is assessed in many different ways, often constructed relative to or against needs and performance, and these dimensions of condition are interpreted or defined in many different ways depending on purpose, organizational mandates, and jurisdictions. For New York City, these are contained, for example, in the City of New York annual *Mayor's Management Report* (NYC Office of the Mayor, 2017, 2018), the *OneNYC* plan (City of New York, 2015), the National Academy of Sciences (2016) report that contained a New York City section, and other sector-specific documents. The American Society of Civil Engineers (ASCE) (2017) report card presented a number of measures for several of the city's infrastructure systems that reflect some potentially weakened conditions that could make parts of the system less resilient to the effects of climate change. Traditional condition measures, however, have not necessarily been linked directly to climate change, and Chapter 8: Indicators and Monitoring identifies some of the relationships that do exist. To make these linkages, inferences are required from underlying knowledge of conditions that potentially undermine the ability of infrastructure to withstand disruptions.
Usage: Usages of infrastructures or consumption of infrastructure services varies considerably depending on the type of infrastructure. Generically, they can be in the form of rates of use, temporal patterns of use, and purpose of use. Most significant, regardless of how usage is measured, is the ratio or comparison of infrastructure usage to capacity, where capacity information is available, since it reflects potential impacts of new stresses on infrastructure designed and managed for different tolerances.

Stakeholder engagement processes

Different forms of stakeholder engagement were undertaken to provide inputs to this chapter. This overlapped to some extent with the stakeholder engagement process for the Indicators and Monitoring Workgroup, since that chapter also focused on infrastructure.

One mechanism for stakeholder engagement was the New York City Climate Change Adaptation Task Force (CCATF). The city convened numerous city agencies and other organizations that oversee infrastructure through this venue covering the five lifeline infrastructure sectors in this report. A number of meetings in particular of the entire CCATF were attended by one or more of the coauthors of this chapter. These meetings were held on July 27, 2016, June 29, 2017, December 19, 2017, and July 26, 2018. Moreover, there were infrastructure-specific meetings, for example, several meetings of the CCATF Transportation Working Group that a representative of the infrastructure chapter attended.

In addition, members of the infrastructure chapter participated in a roundtable organized by the Indicators and Monitoring Workgroup on March 9, 2016 that consisted of a number of city infrastructure agencies. A member of the infrastructure chapter team met routinely with members of the Indicators and Monitoring Workgroup and participated in their ongoing meetings with a couple of city agencies. Details of this process are described in Chapter 8, Indicators and Monitoring.

Another mechanism consisted of informal engagement of members of infrastructure managers for specific portions of the work. The insurance and finance section authors, for example, took advantage of contacts with organizations relevant to that work. The staff of the NYC Mayor's Office of Recovery and Resiliency (ORR) provided important inputs on specific aspects of this chapter. Finally, informal contacts proved to be very valuable through venues such as professional society conferences and meetings (e.g., the ASCE) which afforded the opportunity not only to obtain information through formal presentations but as a basis for informal exchanges as well.

7.2 New York's critical infrastructure systems and updates from NPCC1

The New York City "infrastructure-shed" extends well beyond the borders of the city's approximately 300 square mile area. The term "infrastructure-shed" has been used in the context of climate change by Rosenzweig *et al.* (2011) referring to the scope of the 2010 NPCC (2010). The city both affects and is affected by the region beyond its borders. This is particularly true of its infrastructure.

Critical infrastructure is defined by the New York City CCATF and the NYC Panel on Climate Change as "systems and assets (excluding residential and commercial buildings, which are addressed by other efforts) that support activities that are vital to the city and for which the diminished functioning or destruction of such systems and assets would have a debilitating impact on public safety and/or economic security" (NPCC, 2009:8, footnote 3)

The NPCC3 analyzes five key lifeline sectors plus social infrastructure systems that provide critical infrastructure to the New York metropolitan region: (1) energy, (2) transportation, (3) telecommunications, (4) water, (5) waste and sewers, and in addition (6) social infrastructure. The lifeline sectors as they pertain to NYC's infrastructure are described in more detail in Appendix 7.A. These lifeline sectors represent those that have been singled out by *OneNYC* (City of New York, 2015), PlaNYC SIRR (City of New York, 2013), and the National Infrastructure Advisory Council (NIAC) (2013), and are retained here for the purpose of consistency.

Other areas of infrastructure not specifically singled out in *OneNYC,* such as banking and other financial institutions and solid waste management that have been used by other agencies, such as the U.S. Department of Homeland Security, are not included here. The buildings sector, which cuts across many of these others, are a separate report and inventory of GHG emissions that the city undertakes (City of New York, 2017) and are not included here, except with respect to how the buildings sector connects with other infrastructure.

Each type of infrastructure has one or more technology dimensions or characteristics. Each technology has its own level of risk and resilience. New technologies are continually emerging that can change the nature of risk and resilience for each type of infrastructure.

In its 2010 analysis, the first New York City Panel on Climate Change (NPCC1) presented a table that listed potential infrastructure impacts from climate extremes (NPCC, 2010). NPCC1 dealt extensively with the relationship between key climate change risk factors–higher mean temperature, changes in precipitation, and sea level rise–and their effects on energy, transportation, water supply, wastewater, solid waste, and communications infrastructure (NPCC, 2010). In NPCC3 (NPCC, 2015), those relationships are summarized, and the 2010 table is now updated, appearing in this chapter as Tables 7.1a through 7.1e to incorporate additional climate extremes (see also, Chapters 2–4) and impacts.

In NPCC1 (NPCC, 2010), climate extremes, referred to as climate risk factors, were restricted to temperature, precipitation, and sea level rise. In NPCC3, extreme heat replaces temperature, heavy downpours replace precipitation, and sea level rise is combined with coastal flooding. In addition, cold snaps, drought, and extreme winds have been added.

Tables 7.1a through 7.1e set forth impacts that provide the basis for framing infrastructure indicators and metrics in Chapter 8. These climate extremes are described in more detail in earlier chapters. The impacts listed in Table 7.1a through 7.1e are meant to be illustrative rather than comprehensive.

7.3 Key vulnerabilities, dependencies, and interdependencies

This section describes infrastructure vulnerabilities in the current and future climate. Section 7.3.1 addresses infrastructure vulnerabilities irrespective of climate change (for individual infrastructures separately). Section 7.3.2 superimposes climate change on these vulnerabilities. Section 7.3.3 illustrates how these individual infrastructure sectors are interlinked by dependencies and interdependencies without climate change and Section 7.3.4 illustrates the dependencies and interdependencies with climate change. Energy and transportation infrastructure are emphasized, but other lifeline sectors are also discussed, namely water and telecommunications.

7.3.1 Vulnerabilities for individual infrastructure without climate change

Current vulnerabilities for individual infrastructure systems encompass a number of infrastructure attributes and their social dimensions. These include:

- Initial condition and performance (including designed capacity)
- Extent of use or dependency on the infrastructure, especially relative to capacity
- Accessibility and availability to users, and equity issues arising from differences in these characteristics
- Extent of or repeated exposure to hazard
- Ability to recover from hazard
- Existence of and access to alternative services to support immediate response during and following a disaster, for recovery, as well as to avoid damage at onset

Table 7.1a. Examples of potential illustrative infrastructure impacts from climate extremes: energy[a]

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
Energy (electricity)		(NYCDEP, 2008: 38; ClimAID, 2011: 260, 261, 450; NYC, 2013: 112, 120, 121, 126, 127; Anel *et al.*, 2017:3, 4, 5, 6; Bartos *et al.*, 2016: 6; Schaeffer *et al.*, 2012: 5, 8; U.S. DOE, 2013a,b; U.S. EPA, 2017a; NYC Mayor's ORR, 2018: 13)
Production		
	Extreme heat	- Increased user demand for and consumption of energy potentially straining capacity (U.S. DOE, 2013b: 5); ClimAID, 2011: 450; NYC, 2013: 112; Schaeffer *et al.*, 2012: 8; Anel *et al.*, 2017: 4; NYC Mayor's ORR, 2018: 13) - Increase in extreme energy use (peak load days) (ClimAID, 2011: 450; NYC, 2013: 112)-Increased potential for power interruptions (ClimAID, 2011: 450; NYC, 2013: 126; NYC Mayor's ORR, 2018: 13) - Overuse and strain on equipment, materials, efficiency, and performance, including cooling water needs increasing maintenance (U.S. DOE, 2013b: 2, 5); ClimAID, 2011: 450; NYC, 2013: 120; Schaeffer *et al.*, 2012: 5) - Equipment damage (ClimAID, 2011: 450; NYC, 2013: 120; Anel *et al.*, 2017: 5)
	Cold snaps	- Some production processes may slow down; equipment unprotected from low temperatures and snow and ice accumulation could be damaged depending on material tolerances and existence of icing conditions (ClimAID, 2011: 450)
	Heavy downpours	- Equipment damage from flooding (ClimAID, 2011: 261; NYC, 2013: 121)
	Drought	- Material and processes compromised if drought conditions are prolonged, especially processes dependent upon water inputs and maintenance of water intake levels; likelihood of increased fire risk and inability to fight fires due to insufficient water (NYCDEP, 2008: 38; ClimAID,2011: 310)
	Sea level rise and coastal flooding	- Equipment damage and potential damage to docks and marine-based infrastructure from flooding and corrosive effects of seawater (ClimAID, 2011: 446; NYC, 2013: 127)
	Extreme winds	- Potential production disruptions due to shut in facilities to avoid damage (ClimAID, 2011: 260; NYC, 2013: 121)
Transmission and distribution overhead and underground		
	Extreme heat	- Overuse and strain on equipment, materials, efficiency, and performance, increasing maintenance (ClimAID, 2011: 450) - Equipment damage (ClimAID, 2011: 450) - Increased sag of overhead lines and effects upon power transmission (ClimAID, 2011: 450; Bartos *et al.*, 2016: 6) - Increased downtime in provision of power (ClimAID, 2011: 450)
	Cold snaps	- Some transmission processes may slow down where unprotected equipment is damaged depending on material tolerances and existence of icing conditions (ClimAID, 2011: 450; Anel *et al.*, 2017: 5) - Increase in sag of overhead transmission lines; increased exposure of underground lines to freeze-thaw effects (ClimAID, 2011: 450; Anel *et al.*, 2014: 5)
	Heavy downpours	- Increase in number and duration of local outages from flooded and corroded equipment (ClimAID, 2011: 450)
	Drought	- Materials compromised if drought conditions are prolonged
	Sea level rise and coastal flooding	- Increase in number and duration of local outages from flooded and corroded equipment (ClimAID, 2011: 450)
	Extreme winds	- In areas with overhead lines, power disruption due to fallen lines as well as trees falling on the lines (ClimAID, 2011: 260; NYC, 2013: 126)

Table 7.1b. Examples of potential illustrative infrastructure impacts from climate extremes: transportation[a]

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
Transportation		(Kish and Samavedam, 2013; NYCDEP, 2008: 38, 41; ClimAID, 2011: 310, 311, 312, 341, 342, 345, 356, 450, 451; U.S. DOT Federal Transit Administration (FTA), 2011: 5, 10, 16, 19, 21, 30, 42, 102; NYC, 2013: 173–188; U.S. EPA, 2017b)
Roadways		
	Extreme heat	- Increased road material degradation, resulting in increased road maintenance (ClimAID, 2011: 451; Kish and Samavedam, 2013
	Cold snaps	- Some road surfaces could be damaged depending on material tolerances and resistance to effects of icing and snow accumulation (ClimAID, 2011: 451; U.S. DOT, FTA, 2011: 21)

Continued

Table 7.1b. ***Continued***

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
	Heavy downpours	- Declining serviceability of roadways due to flooding conditions (ClimAID, 2011: 451) - Increased travel delay from increased congestion during street flooding (ClimAID 2011: 451) - Increasing need for pumping capacity and associated increased energy use for additional pumping to remove excess water to prevent flooding (NYCDEP 2008: 41; ClimAID 2011: 342)
	Drought	- Increased road material degradation if drought is accompanied by heat (ClimAID, 2011: 451) - Likelihood of increased fire risk along roadway rights of way and inability to fight fires due to insufficient water (NYCDEP 2008: 38; ClimAID, 2011: 310)
	Sea level rise and coastal flooding	- Declining serviceability of roadways due to flooding conditions (ClimAID, 2011: 451) - Increased travel delay from increased congestion due to persistent high water levels (ClimAID, 2011: 451) - Increased need for ongoing pumping capacity and associated increased energy use for additional pumping to remove excess water continuously to prevent flooding (NYCDEP, 2008: 41; ClimAID, 2011: 342) - Corrosion of roadway support facilities by salt water (NYC 2013: 178)
	Extreme winds	- Increase in roadway accidents from vehicle collisions with road debris and vehicle instability (ClimAID, 2011: 311) - General potential impacts on transportation roadway and bridge structures and vehicles if winds exceed guidance and announced event-specific wind thresholds as it was for Hurricane Sandy, for example (I95 Corridor Coalition, 2013; NYS Office of the Governor, 2012a)
Transit		
	Extreme heat	- Increase in the use of cooling equipment due to increased underground station temperatures (ClimAID, 2011: 451; U.S. DOT, FTA, 2011: 21; NYC, 2013: 182) - Increased rail degradation and equipment deterioration, resulting in increased maintenance (ClimAID, 2011: 451; (Kish and Samavedam, 2013; U.S. DOT, FTA, 2011: 5) - For rail systems dependent on overhead catenaries for power, increase in transit accidents from train collisions with sagging overhead lines and increased potential risk of power outages (ClimAID, 2011: 450)
	Cold snaps	- Some rail components could be damaged depending on material tolerances and effects of icing and snow accumulation (ClimAID 2011: 451; U.S. DOT, FTA 2011: 21)
	Heavy downpours	- Increase in pumping capacity and associated increased energy use to remove excess water to prevent flooding (NYCDEP, 2008: 41; ClimAID, 2011: 342; NYC, 2013: 181) - Increase in train stoppages due to failed switches, signals, and potential third rail flood threats requiring power to be shut (ClimAID, 2011: 345; U.S. DOT, FTA, 2011: 16) - Increase in number of emergency stops due to flooding and power outages (ClimAID, 2011: 451; U.S. DOT, FTA, 2011: 19) - Increase in number of emergency evacuations (ClimAID, 2011: 356; U.S. DOT, FTA, 2011: 102)
	Drought	- Increase in rail and train material degradation if drought is accompanied by heat (ClimAID, 2011: 451; U.S. DOT, FTA, 2011: 10) - likelihood of increased fire risk along rail rights of way and inability to fight fires due to insufficient water (NYCDEP, 2008: 38; ClimAID, 2011: 310)
	Sea level rise and coastal flooding	- Increase in rail degradation and equipment deterioration from saltwater inundation, resulting in increased maintenance (ClimAID,2011: 451; U.S. DOT, FTA, 2011: 42; NYC, 2013: 178, 181)
	Extreme winds	- For commuter rail or elevated subway lines, increase in transit accidents from train collisions with track debris; operating disruptions where trains are required to cease operations (ClimAID, 2011: 312; U.S. DOT, FTA, 2011: 30)

Table 7.1c. Examples of potential illustrative infrastructure impacts from climate extremes: telecommunications[a]

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
Telecommunications		(ClimAID, 2011: 450, 452; NYC, 2013:161-172)
Supplies: facilities that provide electric power for telecommunications (corresponds to electric power above)		
	Extreme heat	- Power disruption/outage frequency and severity affects communication equipment, e.g., computerized controls for power systems (ClimAID, 2011: 452; NYC, 2013: 169)
	Cold snaps	- None expected for supply facilities, except as listed under energy
	Heavy downpours	- Equipment flooded and stored materials damaged (ClimAID, 2011: 452)
	Drought	- Water level and water supply inputs for electric power potentially affected (see electric power) (ClimAID, 2011: 450)
	Sea level rise and coastal flooding	- Increased flooding of electric power equipment and corrosion from salt water (ClimAID, 2011: 452)
	Extreme winds	- For production, disrupted power supply due to electric power production system disruptions (ClimAID, 2011: 450) - For transmission, in areas with overhead lines, power disruption due to fallen lines (ClimAID, 2011: 452; NYC, 2013: 169)
Equipment, for example: fiber optic cable, cell towers, internet, central and local offices, switching facilities, data centers, and telephone exchanges		
	Extreme heat	- Destruction of equipment and increased maintenance (ClimAID, 2011: 452)
	Cold snaps	- None expected for equipment, unless material tolerances and operational requirements are exceeded by reduced temperature and effects of icing and snow accumulation (ClimAID, 2011: 452)
	Heavy downpours	- Excessive precipitation flooding equipment (ClimAID, 2011: 452) - Line congestion, tower destruction, or loss of function (ClimAID, 2011: 452) - Call carrying capacity reduced, lost, or blocked (ClimAID, 2011: 452) - Internet traffic increases and accessibility declines (ClimAID, 2011: 452)
	Drought	- Prolonged drying conditions could affect telecommunication equipment and materials
	Sea level rise and coastal flooding	As in the case of heavy precipitation: - Increased flooding of equipment and corrosion from salt water from increased sea level rise (ClimAID, 2011: 457) - Line congestion, tower destruction, or loss of function (ClimAID, 2011: 457) - Call carrying capacity reduced, lost, or blocked (ClimAID, 2011: 457) - Internet traffic increases and accessibility declines (ClimAID, 2011: 457)
	Extreme winds	- Cell towers and exposed lines subject to toppling, hence disabling communications and electric power connections (ClimAID, 2011: 457)

Table 7.1d. Examples of potential illustrative infrastructure impacts from climate extremes: water, waste, and sewer[a]

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
Water, waste, and sewer		(NYCDEP, 2008: 9, 35, 38, 41, 45; ClimAID, 2011: 89, 104, 444, 445, 446; NYC, 2013: 205–218; 231, 232; AWWA, 2012)
Water supply		
Quantity		
	Extreme heat	- Increased water consumption or demand (NYCDEP, 2008: 9; ClimAID, 2011: 444) - Decline in groundwater and surface water supplies due to increased evaporation, where applicable in the watershed servicing NYC exceeding margins of safety (e.g., "safe yields") (NYCDEP, 2008: 45; ClimAID, 2011: 444) - Reservoir levels decline (NYCDEP, 2008: 35; ClimAID, 2011: 444) - Changes in watershed streamflow (e.g., early snowmelt) cause reservoirs to fill sooner in year and increase spill during Winter-Spring

Continued

Table 7.1d. ***Continued***

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
	Cold snaps	- None expected unless icing conditions exist that can potentially cause freezing in the water supply system components
	Heavy downpours	- Uncertain changes in precipitation producing variable and unpredictable water supplies (NYCDEP, 2008: 9; ClimAID, 2011: 444)
	Drought	- Decline in groundwater and surface water supplies due to lack of replenishment, exceeding margins of safety (e.g., "safe yields") (NYCDEP, 2008: 45; ClimAID, 2011: 444) (NYC is supplied by surface water, with some groundwater as backup supply) - Reservoir levels decline (NYCDEP, 2008: 35; ClimAID, 2011: 444) - Sustained high-volume reservoir stream releases while reservoir storage levels are reduced can lead to damage of release valves
	Sea level rise and coastal flooding	- Impact on emergency supply from salt front movement (NYCDEP, 2008: 9; ClimAID, 2011: 89) - Impact of salt front movement in lower Delaware River may add pressure to increase releases from City reservoirs
	Extreme winds	- Temporary disruption of operations due to operating restrictions in high winds
Distribution of water supply		
	Extreme heat	- Changes in characteristics of water flow through pipes - Material degradation resulting in the potential for more pipeline breaks and water leakage
	Cold snaps	- If icing conditions exist, water movement could be inhibited - Material degradation resulting in the potential for more pipeline breaks and water leakage
	Heavy downpours	- Pressure changes in water distribution system (NYCDEP, 2008: 38) - Increased corrosion (ClimAID, 2011: 446) - Increased water loss (ClimAID, 2011: 444)
	Drought	- Potential materials impairment in prolonged droughts
	Sea level rise and coastal flooding	- Increased flooding (infiltration and inflow) from flooded distribution lines (ClimAID, 2011: 446)
	Extreme winds	- Temporary disruption of operations due to operating restrictions in high winds
Quality		
	Extreme heat	- Increased evaporation in surface water supplies contributes to deteriorating water quality due to concentration of contaminants (ClimAID, 2011: 104) - Longer and more stable reservoir stratification, warmer water temperatures result in potentially significant increases in cyanobacteria/Harmful Algal Blooms (HABs)
	Cold snaps	- None expected unless treatment systems exist and processes are affected by cold
	Heavy downpours	- Impact on water quality from increased turbidity (NYCDEP, 2008: 9; ClimAID, 2011: 444) - Increased concentration of pollutants from pollutant release (ClimAID, 2011: 445)
	Drought	- Disruption of water-dependent collection and treatment processes (ClimAID, 2011: 444)
	Sea level rise and coastal flooding	- Impact on emergency supply from salt front movement (NYCDEP, 2008: 9; ClimAID, 2011: 89) - Potential increase in infiltration into distribution systems (ClimAID, 2011: 446)
	Extreme winds	- Temporary disruption of wastewater treatment operations due to restrictions on supply vehicles operating in high winds - Reservoir shoreline erosion due to high winds and wave action may increase turbidity
Waste		
Closed landfills		
	Extreme heat	- Alteration of chemical composition of contaminants below the surface, changing evaporation rates
	Cold snaps	- None expected unless freezing conditions exist that can threaten the integrity of landfill covers and liners through freeze-thaw cycles (Sterpi, 2015.)
	Heavy downpours	- Unexpected leaching of contaminants where precipitation penetrates the surface of closed landfills
	Drought	- Disturbance in landfill cover and integrity where design is contingent on the maintenance of humidity levels
	Sea level rise and coastal flooding	- Release of contaminants from unexpected inundation of landfills increasing public health concerns
	Extreme winds	- None relevant, assuming closure is secure
Marine transfer stations		
	Extreme heat	- Increased evaporation of contaminants from refuse
	Cold snaps	- None expected except for exposed facilities where temperatures below material tolerances and freeze-thaw cycles can potentially damage facility components

Continued

Table 7.1d. ***Continued***

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
	Heavy downpours	- Marine transportation impeded (NYC, 2013: 231)
	Drought	
	Sea level rise and coastal flooding	- Alignment of marine transfer station docking facilities with landside facilities affected (NYC, 2013: 232)
	Extreme winds	- Temporary disruption of operations due to restrictions on vessels operating in high winds (NYC, 2013: 232)
Curbside refuse		
	Extreme heat	- Increased evaporation of contaminants and decay of refuse, thereby increasing public health concerns from vermin and public nuisance from odors
	Cold snaps	- None expected
	Heavy downpours	- Increased damages to curbside refuse containment and releasing refuse, increasing public health concerns (NYC, 2013: 231)
	Drought	- None expected
	Sea level rise and coastal flooding	- Inundation of refuse from water releases contaminants to streets and waterways, increasing public health concerns (NYC, 2013: 232)
	Extreme winds	- Disturbance of refuge storage and unexpected uncontrolled release of refuse (NYC 2013: 231)
Sewer *(wastewater treatment and conveyance)*		
Quality		
	Extreme heat	- Treatment capability of wastewater treatment plants improved up to a point due to increased heat affecting biological processes but then declines tolerance limits are exceeded (NYCDEP, 2008: 41) - If substantial evaporation or drought occurs, quantity of wastewater becomes insufficient to sustain treatment processes
	Cold snaps	- Treatment systems and processes are compromised if they are affected by cold
	Heavy downpours	- Hydraulic capacity of sewers and wastewater treatment plants exceeded owing to increased flows (NYCDEP, 2008: 9; ClimaAID, 2011: 444; NYC Mayor's ORR, 2018: 15) - Combined sewer overflow facility capacity is overwhelmed and pollutants are discharged into sewer systems and waterways (, 2011: 445; NYC Mayor's ORR, 2018: 15) - Sewer backups (ClimAID, 2011: 444) - Treatment capacity of treatment plants exceeded from dilution from increased flows (ClimAID, 2011: 444) - Decline in water quality reflected in Clean Water Act standard variances (ClimAID, 2011: 446)
	Drought	- Insufficient water for sewer collection systems to operate - Saltwater intrusion (NYCDEP 2008: 9)
	Sea level rise and coastal flooding	- Reduced function of wastewater treatment plants and related infrastructure, including outfalls if sea level overwhelms plant facilities and other infrastructure through regular flooding and ponding upstream and downstream (NYCDEP, 2008: 9; ClimAID, 2011: 446;, October 2013; NYC Mayor's ORR, 2018: 15)
	Extreme winds	- Outdoor facility components can be damaged

Table 7.1e. Examples of potential illustrative infrastructure impacts from climate extremes: selected social infrastructure[a]

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
Social infrastructure		(NYCDEP, 2008: 9; ClimAID, 2011: 174, 449, 446, 450, 453; NYC, 2013: 143–160; Guenther and Balbus, 2014)
Hospitals		
	Extreme heat	- Power disruption/outage frequency and severity affects power-dependent operations; Given the use of electricity in hospitals (U.S. DOE, 2011; Christiansen *et al.*, 2015.), increased use of electricity for cooling (ClimAID, 2011: 450) - Hospital and associated health facility capacity is overwhelmed due to increase in cases of mortality and injuries from heat stress, air quality degradation, vector-borne diseases, and other heat-related health effects (ClimAID, 2011: 453)

Continued

Table 7.1e. ***Continued***

Infrastructure sector and components	Climate extremes[b]	Potential illustrative infrastructure impacts[c]
	Cold snaps	- Given the use of electricity in hospitals (U.S. DOE, 2011; Christiansen *et al*., 2015.), increased use of electric power for heating (ClimAID 2011: 450)
	Heavy downpours	- Equipment flooded and stored materials damaged (ClimAID, 2011: 450; Guenther and Balbus, 2014: 33)
	Drought	- Increased demand on water supply and electric power given the use of electricity in hospitals (NYCDEP, 2008: 9; ClimAID, 2011: 450)
	Sea level rise and coastal flooding	- Increased flooding of equipment upon which hospitals rely heavily (in particular, electric power used in hospitals and telecommunications) and corrosion from salt water (ClimAID, 2011: 446; Guenther and Balbus, 2014: 33)
	Extreme winds	- See sections on impacts of wind on electric power, telecommunications, and other infrastructure related to the functioning of hospitals
Parks and public spaces		
	Extreme heat	- Reduction in vegetation due to heat tolerance problems (ClimAID, 2011: 174)
	Cold snaps	- Reduction in vegetation due to cold tolerance problems (ClimAID, 2011: 174)
	Heavy downpours	- Reduction in vegetation from washouts and flooding of root systems (ClimAID, 2011: 449)
	Drought	- Reduction in vegetation due to water reduction, where supplemental irrigation is not available (ClimAID, 2011: 449)
	Sea level rise and coastal flooding	- Periodic or permanent inundation of vegetation potentially resulting in the transformation of species that can both positively and negatively impact the natural distribution of species (ClimAID, 2011: 446)
	Extreme winds	- Destruction of trees thus reducing tree canopies

Tables 7.1a–e

NOTES AND SOURCES

[a]This table is organized as in NPCC1 (Zimmerman and Faris, 2010, Table 4.1), with climate extremes expanded from 3 to 6 for NPCC3, and includes lifeline infrastructure systems Energy; Transportation; Telecommunications; Water, Waste, and Sewer with the addition of selected Social Infrastructure (hospital and parks subsectors only) as defined centrally for the NPCC3 report. The energy sector focuses on electricity.

[b]The six climate extremes listed here are those defined in Chapters 2–4: extreme heat, cold snaps, heavy downpours, drought, sea level rise and coastal flooding, and extreme winds.

[c]The impacts listed here are illustrative, and are not intended to be comprehensive. Factors other than climate extremes can contribute to impacts given. In some cases, references that pertain to other infrastructure sectors are listed where impacts to those other sectors are implied or mentioned in another sector. Many impacts are identified in or inferred from general literature, common use, and the impacts that occurred during Hurricane Sandy identified in plaNYC "A Stronger, More Resilient New York" (City of New York, 2013). No assignment of probability or level of impact is assumed. The potential illustrative infrastructure impacts as listed do not take into account adaptations or other actions to reduce or avoid the impacts, some of which appear in Appendix 7.B. They do not reflect temporal dimensions, that is, different impacts occur at different time periods. The potential infrastructure impacts are repeated in Chapter 8 (Tables 8.5 and 8.6) for the purpose of consistently linking indicators and their metrics to impacts. The references cited are not meant to be comprehensive, and tend to be specific to or applicable to NYC. Some impacts listed are worded directly as they appear in Table 4.1 in NPCC (2010) in order to maintain consistency.

Abbreviations for some of the references in the Potential Infrastructure Impacts column are:

- ClimAID: Rosenzweig *et al.*, 2011
- DEP: City of New York Environmental Protection, 2008
- NYC, 2013: City of New York, 2013. Strategic Initiative for Rebuilding and Resiliency (SIRR). A Stronger, More Resilient New York

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Table 7.1e. *Continued*

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Each of these characteristics influences how an individual infrastructure system can resist stress. The first two vulnerabilities–condition and usage relative to capacity–are critical characteristics related to vulnerability and are singled out for greater discussion below.

7.3.1.1 Infrastructure condition. If infrastructure is weak to begin with, it will be less able to withstand stress. Table 7.2 presents the condition of selected infrastructure in New York City and in some cases in the region. Numerous organizations work together to maintain the highest level of performance of infrastructure in the region. These include government agencies at state and local levels, professional associations such as American Public Transportation Association (APTA) and the ASCE, and private and nonprofit entities. In New York City, government agencies include the New York City Office of Emergency Management (NYEM in connection with the hazard mitigation plan (NYCOEM, 2014) and other emergency functions), the New York City Mayor's Office of Recovery and Resiliency (NYCORR), NYC Office of the Comptroller, infrastructure owners and operators, and many of the city's community boards. Table 7.2 emphasizes selected illustrative characteristics of infrastructure condition.

Table 7.2. Selected illustrative characteristics of infrastructure condition in or affecting New York City

Infrastructure type and system	Description of condition element applicable to NYC	Selected potential consequences	Time period (if specified)	Reference
Energy				
Electric power				
	Some design, operational, and maintenance levels to meet functional needs, acknowledging that design protocols exist to address this	Frequent and often extensive outages (in terms of number of customers affected and infrastructure affected) in major storms, e.g., - Hurricane Irene: 6.69 million customer outages; - Hurricane Sandy: 8.66 million customer outages[a]	Approx. 2013	U.S. DOE (2013a: v); U.S. DOE (2013b)
Petroleum refining capacity				
	Condition of refining capacity may be affected during extreme weather events	Shutdown of refining capacity (expressed in barrels of oil per day) - Hurricane Irene: 238,000 - Hurricane Sandy: 308,000	Approx. 2013	U.S. DOE (2013a: v); U.S. DOE (2013b)
Transportation				
Transit				
	State of Good Repair (SGR) for New York City (ASCE) transit SGR expressed by component as percentages of components meeting SGR, corresponding to MTA capital plan categories: Meeting SGR - "Train cars, mainline tracks, and switches: 100%" - "Pumps, mainline signals, and stations"-89%, 74%, and 78%, respectively Failing SGR: - "Power 62% and high priority ventilation 60%, subway shops: 46%"	The lower the percentage meeting SGR, theoretically the greater the likelihood of more frequent equipment failures and hence delay and congestion for users; see Chapter 8 for transit indicators	Unspecified	ASCE (2015: 70); MTA (2013: 33)[b]
	- Age of subway components - - Subway cars: About 1/3 > 30 years old - Signals: About 40% > 50 years old	Age of older equipment relative to design lifetimes increases the likelihood that train service will become increasingly disrupted, that is, unable to run over their routes, at least temporarily, and hence rider inconvenience increases	2016	NYS Office of the Comptroller (2017: 1)
Roads				
	Pavement condition: −43% poor; −30% mediocre	Likelihood of inability to withstand water and wind-related effects of extreme events	circa 2015	ASCE (2015: 44)[c]
	Rough roads	Additional vehicle operating costs (per vehicle per year) $694	circa 2015	ASCE (2015: 5)

Continued

Table 7.2. ***Continued***

Infrastructure type and system	Description of condition element applicable to NYC	Selected potential consequences	Time period (if specified)	Reference
Aviation				
	Closeness to airport capacity JFK: expected to exceed current capacity by 130% LaGuardia: 103%	Likelihood of inability to withstand water and wind-related effects of extreme events	2030	ASCE (2015: 8)
Water				
Water supply				
	Water main strength - Number of breaks per year: 406, 513, 563, 397, 424, 520 - Number of breaks per 100 miles of water main (previous 12 months): 5.8, 7.3, 8.0, 5.7, 6.1 Outages and ability to restore water supply quickly: restoration time 4–5 h	Weaknesses in the water supply distribution system reflected in breakage rates could point to the likelihood of a greater inability of those systems to withstand pressures from flooding	Fiscal Year 2013–2017	NYC Office of the Mayor (2017:262-263; 2018:261)[d]; AWWA 2012
Wastewater treatment				
	Waterfront dependency for functionality versus flooding risk Exceedance of design life or "expected useful life" Maintenance of or compliance with water quality standards: effluent and instream Integrity and performance of facility components, e.g., outages, sewer backups, restoration times - Extent of existing impervious surfaces (72% of New York City land area) - Sewer configurations such as combined sewer systems (60% of the system) that can increase vulnerability to flooding	These conditions potentially lead to increased vulnerabilities to various extreme event impacts, particularly coastal flooding and sea level rise, extreme heat, and heavy downpours	Ongoing	NYC Environmental Protection (2013: 1; NYC 2013: 209); ASCE (2015: 75) ASCE (2015: 77); NYC Office of the Mayor (2017: 262, 263; 2018:261) ASCE (2015: 77); NYC Office of the Mayor (2017: 262, 263) NYCDEP (2018a:4; 2018b)

[a]Number of customers is not equivalent to number of people. Consequences are either for facility damage or deliberate shutdowns to avoid facility damage.

[b]Note: SGR determinations are required by the federal MAP-21 law and are implemented by individual transit systems (National Center for Transit Research, 2016: 3).

[c]These results are based upon the TRIP (2016) report that implies that the percentages refer to roadway mileage and that condition is based on pavement condition (TRIP, 2016).

[d]Water system leakages can reduce capacity; the major leak that the city is addressing is in the Delaware Aqueduct water transmission system. This will be addressed through construction of a bypass (NYC Water Board, 2016). In contrast to the NYC breakage rates, a U.S. Canada survey of 281 responding utilities found that "Between 2012 and this 2018 report, overall water main break rates increased by 27% from 11.0 to 14.0 breaks/(100 miles)/year" (Folkman, 2018: 4, 8). By comparison, the NYC Office of the Mayor MMR (2017: 262–263) indicates that NYC breaks per 100 miles are between 5.7 and 8.0 for FY13–FY17. FY18 (NYC Office of the Mayor, 2018: 261)

7.3.1.2 Infrastructure usage versus capacity. The comparison between the extent of use of an infrastructure and the capacity for which it has been designed and managed is a key indicator of infrastructure robustness. Where capacity is exceeded, the ability of an infrastructure to withstand the impacts of additional stresses is potentially diminished. The ratio of use to capacity is often used as an infrastructure indicator, for example, volume to capacity ratio for roadways.

Usage or consumption of electric power and water services and resources have been increasing nationally over time, though in the New York area usage has in some cases been at least stable and possibly intermittently declining in recent decades yet a comparison of usage against capacity is what is relevant for resilience. The transportation sector has generally experienced extensive growth in terms of vehicle miles of travel for road-based travel, bridge and tunnel crossings (NYS Comptroller, 2018: 3), and transit ridership (though transit ridership has shown some declines in the past 4 years (NYS Comptroller, 2018: 3)). Table 7.3 provides examples of some of these infrastructure usage characteristics that can be compared against capacity when such information on capacity becomes available.

7.3.2 Vulnerabilities for illustrative individual infrastructures with climate change

The previous discussion identified some infrastructure vulnerabilities in the absence of climate change. In this section, some specific examples of climate change attributes are introduced and related to selected infrastructure. The focus is primarily on vulnerabilities that arise in coastal areas due to two climate extremes: (1) sea level rise and coastal flooding and (2) temperature. These vulnerabilities contribute to impacts outlined in Tables 7.1a–e.

7.3.2.1 Sea level rise. Many of the components of the city's infrastructure assets and services are at risk from flooding, both directly and indirectly. Direct risk occurs in terms of elevation above sea level, extreme precipitation including flash flooding, and indirect risk to areas that are not in flood-prone areas but are connected to them physically or functionally. Most vulnerabilities relevant to climate change-related sea level rise pertain to location, and thus actual or potential exposure to sea level rise.

Figures 7.1a and 7.1b combined indicate the vulnerability to flooding for selected infrastructures in Lower Manhattan by virtue of flood plain delineations that existed following Hurricane Sandy. The following sections will zoom in on the impacts of flooding events on critical infrastructure sectors.

Transportation. The locations of NYC transportation systems that are commonly flooded or are routes for floodwaters have been known for some time from the histories of flash flooding and intense precipitation and studies of the elevations of these facilities relative to sea level.

A number of studies have identified locations for the most vulnerable components of the city's transit system. See the NYS ClimAID study, for example, Rosenzweig *et al.* (2011), MTA (2009), Jacob *et al.* (2009), Rosenzweig and Solecki (2010); the various components of the city's rail transit infrastructure within various sea level elevations (USACE, 1995; Zimmerman and Cusker, 2001; Zimmerman, 2003); and the subway lines and stations most vulnerable to flooding. See, for example, the August 2007 floods (MTA, 2007).

Zimmerman (2003) summarized the USACE (1995) findings for the elevations of major facilities and components in terms of the National Geodetic Vertical Datum (NGVD) of 1929:

- Amtrak, Metro-North Railroad, Long Island Rail Road: 10 stations were within 10 feet or less of sea level and 4 were between 10 and 12 feet;
- NYC subways and the PATH system: 17 components were within 10 feet and 3 were between 10 and 12 feet;
- Roads, bridges, and tunnels: 21 were within 10 feet and 9 were between 10 and 12 feet;
- Marine facilities: 6 were within 10 feet; and
- Airports: 2 were within 10 feet and 2 were within 10 and 12 feet.

In addition, many other facilities are threatened that are used for storage, cleaning, and maintenance of transportation infrastructure, as well as intermodal facilities for goods movement.

Energy. Historically, many electric power plants were located along shorelines for cooling water and greater access to waterborne transport of supplies. Selected locations were presented in Chapter 4 of

Table 7.3. Infrastructure usage characteristics: energy and transportation

Infrastructure type and system	Description of usage	Illustrative usage details	Time period (if specified)	Reference
Energy				
Electric power	Electricity use	Electricity use increased by 0.31% (GWh) equal to 53,653 GWh in 2016	2015–2016	NYS ISO (2017b: 13)
Transportation				
Roads	Congestion (time and cost of delay)	"New York has the highest daytime congestion rate on arterials and city streets among the major US cities studied" by INRIX	2017	INRIX (2017: 25)
Transit	Ridership	Highest usage volume on record in 2015	2015, based on 1948–2015 annual ridership	MTA (2016); NYS Comptroller (2018)
Transit	Ridership change	Increases in Average Weekday Ridership and Total Ridership were about 7% Declines occurred in Total Ridership due to Declines in Weekend Trips	2011–2016 2015–2016	MTA (2017a) MTA (2017a)

Note: Trends in each sector potentially signify stresses on the existing system unless capacity increases to cover it.

the 2010 NPCC report (NPCC, 2010). In addition to power plants, other energy components, in particular substations, were near enough to coastal areas to have been flooded in Hurricane Sandy. A comparison of Figures 7.1a and b illustrates some of the damages to electric power substations resulting from Hurricane Sandy.

Energy infrastructure in New York City includes power production equipment, transformers, and both underground and overhead distribution lines, each having different vulnerabilities depending on the hazard. Overhead lines are vulnerable to wind and tree damage. Underground distribution lines are vulnerable to salt-water intrusion and water corrosion in general. The operation of transformers and production equipment when directly exposed to water inundation becomes disabled as was apparent as a result of Hurricane Sandy and other similar storms.

A key learning experience is Hurricane Sandy and the associated storm surge that destroyed temporary protection barriers and inundated the Con Edison East 13th Street facility, causing massive flooding to two transmission substations and leading to an intense electric arc (City of New York, 2013).

Impacts from Sandy on the electric distribution system contributed to customers enduring blackout conditions for 4 days, some even lasting up to 2 weeks before power was restored. Much critical control equipment was submerged and damaged due to salt water corrosion. Many of Con Edison electric systems in Manhattan are in the floodplain close to the coastline and are buried underground making them more vulnerable to sea level rise and storm surge (City of New York, 2013). Hurricane Sandy caused catastrophic damage to critical underground systems causing many cascading effects to the electric system within and outside of Manhattan that are interdependent with each other (City of New York, 2013).

Wastewater. New York City's 14 wastewater treatment plants are located on or near the city's waterways, similar to power plants contributing to vulnerability to high water conditions. After Hurricane Sandy, the city conducted an extensive wastewater resiliency plan and analysis detailing the

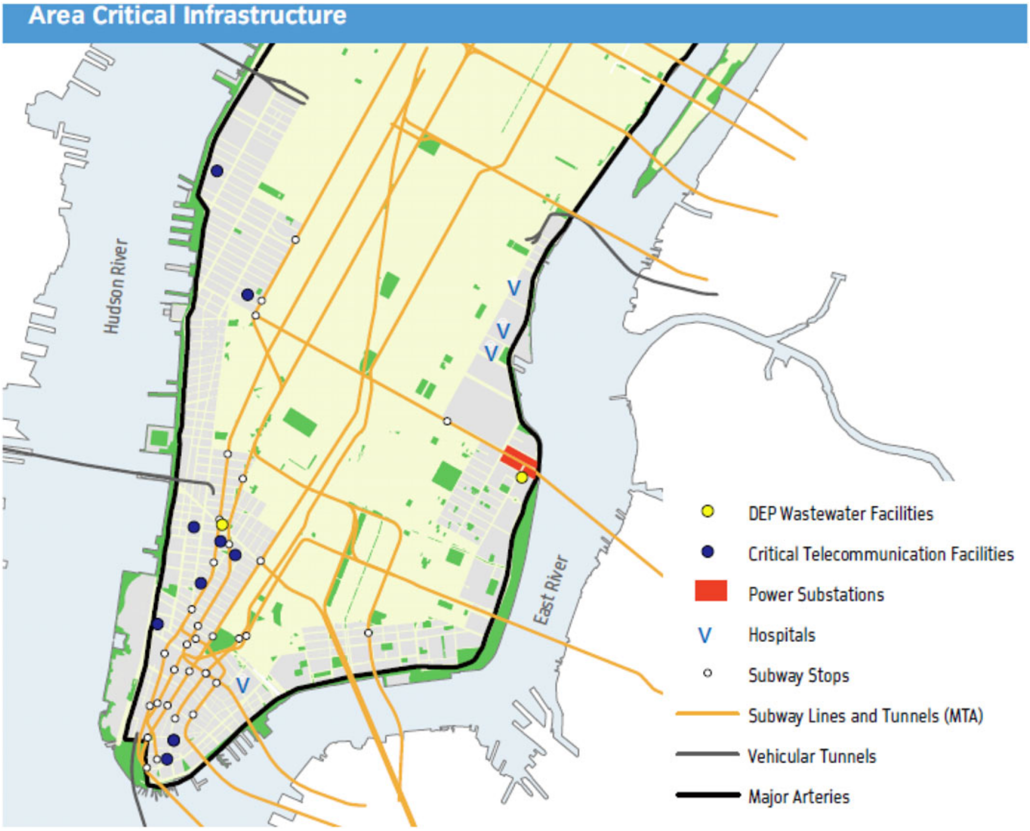

Figure 7.1a. Selected critical infrastructure systems located in or connected with facilities in flood inundation zones, Southern Manhattan, NYC. Source: City of New York, 2013.

components of the wastewater facility plants vulnerable to flooding (NYCDEP, 2013).

The NYC DEP's post-Sandy analysis in 2013 of the vulnerability of the city's wastewater treatment plants and their components to flooding indicated that all 14 of its wastewater treatment plants experienced such vulnerability (NYCDEP, 2013). In addition, the approximately 426 combined sewer overflow facilities (NYS DEC, 2012) and regulators that prevent the surrounding water from flooding city streets are extremely vulnerable to sea level rise and flooding, and their operations could be seriously affected.

These findings do not separate out many of the stresses associated with flooding such as hydrologic stress and undermining of structural supports and corrosion. Many of the vulnerabilities and the consequences associated with flooding are distinct from those associated with sea level rise. Sea level rise is a slow-onset hazard that causes saltwater intrusion damage to infrastructure, while coastal flooding can be acute yet cause intermittent damage.

7.3.2.2 Temperature. The NPCC 2010 report (NPCC, 2010: Table 4.1) sets forth impacts of temperature on the city's infrastructure and Tables 7.1a–e provide more current details. This section focuses primarily on the vulnerability of selected infrastructure sectors to temperature impacts primarily in terms of attributes of materials and structural characteristics, keeping in mind that temperature is measured in a number of different ways. A heat wave, for example, is defined for New York City as 3 or more consecutive days with maximum temperatures at or above 90°F (Horton *et al.*, 2015: Chapter 1).

New York City is experiencing increases in the number and intensity of extreme heat events that can be attributed to a warming climate (Horton *et al.*, 2015). NPCC2 presented these conditions in terms of heat waves (Horton *et al.*, 2015), and

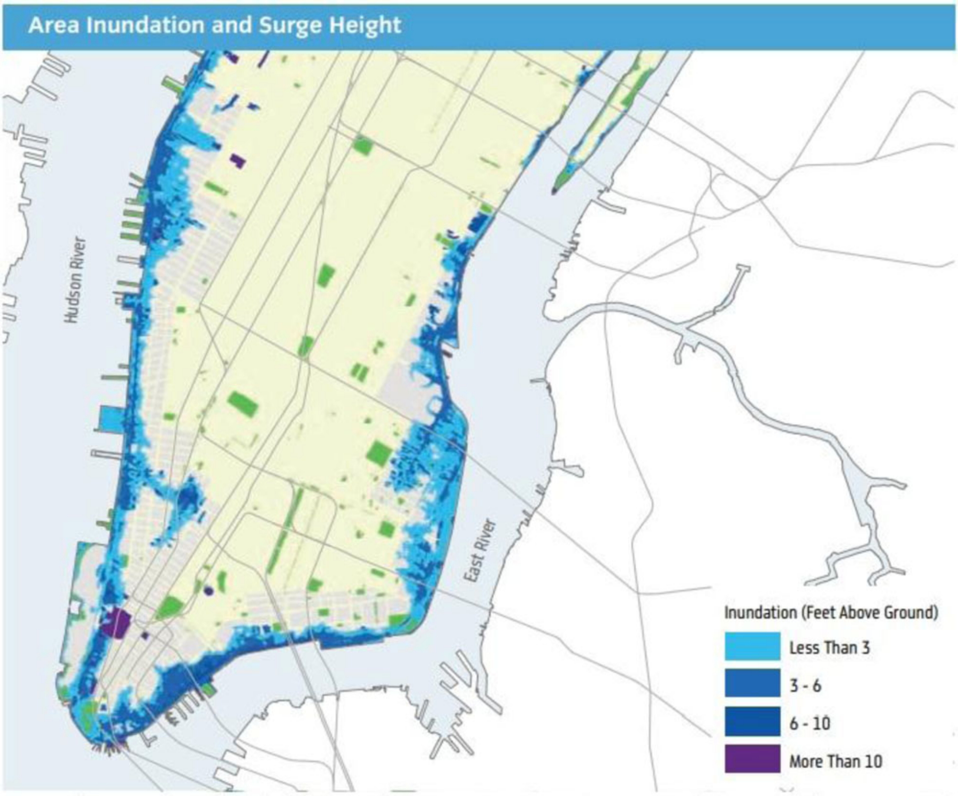

Figure 7.1b. Areas subjected to inundation and surge during Hurricane Sandy where selected critical infrastructure systems are located in or connected with facilities in flood inundation zones, Southern Manhattan, NYC.
Source: NYC SIRR (City of New York, 2013).

NPCC2 as well as future NPCC3 projections (as described in the climate sciences chapter) project these trends to remain throughout of the rest of the 21st century (Horton *et al.*, 2015). While the key physical drivers of extreme heat events are predominantly synoptic climate signals, the built environment of the complex urban core has a magnifier effect, the urban heat island, increasing the intensity of them (Ortiz *et al.*, 2018).

Transportation. Temperatures expressed as unusually high temperatures that are frequent or long duration (e.g., heat waves) have had the effect of deforming transportation materials, for example, concrete used for roadways and other supports such as bridges (Jacobs *et al.*, 2018), asphalt for roadways, and steel for transit rails and vehicle components (U.S. DOT, FTA, 2011). These phenomena are a combination of temperature levels, duration of the heat, environmental loads, usage (e.g., vehicular speed and weight), and the manner in which transportation materials have been installed in light of temperature constraints (Kish and Samevedam, 2013). The New York area transportation systems have experienced the effects of temperature on its operations, and some examples are noteworthy.

With respect to steel rail, the MTA's Metro-North system has experienced actual rail buckling and wheel distortions associated with high temperatures. A derailment near Poughkeepsie was potentially considered to be attributed to high temperatures (Cummings, 2017). This is potentially a system-wide problem and common to rail systems beyond the New York area (U.S. DOT, FTA, 2011) that needs to be addressed in the future, since rail transportation systems were not necessarily designed for such temperature extremes or to the delays associated with reductions in train speeds to reduce heat effects (Kish and Samevedam, 2013).

Furthermore, increased maintenance is often called for to compensate for such vulnerabilities (ClimAID, 2011: 451). The vulnerability of concrete to heat on roadways is also subject how roadways are designed to accommodate heat-related expansion (Jacobs *et al.*, 2018).

Energy. Heat waves can severely stress the electric power system that is built and operated for certain temperature tolerances (U.S. DOE, 2013; ClimAID 2011: 450). Records of past heat wave events indicate that peak loads and blackouts can be related to these extreme heat events. The way overhead transmission and distribution systems are designed can affect vulnerability to sagging, which is related to air temperature and the ability to reduce heat effects (Bartos *et al.*, 2016).

Water supply. A number of earlier studies have identified vulnerabilities of certain water supply components to temperature effects including the relationship between temperature and precipitation and temperature and water demand (NYCDEP, 2008). Water storage facilities are potentially threatened by increased evaporation rates which for New York City is a problem given that its storage facilities, such as reservoirs, are uncovered and are thus, generally vulnerable to evaporation. Increasing temperature can also affect water quality (NYCDEP, 2008).

Wastewater treatment. Following Hurricane Sandy, New York City studied selected effects of storm-related impacts on wastewater treatment (City of New York, 2013). In addition, other studies have noted that wastewater treatment processes which in NYC rely upon action by biological organisms can be affected given the limited tolerance of those organisms to heat.

7.3.3 Vulnerabilities for infrastructure dependencies and interdependencies without climate change

Dependencies and interdependencies among infrastructure systems contribute to vulnerabilities of interconnections when not anticipated, are unexpected, or are uncertain. To examine and address potential climate change risks to critical infrastructure, the City recently reconvened the CCATF in the fall of 2015 to review risks based upon the most recent NPCC2 climate projections for New York City and to develop and coordinate potential mitigation strategies.

As part of CCATF, the city through the Mayor's Office of Recovery and Resiliency (ORR) is working with the U.S. Department of Homeland Security (DHS) and Argonne National Laboratories to focus in particular on risks associated with interdependencies among critical infrastructure sectors. The goals are to better understand the risks posed to networked systems such as energy, telecom, and transportation, in addition to asset-level vulnerabilities, and examine potential asset- and neighborhood-level infrastructure resilience strategies.

Table 7.4 gives examples of infrastructure interdependencies and dependencies among infrastructure sectors that begin to identify some of those directions (Zimmerman and Restrepo, 2009). Although these are in the absence of climate change, they provide a foundation for understanding climate change effects.

7.3.4 Vulnerabilities for infrastructure dependencies and interdependencies with climate change

Table 7.5 briefly illustrates conceptually the nature of infrastructure dependencies and interdependencies relevant to climate change exemplified by electric power as the initiator of the effects and interactions with water and transportation. Key cases applicable to New York City or its region follow, first in terms of dependencies and then extended generally to interdependencies.

Some cases specific to New York City are given below for dependencies and interdependencies. Though the climate change connections were not usually made, ways in which climate change could be related are suggested or inferred.

7.3.4.1 Dependencies for energy and transportation potentially associated with climate change. Under climate change, impacts from heat could exacerbate power outages and lead to transit impacts. Below are examples of electric-transportation sector dependencies in New York City that might be expected:

- 2016–2017 Transit Disruptions from Electric Power Outages. The city's transit system relies upon Con Edison as a power supply. In late 2016, subways were disrupted by a midtown manhole fire and the New York City Transit system experienced outages on several subway lines for about a day (Honan, 2016), which exemplified the power-transit connectivity in NYC. This was one of a series of such outages reflecting the power-transit connections that continued through the following year, for example, on April 21, May 7 and 9 (New York

Table 7.4. Illustrative examples of generic infrastructure interdependencies

Sector providing the service	Sector receiving the service				
	Energy: oil and gas	Energy: electricity	Transportation	Water	Communications
Energy: oil and gas		Fuel to operate power plant motors and generators	Fuel to operate transport vehicles	Fuel to operate pumps and treatment processes	Fuel to maintain temperatures for equipment; fuel for backup power
Energy: electricity	Electricity for extraction and transport (pumps, generators)		Power for overhead and underground transit lines, switches, signals, and lighting	Electric power to operate pumps and treatment processes	Energy to run cell towers and other transmission equipment
Transportation	Delivery of goods, food, raw materials, fuels, and general supplies, workers, and residuals removal; pipelines for energy material transport	Delivery of supplies and workers, and the removal of residuals		Delivery of supplies and workers, and the removal of residuals	Delivery of supplies and workers, and the removal of residuals
Water	Production process water	Cooling and production processes water	Water for vehicular operation; cleaning		Water for equipment and cleaning
Telecommunications	Breakage and leak detection and remote control of operations	Detection and maintenance of operations and electric transmission	Identification and location of disabled vehicles, rails, roads; user service information and processing	Detection and control of water supply and quality	

SOURCE: Modified and expanded from Zimmerman and Restrepo (2009).
NOTES: Exchanges or interconnections within each sector also occur, but are not shown here. These examples are illustrative and not intended to be comprehensive. Cases of dependencies and interdependencies specific to New York City are presented in the context of climate change below.

State Office of the Governor, August 9, 2017), and September 17, 2017.

- 2003 U.S.–Canada Blackout. The extensive 2003 blackout was not a particularly extreme heat event however; it underscores the dependency of transportation on electric services in the event of a disruption. A 2006 study showed that during the 2003 blackout, transit in New York City took about 1.3 times as long to recover and traffic signals 2.6 times as long to recover compared to the length of time it took for power recovery (Zimmerman and Restrepo, 2006).
- September 2016 Power Distribution to the MTA Metro-North Railroad. A high-voltage feeder cable powering the MTA's Metro-North Railroad commuter rail transit system was taken offline, but during that process the adjacent backup unit was disabled, disrupting Metro-North commuter rail service for over a week (Flegenheimer, 2013). The problem was investigated and ensuring the robustness of

Table 7.5. Infrastructure dependencies, interdependencies, and selected climate impacts: illustrated for energy, water, and transportation

Dominant infrastructure (example)	Dependency 1: transportation (transit) dependence on energy	Dependency 2: water dependence on energy	Interdependency: energy-transportation-water
Energy (electric power)	Transportation (transit) depends upon energy for operational controls (signals, switches, lighting) and vehicular power in the case of transit Climate impact: Heat, sea level rise, and storms can disable energy which in turn can disable transportation (transit)	Water supply depends on energy for water conveyance (via pumps) and to provide power for treatment processes, where applicable Climate impact: Heat, sea level rise, and storms can disable energy which in turn can disable water supply systems	Electric power outages affect transportation and water (see dependencies 1 and 2) and then electric power is affected since it depends on water for production processes and transportation for access to resources Climate impact: Heat, sea level rise, and storms can disable interdependent energy, transportation, and water systems, potentially with more severe consequences given the interdependencies

SOURCE: Based on Zimmerman (2018–2019) and Zhu and Zimmerman (September 20, 2018).
NOTE: This hypothetical example portrays energy infrastructure only as electric power. This example covers only the disabling of transportation and water supply from electric power outages; disabling also occurs from direct effects of climate change as well as indirect effects through electric power outages.

power supply to a large transit system suggests operational and managerial control needs.

In each of these examples, commuters heading to work and other transit users were affected by power outages that unexpectedly halted train service. Some solutions are for New York State and New York City to ensure electric power reliability for subway signals, switches, and third rail systems and to improve signaling and switch capabilities. The Governor directed the NYS Public Service Commission (2016) to investigate (NYS Office of the Governor, 2017), and Con Edison has scheduled improvements (Con Edison, May 26, 2017). In the future, these considerations should be expanded to components of the MTA system other than trains but related to train service.

7.3.4.2 Interdependencies potentially associated with climate change. The effects of sea level rise and temperature on individual infrastructures are heightened where several infrastructures are connected. In New York City, water supply distribution lines and electric power lines are often colocated in the same conduits or corridors for cost-saving. Drainage pipes are often located on the underside of highway overpasses or bridges. Under such conditions, sea level rise and high temperatures will affect more than one infrastructure.

Some examples illustrate selected interdependency and climate change phenomena relevant to NYC:

- *Energy and Transportation:* This case is identical to the one above for New York City transit subways in the absence of climate change except that the climate change phenomenon can be specified. First, when heat or sea level rise causes power outages and separately also impairs rail lines and disrupts train operations, then transit riders may shift to other travel modes (e.g., road-based transit that can cause excess roadway congestion). Such congestion will likely prevent electric utility workers from accessing utility equipment (e.g., electric power, water) causing delays in equipment repair (Zimmerman, 2018-2019; Zhu and Zimmerman, September 20, 2018).

  Second, when heat impairs rail travel by distorting the rail lines or when sea level rise floods rail lines and disrupts train operations, not only will transit be directly affected but electrical lines that run near the rail lines will in turn also become impaired.

- *Combined Sewer Overflow (CSO) Facilities and Transportation.* New York City has 426 combined sewer overflow facilities at shoreline locations (NYS DEC, 2012: 1–2). Those CSOs operate in the following way (NYCDEP, 2018b; U.S. EPA, 2017b): when the tide is below the level of the CSO, the CSO regulators can open thus discharging excess water from streets into the waterways surrounding NYC. When the tide increases the regulators close. This is an important mechanism for removing water from land surfaces, including streets.

  Under rising sea level conditions, depending on the height, the regulators could be permanently shut, thereby preventing them to function for street and land surface drainage. When streets are flooded due to CSO interruption, the streets can in turn disrupt water drainage infrastructure further through uncontrolled water discharges from the streets.
- *Energy and Information Technology (IT).* As a result of Hurricane Sandy, IT components were disabled in part due to their connectivity to electric power, estimated to be the major cause of IT outages (City of New York, 2013; Rosenzweig *et al.*, 2011; NYS 2100 Commission, 2013).

  This dependency becomes an interdependency when an electric power outage causes an IT system outage, which in turn prevents the IT-enabled electric power systems to operate. The IT connections to electric power systems occur in several different forms, as computers, sensors, cell towers, etc.
- *Energy and Water Supply.* Water supply delivery to housing units in buildings above six stories relies on power supplies to operate the pumps, and electric power can be vulnerable to the effects of climate change and extreme events. Such units and their locations have been estimated for New York City as a basis for adaptation strategies to avoid interruptible water supplies (Zimmerman *et al.*, 2015).

  Likewise, water supply outages caused by electric power outages can in turn affect energy infrastructure that is dependent upon water for cleaning, operations, cooling, and other functions. When these other infrastructures are deprived of water, they may cease to function especially where water is needed for cooling.
- *Water and Transportation.* Water usage is pervasive across infrastructures, and in turn, water infrastructure relies upon electric power to run pumps and other machinery and transportation to provide water system supplies. Downstate transit depends upon water for potable use and washing operations for its facilities.

  The MTA reported 2.6 billion gallons of water consumed in 2006 for potable purposes across the entire MTA downstate system, and of that, 1.9 billion gallons of water was used for washing as indicated in the report of the Blue Ribbon Commission on Sustainability: Water Sustainability (MTA, 2008). The New York City transit system alone uses about three-quarters of the potable water system used throughout MTA and over 80% of the washwater (2006 water use data) (MTA, 2008).

  Thus, if electric power to these water and transportation systems is disabled (separately to each system), it can produce impacts across both water and transit systems; that is, once the power is disabled to both systems, the impacts will be felt across both. Ultimately, electric power can in turn be affected by transportation and water services.

7.4 Community and infrastructure resilience case studies

Community issues are potentially pervasive in many areas in terms of the extent to which differential impacts and remediation are experienced by communities of different types. The cases in connection with infrastructure, including dependencies and interdependencies among them, associated with electric power, transportation, water, and telecommunications introduced in the previous section provide a context for the cases here.

Two case areas are presented that illustrate the role of infrastructure and its interdependencies and the nature of community and citywide decisions to improve resilience: health care, in particular, hospital row in New York City, and the New York City Housing Authority (NYCHA) in connection with Hurricane Sandy. For each of the cases, key infrastructure interdependencies, specific effects on community, and solutions in terms of current city programs and recommended solutions are the focus.

The cases below are illustrative of social infrastructure. The City of New York (2015: 237) specifically defines social infrastructure as "infrastructure that strengthens communities, such as hospitals, community centers, libraries, and schools, . . . [that] . . . can enhance social resiliency and assist in immediate response after a disruptive event." While Chapter 6 Community-Based Assessments of Adaptation and Equity addresses these directly, the relationships for two examples of these types of social infrastructure to lifeline infrastructures are described here.

7.4.1 Intersection of social and critical infrastructure in hospitals

Health facilities can be particularly vulnerable during extreme weather events, and, like most other types of social infrastructure, rely on and are connected to a vast network of infrastructure services: transportation for access, environmental facilities for cleanliness, and electric power and water to support essential services. To illustrate the interrelationships between social and critical infrastructure, this section will focus on New York City's hospital row. Hospital row is an area along the East River shore of Manhattan, between East 20th to 30th Streets and First Avenue, where many hospitals are located, including three out of the five acute-care hospitals evacuated during hurricane Sandy.

7.4.1.1 Vulnerability. A variety of different types of health facilities are part of the city's healthcare system encompassing hospitals, rehabilitation/long-term care, ambulatory care, pharmacy, and home care settings, and all of these interact with one another. New York City has 62 active hospitals with a total capacity of 26,451 beds (NYC Independent Budget Office (IBO), 2012; Commission on Health Care Facilities in the 21st Century, 2006; New York University Langone web site, 2012).

The NYC Health and Hospitals Corporation (HHC) also known as NYC Health + Hospitals operates the public hospitals and clinics in NYC. NYC Health + Hospitals is the largest municipal health system in the country and it serves more than 1.2 million city residents annually (City of New York, 2015). The NYC Health and Hospitals operates 11 hospitals, 44 neighborhood health centers and 5 postacute/long-term care centers across the five boroughs (NYC Health and Hospitals, undated web site). All of these facilities are dependent upon transportation, electric power, and water for resilience during normal as well as emergency conditions.

During emergencies, maintaining the functioning of acute healthcare facilities is of the highest priority. Evacuation can be life threatening to vulnerable individuals (McGinty, 2015). For example, a study of nursing home residents with dementia reported that evacuation increased the risk of death 30 and 90 days after relocation (Brown *et al.*, 2012).

Because patients in hospitals are ideally expected to shelter in place to minimize the risks to vulnerable patients during most emergencies including extreme weather events such as heat waves and storms, they are heavily dependent on the availability of a reliable backup electricity supply in case of electrical grid failure. The adequate flood protection of critical electrical infrastructure within these facilities is also vital for ensuring the continuity of services.

A report by the U.S. Department of Health and Human Services concluded that "without exception, the loss of (or lack of) emergency power following the loss of municipal grid power was the primary reason that hospitals, adult care facilities, and nursing homes evacuated. Flooded critical infrastructure, such as ground floors, electrical switchgear, and heating/cooling systems, was the secondary reason. In ambulatory settings, the disruption to staff and patient travel became the primary reason for disruption, followed by loss of communication/IT systems" (Guenther and Balbus, 2014: 33).

The Pace Energy & Climate Center (c2013) also emphasized the disabling of hospitals due to electric power outages in the Hurricane: "Approximately half of New York City hospitals' generators malfunctioned during the blackout [citing U.S. EPA CHP], and many other hospitals were unable to sterilize equipment due to insufficient steam pressure [citing the NYC Emergency Response Task Force, October 28, 2003)]".

The vulnerability of these facilities to climate-related extreme events is reflected in some of the effects that Hurricane Sandy had on them. Specifically, five acute-care hospitals shut down in New York City due to Hurricane Sandy, two of which evacuated before and three of which were evacuated after the storm hit (Kinney *et al.*, 2015; Teperman, 2013). Since some hospitals were unable

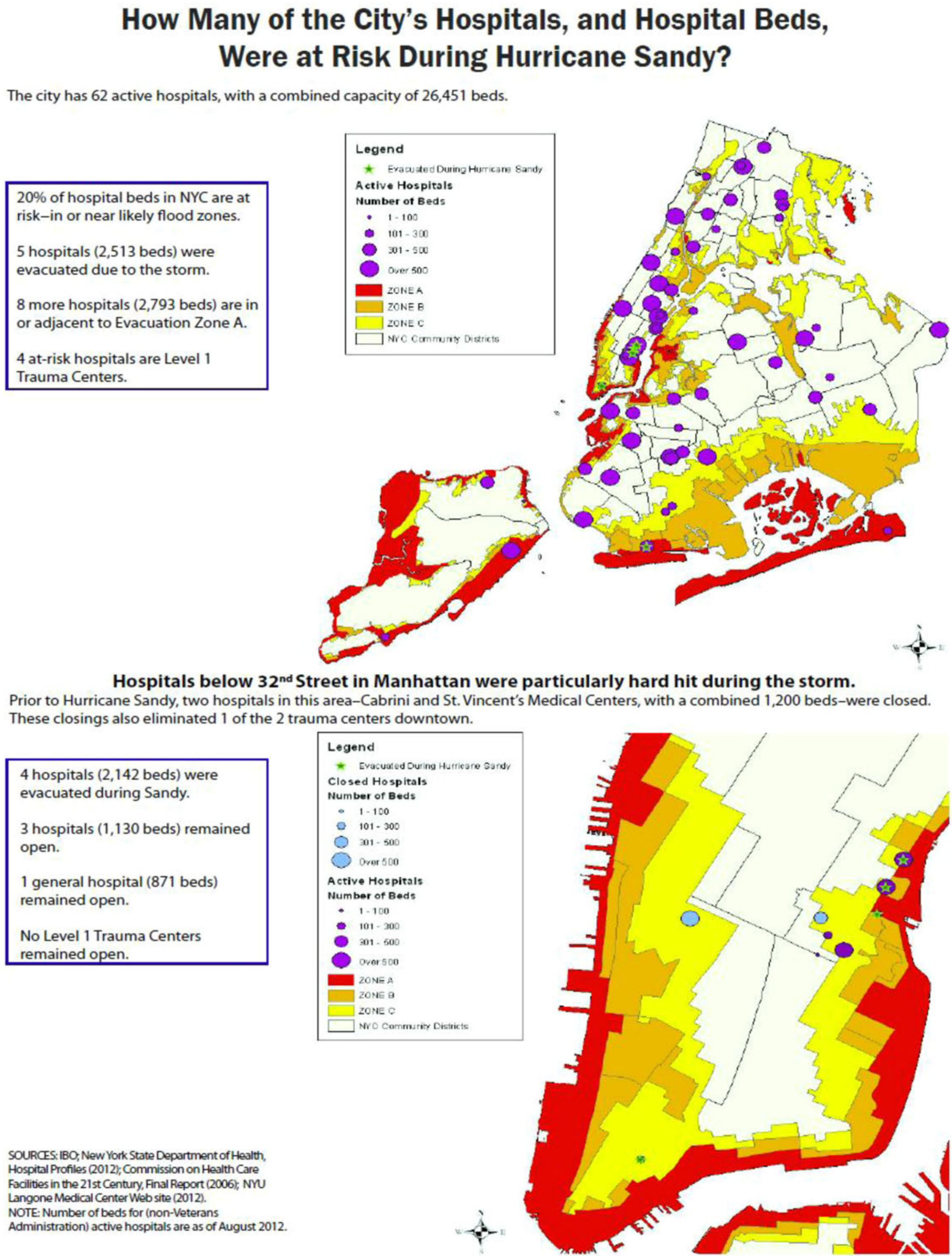

Figure 7.2. Risk to hospitals and hospital beds during Hurricane Sandy.

to ensure continuity of operations, there were substantial delays in returning to normal functions (Powell *et al.*, 2012). Bellevue Hospital, which evacuated patients and staff after the storm hit, did not restore inpatient wards until 2 weeks later (Teperman, 2013). The locations of hospitals and hospital beds considered at risk during Hurricane Sandy are shown in Figure 7.2 along with the city's zone designations for flood hazard at the time (NYC IBO, 2012; NYS Department of Health, 2012; Commission on Health Care Facilities in the 21st Century, 2006).

In 2014, the city announced $1.6 billion in funds from FEMA for hospital repairs, particularly noting repairs for four of the city's hospitals, which are Coney Island, Bellevue, Metropolitan, and Coler (City of New York, 2014). The destruction experienced by the NYU Langone Center illustrates particularly well the magnitude of impacts experienced by the communities served by the Center as a result of infrastructure disruptions.

According to FEMA (U.S. DHS, FEMA, 2017b, c), The NYU Langone Medical Center which is a private nonprofit facility consisting of the NYU School of Medicine, three hospitals, and specialized centers, experienced severe damages to its electrical infrastructure, backup power systems, and communications due to flooding related to storm surge conditions during Hurricane Sandy. The electric power and communications systems are interconnected as well, each relying on the other to function.

Public and private financial support enabled surgery units to open on December 27, 2012, pediatric services to open in January 2013, and emergency services to be available by April 2014. Subsequent funding for repairs supported long-term resilience and key resilience investments included the relocation of electrical equipment, drinking water, and fuel pumps to higher levels, as well as building flood walls aimed at protecting critical infrastructure on hospital campuses to the 500-year flood level (U.S. DHS, FEMA, 2017b,c).

The NYC Independent Budget Office summarized federal financial commitments for hospital repairs. From the nearly 1.6 billion in disaster relief funds, $1.3 billion were added to the city's capital budget and $260.5 million were added to the operating budget (NYC IBO, June 2016). NYC Health + Hospitals (2017) received $231.5 million in federal funds for repair and reconstruction projects, including improved protection from future storms. Of these funds, $208.8 million are planned for 2020 projects.

According to the City of New York Sandy Funding Tracker (NYC Recovery, 2018), some medical facilities where repairs are currently or recently underway include Jacobi Medical Center, Metropolitan Hospital, Roberto Clemente Family Guidance Center, and Bellevue Hospital. Examples of repair projects include "install[ing] pre-connections for external generators, temp boilers, and temp chillers" (Metropolitan Hospital), "build[ing] a floodwall and relocate[ing] the Emergency Department (ED) & critical infrastructure above the 500-year floodplain (Bellevue Hospital)," and strengthening the soffit support system to provide a "rigid system capable of resisting uplift loads experienced during Sandy" (Jacobi Medical Center).

7.4.1.2 Social impacts. Emergency hospital closures during disasters can have a myriad of short- and long-term consequences for the populations they serve and the healthcare system in general. For example, hospital evacuations, the process of moving patients from an at-risk location to a safer zone within the hospital or to another facility (Tekin *et al.*, 2017), may put critically ill patients at increased risk (King *et al.*, 2016) and pose a number of operational challenges for the medical facilities received by patients from evacuating hospitals (Adalja *et al.*, 2014).

According to reports, nearly 2000 patients were evacuated as a result of hospitals closings in the aftermath of Hurricane Sandy and transferred to medical facilities that struggled to meet their needs (City of New York, 2013: 16). One estimate was made by the NYC SIRR (City of New York, 2013) of the total costs to New York City hospitals associated with the emergency response to Hurricane Sandy (City of New York, 2013: 148) but revenue losses or the costs associated with restoring normal operations were probably not included.

The short-term challenges related to patient evacuation and absorbing citywide patient surge only highlight the most immediate social impacts of physical damage to hospitals, and secondary hospital "surge" issues need to be addressed. Studies have demonstrated that some of the greatest effects of a disaster on healthcare services utilization occur in the months and years following the immediate impact (Bell *et al.*, 2018; McQuade *et al.*, 2018; Sharp *et al.*, 2016). According to one analysis, "disasters create a secondary surge in casualties because of the sudden increased need for long-term health care" (Runkle *et al.*, 2012).

Although the mechanism through which disasters may affect long-term demand for healthcare services is not completely understood, it is well established that exposure to disasters poses particular challenges to individuals suffering from chronic health conditions such as heart disease, cancer, chronic respiratory, and diabetes (Mensah *et al.*, 2005; Sharp *et al.*, 2016). Therefore, hospital closures will likely have substantial and long-term consequences for the populations they serve.

7.4.1.3 Recommended adaptation measures. Hurricane Sandy resulted in around $3.1 billion dollars in estimated total healthcare damages, a substantial fraction of which likely reflects damages to hospitals (NYS Office of the Governor, 2012b). Improving the infrastructure resiliency of hospital facilities to climate-related extreme events will be essential for ensuring the continuity of healthcare services and reducing the adverse health impacts of disasters, particularly among the already vulnerable.

Adaptation planning with consideration of the hospital capacity and lifeline infrastructure in vulnerable areas will be essential for minimizing costs and damages to health institutions associated with future extreme weather events. For instance, four of the hospitals that evacuated during Hurricane Sandy New York Downtown Hospital, Manhattan VA Medical Center, Bellevue Hospital, and NYU Langone, are located in low lying areas in the southern portion of Manhattan. The southern portion of Manhattan is characterized by a high concentration of critical infrastructure, such as Con Edison's East 13th Street complex, in addition to a large number of hospitals, including those located in hospital row (City of New York, 2013: Chapter 18).

Health facilities and infrastructure in such vulnerable areas often serve communities well beyond their geographical scope. According to the NYS Department of Health, 20% of all New York City hospital beds are located in or near likely flood zones. Very importantly, a substantial amount of hospitals with over 500 beds are at risk, including Manhattan VA Medical Center, Bellevue Hospital, and NYU Langone (NYC Independent Budget Office, 2012).

Improving the resiliency of healthcare infrastructure is one of the most critical steps necessary to prevent human health and safety impacts during future weather events (Powell *et al.*, 2012; Redlener and Reilly, 2012). This will be especially critical in light of the increasing risk of flooding due to sea level rise. According to one estimate based on NPCC high-end sea level rise projections, "a total of 1000 New York City healthcare facilities will be in the 100-year floodplain by the 2050s (City of New York, 2013: 149)." Although estimates may vary depending on sea level rise scenarios used, this assessment highlights the vulnerability of the city's healthcare infrastructures and prompts urgent resilience measures.

The City of New York has already committed to ensuring better preparedness for future extreme weather events by enacting improved flood protection building codes and implementing emergency power systems resiliency measures (City of New York, 2013). Such measures, together with improved emergency preparedness plans at healthcare facilities, will be critical for ensuring the continuity of operations during climate and weather emergencies.

7.4.2 New York City Housing Authority and access to energy after Hurricane Sandy

The case of the New York City Housing Authority's (NYCHA) experiences in rethinking access to renewable energy during normal and emergency conditions illustrates many of the challenges this affordable housing resource faces in light of climate change and related extreme weather events. NYCHA's course of decision making and its projects also elevate the complexities embedded in Mayor Bill de Blasio's strategic focus on the intersection of equity, with an emphasis on inclusive growth that reduces poverty and expands job opportunities, and climate action designed to reduce risks and vulnerability while building sustainability and resilience at all scales (household, neighborhood, borough, and citywide) according to the OneNYC Progress Report (City of New York, 2018). (See Appendix 7.C for a fuller discussion of equity and climate related to critical infrastructure in New York City.)

Late October 2018 marked the sixth anniversary of Hurricane Sandy, which affected about 60,000 residents and damaged over 200 New York City

Housing Authority buildings. The infrastructure systems of these residential building sustained significant damage—residents had to endure the loss of electricity, elevators, heat, and hot water (Goodson *et al.*, 2016).

More than 400 NYCHA buildings throughout New York City were affected by the hurricane; 402 of those NYCHA buildings lost power, which also disabled elevator and compactor service, and 386 of those buildings lost heat and hot water (New York City CDBG-DR, November 2013; NYS CDBG April 2013). NYCHA housing stock in Coney Island, Brooklyn, sustained significant damage from sand and saltwater infiltration, while damage to other NYCHA housing stock was mostly the result of flooding.

U.S. DHS, FEMA (2015: 23) noted in connection with a New York City application to upgrade various facilities for portions of NYCHA housing and others that:

> The revised information depicted on the P-FIRMs has increased the number of NYCHA buildings located within the 100-year flood zone as compared to pre-Hurricane Sandy conditions. With one exception (Gowanus, located in Shaded Zone X), all NYCHA developments included in this PEA [Programmatic Environmental Assessment] are located in Zone AE.

In Figure 7.3, the location of NYCHA developments are shown with respect to 2015 Preliminary FIRM flood zones, and provided by NYCHA.

In the fall of 2017, NYCHA forecasted that projects designed to repair, fortify systems, and in NYCHA's terms "build back better," will be in construction through 2021 (Honan, 2017). Like almost all residential buildings in New York City, NYCHA infrastructure systems for heat, hot water, elevators, trash compacting, and other functions depend on grid-connected electrical power (U.S. DHS, FEMA, 2015: 7).

NYCHA (2017) is currently incorporating distributed energy resources (DERs) into its $3 billion Sandy Recovery and Resilience program, including one campus-scale microgrid. When complete, over 200 NYCHA buildings will benefit from emergency back-up power for full building loads (rather than critical building functions only). After evaluating generation technologies including combined heat and power (CHP) and solar PV, NYCHA chose to install gas-powered emergency back-up generators connected to a centrally controlled demand management system. NYCHA plans to off-set the maintenance cost of this infrastructure with revenues generated from peak shaving and demand response programs.

NYCHA is building a campus microgrid for more than 6000 residents of its Red Hook East and Red Hook West Houses (Red Hook NY, 2014). The Red Hook Houses back-up electric system may also allow the possibility for future integration with the Red Hook Community Micro-grid, another DER project under the auspices of the New York State Energy Research and Development Authority (NYSERDA) and the New York Power Authority (NYPA); this community-wide microgrid has listed solar and wind as its preferred sources of low-carbon power and natural gas as a backup alternative.

Looking beyond projects directly developed by NYCHA to NYCHA's participation in DER proposals and projects advanced by private entities illustrates the challenges and opportunities involved in designing DER projects that simultaneously meet goals for mitigation, resilience, and public benefit for the housing authority as well as technical viability and financial success for the private-sector partner. Since 2015, NYCHA has provided letters of interest to six DER (microgrid) projects led by private DER developers that in aggregate encompass 13,700 apartments and more than 13 million square feet of public housing. None of these projects have progressed beyond the concept phase.

In 2016, One City Block, a unit of Google, proposed the Eighth Avenue Microgrid, a DER that would include three natural gas–fired CHP microturbines to be located in NYCHA's Robert Fulton Houses, a solar array and a back pressure turbine to be located on the Google building in Chelsea, a West Side Manhattan neighborhood south of NY Pennsylvania Station (NY Prize Stage I Feasibility Study, Eight Avenue Microgrid, ERS, April 2016) (NYSERDA, 2016).

During normal, everyday operation, this DER would provide electricity to One City Block (the Google campus in former Port Authority buildings) and a substantial share of the steam needs of Fulton House's 945 apartments in 11 buildings. During an emergency, this DER would be "islanded' and would provide power for Google and the Fulton Houses apartments for approximately 7 days. This proposal won a first-round planning grant from NYSERDA,

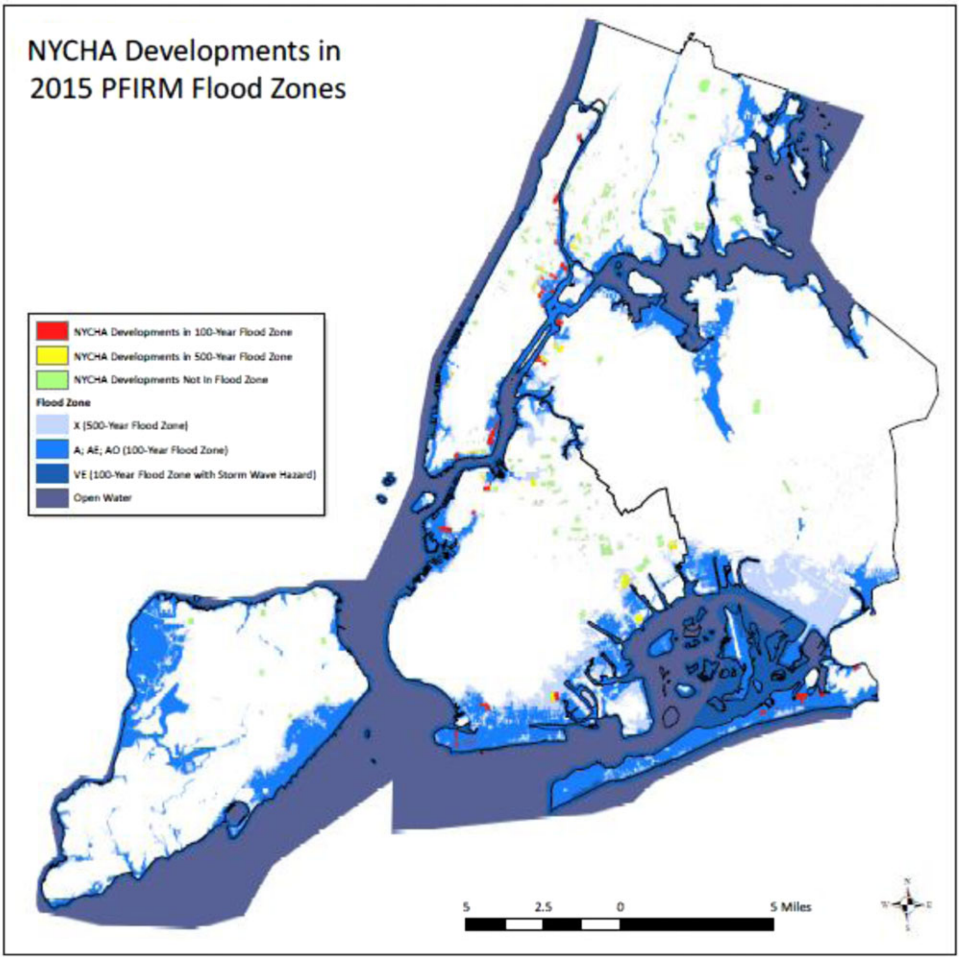

Figure 7.3. NYCHA developments and selected flood zone locations. Source: NYCHA with FEMA 2015 Preliminary FIRM.

but the proposal failed to advance to later stages of the NYSERDA competition. Though this is a single project, it is an important model.

In 2016, NYCHA began to evaluate development options for solar PV-based DERs, informed both by the need to provide emergency back-up power for critical building systems and by its Sustainability Agenda goals (NYCHA, 2017). In light of NYCHA's electric supply contract with the New York Power Authority, capital constraints, and regulatory and rate-structure limitations in its ability to participate in remote net metering and as an off-taker in community distributed solar, NYCHA ultimately came to the conclusion that the currently economically viable solar development option is limited to leasing rooftops and parking canopy space to private solar developers.

Accordingly, NYCHA released two solicitations for solar development: in 2017, for commercial-scale solar projects, and in 2018 for its small buildings. NYCHA seeks to site 25 megawatts of renewables on NYCHA property by 2026; however, it is yet to be seen whether any of these projects could be structured to provide an emergency back-up function for NYCHA's critical building systems.

NYCHA's DER projects, both those led by NYCHA and those in which it is a public-sector participant in a public–private partnership (P3), underscore the substantial, near-term challenges that New York City and New York State face in rightsizing DER projects and designing viable P3s. In addition to the mitigation and resilience benefits of viable DER projects, New York City at a variety of scales—City Hall, borough, neighborhood—should continue to advocate policies that highlight the economic benefits and co-benefits of DERs.

Two incumbent DER operations—one at Co-op City in the Bronx and the other at New York University's Greenwich Village campus—may provide lessons learned as New York City builds out its DERs policy and projects. Building connected to New York University's microgrid on its Greenwich Village campus continued to provide electricity during and after Hurricane Sandy. In the Bronx, Co-op City, home to 60,000 people in 35 high-rise buildings and seven sets of townhouses used its microgrid to continue supplying electricity for heat, hot water, and air conditioning, while nearby neighborhoods went without power (Leonhardt *et al.*, 2015).

New York City and the Empire State's transition to low-carbon and zero-carbon feedstocks for energy by 2050 will transform energy generation, transmission, and delivery as energy users in all sectors (public, private, and independent) move from reliance on utility-scale grid-based power to a system where a growing share of power needs under normal conditions and during emergencies will flow from distributed energy sources linked to battery storage units. This emerging structural shift in the sources and assets for energy, as well as other elements of mitigation, adaptation, and resilience, is creating new challenges, opportunities, economic benefits, and cobenefits in all sectors and many communities, including low-income, low-wealth communities.

7.5 Insurance and finance strategies for citywide resilience

Insurance and finance are key dimensions in achieving infrastructure resilience.

7.5.1 Insurance[a]

Economic and insured losses from hurricanes and floods have increased significantly over the last several decades and are likely to increase further in the future from more intense hurricanes and sea level rise. There is general consensus that improvement in resilience to reduce future disruptions is a smart investment. Research is being conducted to improve understanding of infrastructure resilience from a climate change perspective along with other threats such as cyberattacks. However, the economic and financial considerations of resilience remain less explored.

The insurance industry can catalyze infrastructure resilience by encouraging investment in loss reduction measures prior to a disaster through a reduction in premiums to reflect lower claim payments. Losses from both natural disasters like hurricanes and floods and man-made disaster such as accidents, terrorism, and cyberattacks are often insured through traditional insurance products. Newer financial instruments like catastrophe bonds also facilitate the transfer of a portion of the risk from these types of hazards to investors.

Certain barriers prevent wider use of insurance-related instruments and other market-based incentives for improving infrastructure resilience. For example, government disaster relief can deter both the purchase of insurance and other risk-transfer instruments and investment in mitigation measures, thus increasing the reliance on taxpayers' money to aid the recovery process following severe losses from future disasters.

Addressing the following questions will help facilitate better understanding of the economic and financial facets of resilience:

- Who will pay for cost-effective mitigation measures that enhance resilience against future disasters?
- "What is the best way to finance resilience in the short-term and long-term?" (Kunreuther *et al.*, 2016: 3)
- How can we transfer more risk to the private sector to reduce reliance on post disaster taxpayers' money?

To answer these questions, it is critical to understand the nature of federal disaster relief, economic constraints, and behavioral limitations that need to be overcome. Two infrastructure sectors are the focus of this work: energy utilities and transportation.

7.5.1.1 Nature of federal disaster relief and its relationships to insurance. Governments often serve as the insurer of last resort (King *et al.*, 2013, Pidot, 2007), and the role that the federal

[a]Some of the material in this section is taken from Kunreuther *et al.* (2016). Partial support for this research comes from a grant to Wharton Risk Center from the National Critical Infrastructure Resilience Center of Excellence through the University of Illinois 2015-ST-061-CIRC01, "Identifying and Reducing Barriers to Infrastructure Insurance."

government plays in disaster relief has been continually growing. The Stafford Disaster Relief and Emergency Assistance Act (Public law 100–707) plays a key role in providing emergency funds following disasters that impact public sector infrastructure by providing funds to cover at least 75% of the cost of recovery and repair following a Presidentially declared disaster (it was 100% after Hurricane Katrina). Further details on federal disaster relief funding are discussed in the next section under financing, and this section addresses its relationship to insurance.

While the Stafford Act supports community recovery following a disaster, it can also inhibit infrastructure resiliency in a couple of ways. First, with the knowledge that federal funds may be available following a disaster should their facilities incur damage, infrastructure managers may have less of a financial motivation to invest in loss mitigation measures or to purchase insurance to make their systems more resilient in light of potential future disasters. Second, Stafford Act funding typically only covers the costs to restore an infrastructure system to its predisaster design. It generally does not pay for the costs associated with improving an infrastructure system's resilience to future disasters. When other sources of resiliency funds are available, improvements can be made in conjunction with restoration, but this is often infeasible given budget limitations (Kunreuther *et al.*, 2016).

Though the Stafford Act in its current form serves in some ways as a deterrent to infrastructure resilience, it could potentially be modified to encourage communities and infrastructure managers to exhibit greater financial responsibility and to undertake adaptation measures to reduce losses prior to a future disaster. One revision that FEMA proposed to the Stafford Act would compel a state to meet a disaster deductible prior to receiving recovery funds. The deductible could take on a variety of forms such as emergency savings or predisaster mitigation measures. Such modifications could reduce the reliance of infrastructure systems on federal disaster relief funds and could encourage increased insurance and mitigation (U.S. DHS, FEMA, 2016).

Reliance on federal disaster relief also potentially hinders the ability of the insurance market to effectively price and share risks (King *et al.*, 2013, Pidot, 2007). Improvements to the Stafford Act could potentially address this concern. With reduced reliance on federal disaster relief funds, infrastructure managers will be incentivized to purchase sufficient insurance to cover losses should a disaster occur.

Insurance can also serve as a tool to incentivize mitigation, wherein an infrastructure system could receive a premium discount or improved policy terms if they employ mitigation measures to reduce the potential losses from a natural disaster and insurance premiums reflect this reduction in risk. When evaluating mitigation measures and insurance policies, one also needs to take into account how climate change will impact the environment (e.g., sea level rise). This is important in determining ways to protect existing infrastructure (e.g., sea walls) and in designing insurance mechanisms to support these measures.

In addition to federal disaster relief posing a disincentive to insurance purchase and risk reduction investment, other challenges also limit infrastructure system resiliency. One challenge is a lack of information sharing among critical infrastructure organizations. Due to security concerns, sharing of information about system vulnerabilities between infrastructure organizations typically does not occur. However, this information could be helpful for preparedness planning and for understanding risks associated with infrastructure interdependencies.

A second challenge is a lack of direct experience with major disasters on the part of many infrastructure managers, which may limit the understanding of vulnerabilities in their systems. While some infrastructure managers may gain insight from disasters experienced in other places or by other infrastructure systems, they may be limited in their understanding of necessary investments to reduce future losses and improve system resiliency toward disasters. For these reasons, and in light of budget limitations, decisions and expenditures for improving infrastructure resiliency for the future are often delayed in the absence of economic incentives in the present (Chang *et al.*, 2014).

7.5.1.2 Insurance for specific infrastructure sectors. Insurance needs and policies vary for infrastructure systems based on the type of system, risks faced, funding sources, and other factors. In this section, we consider insurance for electric utilities and transit infrastructure.

Insurance for Damage or Disruption of Electric Utilities. Electric utilities are typically insured, and the cost of the premium is embedded in the electricity rates paid by customers. Insurance needs vary for electricity producers and distributors. Electricity producers are typically insured against property damage and business interruption. Electricity distributors usually also have coverage for business interruption; however, property damage coverage is limited for distribution systems due to the significant exposure of their transmission and distribution lines.

Newer insurance products available to electric utilities provide coverage against losses associated with adverse weather events such as warm winters that impact profits. Separate business interruption insurance for losses associated with compromised or lost data due to operator error and cyber risk from hackers, data malware, and other malicious cyber risks is also available (Bruch *et al.*, 2011).

Transit/Rail Infrastructure Insurance. Rail organizations generally seek private insurance for catastrophe risks. Considerations in insurance coverage for rail companies include the class and size of the railway as well as local laws. Coverage is typically first party on an all-risk, replacement cost basis through companies such as Lexington (AIG), Lloyds, and the continental European market.

The amount of coverage that insured parties received following Hurricane Sandy depended on whether the damage was attributed to flooding or to storm surge. Flood coverage is usually subject to an aggregate limit, whereas storm surge coverage is not. For some infrastructure systems, recovery and restoration after a disaster is a long process, and it can take the insured a long time to recoup their losses as was true following Hurricane Sandy (Kunreuther *et al.*, 2016).

Public transit operators generally have some combination of self-insurance and commercial insurance for their systems, but coverage types and amounts vary greatly between different organizations. Due to budgetary limitations and a focus on insurance needs for other risks, as noted in the prior section, many transit infrastructure systems are not sufficiently insured against natural hazards and other catastrophic risks and are reliant on federal relief funds to recover from catastrophic disruptions.

The U.S. DOT Federal Transit Administration's (FTA) Emergency Relief Program (ERP) provides assistance to public transit operators in the aftermath of an emergency or major disaster, and eligibility for such funding relates in some ways to insurance requirements. The FTA program has helped states and public transportation systems fund the protection, repair, or replacement of equipment and facilities that are damaged due to emergencies and natural disasters (U.S. DOT, FTA, 2018a).

The ERP was established under the Moving Ahead for Progress in the 21st Century (MAP-21) Act, and seeks to improve U.S. DOT and U.S. DHS coordination for the purpose of expediting emergency assistance to public transit systems (U.S. House of Representatives, 2015). The ERP funds emergency relief projects including emergency operations, protective measures, emergency repairs, permanent repairs, resilience improvements, and the purchase of spare parts. Disaster relief resources provided by the FTA are separate from those provided by FEMA.

Flood insurance is required for transit-related buildings and stations and terminals that are situated above-ground and within a FEMA Special Flood Hazard Area (SFHA), also known as the mapped 100-year floodplain. Certain facilities do not require flood insurance, for example, "underground subway facilities, tunnels, ferry docks, or any transit facilities located outside of a SFHA" (Kunreuther *et al.*, 2016: 34).

If a building in the SFHA is uninsured at the time of a disaster and has previously received prior federal funding, the FTA (U.S. DOT, FTA, 2018b) will only fund a reduced amount of disaster assistance. The eligible amount is established by subtracting the maximum limit of coverage ($500,000) available under the National Flood Insurance Program (NFIP) or the amount of prior federal funding received, whichever is less, from the total restoration cost. The ERP received $10.9 billion from the Disaster Relief Appropriations Act of 2013 for Hurricane Sandy recovery (U.S. DOT, FTA, 2018a, b).

The Metropolitan Transportation Authority (MTA): Insurance and Government Relief. Hurricane Sandy provides a good illustration of costs and disruptions to taxpayers associated with insufficient infrastructure resilience. Congress allocated more than $50 billion in funds for Hurricane Sandy recovery efforts across the entire affected area, and more than $17 billion of this funding was allocated for projects in New York City (NYC Sandy Recovery, 2018). A substantial amount of this funding was allocated to infrastructure, including transportation infrastructure systems. The MTA is a public benefit corporation that is responsible for public transportation. MTA experienced more than $5 billion in damage during Hurricane Sandy, including substantial damage to rail and subway systems. The MTA's property insurance paid out at the policy limit of $1.1 billion for Hurricane Sandy, which only covered a fraction of MTA's losses.

The MTA also received $4.2 billion in federal relief from the U.S. Department of Transportation Federal Transportation Administration (FTA) under the ERF. This $4.2 billion included $900 million for resilience improvements. FEMA also provided $3.7 million for emergency repairs to equipment and facilities such as damaged tracks, signals, power lines, communication links, and stations (Kunreuther *et al.*, 2016; Czajkowski *et al.*, 2017).

Following Sandy, the MTA established a Sandy Recovery and Resiliency Division, with a key goal being to protect the many places where their subway system is prone to future flooding (Metropolitan Transportation Authority, 2016).

Following Sandy, the MTA was unable to renew its annual insurance policy under predisaster terms. They were offered only a policy that halved their coverage and doubled premiums, so they sought other forms of risk transfer. In July 2013, the MTA issued a $200 million catastrophe bond with stable premiums over the next 3 years in order to transfer a portion of its exposure to future storm surges to the financial markets. The bond would pay the MTA $200 million if specified storm surge conditions occurred during that period; the funding would be provided rapidly after storm surge damage estimates were completed (Kunreuther and Michel-Kerjan, 2013).

The extensive cost to taxpayers plus the substantial business interruption that occurred in the aftermath of Hurricane Sandy illustrate the need for infrastructure resiliency improvements. Financial and insurance mechanisms, along with regulatory mechanisms, can be used to facilitate resilience via mitigation and insurance. In addition to substantial federal disaster relief expenditures, there was a substantial cost to the insurance industry associated with Hurricane Sandy. Total insured losses equaled around $37 billion. $20 to $25 billion of this cost was incurred by private insurers, with the rest incurred by the NFIP (Kunreuther *et al.*, 2016).

7.5.1.3 Proposals for utilizing insurance to enhance infrastructure resilience. Interactions and interviews with leaders of the insurance and reinsurance industry involved in risk management for rail, transit, air, and marine transportation infrastructure revealed that enhancements to infrastructure resilience and insurance are needed to address the challenge of increasing losses associated with catastrophic events.

Seven recommendations for utilizing insurance to foster resilience in critical infrastructure in the New York metropolitan region as well as other parts of the country emerged from these interviews and a review of the existing literature that are detailed in Czajkowski *et al.* (2017: 2).

The recommendations are (1) continue working toward revisions of the Stafford Act; (2) promote alternative funding vehicles for pre-event resiliency investments linked to discounts in insurance premiums; (3) facilitate catastrophic risk data collection, availability, and analysis to better relate resilience improvements to insurance premiums and cost savings; (4) encourage the development of resilience metrics; (5) support research pertaining to emerging catastrophic risks such as cyber and climate change; (6) consider a redefinition of terrorism for coverage under the Terrorism Risk Insurance Act (TRIA); and (7) promote the comprehensive benefits, beyond a straightforward loss backstop, of catastrophic risk insurance coverage for infrastructure systems (Czajkowski *et al.*, 2017).

7.5.2 Infrastructure finance

A robust and sustainable infrastructure financing system is at the core of infrastructure resilience. A 2016 study of spending in global megacities for resilience and adaptation indicated that New York City ranked first in total spending, ranked second in spending per capita, and tied for third for spending per dollar of GDP for climate change adaptation (Georgeson *et al.*, 2016).

Estimates of infrastructure needs are a useful prerequisite for investment. Needs are usually linked to performance standards, some of which are incorporating resilience in the face of climate change and extreme events, including GHG mitigation measures either directly or indirectly associated with climate change. Chapter 7, Indicators and

Monitoring, of the 2010 NPCC report (Jacob *et al.*, 2010) addressed these metrics, and some are also revisited in Chapter 8, Indicators and Monitoring. For U.S. infrastructure, investment needs have been estimated by the ASCE (2017) as over 4 trillion dollars nationwide for the period from 2015 to 2025 (ASCE, 2017: 8). Needs assessments do not always explicitly or directly include climate change requirements for resilient infrastructure.

The financing mechanisms that support New York City's infrastructure draw from diverse financing sources, in particular with respect to the public and private mix, level of government, and the conditions or applicability, and type of infrastructure. With respect to level of government, one example for transportation is the New York Metropolitan Transportation Council (NYMTC; NYMTC, undated web site), whose functions include "decisions on the use of federal transportation funds for its planning" that encompasses New York City. The mechanisms can also change under different conditions and over time. This section focuses on three financial mechanisms: (1) Federal Disaster Assistance, (2) Bonds, and (3) Green Infrastructure Grant and Loan Opportunities.

7.5.2.1 Federal disaster assistance. Federal disaster assistance is a major source of federal funding available to aid in infrastructure restoration following certain disasters. Some aspects of federal disaster assistance were addressed above in connection with infrastructure and insurance, and this section provides a general coverage of the program as it pertains to extreme events that are relevant to New York City. Moody's Investor Service (2017) used Hurricane Sandy to illustrate the diversity of funds that were provided for emergency relief and recovery, and in particular reflected FEMA's role and the changing nature of its financial resources.

General coverage included:

- Typical FEMA coverage for "emergency response and debris cleanup": minimum 75%
- Usual coverage: 90% or more

Hurricane Sandy coverage included:

- FEMA: 100% "of certain emergency response and cleanup costs"
- Additional disaster relief from Congress: supplements for $48 billion
- Additional sources were: "Community Development Block Grants, FEMA, and National Flood Insurance Program housing aid, other supplemental federal funds and the Sandy supplemental measure" (Moody's Investor Service, 2017: 15). More details on these are provided below.

Disaster assistance for Hurricane Sandy came from the following federal agencies: FEMA (23%), Housing and Urban Development (HUD) (32%), the Department of Defense (DOD) (11%), the Department of Transportation (DOT) (26%), and other Federal agencies (8%). Involvement of Federal agencies besides FEMA and HUD typically depends on the source and scale of the disaster and what types of entities are affected. For instance, the DOT is generally involved when a disaster has a significant impact on transportation infrastructure. Certain sources of federal relief require a Presidential Disaster Declaration under the Stafford Act, while some do not. Additionally, some types of federal funding can be applied to resilience improvements, while others are solely allocated for restoration or replacement in-kind (Kunreuther *et al.*, 2016).

As indicated above in connection with hurricanes, disaster assistance levels administered by FEMA can be expanded and adapted to specific events and targeted for infrastructure. For example, the 2018 California wildfires are a case in point. The linkage between the wildfires and climate change has not been well developed though it is believed to be related in part to the extensive drought period that preceded the fires in California. In response to the southern California fires, FEMA's authority to fund infrastructure improvements was expanded by Congress on November 28, 2017 (U.S. DHS, FEMA, 2017c).

Emergency conditions open up a range of other funding options, such as state and federal disaster relief funds administered, for example, by FEMA and U.S. DOT programs for transportation-related recovery at the federal level to fund state and local areas, including dedicated emergency funds that have had caps (Zimmerman, 2012).

Agencies have made grant provisions for infrastructure that potentially can apply to climate change needs (see, for example, U.S. EPA, 2017a). FEMA also issues hazard mitigation grants (U.S. DHS, FEMA, 2017a).

7.5.2.2 Bonds. Bonds issued for infrastructure include general obligation bonds, revenue bonds, and special purpose bonds such as green bonds, and as indicated in the section on insurance, catastrophe bonds, for example, for the MTA. Catastrophe bonds are issued by reinsurance companies and recently by FEMA in connection with the National Flood Insurance Program (Friedman, 2018). Green bonds are of increasing importance, especially for green infrastructure support (City of New York Office of the Comptroller, April 2015).

Green bonds operate like traditional municipal bonds, but unlike traditional municipal bonds, they are used exclusively to fund environmentally friendly or climate mitigating projects and are often synonymous with climate bonds.

According to the New York City Office of Management and Budget (OMB) information (NYC OMB, December 14, 2018 for these and following quotations), the NYC OMB has indicated that "to date, the City of New York has funded all of its environmentally friendly or climate mitigating projects with traditional municipal bonds, after determining, in consultation with participants in the green bonds market, that green bonds do not provide cost savings to the city and actually include complex reporting requirements that could be administratively burdensome.

Additionally, the investor base for municipal green bonds remains small. The city, as a frequent issuer, minimizes borrowing costs by tapping a broad pool of investors that participates in the larger, more mature traditional municipal bond market."

An example of climate bonds being used in New York City is the MTA Transportation Revenue Green Bonds (The Climate Bonds Initiative, 2018). These bonds were first issued in February 2016 and have resulted in $5,489,500,000 for subway infrastructure renewal and upgrade, including electrification (The Climate Bonds Initiative, 2018). The MTA worked with the Climate Bonds Initiative (2018) to certify the bonds using the Low Carbon Transport criteria.

According to information provided by the NYC OMB, "The decision to issue green bonds does not in and of itself mean that additional funds are available to fund environmentally friendly or climate mitigating projects."

Bond ratings, covered in Chapter 8 on Indicators and Monitoring, are fundamental indicators for the strength of bonds as a financing mechanism. Chapter 8 addresses how bond ratings can reflect climate change considerations. Moody's, Standard & Poor, and Fitch are among the major bond rating organizations, and have generally consistently rated New York City bonds high.

According to information provided by the NYC OMB, NYC OMB has indicated that "Further, both bond rating organizations and investors have consistently commented that the City of New York's disclosure in its offering documents is among the best with regards to its comprehensive discussion of the potential impacts of climate change."

Different public authorities issue bonds separately. Some of the authorities relevant to infrastructure for New York City are the Metropolitan Transportation Authority (MTA) and the Port Authority of NY and NJ for the transportation sector, and the New York City Municipal Water Finance Authority for the water sector.

7.5.2.3 New York State green infrastructure loan and grant programs and New York City climate change needs.

NYS State Revolving Fund (SRF) program

State revolving funds were set up by Congress separately for clean water and drinking water as amendments to the U.S. Clean Water Act in 1987 (U.S. EPA, 2018a) and U.S. Safe Drinking Water Act in 1996 (U.S. EPA, May 8, 2018b), respectively. Eligibility under the Clean Water State Revolving Fund (CWSRF) program has gradually been expanded under various amendments (U.S. EPA, April 18, 2018) to include green infrastructure (U.S. EPA, April 23, 2018; U.S. EPA, May 2016; Environmental Finance Center Network, 2017).

The U.S. Code of Federal Regulations (2011: Article 35.3135(b) indicates that funds are provided by the federal government with at least a 20% state match (U.S. EPA, March 6, 2018). According to the U.S. EPA (2016), green infrastructure projects are eligible for financing for water management, and green infrastructure projects include: stormwater and wet weather issues, energy efficiency, water efficiency, and innovative approaches to managing water resources. "Climate resilience" is explicitly a criterion for funding under SRF (U.S. EPA, 2016: 8) and planning activities connected with climate change are eligible for funding.

As summarized by the U.S. EPA (March 6, 2018), the CWSRF offers a variety of different types of financial support including loans, loan guarantees, purchasing or refinancing debt, debt guarantees to improve interest rates and access to funds, insurance, and under some circumstances "principal forgiveness, negative interest rate loans, or grants." In New York State, Clean Water State Revolving funds are coadministered by the NYS Environmental Facilities Corporation (EFC) and the NYS Department of Environmental Conservation. Similarly, the Drinking Water State Revolving funds are coadministered by the NYS EFC and the NYS Department of Health.

Examples of applicable wastewater and clean water improvements eligible for funding under the NYS EFC include: "construction or restoration of sewers and wastewater treatment facilities, stormwater management, landfill closures, as well as habitat restoration and protection projects" (NYS EFC, undated web site, Clean Water State Revolving Fund).

The EFC provides low-cost financing in the form of low to no interested loans through the CWSRF and Drinking Water State Revolving Fund. Both funds compile an annual priority list to strategically issue loans as funding allows. For fiscal year 2018, of the potential New York City projects on the CWSRF priority list, two are specifically for green infrastructure: one is for a green roof and the other is for NYC DOT porous pavement (NYS EFC, 2018).

The NYC OMB (December 14, 2018) notes further that "Through its Municipal Water Finance Authority and the Department of Environmental Protection, NYC is the largest recipient of the NYS CWSRF and DWSRF funds, which are used to fund a number of environmental projects, such as the Newtown Creek Wastewater Treatment Plant upgrade."

Green Grant Programs

In addition to lending money, the EFC also provides several grant opportunities: the Water Infrastructure Improvement Act Grants for infrastructure projects at municipally owned sewage treatment or public water systems, the Inter-municipal Water Infrastructure Grants Program for projects impacting multiple municipalities, the Integrated Solutions Construction Grants for green infrastructure components of Clean Water State Revolving Fund projects, the Green Innovation Grant Program (GIGP) for green infrastructure projects not receiving revolving fund loans, and Engineering Planning Grants for planning costs associated with water infrastructure projects.

Focusing on the GIGP, the GIGP (NYS EFC, undated web site, Green Innovation Grant Program) is specifically targeted to the support of a variety of different types of green infrastructure projects. The funding provides "a minimum of 40% up to a maximum of 90% of the total eligible project costs as provided in the application. A minimum of 10% up to 60% match from state or local sources is required." (EFC undated web site, Green Innovation Grant Program.)

The EFC reported that "Through 8 Rounds, GIGP has awarded $140.2 million to over 190 GIGP projects across New York State" (NYS EFC, 2017a). Under the GIGP from 2009 through 2016, New York City funding under the GIGP accounted for about 7% of the total statewide funding (NYS EFC 2017b).

Most of the projects funded in New York City under the GIGP occurred in 2011 and 2012, with those 2 years accounting for 60% of the total through 2016 (NYS EFC, 2017b). The last Green Innovation Grant reported for New York City was in 2015 for a Department of Transportation project valued at $1,200,000 (NYS EFC, 2017b).

7.6 Interactions with mitigation: energy and transportation

Transformation of the five boroughs of the City of New York into a sustainable metropolis over the course of the 21st century will require all sectors of the city—public, private, and independent sectors—to reduce locally generated sources of carbon emissions as well as indirect transboundary emissions that are embedded in the imported goods and services New York City consumes.

Efforts to reduce carbon from the built environment and vehicles—important sources of locally generated CO_2—have received more policy focus than efforts to reduce indirect, transboundary emissions that are part of every New Yorker's carbon footprint. Details on how New York City is preparing to reach its commitment of reducing GHG emissions 80% by 2050 are presented in Appendix 7.C.

This section highlights the important interface between two key infrastructure systems–energy and transportation–and mitigation efforts that must accompany resiliency efforts. Within these two sectors, some conflicts or tensions between mitigation and adaptation are illustrated with examples.

7.6.1 Energy

The interface between energy and other sectors is a key to mitigation efforts given the substantial contribution of the built environment to energy-related emissions in New York City either directly or indirectly. Energy providers have an interest in the energy efficiency of their clients if they are to lower the carbon footprint of energy. The providers need to manage peak load efficiently with greater certainty about capacity and growth.

New construction and major renovation of infrastructure in the private sector and independent sectors in the five boroughs of the city offer major opportunities to reduce CO_2 emissions and transition to lower carbon, greener energy feedstocks, coupled with initiatives to reduce water and waste footprints in the built environment which includes infrastructure.

Increased use of solar energy on a building scale is growing in importance in NYC. As of July 2018, there are over 154 MW across 15,000 solar installations in NYC. This is a sixfold increase from December 2013 (since this current Administration took office). For example, Grant (2017) summarized the Stuyvesant Town complex's plans to add solar energy to many of its building. Other means of improving energy use have been cited as well. The Urban Green Council was cited as indicating that from 2010 to 2015 energy reduction in existing buildings has amounted to 10% from power plant improvements and oil to natural gas conversions (Grant, 2017).

Distributed generation and new technologies such as micro-grids to improve the resilience of the energy delivery system are underway. The development of resilience is not only occurring at the facilities level, but also at the level of the users. Energy efficient buildings are a top priority and have expanded in NYC.

As indicated by the National Academies (NAS) (2016: 59): "The government of New York City exercises direct control over a small share of the built environment through ownership or use for governmental purposes as well as regulation over other sectors. Mazria (2015) offered a guide to proposed changes in the New York City Energy Conservation Code to support energy efficiency and renewable energy in order to catalyze a reduction of GHG emissions from the built environment that is largely controlled by the private sector and nonprofit or civic sector."

Some adaptation measures are not without conflicts with mitigation. For example, air cooling is needed to adapt to increasing heat waves; however, it contributes to energy demand which in turn increases CO_2 emission. The IEA (2018) has identified many interconnections between air cooling and electric power usage. In particular, the IEA (2018) report notes that air cooling is growing faster than any other sector for energy use, is currently 10% of the use of energy globally, and by 2050 is expected to account for 37% of electricity demand, and energy demand from AC use could be reduced with better performing units that potentially can reduce CO_2 emissions from that source.

7.6.2 Transportation

A number of components for transportation mitigation are critical in NYC. First is the conversion of public transit diesel to combined electric diesel or entirely electric facilities to reduce diesel-related emissions, which is one type of fuel option. The second pertains to privately owned vehicles associated with surface transportation, for example, the switch to electric vehicles to reduce or avoid transportation emissions.

Connected with both of these is the feedstock issue, that is, where energy for transportation is coming from and to what extent these energy feedstocks can become greener. These issues pertain to decisions at much broader geographic levels and across many economic sectors, that is, transboundary issues, and these problems are beyond New York City and NYS MTA control.

A third component of transportation-related mitigation is the promotion of nonmotorized-based modes of travel such as biking and walking. New York City has promoted these modes through expanded numbers of bike lanes and pedestrian walkways and the availability of bike-share facilities.

A fourth component is an important transportation and urban planning and land use connection in mitigating energy use by transportation. Finally, other options are overall reduction of vehicle-miles of travel through demand management, increased use of transit, and new "shared mobility" concepts.

7.7 Conclusions and recommendations

The introduction of relatively new elements pertaining to infrastructure in NPCC3 provides lessons learned and new directions for future New York City resiliency efforts to parallel climate change projections.

Underlying or prior condition of infrastructure systems, usage versus capacity, and their ability to cope with environmental stresses are key factors in existing and future infrastructure vulnerabilities. An important element is locational lock-in that is, addressing long-standing traditions of the location of infrastructure facilities as well as the users of the services in areas vulnerable to damaging consequences of extreme events and climate change. An equity dimension exists in that not all sectors of society experience these infrastructure system conditions equally.

Interconnections among different infrastructures in the form of dependencies and interdependencies are becoming recognized as important factors in the escalation of adverse consequences resulting from extreme events and climate change. The next step will be to identify where the vital interconnection points are that produce cascading effects, the process by which those cascades occur, and how to reduce their effects through management and in some cases decentralization of infrastructure services to reduce intersection points. Data collection and metrics development are crucial to understanding and enhancing resilience, particularly toward emerging risks like climate change and cyber security.

New York State and New York City have experimented with the design, development, and deployment of DERs and battery storage. As the initiatives in Red Hook and Chelsea illustrate, these energy projects have created an opportunity to rigorously rethink and redefine the optimal balance between the share of energy that should be produced by utility sources, and the share of power that can be generated locally and close to the source of energy use under normal operating conditions.

Insurance and finance policies continually evolve to provide opportunities to reduce the cost of the consequences of climate change that can further expand to support adaptation and mitigation. Stafford Act funding following a disaster can serve as a disincentive to investment in resilience improvements, but modifications to the Stafford Act could help address this issue. Potential modifications could include availability of funding to implement resilience improvements in conjunction with repairs, and mechanisms to encourage predisaster resilience improvements and insurance purchase.

In this regard, public–private partnerships are essential for facilitating infrastructure resilience, particularly for publicly owned infrastructure systems which often lack budget for resilience improvements. These partnerships can involve insurance or financing mechanisms. Many of the mechanisms reflect a patchwork of applicability, and a coordination of these two areas is an important future direction to achieve consistent infrastructure goals to reduce climate change consequences.

Mitigation and adaptation tensions arise with respect to infrastructure choices, and some examples were presented for energy and transportation above. According to Grafakos *et al.* (2018: 105), these tensions are multidimensional and differ with respect to "spatial, temporal, institutional, and administrative scales." Attention to this will involve moving toward resolving conflicts and moving toward mechanisms that are more synergistic through processes to identify and resolve such conflicts.

The overall key findings and recommendations for critical infrastructure in the face of climate change are summarized below.

7.7.1 Key findings

1. Key infrastructure vulnerabilities exist for individual and interdependent infrastructure that are:
   - Not directly related to climate change, yet affect infrastructure resilience or the ability to withstand climate change stresses; examples include (1) low physical and functional condition and (2) usage potentially exceeding capacity; both indicate potential vulnerabilities for NYC
   - Directly related to climate change factors, such as heat, extreme precipitation, sea-level rise, and storms, for example, many vulnerabilities are locationally based: inventories indicate low-lying infrastructures
   - Creating the potential for vulnerabilities where interdependencies are involved, in the form of cascading impacts and these are not comprehensively understood
2. Community and infrastructure resilience case studies presented real-world instances of the

interface between critical infrastructure systems and climate change:

- Hospitals: New York City's 62 hospitals are dependent on transportation, power, and water, especially in emergencies; many hospitals and these infrastructures are at risk from flooding from location.
- NYCHA: In Hurricane Sandy, infrastructure service outages affected hundreds of buildings and thousands of residents; distributed energy and other service strategies are benefits.
- New York City's and New York State's transition to low-carbon and zero-carbon feedstocks for energy by 2050, as exemplified by NYCHA's exploration of distributed energy, will transform energy generation, transmission, and delivery.

3. Insurance mechanisms and federal disaster relief can be improved for better coverage in disasters; numerous and diverse financing mechanisms exist potentially applicable to climate risks; studies show that investments before disasters can lower postdisaster costs.

7.7.2 Key recommendations

NPCC3 makes the following recommendations for continued work in research and policy to address critical infrastructure risks in the New York metropolitan region:

Recommendations for Research:

- Improve knowledge of interactions between infrastructures and climate risks to understand vulnerability, requiring new science and data.

Recommendations for the City:

- Continue to work with the energy sector to develop improved resiliency to power outages.
- Increase financial strength, invest in infrastructure maintenance and upgrades, and work with insurance companies to encourage incentives with attention to the risks that infrastructure systems and their users experience.
- Integrate equity dimensions into planning for infrastructure adaptations to climate change in light of the four visions of OneNYC.
- Identify where the vital interconnection points are among different infrastructures (i.e., dependencies and interdependencies) to reduce cascading effects resulting from extreme events and climate change through management and in some cases decentralization.
- Provide access to infrastructure data and resources to explore infrastructure risks associated with climate change.

Acknowledgments

The Working Group gratefully acknowledges the inputs on earlier drafts by members of the NPCC team and leadership, the NYC Mayor's Office of Recovery & Resiliency, the insights provided by members of the Climate Change Adaptation Task Force (CCATF), and various external reviewers. In addition, Gina Tonn, Postdoctoral Research Fellow at the University of Pennsylvania Wharton Risk Management and Decision Processes Center, is acknowledged for her inputs on the insurance section. Ryan Brenner, Master of Science in Public Policy (2018) from the NYU Wagner Graduate School of Public Service is acknowledged for his research that contributed to various portions of this chapter funded by Columbia University with support from the NYC Department of Environmental Protection.

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Appendix 7.A. The "infrastructure-shed" and critical infrastructure systems in the New York metropolitan region

The "infrastructure-shed." The Regional Plan Association (2016: 5, 6, 8, 24) has specifically emphasized the central place of infrastructure among other elements in its plan for the New York region's future. A few components of the infrastructure-shed are described briefly below, but each sector is presented in more detail in the infrastructure lifelines section that follows.

Energy. According to Con Edison, one of the major distributors of NYC's electric power, the Con Edison service area, is cited as 604 square miles including service areas that extend beyond New York City boundaries (Con Edison Company undated web page accessed June 16, 2017). National Grid (National Grid, undated) also serves certain portions of the city, namely, Staten Island, Brooklyn, and part of Queens for gas (National Grid). According to the New York State Independent System Operator 2016 power trends report, the energy usage in the downstate area is about 1.5 times greater than what it generates, indicating that energy has to be obtained from outside of the city (NYS Independent System Operator (ISO) 2016).

Transportation. New York City encompasses transportation infrastructure managed by numerous transit, road, and bridge agencies. The road system consists of Federal, state, and local owned and/or operated roadways, bridges, and tunnels. The agencies involved in the management of this infrastructure include the NYC DOT, the Port Authority of NY and NJ, NYS DOT, and the NYS Metropolitan Transportation Authority (MTA). For transit, the NYS Metropolitan Transportation Authority (MTA) is the largest provider of transit for the city extending to portions of its region as well. The Port Authority of NY and NJ, NJ Transit and Amtrak also manage bus and rail transit. According to the MTA's description of its network, the MTA service area extends over 5000 square miles (MTA, 2016, 2017), more than 16 times the area of the city reflecting its reach well beyond the city's borders. Both passenger and freight rail transit are affected by conditions outside of the city given the flow of goods in and out of the city that is carried by rail and the commuters in and out of the city as well for jobs, recreational, educational, and other activities. For example, extreme weather, accidents, or other sources of disruption occurring in areas outside of the city inevitably affect the ability of people, goods, and services to move in the region. The U.S. Census Bureau definition of its term "Metropolitan Statistical Area" is generally based on travel in terms of economic connectivity. The effects of transportation infrastructure often act through intermediaries in the form of other infrastructures that transportation is dependent on in particular electric power. When a massive electric cable outage occurred to the north of the city, Metro-North lines were disabled for over a week. The extent of the total impact area is referred to as the New York metropolitan region; however, the reach of each infrastructure is different.

Water. As noted in Chapter 2, the water supply systems draw from a watershed that is almost seven times the area of the City (NYC DEP), and New York city residents and businesses are affected when the infrastructure in areas outside of the city experiences disruptions.

Infrastructure lifeline sectors——new elements of risk and resilience. Definitions of critical infrastructure identify almost a dozen and a half different categories that include Chemical, Commercial Facilities, Communications, Critical Manufacturing, Dams, Defense Industrial Base, Emergency Services, Energy, Financial Services, Food and Agriculture, Government Facilities, Healthcare and Public Health, Information Technology, Nuclear Reactors, Materials, Transportation Systems, and Water and Wastewater Systems (U.S. DHS, 2013).

Energy. The energy system serving New York City consists of an extensive array of facilities from production through end usage. A list of the existing electric power production facilities was compiled by the NYS ISO (2017a: Table III-2). Con Edison, for example, indicates that it manages 95,720 miles of underground cable and 34,215 miles of overhead cable each with transformers and other support systems (Con Edison undated web page, accessed June 16, 2017). Each of the components requires a unique set of protection measures against destruction associated with extreme weather events and climate changes ranging from elevation, submersion, sealing, and operational controls (Con Edison and Orange and Rockland Utilities, 2015).

The main energy service providers for New York City are Consolidated Edison (Con Ed), the New York Power Authority, and National Grid, with the latter providing natural gas. In addition, the Long Island Power Authority (LIPA) provides electric service to the Rockaways in Queens. According to NYS Independent System Operator (ISO), New York City annual energy use has been declining: Over the 2010–2014 period, NYS ISO power trends data indicated a drop of 4.7% in annual usage of electric energy in New York City (from 55,114 to 52,541 GWh) with a decline occurring each year (NYS ISO, 2015: 10), which NYS ISO primarily attributes to recent cooler summers, that may not be likely to continue (see Chapter 2) and also increased use of more energy efficient appliances. From 2014to 2015, however, usage increased by 1.8% though still indicating an overall drop in the 2010–2015 of 3% (NYS ISO, 2016: 10), and NYS ISO generally attributed these changes in energy use to changes in weather and economic activity (NYS ISO, 2016: 7). In the 2015–2016 period, New York City was the only one of the ISO-defined regions that increased in annual electric energy usage by 0.31% from 53,485 to 53,653 GWh (NYS ISO 2017a: 13). The NYS ISO (2017a: 12, 16) forecasts both with and without weather taken into account generally anticipated declines in annual energy usage over a 10 year period from 2017 to 2027 along with an increase in summer peak demand and a decrease in winter peak demand.

Transportation. The transportation system serving the City of New York is comprised of over thousands of miles of surface transportation via various conduits such as roadways, bridges, tunnels, rail, waterways, air, and pipelines. In addition, there are related infrastructures such as terminals and stations and for water-based transportation, ports, and docks. These in turn are owned and/or managed by many organizations. For transit exclusive of pipelines, these include the New York State Metropolitan Transportation Authority (MTA), the Port Authority of NY and NJ facilities such as PATH and the region's airports, NJ Transit, AMTRAK, freight rail companies, and Federal, State, and local highway authorities or transportation departments.

The NYS MTA network consists of almost 9000 rail and subway cars, over 5700 buses across 2080 rail track miles, and 2952 bus route miles (MTA, The MTA Network, undated web site). According to MTA, its network of facilities supports about 2.7 billion trips per year and accounts for about half of the total transit ridership in the U.S. (APTA, 2015). Numerous other support facilities for equipment and operations are a part of MTA's network. One way its robustness is measured is in terms of service disruptions in the form of mean distance between failures (MTA Performance Data Sets undated web site), which is defined for subways, for example, as "Average number of miles a subway car travels in service before a mechanical failure that makes the train arrive at its final destination later than 5 minutes." The lower the number, the worse the performance is with respect to this particular characteristic (MTA undated web site). Fitzsimmons (2017) cited a decline to 120,000 miles in November 2016 compared with 200,000 in November 2010. Fitzsimmons (2017) cited other performance indicators such as number of subway delays, and the NYC Office of the Comptroller (2009) identified a number of different indicators, some of which would be relevant for potential climate change impacts. Delays due to signal and switch failures have received considerable attention.

The viability of the bus and rail transit system reflects Metropolitan Transportation Authority's post-Hurricane Sandy capital projects as well as other MTA plans and programs. Examples of these capital projects include extensive repairs to the subway tunnels, switches, and signals (MTA, 2017; MTA web site Fix&Fortify program). The time period over which these improvements occur could be aligned with NPCC forecasts for heat and precipitation. This is also true of the network of other transportation facilities and services in New York City and probably other infrastructures as well.

Some adaptations since Sandy have been undertaken ranging from short-term (episode-specific, often operational measures) to medium-term measures including flood protection, water removal, and green infrastructure (U.S. Environmental Protection Agency (EPA) July 3, 2018). Transportation projects after Hurricane Sandy have initially focused on repair of damage but have since employed flood protection and other adaptation measures, some of which are discussed in the adaptation section.

Two communities that are being studied by the NPCC3 Community WG that have been identified as having transportation and flooding issues are Hunts Point in the Bronx and Sunset Park in Queens (see Chapter 6: Community-Based Assessments of Adaptation and Equity). At Hunts Point, transportation circulation is relatively restricted, and some of the areas within Hunts Point are susceptible to flooding though these areas barely missed flooding during Hurricane Sandy. The Sunset Park area encompasses portions of the proposed Brooklyn Queens Light Rail whose route partially traverses floodplain areas. Sunset Park is currently served by three subway lines around its periphery: The northern and eastern portions of Sunset Park are served by the D line, the western portion by the R line, and the western and southern portion by the N line. It is also served by bus transit lines.

Water/wastewater. According to NYCDEP, the New York City water supply system encompasses a nearly 2000 square mile watershed north and west of NYC (NYCDEP 2017d: 2). The water supply system is managed by New York City and portions of the counties directly to its north: Westchester, Putnam, Orange, and Ulster. The facilities consist of three water systems–Croton, Catskill, and Delaware, three water tunnels, 19 reservoirs, and thousands of miles of conveyance systems consisting of transmission and distribution networks.

Extensive work is underway to complete the third water tunnel that will provide part of the system within the city's borders with a redundant water distribution system, and that redundancy will support resilience (NYC Special Initiative for Rebuilding and Resilience (SIRR), 2013: 63; NYCDEP 2017d Drinking Water Supply and Quality Report).

The New York City wastewater treatment system consists of 14 wastewater treatment plants, numerous pumping stations that support them, about a half-dozen sludge treatment plants, most of which are located near the wastewater treatment plants, and about 6000 miles of collection lines with a few pumps to convey the wastewater where gravity is not sufficient (NYCDEP, 2013). In addition, there are combined sewer overflow facilities that handle stormwater flows. In many parts of New York City, the wastewater collection system does not separate sanitary sewage and storm sewage, and combined sewers are estimated at 60% of the city's sewer system (NYCDEPa, 2018: 4) The City of New York has embarked on ambitious green infrastructure programs aimed at water management through nonstructural controls (NYCDEPa, 2018: 37–38) such as the Staten Island Bluebelt project (NYCDEP, undated web site accessed June 16, 2017).

The city tracks the viability of its distribution infrastructure for both water and sewer in terms of breakage rates and service interruption and has reported declines in those rates recently as well as declines in restoration time summarized earlier in this chapter (NYC Office of the Mayor Management Report (MMR), 2017: 262–263; 2018: 261) (see Chapter 8: Indicators and Monitoring).

Telecommunications. The telecommunications structure within New York City provides telephone, wireless, Internet, and cable services. Verizon is the incumbent telecom franchise in NYC. Telecommunications infrastructure consists broadly of buildings that house communication equipment, exchanges, switches, and computers; cabling for signal transmission and conduits; intermediary locations such as cell towers that house telecommunication equipment (Wikipedia, 2017), and equipment at user locations (City of New York, 2013: 163). The expanse of the system and its network is comprised of: "... over 50 thousand miles of cabling, thousands of cell sites [or cell towers where telecommunication facilities are located], and nearly 100 critical facilities." "New York City accounts for approximately 3% of the world's web traffic—even though the city is home to only 0.1% of the world's population" (City of New York, 2013: 163). Telecommunication infrastructure is not only vulnerable to power outages and damages also to backup power facilities which was experienced during and after Hurricane Sandy (City of New York, 2013: 168), but also to the stresses created by direct impingement by floodwaters and wind and water-driven debris. The intensely complex and interconnected networks and rapidly changing technologies that characterize the telecommunications sector create challenges to addressing its climate vulnerabilities.

Appendix 7.B. Compendium of selected adaptations[b]

A wide range of strategies specific to infrastructure are under consideration and in many cases are underway throughout the United States and the world to strengthen the resilience of the infrastructure against the consequences of climate change across numerous infrastructure sectors. These are aimed at increasing the resilience of the built environment overall and the social systems it serves. These generally fall under the heading of adaptation. These have tended to occur separately for each type of infrastructure though some protective measures afford simultaneous and coordinated protection.

Many of these strategies and approaches were introduced in the main section of the report. A few additional approaches are introduced here for illustrative purposes and generally pertain to introducing flexibility into the design and operation of infrastructure. Adaptation measures encompass design strategies for new and retrofitted infrastructure. A number of different design guidelines have been summarized for adaptation measures depending on the type of construction and the location of a facility (NYC Mayor's ORR, 2018: 27, Climate Resiliency Design Guidelines). Examples of design and construction measures suggested in the guidelines and elsewhere include relocation, elevation, hardening, barriers, reconfigurations (e.g., elevating structures for flooding and sea level rise), providing flexible routing (e.g., among transportation modes), altering materials, etc., and the relevance very much depends upon the nature of the hazard. Operational measures in addition to design have also been put forth to support flexibility, for example, by using alternative resources, configurations for infrastructure facilities, and usage or consumption. In many cases, these adaptation measures have been known for some time. The NYC Department of City Planning's waterfront plan that predated Hurricane Sandy set forth a number of strategies aimed at resilience pertaining to flooding in the areas of "retreat," "accommodation," and "protection," many applicable to infrastructure (NYC DCP, 2011: 109–110) and they also identified a number of adaptation measures within the city after Hurricane Sandy (NYC DCP, 2013b). Protective mechanisms, for example, include many structural approaches involving gates, seawalls, and others. These mechanisms were expanded considerably in the New York area following Hurricane Sandy (City of New York, 2013; New York State 2100 Commission, 2013; NYS Department of Environmental Conservation, 2016), and have been listed by the NYC Mayor's Office of Recovery & Resiliency (2017: 24) as design interventions in connection with sea level rise. Green infrastructure is an expanding area of interest for adaptation primarily for water management (U.S. EPA, undated web site accessed June 16, 2017), but other approaches exist as well such as urban tree canopies (O'Neil-Dunne, 2012). New York City has been pursuing a project originally developed as the "Big-U" (Rebuild by Design, 2017) and currently referred to as the East Side Coastal Resiliency (ESCR) project, the Lower Manhattan Coastal Resiliency (LMCR) project, and Two Bridges (NYC, 2018a, b), that combines structural and green infrastructure approaches and numerous strategies targeted specifically to improve transportation resilience after Hurricane Sandy (U.S. DOT, FHWA 2017).

[b]The NYC ORR (2018: 36) Climate Resiliency Design Guidelines defines adaptation as: "Adjustment in natural or human systems to a new or changing environment that seeks to maximize beneficial opportunities or moderate negative effects." Adaptation was defined by the IPCC (2007) early in the climate change assessment process in the following ways: "Adaptation Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory, autonomous and planned adaptation: Anticipatory adaptation – Adaptation that takes place before impacts of climate change are observed. Also referred to as proactive adaptation. Autonomous adaptation – Adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. Also referred to as spontaneous adaptation. Planned adaptation – Adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state." "Adaptive capacity (in relation to climate change impacts) The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences."

A number of efforts are underway for managing water, for example, stormwater management (NYCDEP, 2018), measures specific to wastewater treatment plants and related facilities such as pumps (NYCDEP, 2013: 9–10) and tailored by NYCDEP to specific plants, and land management through flood zoning (NYCDCP, 2013a). One relatively newer land management mechanism primarily for controlling and managing water is green infrastructure. The NYC Department of Environmental Protection has embarked upon a green infrastructure program to comply with the NYS DEC consent orders for combined sewer overflows (NYC EP, 2017). NYCDEP manages an extensive program to install green infrastructures, and indicates thousands of these have been installed throughout the city using a variety of technologies between 2011 and 2016 (NYC EP, 2017). The U.S. EPA defines green infrastructure as: "Green infrastructure uses vegetation, soils, and natural processes to manage water and create healthier urban environments. At the scale of a city or county, green infrastructure refers to the patchwork of natural areas that provides habitat, flood protection, cleaner air, and cleaner water. At the scale of a neighborhood or site, green infrastructure refers to stormwater management systems that mimic nature by soaking up and storing water." (U.S.EPA, June 13, 2014).

Specific infrastructure agencies have developed extensive adaptation mechanisms. For example, the MTA (2009; 2017) has set forth numerous measures to protect its transit infrastructure and the U.S. DOT (2011) has considered a broader scale of measures applicable to the city. The city's transit system has undertaken adaptation measures in response not only to Hurricane Sandy's impacts but also to current and anticipated impacts of climate change aimed primarily at temperature and flooding associated with precipitation and sea level rise (MTA, 2017: 4). The 2016 commitment for 46 projects was $751 million with a total of $3 billion in overall resilience funds, and additional funds were indicated for 2017 and 2018 (MTA, 2017: 12). The projects consist of strengthening the condition and design of MTA facilities, relocation of equipment to higher elevations, and barriers.

Consolidated Edison Company of New York and Orange & Rockland Utilities (2013) developed an extensive set of primarily structural mechanisms to protect its electric power infrastructure. The portion of the city's electric power system operated by Con Edison went through an extensive adaptation review following hurricane Sandy involving various techniques such as sealing, cable removal and reconnection flexibility, submersion, strengthening of overhead electric power polls, tree trimming, and numerous other measures (Consolidated Edison Company of New York and Orange and Rockland Utilities, 2013). The 2013 plan has now, according to Con Edison, been updated and portions of it have been implemented with an estimated $1 billion investment (Con Edison, October 19, 2017). Con Edison reported a $1.6 billion investment for work begun in 2016 that included the following improvements:

- "12 network transformers;
- 70 overhead transformers;
- 16 underground feeder sections connecting manhole structures and transformer vaults;
- 37overhead sections of power lines, and reinforcement of 25 electric feeders . . .
- a new underground electric network to help meet growing energy needs on the west side of midtown Manhattan . . .
- and completing a $1 billion, 4-year storm hardening plan to protect infrastructure and customers from the impact of major storms, like hurricanes." (Con Edison, July 12, 2016).

Con Edison estimated that through October 19, 2017, 250,000 outages had been averted through "the installation of more than 1,000 'smart' switches on its overhead system, submersible equipment that can withstand flooding, redesigned underground electrical networks, and numerous other steps to avoid outages," circuit breakers to achieve more rapid recovery, flood walls and seals specified in their 2013 plan and numerous other design and operational changes (Con Edison, October 19, 2017).

Summary of shoreline programs and plans. New York City has about 520 miles of shoreline (NYC DCP, 2016: 7). Portions of it are at sea level or within margins that are potentially vulnerable to flooding from sea level rise as well as storm surge. The coastal boundary for both developed and undeveloped shoreline areas is defined relative to sea level (NYC DCP, 2016: 9). Numerous proposals for altering the coast exist some of which are protective in light of climate change and others not, but have the potential for integrating climate change. These include some of the suggestions in the NYC DCP (2011) Vision 2020 waterfront plan, the NYC (2013) designs for many of the shorefront locations in and around the city, the Waterfront Alliance's (2018) plans and manual for coastal planning, and the post-Sandy competitions that included the selection of the Big U project. Current city programs such as zoning and land use should continue to incorporate these ideas.

Parkland. An important aspect of the resiliency of NYC's shoreline is the extent to which parkland can buffer the effects of storm surge, sea level rise, and coastal flooding. Parks near coastlines can provide temporary inundation areas that can recover relatively quickly after extreme weather events involving flooding. Permanent increases in sea level are more challenging, however. Some social infrastructure overlaps with and depends upon transportation infrastructure, such as bike and pedestrian paths. Parks often provide protection of neighborhoods from severe weather by providing shade from trees; however, trees can also be vulnerable to extreme wind events.

Shoreline parks comprise the largest portion of the parks managed by the New York City Department of Parks comprising "7,300 acres or 30% of its total land area and found along 150 miles—or almost 30%—of the city's total coastline," and in addition natural areas comprise another 9900 acres under the Department's jurisdiction (NYC EM 2014: 59).

A number of concepts for using land susceptible to flooding to absorb water have been put forth. Within NYC, the Staten Island Bluebelt provides such an example. The NYCDEP (c2013) describes it as "natural drainage corridors, called Bluebelts, including streams, ponds, and other wetland areas. Preservation of these wetland systems allows them to perform their functions of conveying, storing, and filtering stormwater. In addition, the Bluebelts provide important community open spaces and diverse wildlife habitats. The Bluebelt program saves tens of millions of dollars in infrastructure costs when compared to providing conventional storm sewers for the same land area." Similar ideas have been put forth for Boise, Idaho (Barker, 2017), the Trinity River System (Water Environment Federation, 2017), and as the ideas for "Sponge Cities" particularly in China (Garfield, 2017). Other approaches include integrating transportation and water management, for example, in Kuala Lumpur where a six mile tunnel is used for traffic control in dry weather and the conveyance of stormwater in wet weather (Zimmerman, 2012: 115; Stormwater Management and Road Tunnel (SMART, undated website). Finally, the U.S. EPA and the City of New York along with a number of other cities throughout the country and the world have been leaders in developing green infrastructure concepts that serve as both mitigation and adaptation measures. Although the concept has been used for a number of different environmentally purposes, its use for water absorption or storm water management is key to confronting some of the flooding aspects of climate change.

For 2015, the Trust for Public Land (2016) listed 39,615 acres of parkland within the City, comprising about a fifth of its land area (TPL, 2016: 5). Of that, three-quarters is under the jurisdiction of the NYC Department of Parks and Recreation, and New York City ranks second in the set of high-density cities in percent parkland (TPL, 2016: 9). There were 4.7 acres per 1000 residents, and New York City ranked 13th in the high density city group (TPL, 2016: 10). Park access is very high for NYC, and is critically dependent upon transportation infrastructure. TPL indicated that 97% of NYC's population was within a half mile of a park–walking distance, unobstructed, from a road (TPL, 2016: 13). Two characteristics of parks interrelated with infrastructure and climate change are first the proximity of some parks to coasts and hence, the potential vulnerability to sea level rise and second the integration of trees in parks and elsewhere that affects urban heat levels. Given the extensive coastline of New York City and its attractiveness for recreation, a large number of parks are located along the city's shoreline (NYC Department of City Planning, 2011: 11). The city has acquired 1250 acres of waterfront parks since 1992 with Staten Island having the highest acreage, followed by Brooklyn, Queens, the Bronx, and Manhattan (NYC, 2011: 11). Many of those parks that are in flood zones are potentially prone to flooding during weather extremes.

Jamaica Bay represents an extensive program of shoreline and estuary planning and management with the participation of numerous organizations including the Science and Resilience Institute at Jamaica Bay (SRIJB) aimed in part at increasing

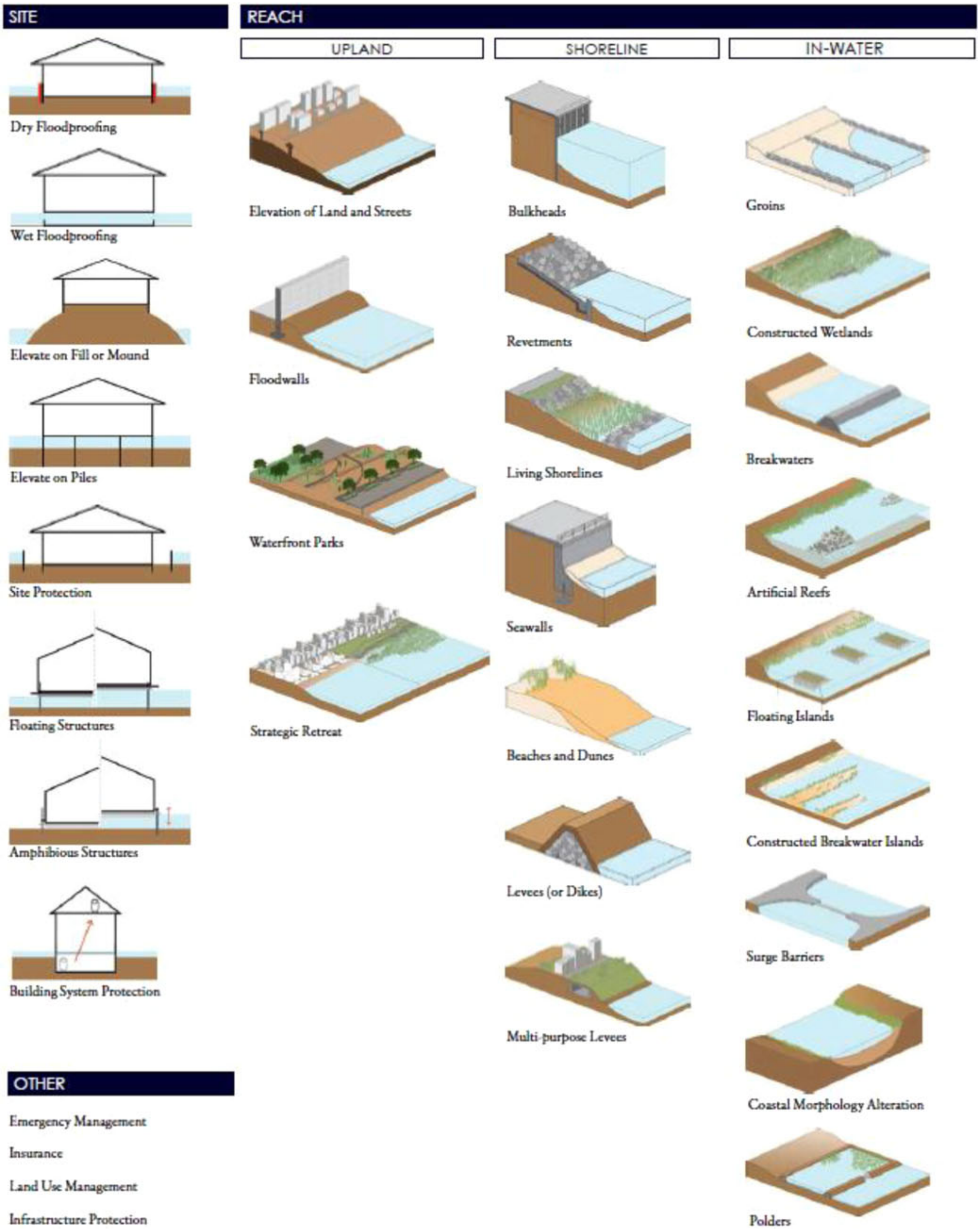

Figure 7.B.1. Strategies for coastal resilience by location. Source: New York City Department of City Planning, 2013.

the resilience of the area to future storms. The Institute has partnered with The City of New York and National Park Service and affiliates with the NYC Department of Environmental Protection on projects and events, in particular the Jamaica Bay Watershed Protection Plan (http://www.srijb.org/sotb2016/). With respect to infrastructure, a recent study identified eight different organizations for utilities and 14 involved in transportation (Sanderson *et al.*, 2016).

Shoreline planning and modifications. Numerous agencies have taken part in planning for the increased resilience of New York City's shoreline in light of Hurricane Sandy and prior to it. A

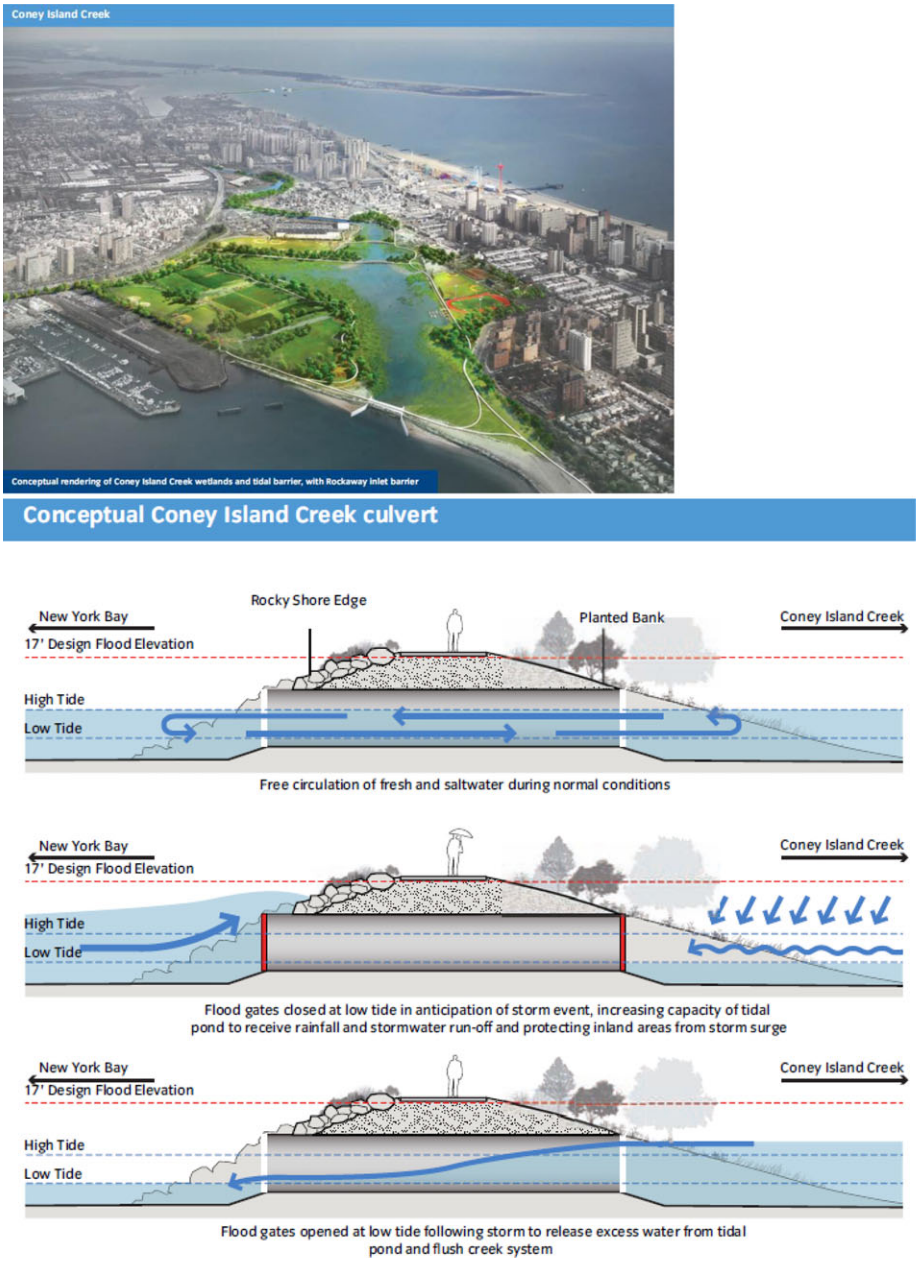

Figure 7.B.2. Example of possible shoreline modifications proposed in the NYC SIRR (2013). Source: City of New York, 2013.

few examples are given below in addition to the work in Jamaica Bay that cuts across park and shoreline modification efforts. Two major programs that New York City is a part of are: Rebuild by Design (http://www.rebuildbydesign.org/) funded by the U.S. Department of Housing and Urban Development (HUD) with not for profit organizations and philanthropies (http://www.rebuildbydesign.org/about) and the Rockefeller Foundation 100 Resilient Cities with which Rebuild by Design has partnered (http://www.100resilientcities.org/about-us/). These have particularly targeted shoreline areas in addition to supporting actions for a broader base of hazards related to infrastructure and other areas.

Figure 7.B.1 portrays the work of the NYC DCP (2013b) visualizing different shoreline modifications that increase resilience depending upon the characteristics of the shoreline and the adjacent water environment. These apply not only to buildings, but also to infrastructure.

Extensive efforts were made in the New York City Special Initiative for Rebuilding and Resilience (SIRR) to identify ways in which selected shorelines could be adapted to create greater resilience. Figure 7.B.2 gives just one example of the many potential modifications to NYC's shoreline to improve its resilience provided by the NYC SIRR by taking into account the dynamics of the water environment. The area below is identified as Coney Island Creek in the SIRR.

Appendix 7.C. New York City greenhouse gas goals

Like other C40 cities in North America (C40 is a network of cities committed to addressing issues related to climate change (https://www.c40.org/about)), New York City under the mayoral administrations of Michael Bloomberg (2002 through 2014) and Bill de Blasio (2014–present) has maintained city government's commitment to reducing citywide human-generated greenhouse gases (GHG) 80% by 2050. Achieving that 80 × 50 goal of cutting city-generated emissions requires a major focus on New York City's built environment. The building stock of the city's five borough (counties) generates nearly 70% of the emissions in 2015 (Inventory of New York City Greenhouse Gas Emissions, April 2017). Progress toward the goal of reducing city-generated carbon emissions has been incremental but encouraging as the city government and the state government in Albany implement policies to alter energy-consumption practices in all sectors (public, private, and independent).

In keeping with the 80 × 50 commitment, Mayor de Blasio announced the outlines of proposed legislation to reduce emissions from fossil fuel consumed onsite in buildings primarily for heating and hot water—apartment houses, office buildings, and warehouses—with more than 25,000 square feet (Neuman, September 15, 2017). This mayoral initiative, announced in the fall of 2017 while United Nations met in New York and reaffirmed the tenets and goals of the Paris Climate Accord, promised to impose strict standards on as many as 23,000 inefficient buildings in this category by 2030. Clearly, final provisions of this mayoral legislative initiative—even its fate—will be subject to negotiations between the mayoral administration and the New York City Council as well as efforts by interested parties, from business sectors like commercial real estate to environmentalists focused on climate mitigation issues. This particular de Blasio initiative, whatever its final shape or fate, also opens up space for the policy and research infrastructure of the city and the state to pose at least two questions related to achieving the 80 × 50 goal. These efforts to reduce and cap CO_2 emissions in buildings have been supported by city legislative initiatives (The Council of the City of New York, November 20, 2018; Kaufman, November 20, 2018).

Does the current inventory of city-led and state-led 80 × 50 programs add up to a comprehensive, milestone-driven approach to reducing emissions from the built environment 80 × 50? Are the city programs and state programs designed in a way to substantially reduce GHGs across all four classes of property in the city—Class I (most residential property of up to three units and small condominiums), Class II (mostly rental, cooperatives, and condominiums), Class III (utility property), and Class IV all commercial and industrial property not in Classes I, II, and III)? Are the GHG-reduction programs of New York City and Albany equally robust across all categories of the built environment in the five boroughs? Which city-led and state-led GHG programs are comprehensive and robust? Which are pilots with limited reach and impact? Are the seven goals, next steps, and implementation timelines of One City Built to Last: Transforming New York City Buildings, Technical Working Group Report sufficient? Some of the current patterns and trends inform some of these questions.

The City of New York (September 2017) report "OneNYC 1.5 Celsius Aligning NYC with the Paris Climate Agreement" tracked emission changes in a number of sectors, two of which were directly infrastructure related: transportation and waste (including wastewater treatment). However, the other sectors for which emissions were tracked (residential, commercial, and institutional) include changes in emissions from electricity use, a key infrastructure sector tracked by NPCC. Emissions were all reported as tons of carbon dioxide equivalent, but fugitive natural gas, compostable waste, and wastewater treatment measured methane and nitrous oxide emissions.

Overall, total emissions reported from 2016 (the most recently available data) are down 15% compared to emissions from 2005: down from 61.08 to 51.91 million tCO2e. About 67% of these emissions are from stationary sources (residential, commercial, and institutional), 30% are from transportation, and 3% are from waste. In absolute terms, emissions from stationary sources decreased the most from 2005 to 2016: down 18.5% from 42.39 to 34.56 million tCO_2e. Emissions from waste decreased the most in terms of percent change from 2005 to 2016: down 21% from 2.28 to 1.80 million tCO_2e. Transportation had a much more modest decrease: down 5.2% from 16.41 to 15.55 million tCO_2e.

Under the transportation sector, subway and commuter rail emissions decreased 41.9% from 953,856 to 554,345 tCO_2e and emissions from buses decreased 14.7% from 687,896 to 586,830 tCO_2e, but emissions from passenger cars and trucks remained relatively constant (a 3.6% decrease of 12.88–12.42 million tCO_2e for passenger cars and a 3.5% increase of 1.81–1.87 million tCO_2e for all trucks) and marine navigation emissions increased 82.8% from 49,962 to 91,353 tCO_2e.

In New York City's Roadmap to 80 × 50 report, the de Blasio administration framed its decarbonization strategy, in part, as a guide "on how to grow a dynamic and inclusive economy to spur innovation, develop globally-recognized industries with the potential for high-paying jobs, and to make the city more resilient against climate change and other 21st century threats."(NYC Office of Sustainability, September 2016). This section of the 2016 report identifies equity as "an explicit guiding principle" of the city's environmental agenda. This commitment to equity as a guiding principle will need to be articulated and actualized in the city's emerging DERs strategy, policies, and projects. As New York City pursues DERs projects as part of its decarbonization strategy for achieving 40 × 30 and 80 × 50, city agencies, community-based organizations (CBOs), other nongovernmental organizations (NGOs), and businesses will need to embed equity in DERS and various forms of community energy strategies.

This commitment to equity will likely require a continuing focus on understanding and developing the economic benefits and cobenefits of DER projects in the five boroughs. The criteria for assessing the viability of a DERS project ought to rigorously evaluate issues related to the flow of economic benefits and cobenefits. These economic issues include forms of ownership of DERS, beneficiaries of the sale of excessive power capacity (via energy arbitrage, NY ISO demand response programs, etc.) Roadmaps for building equity into DERS policies and projects can be found in variety of places, including:

- PATHWAYS TO RESILIENCE (P2R): Transforming Cities in a Changing Climate | Kresge Foundation, Movement Strategy Center, The Praxis Project and the Emerald Cities Collaborative | 2015 (Movement Strategy Center, 2015);
- NYSERDA's Reforming the Energy Vision (REV) Working Group II, Subcommittee on Microgrids and Community Grids: Ownership and Control (WG 2, _ Microgrids and Community Grids _Fina Report & Appendices.pdf) (NYSERDA) (NYSERDA, 2015);
- Beyond Sharing — How to Take Ownership of Renewable Power, Institute for Local Self-Reliance, 2016;
- Principles of a Pluralist Commonwealth, Gar Alperovitz and the Democracy Collaborative, 2017, Ownership: Why Is Ownership a Key Determinant of System Structure? (Alperovitz and the Democracy Collaborative, 2017).

In light of the new set of challenges, opportunities, economic benefits, and cobenefits that will accompany New York City and New York State's transition to a low-carbon economy, City Hall could impanel a commission made up of city agencies and stakeholders in the independent and private sector to: map the emerging challenges, opportunities, economic benefits, and cobenefits; formulate recommendations about how the flow of those benefits can be leveraged to create new sources of economic opportunity in low-income, low-wealth communities in the five borough.

High on the list of issues that the commission could examine are: defining economic benefits and cobenefits to include not only green jobs and lower energy bills, but also the opportunities for people and entities in low-income, low-wealth communities to be owners, investors, and shareholders in new green energy enterprise (distributed energy resources, DERS) and other forms of climate-friendly projects that lead to mitigation, adaptation, and resilience.

Identifying any legal or regulatory obstacles at the city and state scales that would stymie the development of neighborhood-owned co-operatives, B corporations, traditionally structured green businesses, NGO-owned, CBO-owned businesses that can help people and community institutions build ownership and wealth; and cataloguing and benchmarking pathways/modalities in use in the United States and overseas for leveraging the creation of income and wealth for individuals and community-based entities that work with people in low-income, low-wealth communities.

The second mitigation issue that deserves greater and sustained focus involves accounting for and dealing in a meaningful way with the share of the New York City's carbon footprint that is generated beyond its political boundaries. New Yorkers, like all residents of megacities, suburbs, towns, and rural areas, are responsible for transboundary emissions. They consume carbon-intensive goods (from cars to clothing to food and appliances) and services that are imported from other parts of the United States and the rest of the world.

Policies and actions that appear to be sustainable locally (at the city or metropolitan-region scales) ought to account for the total planetary-level environmental and social consequences of local consumption patterns (NAS, 2016). GHG mitigation policies and programs ought to take account of and take actions that recognize the biophysical limits of the planet; all cities need to identify and pursue specific policies that reduce the city's metabolism, mostly composed of material and energy flows (NAS, 2016). Accounting for and working to reduce transboundary GHG emissions will require cities across all sectors to play a major role in managing Earth's finite resources in a sustainable way (Seitzinger *et al.*, 2012 in NAS, 2016).

World cities, New York included, could agree on a methodology for accounting for transboundary GHG emissions, estimate those emissions and report them, along with implementing long-terms strategies for reducing each city's transboundary footprint. To that end—the collection of transboundary data and the analysis of it—the National Science Foundation's Advisory Committee for Environmental Research & Education issued a 2018 report, Sustainable Urban Systems: Articulating a Long-Term Convergence Research Agenda (Sustainable Urban Systems Subcommittee (National Science Foundation, 2018). This report by the advisory committee's Sustainable Urban Systems Subcommittee offers a guide to researchers and stakeholders on how to conduct convergent science required to understand the local and transnational footprints of cities and metropolitan regions. According to the report, the key elements of the next cycle of sustainable urban systems science ought to lead to the production of in-depth knowledge of (NSF, 2018: 16):

- "Single urban/metropolitan regions where multiple sustainability outcomes are addressed for a multi scale systems perspective that connects homes, businesses and communities to regional and global scales.
- Multiple cities and communities, exploring relationships among networks of communities and identifying city/urban typologies for the study of cohort groups and comparison groups.
- Supra-aggregations of cities and urban areas, e.g., all urban areas in an electrical grid region, nation, world-region, or the world, to study the collective impact of urban transformation on people and the planet."

Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report Chapter 8: Indicators and Monitoring

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Contents

8.1 Introduction

The Indicators and Monitoring chapter of the first New York City Panel on Climate Change Report began with the paradigm: *What cannot be measured cannot be managed* (Rosenzweig *et al.*, 2010). This statement is as valid today as it was then.

The NPCC1 (2010) Indicators and Monitoring chapter addressed the need for assembling a suite of indicators to monitor climate change and adaptation in order to inform climate change decision making. It outlined criteria for selection of indicators (*policy relevance, analytic soundness, measurability*), defined categories of indicators (*physical climate change; risk exposure, vulnerability, and impacts; adaptation; new research*), and provided examples of specific indicators. Table 8.1 is a summary table of indicator development contribution from the NPCC1 I&M chapter (Jacob *et al.*, 2011). The chapter explored the institutional requirements for indicator data availability, continuity, archiving, and public accessibility.

NPCC2 (2015) focused on how New York City's climate measurement, monitoring, and assessment activities may be better coordinated and enhanced to guide the city in becoming more responsive to ongoing climate change (Rosenzweig *et al.*, 2015). It laid out a process by which a Climate Resilience Indicators and Monitoring System could be developed based on the opportunities and gaps in its existing monitoring efforts.

The combination of the climate trends presented in NPCC1 and updated in NPCC2, the documentation of existing monitoring efforts, and the laying out of an indicators and monitoring development process have helped the city to advance toward a risk-oriented process for climate-oriented indicators and monitoring. Figure 8.1 depicts the iterative risk management scheme for indicator selection that is used by the NPCC. The indicator and monitoring studies of NPCC1 and NPCC2 have made significant progress in steps 1–3 of the figure, and steps 4–5 are the primary indicator and monitoring foci of NPCC3 that also provides guidance for steps 6 and 7.

Steps 4 and 5 remain the primary foci of NPCC3; however, in accordance with the steps outlined in Figure 8.1, the NPCC3 I&M team has also accomplished the following 5 of the 7 steps:

1. Interacted with New York City's Climate Change Adaptation Task Force (CCATF),

doi: 10.1111/nyas.14014

Table 8.1. Basic climate change variables for monitoring and development of indicators (from NPCC1, Jacob *et al.*, 2010)

	Climate hazard	Location	Time series	Timescale	Source
Temperature	Mean temperature	Central Park	1876–Present	Daily, monthly	NCDC
		Kennedy Airport	1948–Present	Daily, monthly	NCDC
		LaGuardia Airport	1947–Present	Daily, monthly	NCDC
	Days with temp > X^0F	Central Park	1944–Present	Monthly	NCDC
	Days with temp < X^0F	LaGuardia Airport	1948–Present	Monthly	NCDC
	Number of consecutive days (thresholds preset, requires further processing to customize)	Central Park	1876–2001	Monthly, annual	NCDC
		Kennedy Airport	1949–Present	Monthly	NCDC
			1949–2001	Monthly, annual	NCDC
		LaGuardia Airport	1948–2001	Monthly, annual	NCDC
	Global surface temperature	Global value	1880–Present	Annual	NCDC
	U.S. Heat Stress Index	New York City	1948–Present	Annual	NCDC
Precipitation	Total precipitation	Central Park	1876–Present	Daily, monthly	NCDC
		Kennedy Airport	1949–Present	Daily, monthly	NCDC
		LaGuardia Airport	1947–Present	Daily, monthly	NCDC
	Drought	New York City Region	1900–Present	Monthly	NCDC
	Thunderstorms/lightning	New York County	1950–Present	Daily	NCDC
	Snow	Central Park	1876–Present	Daily, monthly	NCDC
		Kennedy Airport	1948–Present	Daily, monthly	NCDC
		LaGuardia Airport	1947–Present	Daily, monthly	NCDC
	Downpours (precipitation rate/hour)	Kennedy Airport	1949–Present	Hourly	NCDC
		LaGuardia Airport	1948–Present	Hourly	NCDC
	Days with rainfall > x inches	Central Park	1944–Present	Monthly	NCDC
	Number of consecutive days (thresholds preset, requires further processing to customize)	Central Park	1876–2001	Monthly, annual	NCDC
		Kennedy Airport	1949–Present	Monthly	NCDC
			1949–2001	Monthly, annual	NCDC
		LaGuardia Airport	1948–Present	Monthly	NCDC
			1948–2001	Monthly, annual	NCDC
Sea level rise and coastal storms	Sea level rise – mean water level	the Battery	1856–Present	Monthly	NOS
		Sandy Hook, New Jersey	1932–Present	Monthly	NOS
	Hourly height water level	the Battery	1958–Present	Hourly	NOS
	Extreme winds	Sandy Hook, New Jersey	1910–Present	Hourly	NOS
	Tropical cyclones	Central Park	1900–Present	Daily	NCDC
		New York	1851–Present	Annual	NCDC
Other	Greenhouse gas index	Global value	1979–Present	Annual	ESRL

with New York City's Office of Recovery and Resiliency (ORR), with New York City's Department of Transportation, and with New York City's Comptroller's office. These interactions were carried out via workshops, meetings, and teleconferences
2. Focused on the energy and transportation sectors because of data availability, ease of accessibility relative to other sectors, and time
3. Selected a set of preliminary indicators
4. Presented the set of preliminary indicators to stakeholders at CCATF meetings for feedback and to scope implementation
5. Considered indicator revisions based on stakeholder feedback

Steps that remain include:

6. Provide guidance to the NPCC4 team in setting up an I&M system that reflects the defined framework
7. Provide guidance to the NPCC4 team in conducting evaluation, iterative research, and stakeholder interaction through time

Stakeholder interactions for the I&M co-generated process

In developing the proposed New York City Climate Resilience Indicators and Monitoring (I&M) System presented in this chapter, a co-generation process took place between the author team, germane

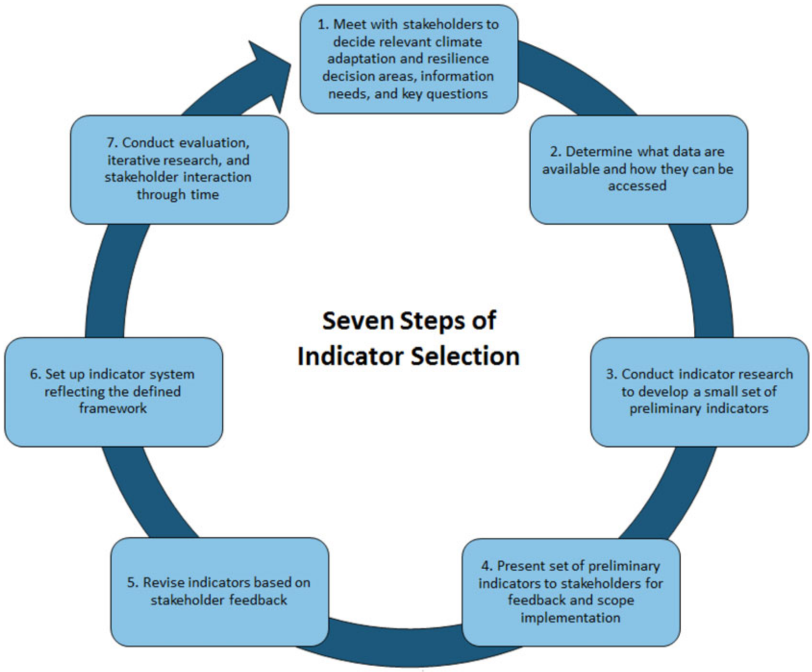

Figure 8.1. Iterative risk management indicator and monitoring selection process (NPCC, 2015).

stakeholders, research scientists, and climate experts (See Appendix 8.A. for full description of the process). The process also included reviewing the current literature on risk-oriented indicators and monitoring for climate change resiliency.

The genesis of the co-generated process is rooted in the NPCC aligning its initial broad indicators and monitoring framework to the five key "lifeline" infrastructure sectors (1)transportation, (2) energy, (3) telecommunications, (4) social infrastructure, and (5) the combined sector consisting of water, sewer, and waste that were identified by the New York City Climate Change Adaptation Task Force (CCATF).

These five sectors and their possible links to climate are highlighted in Table 8.2. Some additional preliminary discussions, including potential brainstorming around indicators and data sources, also occurred between the NPCC and some CCATF members. These were followed by a workshop, a roundtable, and continuing discussions throughout the scoping and drafting process.

The primary CCATF agencies and organizations engaged included The Metropolitan Transportation Authority, The NYC Department of Transportation, The NYC Department of Environmental Protection, Port Authority of New York and New Jersey, Eastern Generation, and Con Edison. Additional feedback was also obtained from the NYC Emergency Management Office and The NYC Comptroller's Office.

The development of the chapter included review of key literature by the authors and review by key stakeholders:

- ***Key literature.*** As in the case of Chapter 7, the following NPCC and government literature were used: NPCC1 (2010) and NPCC2 (2015); *PlaNYC* (City of New York, 2013); *OneNYC* (City of New York, 2015); the *1.5 Celsius Aligning NYC with the Paris Climate Agreement* report (City of New York, 2018a); the NYC Mayor's Office of Recovery & Resiliency Climate Resiliency Design Guidelines (NYC Mayor's ORR, April 2018); the NYC Office of the *Mayor Mayor's Management Report* (2017); New York State reports, particularly following Hurricane Sandy (e.g., NYS, 2013); and U.S. Department of Homeland Security (DHS) reports (U.S. DHS, 2013, 2015)
- ***Key stakeholders and reviewers.*** The NYC CCATF, The NYC Department of Transportation, The NYC Mayor's Office of Recovery & Resiliency, The NYC Emergency Management

Table 8.2. Key climate extremes identified five key proposed NYCLIM sectors based on feedback and interactions with the New York City Climate Change Adaptation Task Force

City-selected sectors	Climate extremes
Transportation	Sea level rise and coastal flooding; extreme heat and humidity; extreme winds
Energy	Sea level rise and coastal flooding; extreme heat and humidity; cold snaps
Telecommunications	Sea level rise and coastal flooding; extreme heat and humidity; extreme winds
Social infrastructure	Sea level rise and coastal flooding; extreme heat and humidity; heavy rainfall/inland flooding
Water, sewer, and waste	Sea level rise and coastal flooding; extreme heat and humidity; heavy rainfall/coastal flooding

Office, and The NYC Comptroller's Office, The NYC Office of Management and Budget, The Metropolitan Transportation Authority, The NYC Department of Environmental Protection, Consolidated Edison, and The Port Authority of New York and New Jersey.

Organization of chapter

This chapter presents the work that has been undertaken by NPCC3 to advance the conceptualization and recommendation of a proposed New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM). While NPCC1 and NPCC2 were primarily focused on enhancing the resiliency of critical infrastructure throughout the city and region, NPCC3 has broadened its scope to include social vulnerability and economic indicators. The chapter also presents several case studies to illustrate the status of indicator development for the City. Moreover, it provides a detailed set of indicators in the Appendix.

Section 8.2 reviews the literature on existing climate change indicators and monitoring systems so that New York City may learn from what other cities and levels of government have done. Section 8.3 offers the framework for a proposed New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM). Sections 8.4 and 8.5 explore indicators specifically aimed, respectively, at the transportation and the energy sectors, and Section 8.6 covers selected infrastructure interdependencies for those two sectors.

Section 8.7 discusses financial and economic indicators, and Section 8.8 provides insights for aggregate economic well-being and how to measure it as a function of the potential costs of climate change. Section 8.9 discusses the implementation of the proposed NYCLIM, and the final Section, 8.10, provides a conclusion that discusses gaps in knowledge and/or missing data, and avenues for implementation and further research.

Appendix 8.A describes the co-generation process in greater detail. Appendix 8.B offers a short introduction to how the steps in Figure 8.1 can reflect and incorporate a dynamic climate and its detection and activity to human activity. An I&M system needs to accurately account for how the future climate of the city might evolve over the near term (2020s), medium term (2050s), and long term (2080s, 2100, and beyond).

8.2 Climate change indicators and monitoring systems relevant to urban areas

This section is an illustrative listing of local, regional, national, and international contributions relevant to urban climate change indicator and monitoring systems, such as the one being recommended in this chapter. The creation of effective indicators for assessing vulnerability to climate change must begin with clear understanding of the diversity of local and regional domains (Downing *et al.*, 2001). They need to be connected clearly with ranges of adaptation strategies and options so that they can eventually identify vulnerabilities and adaptation measures related to observed situations and/or their projected future.

It follows that spatial and temporal scales are critical dimensions for indicators regardless of context and that consistency across contexts needs to be assured to allow at least qualitative if not quantitative comparisons over time and space, and to detect trends and differences.

8.2.1 U.S. global change indicators and monitoring

There are at least three depositories of indicators of climate change located within the U.S. government. They generally report historical values at various time scales and at various levels of geographic scale, and they sometimes provide both graphical plots of the data and illustrative maps for visual representation. Appendix 8.C records their contents and electronic locations. Specific indicators that are most relevant for analyses of urban vulnerability and resilience like NPCC3 are indicated.

Linking fundamental framework elements of the macroscale national I&M systems to New York City's climate resiliency indictors can be helpful in regard to the understanding of trends. By collecting, archiving, and analyzing some of the same indicators at the New York metropolitan region scale, the NYCLIM proposed in this chapter by the NPCC3 could provide perspective, for instance, on whether the climate trends it is experiencing are similar or different from regional and national trends (Rosenzweig and Solecki, 2018).

- U.S. Environmental Protection Agency (EPA)

Historical trajectories of annual and sometimes monthly data at national, regional, and occasionally local scales are provided for greenhouse gas and short-lived pollutant emissions, weather, and climate (temperature, precipitation, extreme events, tropical cyclones, river flooding, and drought), health (heat-related deaths, lyme disease and West Nile virus, growing seasons lengths), and oceans (coastal flooding, land loss, Arctic sea ice); see https://www.epa.gov/climate-indicators.

- National Oceanographic and Atmospheric Administration (NOAA)

Historical trajectories of annual data at national, regional, state, and occasionally local scales are provided for yearly climate rankings for precipitation, temperature, and drought; extremes (hot and cold, wet and dry); societal impacts (crop moisture, energy demand, wind, wildfires, $1 billion disasters, West Nile virus, hurricanes, tornadoes); and oceans (sea level rise, Arctic sea ice, sea surface temperature, oscillations (ENSO, NAO, PDO, PNA)); see https://www.ncdc.noaa.gov.

- United States Global Change Research Program (USGCRP).

Historical trajectories of annual data at national and global scales are provided for greenhouse gases, surface temperature, start of spring, surface temperature, and Arctic sea ice; see https://globalchange.gov/explore/indicators.

8.2.2. *Global cities and selected New York City indicators and monitoring sources*

Other urban-scale compilations of I&M measures have been developed that included New York City. Examples are summarized below, and results for both indices are contained in Appendix 8.C.

- The National Academies (2016) produced "Pathways to Urban Sustainability: Challenges and Opportunities for the United States" that identified numerous climate-related indicators and applied them to nine cities, including New York City.
- The Economic Intelligence Unit (2012) as part of its Green Cities Index covered New York City as part of its North America study.
- Urban Climate Change Research Network (UCCRN) *Second Assessment Report on Climate Change and Cities (ARC3.2)* through its Case Study Docking Station (CSDS) collects data on a set of useful indicators for cities (Rosenzweig *et al.*, 2018). New York City is represented by several case studies in the ARC3.2 CSDS.

8.3. Framing the New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM)

Figure 8.2 depicts the proposed operational components of the proposed NYCLIM. These operational components include data processing centers and online repositories of climate change adaptation databases that are equipped with references, resources, topical categories, and key words. Additionally, the proposed system includes community–stakeholder partnerships that inform decision makers and contribute to prudent, equitable, and scientifically sound climate change policy. The system would also be robust and flexible enough to incorporate ongoing research and new knowledge, the potential for indicators to change, and for new indicators to be developed.

Variables of a future, proposed NYCLIM should include climate extremes, social vulnerability sectors and their interdependencies, infrastructure vulnerability, and decision time frames. Purpose,

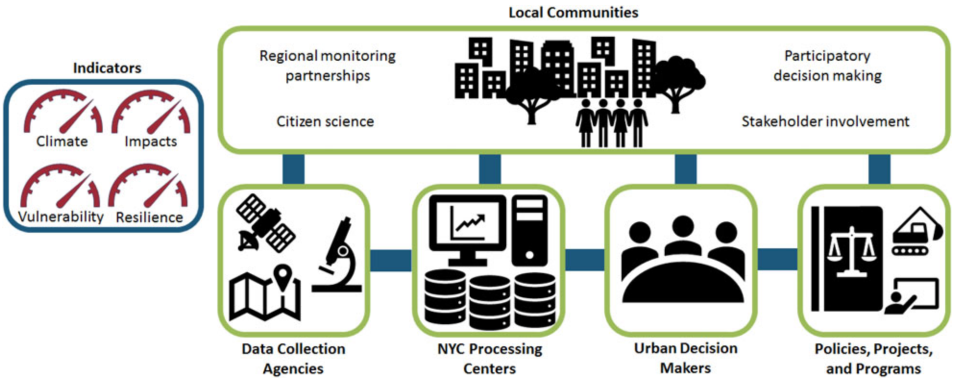

Figure 8.2. Prototype structure and functions of the proposed New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM). The proposed system tracks four types of indicators from data collection agencies, processing centers, urban decision makers, and policies, projects, and programs. The proposed NYCLIM is co-generated by scientists, practitioners, and local communities to determine which indicators should be tracked over time to provide the most useful information for planning and preparing for climate change in New York City.

metrics, data availability, and potential challenges and/or limitations should also be suggested for each indicator.

The selection of indicators that reflect climate, social, infrastructure, and economic variables can enable the tracking of:

1. **Climate:** Climate variables that portend related stress for human systems;
2. **Impacts:** Links that display how and when that stress produces the physical and social impacts of the climate change;
3. **Vulnerability:** Associations that can preview vulnerabilities that are the critical manifestations of climate from climate change impact information; and
4. **Resilence:** Indicators that inform and help decide adaptive response to promote resilience.

For each indicator, a rationale, measurement units, definitions, and data sources are provided. Multistep links to resiliency may be either direct or indirect, and either work alone or as part of a collection of amplifying drivers. In Appendix 8.D, we systematically summarize in a matrix form how to organize the information that could be made available to define, characterize, and quantify an indicator and its purpose.

8.3.1. Climate extremes

The NPCC3 tracked six climate extremes that are important for monitoring climate change (see Chapters 2, 3, and 4). They are extreme heat and humidity, heavy downpours, drought, sea level rise and coastal flooding, extreme winds, and cold snaps. A robust set of climate indicators enables the quantification of trends and importantly the juxtaposition of these trends with climate projections. Table 8.3 highlights such an example for temperature (see Chapter 2, Climate Science).

To analyze where current temperature trends fall within the NPCC2 projections for the 2020s, monthly temperature data (1971–2017) from the Central Park, New York weather station were analyzed (Table 8.3). For the annual average and the winter (DJF) and summer (JJA) seasonal averages, the linear trend in temperature change was computed. The rate of warming per year was multiplied by the number of years in the observed period. This amount of warming was then compared to the ranges of projections from the NPCC2 report.

For the annual and summer warming, observed increases in temperature fall below the 10th percentile projection value. For the winter, the observed warming falls within the middle range of projections.

As a caveat, it is important to note that while the observations (based on the linear warming trend) fall within the lower end of the projections, the most appropriate comparison, which would take the observed future period and subtract the observed base period, cannot be computed as the future window is too short and the average would be dominated by year-to-year variability. On a related note, some indicators may track how climate projections themselves change as climate science and observations progress.

Table 8.3. Comparison of climate trends from 1971 to 2017 compared to NPCC2 projections for the 2020s

	Linear warming trend (1971–2017)	2020s NPCC2 projections—low estimate (10th percentile)	2020s NPCC2 projections—middle range (25th–75th percentile)	2020s NPCC2 projections—high estimate (90th percentile)
Annual	1.43°F	1.5°F	2.0°F–2.9°F	3.2°F
Winter (DJF)	2.42°F	1.4°F	2.0°F–3.2°F	3.7°F
Summer (JJA)	0.55°F	1.8°F	2.1°F–3.1°F	3.3°F

Note: These comparisons should be viewed with caution because of the role that natural variation plays in the short term.

8.3.2. *Social vulnerability*

NPCC3 has a major focus on social vulnerability (see Chapter 6, Community-Based Assessments). Chapter 6 includes a detailed description of social vulnerability indicators.

8.3.3. *Sectors*

With inputs from ORR and from the CCATF and the agencies that comprise it, NPCC3 selected five sectors (Fig. 8.3) related to critical infrastructure—energy, transportation, telecommunications, transportation, and water, waste, and sewers. Through stakeholder interactions, the NYCLIM proposed here identifies the major climate-related risks for each sector exemplified by heat in Table 8.3. Due to data availability, ease of data accessibility, and time constraints, this chapter only focuses on the energy and transportation sectors. The underlying pentagon of the five sectors of Figure 8.3 draws attention to interdependencies across the sectors, both in terms of their functional interconnections and in terms of the climate variables that may drive multiple impacts and vulnerabilities.

8.3.4. *Infrastructure vulnerability, impacts, and resilience*

Indicators will enable the comparison of past, present, and future vulnerabilities, impacts, and ultimately resilience. For example, these indicators relate to the management of climate impacts. Their purpose is to track whether climate adaptation policies and measures are gaining or losing ground to manage the risks to which the city, its population, assets, infrastructure, and economy are exposed. This set of indicators focused on infrastructure is aimed to provide a sound quantitative database that can help the city to make decisions on relevant policies, planning and funding priorities, and to allow the city to optimally manage its social, economic, and fiscal health vis-à-vis climate challenges encompassing a risk-oriented framework.

8.3.5. *Decision-making time horizons*

An indicator can address multiple time horizons. For the physical climate indicators, the time horizons directly rely on the projections in Chapter 2, New Methods for Assessing Extreme Temperatures, Heavy Downpours, and Drought; Chapter 3, Sea Level Rise; and Chapter 4, Coastal Flooding. These are the 2020s, 2050s, 2080s, and the year 2100. For indicators and time frame of social vulnerability, see Chapter 6, and for the risk time frames of critical infrastructure, see Chapter 7, Critical Infrastructures. Certain infrastructure systems such as transportation, rights of way, bridges, and tunnels may, in some instances, have expected useful life times beyond the upper time limit (2100) for which Chapters 2, 3, and 4 provide climate projections.

We distinguish broadly three time horizons for the risk-related indicators: short term (ST) through the 2020s (2010–2039 time frame), medium term (MT) in the 2050s (2040–2069 time frame), and long term (LT) in the 2080s (2070–2099 time frame), 2100, and beyond. These horizons dovetail approximately to the climate science time slices of the 2020s (ST), 2050s (MT), and 2080s–2100 (LT) (see Chapters 2, 3, and 4). The boundaries between the time horizons are left imprecise to reflect a degree of uncertainty in their distinction from one application to another.

Details in our constructions are recorded in Appendix 8.E. The chapter looks forward, as decision makers do, from the immediate term into uncertain climate futures. A key question is: Can we describe climate futures in decadal steps so that the essential short-, medium-, and long-term contexts can be rigorously distinguished in ways that are consistent with the 2100 distributions? Box 8.1

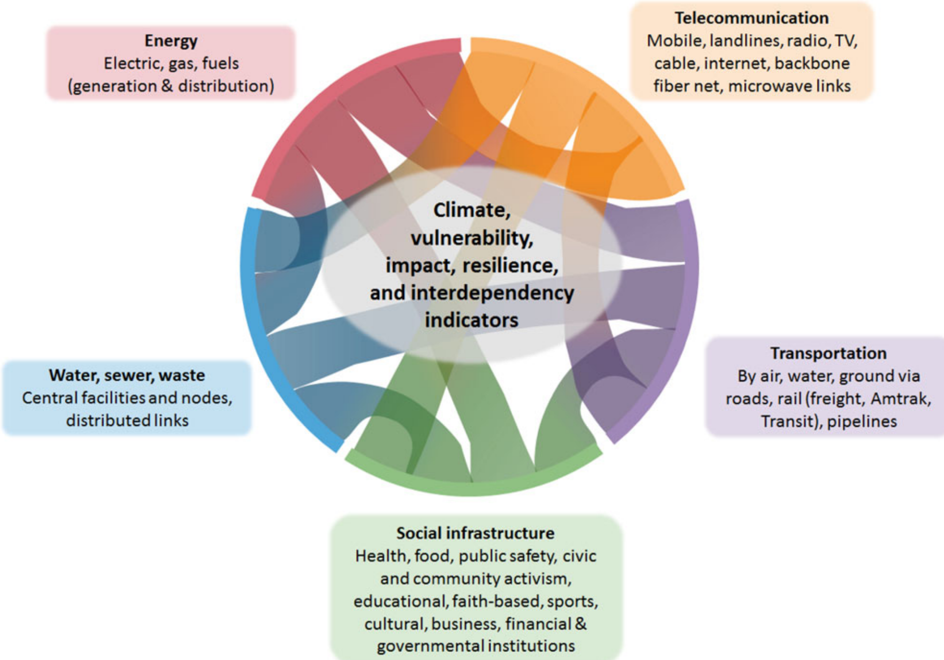

Figure 8.3. Five city-selected lifeline infrastructure sectors.

explores how this challenge is being addressed in Miami Beach.

8.4. Transportation indicators

Extreme heat and humidity, cold snaps, heavy downpours, extreme winds, sea level rise, and coastal flooding are increasing in frequency and intensity (see Chapters 2, 3, and 4), posing major hazards that produce climate-related risk for the transportation sector. Key indicators can track these changes, their impacts on New York City transportation infrastructure, and even highlight changes in vulnerability and resiliency of that system over time. Potential indicators related to transportation and their associated purpose, definitions, metrics, time frames, and data sources are summarized in Table 8.4. Background information on climate issues

Box 8.1. The time horizon challenge: responding to flooding in Miami Beach

Miami Beach has experienced a 400% increase in tidal flooding since 2006. The city understood that crafting indicators to monitor changes in sea level rise and associated flooding risk as well as changes in social and economic vulnerability was essential to building some pre-emptive skill into risk management programs and policies, even back to the immediate time frame. Miami Beach is now in the midst of a $400 million project to raise roads and install new sewers and pumping stations. This project was initially designed to hedge against the upper tails of sea level rise futures, and the city was committed to monitoring the oceans to see when the new infrastructure might be overwhelmed. However, actual adaptations were designed to just deal with increased nuisance flooding while at the same time allowing more development. The adaptations are unlikely to be effective in the long run, given current sea level rise projections. Planners, therefore, face a complicated question: What indicator could be constructed to properly characterize current adaptation investments that may encourage additional real-estate development, vis-à-vis the adaptation investments' long-term efficacy, sustainability, or lack thereof?

Sources: Wdowinski *et al.*, 2016; Miami New Times, 2016; and NPR, 2016.

Table 8.4. Illustrative and potential climate-linked critical indicators for selected climate extremes for New York City's transportation sector (road and rail systems only)—impacts, indicators, metrics, and data sources

Climate extremes[a]	Potential infrastructure impacts[b]	Potential indicators[c]	Potential indicator metrics[c]	General illustrative and potential data sources
Extreme heat and humidity			Road[d]	
	– Increased road material degradation, resulting in increased road maintenance	1. Distortion including buckling of road surfaces 2. Number, frequency, and cost of repairs 3. Emergency safety alerts, etc. 4. Working days of pavement crews (attributable to both climate and non-climate factors)	1. Extent (e.g., area) of roadway segments requiring repair 2. Cost in dollars of roadway repair over time, considering changes in labor and material costs 3. Number and duration of activations 4. Number and cost of changes in work day allocations (attributable to both climate and non-climate factors)	1. NYC DOT, NYS DOT, PANYNJ 2. NYC DOT, NYS DOT, PANYNJ 3. NYCEM 4. NYC DOT, NYS DOT, PANYNJ
			Rail[d]	
	– Increased heat stress on rail equipment	1. Distortion including buckling of rail lines and rail connectors	1. Number and mileage of rail lines buckling; change in zero thermal stress temperature (which can be considered a baseline in terms of temperature at which running rail is neutral/unstressed)	1. NYS MTA/NYC Transit; PANYNJ
	– Increased use of cooling equipment due to increased underground station temperatures	1. Increased use of cooling equipment: frequency of use 2. Disruptive fires 3. Emergency alert activations	1. Cost of increased cooling 2. Number and intensity of disruptive fires 3. Number and duration of safety alerts	1. NYS MTA/NYC Transit; PANYNJ 2. NYS MTA/NYC Transit; PANYNJ 3. NYS MTA/NYC Transit; PANYNJ; NYC EM
	– Increased rail degradation and equipment deterioration, resulting in increased maintenance	1. Subway on-time performance 2. Working days of rail crews (attributable to both climate and non-climate factors)	1. Yearly average, but sampled every day, if possible to allow correlation with extreme heat, and for each subway line 2. Number, frequency, and costs of rail components and labor costs (attributable to both climate and non-climate factors)	1. NYS MTA/NYC Transit; PANYNJ 2. NYS MTA/NYC Transit; PANYNJ
	– For rail systems dependent on overhead catenaries (or cables) for power, for example, commuter rail, potential increase in transit accidents from train collisions with sagging overhead lines	1. Delays due to transit conditions 2. Health effects on passengers and workers	1. Number, types, and duration of delays 2. Number and severity of medical emergencies	1. NYS MTA/NYC Transit; PANYNJ 2. NYS MTA/NYC Transit; PANYNJ, NYCEM
	– Decreased service and/or lack of service	1. Number and duration of service disruptions (weather related) in terms of customer wait time 2. 311 complaints	1. Customer wait time; length of trips 2. Frequency and volume of 311 complaints	1. NYS MTA/NYC Transit; PANYNJ 2. NYC EM; NYC311
Cold snaps			Road[d]	
	– Some road surfaces could be damaged depending on material tolerances	1. Road surface disruptions, blockages, congestion	1.a Number, frequency, and duration of service disruptions; trip delay time 1.b Miles and area of roadways and access points affected	1.a NYS DOT, NYC DOT 1.b NYS DOT, NYC DOT
	– Increased use of snow and ice removal, where snow and icing accompany cold snaps	1. Deployment of Department of Sanitation (DSNY) salt/sand trucks	1. Number of trucks deployed to clear roads and area of roadways affected	1. NYC DOT, DSNY
			Rail[d]	
	– Service disruption	1. Subway on-time performance 2. Decreased service and/or lack of service; customer wait time	1. Yearly average, but sampled every day, if possible to allow correlation with extreme cold temperatures, and for each subway line 2. Number and duration of service disruptions; trip delay time	1. NYS MTA/NYC Transit; PANYNJ 2. NYS MTA/NYC Transit; PANYNJ

Continued

Table 8.4. *Continued*

Climate extremes[a]	Potential infrastructure impacts[b]	Potential indicators[c]	Potential indicator metrics[c]	General illustrative and potential data sources
Cold snaps		Road[d]		
	– Increased use of snow and ice removal, where snow and icing accompany cold snaps	1. Deployment of DSNY salt/sand trucks 2. Working days of outdoor MTA crews	1. Number of trucks and other specialized snow clearance equipment deployed to clear rail lines and length of rail affected 2. Number of extra days and costs per day	1. NYS MTA/NYC Transit; PANYNJ; DSNY; railroad owners and operators 2. NYS MTA/NYC Transit; PANYNJ; NYC-DOS
	– Some rail components could be damaged depending on material tolerances	1. Increased maintenance 2. Working days of outdoor MTA crews	1. Number and costs of repairs 2. Number of extra days and costs per day	1. NYS MTA/NYC Transit; PANYNJ; NYC-DOS 2. NYS MTA/NYC Transit; PANYNJ; NYC-DOS
Sea level rise and coastal flooding		Road[d]		
	– Declining serviceability of roadways due to flooding conditions	1. Road obstructions and restrictions	1. Number of storm-flood-related closures of major road arteries, for example, Belt Parkway and/or West-Side and/or FDR Highways	1. NYSDOT, NYC DOT
	– Increased travel delay from increased congestion due to persistent high water levels	1. Road-related closures, such as ramps and tunnels 2. Overall road service condition	1. Number of road closures/year 2. Level of service (LOS) based on volume to capacity ratios and extent of roads at or exceeding LOS E and F	1. NYSDOT, NYC DOT 2. NYSDOT, NYC DOT
	– Increased need for ongoing pumping capacity and associated increased energy use for additional pumping to continuously remove excess water to prevent flooding	1. Road-related closures, such as ramps and tunnels 2. Energy use for pumping operations	1. Number and duration of road closures/year 2. Marginal increase in energy use in kWh	1. NYS DOT 2. NYS DOT, 3. ; Con Edison
	– Increased use of barriers and road hardening to prevent erosion and overtopping	1. Bulkhead/street end hardening	1. Number and cost of construction of hardening structures	1. NYSDOT, NYC DOT
	– Deterioration (corrosion) of roadway support facilities by salt water	1. Signal, CCTV, and street light disruptions	1. Frequency of water intrusion into electrical systems and conduits, degree of damage, and outages	1. NYS DOT, NYC DOT; NYC DEP
		Rail[d]		
	– Increased rail degradation and equipment deterioration from saltwater inundation, resulting in increased maintenance	1. Train arrival/ departure delays 2. Flooding, debris damages, corrosion, water intrusion 3. Equipment damage and repair costs	1. Mean distance between failures for trains; signal and switch malfunction frequency (to the extent that other non-climate factors do not override climate effects); Number and frequency of alerts, for example, MTA service alerts 2. Volume of debris accumulation 3. a. Capital versus operations cost changes b. Equipment retrofit needs: number and cost of relocating equipment c. The number of protected or flood-proofed subway entrances, given at the end of each calendar year, in the 1%/year flood zone or other specified flood zones, compared to the total number of subway entrances in this zone	1. NYS MTA/NYC Transit 2. NYS MTA/NYC Transit 3. NYS MTA/NYC Transit
	– Service disruptions	1. Subway on-time performance 2. Rail tunnel, track, and station closures 3. Effects of environmental hazards on services	1. Number and duration of service disruptions; on-time performance rates 2. Number and duration of closures 3. Extent and severity of environmental and public safety hazards	1. NYS MTA/NYC Transit 2. NYS MTA/NYC Transit 3. NYS MTA/NYC Transit

Continued

Table 8.4. ***Continued***

[a]Climate extremes in Table 8.4 related to transportation are as defined in NPCC3 as follows:
Extreme heat and humidity pertains to heat waves as described in Chapter 2, using the National Weather Service (NWS) definition "as three (or more) consecutive days with temperatures of at least 90°F (32.22°C)" and also considers days per year above 90°F and 100ºF. Other concepts include worst daily heat–humidity combination "wet-bulb" temperature per year; Heat index: 2-consecutive days of heat index 80–105°F; Monthly and yearly degree cooling days for NYC (NYS ISO, 2017a zone J). Chapter 2 also develops definitions for heat wave frequency, duration, and intensity all of which potentially affect infrastructure.
Cold snaps are defined as number of days below a threshold temperature and is reflected in the number of cooling days.
Sea level rise and coastal flooding is defined in Chapters 3 and 4.
[b]Potential infrastructure impacts and the references for each of the impacts are in general from the third column of Table 7.1b (see Chapter 7), with a few differences, in order to consistently link impacts to indicators and metrics. The end of Table 7.1 provides references for impacts listed in Table 8.4 as well. As indicated in footnote *c* for Table 7.1b, the impacts listed here are illustrative and are not intended to be comprehensive. Non-climate–related factors in addition to climate extremes can contribute to impacts, indicators and indicator metrics listed here. More knowledge and analysis would be required to separate climate and non-climate factors. The indicators are thus labeled "potential" for consideration and review by relevant agencies. Sources that underscore this selection and also provide additional information for each impact are located in footnote (*d*) below.
[c]Metrics apply to each indicator associated with each impact (in a given row) even where multiple indicators and metrics are listed. References for indicators, metrics are contained in the chapter text and references here and in Chapter 7. For detailed references not repeated here see those accompanying Table 7.1b.
[d]For additional examples and details for potential climate-related transportation impacts and indicators, see, for example:
For the U.S.: U.S. DOT, FHWA, Office of Planning, Environment, & Realty (HEP). 2015. Tools. Climate change adaptation. Sensitivity matrix. https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/.
U.S. DOT, FHWA, Office of Planning, Environment, & Realty (HEP). 2015. Tools. Climate change adaptation. Sensitivity matrix. https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/.
National Academies, National Research Board, Transportation Research Board. 2008. Potential impacts of climate change on U.S. transportation. Washington, DC.
http://onlinepubs.trb.org/onlinepubs/sr/sr290.pdf.
U.S. Climate Change Science Program. 2008. Impacts of climate change and variability on transportation systems and infrastructure: Gulf Coast study, phase I. Synthesis and Assessment Product 4.7. https://www.globalchange.gov/browse/reports/sap-47-impacts-climate-change-and-variability-transportation-systems-and
For New York State and New York City: Various analyses and planning efforts in connection with the aftermath of Hurricane Sandy cited in Chapter 7 (e.g., the NYS 2100 Commission, City of NY SIRR, etc.)
Rosenzweig, C., W. Solecki, A. DeGaetano, *et al.* Eds. 2011. Responding to climate change in New York State: the ClimAID integrated assessment for effective climate change adaptation. Technical Report. New York State Energy Research and Development Authority, NYSERDA, Albany, NY. www.nyserda.ny.gov.

related to the transportation sector was presented in Chapter 7.

Table 8.4 refers to the portion of the transportation sector that focuses on rail and roads, and does not include marine or air transportation or other road-related structures such as bridges, for example. Indicators and metrics are illustrative only. They emphasize physical infrastructure measures and certain aspects of social impact but generally not those that are health or safety related (see Chapter 6, Community-Based Assessments of Adaptation and Equity). Nonclimate-related factors in addition to climate extremes can contribute to impacts, indicators, and indicator metrics listed here. The impacts, indicators, and metrics are thus labeled "potential" for consideration and review by relevant agencies.

Potential data sources listed are only some of the major organizations that provide some of the data sources through publicly available documents or organizations. These organizations do not necessarily currently use the indicators. Data sources across most of the indicators and metrics for rail transit include but are not limited to: U.S. DOT, FTA, NYS MTA and MTA NYC Transit, the Port Authority of NY and NJ (PANYNJ), NY Metropolitan Transportation Council (NYMTC), NJ Transit and Amtrak as relevant to rail transit; NYC ORR; NYC Department of Sanitation (DSNY) for debris and trash removal as relevant; for emergency functions, NYC Office of Emergency Management (NYCEM). Data sources for roadways include but are not limited to: U.S. DOT, NYS DOT, NYS DOT, NYC EDC, and PANYNJ.

Not all of these agencies are listed in the data source column. Data sources apply to each indicator and metric listed for a given impact (in a given row).

Data availability is subject to release by the agencies. The listing of data sources in this table indicates only that relevant data may be available. It does not indicate ability or willingness of source entity to share information.

Many sources of historical records of various lengths and geographical scales are available to provide the basis for climate indicators, but not all of them would work at citywide and/or larger or smaller scales (See Appendices 8.C.1 and 8.C.2).

Scope and data sources

The transportation sector addressed here focuses only on rail and roads. Some transportation indicators that potentially can be related to climate change exist for example for the New York City transit systems from the MTA performance indicator database (MTA undated web site), for streets and bridges from the NYC *Mayor's Management Report* (NYC Office of the Mayor, 2017), and for national-scale bridge indicators applicable to the city from the U.S. National Bridge Inspection Program and the standards upon which it is based (U.S. DOT, FHWA https://www.fhwa.dot.gov/bridge/nbis.cfm) and the National Bridge Inventory Program (U.S. DOT, FHWA https://catalog.data.gov/dataset/national-bridge-inventory-system-nbi-1992-b9105).

Time frames

Once these data sources have been assessed for use in the proposed NYCLIM (Section 8.9), the next step will be to assess the potential for finding or creating forward-looking indicators for the medium and long terms that are anchored on the most recent short-term end-points of the existing historical series.

Three time periods are used: short-term, medium-term and long-term time periods (see Appendix 8.E for detailed discussion on time periods). For example, climate-related impacts on transportation expressed in terms of indicators over time given in Table 8.4 include:

- In the short term (2020s), temperature-related impacts and flooding could lead to disruptions of road and rail infrastructure (e.g., track, roads, signals, switches, lighting, and power systems). These could be intermittent depending upon the length of the impacts; however, regardless of the time period, once the equipment is disabled, repairs will have to be made.
- In the medium term (2050s), the impact identified in the short term could persist into the medium term, should the risk factors persist.
- In the long term (2080s, 2100, and beyond), major dislocations of transportation infrastructure and population could occur, should the impacts persist over long periods of time.

Examples

An example of a set of simple transportation-related vulnerability indicators is related to the number of nuisance flooding of low points on the FDR Drive along the East River in Manhattan, of the West Side Highway (WSHW) along the Hudson River, and of the Belt Parkway in Brooklyn and Queens. Such nuisance flood data and impacts on NYC transportation could potentially be provided by the NYC DOT (or other city agencies, like NYCDEP), or could be inferred from or linked to tide gauge readings at the Battery in Manhattan when they exceed a certain threshold value known to be associated with such nuisance flooding.

These indicators of transportation system disruption from nuisance flooding could contribute to decision making regarding whether city agencies close traffic on the major arteries near the coast in anticipation of surge and flood forecasts (such as provided by NOAA's NHC, NWS, or SIT; for sources, see footnote).

Another important measure to track is the buckling of rail lines from persistent heat waves. The FTA estimates that the buckling of rail lines will increase with increasing 90-degree days (FTA, 2011). The New York area is not in the highest area for heat but the amount estimated for number of days exceeding 90°F is still in the range of 40–60 more days.

8.4.1 Case study 1: Transportation, sea level rise, and coastal flooding

Inundation of a large part of the New York City subway system was one of the most consequential impacts of Hurricane Sandy (Fig. 8.4). The National Climate Assessment reported that "The nation's busiest subway system sustained the worst damage in its 108 years of operation on October 29, 2012, as a result of Hurricane Sandy" (NCA, 2014). Millions of people were left without service for at least 1 week after the storm, as the Metropolitan Transportation Authority rapidly worked to repair extensive flood damage. It follows that developing indicators for

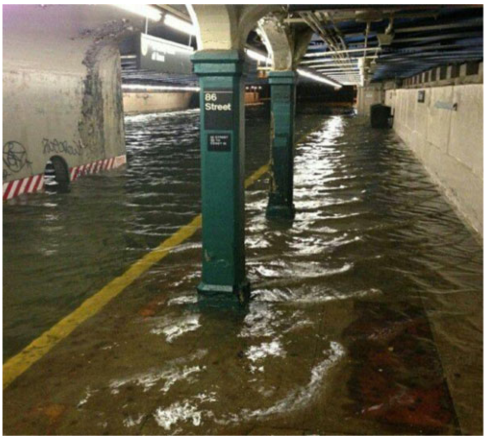

Figure 8.4. Hurricane Sandy causes flooding in New York City's subway (86th Street Lexington Ave. Station, Upper East Side in Manhattan). *Source*: https://www.pinterest.com/pin/218143175672242767/.

the flood hazards across the subway system would be a good idea, that is, indicators of the vulnerability of the system to flood hazards and how they might change over time as the climate and the city evolve. These indicators may include either direct or indirect estimates of how far into the future implemented adaption measures can be expected to be effective.

The experience of NYC during Hurricane Sandy suggests a general indicator whose purpose, calibration, and data can be characterized as:

1. *Indicator*. Direct flood risk/resilience of the New York City Transit (NYCT) subway system.
2. *Purpose*. To measure the vulnerability of the subway system and to keep track on a yearly basis of adaptive measures so that decision makers will know whether and/or how fast the system's resilience is increasing, being maintained, or—in the face of continued sea level rise and storms—deteriorating.
3. *Metrics*. On an annual basis, the number of protected or flood-proofed subway entrances and other openings in the 1%/year flood zone, or at and below elevations with a specified freeboard above the 1%/year base flood elevation (BFE) can be quantified. The 2015 Preliminary Flood Insurance Rate Map has indicated the total number of subway entrances in this zone, or at and below the specified elevation including freeboard.
4. *Data Sources*. (1) FEMA and/or ORR for 1%/year flood zone maps with their BFEs (in feet), referenced to a vertical datum, for example, NAVD88; (2) NYCT for list of protected/flood proofed subway entrances in 1%/y zone including freeboard, or at or below a defined retrofit target elevation, and of total number of entrances in the so-defined flood zone.

Discussion

There are, however, challenges and potential problems that should be explored. For example, FEMA flood zone maps can change over time, either because of changes in methodology, or because of the climate, including storm statistics and sea level rise, and they require periodic updates related to the frequency of flooding. Even now, there is uncertainty which 1%/year flood zone maps and related BFEs to use: those generated by FEMA before Sandy, or those proposed by FEMA since.

The Direct Flood Risk/Resilience indicator provides a measure of resilience based on the 1%/year probability level. It does not provide information about what resilience the system has against less probable but more severe flood events, for example, those based on 0.2%/year or even lower probabilities, or those amplified by future sea level rise. The latter depend on future SLR rates for given future time horizons. This could be partly remedied by reporting the number of subway stations binned in 1-foot increments of their protection levels above the 1%/year FEMA BFEs. This would rely on the willingness and ability of the operating stakeholder to provide this more detailed information.

Flood-proofing subway entrances does not imply that the entire subway system is resilient. Switches and signals are also weak points. Subway maintenance yards are another point of vulnerability. Ventilation grates (often at or near street or sidewalk levels) must be flood-proofed, as well as ventilation shafts. Additionally, other system components such as electric power supply, communications, and control systems must all be protected at the same probability level, if not beyond, to make the system fully resilient. It follows that this single, specific sample indicator is more a proxy for resilience awareness of the operating agency—a first step to the ultimate goal of defining more specific measures of system resiliency.

Several suggestions for improvement of the Direct Flood Risk/Resilience indicator come to mind. Any given subway station is generally served by multiple entrances (e.g., in Manhattan, these are often separate for uptown and downtown directions). Therefore, an alternative indicator may be the number of protected/flood-proved subway stations rather than entrances. Another option is even broader: the number of completely protected subway lines. That level of aggregation, though, presents its own difficulties because line designations and routing can vary between weekdays and weekends, or even across the hours of the day, repair interruptions, or long-term construction projects. For details of NYCT's current subway flood risk reduction program, see Box 8.2

8.5. Energy indicators

Heat waves/extreme heat, cold snaps, and coastal flooding and sea level rise are increasing in frequency and intensity (see Chapters 2–4), and other extreme weather events have also been identified as major hazards that produce climate-related risk for the energy sector. The purpose, definitions, metrics, time frames, and data sources characterized are summarized in this section (see Table 8.5). Background information on climate issues related to the energy sector was presented in Chapter 7.

Table 8.5 refers to the portion of the energy sector that focuses on electricity. Energy supply in the form of fuel and its related infrastructure is not included here. Indicators and metrics are illustrative only. They emphasize physical infrastructure measures and certain aspects of social impact but generally do not include health- or safety-related impacts (see Chapter 6, Community-Based Assessments of Adaptation and Equity). Non-climate–related factors in addition to climate extremes can contribute to impacts, indicators, and indicator metrics listed here. The impacts, indicators, and metrics are thus labeled "potential" for consideration and review by relevant agencies.

Potential data sources listed are only some of the major organizations that provided some of the data sources through publicly available documents or organizations who could potentially use the information. These organizations do not necessarily currently use the indicators. Data sources across most of the indicators and metrics for energy are Con Edison, the Long Island Power Authority, National Grid, the NYS Public Service Commission, NYSERDA, the NYS Independent System Operator (ISO), and a number of the electric power owners and operators of generating facilities. Not all of these organizations are listed in the data source column. Data availability is subject to release by the agencies. The listing of data sources in this table indicates only that relevant data may be there. It does not indicate ability or willingness of source entity to share information.

As in the discussion of transportation indicators above, many sources of historical records of various lengths and geographical scales are available to provide the basis for indicators, but not all of them would work at citywide and/or larger or smaller scales (see Appendices 8.C.1 and 8.C.2). Many of the historical records selected for the transportation indicators will also likely be appropriate for energy-specific hazards. As with the transportation indicators, assessment of existing data sources is the first step, followed by finding or creating forward-looking indicators for the medium and long terms.

Indicators and data sources

Potential energy reliability indicators include:

- System Average Interruption Duration Index (SAIDI) is commonly used as a reliability indicator by electric power utilities. SAIDI is the average outage duration for each customer served (U.S. DOE PNNL, 2016: A.13)
- System Average Interruption Frequency Index (SAIFI) or the average number of interruptions that a customer would experience (U.S. DOE PNNL, 2016: A.13).

These indicators are not very sensitive to extreme climate events. Hence, other indicators and reliable data sources will be sought to characterize the vulnerability or resiliency of electric services to extreme climate events. Cooperation with the NYS PSC and/or NYC EM needs to be pursued.

In early 2000, Con Edison developed the Network Reliability Index (NRI) model to evaluate the reliability of its underground low-voltage network system. The program simulates failures using the Monte–Carlo method and runs long-range (20 years) simulations to determine the NRI values for various design configurations and under varying conditions including heat waves. Con Edison is

Box 8.2. The Metropolitan Transportation Authority and the level of tolerable risk

On October 29, 2012 Hurricane Sandy flooded a significant portion of the MTA's New York City subway system. A study produced only a year earlier had analyzed such flooding for a generic 100-year storm (Jacob *et al.*, 2011). The MTA's New York City Transit (NYCT) division used this information to prepare for the storm operationally, including the removal of critical signal and control systems in many of the tunnels forecast to be flooded, in order to prevent these systems from being exposed to corrosion by brackish flood waters. This measure shortened the downtime of most of the subway system from a forecasted 3–4 weeks to 1 week.

A large portion of the economy comes to a virtual halt without a functioning subway. However, long-term structural damage to many tunnels, including those traversing the East River that connect Manhattan with Brooklyn and Queens, has required full-time or weekend closures to repair in subsequent years, causing longer commutes for many New Yorkers having to use alternate routes. The post-Sandy tunnel and station repair program is ongoing in 2017 and beyond, at a total cost of many billions of dollars.

From the experience of Hurricane Sandy, and the NPCC's climate and sea level rise forecasts, it was clear that the risk exposure for the MTA and its impact on NYC's economy is high. The vulnerability of its various transportation systems, and of the subway in particular, to repeated, increasingly more frequent and severe storm flooding is clear. Hence, the MTA opted to devote a major portion of its current and future capital programs to reduce its flood risk exposure.

The NYCT began an inventory of openings into the belowground system that are at elevations low enough to be at risk of flooding. Because NYC and FEMA were in the process of developing new flood zone maps for the 1%/year flood (the "100-year flood"), related new base flood elevations (BFE), and a 0.2%/year flood map ("500-year flood") with its higher flood elevations recommended for critical assets, the NYCT decided not to wait for this mapping process to be completed.

After considerable evaluation of risks, costs, and benefits, it decided to adopt the NOAA SLOSH computations for storm surge elevations for a Saffir Simpson Category 2 hurricane, or more specifically its MOMS (maximum of maximum elevation for hundreds of simulations of artificial category-2 storm tracks), and then added 3 feet on top of the SLOSH Category-2 MOMS to account for sea level rise. Three feet, or 36 inches of sea level rise corresponds to a time horizon up to about the 2080s at the NPCC mid-range (25–75th percentile) SLR forecast, and to about the late 2050s for the NPCC high estimate (90th percentile) SLR forecast. This design level results, for instance, in a design elevation of 19 ft NAVD 1988 at the Battery in Lower Manhattan. In 2012, Sandy crested there at about 11.3 ft NAVD 1988. Hence, this choice is likely to provide considerable safety for about half a century, if the engineered protective measures perform as intended.

At this flood design elevation (Cat 2 + 3 ft), the NYCT has aimed at retrofitting a total of more than 3600 openings ranging from subway entrances, ventilation shafts, side walk level ventilation grates, manholes and others with about a dozen different engineered cover designs, some closing automatically and others needing prestorm deployment or activation by teams of workers to seal the openings, and elevation of grates.

This information was compiled from the following sources:

MTA. 2017. MTA climate adaptation task force resiliency report.
Accessed January 28, 2019. http://web.mta.info/sustainability/pdf/ResiliencyReport.pdf

Miura, Y. *et al.*, 2017. Vulnerabilities in New York City subway system to sea level rise and flooding. Unpublished Report for the MTA, prepared by the Columbia University Climate Change Adaptation Team (CCCART). Department of Civil Engineering, under supervision of Prof. G. Deodatis and K.H. Jacob. 16 pages, 8 figures, 5 tables. Columbia University 2017.

U.S. Department of Transportation (2018). As of December 2018, the MTA has posted a total of about $ 4.55 Billion in both Sandy recovery and resiliency capital investments combined, obtained from federal funds. Accessed January 28, 2019. https://www.transit.dot.gov/funding/grant-programs/emergency-relief-program/fta-funding-allocations-hurricane-sandy-recovery-and

Table 8.5. Illustrative and potential climate-linked critical indicators for selected climate extremes for New York City's energy sector—impacts, indicators, metrics, and data sources (electricity related to production, transmission, and distribution)

Climate extremes[a]	Potential infrastructure impacts[b]	Potential indicators[c]	Potential indicator metrics[c]	General illustrative and potential data sources[d]
Extreme heat and humidity			Production	
	– Increased user demand for and consumption of energy potentially straining capacity	1. Power outages	1.a. System Average Interruption Frequency Index (SAIFI)—# of outages per 1000 customers, adapted to incorporate climate 1.b. Customer Average Interruption Duration Index (CAIDI)—average duration of an outage in hours, adapted to incorporate climate 1.c. Number of customer hours of electric grid outages/year in all of NYC, or for a specific borough	1. NYS Public Service Commission
	– Increased potential for power interruptions	1. Power interruptions in the form of brownouts or planned voltage reductions	1.a. SAIFI and CAIDI metrics described above 1.b. Number of brownouts (voltage reductions) /customer/year 1.c. Number and frequency of voltage reductions	1. NYS Public Service Commission
	– Increase in extreme energy usage (peak load days)	1. Peak demand	1. Measures of power demand and usage as inputs into frequency of peak loading, for example, ratio of peak to average load	1. Con Edison; NY Power Authority (NYPA); NY Independent System Operator (NYISO); NYS Public Service Commission
	– Overuse and strain on equipment, materials, efficiency and performance, increasing maintenance	1. Operational issues	1. Measures of reductions in equipment design life and performance	1. Con Edison
	– Equipment damage	1. Recorded equipment outages	1. Equipment replacement rates and cost	1. Con Edison; U.S. DOE, LBNL (2018)
			Transmission/distribution	
	– Overuse and strain on equipment, materials, efficiency and performance, increasing maintenance	1. Reduction in transmission due to sag for overhead power lines	1.a. Measures of sag including proximity of transmission and distribution lines to the ground. 1.b. Percent reduction in power transmission due to sag to the extent this has not been accounted for in normal power system planning	1. Con Edison
	– Strain on equipment due to increased demand relative to capacity of transmission and distribution systems to accommodate increased capacity	1. Power outages and brownouts	1.a. System Average Interruption Frequency Index (SAIFI)—# of outages per 1000 customers, adapted to incorporate climate 1.b. Customer Average Interruption Duration Index (CAIDI)—average duration of an outage in hours, adapted to incorporate climate 1.c. Number of customer hours of electric grid outages/year in all of NYC, or for a specific borough	1. NYS Public Service Commission

Continued

Table 8.5. *Continued*

Climate extremes[a]	Potential infrastructure impacts[b]	Potential indicators[c]	Potential indicator metrics[c]	General illustrative and potential data sources[d]
Cold snaps		Production		
	– Unprotected equipment could be damaged depending on material tolerances and existence of icing conditions	1. Level and duration of equipment malfunctions from cold sensitivity 2. Reported performance decline in production 3. Equipment replacement	1. Interruptions in production processes 2. Equipment replacement rates 3. Equipment replacement rates and cost	1. NYISO 2. NYISO 3. Con Edison; U.S. DOE, LBNL (2018)
		Transmission/distribution		
	– Some transmission may be affected where unprotected equipment is damaged depending on material tolerances and existence of icing conditions	1. Level and duration of equipment malfunctions from cold sensitivity to the extent that equipment is sensitive to cold 2. Level and duration of equipment malfunctions from cold sensitivity to the extent that equipment is sensitive to cold	1. Equipment replacement rates	1. Con Edison 2. Con Edison
	– Increase in number of underground fires, manhole explosions most of which occur in winter months due to the effects of road salting	1. 311, Fire department emergency calls	1. Number of 311 and FD calls per unit time; call response rate; workers deployed for repairs (including municipal assistance teams)	1. Con Edison, NYCEM, FDNY, NYC311
Sea level rise and coastal flooding		Production		
	– Equipment damage from flooding and corrosive effects of seawater	1. Equipment damage and repair costs 2. Instances of asset damage from specific storms	1. Capital versus operations cost in retrofitting equipment 2. Number of energy assets flooded during a hurricane (e.g., Fig. 8.5)	1. Con Edison; U.S. DOE, LBNL (2018) 2. US DOE, 2013a
		Transmission/distribution		
	– Increase in number and duration of local outages from flooded and corroded equipment	1. Service disruptions 2. Flooding, debris damages, corrosion, water intrusion	1. Number and duration of facility shutdowns related to SAIFI 2.a. Number and level of business losses and their associated costs 2.b. Number and duration of service disruptions 2.c. Number and extent of disruptions to plant and facility operations 2.e. Increased capital needs for repairs 2.f. Extent and severity of environmental and public safety hazards	1. Con Edison 2. Con Edison; NYCDEP

Continued

Table 8.5. ***Continued***

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[a]Climate extremes in Table 8.5 related to transportation are as defined in NPCC3 as follows:
Extreme heat and humidity pertains to heat waves as described in Chapter 2, using the National Weather Service (NWS) definition "as three (or more) consecutive days with temperatures of at least 90°F (32.22°C)" and also considers days per year above 90°F and 100°F. Other concepts include worst daily heat-humidity combination "wet-bulb" temperature per year; Heat index: 2-consecutive days of heat index 80–105°F; Monthly and yearly degree cooling days for NYC (NYS ISO, 2017a zone J). Chapter 2 also develops definitions for heat wave frequency, duration, and intensity all of which potentially affect infrastructure.
Cold snaps as a climate extreme are defined as number of days below a threshold temperature and are reflected in the number of cooling days.
Sea level rise and coastal flooding are defined in Chapters 3 and 4.
[b]Potential infrastructure impacts and the references for each of the impacts are in general from the third column of Table 7.1a (details not repeated here), with a few differences, in order to consistently link impacts to indicators and metrics. The end of Table 7.1 provides references for impacts listed in Table 8.4 as well. As indicated in footnote (*b*) for Table 7.1a "The impacts listed here are illustrative and are not intended to be comprehensive. Non-climate–related factors in addition to climate extremes can contribute to impacts, indicators and indicator metrics listed here. More knowledge and analysis would be required to separate climate and non-climate factors." The indicators are thus labeled "potential" for consideration and review by relevant agencies. Sources that underscore this selection and also provide additional information for each impact are located in footnote (*d*) below.
[c]Metrics apply to each indicator associated with each impact (in a given row) even where multiple indicators and metrics are listed. References for indicators and metrics are contained in the chapter text, in references here, and in Chapter 7.
SAIFI, SAIDI, and CAIFI are expressed in terms of customer impacts; however, these impacts can originate across production, transmission, and/or distribution components of the electric power system. Table 8.5 references SAIFI, SAIDI, and CAIFI at all of these stages for extreme heat but are also applicable to other climate extremes. Distribution systems are likely to account for the majority of outages. However, data on how outages occur across production, transmission, and/or distribution are not available, so the indicator is cited for both the production and transmission/distribution sections. That outages are considered at least possible at the production stage is acknowledged by the NYSISO (2017b: 24) in its use of the terms "Loss of Load Expectation" and "Unplanned system outage," specifically with respect to power-generating facilities. An additional consideration is that outages at the facility level do not always translate into customer outages.
[d]For additional examples and details for potential climate-related energy impacts and indicators, see, for example:
For the U.S.: U.S. DOE. 2013a. U.S. energy sector vulnerabilities to climate change and extreme events.
https://www.energy.gov/sites/prod/files/2013/07/f2/20130710-Energy-Sector-Vulnerabilities-Report.pdf.
U.S. EPA. 2017. Climate change impacts climate impacts on energy.
https://19january2017snapshot.epa.gov/climate-impacts/climate-impacts-energy_.html.
For New York State and New York City: Various analyses and planning efforts in connection with the aftermath of Hurricane Sandy cited in Chapter 7 (e.g., the NYS 2100 Commission, City of NY SIRR, etc.).
Rosenzweig, C., W. Solecki, A. DeGaetano, *et al.* Eds. 2011. Responding to climate change in New York State: the ClimAID integrated assessment for effective climate change adaptation. Technical Report. New York State Energy Research and Development Authority, NYSERDA, Albany, NY. www.nyserda.ny.gov.
An example of these indicators in practice can be seen in Figure 8.5, where the U.S. DOE (2013a) compared damages to the number of energy assets from Hurricanes Irene and Sandy in New York.

currently conducting a climate change vulnerability study and is using the NRI model to evaluate the reliability of its networks under future climate conditions. NRI is an example of an indicator that is sensitive to extreme climate events and can be evaluated against climate projections.

A key climate-related indicator is the extent to which energy demand or usage changes in response to weather changes, in particular as the temperature warms (though energy use also goes up in cold periods as well). The NYS ISO provides forecasts of demand against which projected summer temperatures could be compared (NYS ISO, 2017a, b).

Time frames

As in the case of transportation, time periods are designated as short term, medium term, and long term. For example, climate-related impacts on energy expressed in terms of indicators over time given in Table 8.5 include:

- In the short term (2020s), temperature-related impacts and flooding could lead to disruptions of energy production, transmission, and distribution systems. These could be intermittent depending upon the length of the impacts; however, regardless of the time period, once the equipment is disabled, repairs will have to be made.

Table 8.6. Existing and recommended reliability indicators for electric distribution grids

SAIFI	Measures system-wide outage frequency for sustained outages
SAIDI	Measures annual system-wide outage frequency for sustained outages
MAIFI	Measures frequency of momentary outages. Momentary outages and the power surges associated with them can damage consumer products and hurt certain business sectors
CAIDI	Measures average duration of sustained outage per customer
CEMI-3	Measures the percentage of customers with three or more multiple outages. This metric helps to measure reliability at a customer level and can identify problems not made apparent by system-wide averages
CELID-8	Measures the percentage of customers experiencing extended outages lasting more than 8 h
Power quality	Measures for voltage dips/swells, harmonic distortions, phase imbalance, and lost phase(s)

SOURCE: Galvin Electricity Initiative 2011: Electricity Reliability; http://galvinpower.org/sites/default/files/Electricity_Reliability_031611.pdf.

- In the medium term (2050s), the impact identified in the short term could persist into the medium term, should the risk factors persist.
- In the long term (2080s, 2100, and beyond), major dislocations of energy infrastructure and population could occur, should the impacts persist over long periods of time.

Table 8.5 primarily addressed energy indicators for which data generally exist. There are a number of additional indicators that in the future potentially could be related to climate change when data become available. These have not been included in the table. Examples of potential climate change energy sector indicators are:

- Extent to which overhead line sag contributes to decreased performance of electric transmission and distribution and the occurrence of outages where decreased performance cannot accommodate existing loads (Bartos *et al.*, 2016)
- Refinement of the SAIFI indicator to explicitly include climate change above what it currently includes as weather-related effects
- Relevance of various input measures such as worker availability and the availability of materials to climate change in a way that can be related to output indicators

8.5.1 Case study 2: Energy

Following the template of the first case study, we now turn to proposing an indicator for critical infrastructure in the energy sector in response to its established vulnerability to extreme weather events. Its characteristics include:

1. *Indicator.* Power outages from extreme weather events.
2. *Purpose.* To measure the vulnerability of the electric grid to extreme weather events as climate change is likely to increase extreme events in both amplitude and frequency.
3. *Metrics.* Number of customer minutes per year with lost electric power in New York City due to extreme weather (i.e., from extreme temperature and heat waves, extreme winds, thunderstorms, inland and coastal flooding, icing, and snow).
4. *Data sources.* Media reports, Con Edison, NYS Public Service Commission, NWS, Northeast Regional Climate Center (at Cornell University).

Discussion. Potential limitations regarding power outage indicators emerge here, as well. There exist a number of standard indices used by the electric utility industry, their consultants, and by state and federal oversight agencies. Examples of recommended electric reliability indicators are shown in Table 8.6. Con Edison reports in their annually issued Sustainability Reports the SAIFI and CAIDI values. SAIFI is the yearly number of service interruptions divided by the number of customers served; CAIDI is the total customer minutes of outage divided by the total number of customers affected, averaged annually.

The lower the index, the better the performance. Con Edison reported for 2015 a SAIFI of 0.112 interruptions per customer and a CAIDI of 186 minutes per interruption per customer. By definition, the two measures do not include severe weather events resulting in customer interruptions exceeding 24 hours. Also,

Table 8.7. Con Edison outage indicators for 2008–2012

2012	2011	2010	2009	2008
0.102[a]	0.147	0.129	0.104	0.126
138.0[b]	162.6	154.2	136.2	118.2

[a]SAIFI = number of service interruptions divided by total number of customers served.
[b]CAIDI = total customer minutes of interruptions divided by total number of customers affected, i.e., the average duration of minutes for service to be restored.
NOTE: The lower the values, the higher the performance.

weather-related outages are not identical to climate related outages.[a] In order for the measures to be adaptable as climate change indicators, these dimensions would have to be added potentially in the form of new or supplemental indicators. For a Con Edison summary of these two indices for the years 2008 through 2012, see Table 8.7.

Despite the major impact of power outages in Lower Manhattan following Hurricane Sandy in October/November of 2012, neither the SAIFI nor the CAIDI shows an uptick in Table 8.7, probably since as indicated above the indicators are not incorporating major storms in which customers lose power for more than 24 hours.[b] This shows that neither indicator is sensitive to the information desired to demonstrate how vulnerable or resilient the electric grid is with respect to weather extremes, which are projected to increase in frequency and intensity with climate change. These findings are potentially also due to the fact that the data are averaged over an entire year. Another reason is that the indicators are normalized by the total number of customers affected.

8.6. Infrastructure interdependency indicators

Interdependencies among infrastructure sectors are increasingly being recognized (Rinaldi *et al.*, 2001) and are of increasing interest given their potential to escalate the consequences of climate change (see Chapter 7). U.S. federal agencies, for example, have underscored the importance of these relationships, in particular the U.S. Department of Homeland Security (2013) and the U.S. Department of Energy (2014). The U.S. DOE now conducts all-hazards infrastructure planning (including weather hazards) and has developed the concept of the energy/water nexus to reflect interconnections in those two sectors (U.S. DOE, 2014).

Some work has been emerging to quantify indicators of such interrelationships, even indirect ones. General indicator types are described in Box 8.3 and specific measures and indicators of interconnectedness are presented in Table 8.8. Infrastructure interdependency examples specific to New York City are presented in Chapter 7 as a basis for the indicators presented in this chapter.

There are caveats, however, related to the effectiveness of interdependency indicators for climate change. One caveat is the extent to which the phenomena these indicators measure fully reflect interdependencies or are related to factors other than interdependencies. A second set of caveats pertains to how transferrable and scalable they are. A third set of caveats relates to whether the interdependencies can be linked to future resilience and climate change. This last consideration is significant for the mission of the NPCC and is thus an important direction for new research.

8.6.1 Electric power and transportation interdependencies

As a foundation for developing infrastructure interdependency and dependency indicators for electric power and transportation, it is important to understand the ways in which electric power and transportation are interconnected both functionally and spatially. In order to capture interdependencies as well as dependencies, a broad view of what constitutes the two systems is needed. Examples of the functional relationships between electric power and transportation include:

[a]SAIFI and CAIDI metrics come in two forms: one version of the metric that excludes any severe weather events resulting in customer interruptions exceeding 24 h; and another version that does include the severe weather events. For a published version that includes severe weather events, see: https://www3.dps.ny.gov/W/PSCWeb.nsf/96f0fec0b45a3c6485257688006a701a/d82a200687d96d3985257687006f39ca/$FILE/Service%20Reliability%20Report%202013.pdf

[b]The New York State Public Service Commission annually publishes a report that provides SAIFI and CAIDI values that include severe weather events where customers lose power for more than 24 hours. The link is provided in the preceding footnote. Similarly, OneNYC's infrastructure chapter reports a New York City-specific CAIDI and SAIFI that includes all weather events.

Box 8.3. Types of interdependency indicators

Consumption or usage indicators pertain to dependencies and interdependencies based on the quantity one infrastructure uses of another in terms of levels or rates of use. The dependencies become interdependencies when the usage by infrastructure A affects that of infrastructure B and usage levels or rates by B then affect infrastructure A. Input–output indicators are one way of expressing consumption or exchanges among infrastructure sectors (Haimes *et al.*, 2005).

Proximity indicators can be formulated that indicate how close spatially one infrastructure or a component is to another. For example, electrical lines are often run along transportation corridors. Water supply or drainage lines are often run along bridges or overpasses. The significance is that should one infrastructure become disabled it can disrupt another one that is close by. Zimmerman (2004) conducted a study of selected infrastructure distribution lines to identify which ones tended to affect others the most, using an index constructed as the ratio of the number of times a given infrastructure affects (causes failure in) other infrastructures to the number of times that infrastructure is affected by others. She found that roads, gas lines, and electric power lines were affected by other systems more than they affect others; water lines on the other hand affected other distribution systems more than it was affected by the others.

Recovery indicators are common measures of interdependence, though indirect ones. They can be expressed in terms of how long one infrastructure takes to recover relative to another one it is dependent on for recovery. Zimmerman and Restrepo (2006) identified how long it took one infrastructure dependent on electric power to recovery after electric power was restored in the massive U.S.–Canada electric power outage in 2003. The U.S. DOE routinely uses these recovery measures for individual energy infrastructure (see, e.g., U.S. DOE, 2009).

These and other measures of interconnectedness can be applied at any scale from individual structures to neighborhoods and citywide levels depending on data availability.

Examples of these indicators are given in Appendix 8.C and Appendix 8.F.

- Electric power is used for transit signals, switches, and to provide power to trains via the third rail in the case of subways or via overhead electrical lines in the case of the commuter rail systems that connect city transit systems to the region.
- Electric power is necessary for traffic signals, signage, and lighting to ensure road safety. Electric power is used to operate the pumps that distribute fuel. This function provides fuel such as gasoline not only for vehicular travel but also to transport electric power supplies, personnel, and other resources, which in turn service transportation.
- Electric power and transportation infrastructure are often colocated or spatially contiguous. Electric power distribution lines, for example, are often located along transportation corridors such as rights of way and transportation tunnels and the transportation corridors are needed for the physical support of electric power lines.

These individual relationships between transportation components and electric power become interdependencies in the context of a larger network. As described in Chapter 7, the interdependencies are apparent when the entire transportation system is considered—both transit and road-based transportation. When electric power outages (at either distribution lines or substations) produce transit outages, transit users are likely to rely upon road-based transportation. This in turn increases congestion on those roads.

Translating this into indicators is challenging. One way is to examine relationships in terms of recovery rates along the electric power–transit, transit–roadway, and roadway–electric power linkages. This is analogous to the use of such rates by Zimmerman and Restrepo (2006).

The same effect can occur in a severe windstorm or flooding—the catenaries and pantographs can be damaged, undermining both the electric power system and transit.

An overview of the indicators for infrastructure interdependencies is provided in Table 8.8.

8.6.1 Case study 3: Transportation–energy interdependencies

The third case study explores how indicators can be derived to track how interdependencies between the

Table 8.8. Climate-linked critical indicators for energy-transportation interdependencies

Climate extremes	Indicators	Indicator metrics	Potential data sources
Extreme heat and humidity Cold snaps Sea level rise and coastal flooding	Recovery ratios comparing recovery of one indicator versus another that is dependent on the first one	Ti/Tj where T = recovery time i = first infrastructure j = second infrastructure that depends on the first one	Zimmerman and Restrepo (2006)
	Relative usage of two infrastructures by one another	Ui/Uj where U = usage or consumption i = first infrastructure j = second infrastructure that depends on the first one	U.S. DOE (2014)
	Network proximities	Betweenness Centrality correlation with extreme heat, if possible for each subway line	Wasserman and Faust (1994)
	Subway outages and electric grid problems	Number of subway outages due to electric grid problems/year; rate of subway recovery once electric power is restored; change in road congestion following restoration of transit power once transit users are able to return to transit rather than using road-based travel	NYC Transit Con Edison

energy and transportation sectors cause disruption (see Box 8.4). The indicator is power failures causing transportation disruptions, and these transportation disruptions affect the ability of electric power to recover.

1. *Indicator*. Power failures causing transportation disruptions.
2. *Purpose*. To show the dependence of transportation in the New York metropolitan region on the performance of the electric power grid and the dependence of electric power systems on transportation to move workers and supplies. Interdependencies are captured in this enlarged system that includes

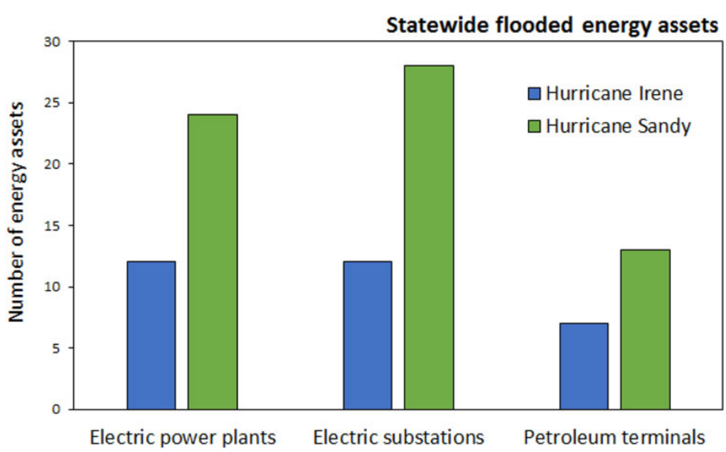

Figure 8.5. Comparative damages to energy assets in flooded areas in New York (statewide) during Hurricane Irene (2011) and Sandy (2012). *Source*: Drawn from U.S. DOE (2013a).

Box 8.4. Interdependent effects of heatwaves on electric power and transportation

Given that electrical power and transportation infrastructure are connected functionally, climate change phenomena such as increasingly frequent and intense heatwaves, heavy downpours, and coastal flooding exacerbated by sea level rise can disrupt not just one of these infrastructures but can damage the others colocated with it. One example of these interconnections is the effect of heatwaves on power systems and the consequent disruptions in rail transit that rely upon electric power.

Trains and power lines are often in close physical proximity for the provision of power for transit. One of the effects of prolonged and excessive heat is that the aerial power lines in the form of catenaries that convey power to trains via pantographs connected to the trains expand and sag and become entangled in the pantographs. A pantograph is a movable metal arm that connects to overhead electrical wires called catenaries that conveys power from those overhead lines to the trains (Dahlberg, 2006). The effect of heat on the pantograph-catenary systems, which already has some instabilities, has been reported for the rail systems that service the New York metropolitan region (FTA, 2011). Figure 8.6 shows the complex system of overhead wires (catenaries) and the pantographs that enable electric trains to function.

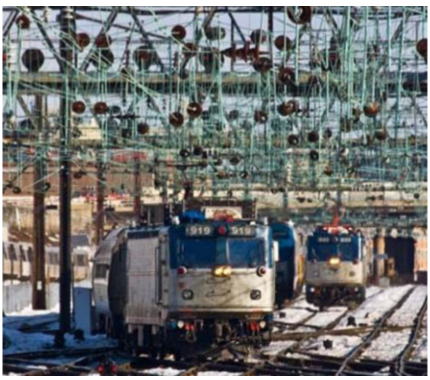

Figure 8.6. Northeast Corridor catenary & power supply systems. *Source*: http://www.nec-commission.com/cin_projects/catenary-power-supply-systems/.

not only transit and electric power for transit, but also the roadways that absorb transit riders during transit outages.

3. *Metrics.* A first level of metrics pertains to signal, switch, and third rail electric power failures expressed as subway-related power outages, delay times, or recovery times; correlation between subway-power outages and train delays or stoppages; and lighting and signal failures on roadways and pump failures at fuel dispensing stations. Each level of outage can then force users to change travel modes, and when roadway travel is chosen, road congestion can occur, and road congestion measures in terms of hours of delay and cost of delay come into play.

4. *Data Sources.* Subway (MTA), Rail (MTA, NJ Transit, NYPA, NY, etc.); Road way performance indicators (NYS DOT, NYC DOT for impacts, alerts, etc.).

Discussion. Databases related to system failures are often difficult to obtain from the relevant agencies. Further, electric power data are usually based upon customer calls, but customer calls can understate outages because customers often cannot communicate with the electric power provider due to the power outage itself. Customer calls can also overstate the outages because the same customer may call repeatedly. A customer as defined by Con Edison is not equivalent to a person but signifies a connection.

Connectivity of data sources between Con Edison and transportation owners and operators is difficult to establish. Communication is expected to be improved when advanced metering infrastructure is installed by Con Edison, which is estimated to be completed by 2022 (Con Edison, undated website; Con Edison, 2018; T&D World Magazine, 2016)

8.7. Financial and economic indicators

This section links climate change to indicators of the financial health of the city as reflected in published bond credit ratings. Section 8.7.1 speaks to the city's credit rating. The next section brings specific background and climate change to bear. Section 8.7.3 brings recent events to the discussion, including Hurricane Sandy. The final section offers suggestions about important indicators. The following section of this chapter suggests

Table 8.9. Revenue budget for NYC for two fiscal years

City funds and capital budget transfers:	FY 2016	FY 2017
General-property taxes	$24,024,997,000	$24,446,997,000
Other taxes[a]	$30,618,309,000	$30,153,735,000
Miscellaneous revenues	$6,406,641,677	$7,608,391,692
Unrestricted federal and state aid		$56,791,504
Disallowances against categorical grants	($15,000,000)	$613,000,000
Federal categorical grants	$7,672,756,307	$8,966,179,735
State categorical grants	$13,672,651,898	$14,450,399,895
Net total revenue budget	$82,115,790,244	$85,825,011,478

[a]Other taxes include *general sales taxes, personal income taxes, general corporation taxes, commercial occupancy taxes, unincorporated business taxes*, real property transfer fees, mortgage recording fees, *hotel taxes*, etc.
NOTE: Italicized revenue sources are potentially sensitive to large extreme weather events.
Source: City of New York *Expense Revenue Contract* for fiscal year 2018.

using credit rating that reflects climate risks to the calculus as an aggregate indicator of financial health for the city at large.

8.7.1. Indicators regarding the NYC bond credit rating

Credit rating entities (Standard and Poor's, Moody's, Fitch, etc.) create and report macroscale indicators of financial health and are, therefore in the converse, macroscale indicators of vulnerability. It is important to note that financial vulnerability depends on both exposure to external sources of stress and the capacity of the borrower to respond and to adapt in anticipation of future events and the stresses that might arise from variation in underlying financial stability.

Credit rating entities focus on "Key Credit Factors (KCF)." These factors are highlighted in Appendix 8.G where Panel A describes the major considerations for ratings from AAA through BBB and Panel B adds details at the KCF level. Highlighting in both panels suggests where climate change vulnerabilities might play a role in current or future credit ratings and where NYC is particularly strong.

For municipalities like NYC, major credit factors focus on sources of revenue from which funds for interest and repayment of principal are drawn, management, track record, and practices as well as liability burden and liquidity. In NYC, the revenue sources include property, sales taxes, income taxes, hotel occupancy taxes, and the like. Table 8.9 replicates a recent budget report from the city; entries highlighted with italics and underlining are potentially relevant to considerations of climate risk.

NYC has maintained an AA category since 2007, and so it has survived both Hurricane Sandy and the financial crisis of 2008–2009. However, Appendix 8.G shows that the city is vulnerable to a downgrade to an A rating in the event of significant climate change that could be construed as a source of an "adverse effect." The city issues bonds with maturities out to 30 years, and sometimes longer.

Recent history shows that concern about the current vulnerability of the city's bond rating to climate change is minimal, due in part to the city's record of strong financial management since the 1970s financial crisis. Looking into the future, some risks driven by climate change may materialize that the city will have to manage.5

8.7.2. Specific background on NYC bond credit ratings and climate change

Two of the three rating agencies that rate NYC bonds, Moody's (see Box 8.5), and Standard and Poor's have recently published reports that describe how they consider climate change in their municipal ratings (See Standard and Poors, 2015). Neither agency nor the third, Fitch, has explicit, stand-alone ratings criteria related to climate risk. Instead, the new publications from Moody's and Standard and Poor's describe how credit risk from climate change is "embedded" in their analysis of existing rating factors such as economic strength and diversity, fiscal strength and liquidity, and governance. All three rating agencies also cite the importance of federal support in disaster recovery situations.

These interpretive releases from Moody's and Standard and Poor's do not change their rating frameworks and criteria. Rating agencies generally

Box 8.5. Recent developments in climate risk and municipal bond ratings

Moody's (2017) released a publication that discusses climate risk and municipal bond ratings. In their "Sector-in-Depth" report, they report four major findings that will continue to inform their credit rating process in their summary of environmental risks. To quote from the first page:

- "Global climate change is forecast to increase the US' exposure and vulnerability to a range of factors such as severe heat, changes in precipitation patterns, and rising sea levels. . . . If federal, state and local governments do not adapt, these risks are forecast to become more severe over time. However, we anticipate that some level of adaptation and mitigation strategies will be adopted to lessen these impacts."
- "The negative economic effects of climate change vary by region. . . . The primary quantifiable impacts are damage to coastal property as a result of floods and rising sea levels . . . ."
- "Credit risks resulting from climate change are embedded in our existing approach to analyzing the key factors in our methodologies. Our analysis of economic strength and diversity, which signals the speed with which an economy may recover, captures climate-driven risks such as economic disruption, physical damage, health and public safety, and population displacement."
- "Local, state, and federal tools for both immediate response and long-term recovery enhance resilience to the physical and economic impact of extreme weather events."

This confirms the underlying consideration of climate change risks by a major rating agency. Since Hurricane Sandy, NYC has been aware of the risks described in the third bullet and has responded accordingly. With respect to the fourth bullet, NYC recognizes that responses and anticipatory planning "can" enhance resilience, but nothing is guaranteed, and negative economic effects will not necessarily be driven to zero (adaptation can "lessen" impacts from the first bullet).

The Moody's November 28, 2017 report is evidence that rating agencies generally move deliberatively and in consultation with market participants when they seek to change formal credit rating criteria and their application.

Absence from the *explicit* ratings criteria does not mean climate change cannot affect the financial health of municipal bond issuers. Climate impacts can be considered in current ratings if they manifest themselves as immediate "disaster" situations, such as Hurricane Sandy, because long-term effects of disasters may affect the local economy, demographics, and/or infrastructure needs for a long time.

The current ratings approach to climate-related disasters is based largely on assumptions about access to FEMA support and related federal assistance to fund immediate recovery and to rebuild public infrastructure, as well as the overall financial health of the government. The affected government needs to have the expertise and liquidity to manage the immediate situation and the recovery process at home; that is, it must (sometimes) be able to front the expenses that FEMA will eventually reimburse (though this may take years). Where there are good underlying credit fundamentals, there may be no impact on credit ratings from a disaster—even one as large as Sandy.

Over the longer term, though, effects of climate change could test the government's economic resiliency and its ability to finance and execute adaptive measures, especially if large storms become more frequent and perhaps more intense. This would happen even if rating agencies did not explicitly account for the climate change attribution.

For example, three 500-year floods in the Houston area over 3 years (the last of which was caused by Hurricane Harvey) and three hurricanes over 12 years have had an impact. The City of Orange, a suburb of Houston, has been placed on a watch list by S&P Global Ratings indicating that its AA-minus rating might fall due to uncertainty regarding potential deterioration in the city's tax base, financial flexibility, and liquidity available to fund expenditures related to Hurricane Harvey recovery and cleanup efforts. Rockport, another suburb of Houston, saw the eye of Harvey pass over its town hall. It is also on the watch list for its AA rating by S&P because of the risk that the city's tax base will deteriorate as well as its uncertain financial flexibility and liquidity available to fund expenditures related to Hurricane Harvey recovery and cleanup efforts.

Both findings are from *S&P Global Ratings* and were reported in The Bond Buyer by Williamson (2017). Neither explicitly speaks to climate change but adding climate change to the guidelines for assessing risk could make conclusions like these more likely because the potential of worsening futures could increase.

Table 8.10. Potential climate-linked critical credit rating indicators for New York City

Climate hazard	Generic indicator	Indicators	Indicator metrics	Potential data sources
Coastal flooding	Storm surge amplification driven by NYC-specific sea level rise (SLR)	Sea level rise and projected storm surge specific to NYC	Sea level rise and flood-plain mapping	NOAA, FEMA and *future NPCC climate science products: NPCC4, NPCC5, etc.*
	Vulnerable properties—public and private	Flooding intensity and frequency	Highway, subway, and property flooding	DoT, MTA, NYC Comptroller & *future NPCC products*
	Projected changes in hurricane frequency and intensity	Evolving science-specific to NYC	Observed frequency and intensity of east coast hurricanes possible for each subway line	Literature as assessed in *future NPCC products*

move deliberatively and in consultation with market participants when they seek to change formal credit rating criteria and their application.

End of year, Moody's, Standard and Poor's, and Fitch rating reports for New York City's General Obligation bond credit, each dated December 1, 2017, do not discuss climate change. However, given the new rating guidelines, agencies may want to pay increasing attention to how climate change can affect municipal credit, state, and local governments. That is to say, in the future, the annual rating documents could begin to focus on climate impacts. The content of these reports confirms the validity of the highlighting in Appendix 8.G.

It is more difficult to translate the possible responses of rating agencies into anticipated future credit rating adjustments because of uncertainty about the effects of climate change and adaptations to its effects, not to mention uncertainty about the cognizance of the credit rating entities of climate change possibilities. Perhaps most importantly, though, just because future climate change may be beyond the scope of current municipal bond ratings criteria does not mean that it should be beyond the scope of considerations by NYC.

8.7.3. Current financial and climate conditions in New York City

NYC's revenue sources are large and diversified. It would therefore appear that, from year to year, risk from events that can be attributed to climate change on the ability of the city to meet its financial obligations is small. The effects of such events on the tax base are difficult to anticipate, but NYC has experienced one particularly germane exposure to the potential manifestations of climate change and another severe economic event. Both have been weathered successfully—Hurricane Sandy and the financial crisis that began in late 2008.

Indicators that might influence "key credit factors" for both events—tax receipts (before and after the event) and the manifestations and duration of any necessary recovery expenditure (also indicated by tax receipts, but including up-front coverage of expenses that will be reimbursed, eventually)—show very modest variation, substantial resilience, and quick recovery. A review of major sources of income for the city (at an aggregate level) starting before Hurricane Sandy and extending beyond showed very little variance in the historical data.

8.7.4. Credit rating indicators

Risk from climate change to the credit rating is currently minimal, given how the city manages its resources—particularly given its diverse sources of revenue and its forward-looking infrastructure investment program. NYC has shown sufficient resilience to "weather stormy" financial and climatological conditions. On the climate side, a series of climate-related events could be driven by sea level rise *and* detected changes in the pattern of the intensities, frequencies, and pathways of Atlantic hurricanes born off of the western coast of Africa (see Chapter 5, Mapping Climate Risk). There are three critical indicators of potential risk to the city's credit rating that should be monitored and projected (see Table 8.10) and more focused indicators would include the more detailed suggestions in Table 8.11.

Historical data for these very specific indicators are available from a range of sources related to New York City. For example, sources such as census tracks are reported in http://furmancenter.org/floodzonedata/map. Projections may be available from those who are planning for future development. The climate connection is clear, but

Table 8.11. Potential detailed coastal flooding indicators related to New York City credit rating

1. Estimated total housing units in floodplains
2. Estimated total renter-occupied housing units in floodplains
3. Estimated share in percent of all housing units that are in floodplains
4. Estimated share in percent of floodplain housing units that are in 2+ unit buildings
5. Estimated share in percent of floodplain housing units that are located in buildings built before 1960
6. Estimated total subsidized rental housing units in floodplains
7. Estimated poverty rate in floodplains

they have not yet been quantified; and so projections into the medium- and long-term risk, in terms of likelihood, cannot be reported.

In terms of risk calculations that include both likelihood and consequence, the first two reflect ongoing challenges—the first addresses likelihood of a significant source of economic and social damage, while the second highlights consequence in terms of economic value and therefore to some degree the stability of the city's tax base. The third also incorporates likelihood, but suggests monitoring both observed data as reported by the National Weather Service and the scientific literature that links detected deviations in hurricane experience with attribution to the increases in global mean temperature.

Increases in global mean temperature also drive confirmed observations of rising sea levels around the globe and increases in the frequency and intensity of extreme precipitation, but sea level rise is amplified in New York City (see Chapter 2, Climate Science and Chapter 3, Sea Level Rise) and an impervious topography collects water in specific locations. Future iterations of the climate science chapters of future NPCC reports will be critical in tracking and reporting all of these indicators.

8.8. Indicators of aggregate economic health

Decision makers frequently ask for aggregate economic data about the potential costs of climate change. Hsiang *et al* (2017) is one of the best available examples of a rigorous analysis designed to aggregate those damages for the United States. Several observations can be drawn from their work:

1. Their estimates are based on selected available local analyses. New York City is included for coastal vulnerability for storms like Hurricane Sandy as well as more ordinary coastal storms and other extreme precipitation events.
2. Their estimates can now be tracked not only to temperature change, but also to transient damages along collections of global greenhouse emissions trajectories that are targeted, along median scenarios, to specific temperature targets like 1.5, 2.0, 2.5, and 3.0°C (Yohe, 2017).
3. Those trajectories also reflect uncertainty around transient temperature increases based on calibrations of scientific uncertainty. They can be downscaled to specific localities like NYC, and they can also be expanded to reflect noneconomic reasons for concern (like mortality driven by extreme heat).
4. Their economic estimates are dominated by rigorous but contentious estimates of the statistical value of life—a contentious concept at best.

Finally, Hsiang, *et al* (2017) confirm a conclusion that was perhaps first articulated forcefully in the contribution of Working Group II (Chapter 18 (IPCC, 2001a)) as well as both the Synthesis Report for Working Group II and the synthesis report for the IPCC Third Assessment and (IPCC, 2001b)—economic estimates are:

(1) Incomplete in their coverage of all economic sectors; and
(2) Missing the ameliorating effects of adaptation.

So they are, simultaneously, underestimates (because they miss damages) and overestimates (because they do not include adaptation). This is why most assessments, including the National Climate Assessment (NCA, 2014), and the fourth and fifth IPCC assessments (2007a, b and 2014a, b), shy away from reporting aggregate economic damages.

By way of contrast, municipal credit ratings offer gross measures of economic health and resilience on the basis of the reliability of sources of local tax revenue (the sources of revenue to pay back principle as well as annual interest obligations).

Now that credit ratings are explicitly recognizing economic risks from climate change from historical data and projections, the credit rating agencies are taking up this challenge. They are now beginning to include considerations of projected adaptations, diversification across revenue sources, and the capacity to respond to disastrous climate-driven events without facing measurable fiscal stress.

Future credit ratings may well include consideration of the complicated risks that climate change poses. These need to be included in economic measures of vulnerabilities calibrated in useful metrics that can be translated into fiscal stress on sources of bond security. The results are aggregate expressions of economic risk calibrated not by dollars directly, but by letter grades. AAA is better than AA and both are much better than BB. The economic health of NYC vis-a-vis climate-related risk is better than Houston's. It follows that simply following credit ratings for specific locations (and for specific types of projects with different time horizons) is a useful indicator of the city's financial health.

8.9. Implementation of the proposed NYCLIM

An effective, meaningful, and comprehensive city-wide response to ongoing climate change will require an operational, systematic, centralized coordination of I&M networks, climate and social scientists, stakeholders, federal, regional, and local data collection agencies and monitoring partnerships, policy makers, citizen scientists, and empowered local community people. Such an organized system of agencies, people, and resources creates a community of practice that enhances the climate resilience process, its practice, and its decisions. Proper protocols for the process of selecting and systematically monitoring of key indicators and proper protocols for resiliency and for flexible adaptation pathways may then be co-generated, implemented, and sustained. The proposed NYCLIM is envisioned to be such a system. The all-encompassing goal would be to contribute to state-of-the-art resiliency and adaptation strategies for New York City and its surrounding region.

8.10 Conclusions and recommendations

Concluding remarks are outlined below in several categories—key indicators, proposed I&M system, recommendations for policy, and recommendations for research.

8.10.a. Key indicators

After studying the transportation and energy sectors and their interdependencies as depicted in Figure 8.3, the following indicators have been identified as important in the context of climate change in regard to salience, accuracy, and accessibility.

Transportation

- Number, frequency, extent, and duration of facility and material damages to road and rail systems
- Extent and cost of service delays to road and rail users

Energy

- Magnitude of the number, frequency, geographic extent, and duration of service outages
- Extent, cost, and inconvenience of electric power service delays in terms of SAIDI and SAIFI—if they can be enhanced to reflect weather and climate-related impacts as well as to incorporate and adapt tools such as benefit and cost calculators for energy disruptions (e.g., U.S. DOE, Lawrence Berkeley National Laboratory, 2018).

Interdependencies

- Influence, in terms of likelihood and severity, of the combination of climate extremes and dependent and interdependent infrastructure connections on infrastructure services
- Calibrated risk factors and infrastructure recovery rates for dependent and interdependent infrastructures

The above list is by no means comprehensive, but it addresses those that have been most commonly identified in the extensive literature upon which Tables 8.4, 8.5, and 8.8 are based and expanded in Tables 7.1-3 in Chapter 7.

8.10.b. Proposed I&M System

1. Climate and extreme weather events are critical stressors. Their impacts upon infrastructure have commonly been identified as potential factors (see Chapter 7); however, finding performance indicators that are not

influenced by non-climate events (so-called confounding factors) can be difficult. Their influences make detection and attribution difficult and uneven. In short, attribution is now and will likely remain a significant challenge. For forward-looking adaptation, though, attribution is essential in order to address fundamental causes of risk and to refine adaptation approaches.

2. A centralized, coordinated, I&M system for NYC, where specific roles, responsibilities, and interaction or coordination are identified (as implied in the proposed NYCLIM), is essential for comprehensive, city-wide risk assessment and course-correction toward climate change adaptation and resiliency goals and targets. This recommendation for consideration is especially important for the design of short- to medium- to long-term selected investments targeted to adaptation.

   The system should incorporate a consistent set of measures in order to capture changes in climate conditions, goals, and targets over time. City government, scientists, and other interested and responsible parties are the drivers of this process.
3. An effective I&M system must be sufficiently robust and comprehensive to track key climate variables and to associate ranges of possible future states to ranges of possible adaptation strategies. The system must accommodate various options so that it can identify vulnerabilities and adaptation measures related to observed conditions and/or their projected futures.
4. Spatial and temporal-scale resolutions need to be consistent and comparable across sectors if the I&M system is to detect effectively trends and differences across sectors and to allow for qualitative and/or quantitative comparisons. That is to say, the people who accept responsibilities distributed across spatial, temporal, and actors defined in the proposed NYCLIM must be able to confer with each other using a consistent vocabulary, and the measures themselves should include those that are consistent over time.
5. The construct of three broad time horizons (see the Appendix 8.E. for details)—long term (2080s, 2100, and beyond), medium term (2050s), and short term (2020s)—and the boundaries between them have been instructive in framing risk-related indicators and their uncertainties from one application of indicators to another. The boundaries between those three periods may need adjustment in response to how the future evolves.
6. Creating a set of preliminary, co-generated decision-support indicators for the energy and transportation sectors and selected dependencies and interdependencies among infrastructure sectors has been identified as a critical element in support of the city's adaptive responses to promote resilience.
7. Key findings related to financial indicators include:
   - Credit ratings for specific locations (and for specific types of projects with different time horizons) are useful indicators, as well, because they are consistently crafted by independent experts working separately.
   - Climate vulnerability of the city's stable AA credit rating is small (stable through the financial crisis and Hurricane Sandy).

8.10.c. Policy recommendations

- New York City should take on the responsibility to coordinate a climate indicator and monitoring system across multiple governance entities that provides periodic analytical reports on indicator trends to aid in policy, planning, and financial decisions. The goal is to protect the region's citizens and assets under changing climate conditions. In order to accomplish this, the city should:
  - Develop and implement the proposed New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM) that defines scope, explicitly provides information on relevant spatial and temporal scales, and facilitates integration across agencies, levels of governance, sectors, and spatial and temporal scales.
  - Designate one of its agencies and an academic partner to oversee its operations (community engagement, stakeholder interactions, data collection, storage and

management, analysis, personnel and funding, etc.).
– Facilitate a co-generation process for the development and dissemination of the NYCLIM that involves community engagement and regional stakeholders through time.
– Support evaluation and iterative research on indicators and monitoring.

8.10.d. Recommendations for research

NPCC3 makes the following recommendations for continued research to improve the New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM) and address ongoing climate risks in the New York metropolitan region:

- Analyze how and to what extent indicators can be linked to current and future resilience decision making under changing climate conditions, including the increasing frequency of extreme events.
- Develop improved datasets for extreme events and system failures related to the transportation and energy sectors (and other sectors as well), and utilize multifactor analysis techniques to understand complex trends in variables that affect service provision.
- Quantify economic and/or financial impacts of climate risks for use by credit rating agencies and other third-party stakeholders.

Acknowledgments

The NPCC3 Indicators and Monitoring authors thank all the New York City agencies and regional organizations that contributed to the Indicators and Monitoring chapter.

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Appendix 8.A. Further details on stakeholder engagement and co-generation process for Chapter 8, Indicators and Monitoring, and proposed NYCLIM

The I&M Work Group held a roundtable with the CCATF on Wednesday, March 9, 2016. Twenty-seven CCATF and NPCC members participated in the workshop, as well as individuals from city agencies, including the New York City Office of Recovery and Resiliency, the Department of City Planning, and the Department of Environmental Protection. The workshop featured two of the main architects of the Indicators and Monitoring System section of the U.S. National Climate Assessment—Dr. Anthony Janetos and Dr. Melissa Kenney. Dr. Janetos led the workshop and made a presentation on "*Developing a pilot indicator system for U.S. climate changes, impacts, vulnerabilities, and responses.*" From this roundtable, a list of resiliency indicators already being tracked by stakeholder attendees was developed. A key action item from the roundtable was to begin a "straw-man" of the pilot for a coordinated way of tracking these and other relevant indicators for the five CCATF-NPCC3 sectors.

On July 27, 2016, a joint CCATF-NPCC meeting was held. Participants included about 40 CCATF stakeholders and 13 NPCC3 members. The breakout sessions at the workshop were devoted to getting input from the CCATF members across the workgroups on their I&M needs. Stakeholders reflected on potential climate and impact indicators within each of their sectors, and notes were collected from those discussions. The main message from this joint meeting was to create a system that will allow indicators of climate change to be able to inform decision making and facilitate NPCC3 research into decision-making contexts.

Throughout the process, a plethora of iterative conversations and meetings that fostered the I&M co-generation process were held between the I&M Work Group and stakeholders. Moreover, a member of the author team who is also a member of the NPCC3 leadership regularly attended and participated in CCATF meetings. The main stakeholders involved in the co-generation process included the following: The Metropolitan Transportation Authority, The NYC Department of Transportation, The NYC Department of Environmental Protection, Port Authority of New York and New Jersey, Eastern Generation, The NYC Emergency Management Office, and The NYC Comptroller's Office.

Appendix 8.B. Short introduction to detection and attribution

In communicating degrees of certainty in the findings, the IPCC (2014a) reported a greater confidence in the projection of climate change-related phenomena than in the detection and attribution of observed impacts (see Fig. 8.B.1). Working from this conclusion, it is important to investigate two fundamental questions:

> How can confidence in projected vulnerabilities and impacts be greater than confidence in attributing what has heretofore been observed in ways that are consistent with expectations derived from statistical foundations?

> Are there characteristics of recent historical data series that portend achieving high confidence in attribution to climate change?

That is, one might expect that confidence in attribution-based projection should decrease outside the sample domain due to the inherent variability of future outcomes. Why is this not reflected in the IPCC results? It turns out that the long-term nature of adaptation and mitigation strategy planning and the requisite understanding of the underlying physical and social processes by which confidence in projections can legitimately be evaluated can illuminate the foundations of strategies for iterative risk management and that they also explain what might otherwise be viewed both as a contradiction of rigor and an obstacle for rigorous policy evaluation.

To demonstrate how confidence in projection can be higher than confidence in attribution of a detected phenomenon, it is necessary to investigate the effects of confounding factors imposed, for example, by site-specific socioeconomic development pathways in the context of climate change. These are effects that must be considered when attributing observed climate change to associated increases in risk and using that attribution to create projections into the future. They explain why the science supports attribution of the recent drought in the Southwest to anthropogenic warming, while it does not yet support a similarly conclusion for the recent California drought where diverse topography and the proximity of an ocean confound the statistics of what would seem to be a straight forward attribution. Based on a growing number of observations indicating the unequivocal nature of the observed climate warming trend, though, we should expect that the impact of climate change, and consequentially the "climate signal," would increase with time, while the impact of confounding variables like geographical characteristics could be expected to remain static or at least trend less significantly. As a result, the relative strength of the climate change signal can be enhanced over time and explain the underlying foundation of the Figure 8.B.1 results.

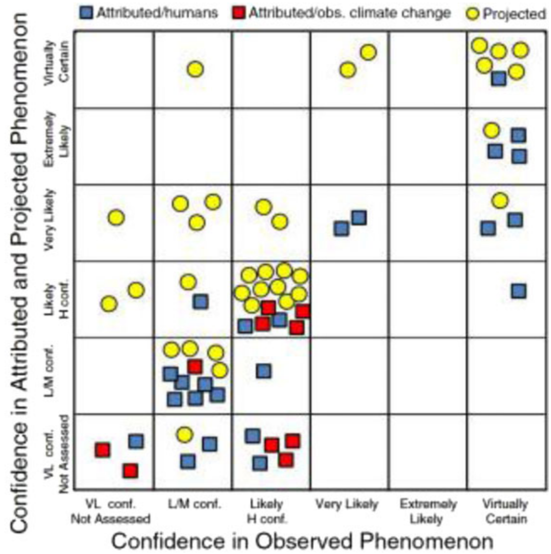

Figure 8.B.1. Higher confidence in projected outcomes versus observed outcomes. *Source*: Figures 1–6 with reference to Tables 1 and 2 in Burkett *et al.* (2014).

Appendix 8.C. Catalogs of existing indicators of climate change

Table 8.C.1. A sample of indicators from U.S. Federal agencies and administrations

Environmental Protection Agency (EPA) climate indicators	
Source: https://www.epa.gov/climate-indicators.	
Indicator	
Emissions	
GHG emissions by type (gT;CO2e)	National and Global since 199 (X)
GHG emissions and sinks (gT;CO2e) by sector by sector	National and Global since 1990 (X)
GHG emissions per capita (gT;CO2e/pop)	National since 1990 (X)
GHG emissions per dollar (gT;CO2e/$)	National since 1990 (X)
Weather and climate	
Average temperature (°C)[a]	48 states and Global since 1990 (X)
Heat wave index (index #)[a]	National since 1890 (X)
Area of very hot summers (km^2)[a]	48 states since 1910 (X)
Area of very cold winters (km^2)[a]	48 states since 1948 (X)
Change in very hot summers[a]	48 states 1948–2015 (X)
Change in very cold winters[a]	48 states 1950–2015 (X)
Precipitation[a]	48 states since 1901 (X)
Change in precipitation[a]	48 states and Global since 1901 (X)
Extreme 1-day precipitation (# days)[a]	48 states since 1901 (X)
Unusually high precipitation[a]	48 states since 1895 (X)
Hurricanes and cyclone (power indices)	North Atlantic since 1860 (X)
Change in riverine flooding:	National 1965–2015 (X)
Change in magnitude[a]	National 1965–2015 (X)
Change in frequency[a]	National 1965–2015 (X)
Average drought conditions (PDSI)	48 states since 1890 (X)
Land under drought with five severity levels	National and Southwest since 2000 (X;Y) X
Health	
Heat-related deaths (# days)[a]	National since 1978 (X)
Summer deaths - heat and cardiovascular (#)	National & Chicago since 1999 abd 1995 (X)
Heating and cooling degree days (#)[a]	National since 1890 (X)
Change in heating (# degree days)[a]	National since 1895 (X) 1895–1954
Change in cooling (# degree days)[a]	National since 1955 (X)
Lyme disease (# cases per year)[a]	National since 1990 (X)
Change in Lyme incidence (# cases)[a]	Northeast to Minnesota 1991–2015 (X;Y) Minnesota
Change in Lyme incidence (# cases)[a]	Selected sites 1996 & 2015 (X;Y)
West Nile virus dispersion (# cases)[a]	National since 2000 (X)
Length of growing season (# days)	48 states since 1890 (X)
Change in season length (# days)	48 states 1895–2015 (X)
Change in first frost (# days)	48 states 1895–2015 (X)
Change in last frost (# days)	48 states 1895–2015 (X)

Continued

Table 8.C.1. *Continued*

Oceans	
Land lost (km^2)	East coast since 1996 (X;Y)
Change in frequency of coastal flooding[a]	National 2010–2015 (X:Y)
Arctic sea ice (km^2)	Arctic Ocean since 1975 (X;Y)
Lake ice (km^2)	Selected locations since 1840 (X;Y)
Ice thawing date (# days)	48 states since 1905 (X;Y)
National Oceanographic and Atmospheric Administration (NOAA) climate indicators	
Source: https://www.ncdc.noaa.gov.	
Indicator	
National temperature index	National (X;Y;Z)
Climate rankings	Global, national, regional (X;Y;Z)
Temperature (degrees C)[a]	(X;Y)
Precipitation (versus average)[a]	(X;Y)
Degree days (degree days)	(X;Y)
Palmer drought index	(X;Y)
Extremes:	Global down to U.S. cities (X;Y;Z)
Climate extremes index	
Very cold/hot (mean max and min) (degrees C)[a]	
Very wet/dry (mean max and min) (versus average)[a]	
Societal impacts:	Global down to U.S. cities (X;Y;Z)
Crop moisture (index #)	
Energy demand (index #)[a]	
Air stagnation (index #)	
Wind (mean monthly m/s)[a]	
Wildfires (# and total acres)	
Heat stress (index #)[a]	
$1b climate disasters (#)[a]	1980–2017 (X;Y;Z)
Hurricanes (#/year)[a]	
Tornadoes (#/year)	
Other:	
Sea level rise (mm/year)[a]	Local, national, global (X;Y;Z)
Arctic sea ice (km^2 in April)	(X;Y;Z)
Snow cover (km^2 in April)	Local, national, global (X;Y;Z)
Sea surface temperature (degrees C)	Global, regional (X;Y;Z)
ENSO, NAO, PDO, PNA[a] (indices)	Global, national, regional (X;Y;Z)
United States Global Change Research Program (USGCRP) climate indicators	
Source: https://globalchange.gov/explore/indicators.	
Indicator	
Frost free season *(difference from average # days)*	National average for 30 years (X)
Annual GHG index	Global since 1980 (X)
Arctic sea ice *(km^2)*[a]	Arctic Ocean (September since 1979 (X;Y) since 1979
Atmospheric CO_2 *(ppm CO2e)*	Global since 1980 (X)
Average surface temperature (degrees C)	Global since 1980 (X)
Start of spring (difference from average (# days)	48 states since 1900 (X)
Annual terrestrial carbon storage (Gt C)	48 states since 2004 (X)

[a]The denotation of indicators that are relevant to urban resilience at a local scale; these provide at least a larger scale context with which local indicators must be consistent.

NOTE: Parenthetical notation reflects the character of the content of the files according to: "Historical Data" by X, "Graphical Plots" by Y, and Geographical Maps" by Z).

Table 8.C.2. Other climate indicators related to infrastructure. National Academies (2016)

Indicator	Metric and units	Geographic Scope[a]/NYC values (bold, underlined)	Historical/time period (based on time indicated in table or refs.)
Environmental[a] (National Academies, 2016: pp. 154–156)			
Air quality	NAAQS $PM_{2.5}$ ppm	**10.8**	2011
	Air Quality Index (U.S. EPA)	**366**	2012
	Total days	**130**	
	#days exceeding good	**214**	
	moderate	**150**	
	maximum	**55**	
	Median days		
Greenhouse gas emissions (CO_2)		SMA	2010
Residential[a]	CO_2 per capita	**1.8**	
commercial[a]	per GDP	**0.01**	
industrial[a]	per GDP	**NA**	
Water quality	Number of impaired waterways	State only 1543	2012
Hydrology			
Precipitation[a] (average annual)	Inches/year	**46.23**	2016
Landslide vulnerability	USGS index (low, medium, high)	**L**	2014
Tree coverage[a]	% land coverage by canopy	**21**	2015
Parks	Acreage/1000 resid.	**4.6**	2014
Ecological footprint	Global hectares/capita	**6.1**	
Natural hazards vulnerability	# Events 1/1/05–6/1/15	**656**	1/1/05-6/1/15
Economic[a] (National Academies, 2016: pp. 156–158)			
Employment			
% employees by U.S. Census sector	% of total employment	**Numerous 0.1–25.2%**	2014
Financial strength	Bond ratings	**AA**	2014, 2015
Median household income	Dollars	**$53,107**	2009-2013
Unemployment rate	% Census based (population > 16 years old)	**7.2**	2014
Energy (National Academies, 2016: p. 158)			
Usage rates: residential[a]	MMBtu/capita	**49.4**	2005, 2010
commercial[a]	per GDP	**0.6**	
industrial[a]	per GDP	**NA**	
Cost (residential)[a]	Ave. cents per kWh	**23.21**	2005, 2010
Disruption[a]	SAIDI	**19.0**	2011, 2013 (depending on city)

Continued

Table 8.C.2. ***Continued***

Indicator	Metric and units	Geographic Scope/NYC values (bold, underlined)	Historical/time period (based on time indicated in table or refs.)
Transportation[a] (National Academies, 2016: p. 158)			
Transportation mode	% public transportation	**58.7**	Circa 2010
Walkscore[a]	Computed—out of 100 total	**88**	NA
Usage: Road travel (United States)[a] Road travel (cities)[a]	Annual VMT, DVMT/cap	U.S. **290,116** Cities **16.3**	2012
Licenses	Licenses (driving age)/1000 drivers	**705**	2013
Travel time	Mean travel time to work (total in minutes)	**44.6**	2014
Road congestion	TTI (automobiles) Annual delay (h/commuter) Fuel excess (gals.) Cost/commuter	**74** **35**	2015
Public transportation use[a]	Average weekday ridership	**11,664**	2014
Water[a] (National Academies, 2016: p. 158)			
Total water usage Individual use	Gallons/cap/day Average gallons per capita/day	County Cities **75**	2010
Social[a] (National Academies, 2016: pp. 158–162; 164)			
Population	Total individual population	**8,491,079**	2010
Demographics	Quantitative (not related to CO_2 without conversion)	Multiple	2010
Housing	Quantitative (not related to CO_2 without conversion)	Multiple	2010
Education	Quantitative (not related to CO_2 without conversion)	Multiple	2010
Public safety	Quantitative (not related to CO_2 without conversion)	Multiple	NA
Health	Quantitative (not related to CO_2 without conversion)	Multiple	2014

[a]Data provided for Vancouver, Los Angeles, New York, Philadelphia, Pittsburgh, Chattanooga, Grand Rapids, Cedar Rapids, Flint, and the United States; however, the indicators are applicable to any cities and data sources cover a wide variety of other cities.
NA, not available.
SOURCE: National Academies of Sciences, Engineering, and Medicine. 2016. Pathways to urban sustainability: challenges and opportunities for the United States. Washington, DC: The National Academies Press. https://www.nap.edu/catalog/23551/pathways-to-urban-sustainability-challenges-and-opportunities-for-the-united.
Summary from Appendix B: Details for urban sustainability indicators (nine cities)
NOTE: Starred indicators in bold are those extracted or summarized from NASEM (2016) most directly related to climate change; bolded and underlined values signify those specifically identified for NYC. Plots are not consistently used, however; spider diagrams are used for some of the indicators

Table 8.C.2., *Continued*
Economic Intelligence Unit (EIU)

Indicator	Metric and units	Scope NYC values (bold, underlined)	Historical/ time period
CO_2		Global—city specific	
CO_2 Intensity	Total emissions (weight[a])/GDP	**145**[c]	2002
CO_2 Emissions	Total emissions per capita	**8.6**[c]	2002
CO_2 Reduction strategy	quantitative amount of reduction achieved; Qualitative: plan assessment;	–	
ENERGY [p. 91]		Global—city specific	
Energy consumption	Gigajoules (GJ)/capita	**64.7**	2009
Energy intensity	GJ or megaJ/GDP[b]	**0.5**	2009
Renewable energy consumption	Quantitative % of energy from renewable sources (e.g., based on teraJ); Qualitative assessment		
Clean and efficient energy policies	Qualitative assessment of commitment		
Buildings[a]		Global—city specific	
Energy consumption of residential buildings	#LEED certified buildings/100,000 persons	**1.1**	2010
Energy-efficient building standards	Qualitative		
Energy-efficient building initiatives	Qualitative		
Transport[a] [p. 91][c]		Global—city specific	
Use of noncar transport	% workers using noncar modes	**37.2**	2009
Size of noncar transport network	Availability of public transport including length of system miles/miles^2	**1.8**	2009
Ave. commute time	Ave. commute time in minutes from residence to work (minutes)	**34.6**	2009
Annual vehicle revenue miles	miles/person	**68.5**	2009
Maximum public transport vehicles per square mile	Vehicles/miles^2	**44.9**	2009
Congestion reduction policies	Qualitative		
Waste and land use[a]		Global—city specific	
Municipal waste production	Total annual municipal waste per capita (collection)	–	
Waste recycling	% recycled	**30.4**	2006
Waste reduction policies	Qualitative	–	
Green land use policies	Green space as % of total area	**19.7**	2008
Water[a]		Global—city specific	
Water consumption	Ave. daily water consumption (gallons) per capita	**69.3**	2005
System leakages	% water leakage	**14.2**	2009
Wastewater system treatment	Stormwater management plan		
Water efficient and treatment policies	Qualitative		
AIR QUALITY[d] [p. 91]		Global—city specific	
Nitrogen dioxide	Emissions (in lbs)/year/person	**29**	2005
Sulfur dioxide	Emissions (in lbs)/year/person	**10**	2005
Ozone	Emissions (in lbs)/year/person	–	
Particulate matter	Emissions (in lbs)/year/person	**6**	2005
Clean air policies	Qualitative		
Environmental governance[a]		Global—city specific	
Green action plan	Qualitative		
Green management	Qualitative		
Public participation in green policy	Qualitative		
Social[a] [p. 88]			
Wealth	GDP/capita (in $s)	**56,900**	
Employment	Goods employment %	**9**	
	Service employment %	**91**	
Population density [p. 91]	Persons/sq miles	**27,666.8**	2009

[a]Weight measures vary for different continents.
[b]Base years for GDP vary, for example, for Europe, it tends to be 2000.
[c]Data are for the MSA or Metro.
[d]Data are for county.

SOURCE: Extracted from Economist Intelligence Unit (EUI). 2012. The Green City Index. A summary of the Green City Index research series. Munich, Germany: Siemens.

NOTE: The Green City Index covers the United States and Canada (27 cities), Europe (30 cities), Asia (22 cities), Latin America (17 cities), Africa (15 cities), and Australia and New Zealand (7 cities). The approximate date of the indices is 2012 though the data can range from 2000 to 2012.

Table 8.C.2., *Continued*

Dependencies and interdependencies (see following tables for examples of indicators)

1. **Recovery rates**

a. Component-specific intraenergy relationships. U.S. Department of Energy (DOE). 2009. Comparing the impacts of the 2005 and 2008 hurricanes on U.S. energy infrastructure. http://www.oe.netl.doe.gov/docs/HurricaneComp0508r2.pdf.

b. Electric power dependency-based recovery rates. Zimmerman, R. & C.E. Restrepo., 2006. The next step: quantifying infrastructure interdependencies to improve security. *Int. J. Crit. Infrastruct.* **2**: 215–230. Transportation, water, and industrial recovery rates based on dependence on electric power and relative to when power was restored after the 2003 blackout.

2. **Qualitative and quantitative interdependencies/dependencies among infrastructure sectors**

a. Production/consumption-based interconnections (between water and energy)

U.S. DOE. 2014. The water–energy nexus: challenges and opportunities. Washington, DC: U.S. DOE.

b. Input–output (expressed as material flows and value in dollars)

Example: Haimes *et al.*, 2005. Inoperability input–output model for interdependent infrastructure sectors. I: theory and methodology. *J. Infrastruct. Syst.* **11**: 67–79.

c. Network-based quantifications

Apostolakis, G.E. & D.M. Lemon., 2005. A screening methodology for the identification and ranking of infrastructure vulnerabilities due to terrorism. *Risk Anal.* **25**: 361–376.

d. Interrelationships identified

Zimmerman, R. & C.E. Restrepo., 2009. Analyzing cascading effects within infrastructure sectors for consequence reduction. In *Proceedings of the HST 2009 IEEE Conference on Technologies for Homeland Security*, Waltham, MA, pp. 165–170. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber = 05168004 Provides a table of interdependencies (qualitative) (see below); used in the U.S. DHS (2015) Energy Sector Specific Plan.

3. **Effects based on physical proximity**

a. Rinaldi, S., J. Peerenboom, T. Kelly. 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Contr. Syst. Magazine* **21**: 11–25.

b. Zimmerman, R., 2004. Decision-making and the vulnerability of critical infrastructure. In *Proceedings of IEEE International Conference on Systems, Man and Cybernetics, SMC 2004.* W. Thissen, P. Wieringa, M. Pantic & M. Ludema, Eds.: 4059—4063, Volume 5. The Hague, The Netherlands: Delft University of Technology. Case-based study of transportation, energy and water distribution system dependencies.

Table 8.C.2., *Continued*
Recovery rates, interconnections, and physical effects

Indicator	Metric	Geographic scope	Historical/time period	Types of infrastructure
1. Recovery rates				
a. U.S. Department of Energy (2009)	Time in days for restoration of key energy infrastructure after the 2005 and 2008 Hurricanes	National		Energy and water
b. Zimmerman and Restrepo (2006)	Recovery time of one infrastructure relative to another as: Ti/Te Ti = sector recovery time Te = energy recovery time	National (selected places)	2003 Electric power outage	Electric power; transportation (transit, road, air) and manufacturing
2. Quantitative and qualitative interconnections				
a. Component-specific links				
U.S. Department of Energy (2014)	Water for energy (by use category) Numerous quantitative measures (to be itemized)			Energy Water
U.S. Department of Energy (2014)	Energy for water (by use category) Numerous quantitative measures (to be itemized)			Energy Water
b. Input–output				
Haimes *et al.* (2005)	I/O relationships for $ exchanges among sectors	Industry level, United States		Numerous (based on I/O)
c. Network-based				
Apostalakis and Lemon	Network connection measures	Industry level		Energy and water subsectors
d. Identification of interconnections				
Zimmerman and Restrepo (2009)	Qualitative			
3. Quantitative effects based on physical proximity				
a. Rinaldi *et al.* (2001)	Qualitative	–		
b. Zimmerman (2004)	Count of times one distribution disables another and direction	National—case based (80 cases)		

Sectors generating and receiving service from another sector

Sector generating the service to another (receiving) sector	Sector receiving the service Energy: oil and gas	Energy: electricity	Transportation	Water	Communications
Energy: oil and gas		Fuel to operate power plant motors and generators	Fuel to operate transport vehicles	Fuel to operate pumps and treatment	Fuel to maintain temperatures for equipment; fuel for backup power
Energy: electricity	Electricity for extraction and transport (pumps and generators)		Power for overhead transit lines	Electric power to operate pumps and treatment	Energy to run cell towers and other transmission equipment
Transportation	Delivery of supplies and workers	Delivery of supplies and workers		Delivery of supplies and workers	Delivery of supplies and workers
Water	Production water	Cooling and production water	Water for vehicular operation; cleaning		Water for equipment and cleaning
Communications	Breakage and leak detection and remote control of operations	Detection and maintenance of operations and electric transmission	Identification and location of disabled vehicles, rails, and roads; the provision of user service information	Detection and control of water supply and quality	

Source: Zimmerman, R. & C.E. Restrepo., 2009. Analyzing cascading effects within infrastructure sectors for consequence reduction. In *Proceedings of the HST 2009 IEEE Conference on Technologies for Homeland Security*, Waltham, MA, pp. 165–170. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber = 05168004. This table was used in the U.S. DHS (2015) Energy Sector-Specific Plan.

Appendix 8.D. Matrix to organize information that defines an indicator

Figure 8.D.1 displays a matrix structure through which this information can be displayed coherently and by which existing gaps in coverage can be discovered. This sample matrix shows how complex the task is to pursue the development of valid and purposeful indicators if executed in a rigorous way. Figure 8.D.1 illustrates the complexities that ideally need consideration when devising indicators, with an example for just one of the infrastructure systems (in this case, the electric energy grid).

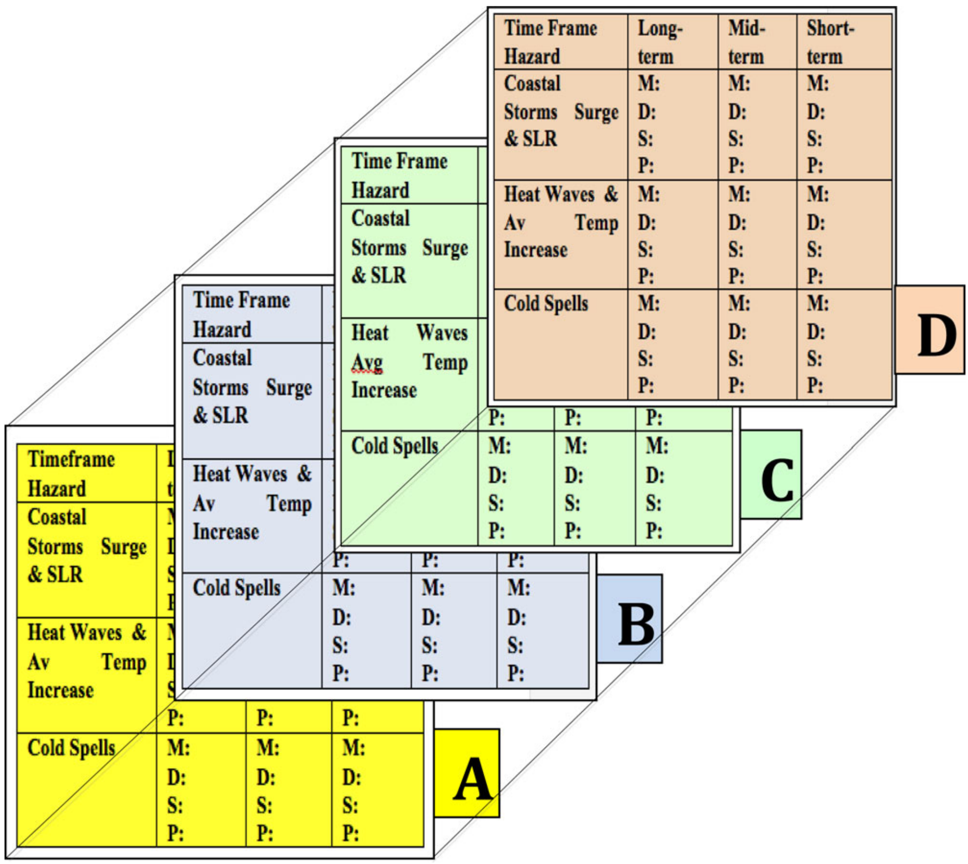

Figure 8.D.1. The matrix template for organizing information.

Figure 8.D.1 *Legend*: This 3-D generic matrix for indicators may apply, for instance, to the electric power grid. Indicators for **A**: Climate Extreme, for example for Weather Extremes; **B**: Impact; **C**: Vulnerability **D**: Resilience. In each of these four indicator planes, there are (for energy) three hazards considered (storms, heat waves, and cold spells), and for the three time horizons (short, medium, and long term). Each individual indicator (boxes) has four Attributes: **P = Purpose** (what is attempted to be achieved when using this indicator); **M = Measurement** (what variable or quantity is measured); **D = Definition** (provides exact metrics and applicable location where necessary); and **S = Data Source** (agency, differentiates between verified or expected).

There are intended to be four designated indicators A through D for each infrastructure type (climate, impacts, vulnerability, and resilience; they were earlier listed in Section XYZ); there are three time horizons (short, medium, long); 3 hazard types (storms/SLR, heat, cold spells); and for each indicator, four attributes need to be defined (purpose, definition, metrics, source). If each indicator element were to be fully realized, this implies, that a combination of at least 4 × 3 × 3 × 4 = 144 indicator elements would have to be provided, for a total of 36 indicators per infrastructure. That puts extraordinary demands not only on the efforts for developing the indicators, but also, in the future, to maintain and update them. If rigor were the objective, lesser effort may weaken the indicator's credibility and therefore utility. But in reality, striding for perfection is the death of progress, and hence the matrix elements may not all be provided with valid information. The matrix—for all practical matter—will remain an often sparsely filled one. In some instances, the matrix elements may be filled as time progresses.

Appendix 8.E. Spectrum of time frames

Our approach, and our applications to sectoral case studies, emphasizes that time frame is a critical factor in all I&M efforts for climate extremes, but perhaps most emphatically in the beginning step—characterizing the climate sequentially across a dynamic future while anchoring projections of the future onto historical data. We have noticed that stakeholders look at time from the shortest time frame (the immediate scale) to the longest. We begin with this pragmatic perspective, but we also move in a second section of this Appendix to consider time in the opposite direction; our point is to highlight how the general purpose of an indicator may be extended across multiple time scales based on the long-term distributions being offered by the scientific community—thus the necessity of also working backward.

8.E.1 Time scales calibrated from now to the beginning of the next century

8.E.1.a. Short term (2020s). I&M activities in the short term have emerged in two sub-scales: immediate and short term. One, characterized here as the "immediate-scale," refers to observed risks to which the administration of the city responds on a routine, largely operational basis to maintain a "societal level of acceptable risk" (see NPCC1), in general, and to ameliorate demonstrative impacts on the consequence side of the risk calculation, in the specific. The city already monitors indicators of the critical variables that trigger well-established responses to well-understood sources of social and economic vulnerability. They are generally urgently implemented in a reactive mode (though sometimes with some anticipation in cases where decision protocols are informed by one or more strong, process-based forward-predictive indicators). Issuing evacuation advisories for neighborhoods while a hurricane of a forecasted strength approaches the city and poses anticipated coastal storm surge flood risks within 8 h is a classic example, here.

In practice, the drivers of such a harmful event are monitored; if a change is detected, established protocols enable the city to respond almost immediately as a matter of course. City residents have already factored this reactive foundation of a dynamic safety net into their daily lives, so they know what to expect and how to respond. NPCC1 showed explicitly that the city and its various departments

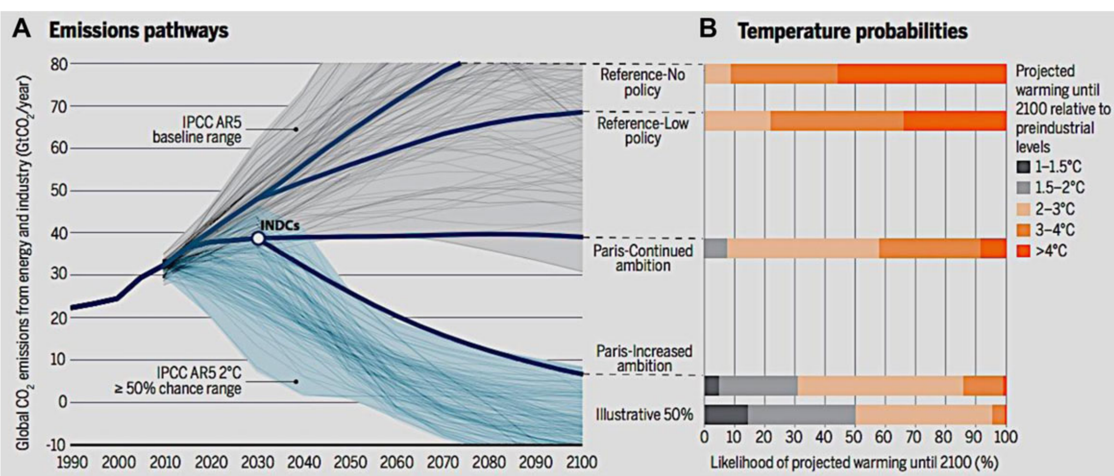

Figure 8.E.1. CO_2 emissions scenarios and associate temperature distributions for the year 2100 under five alternative policy scenarios. *Source*: Fawcett *et al.* (2015).

Box 8.E.1. Annual likelihoods of experiencing 95th percentile or anomalous summer heat (relative to the 1971 through 2000 historical record) during the summer months in New York City

Working from the median "no-policy" baseline trajectory in Fawcett *et al* (2015, Fig. 8.E.1.) brings global emissions to nearly 95 $GtCO_2$ per year by the end of the century. It is defined by two boundary conditions. For 2010, annual global emissions begin around 30 $GtCO_2$ and grow initially at approximately 6% per year. Emissions reach 95 $GtCO_2$ by 2100 because the rate of growth depreciates by 0.5% per year.

Corresponding transient temperature trajectories can be calculated from a linear relationship between contemporaneous cumulative emissions and transient temperature reported in NRC (2010, pages 102–103 and Fig. 4.9): 1.75 °C per 1000 GtC is the median estimate. Higher and lower trajectories, here, are driven by uncertainty around the behavior of sinks in higher temperatures and around the sensitivity of the climate to external forcing: the 95th percentile temperature for any emissions total is 70% above the temperature associated with median, and the 5th percentile temperature is 40% below the median.

Constrained emissions pathways through 2100 can be anchored, for example, by two trajectories that limit the *median* estimated increases in transient temperature to 1.5 °C and 2.0 °C above preindustrial levels (2.7°F and 3.6°F; see Yohe, 2017). They are "ideal" and comparable in the sense that each of them reduces emissions over time so as to maximize the discounted logarithmic-derived utility generated by emissions through 2100. That is to say, they solve two parallel Hotelling-style exhaustible resource problems where cumulative emissions constraints derived from NRC (2010) serve as operating "supply" constraints on total emissions for the two temperature targets: 1715 and 2575 $GtCO_2$, respectively. The Hotelling results, with logarithmic utility, mean that emissions face downward exponential pressure relative to the initial 6% annual growth at a rate equal to the associated utility discount factor for each target.

Anticipated changes in the likelihood of experiencing the anomaly or 95th percentile summer heat *every year* are derived from NRC (2010, page 102). For reference, #ONENYC reports an average of two prolonged heat waves per year during the baseline observation period (1971–2000); NPCC portrays a plus or minus 2 range in that estimate around that mean for the same historical period (see Chapter 2 Climate Science). The anomaly from 1971 through 2100 represents the warmest average summer temperature calibrated from June 1st through August 31st; the 95th percentile represents the average summer temperature for the second warmest summer over the same time period. Reported projections for *each year* are calibrated along alternative emissions trajectories in terms of the likelihood that the average summer temperature will exceed the temperatures of anomalous year or the 95th percentile year. For 1.8, 2.8, and 3.8 degree Centigrade increases in the global mean temperature (3.2°F, 5.0°F, and 6.8°F), these likelihoods for the 95th percentile temperature are 80% (plus or minus 10%) for 1.8 degrees C (3.2°F) of global warming and 95% (plus or minus 5%) for 2.8 and 3.8 degrees C (5.0°F and 6.8°F), respectively; for the anomalous temperature maximum, they are 30% (plus or minus 20%), 80% (plus or minus 10%), and 95% (plus or minus 5%) for 1.8, 2.8, and 3.8 degrees C (3.2°F, 5.0°F, and 6.8°F) of global warming, respectively.

Taking another perspective, working with the median likelihood projections for the anomalous and 95th percentile projections, results for the "no-policy" scenario in Figure 8.E.2 show that the likelihood of experiencing the anomalous hot summer *every year* climbs from less than 5% to roughly 70% at 3.25 degrees F of warming and to 95% with 5 degrees F of warming. The likelihoods of experiencing the 95th percentile summer heat *every year* are higher immediately and can reach more than 75% in either policy future. Returning to a future where mitigation is aggressive worldwide, the value of moving to a 1.5 degree C (2.7°F) temperature target compared to a 2.0 degree target (3.6°F) is available. Reductions of roughly 10 percentage points in the likelihood projections for *each year* can be expected midcentury, while reductions are in the range of 20 percentage points by 2100–not all that significant in the grand scheme of adaptation considerations when the no-policy threat is so severe.

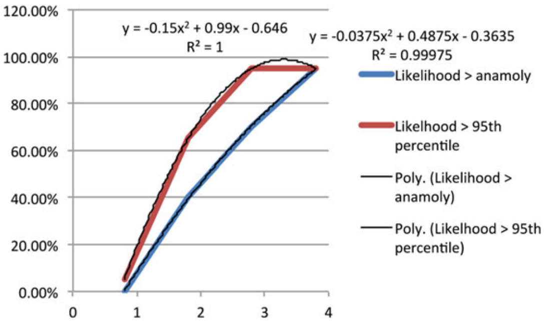

Figure 8.E.2. Likelihood of anomalous heat events in New York City along a no-policy scenario.

frequently reflect societal levels of acceptable risk into their regulations and codes to protect social capital; this cannot guarantee that a particular "bad state of nature" will never occur, but it attempts to keep the likelihood of such an event below a specified, socially tolerable threshold. Relevant social and economic indicators of vulnerability must be monitored to see that the consequences of risks are factored into adjustments to both short- and long-term response protocols. Short-term reactive processes are not an explicit charge of NPCC, but it is possible to explore how a carefully designed I&M system in the medium term and even in the long term might improve the dynamic efficacy of immediate-scale responses as acceptable risk targets become harder to maintain unless the risk exposure is lowered by adaptive measures. Also, city agencies have explicitly asked NPCC to help them assess what may be likely false alarm rates and what may be appropriate trigger thresholds for declaring weather-related emergencies since setting emergency actions into motion is associated with considerable costs, but setting trigger levels too high may cause occasional losses that could have been avoided with lower trigger levels.

The need to monitor selected social and economic indicators is only one of many reasons why the NPCC considers the lengths of time stretching to 10 years as a separate category. Another is the observation that the manifestations of climate change can emerge over periods shorter than a decade. Box 8.1 provides an urban example from outside the state. It follows that monitoring indicators that give anticipatory information about the next 10 years of variables that are critical for decision making within that time frame (and in anticipation of investments over the longer term) has enormous value (regardless of when the next 10 years start on the long calendar to 2100 and beyond). As the box shows, sea level rise impacts can, for example, range from dramatic increases in the incidence of nuisance flooding in particular locations to amplifying the intensity of more serious surge-flooding from coastal storms in those same locations in as little as 10 years.

8.E.1.b. Medium term (2050s). Monitoring indicators of climate change and vulnerability in the medium term strives to choose variables that

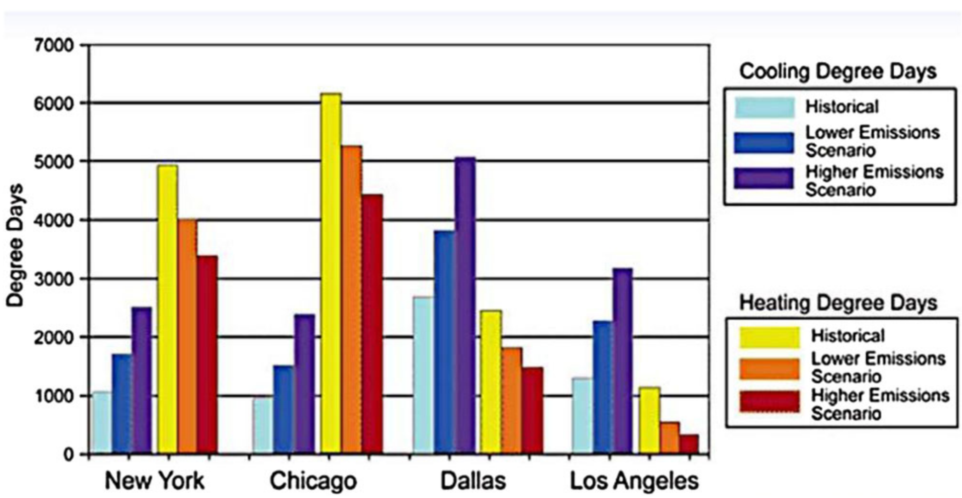

Figure 8.E.3. Changes in CDD and HDD for two emission scenarios and for four cities, including NYC, from before 2000 (historical) and the period 2080–2099. *Source*: USGCP 2009 as presented by US DOE, 2013b.

Box 8.E.2. Heating degree days and cooling degree days

The definition of heating degree days (HDDs) and cooling degree days (CDDs) as referred to in Table 8.E.1 and Table 8.E.2 is as follows: "Degree Days" are climate metrics that can be used to project the energy demand required for space heating and cooling as outdoor temperatures depart from a range of comfortable temperatures. HDD and CDD are defined as the time-integrated difference (over a month or a year) between the mean daily temperature and a reference temperature; for the latter 65°F (18 °C) is typically used in the United States. The monthly and total yearly HDDs and CDDs for New York City, as measured at La Guardia Airport, are displayed in Table 8.E.1 and Table 8.E.2, respectively, for the period 2007 through 2017. "Normal" is defined as the 30-year degree-day average value for the period 1971–2000. Note: the lower the HDD, the warmer the weather since less heating is needed; and the higher the CDD, the warmer the weather as more cooling is needed.

provide insight into which portion of the diverse range of possible long-term futures derived from extensive scenario analysis is most likely, or most extreme, or perhaps even most benign. The goal, here, is to identify and monitor indicators that serve as transparent harbingers of what should or should not be anticipated for the most critical drivers of fundamental risk analyses. Analyses can be targeted, for example, to inform the design and implementation of protective measures and/or other transient projects.

Monitoring selected indicators in the medium-term is, therefore, an exercise in looking for detectable changes in variables that can be attributed to climate change and upon which one can build robust triggers for anticipatory investment decisions—decisions for protecting existing and designing new public and private infrastructure as well as public and private property, more generally. The *Preliminary Climate Resilience Design Guidelines* issued in 2017 by the NYC Mayor's *Office of Recovery and Resilience* (ORR) provides guidance for choosing climate-resilient design parameters, approaches, and adjustments for the useful life of assets (buildings, facilities, infrastructure); see this useful lifetime is often longer than the formally assigned design lifetime. (http://www1.nyc.gov/assets/orr/images/content/header/ORR_ClimateResiliencyDesignGuidelines_PRELIMINARY_4_21_2017.pdf.

Table 8.E.1. HDD—monthly and yearly ("total") heating degree days for NYC (La Guardia) 2007–2017

	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	Normal
January	780	903	1086	1123	899	846	1081	988	1114	848	806	1008
February	614	769	1136	938	851	680	794	871	780	810	981	861
March	738	499	835	866	755	438	714	520	713	683	682	713
April	246	357	344	412	366	294	354	219	360	321	421	392
May	122	145	53	88	128	69	114	82	111	148	75	136
June	16	2	35	0	4	11	4	0	27	0	3	16
July	0	0	0	0	0	0	0	0	0	0	0	1
August	0	0	0	0	0	0	0	0	0	0	6	1
September	10	5	3	14	31	9	19	0	23	15	5	40
October	76	161	217	166	172	173	223	163	256	252	91	249
November		378	352	579	577	591	383	461	395	547	530	524
December		759	435	752	826	681	662	923	868	802	808	836
Total		3978	4496	4938	4609	3792	4288	4227	4647	4426	4408	4777

NOTE: The HDD and CDD, when monitored over sufficiently long periods, can show climate trends, which apart from temporal monthly or annual variability, shows an overall warming trend in the NYC area as demonstrated by Tables 8.4 and 8.5 and it does so in the context of energy needs for (less) heating needs in the winter and (more) cooling needs in the summer, over just this 11-year period. The lower the HDD, the warmer is the weather.

Table 8.E.2. CDD—monthly and yearly ("total") cooling degree days for NYC (La Guardia) 2007–2017

	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008	2007	Normal
January	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0
March	0	5	0	0	0	0	0	0	0	0	0	1
April	30	8	2	0	0	18	1	13	31	5	10	6
May	73	106	119	49	87	102	72	124	51	30	129	54
June	277	269	226	230	278	254	239	337	131	325	276	209
July	413	506	445	380	505	484	486	557	301	470	401	377
August	329	519	451	322	340	430	346	428	403	318	385	336
September	211	271	281	178	129	184	195	232	117	184	251	141
October	96	46	14	24	49	31	24	21	7	14	114	17
November		2	5	0	0	0	0	0	0	0	0	1
December		0	1	0	0	0	0	0	0	0	0	0
Total		1732	1544	1183	1388	1513	1363	1712	1041	1346	1566	1142

The key here can also be to identify indicators of near-term projections of climate change variables that effectively inform portraits of future conditions that are useful in designing responsive adaptation projects. These are *flexible adaptations* that can, with some notice, be adjusted over longer time frames than those considered in the short and medium terms. For example, the air-vents for the new rail tunnel under the Hudson River must be located directly over the tunnel on undeveloped property; there are only two locations that meet these criteria, and they are both near the shoreline on low land that can flood. The tidal range of the Hudson in the area is sensitive to sea level rise and thus increasing risk as the tunnel matures through its 100+ year life span. Sea level rise poses a monitorable and measureable hazard, notably as it contributes to storm tides, but the first iteration of the vents need not necessarily protect against the 2100 sea level. Designing vents to which additional height could easily be added (as needed), that is, at as yet undetermined times in the future (depending on the pace of sea level rise, and/or changes in frequency/severity of storms), could be a solution. The indicators for such projects should monitor and measure more than sea level rise; they should also be sensitive to satisfying the design and implementation needs of additional protective measures that solidify a long-term transition to new and sustainably resilient public and private infrastructure and property.

Quoting another example, the post-Sandy SIRR Report proposed, as an interim adaptation option, the installation of temporary, removable floodwalls in Red Hook, Brooklyn (SIRR, 2013, Initiative 23). It may be desirable to have an indicator that shows the annual number of deployments of such removable flood protection devices, and from that indicator infers the circumstances under which they become unreliable protective devices, or when their increasingly frequent deployment becomes operationally too costly. Collecting this information could inform a warning or monitoring mechanism designed to indicate when a longer term, permanent solution needs to be planned, designed, financed, and put into place.

8.E.1.c. Long term (2080s, 2100, and beyond). Long-term I&M anticipates, through forward-looking risk analyses across diverse scenarios, indicators that would (1) inform long-term investments; (2) inform the need to provide dynamic adaptive hedging strategies to protect those investments; and (3) consider changes in landuse and zoning, including, where appropriate, relocation to higher ground. Care must be taken, here, in considering the interdependencies across different types of infrastructure, because the most effective long-term indicators for one type of infrastructure may not include all of the indicators required and listed for another that in turn may adversely affect the initial infrastructure. The key to (1) is to identify projections of climate change indicators across multiple models and distributions so that they can be used in the initial planning and implementation stages of long-term infrastructure and property investments. For example, this may include options to finance buy-outs of flood-prone communities and provide assistance for their strategic relocation. The key to (2) is to identify sources of vulnerability for the investments along these projections, adaptive responses that could ameliorate that vulnerability, and indicators that could be tied to decision triggers as the future unfolds. The key to (3) is to find indicators and appropriate metrics that would show that engineered protection and/or accommodation of certain assets becomes ineffective, whether physically or economically, with time (i.e., due to continuing sea level rise); and that a relocation to higher ground (if and where available) becomes either unavoidable or economically advantageous. Such relocations may hinge on changes in land-use and/or zoning, and setting aside the necessary finance mechanisms. All of these measures require considerable lead times, and any indicators that serve as triggers need to account for such long lead times. For instance, London's protective Thames Barriers are assessed in the face of sea level rise to become progressively ineffective by mid-century. The responsible agencies have developed already a plan for their substitution with a new comprehensive flood management plan named Thames Estuary 2100 (TE2100; https://www.gov.uk/government/publications/thames-estuary-2100-te2100).

8.E.2. Time scales calibrated from 2100 to today

8.E.2.a. The long term (2080s, 2100, and beyond). Notwithstanding that the current policy-making focus on looking historically from today, it is essential that indicators be calibrated to projections of the future, as well; they need to be informed by the limitations of scientific knowledge that have focused attention on the year 2100 and not the decades that stretch from now until then.

We use Figure 8.E.1, extracted from Fawcett *et al.* (2015), to anchor this perspective in contemporary research. Figure 8.E.1.a (left) depicts projections of future energy and industrial CO_2 emissions from multiple models under five alternative policy regimes: a no policy reference; a reference low policy alternative; a continuation of the Paris Accord past 2030, a transition from the Paris Accord to a more aggressive global policy in 2030, and an even more aggressive policy stance that keeps the likelihood of exceeding 2 °C by 2100 below 50%. These scenarios are described in the IPCC AR5 Scenario Data Base (http://bit.ly/AR5Scenarios).

Figure 8.E.1.b (right) reflects probability distributions of temperature increases through 2100 for the five policy alternatives. Each distribution is different, and each is supported by subsets of emissions scenarios and associated temperature scenarios from roughly 2010. These subsets are typically characterized by similarities in the specification of some critical drivers of climate change (notably economic growth, economic diversification across multiple sectors, trade interdependency, and energy intensity across fossil and nonfossil sources) and the sensitivity of climate impacts to those drivers (not only temperature change). Together, they divide a complicated future into five more manageable cohorts of 80-year emissions trajectories that can be differentiated one from another not only by different policy regimes, but also by careful accounting of differences in the specifications of their underlying drivers and assumed sensitivities. From there, a wide range of other manifestations that are summarized in the IPCC "Reasons for Concern" (IPCC, 2014c) can be attached to each cohort—for example, trajectories of extreme weather, sea level rise and storm surge, increases in average temperature, heat waves, cold snaps, extreme winds, heavy rainfall, inland flooding—the climate hazards that have already been identified above for the five key sectors.

8.E.2.b. The medium term. Figure 8.E.1. is all about the long term, but the long term is nothing more than a series of distinct medium and short terms that follow one after another. Moreover, the pattern of short- and medium-term decision periods marches forward as time passes; that is, 2060 is now part of the long-term horizon, but it will be in a medium-term horizon in 2030 and a short-term horizon in 2050. These two simple observations of decision-term interdependence illuminate an advantage of approaching the time dimension of the indicator/monitoring issue from the long term very clear. Long-term trajectories characterized by specifications of underlying driving and sensitivity parameters of manageable cohorts necessarily pass through the 10- and 30-year thresholds for the other time periods, starting now and moving into the future.

Recent work in support of the Special Report on Limiting Temperature to an increase of 1.5 degrees Centigrade (2.7 degrees Fahrenheit) that is under preparation by the Intergovernmental Panel on Climate Change offers some encouraging context. Box 8.E.1 is an example from Yohe (2017); indeed, it offers insight into the incidence of extreme heat (a critical climate driver of concern for all five of the NYC key sectors) in decadal increments along two mitigation scenarios as well as a business as usual future— all portrayed in Figure 8.E.1 above from Fawcett *et al.* (2015). The decadal increments, in fact, inform not only the medium term, but also the short term and how the planet will track to reach the 2100 benchmarks.

8.E.2.c. The short term (2020s). Turning finally to the *immediate* time scale of New York City rule-of-thumb responses to observed climate-related threats. Some of the indicators that are already being monitored to inform the very short-term responses will likely match (or at least correlate well statistically) to at least some of the drivers of the longer terms described above. That is to say, the sensitivities of these "rule of thumb" indicators to climate change can be calibrated from historical data (e.g., number of heat waves per year with 3 consecutive days with average temperatures at or above 95 degrees Fahrenheit), and a link to the drivers of projected climate change can thereby be established. This link is, perhaps, one new step in the process of anchoring these indicators with characterizations of current and past conditions (including distributions of the likelihood of crossing some threshold of tolerable risk to which the city must respond). It is also the foundation of a process that can provide the city with insight into how the efficacy of their rules of thumb can be expected to evolve over time along the early parts of the alternative cohorts of long-term scenarios—valuable information in any attempt to estimate when it might be prudent to amend existing decision rules.

Melding the forward and backward perspectives, the changes in HDD and CDD have been projected for the period 2080–2099 for four major cities in the United States, located in four different climate zones, for a low emission scenario (B1) and a very high emissions scenario (A1FI), in the IPCC terminology. Note that the four cities, NYC, Chicago, Dallas, and Los Angeles, are located in four different climate zones which lead to different patterns, spatially and temporally, for the changes in HDD and CDD, as demonstrated in Figure 8.E.3. The higher the CDD, the warmer is the weather.

Appendix 8.F. Interdependency indicators

A theoretical framework that organizes thoughts around sector interdependencies is shown in Figure 8.F.1. In the figure, indicators for the energy sector (totaling n in number) are reflected as $\{E_1, \ldots E_n\}$ of which the first "E_{Ea}" are specific to energy and the remaining (n–E_{Ea} –1) are shared with the transportation sector. Indicators for the transportation sector (totaling m in number) are reflected as $\{T_1, \ldots T_m\}$ of which the first "T_{Ta}" are specific to transportation and the remaining (m–T_{Ta}–1) are shared with the energy sector. That is to say, sets $\{E_{Ea+1}, \ldots E_n\}$ and $\{T_{Ta+1}, \ldots T_m\}$ are the collections of the same indicators; they live in the intersection of the energy and transportation ovals. Other interdependence indicators are possible; they are distinct and indicated outside the intersection by $\{I_1, \ldots I_O\}$.

8.F.1. Recovery ratios (ratios of recovery rates). A common measure of interdependence and dependence is recovery rate. The indicator can be expressed as the ratio of the rate of recovery of a secondary-dependent infrastructure to the recovery of a primary or initial infrastructure that represents a first stage. This can then cycle through many stages advancing over time and in some cases, over multiple-dependent infrastructure systems.

Example: Using electric power as a starting point, a first-stage recovery ratio for NYC during the 2003 blackout, linking electric power and transit, is:

The time T_i it takes for an infrastructure dependent upon electric power to recover divided by the time T_e it takes for electric power to recover. This is illustrated for transit component recovery in NYC following the 2003 blackout (Zimmerman and Restrepo, 2006): T_i/T_e, where T_i is the time to recover for a given infrastructure, and T_e is the time for electric power to recover. The results for NYC transportation systems were as follows (Zimmerman and Restrepo, 2006):

For NYCT subway signals, the ratio is 1.3.

For NYC DOT Street Traffic signals, the ratio is 2.6.

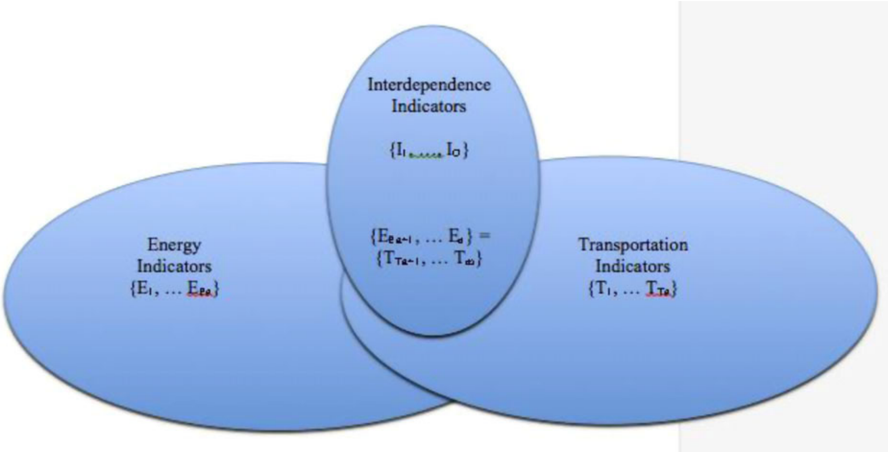

Figure 8.F.1. **A schematic diagram of indicators for the energy and transportation sectors and possible interdependences.**

The electric power to transportation linkage can become an interdependency when a failure of a transportation system can prevent electric power repair workers from getting to the damaged electric power sites in order to repair them.

Recovery times have been computed for single infrastructures following major weather events. For example for electric power following hurricanes, recovery displays distinctly different patterns for different weather events and energy components. These recovery footprints, specified at the level of energy components, were developed for example for hurricanes by the U.S. DOE (DOE, 2009, 2013a), and are a first step in formulating interdependencies.

Transit recovery following Hurricane Sandy has been documented by the MTA for each of its 25 NYCT subway lines, and appears in a couple of publications (Zimmerman, 2014; Kaufman *et al.*, 2012), and when connected to electric power outages become dependencies and interdependencies.

8.F.2. Usage rates and ratios. The extent to which one infrastructure uses the outputs of another and in turn provides inputs to the other is a measure of interdependency. These relationships at infrastructure sector levels are often displayed as "Sankey" diagrams. An example is the flow of energy sources to different sectors of the economy (USDOE, 2016; US EIA, 2013).

Across different infrastructure sectors, the U.S. Department of Energy (2014), for example, has an extensive set of quantified measures of use of water by energy and energy by water disaggregated by energy production technology.

U.S. Department of Energy (DOE) (2014). The water-energy nexus: Challenges and opportunities, Washington, DC.

For New York City, another example of usage across infrastructures exists for water and transit. For example, data exist (MTA, 2008) for the usage of water by MTA transit systems. For 2006, the MTA Commission indicated that approximately 2.6 billion gallons per year of water was used for potable purposes and another 156 million gallons per year was used for wash operations. Of those totals, NYC Transit used 1.9 billion or almost three quarters of the potable water and over 80% of the MTA wash water volumes used in that year (bus and subways combined).

8.F.3. Network characteristics. Measures of network properties are commonly applied to infrastructure components and can be extended to interdependencies.

These network measures include, for example, "betweenness" and "centrality" that measure the closeness of portions or components of systems to one another as well as the density (Wasserman and Faust, 1994).

Appendix 8.G. Credit rating supplemental material

The text below highlights factors and revenue sources that could be sensitive to large extreme weather events that could have been attributed to anthropogenic climate change, or at least, the weather manifestations of a dynamic climate. It turns out that they are not. The positive characteristics for NYC have sustained an AA rating through Hurricane Sandy and the financial crisis that began in 2008 (Source: http://www.ott.ct.gov/debt_creditratingprocess.html).; the text in ***bold italics*** highlights *positive characteristics for NYC that have sustained an AA rating through Hurricane Sandy and the financial crisis).*

(*Source*: http://www.ott.ct.gov/debt_creditratingprocess.html).

Criteria for credit ratings:

AAA (Aaa)

Bonds rated AAA have the highest ratings assigned by rating agencies. They carry the smallest degree of investment risk. Issuer's capacity to pay interest and principal is extremely strong.

AA (Aa)

Bonds rated AA are judged to be of high quality by all standards. They differ from the highest rated (AAA) bonds only in a small degree. Issuer's capacity to pay interest and principal is very strong (Optional relative standing within a rating category: +/– (Fitch Ratings, Kroll, Standard and Poor's Global Ratings); 1,2,3 (Moody's)).

A

Bonds rated A have strong capacity to pay interest and repay principal although they *are somewhat more susceptible to the adverse effects of changes in circumstances and economic conditions than bonds in higher rated categories.* (Optional relative standing within a rating category: +/– (Fitch Ratings, Kroll, Standard and Poor's Global Ratings); 1,2,3 (Moody's)).

BBB (Baa)

Bonds rated (BBB) are considered medium-grade obligations. They are neither highly protected nor poorly secured. Interest payments and principal security appear adequate for the present *but certain protective elements may be lacking or unreliable over any length of time.* These bonds lack outstanding investment characteristics and have speculative characteristics as well (Optional relative standing within a rating category: +/– (Fitch Ratings, Standard and Poor's Global Ratings);

1,2,3 (Moody's)).

More detailed elements involved in determining a credit rating

Economic Factors

Evaluation of historical and current economic factors—climatic factors projected forward could play a role, here.

Economic diversity

Response to business cycles—*and climate cycles.*

Economic restructuring

Assessing the quality of life in the given area

Debt/issue structure

Economic feasibility and need for project

Length of bonds' maturity, short-term debt financing

Pledged security and other bondholder protections

Futuristic outlook: capital improvement plan

Financial factors

Sufficient resources accumulated to meet unforeseen contingencies and liquidity requirements—climate vulnerability, especially if repeated frequently, over a short period of time.

Ongoing operations are financed with recurring revenues

Prudent investing of cash balances

Ability to meet expenditures within economic base

Management/structural factors

Organization of government and management

Taxes and tax limits

Clear delineation of financial and budgetary responsibilities

Continuing disclosure

Expanded analytical topics—investment policies and practices

Portfolio composition-credit risk, diversification, and market risk

Leverage-increase of assets to enhance yield

Liquidity management-portfolio maturity profile that matches cash flow

Infrastructure needs—significant investment to fund adaptive infrastructure could create fiscal stress.

Willingness to pay

Portfolio composition-credit risk, diversification, and market risk

Leverage-increase of assets to enhance yield

Liquidity management-portfolio maturity profile that matches cash flow

Infrastructure needs.

Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report Chapter 9: Perspectives on a City in a Changing Climate 2008–2018

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Keywords: climate projections; urban areas; impacts; regional assessment

Contents

Introduction

Cities experience multiple environmental shifts, stresses, and shocks—such as air and water pollution—and a variety of extreme events simultaneously and continuously. Current urban programs have focused on limiting the impacts of these conditions through a portfolio of multifaceted strategies, such as regulations and codes, management and restoration projects, and citizen engagement. Global climate change represents a new environmental dynamic to which cities now have to respond.

While global climate change by definition has impacts worldwide, residents and managers of cities, like New York, typically perceive changes in their own local environments. In most cities, temperature is warming with increasingly hotter and longer heatwaves, and heavier downpours are leading to more frequent inland flooding. In coastal cities, sea levels are rising, exacerbating coastal flooding.

Analyzing and understanding the impacts of climate change on cities is important because of the dramatic growth in urban populations throughout the world. An estimated nearly 4.0 billion people reside in urban areas, accounting for 52% of the world's population (UN, 2017). That percentage will increase dramatically in the coming decades as almost all of the growth to take place up to 2050 will be in urban areas (UN, 2017).

The New York City metropolitan region (NYMR)—the five boroughs (equivalent to counties) of New York City and the adjacent 26 counties in the states of New York, New Jersey, and Connecticut—is an ideal model of an urban agglomeration. Approximately 8.6 million people live in the five boroughs and more than 15 million people live in the neighboring smaller cities, towns, and villages (City of New York, 2018a; US Census, 2017). The population of the five boroughs is projected to add 1 million people by 2030, while the total region is projected to reach 26.1 million (NYTC, 2015).

The original work on science-based assessments of climate change impacts in the NYMR began with *Climate Change and A Global City: The Metropolitan East Coast Regional Assessment of Potential Climate Variability and Change* (MEC Report) (Rosenzweig and Solecki, 2001a; Rosenzweig and Solecki, 2001b); (see also, Gornitz *et al.* (2002) and Major, (2003)).[a] This foundational work laid the groundwork for a

[a]Early efforts at illustrating climate change challenges also included the Regional Plan Association's *Baked Apple* report (Hill, 1996) and the Environmental Defense Fund's *Hot Nights in the City* report (EDF, 1999).

doi: 10.1111/nyas.14017

 Ann. N.Y. Acad. Sci. 1439 (2019) 280–305

stakeholder–scientist partnership to address climate change challenges in the region.

The objective of this chapter is to situate the third report of the New York City Panel on Climate Change (NPCC3) in the context of the role of cities in responding to climate change and the history of how New York City in particular has addressed climate change since the Metropolitan East Coast Assessment published in 2001 and the founding of the NPCC in 2008 (Rosenzweig and Solecki, 2001a; Rosenzweig and Solecki, 2010; Rosenzweig and Solecki, 2015).

The NPCC process has been both evolutionary and transformative. Its antecedents emerged in the late 1990s as the question of climate change and cities became first intertwined (e.g., EDF, 1999). From early on, there was recognition that new climate science, an understanding of how urban populations are vulnerable, and of how best to respond would emerge incrementally with occasional breakthroughs of new understanding as well as via significant trial and error.

The chapter presents an analysis of the how climate trends, projections, impacts, and responses have evolved over the past 20 years for New York City and its metropolitan region, and the contributions of the NPCC in the decade since 2008. It describes how these efforts can be expanded to provide future decision makers and practitioners in the city and region with the comprehensive knowledge foundation needed to guide and implement flexible adaptation pathways centered on resilience practice.

Flexible adaptation pathways are defined as a suite of mechanisms and actions that together enable meaningful responses to current climate risk while, as much as possible, also provide opportunities for a full suite of additional actions, which could be achieved via future adjustments and shifts in policy (Yohe and Leichenko, 2010).

As Co-Chairs of the NPCC over this period, we hope to define its advances and set them within the broader frame of climate change and cities in general as well as its future. This 10-year review of progress in building a knowledge base for risk-based response and adaptation pathways in NPCC1 (Rosenzweig and Solecki, 2010), for resiliency—NPCC2 (Rosenzweig and Solecki, 2015), and now with refined tools and methods—NPCC3, defines a point of departure for future co-development of New York City's response to climate change.

9.1. Leadership role of cities

New York City has engaged with and learned from other cities that also have been actively involved with climate change analysis and action.

City-to-city interactions

One of the ways New York interacts with Boston and Philadelphia on climate change is through the Consortium for Climate Risk in the Urban Northeast (CCRUN), an NOAA-funded Regional Integrated Sciences and Assessments (RISA) project. NOAA's RISA program supports research teams that help expand and build the nation's capacity to prepare for and adapt to climate variability and change. CCRUN's geographic domain includes Pennsylvania, New Jersey, New York, Connecticut, Rhode Island, and Massachusetts, and is currently the only RISA team with a principal focus on climate change adaptation in urban settings.

New York City and Copenhagen are actively cooperating on sharing knowledge about responses to cloudbursts and heavy downpours. The NYC Department of Environmental Protection (DEP) is the lead agency on this project from New York. DEP launched the first phase of the "Cloudburst Resilience Planning Study" in 2016, based on the City of Copenhagen's Cloudburst Management Plan 2012. After a large event in Copenhagen in 2011, the city initiated 300 projects to drive storm water away from populated areas and to better manage flooding.[b]

Applying this approach to Southeastern Queens where stormwater drains southward toward Kennedy Airport and Jamaica Bay, the New York study assessed risks, prioritized responses, and developed community-based solutions for managing local cloudbursts.[c] Both cities sought to use a combination of blue-green and traditional infrastructure to manage flooding by replacing asphalt with grass to slow runoff, or by designing green spaces so that water flows into spaces where it can be stored temporarily, for instance by lowering basketball courts and playgrounds into the ground to catch rainwater. It is estimated that the total benefit of

[b]https://www.nytimes.com/2018/09/27/nyregion/new-york-flooding.html

[c]http://www.nyc.gov/html/dep/html/about_dep/cloudburst.shtml

applying Copenhagen's Cloudburst Strategy to New York is $603m USD.[d] This partnership demonstrates how international collaboration among cities, and engagement between city governments, can result in more resilient cities.

The cities of New York and London, UK have long communicated with each other regarding their response to climate change. The London Climate Change Partnership, with connection to a wide group of organizations and the Greater London Authority as lead, has produced a series of studies and reports focused on metropolitan London (London Climate Change Partnership, 2002a,b). Early on in NPCC1, representatives from London presented to the panel and shared cutting-edge climate assessment advances such as flexible adaptation pathways.

Overall, the United Kingdom central government has been a leader with respect to developing the science of assessing climate change impacts on cities, such as through the Adaptation and Resiliency in the Context of Change[e] network, which was established by the UK Climate Impacts Program. A number of regional studies have already been undertaken there. For example, the ASCCUE Project (Adaptation Strategies for Climate Change in the Urban Environment) conducted research in Manchester, England, specifically on the integrity of structures and the vulnerability of communities in the face of flooding (ASCCUE, 2003; Handley and Carter, 2006). In the Mayor's London Plan, response to climate change includes objectives for green roofs, managing flood risk, sustainable buildings, and reducing waste (Greater London Authority, 2011).

City Networks

There are several networks of cities that help to enable urban decision makers to respond to climate change in regard to both adaptation and mitigation. The C40 Cities Climate Leadership Group, established in 2005, connects about 100 of the world's cities, representing more than 550 million people and one quarter of the global economy. Created and led by cities, C40 is focused on tackling climate change and driving urban actions that reduce greenhouse gas emissions and climate risks while increasing the health, wellbeing, and economic opportunities of urban citizens.

ICLEI—Local Governments for Sustainability is a leading network of more than 1500 cities, towns, and regions committed to building a sustainable future. By helping the ICLEI network to make their cities and regions sustainable, low-carbon, resilient, biodiverse, resource-efficient, and healthy with a green economy and smart infrastructure, ICLEI impacts more than 25% of the global urban population. ICLEI's mission is to build and serve a worldwide movement of city governments to achieve tangible improvements in global sustainability, with a specific focus on addressing climate change through cumulative local actions.

The Rockefeller Foundation 100 Resilient Cities (100 RC) initiative (http://www.100resilientcities.org/) is another example of a climate change and cities network. This network was built through grants to cities to fund resiliency officer positions and conduct resiliency planning and programs. New York City is a 100RC member and through the network has been able to share advances and lessons learned with other cities.

9.2. Climate change in the New York metropolitan region

New York City is representative of the kinds of climate change challenges that may be experienced by other cities around the world, especially those located in emerging metropolitan conurbations. How the region is impacted by global climate change and how it will respond to the many-faceted challenges may be seen as a bellwether for other similar urbanized regions in both developed and developing countries.

In the New York metropolitan region, income growth has increased in recent years, and environmental threats such as the risk of hurricane damage (as clearly evidenced in the past decade), air pollution and heat stress, and water pollution persist. Although urban and suburban land uses have increased dramatically in the past several decades, approximately 60% of the land is still covered by farms and forests including the extensive NYC drinking water supply watershed region (Cox, 2014).

[d]https://www.c40.org/case_studies/cities100-new-york-city-and-copenhagen-cities-collaborating-on-climate-resilience
[e]https://www.arcc-network.org.uk/

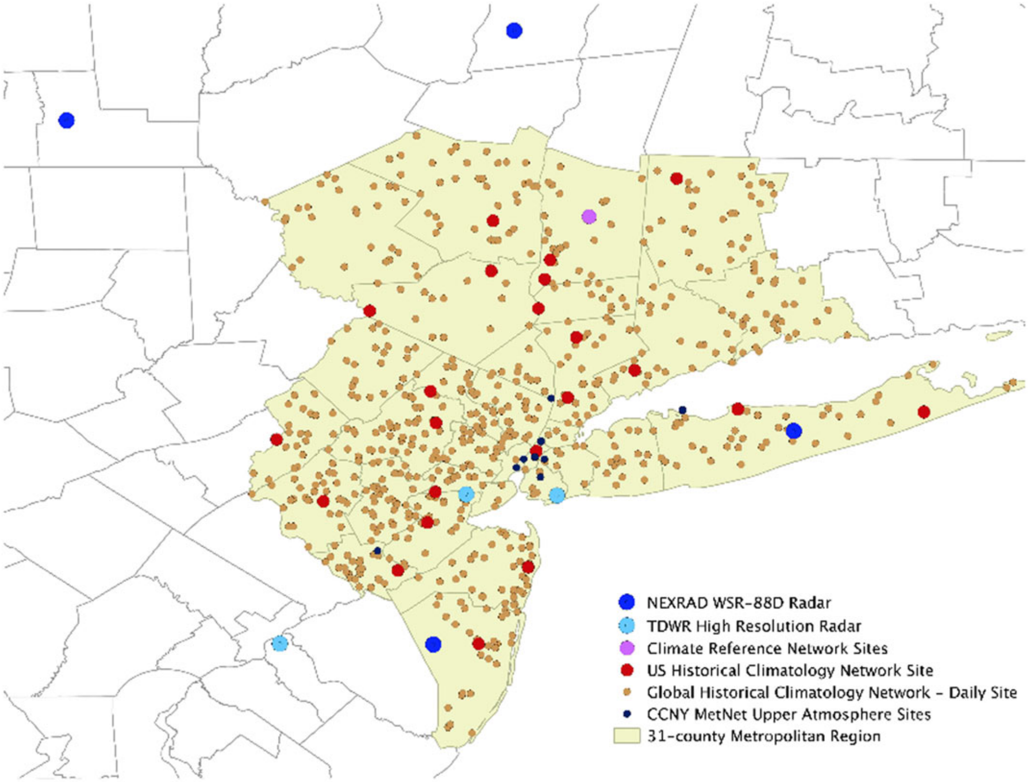

Figure 9.1. Sites important in supporting climate change monitoring in the New York Metropolitan Region. These include NOAA's Historic Climatology Network (HCN) and Climate Reference Network (USCRN), the City College of New York Upper Atmosphere Monitoring Sites, and Weather Radar Sites operated by the National Weather Service and the Federal Aviation Administration. *Image Source*: NPCC, 2015.

In the case of NYC and its history of climate change projections and assessments, stakeholders and decision makers in the region now understand climate warming as a range of diverse and interrelated impacts, as well as the need for dedicated climate change monitoring (Fig. 9.1) (see Chapter 8, Indicators and Monitoring; Solecki and Rosenzweig, 2014). This growing recognition and understanding has emerged over the past decade and an half, especially since the release of the 2001 Metropolitan East Coast Assessment report.

9.3. NPCC as an ongoing assessment process

As the MEC Report (Rosenzweig and Solecki, 2001a) concluded:

> The complex nature of potential climate change impacts in urban regions poses tremendous challenges to urban managers to respond cooperatively, flexibly, and with far longer decision-making timeframes than currently practiced. Given the already fragmented nature of urban environments and jurisdictions, the political and social responses to the global climate issue in cities should begin at once. Transforming urban management to better prepare for climate change will safeguard against negative feedbacks in the Metro East Coast Region and around the world.

An intense rain event in early August of 2007, which flooded large portions of the NYC subways followed two similar events, precipitated additional focus on climate vulnerability, impacts, and adaptation issues. Two and a half inches of rain fell in one day. This extreme event brought the potential for climate-related disruption to the attention of the city and state, as well as to the Metropolitan Transportation Authority (MTA).

The New York City Panel on Climate Change (NPCC) was commissioned by then Mayor Michael Bloomberg in August, 2008. It came shortly after the launching of the PlaNYC Sustainability Plan (City of New York, 2007). Between the end of the MEC

Assessment and the founding of NPCC in 2008, the New York City DEP actively continued to work on climate change vulnerability and impacts assessment efforts (NYC DEP, 2008). At the same time, the Mayor's office began efforts to consider climate mitigation strategies for the city as part of PlaNYC.

The NPCC initiated work in August of 2008 and released its first assessment on climate change in New York City in 2010 (referred to here as NPCC1), incorporating new methods for predicting climate changes (Rosenzweig and Solecki, 2010).

Since 2008, the NPCC has essentially functioned as a *sustained assessment* for the city and metropolitan region of New York. According to the 2014 National Climate Assessment, a sustained assessment, in addition to producing assessment reports as required by law, recognizes that the ability to understand, predict, assess, and respond to rapid changes in the global environment requires ongoing efforts to integrate new knowledge and experience (Hall *et al.*, 2014).

This is accomplished by (1) advancing the science needed to improve the assessment process and its outcomes, building associated foundational knowledge, and collecting relevant data; (2) developing targeted scientific reports and other products that respond directly to the needs of federal agencies, state and local governments, tribes, other decision makers, and end users; (3) creating a framework for continued interactions between the assessment partners and stakeholders and the scientific community; and (4) supporting the capacity of those engaged in assessment activities to maintain such interactions (Hall *et al.*, 2014).

The NPCC has provided an essential enabling condition for New York to proactively and flexibly adapt to changing climate conditions. The challenge now is to sustain this function into the future under even more challenging climate change conditions. In August 2012, the City Council of New York passed Local Law 42 that codifies the NPCC, requiring it to present updated climate risk information and communication at least once during each mayoral administration.

The NPCC released its second assessment on climate change for the City of New York in 2015, referred to here as NPCC2 (2015). NPCC2 incorporates up-to-date climate observations and projections, impacts research, and policy analysis, as well as lessons learned as a result of Hurricane Sandy in 2012.

Mayor de Blasio convened the third NPCC (NPCC3) in June, 2015. NPCC3, published in 2019, builds on the foundations of NPCC1 (2010) and NPCC2 (2015) and extends its framing and range of activities to focus on extreme events and new methods for analyzing them. Importantly, NPCC3 addresses the essential role of communities in preparing for climate change.

The NPCC, in its three iterations, has served as a knowledge provider to the Climate Change Adaptation Task Force (CCATF) that was founded at the same time. The CCATF body, also convened by the Mayor, brings together resource managers of the critical sectors in the city and region to coordinate development of resilience to climate change.

One of the main functions of the NPCC has been to develop a unified scenario process that resulted in "climate change projections of record" for the CCATF, the city more broadly, and the region to use in its resilience projects. For example, the NYC Climate Resiliency Design Guidelines[f] use the NPCC projections, and were created to help ensure that city capital projects are designed to withstand the impacts of climate change.

Over the period since its founding in 2008, three questions emerge from the NPCC assessments:

1. Have climate change projections for NYC changed over time?
2. What has the NPCC learned about observed and projected climate change impacts?
3. How do stakeholders use the evolving NPCC information?

9.4. Regional climate and projected change

To assess the impacts of climate change and to study climate–society interactions in New York City, researchers use historical climate trends, current climate extremes, and future climate change scenarios (Rosenzweig and Solecki, 2001a; Rosenzweig and Solecki, 2010; NPCC, 2015). NPCC2 found that

[f] The NYC Climate Resiliency Design Guidelines, Version 2.0, 2018, can be accessed at: https://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v2-0.pdf.

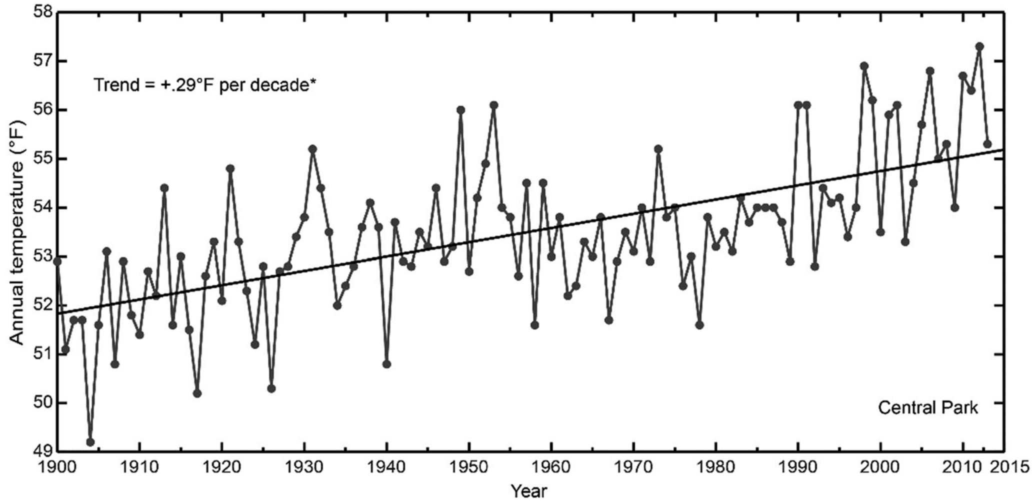

Figure 9.2a. Average annual temperature in New York City (Central Park), 1900–2013 (NPCC2, 2015).

historically, average annual temperatures in NYC have increased about 3°F (1.6 °C) between 1900 and 2013 (Fig. 9.2a). Overall, the warming has been greatest in the winter months compared to the annual average increase (Rosenzweig and Solecki, 2010; Rosenzweig *et al.*, 2011a).

Precipitation levels in the NYMR have increased by roughly 0.8 inches per decade between 1900 and 2015, with the amount of year-to-year variation greater than for the temperature data (Fig. 9.2b). According to NPCC2, the variation in precipitation has increased over the past century, especially since the 1970s, with a standard deviation of 6.1 inches in year-to-year precipitation from 1900 to 1956, increasing to 10.6 inches from 1957 to 2013 (NPCC, 2015).

Over the period of the MEC Report and the NPCC, several striking examples of climate extremes in New York City have hit the region since the late 1990s, including Hurricanes Floyd (1999), Irene (2011), and Sandy (2012). These episodes have been used as important "case studies" that presented opportunities for evaluating climate impacts and responses in the region.

For New York City, global climate models predict that climate change will bring higher temperatures

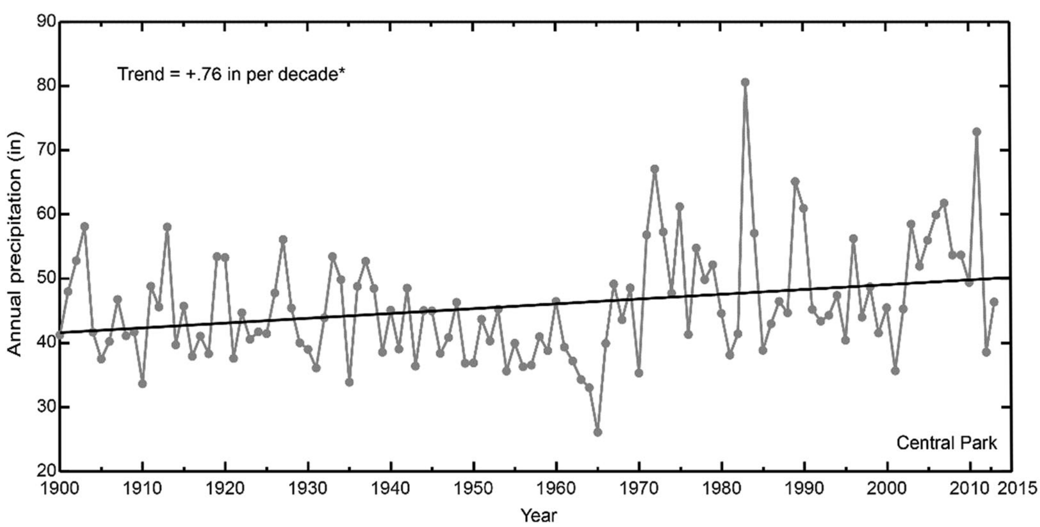

Figure 9.2b. Annual precipitation in New York City (Central Park), 1900–2013 (NPCC2, 2015).

all year long, more heat waves in the summer, rising sea levels, shorter coastal flooding recurrence periods, and inland flooding due to more frequent intense rainfall events. The number of droughts may increase by the end of the century, especially during the warm months, although drought projections are marked by a large amount of uncertainty (Shaw *et al.*, 2011). The question arises, Have these projections changed over time as new observations and models have emerged? This leads to another question: Do changes in projections make it difficult for decision makers and practitioners?

Climate scenarios

For the MEC assessment in 2001, future climate change scenarios could be viewed as "practice climates" for urban decision makers. They were defined as plausible combinations of climatic conditions that may be used to project possible climate impacts and to evaluate responses to them (Rosenzweig and Solecki, 2001a). They were a heuristic tool that began the process of social learning around the potential directional change in climate, which decision makers had previously viewed as unchanging or static.

As the NPCC advanced and uptake by NYC decision makers increased, the climate scenarios have become "projections of record" that are used as key inputs in resilience programs and projects. After the NPCC2 2015 projections were developed, the city began using them widely in resilience projects, culminating in the NYC Climate Resiliency Design Guidelines (City of New York, 2018b).

When NPCC3 began considering the development of a new set of projections to be published in 2019, discussions were held with regard to the state of the science because new scenarios for the IPCC 6th Assessment Report were not yet widely available. Further, the incorporation of the NPCC 2015 projections in resilience projects was still very much in progress. Therefore, no new climate projections were developed by NPCC for the 2019 Report. NPCC3 confirms NPCC2 projections for temperature, precipitation, and sea level changes as those of record for New York City.

NPCC climate scenarios are based on observed climate data and downscaled projections from global climate models (GCMs). Since 2001, climate change projections for New York City have been derived from evolving GCMs. They are mathematical models that simulate future temperature and precipitation changes in response to trajectories of greenhouse gas concentrations in the atmosphere, as well as trends in sulfate aerosols and other radiative forcings. Early GCMs projected climate responses at relatively coarse-scaled gridbox resolutions of $\sim 2.5^{\circ} \times 3.75^{\circ}$ lat. × long. (or $\sim 175 \times 200$ miles) (Rosenzweig and Solecki, 2001a), but these have improved over time. Since the MEC assessment, NPCC 2010 used slightly refined GCM gridbox resolutions at $\sim 160 \times 190$ miles, and more refined resolutions of $\sim 125 \times 115$ miles for NPCC 2015.

In all three of the series, projections were developed for the 2020s, the 2050s, and the 2080s, with the addition of 2100 in the most recent projections of NPCC 2015. For the first time, the NPCC3 discusses post-2100 changes, especially in regard to the potential for continuing sea level rise. The methods for projecting climate change in the NYMR over the past decade are summarized in Table 9.1.

The evolution of these projections is presented in Table 9.2 for temperature and Table 9.3 for precipitation. While the projected changes in temperature as a result of climate change have shifted slightly as methods have developed over the past decade, they are generally consistent, showing temperature change projections ranging between 4°F and 10°F for the 2080s. Precipitation changes were projected to range between –2% and 30% in the earlier MEC study, but the more recent projections by NPCC 2010 and NPCC 2015 with larger numbers of newer GCMs narrowed that range to 5–13%.

Sea level rise

The rate of sea level rise in the city since 1900 has averaged approximately 1.2 inches per decade, with some regional and temporal variation (see Chapter 3, Sea Level Rise). This rate is approximately twice the rate of the global average rise due to regional land subsidence linked to isostatic rebound of formerly glaciated land to the north of the city (Rosenzweig and Solecki, 2001a; NPCC, 2015). Climate change will exacerbate sea level rise as glacial ice continues to melt (i.e., in the Greenland and West Antarctic ice sheets), because of thermal expansion of the upper layers of the ocean, and other factors.

Methods for projecting sea level rise have become more refined over the past decade and now utilize a complex set of global and regional inputs from scientific literature, GCMs, and expert

Table 9.1. Methods for calculating New York City climate change projections from MEC, NPCC 2010, and NPCC 2015

Publication	Year	# of GCMs	Greenhouse gas emissions scenarios	Ranges presented
Metropolitan East Coast Assessment (MEC)	2001	Two GCMs	Five scenarios Current trends,[a] HCGG,[b] HCGS,[c] CCGG,[d] and CCGS[e]	Lowest to highest
New York Panel on Climate Change 2010 (NPCC 2010)	2010	16 GCMs Seven for sea level rise	Three scenarios A2,[f] A1B,[g] and B1[h]	Minimum value Central range (middle 67% of values) Maximum value Literature-based rapid Rapid ice-melt scenario (for sea level rise projections only)
New York Panel on Climate Change 2015 (NPCC 2015)	2015	35 GCMs 24 for sea level rise	Two scenarios RCP 4.5[i] and RCP 8.5[j]	Low estimate (10th percentile) Middle range (25th–75th percentile) High estimate (90th percentile)

[a]Projection of historical temperature and precipitation trends (1900–1999).
[b]Hadley Centre, with forcing from greenhouse gases.
[c]Hadley Centre, with forcing from greenhouse gases and sulfate aerosols.
[d]Canadian Centre, with forcing from greenhouse gases.
[e]Canadian Centre, with forcing from greenhouse gases and sulfate aerosols.
[f]From the IPCC Special Report on Emissions Scenarios (2000), the A2 emissions scenario assumes that relatively rapid growth and limited sharing of technological change combine to produce high greenhouse gas levels by the end of the 21st century, with emissions growing throughout the entire century.
[g]From the IPCC Special Report on Emissions Scenarios (2000), the A1B emissions scenario assumes that the effects of economic growth are partially offset by the introduction of new technologies and decrease in global population after 2050. This trajectory is associated with relatively rapid increases in greenhouse gas emissions and the highest overall CO_2 levels for the first half of the 21st century, followed by a gradual decrease in emissions after 2050.
[h]From the IPCC Special Report on Emissions Scenarios (2000), the B1 emissions scenario combines the A1 and A1B population trajectory with societal changes tending to reduce greenhouse gas emissions growth. The net result is the lowest greenhouse gas emissions of the three scenarios, with emissions beginning to decrease by 2040.
[i]From Moss *et al.* (2010), the Representative Concentration Pathway (RCP) 4.5 refers to an emissions scenario where the total concentration of carbon dioxide equivalent (CO_2e) in the global atmosphere grows to 650 ppm by 2100, and then stabilizes thereafter. RCP 4.5 is typically seen as a medium scenario.
[j]From Moss *et al.* (2010), the RCP 8.5 refers to an emissions scenario where the total concentration of CO_2e in the global atmosphere grows to greater than 1370 ppm in the year 2100, with no signal of halting growth. RCP 8.5 is typically seen as a high end—business-as-usual scenario.

elicitation. Projections for sea level rise in New York City over the past decade are summarized in Table 9.4.

As with temperature and precipitation, no new average annual sea level rise projections were developed for NPCC 2019, but an Antarctic Rapid Ice Melt (ARIM) scenario was developed to raise awareness of the growing risk at high end of the distribution. Recognizing the increasing risks from recent observations that ice melt has been occurring more quickly than previously thought (Shepherd *et al.*, 2018; Sweet *et al.*, 2017; Slangen *et al.*, 2017), the NPCC saw a need for gaining an improved understanding of the potential upper limits to global mean sea level rise by 2100 as an important scientific objective to aid in critical and long-lived infrastructure decisions. The NPCC therefore developed a high-end scenario for sea level rise incorporating the effects of rapid ice melt from the Antarctic—the ARIM scenario.

Table 9.2. Evolution of temperature projections over the 21st century for New York City from MEC, NPCC 2010, and NPCC 2015

Publication	Baseline	Range	2020s[a]	2050s[a]	2080s[a]	2100[a]
Metropolitan East Coast Assessment, 2001	50°F 1961–1990	Lowest to highest	+1.7°F–+3.5°F	+2.6°F–+6.5°F	+4.4°F–+10.2°F	–
New York Panel on Climate Change, 2010	55°F[b] 1971–2000	Minimum value	+0.5°F	+2.5°F	+3.0°F	
		Central range (middle 67%)	+1.5°F–+3.0°F	+3.0°F–+5.0°F	+4.0°F–+7.5°F	–
		Maximum value	+3.5°F	+7.5°F	+10.0°F	
New York Panel on Climate Change, 2015	54°F[b] 1971–2000	Lowest (10th percentile)	+1.5°F	+3.1°F	+3.8°F	+4.2°F
		Middle (25th–75th percentile)	+2.0°F–+2.9°F	+4.1°F–+5.7°F	+5.3°F–+8.8°F	+5.8°F–+10.4°F
		Highest (90th percentile)	+3.2°F	+6.6°F	+10.3°F	+12.1°F

[a]Temperature projections are shown for the 2020s (2010–2039), 2050s (2040–2069), 2080s (2070–2099), and 2100.
[b]Different sets of weather stations were used for NPCC 2010 and NPCC 2015, resulting in slightly difference baseline values.
NOTE: No new average annual temperature projections were developed by NPCC (2019).

Table 9.3. Evolution of precipitation projections over the 21st century for New York City from MEC, NPCC 2010, and NPCC 2015

Publication	Baseline	Range	2020s[a]	2050s[a]	2080s[a]	2100[a]
Metropolitan East Coast Assessment, 2001	46.5 inches 1961–1990	Lowest to highest	+1%–+9%	–16%–+14%	–2%–+30%	–
New York Panel on Climate Change, 2010	46.5 inches[b] 1971–2000	Lowest value	–5%	–10%	–10%	
		Central range (middle 67%)	+0%–+5%	+0%–+10%	+5%–+10%	–
		Highest value	+10%	+10%	+15%	
New York Panel on Climate Change, 2015	50.1 inches[b] 1971–2000	Lowest (10th percentile)	–1%	+1%	+2%	–6%
		Middle (25th–75th percentile)	+1%–+8%	+4%–+11%	+5%–+13%	–1%–+19%
		Highest (90th percentile)	+10%	+13%	+19%	+25%

[a]Precipitation projections are shown for the 2020s (2010–2039), 2050s (2040–2069), 2080s (2070–2099), and 2100.
[b]Different sets of weather stations were used for NPCC 2010 and NPCC 2015, resulting in slightly difference baseline values.
NOTE: No new average annual precipitation projections were developed for NPCC (2019).

Table 9.4. Evolution of sea level rise projections over the 21st century for New York City from MEC, NPCC 2010, and NPCC 2015

Publication	Baseline	Range	2020s[a]	2050s[a]	2080s[a]	2100[a]
Metropolitan East Coast Assessment, 2001	0 inches 1961–1990	Lowest to highest	5.4–9.5 inches	8.6–20.1 inches	16.7–37.5 inches	–
New York Panel on Climate Change, 2010	0 inches 2000–2004	Lowest value	1 inch	5 inches	9 inches	–
		Central range (middle 67%)	2–5 inches	7–12 inches	12–23 inches	
		Highest value	6 inches	14 inches	26 inches	
		Rapid ice-melt scenario	5–9 inches	19–29 inches	41–55 inches	
New York Panel on Climate Change, 2015	0 inches 2000–2004	Lowest (10th percentile)	2 inches	8 inches	13 inches	15 inches
		Middle (25th–75th percentile)	4–8 inches	11–21 inches	18–39 inches	22–50 inches
		Highest (90th percentile)	10 inches	30 inches	58 inches	75 inches
New York Panel on Climate Change, 2019	0 inches 2000–2004	Antarctic Rapid Ice Melt (ARIM) scenario[b]			81 inches	114 inches

[a]Sea level rise projections are shown for the 2020s (2020–2029), 2050s (2050–2059), 2080s (2080–2089), and 2100.
[b]ARIM represents a new, physically plausible upper-end, low probability (significantly less than 10% likelihood of occurring) scenario for the late 21st century, derived from recent modeling of ice sheet-ocean behavior. The ARIM scenario is based on DeConto and Pollard (2016), Kopp *et al.* (2014; 2017), and informed expert judgments about maximum plausible ice loss rates from Antarctica (Sweet *et al.*, 2017). However, uncertainties remain regarding ice sheet processes and atmosphere, ocean, and ice sheet interactions.

Mean sea level rise associated with global warming will increase the flooding area in low-lying coastal areas throughout NYC and represents a key threat (Table 9.5). Heightened flood potential due to sea level rise during future hurricanes and nor'easters will cause the most substantial damage.

Given the projected rates of sea level rise, NPCC 2015 estimates by the 2080s, a coastal storm event comparable to a current flood level with a 1 percent chance of annual occurrence could occur 10 to 15 times for often under the worst-case emissions scenario. In more extreme although less certain estimates, a current flood level with a 0.2 percent chance of annual occurrence could increase to a 2 percent chance of annual occurrence (NPCC, 2015).

Even more moderate scenarios have the potential for destructive impacts. For example, the scenario with the lowest projected sea level rise implies that a current 100-year coastal flood could potentially occur every 25–30 years by the 2080s (NPCC, 2015).

As demonstrated by Hurricane Sandy and other recent storms highlighted in Table 9.6, the risks to many of the region's most significant infrastructure will be amplified as a result of sea level rise and the

Table 9.5. Shifting future 1% (100-year) and 0.2% (500-year) flood elevation areas in New York City with increasing sea level rise through 2100. Projections are for the high estimate (90th percentile)

	Area (mi^2)
100-year flood scenario	
FEMA 2013 Preliminary FIRM	50
Projected 2020s, 10”	59
Projected 2050s, 30”	72
Projected 2080s, 58”	85
Projected 2100s, 75”	91
500-year flood scenario	
FEMA 2013 Preliminary FIRM	66
Projected 2020s, 10”	76
Projected 2050s, 30”	84
Projected 2080s, 58”	94
Projected 2100s, 75”	99

Source: NPCC, 2015.

associated augmentation in storm surges (NPCC, 2015). Standard practice in public policy has been to place the necessary, yet locally unwanted land uses (LULUs,) on marginal lands. One example of this is placing transportation infrastructure near wetlands, bays, and estuaries, which has engendered some unintended consequences.

The Hackensack Meadowlands in northern New Jersey, located some 5 km west of New York City, is a model case of this practice. This area is a low-elevation, degraded wetland harboring critical ship, train, air, road, and pipeline infrastructure that crisscrosses the terrain; these intertwining components are at increased risk of flooding due to sea level rise. The storm surge associated with Hurricane Sandy, for example, caused significant flood damage in the Meadowlands, and the Federal Department of Housing and Urban Development is providing $150 million to restore these wetlands and strengthen their resilience to future coastal storms (Leichenko and Solecki, 2013; U.S. Department of Housing and Urban Development, 2014).

9.5. Climate change impacts

Climate change presents challenges and opportunities for the socioeconomic and ecological systems of New York City. The climate stresses described above, in turn, are likely to inundate coastal wetlands, threaten vital infrastructure and water supplies, raise summertime energy demand, and affect public health, all at the same time. These concurrent impacts could also result in other yet-to-be realized impacts on the local quality of urban life and economic activity. Hurricane Sandy revealed the potential for difficult-to-predict, system-level cascading impacts that could occur with climate change-enhanced extreme events. Given the region’s prominent position in the global urban economic hierarchy and potential disruption of business activities, the effects of these local extreme events could be felt at national and international scales.

In this section, we discuss some of the direct and indirect impacts of climate change and how these will interact and, in the regional context, create secondary and tertiary effects. The impacts of climate change are becoming increasingly tangible and fall into a number of nonmutually exclusive categories (direct, indirect, interactive, and integrative) (Table 9.7). Furthermore, the skill in predicting regional climate has sharpened over the past 10 years (see Section 9.4).

Simultaneously, a dynamic process has developed between climate change scientists and public policymakers in cities throughout the world (Rosenzweig *et al.*, 2018). Policymakers and practitioners are being challenged to understand the implications of climate shifts for their cities and to devise adaptations and adjustments to these emerging conditions.

These include physical changes in infrastructure such as higher seawalls for coastal cities (Dawson *et al.*, 2018) and the restructuring of water supply systems (Vicuña *et al.*, 2018); changes in decision making such as coordinating management strategies among overlapping jurisdictions (Romero-Lankao *et al.*, 2018); incorporating urban planning and design (Raven *et al.*, 2018); and far-reaching societal shifts such as disinvestment in highly vulnerable coastal sites and increased support for at-risk populations such as the poor or elderly (Reckien *et al.*, 2018). These responses will inevitably also interact with other ongoing processes of societal and ecological transformation in large urbanized zones (Solecki *et al.*, 2013; McPhearson *et al.*, 2018).

Coastal wetlands

The vulnerability of the New York metropolitan region’s remaining coastal wetlands to climate change was first documented in the MEC study (Hartig *et al.*, 2001). There are few remaining marsh

Table 9.6. Extreme coastal storm events in New York City from 1999 to 2012

Coastal storm	Date	Description
Hurricane Floyd	September 16–17, 1999	• Category: TS-1 • Central pressure: 974 mb • Wind speed: 70 mph • Major inland riverine flooding with 24-h rainfall totals between 10 and 15 inches in upstate New Jersey and New York
Hurricane Irene	August 27–29, 2011	• Category: TS[a] • Central pressure: 959 mb[b] • Wind speed: 65 mph[c] • 3–6 foot storm surge above normal tide levels[d] • NYC issued its first ever mandatory evacuation of coastal areas, covering 370,000 residents[e] • NYC subway service suspended evening of August 27th, not fully restored until August 29th[f] • Estimated $100 million in damages[g] • One attributed death in NYC[h]
Hurricane Sandy	October 29–30, 2012	• Category: TS[i] • Central pressure: 965 mb[j] • Wind speed: 74 mph[k] • Storm surge reached 9.4 feet above normal tide levels and storm tide reached 14.06 feet above Mean Lower Low Water (MLLW) at The Battery, flooding lower Manhattan[l] • NYC issued its second-ever mandatory evacuation of coastal areas[m] • Estimated $19 billion in damage to the city[n] • At least 52 attributed deaths in NYC[o] • 800,000 customers lost power in NYC[p]
November 2012 Nor'easter	November 7–10, 2012	• Followed in wake of Hurricane Sandy, bringing strong winds and downed power lines to areas recovering from previous storm • Central Park recorded 2.8 inches of snowfall, setting new daily record,[q] with snow affecting those in temporary shelters due to Hurricane Sandy

[a]http://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf
[b]http://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf
[c]http://www.nytimes.com/2011/08/29/nyregion/wind-and-rain-from-hurricane-irene-lash-new-york.html?smid=pl-share
[d]http://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf
[e]http://www.nyc.gov/html/oem/html/hazards/storms_hurricanehistory.shtml
[f]http://www.nws.noaa.gov/om/assessments/pdfs/Irene2012.pdf
[g]http://www.nyc.gov/html/oem/html/hazards/storms_hurricanehistory.shtml
[h]http://www.nhc.noaa.gov/data/tcr/AL092011_Irene.pdf
[i]http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf
[j]http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf
[k]http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf
[l]http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf
[m]http://www.nyc.gov/html/oem/html/hazards/storms_hurricanehistory.shtml
[n]http://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf
[o]Seil *et al.*, 2016.
[p]http://www.nyc.gov/html/recovery/downloads/pdf/sandy_aar_5.2.13.pdf
[q]http://usnews.nbcnews.com/_news/2012/11/07/14987947-noreaster-snow-layers-sandy-destruction-more-evacuations-more-power-outages?lite

areas, all of which function to provide critical habitat for wildlife, particularly migratory waterfowl species. The wetlands also provide ecosystem services to coastal communities by inhibiting coastal storm surges onto developed lands and by naturally purifying water systems. In addition, the encroachment of land development on wetlands has prevented the ecosystem from naturally responding to sea level rise through accretion and in-migration (Solecki and Rosenzweig, 2001).

Table 9.7. Categories of potential climate change impacts

Impact type	Description
Direct	Direct connection of climate change to a local environmental change, e.g., global climate warming contributing to local sea level rise
Indirect or dependent	Multistepped process through which direct impacts eventually result in an effect, e.g., increased droughts leading to a decline in drinking water supplies
Interactive or interdependent	Two or more climate-related changes causing an impact, e.g., increased energy demand due to more heat waves leading to electrical blackouts and brownouts, in turn resulting in greater heat stress for those left without air conditioning
Integrative	One or more climate change-related changes becoming integrated with ongoing, local-scale environmental changes such as global temperature change exacerbating a city's existing urban heat island

Severe wetland loss in the region has already been recorded. The marsh islands in the Jamaica Bay National Wildlife Refuge in Brooklyn and Queens decreased approximately 10% in area from 1959 to 1998 (Hartig *et al.*, 2001), and research has shown that a significant amount of this loss is likely to have resulted from 20th century sea level rise (Hartig *et al.*, 2002). Future climate scenarios illustrate that the rate of sea level rise will likely exceed the accretion rate of these wetlands by 2050, resulting in even more rapid loss. In addition to this, the increasing rate of summer evapotranspiration and water deficits that are projected for the mid-to-late century further signify that the total extent of wetlands is likely to be reduced (Wolfe *et al.*, 2011).

Water supply

Managers of the NYC water supply system will face challenges from increased climate variability and climate change (Major, 2003). Periods of extreme rainfall followed by periods of drought are projected in future climate scenarios for the region (see Chapter 2, Climate Science). While changes in future precipitation are less certain than temperature changes, climate projections indicate that there will likely be greater hydrologic variability (Rosenzweig and Solecki, 2010; Rosenzweig, *et al.*, 2011a).

Expected sea level rise will interact with the region's water supply infrastructure. Many features in the region, including pumping stations, treatment facilities, and intake and outflow sites, are now vulnerable to storm-surge flooding, and under conditions of climate change will be directly subject to more frequent flooding. Still under investigation is the potential increased threat of salt-water intrusion into regional groundwater supplies and at surface water withdrawal sites, such as the Chelsea pump station on the Hudson River where NYC would get supplemental water during periods of extreme drought (Major and Goldberg, 2001; Shaw *et al.*, 2011).

Research that began in 2001 has indicated that the New York City water supply system—one of the largest in the world with a storage capacity of 570 billion gallons—should be able to respond to both the expected increase in annual temperatures and greater variability in the rainfall (Major and Goldberg, 2001; Shaw *et al.*, 2011; NAS, 2018). However, shifts in the pattern of supply to New York City watersheds could potentially overwhelm the response capacity of smaller systems in the region.

More recently, researchers have begun examining the interdependent vulnerabilities between the water supply system and other critical infrastructure systems, such as the electricity supply system (Zimmerman and Faris, 2010; see Chapter 7, Critical Infrastructure). As noted in Chapter 2, Climate Science, of this report, while there has not been a major drought since the 1960s in the New York metropolitan region, analysis based on tree-rings from the last 250 years shows that 10-year or longer droughts have occurred, and therefore the possibility of future drought events should be considered in planning.

Energy demand

Climate change will have direct impacts on energy demand in the region. Demand for winter energy will decrease as seasonal temperatures become warmer, while cooling demand will rise significantly in the summer due to more frequent and intense heat extremes (Hammer *et al.*, 2011). Summer demand could be especially strong during heat waves as illustrated by the set of heat waves described in Table 9.8. In 2002, the temperature rose

Table 9.8. Extreme heat wave events in New York City from 1999 to 2013

Heat waves		
11-day heat wave	July 23–August 2, 1999	• Second-longest heat wave on record (longest was 12 days in 1953) • Preceded by two heat waves (4 and 5-day) earlier in July that were responsible for at least 27 heat-related deaths city-wide[a]
4 successive heat waves	July–August, 2002	• Temperature rose higher than 90°F 25 times and exceeded 100°F twice • 8-day heat wave; 9-day heat wave
3-day heat wave	July 25–27, 2005	• 3 consecutive days with temperatures reaching 90°F or higher • Con Edison broke its energy use record, with 13,059 MW[b]
10-day heat wave	July 27–August 5, 2006	• 10 consecutive days with temperatures reaching 90°F or higher • 140 attributed deaths in NYC deaths (direct and indirect)[c] • Con Edison broke its energy use record, with 13,103 MW[d]
4-day heat wave	July 21–24, 2011	• 4 consecutive days with temperatures reaching 90°F or higher; 2 consecutive days with temperatures reaching 100°F or higher • Con Edison broke its energy use record, with 13,189 MW of energy[e] • Temperatures in Central Park reached 104°F (108°F in Newark NJ) on July 22nd, hottest day since July 21, 1977 • 24 heat-related deaths reported[f]
7-day heat wave	July 14–20, 2013	• 7 consecutive days with temperatures reaching 90°F or higher • 2 consecutive days with > 100°F temperatures[g] • Con Edison broke its energy use record, with 13,214 MW of energy[h] • NY State ISO broke its energy use record, using 39,955 MW of power[i] • 19 heat-related deaths; approximately 140 natural cause deaths related to extreme heat, during the 2013 warm season[j]

[a]https://www.nytimes.com/1999/07/10/nyregion/heat-wave-toll-climbs-to-27-dead-in-new-york-city.html
[b]http://www.nytimes.com/2006/08/01/us/01cnd-heat.html
[c]http://www.nytimes.com/2006/11/16/nyregion/16heat.html?_r=0
[d]http://www.nytimes.com/2006/08/01/us/01cnd-heat.html
[e]http://www.foxnews.com/weather/2013/07/20/nyc-breaks-power-usage-record-during-heat-wave/
[f]http://online.wsj.com/articles/a-summer-of-normal-temperatures-for-new-york-with-few-scorchers-1408756894
[g]http://www.bloomberg.com/news/2013-07-19/heat-wave-may-peak-with-temperatures-near-or-at-100-in-new-york.html
[h]http://www.bloomberg.com/news/2013-07-19/heat-wave-may-peak-with-temperatures-near-or-at-100-in-new-york.html
[i]http://www.bloomberg.com/news/2013-07-19/heat-wave-may-peak-with-temperatures-near-or-at-100-in-new-york.html
[j]https://www1.nyc.gov/assets/doh/downloads/pdf/epi/databrief47.pdf

above 90°F for 25 days during July and August, and went over 100°F twice.

Climate change scenarios in NPCC 2015 project that the average number of days at or above 90°F will increase three- to fourfold by the 2080s (NPCC, 2015). An indication that extreme heat is already impacting New York City energy demand is that in each of the four major heat waves from 2005 to 2013, Con Edison broke a new energy-use record (Table 9.8). On average, during each warm season in NYC, there are 13 heat stroke deaths, 150 hospital admissions, and 450 emergency department visits for heat-related illness; an average of 115 natural-cause deaths are associated with extreme heat each year.[g]

During a heat wave of 1999 that occurred as the MEC Report assessment was underway, the region

[g]https://www.cdc.gov/mmwr/preview/mmwrhtml/mm6231a1.htm 2); https://www.ncbi.nlm.nih.gov/pubmed/27081885

experienced a record peak demand for electrical power that precipitated brownouts and an extended blackout during the heat wave (July 6th) in largely minority sections of the city (upper Manhattan and the South Bronx) (Rosenzweig and Solecki, 2001a). Residents and local politicians argued that the blackout revealed that the local power authority (Consolidated Edison) had not properly maintained the equipment serving these neighborhoods putting the populations of color at comparatively higher risk.

Although a Public Service Commission review found that this was not the case (State of New York, 2000), this type of integrative impact highlights the need for focus on disadvantaged communities so that they are not disproportionately affected by similar future events (Wilgoren and Roane, 1999). Such events might foreshadow future extreme electricity demand events, and real or perceived inequities that might arise in the face of environmental risk exposure.

Public health

Inequity and the spatial and demographic unevenness of climate change impacts are probably no better expressed than in the risks to the public health sector in urban regions (Kalkstein and Greene, 1997). Typically, direct and integrative impacts occur under these circumstances. Populations in urbanized places like New York City are likely to experience increased exposure to heat stress conditions, greater potential of water-borne or vector-related disease outbreaks, and higher concentrations of secondary air pollutants resulting in increased frequency of respiratory ailments and attacks, such as asthma (Kinney *et al.*, 2011; see Chapter 6, Community-Based Adaptation). The poor, elderly, very young, and immuno-compromised will be at greatest risk. New York City, like other large cities, has significant populations of these individuals. Recent studies of the effects of Hurricane Sandy have highlighted the vulnerability of impoverished populations in critical flood zones (Lane *et al.*, 2013; Kinney *et al.*, 2015).

Interactions between electric energy demand and health effects are likely to occur under conditions of climate change. For example, heat stress and heat-related mortality are projected to a major direct health impact of climate change (NPCC, 2015). Populations at heightened risk of heat stress and heat-related mortality will be those without access to air conditioning. Already, air conditioning access is not equitably distributed at the individual and neighborhood level, with wealthier people and neighborhoods having greater access (NYC DOHMH, 2014).

Air conditioning use, though, could become especially problematic during summer heat waves that result in increased cooling demand and possible, subsequent electricity blackouts unless actions are taken to ensure that people who need air conditioning to safeguard health have access while others, including businesses, use air conditioning responsibly during extreme heat events (Lane *et al.*, 2013; NYC DOHMH, 2014). Risk of morbidity and mortality in New York becomes severe if blackouts occur during an extreme heat event (Dominianni *et al.*, 2018) (Kinney *et al.*, 2015).

As found in the MEC report and other studies, heat waves will also exacerbate secondary air pollution problems in the region (Kinney *et al.*, 2001; Knowlton, 2004). Peak electricity demand and fossil fuel burning during heat waves result in an increase of primary air pollutants, for example, nitrogen oxides (NOx). These pollutants are then converted into secondary air pollutants, like ozone. Increased concentrations of secondary pollutants are associated with higher numbers of respiratory-related health attacks and hospitalizations.

Vector-borne diseases are spread by organisms such as ticks and mosquitoes, and disease incidence is influenced by climate factors (Kinney *et al.*, 2015). Early in the MEC assessment, summer events of 1999 provided evidence of integrative climate change-related health impacts (Rosenzweig and Solecki, 2001a). Throughout the late summer of that year, birds starting dying throughout NYC. By September, a few people in the region came down with unusual flu-like illnesses. Within a few weeks, several victims had died, and the region erupted in a full-fledged public health crisis. Within weeks, the cause had been narrowed to two species of freshwater mosquitoes, and eventually the specific viral strain that they were carrying was isolated as West Nile-like Virus—recorded for the first time in North America.

While the process by which the mosquitoes became infected was unclear, how the mosquitoes' populations were able to grow so dramatically in late summer is illustrative of the society's vulnerability to climate variability (Kinney *et al.*, 2011). A likely scenario is that early summer drought warning had forced homeowners in suburban Queens to temporarily stop using their backyard pools. The pool water remained stagnant for several weeks and was followed by heavy end-of-summer rains. Mosquito experts later stated that this was the ideal condition under which to promote the growth of the two species of mosquito later defined as the virus carriers. Though the number of mosquitos infected with West-Nile virus is not directly caused by increasing climate change, the number of total mosquitos is likely to rise with a warmer and wetter climate; this makes the potential for an elevated risk of mosquito-borne diseases such as West-Nile virus in New York a legitimate concern.

Community resiliency

The NPCC3 report presents key findings related to community resiliency in New York City (see Chapter 6, Community-Based Adaptation). The Community-Based Asessements of Adaptation and Equity Work Group investigated patterns of spatial vulnerability to climate change across neighborhoods and communities in New York City. This task, which draws attention to issues of *distributional equity* in vulnerability (i.e., spatial or temporal differences), was accomplished through compilation, review, and assessment of recent vulnerability mapping studies conducted in New York and elsewhere in the United States.

The aim of NPCC3 Chapter 6 was to identify common patterns and indicators of spatial vulnerability and to provide guidance on methods and indicators that can be used to monitor and track neighborhood vulnerability over time.

The Work Group also developed case studies of climate change risks, vulnerability, and adaptation in socially and economically disadvantaged communities. This task, which incorporates the consideration of *contextual equity* (i.e., communities with multiple stresses), was accomplished in collaboration with three community-based organizations (CBOs)—WE ACT for Environmental Justice in Harlem, THE POINT CDC in Hunts Point, and UPROSE in Sunset Park. All of these CBOs are situated in predominantly minority and low-income neighborhoods, and all have either developed or are in the process of developing climate adaptation plans for their communities.

An examination of community-based adaptation planning efforts was conducted in several New York City neighborhoods. The task, which was accomplished through collaboration with CBOs and New York City planners, explored how *procedural equity* (i.e., imbalance with respect to access to the decision-making process) is incorporated in development and implementation of adaptation plans.

An examination of current practices for incorporating equity in urban adaptation planning efforts is the final step. This task was accomplished via comparative investigation of how New York and other cities in the northeastern United States incorporate principles of distributive, contextual, and procedural equity into community adaptation planning.

9.6. How stakeholders use NPCC3 information

The NPCC has developed a range of new types and formats of information in a co-generation process with stakeholders. These include new climate data and projections as well as tools and methods to foster communication and situate these data and information products into a variety of resiliency and adaptation strategies.

Interactions with stakeholders and users of climate information have been emphasized throughout the NPCC process from the beginning in 2008. Most recently, NPCC3 members interacted with a variety of stakeholders, including scientists, members of city government agencies, infrastructure managers, and communities to "co-generate" the information that is presented in this report. In the NPCC context, the term "co-generation" refers to an iterative process of discussion and development of climate science information between scientists and stakeholders conducted to improve decision making.

These interactions included (1) discussion of relevant science needs that decision makers had; (2) communication via email, phone calls, and in-person meetings or workshops; and (3) reviews of draft report data, figures, and text. Throughout this process, NPCC3 scientists responded to and incorporated stakeholder feedback into its work, culminating in the final NPCC3 Report.

NPCC portfolio approach to resilience

In regard to responses to increasing climate risks, the city has adopted a wide range of strategies, in

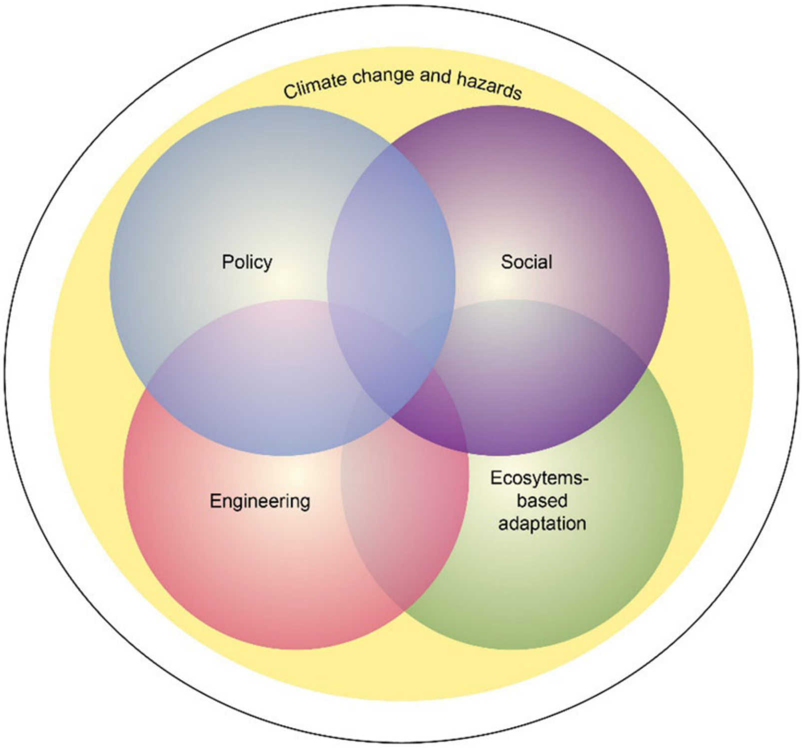

Figure 9.3. Portfolio approach to resilience.

essence taking a "portfolio approach" that includes programmatic, social, engineering, and nature-based adaptive initiatives (Fig. 9.3).

The NPCC has embedded this portfolio approach to resilience within its flexible adaptation pathways framework whereby each resiliency action can be set within a set of adaptation steps highlighted in NPCC1 as an eight-step process (see Chapter 1 Introduction). Over time, it has become increasingly clear that adaptation strategies take on a variety of conditions and contexts from small and discrete (e.g., a single wetland restoration effort to promote storm surge wave attenuation) to large and widespread (e.g., a series of actions to promote resiliency of the New York City transit system).

Some adaptation strategies represent policy regime shifts that once made are difficult to undo and limit return to an earlier state or adjustment to an alternate policy position (i.e., adaptation lock-in)(Ürge-Vorsatz *et al.*, 2018). The consideration of a large-scale storm surge barrier across the New York harbor is one such large, "game-changing" proposal. As described in NPCC1, the position of NPCC has been to recommend a comprehensive assessment of potential physical, biophsyical, and socioeconomic outcomes before any such activity is undertaken.

As an additional consideration, the NPCC presents the following typology of evaluation and assessment for this and other potential future adaptation strategies (see Fig. 9.4). In the typology, as the flexibility of the adaptation strategy decreases and its relative size increases, the need for assessment and analysis increases.

9.7. Policy recommendations and outcomes

Policy recommendations in each of the NPCC reports have helped to engage New York City decision makers in crafting long-term adaptation plans that have evolved through time. Assessment recommendations have contributed to the establishment of the Consortium for Climate Change Risk in the Urban Northeast (CCRUN) and the ongoing NPCC, which is now mandated by law to provide climate risk information to each successive mayoral administration. Recommendations from these assessments and their outcomes are described in Table 9.9.

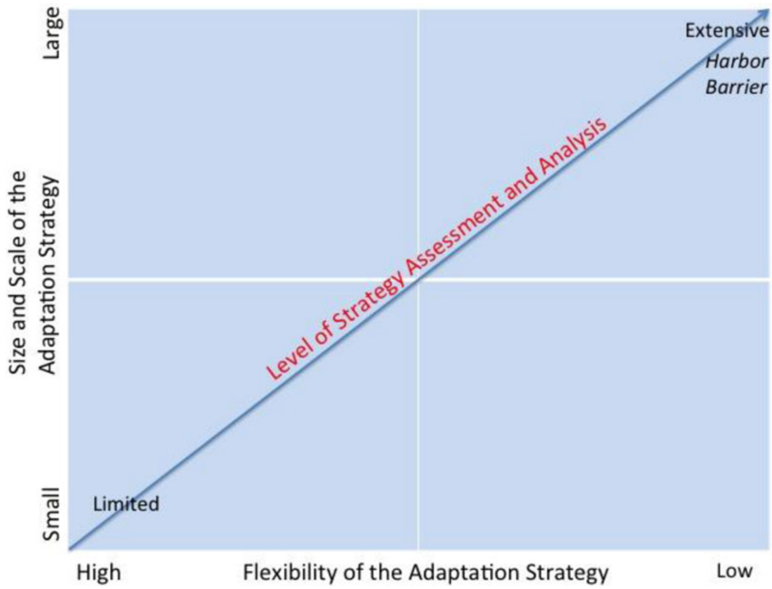

Figure 9.4. Adaptation assessment typology and required level of assessment.

9.8. Scoping NPCC's next phase: regional integration

The first decade of NPCC has yielded a series of important findings and lessons, and sets forth a pathway to consider some next steps. For example, it seems pressing that part of the evolution of the NPCC assessment should focus on assessing vulnerability, tracking impacts, evaluating adaptation measures, and providing a guide for coordinated resilience action across the entire New York metropolitan region.

Such a regional approach would benefit from incorporating a full range of sectors, and from taking the full range of dependencies and interdependencies into account in order to avoid siloed responses across multiple levels of government, as well as agencies and departments. The assessment process should create a unified set of scenarios to be used throughout the region and should include a benchmarked analysis of indicators from the proposed New York City Climate Change Resiliency Indicators and Monitoring system (NYCLIM) presented in Chapter 8 of this report (see NAS, 2018).

Such an ongoing regional assessment process can help to further important discussions about challenging issues such as potential land use change and strategic relocation in the region, given the increasing risks to coastal areas. For example, the NPCC could facilitate a region-wide discussion of strategic relocation by convening a Climate Change Summit once during each administration so that responses to this and other key issues could be explored and coordinated.

Funding and resources

A key challenge for the ongoing NPCC process is funding its activities. The Rockefeller Foundation funded the first NPCC. The NPCC2 was funded by the City of New York for new projections following Hurricane Sandy. The New York City DEP and FEMA through the New York City Emergency Management partially funded NPCC3. Throughout NPCC2 and NPCC3, the NOAA-funded RISA program through its CCRUN provided technical support. NASA has contributed to the NPCC efforts through the Climate Impacts Group at NASA Goddard Institute for Space Studies. Going forward, it is essential that consistent resources and the means to provide them are developed for the NPCC scenario development, assessment, and monitoring functions.

9.9. Perspectives

The climate assessments for NYC produced since 1999 elicit several observations regarding the evolving character of climate change and its implications as an emerging type of environmental

Table 9.9. Policy recommendations and outcomes from MEC, NPCC 2010, and NPCC 2015

Policy recommendations	Outcomes
Metropolitan East Coast Assessment	
A regional Climate Awareness Program would be effective to inform decision makers and the general public about current climate processes, lessons learned in responding to climate extremes, and future climate change	• Northeast RISA—Consortium for Climate Risk in the Urban Northeast (CCRUN)—was established in 2010 with funding from NOAA to provide stakeholder-driven research from Boston to Philadelphia
A regional Climate Inter-Agency Task Force should be formed to identify potential climate-related events and conditions (e.g., coastal infrastructure at risk, disease outbreaks, and water supply vulnerabilities) and proactively propose responses. The taskforce should also consider events that would require emergency actions and/or large-scale societal responses	• Climate Change Adaptation Task Force (CCATF) was convened in 2008 by NYC Mayor Michael Bloomberg
New York Panel on Climate Change 2010	
Create a mandate for an ongoing body of experts that provides advice and prepares tools related to climate change adaptation for the City of New York. Areas that could be addressed by this body include regular updates to climate change projections, improved mapping and geographic data, and periodic assessments of climate change impacts and adaptation for New York City to inform a broad spectrum of climate change adaptation policies and programs	• Local Law 42 codified the New York Panel on Climate Change as an established, ongoing body of New York City government (2012)
Conduct a review of standards and codes to evaluate their revision to meet climate challenges, or the development of new codes and regulations that increase the city's resilience to climate change. Develop design standards, specifications, and regulations that take climate change into account, and hence are prospective in nature rather than retrospective. New York City should work with FEMA and NOAA to update the FIRMs and SLOSH maps to include climate change projections	• NYC Special Initiative for Rebuilding and Resilience (2012) • Building Resiliency Task Force formed after Hurricane Sandy • Climate Resiliency Design Guidelines released in 2018
New York Panel on Climate Change 2015	
Coordinate with state and federal partners on climate change projections and resiliency programs. Specifically, FEMA should incorporate local sea level rise projections into its coastal flood methodology and mapping. This enables residents as well as planners to utilize the best available information as they develop and implement climate resilience strategies	• FEMA FIRMs update process initiated to include new flood risk projections • NOAA Coastal Mapper utilized NPCC2 projections • Amendment to Executive Order 11988 to use "best-available and actionable science" for flood hazards and community exposure[a]

[a]https://obamawhitehouse.archives.gov/the-press-office/2015/01/30/executive-order-establishing-federal-flood-risk-management-standard-and-

challenge within cities. These considerations include (1) the need to provide information to stakeholders on how key decision-relevant variables may change at finer temporal (i.e., seasonal, monthly, daily, and subdaily) rather than annual timescales and spatial scales; (2) the interactive and integrative character of the impacts; (3) the importance of the onset speed of changes and impacts; (4) the critical need to understand uncertainty and predictability in regard to both projections and impacts; and (5) the transformative trajectory toward integrated implementation of both mitigation and adaptation strategies (Rosenzweig and Solecki, 2018).

Finer-scale projections

The first observation is that it is essential to understand the level of variation within aggregate climate trend and forecast data sets. For example, yearly forecasts of climate conditions often mask seasonal variations that could be important with respect to certain impacts and affected groups. In NYC, a focus on the steady rise in observed mean annual temperatures hides the fact that the temperature increases have been especially pronounced during the winter months, which is particularly relevant for water managers who look toward this time of year for reservoir recharge.

Other data variations include the spatial heterogeneity of the potential changes, which increasingly are being revealed through the application of finer-scale regional climate modeling. This is addressed in the climate science chapter of this NPCC3 Report (see Chapter 2, Climate Science), which tests the use of RCMs for use in future NPCC assessments. RCMs operate at a much finer spatial scale than GCMs (i.e., tens of kilometers versus hundreds of kilometers in scale) and as a result can portray climate change processes not resolved in the GCMs (Horton *et al.*, 2011).

In the case of NYC, for example, the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5) RCM results illustrate a much wider range of temperature shifts between coastal and inland locations (Lynn *et al.*, 2004). This difference was largely driven by the moderating near-shore influence of the Atlantic Ocean and coastal sea breezes, a phenomenon not simulated by the coarser-scale GCMs, but captured by the MM5 RCM. However, regional climate modeling adds additional uncertainty due to sensitivity to model configurations (Lynn *et al.*, 2010).

Observed and projected impacts

Another critical observation is that documenting the urban impacts of recent climate change (e.g., during the past century and especially since the 1970s when the recent period of rapid warming began) is helpful in understanding the potential impacts of future climate change on cities. This is addressed in the Indicators and Monitoring chapter of this report (see Chapter 8), the MEC Report (Rosenzweig and Solecki, 2001a) and the first two NPCC Reports as well (NPCC1, Rosenzweig and Solecki, 2010; NPCC2, Rosenzweig and Solecki, 2015). Impacts on both critical infrastructure (see Chapter 7) and on communities (see Chapter 6) are also analyzed by NPCC3.

Climate change has already engendered associated impacts in cities. Documenting these impacts is important for developing a more informed conception of possible future shifts. Recent IPCC Working Group II reports analyze climate change impacts currently underway (IPCC, 2007; IPCC, 2014). At the moment, there are relatively few detailed observed climate impact assessments for urban areas that document recent changes and attribute them to the changed climate.

Urban region integrated assessments

In regard to future urban impacts, a systematic set of comparative climate change assessments needs to be done for varying classes of cities (e.g., coastal cities versus inland cities, mid-sized cities versus large cities, middle-latitude versus tropical cities, etc.). A key variable distinguishing cities is whether they are classified as low-, medium-, or high-income. This effort has now been taken on by the Urban Climate Change Research Network (UCCRN) through its assessment reports on climate change and cities (ARC 3.1 and ARC 3.2) (Roseznweig *et al.*, 2011c; Rosenzweig *et al.*, 2018 and see www.uccrn.org).

Prominent example assessment studies other than NPCC either completed or underway include climate proofing in Rio de Janeiro, Brazil; New Orleans, Louisiana lessons from Hurricane Katrina; Mexico City, Mexico's Virtual Center on Climate Change; Santiago, Chile's water management and spatial planning; and Sydney, Australia's Sustainability Framework for its urban transportation system (Rosenzweig *et al.*, 2011b). These assessments help illustrate similarities and differences among and between the cities and potentially reveal pathways for meaningful response.

A crucial element of these studies is specifying the interaction between current and potential climate change impacts and the existing pattern of environmental change within each city. Climate change may be viewed as yet another stress for a city where dense population and intensive economic activity already have put tremendous demand on local and non-local land, water, and energy resources.

In the case of NYC, the New York metropolitan region has been dramatically altered, particularly in the older urban and suburban areas. Approximately 40% of the metropolitan land area has been fully converted to urban uses, with significant reduction in vegetative cover, loss of wildlife habitat, and degradation of environmental quality. The rate of land conversion has accelerated in the past several decades although the rate of population growth has slowed (Yaro and Hiss, 1996; Cox, 2014). These have set off a significant amount of local and regional environmental change and dramatic reduction of ecosystem service provision capacity (McPhearson *et al.*, 2013; Elmqvist *et al.*, 2013), separate from global climate change.

Defining the connection between exogenous (e.g., global climate warming) and endogenous environmental changes (e.g., suburbanization) often is hampered by limited information on the rate and character of local environmental alterations and on baseline conditions (Leichenko and Solecki, 2013).

An example of a significant interaction between these different scales of environmental change is illustrated by connection between global climate change and the local urban heat island effect(UHI). Local land use alters the energy balance causing increased temperatures to which urban residents are exposed. When evaluating the rate of temperature increases in an urban area, it is important that the observer distinguish between the UHI signal and the global climate change signal and to understand how they might be interacting. While UHI is a known phenomenon, a crucial question remains as whether global climate change will lessen or enhance the heat islands of cities. Clearly, there will be interactions (Rosenzweig *et al.*, 2005), yet the overall net effect of the impacts is not yet clear.

Uncertainty

Another important aspect of understanding global climate change as a local urban environmental challenge is addressing the associated levels of uncertainty and predictability. As a primary assertion, one needs to recognize that climate models such as GCMs and RCMs do not produce predictions of future climate conditions but instead present scenarios of future climate conditions based on specific sets of assumptions. Climate model results do not represent data for any specific day, season, or year in the future.

The standard protocol for the use of climate models for local down-scaled projections, beyond extensive calibration and validation with observed data at regional scales, is the definition of the range of variation across a set of models and scenario assumptions. In the case of NYC climate assessment research, numerous separate GCM model results of future temperature and precipitation changes have now been compared (NPCC, 2015). A cutting-edge issue within climate assessment work is the development of statistical methods, often performed through the use of Bayesian approaches, to better numerically define and communicate the amount of variation within the run results of one model or results across a set of models.

Tipping points, thresholds, and transformations

A central challenge is to better understand the possibility of gradual change shifts over time or possible sudden, more rapid changes. The analogy of the dimmer switch versus the on-off light switch and the identification of associated system-level tipping points have been introduced into climate change science discourse (U.S. National Research Council, Committee on Abrupt Climate Change, 2002; Lenton and Ciscar, 2013). While these are presented within the context of global-scale phenomena such as the thermohaline circulation (i.e., sudden shifts in Atlantic Ocean currents), the implications for cities and the possibility of facing rapid shifts as well as gradual ones have important implications for impact assessment and policy response.

A crucial remaining question is how well the institutions in cities, such as those present in the New York metropolitan region, will be able to respond to climate change as a local environmental challenge (Bulkeley *et al.*, 2015; Solecki *et al.*, 2013). For most urban areas, barriers typically exist to effective regional institutional response to climate change and such problems are often inherent in urban environmental management (Rosenzweig *et al.*, 2014). More than a thousand political jurisdictions, home rule, and a splintered political landscape characterize the NYMR. Besides federal and regional designations, the region is divided jurisdictionally across 3 states, 31 counties, and hundreds of municipalities. In this setting, short-term political concerns tend to dominate.

Policy responses to climate change are also hampered by the generally reactive nature of management organizations. Institutional action is often directed at immediate and obvious problems. Issues that might emerge fully only after several decades are perceived as less pressing.

Another set of barriers reflects the complications associated with climate change itself. In most cases, environmental and natural resource agencies and organizations already have defined their own basic assumptions regarding the nature and rate of environmental change in the region. These institutions need to incorporate the highly dynamic environment that could be associated with climate change into their *modus operandi*. The multidimensional nature of the potential impacts and resulting interactive and integrative effects and the scientific uncertainty regarding climate change also make responses difficult.

These conditions are challenging decision-making agencies and institutions to address some of these basic assumptions regarding urban systems and how they are managed. The complexity of the situation is compounded when it is realized that truly effective management responses should include both adaptation (i.e., lessen the overall effect of the impacts) and mitigation (i.e., lessen the rate and magnitude of global climate change by reducing greenhouse gas emissions).

While it is unclear how cities will respond to climate change impacts as they unfold over time, how they have responded to local environmental change in the past reveals some insights. Cities often have been sites of environmentally sustainable action (McGranahan *et al.*, 2001), and some scholars now present the argument that they are leading the way with regard to developing and implementing transformative climate pathways (Rosenzweig *et al.*, 2010; Rosenzweig, 2011; Kousky and Scheider, 2003; Rosenzweig and Solecki, 2018).

Environmental change and threats in previous eras were typically ignored or held in check until the issue became a significant crisis of some sort—economic, social, and/or health related (Solecki, 2012). It is during these moments that new policies can be implemented. In the case of New York City's pursuit of a stable water supply, the city faced shortages and minor problems for almost half a century until a series of disease outbreaks forced local officials to develop a copious source of drinking water. This became the first significant step in the construction of the extensive water supply system now in place (Gandy, 2003).

The response to Hurricane Sandy is another example, bringing explicit recognition that increasing climate risks must be brought into decision-making related to recovery and rebuilding (Rosenzweig and Solecki, 2014).

While the typical response of cities has been to seek solutions to their environmental problems by going beyond their borders, either in search of resources (via an ecological footprint) or as a location to dump wastes (see as example Tarr, 1996), the case of responding to climate change impacts is following a different pattern, with cities taking responsibility for both reducing their own greenhouse gas emissions and for developing the resilience needed to minimize impacts on their most vulnerable communities (Rosenzweig, 2011).

9.10. Conclusions

Throughout its 10-year history, the NPCC has functioned as a sustained assessment for the city and metropolitan region of New York. This knowledge platform has provided an essential enabling condition for New York to proactively and flexibly adapt to changing climate conditions.

Climate change is already affecting and will continue to affect people in cities multidimensionally. In the case of New York City, heightened frequencies of storm surges will damage major infrastructure in addition to already-threatened coastal wetlands. Health impacts of climate change will be intertwined with the effects of augmented heatwaves on energy demand and extent of equitable access to air conditioning (Rosenzweig and Solecki, 2001a).

The analysis of New York City and its actions on climate change resiliency presented in this chapter demonstrates a strong and socially beneficial relationship between science-based assessments benchmarked through time and policy outcomes. Over the last 10 years, explicit regional assessments that document evolving climate trends, present state-of-the-art climate change projections, and provide detailed impacts and adaptation strategies for key sectors such as energy, water, and health have led to the implementation of a wide range of climate resilience measures. The case of Hurricane Sandy, highlighted throughout the chapter, further shows the role that major extreme climate events can play in catalyzing resilience action in cities.

Urban growth and economic development, by definition, have been major agents of local environmental change. These two processes have brought the relative reach of cities to all corners of the globe. At the same time, both contribute to global climate change, which increasingly has the potential to significantly impact cities.

Cities then, more and more, are the sites where the mediation of climate change as local *and* global environmental change is taking and will take place. Observations from New York City reveal that effective responses by cities to these intertwined processes can be facilitated by the engagement of local experts with stakeholders to undertake assessments that are benchmarked through time. This ensures that a city's implementation of climate change responses may be based on recent analyses of climate trends, state-of-the-science climate projections, accurate representation of potential impacts and vulnerabilities as they are distributed across the urban area, and adaptation strategies that have been carefully examined by local experts.

The NPCC is a testament to the foresight of the City of New York. Its ongoing activities show that the city recognizes that climate change is a "moving target" and that responding to its challenges requires knowledge to be continuously created, synthesized, and shared.

Acknowledgments

We thank Carly Paine, Megan O'Grady, Lesley Patrick, Daniel Bader, and Danielle Manley for their dedicated work as program managers of the Metro East Coast Assessment and the New York City Panel on Climate Change Assessments over the period 1999 to 2019.

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Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Advancing Tools and Methods for Flexible Adaptation Pathways and Science Policy Integration*
ORIGINAL ARTICLE

New York City Panel on Climate Change 2019 Report: Conclusions and Recommendations

Understanding climate change in cities is important because of the dramatic growth in urban populations, and thus vulnerability, as well as the emerging role of cities as first responders to climate change. Since 2008, the New York Panel on Climate Change (NPCC) has analyzed climate trends, developed projections, explored key impacts, and advised on response strategies. Charting a future course for the NPCC ensures that New York City (NYC) continues to develop resilience for the five boroughs and the surrounding metropolitan region, and play its role as a climate change leader for other cities, not only in the United States but also around the world.

As set forth by Local Law 42 of 2012, the New York City Panel on Climate Change 2019 Report provides tools and methods for implementing region-wide strategies. These tools and methods can be used to observe, project, and map climate means and extremes; monitor risks and responses; and engage with communities to develop effective programs.

The report finds that recent increasing trends in temperature and precipitation in Central Park are generally tracking the NPCC 2015 projections for the 2020s time period encompassing the years of 2010–2039.[a] NPCC2 confirms the use of the NPCC2 2015 projections for decision making by the city and region.

NPCC conducts and guides research that has high potential value for flexible adaptation planning. It supports the large body of evidence indicating that decision makers are better served by consideration of future climate risks, rather than by reliance on the climate of the past, in development of resiliency policies and programs.

[a]These comparisons should be viewed with caution because of the role that natural variation plays in the short term.

New methods for extreme temperatures, heavy downpours, and droughts

Projected increases in the frequencies and intensities of extreme events pose particular challenges to NYC. At the request of the NYC Mayor's Office of Recovery and Resiliency, the six climate extremes considered in NPCC3 are extreme heat and humidity, heavy downpours, droughts, sea level rise and coastal flooding, extreme winds, and cold snaps.

NPCC3 has begun to develop and test new methods for observations and projections to be used in resilience planning for the region. Using expanded observations, bias correction, and regional climate models, these methods can provide quantitative analyses for heat extremes, heavy downpours, and droughts. They are available for developing the next full set of NPCC projections.

Based on these and other methods, the next generation of global and regional climate model outputs will be used in upcoming NPCC assessments to create a new unified set of projections for decision making in the New York metropolitan region. The methods tested by NPCC3 using global and regional climate model ensembles and scenarios will enable the updated identification of climate change "hotspots" of vulnerability at finer spatial scales within the city and across the region.

Recommendations for research

- Analyze the declining impacts of heat over time (presumably due to increased prevalence of air conditioning), examine thresholds of heat and humidity effects on human health, and develop projections and interventions that will be most effective in NYC's hotter climate.
- Determine benchmarks for subhourly extreme precipitation and associated flooding events using satellite data and rain gauges. Use these benchmarks to develop subhourly extreme precipitation projections that take into account

doi: 10.1111/nyas.14032

urban meteorological effects and identify neighborhoods likely to be flooded.

- Characterize large-scale conditions that may lead to drought based on further instrumental, tree-ring, and other paleoclimate indicators, and climate model analyses in the region.
- Study the association of polar air outbreaks extending into the New York metropolitan region and recent climate trends, and project how these might change over the coming century.

Recommendations for policy

- City agencies should work with the NPCC to improve quantitative heat wave projections. Such agencies could include, for example, the New York City Department of Health and Mental Hygiene, Emergency Management, and the National Weather Service. Together, such groups can investigate how best to prepare for future revisions of heat advisory criteria that consider changing combined effects of temperature and humidity (i.e., heat index).
- The NYC Department of Environmental Protection, NYC Emergency Management, and Mayor's Office of Recovery and Resiliency should commission a study to determine what levels of heavy rainfall (intensity, duration, and frequency) cause nuisance, moderate, or catastrophic flooding in NYC.
- Although there has not been a major, multiyear drought since the 1960s in the New York metropolitan region, the possibility of future droughts should be considered in planning based on long-term records.

Sea level rise

Recent increasing ice mass losses in Greenland and Antarctica, advances in modeling ice sheet–ocean–atmosphere interactions, as well as potential for marine ice-shelf instability in West Antarctica raise the prospects of higher sea levels than previously assumed. A growing awareness therefore exists for the need to consider high-impact, low-probability scenarios in coastal risk management, particularly when planning for long-lived infrastructure development. This new perspective also informs the need to supplement the NPCC (2015) sea level rise projections with an alternative, extreme scenario—the Antarctic Rapid Ice Melt (ARIM) scenario.

Because of the longevity of atmospheric CO_2, temperatures and sea level will continue to rise even after stabilization or reduction in greenhouse gas emissions. With total cessation of further anthropogenic CO_2 emissions by mid-century, CO_2 and atmospheric temperatures would slowly begin to decrease after several decades. But most of the CO_2 would still remain in the atmosphere and take centuries to millennia to slowly dissipate. This, and slow heat penetration into the deep ocean, would cause sea level to rise continuously well beyond 2100 due to thermal expansion alone.

Therefore, as a first step, further research into sea level change for the next several centuries, to 2200 and 2300, should be explored. In addition, the consequences of long-term sea level rise scenarios on coastal flooding, including those stemming from low-probability, high-end scenarios, should also be examined.

Recommendations for research

- Monitor trends in sea level rise and in the processes contributing to sea level rise in the New York metropolitan region.
- Research the processes leading to the destabilization of the Antarctic and Greenland ice sheets.
- Study trajectories of potential sea level rise that continue after 2100 in light of the sea level rise commitment on longer timescales.
- Examine the consequences of long-term sea level rise scenarios on coastal flooding, including those stemming from low-probability, high-end scenarios.

Recommendations for policy

- NYC Mayor's Office of Recovery and Resiliency should be aware of the increasing high-end risks, such as ARIM, affecting sea level rise in the New York metropolitan region as flexible adaption pathways for climate change evolve.
- Because of the long life span of some infrastructure, as well as the projected continuation of sea level rise beyond 2100, the city should be aware of sea level rise scenarios that extend into 2200 or 2300, when ice sheet destabilization effects will become even more pronounced. Sea level scenarios on such long time frames

are highly uncertain, but need to be taken into account with appropriate caveats.

Coastal flooding

In regard to coastal flooding, NPCC3 has reviewed key processes, summarized historical trends and present-day flood hazards, and assessed how sea level rise will affect storm-driven and tide-driven future flooding. An improved understanding of present and future flood risk should be helpful to NYC for effective long-term planning.

The combined dynamic/static NPCC3 analysis shows that monthly flooding will not be a widespread problem until the 2050s or later, but by late in the century, it could impact most of the neighborhoods immediately surrounding Jamaica Bay, as well as several other low-lying neighborhoods of the city. Areas particularly susceptible to monthly tidal flooding include Rockaway Peninsula, Howard Beach, and Coney Island and areas immediately to the north. Under the new ARIM scenarios, sea level rise by the end of this century could raise daily tidal flooding to levels even more severe than that which occurred during Hurricane Sandy.

A static assessment of storm-driven flooding shows how extreme events such as the 100-year and 500-year floods will rise with a variety of sea level rise projections, ranging from 10th to 90th percentiles for the 2020s, 2050s, 2080s, and 2100 and including the ARIM scenarios for the 2080s and 2100. Assumptions on future emissions pathways are shown to cause large differences in the sea level rise projections, and as a result, the flood projections. Moderate differences can also arise from differing methods for combining probabilities of storm tides and sea level rise.

Recommendations for research

- Continue to research flood hazards in the New York metropolitan region, including investigations of historical or sedimentary archives, flood modeling, storm modeling, and comparisons of how different hazard assessments compare.
- Conduct research into future changes to tropical, extratropical, and hybrid cyclones, given remaining substantial uncertainties.
- Analyze changing types of storms associated with extreme winds and climate change, particularly the association of changes in extratropical cyclones and their frequency and intensity in the New York metropolitan region, and the incorporation of convective storm events into climate model outputs.

Recommendations for policy

- Since it may not be possible to protect all shorelines from extreme coastal floods and sea level rise, NYC should continue to explore a wide range of structural and nonstructural risk reduction approaches, including paradigm-shifting concepts such as strategic relocation programs on floodplains and densification on high ground.

Mapping climate risk

Mapping of climate risk is a key activity of the NPCC. It is a major method for communicating how citizens in the New York metropolitan region may experience future changes. NPCC3 presents sea level rise and coastal flooding maps that are based on the latest LiDAR information for the city and region, specifically the 2017 NYC LiDAR capture.

Recommendations for research

- Use flood data that incorporate confidence intervals into modeled results. Error in the topographic elevation data, sea level rise projections, and FEMA model outputs all introduce uncertainty and limit accuracy. Estimates of population, facilities, and infrastructure within the future flood zones are associated with this uncertainty. For this reason, possible future work should consider using flood data that incorporate confidence intervals in their modeled results.
- Include mapping of concurrent events, for example, the cumulative effects of storm surge combined with intense rainfall that might impact the movement, timing, and drainage of floodwaters. Although coastal flooding dominates in NYC, fluvial and urban street flooding occurs during intense rainfall events resulting in overflows in residential and municipal drainage systems.
- In association with the proposed New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM), map indicators that address climate risk, impact,

vulnerability, and adaptation concerns. Issues that need to be considered when developing climate risk indicator maps include spatial extent of the data, cost effectiveness, and ability to illustrate the concept/concern in question.

Recommendations for policy

- NPCC should continue to interact with FEMA in future years, particularly regarding their initiative to work with the city to map future flooding for adaptation planning.

Community-based assessments of adaptation and equity

NPCC3 explored equity in community-based adaptation planning in NYC using a framework that incorporated three key dimensions: *distributional*, *contextual*, and *procedural*. Distributional equity emphasizes disparities across social groups, neighborhoods, and communities in vulnerability, adaptive capacity, and the outcomes of adaptation actions. Contextual equity considers how social, economic, and political factors and processes contribute to vulnerability and shape adaptive capacity. Procedural equity emphasizes the extent and robustness of public and community participation in adaptation planning and decision making.

Recommendations for research

- Investigate the use of co-production processes that include community groups in planning for climate change resiliency and their adaptability to NYC.

Recommendations for policy

- In NYCLIM, there should be future tracking of social vulnerability and its relation to climate change using established indexes[b] and individual variables.
- All forms of equity should be reflected in climate adaptation efforts, particularly if resiliency planning is focused at the neighborhood level.
- City officials should work side by side with communities at the outset and throughout the process to co-design and co-implement neighborhood-based climate adaptation projects. This will help to incorporate local contexts and ensure procedural equity in adaptation planning.
- Climate adaptation projects should contain a stronger focus on community development to reduce the potential of displacing longtime residents and to promote the social sustainability of local communities.

Resilience strategies for critical infrastructure

Interconnections among different infrastructures in the form of dependencies and interdependencies are becoming recognized as important factors in the escalation of adverse consequences resulting from extreme events and climate change. Next steps will be to identify where the vital interconnection points are that produce cascading effects, the process by which those cascades occur, how to reduce their effects through management, and the role of decentralization of infrastructure services to reduce intersection points. Data collection and metrics development are crucial to understanding and enhancing resilience.

Insurance and finance policies continually evolve to provide opportunities to reduce the cost of the consequences of climate change that can further expand to support adaptation and mitigation. Potential modifications could include availability of funding to implement resilience improvements in conjunction with repairs, and mechanisms to encourage pre-disaster resilience improvements and insurance purchase. In this regard, public–private partnerships are essential for facilitating infrastructure resilience, particularly for publicly owned infrastructure systems that often lack resources for resilience improvements. Coordination of insurance and finance is an important future direction to achieve comprehensive resiliency in infrastructure that reduces negative climate change consequences.

Recommendations for research

- Advance knowledge of interactions among infrastructure types and climate risks to better understand evolving vulnerability conditions.
- Improve assessments of effectiveness of green infrastructure (e.g., tree planting and green roofs) in reducing the urban heat island and

[b]For example, University of South Carolina Hazards and Vulnerability Research Institute Social Vulnerability Index of the United State (SOVI); the Center for Disease Control Social Vulnerability Index (SVI).

excessive urban street and basement flooding, in light of anticipated increasing extreme rainfall events.

Recommendations for policy

- Since increased frequency of extreme heat will drive peak energy demand for air conditioning, the city should continue to work with the energy sector to develop improved resiliency to power outages.
- Identify where the vital interconnection points are among different infrastructures (i.e., dependencies and interdependencies) to reduce cascading effects resulting from extreme events and climate change through management and in some cases decentralization.
- Through management, and in some cases decentralization, the city should reduce cascading effects of dependencies and interdependencies resulting from extreme events and climate change.
- To increase resilience and ensure quality of life, the city should increase financial strength, invest in infrastructure maintenance and upgrades, and work with insurance companies to encourage incentives with attention to the risks that infrastructure systems and their users experience.
- Operators should provide access to infrastructure data and resources and work with scientists to explore infrastructure risks associated with climate change.

Indicators and monitoring

A centralized, coordinated, indicators and monitoring (I&M) system for NYC, where specific roles and responsibilities are identified, as described in the proposed NYCLIM, is essential for comprehensive, city-wide risk assessment and course correction toward climate change adaptation and resiliency goals. This is especially important for the design of short- to medium- to long-term investments targeted to adaptation. The proposed system should incorporate a consistent set of measures of climate, impacts, vulnerability, and resiliency to capture changes in climate conditions and progress toward implementation over time.

An effective I&M system must be sufficiently robust and comprehensive to track key climate variables and adaptation strategies. The system must identify vulnerabilities and adaptation measures related to observed conditions and their projected futures.

Spatial and temporal scale resolutions need to be consistent and comparable if the I&M system is to detect effectively trends and differences across sectors and enable effective comparison.

Recommendations for research

- Conduct research on how and to what extent indicators can be linked to current and future resilience under changing climate conditions, including increasing frequency of extreme events.
- Develop social vulnerability indicators, and infrastructure indicators (including dependencies and interdependencies), and mapping tools for NYCLIM.

Recommendations for policy

- The City should take on the responsibility to establish/pilot a climate indicator and monitoring system across multiple governance entities that provide periodic analytical reports on indicator trends to aid in policy, planning, and financial decisions. The goal is to protect citizens and assets under changing climate conditions. To accomplish this, the city should:

    - Designate one of its agencies and an academic partner to oversee the pilot indicator and monitoring system operations (community engagement, stakeholder interactions, data collection, storage and management, analysis, personnel and funding, etc.).
    - Facilitate a co-generation process for the development and dissemination of the NYCLIM system that involves community engagement and regional stakeholders through time.
    - Develop and implement a NYCLIM system that defines scope, explicitly provides information on relevant spatial and temporal scales, and facilitates integration across agencies, levels of governance, sectors, and spatial and temporal scales.

- Support evaluation and iterative research on climate change resilience.

Overall NPCC 2019 report recommendations for the City

The NPCC has provided an essential enabling condition for NYC to proactively and flexibly adapt to changing climate conditions. The challenge now is to sustain this function into the future. To meet this challenge, the city should consider the following set of broader recommendations:

- The City should establish a pilot system for NYCLIM that includes an initial set of indicators for variables to be tracked, including climate observations, social vulnerabilities, and economic metrics from the NPCC 2019 Report.
- As specified in Local Law 42 of 2012, the NPCC should be tasked with developing next-generation climate change projections for use by the city. These new projections of record, which need to be funded by the city, should include the potential for emerging high-end risks such as the ARIM.
- The City should task the NPCC to coordinate with other regional organizations, such as the Consortium for Climate Risk in the Urban Northeast (CCRUN), to conduct integrated climate assessments for the New York metropolitan region on a regular basis. These assessments should encourage the participation of a wide range of city and regional agencies and communities, and a full range of systems and sectors.
- As part of this on-going more integrated assessment process, the city should host a climate summit once during every mayoral term. The climate summits will bring together all of the key groups—both scientists and stakeholders—working on climate change in the New York metropolitan region to present key findings, share best practices, and develop coordinated approaches.