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New York City Panel on Climate Change 2019 Report Chapter 8: Indicators and Monitoring

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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),

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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 $> X^0$F	Central Park	1944–Present	Monthly	NCDC
	Days with temp $< X^0$F	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

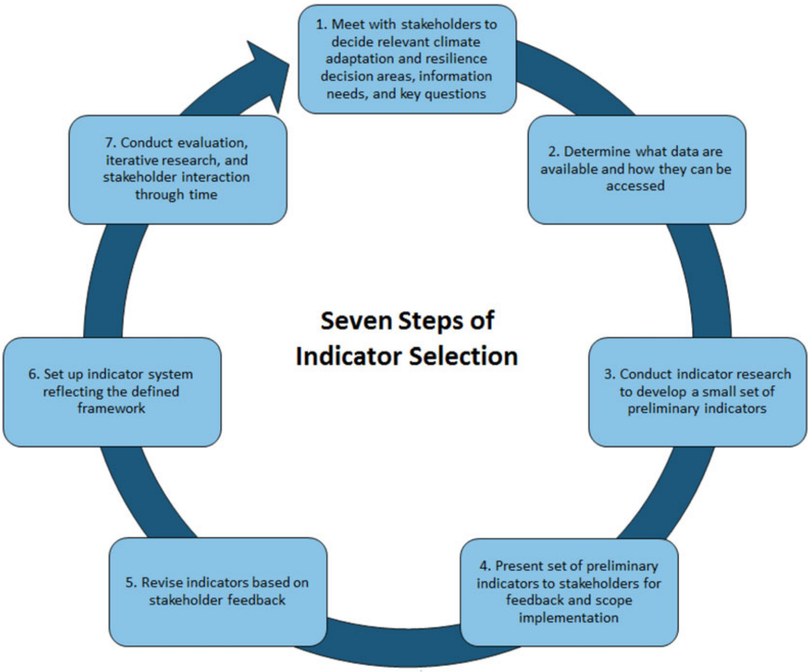

Figure 8.1. Iterative risk management indicator and monitoring selection process (NPCC, 2015).

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,

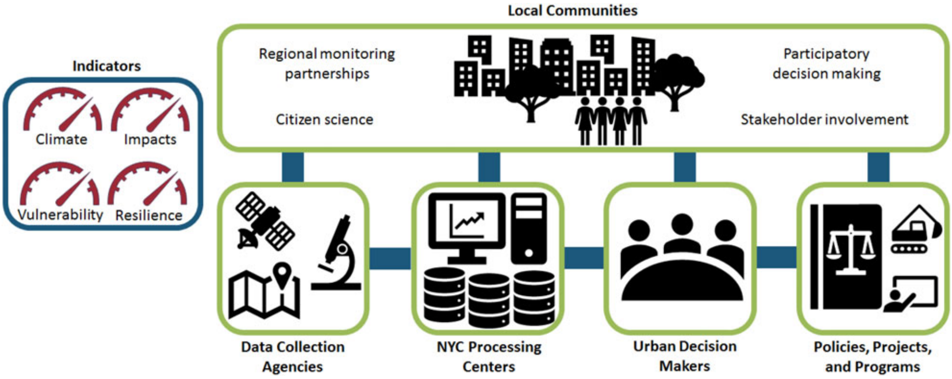

Figure 8.2. Prototype structure and functions of the proposed New York City Climate Change Resilience Indicators and Monitoring System (NYCLIM). The proposed system tracks four types of indicators from data collection agencies, processing centers, urban decision makers, and policies, projects, and programs. 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

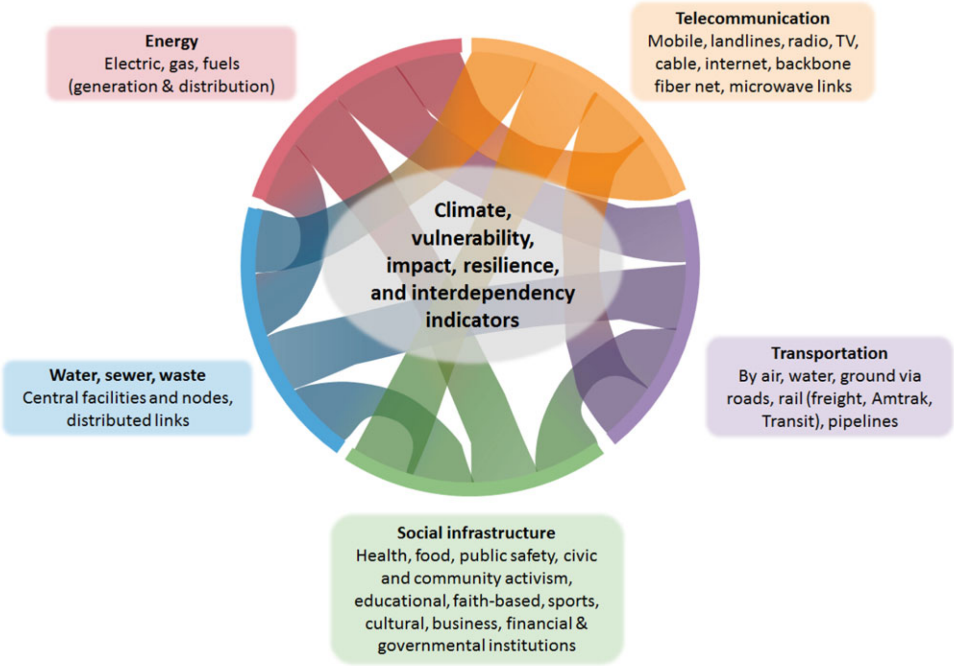

Figure 8.3. Five city-selected lifeline infrastructure sectors.

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; NYCDOS
	– 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; NYCDOS 2. NYS MTA/NYC Transit; PANYNJ; NYCDOS
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*

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[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 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 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

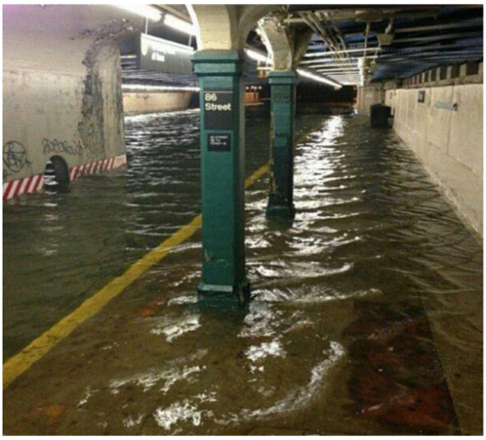

Figure 8.4. Hurricane Sandy causes flooding in New York City's subway (86th Street Lexington Ave. Station, Upper East Side in Manhattan). *Source*: https://www.pinterest.com/pin/218143175672242767/.

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.

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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:

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[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

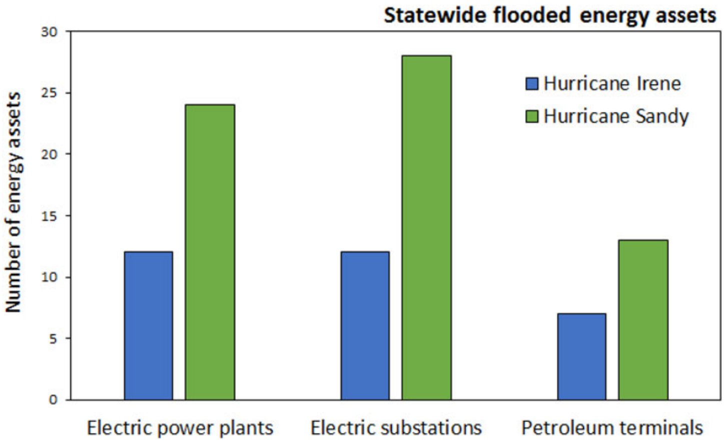

Figure 8.5. Comparative damages to energy assets in flooded areas in New York (statewide) during Hurricane Irene (2011) and Sandy (2012). *Source*: Drawn from U.S. DOE (2013a).

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.

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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.

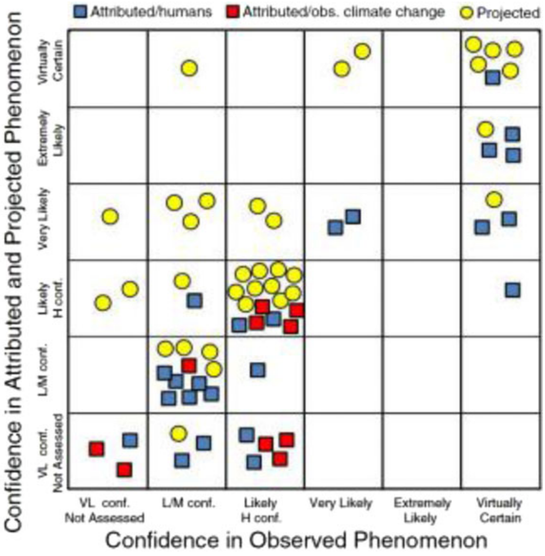


Figure 8.B.1. Higher confidence in projected outcomes versus observed outcomes. *Source*: Figures 1–6 with reference to Tables 1 and 2 in Burkett *et al.* (2014).

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	National and Global since 1990 (X)
by sector	
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:	Annual VMT, DVMT/cap	U.S. **290,116**	2012
Road travel (United States)[a]		Cities **16.3**	
Road travel (cities)[a]			
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)	**74**	2015
	Annual delay (h/commuter)	**35**	
	Fuel excess (gals.)		
	Cost/commuter		
Public transportation use[a]	Average weekday ridership	**11,664**	2014
Water[a] (National Academies, 2016: p. 158)			
Total water usage	Gallons/cap/day	County	
Individual use	Average gallons per capita/day	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)		

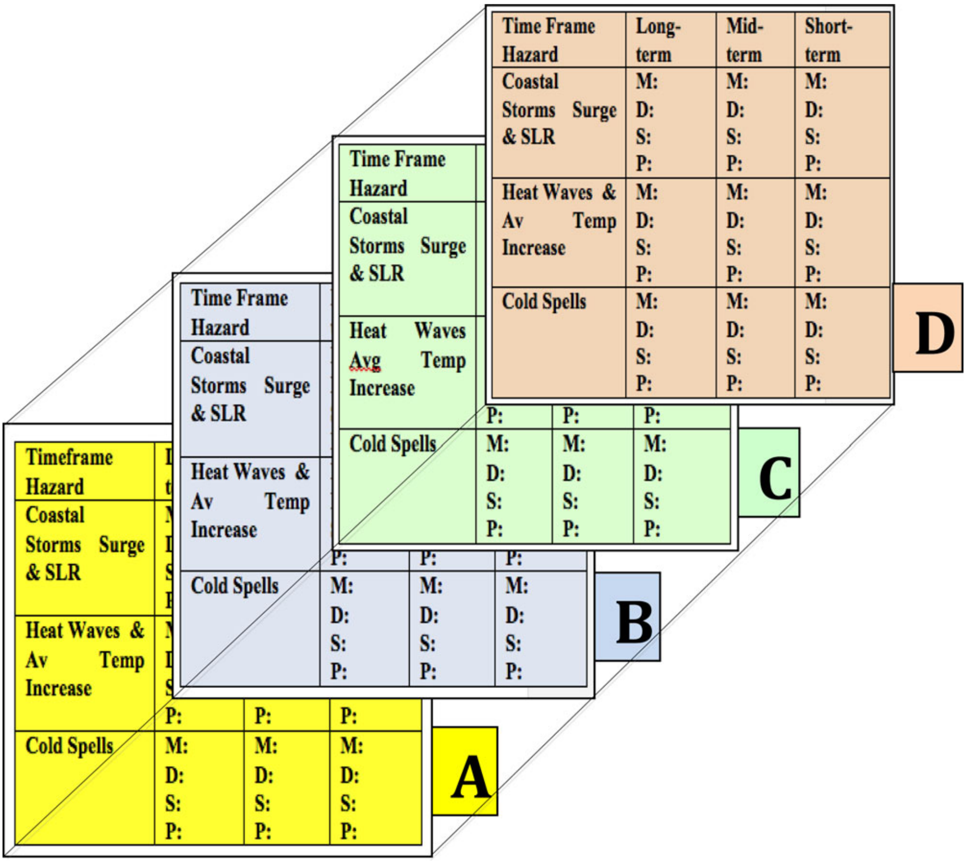
Sectors generating and receiving service from another sector

	Sector receiving the service				
Sector generating the service to another (receiving) sector	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.



Time Frame Hazard	Long-term	Mid-term	Short-term
Coastal Storms Surge & SLR	M: D: S: P:	M: D: S: P:	M: D: S: P:
Heat Waves & Av Temp Increase	M: D: S: P:	M: D: S: P:	M: D: S: P:
Cold Spells	M: D: S: P:	M: D: S: P:	M: D: S: P:

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).

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). 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

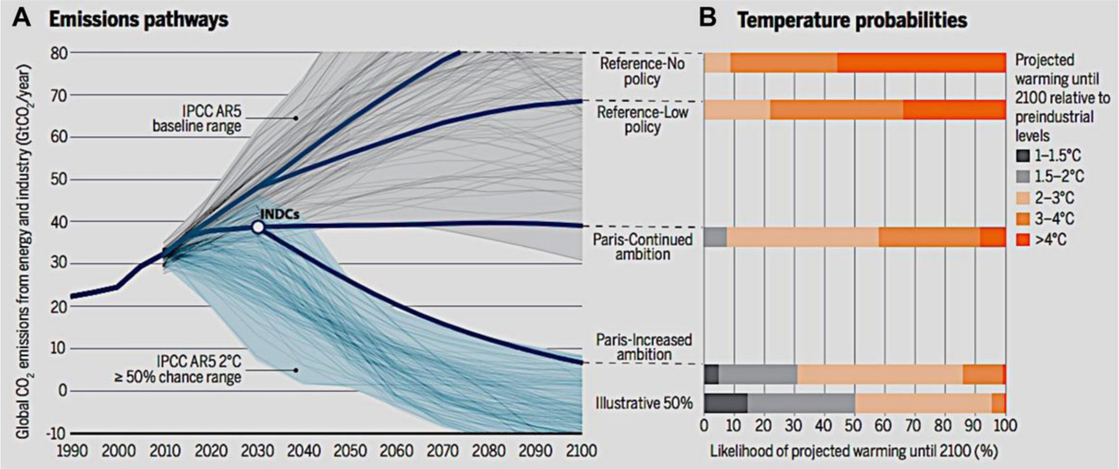


Figure 8.E.1. CO_2 emissions scenarios and associate temperature distributions for the year 2100 under five alternative policy scenarios. *Source*: Fawcett *et al.* (2015).

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.

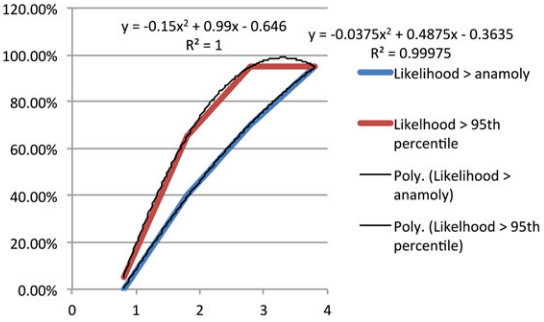


Figure 8.E.2. Likelihood of anomalous heat events in New York City along a no-policy scenario.

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

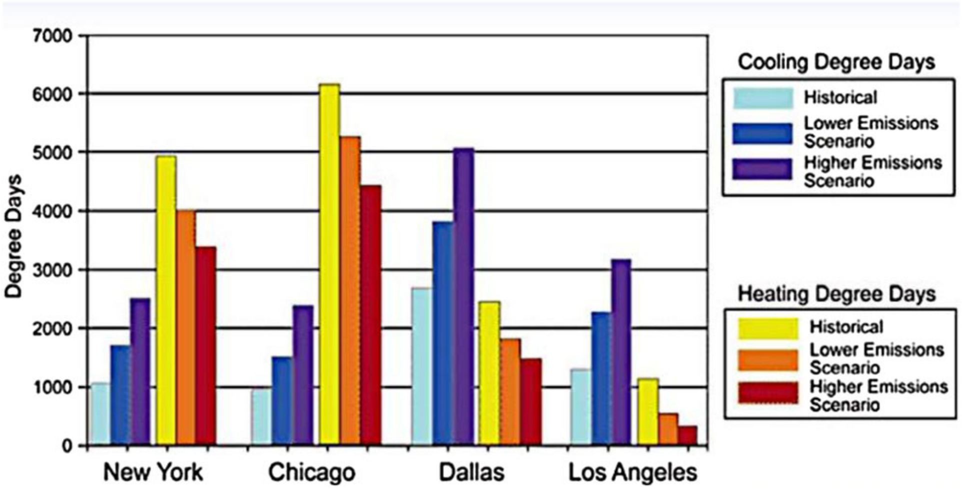


Figure 8.E.3. Changes in CDD and HDD for two emission scenarios and for four cities, including NYC, from before 2000 (historical) and the period 2080–2099. *Source*: USGCP 2009 as presented by US DOE, 2013b.

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.

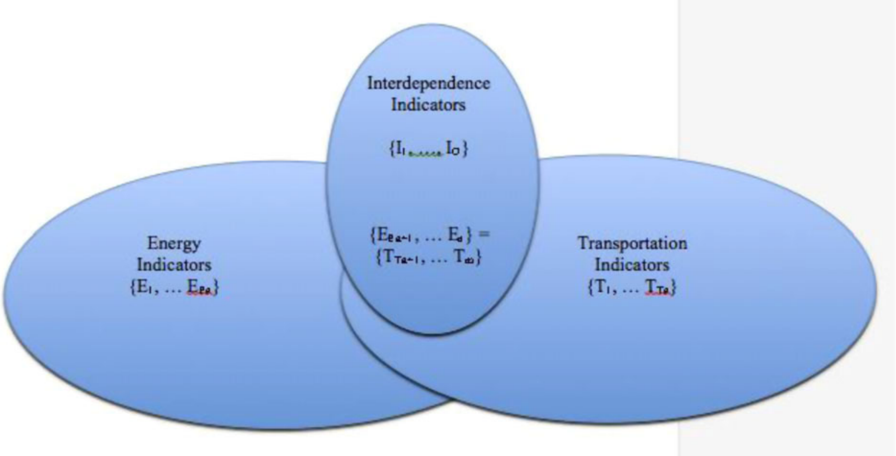


Figure 8.F.1. A schematic diagram of indicators for the energy and transportation sectors and possible interdependences.

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.