

# New York City Panel on Climate Change 2015 Report

## Chapter 1: Climate Observations and Projections

Radley Horton,<sup>1,a</sup> Daniel Bader,<sup>1,a</sup> Yochanan Kushnir,<sup>2</sup> Christopher Little,<sup>3</sup> Reginald Blake,<sup>4</sup> and Cynthia Rosenzweig<sup>5</sup>

<sup>1</sup>Columbia University Center for Climate Systems Research, New York, NY. <sup>2</sup>Ocean and Climate Physics Department, Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY. <sup>3</sup>Atmospheric and Environmental Research, Lexington, MA. <sup>4</sup>Physics Department, New York City College of Technology, CUNY, Brooklyn, NY. <sup>5</sup>Climate Impacts Group, NASA Goddard Institute for Space Studies; Center for Climate Systems Research, Columbia University Earth Institute, New York, NY

Address for correspondence: Radley Horton, Associate Research Scientist, Columbia University Center for Climate Systems Research, 2880 Broadway, New York, NY 10025. rh142@columbia.edu

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### Introduction

During 2013 and 2014, numerous international (IPCC, 2013) and national (Melillo *et al.*, 2014; Gordon, 2014) reports have concluded that human activities are changing the climate, leading to increased vulnerability and risk. Since the industrial revolution, fossil fuel burning, industrial activity, and land use changes have led to a 40% increase in heat-trapping carbon dioxide (CO<sub>2</sub>), and an approximately 150% increase in methane (CH<sub>4</sub>), another powerful greenhouse gas (GHG), has been observed. Global temperatures have increased by close to 1°C since 1880 as the upper oceans have warmed and polar ice has retreated. These and other climate changes are projected to accelerate as greenhouse gas concentrations continue to rise.

In the coming decades, climate change is extremely likely to bring warmer temperatures in the New York metropolitan region (see Box 1.1 and Fig. 1.1 for key definitions and terms). Heat waves are very likely to increase; total annual precipitation will likely increase and brief, intense rainstorms are very likely to increase.

Because of incomplete knowledge about exactly how much climate change will occur, choosing among policies for reducing future damages requires prudent risk management (Yohe and Leichenko, 2010; Kunreuther *et al.*, 2013). Given differing risk tolerances among stakeholders, a risk management approach allows for a range of possible climate change outcomes to be examined with associated uncertainties surrounding their likelihoods.

The New York City Panel on Climate Change 2 (NPCC2) projections can be used to inform planning across multiple governmental scales (e.g., city, county, state) in the New York metropolitan region. Such coordinated efforts can serve as test cases for successful local, state, and federal coordination for integrated climate adaptation initiatives.

This chapter describes the global climate system, and presents observed temperature and precipitation trends and projections for the region. Chapter 2 (NPCC, 2015) focuses on sea level rise and possible changes in coastal storms. Chapter 3 and Chapter 4 (NPCC, 2015) describe efforts to better understand the region's vulnerability to coastal flooding during coastal storms.

The treatment of likelihood related to the NPCC projections is similar to that developed by the Intergovernmental Panel on Climate Change Fourth and Fifth Assessment Reports (IPCC, 2007; 2013), with six likelihood categories (Box 1.1 and Fig. 1.1). The assignment of climate hazards to these categories is

<sup>a</sup>Lead authors.

## Box 1.1. Definitions and terms

### **Climate change**

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

### **Global climate models (GCMs)**

A GCM is a mathematical representation of the behavior of the Earth's climate system over time that can be used to estimate the sensitivity of the climate system to changes in atmospheric concentrations of greenhouse gases (GHGs) and aerosols. Each model simulates physical exchanges among the ocean, atmosphere, land, and ice. The NPCC2 uses 35 GCMs for temperature and precipitation projections.

### **Representative concentration pathways (RCPs)**

RCPs are sets of trajectories of concentrations of GHGs, aerosols, and land use changes developed for climate models as a basis for long-term and near-term climate-modeling experiments (Figure 1.2; Moss *et al.*, 2010). RCPs describe different climate futures based on different amounts of climate forcings<sup>b</sup>. These data are used as inputs to global climate models to project the effects of these drivers on future climate. The NPCC2 uses a set of global climate model simulations driven by two RCPs, known as 4.5 and 8.5, which had the maximum number of GCM simulations available from World Climate Research Programme/Program for Climate Model Diagnosis and Intercomparison (WCRP/PCMDI). RCP 4.5 and RCP 8.5 were selected to bound the range of anticipated GHG forcings at the global scale.

### **Climate change risk information**

On the basis of the selection of the 2 RCPs and 35 GCM simulations, local climate change information is developed for key climate variables—temperature, precipitation, and associated extreme events. These results and projections reflect a range of potential outcomes for the New York metropolitan region (for a full description of projection methods, see Section 1.3).

### **Climate hazard**

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

### **Uncertainty**

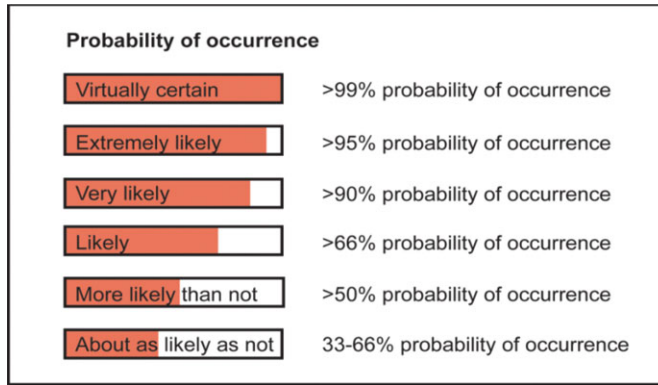
Uncertainty denotes a state of incomplete knowledge that results from lack of information, natural variability in the measured phenomenon, instrumental and modeling errors, and/or from disagreement about what is known or knowable (IPCC, 2013). See Box 1.3 for information on sources of uncertainty in climate projections.

based on observed data, global climate model simulations, published literature, and expert judgment.

<sup>b</sup>A climate forcing is a mechanism that alters the global energy balance, causing the climate to change. Examples of climate forcings include variations in GHG concentrations and volcanic aerosols.

## 1.1 The global climate system

The global climate system is comprised of the atmosphere, biosphere, hydrosphere, cryosphere, and lithosphere. The components of the climate system interact over a wide range of spatial and temporal scales. The Earth's climate is largely driven by the energy it receives from the sun. This incoming solar

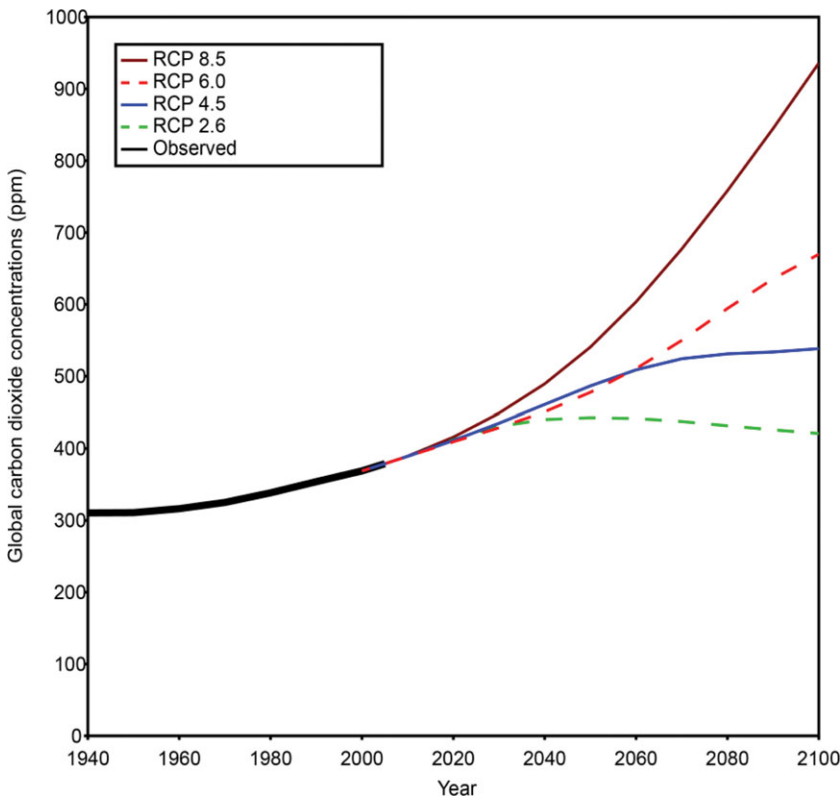


**Figure 1.1.** Probability categories used by NPCC2. Source: IPCC, 2007; 2013.

radiation (shortwave radiation) is partly absorbed, partly scattered, and partly reflected by gases in the atmosphere, by aerosols, by the Earth’s surface, and by clouds. The Earth reemits the energy it receives

from the sun in the form of longwave, or infrared, radiation.

Under equilibrium conditions, there is an energy balance between the outgoing terrestrial longwave



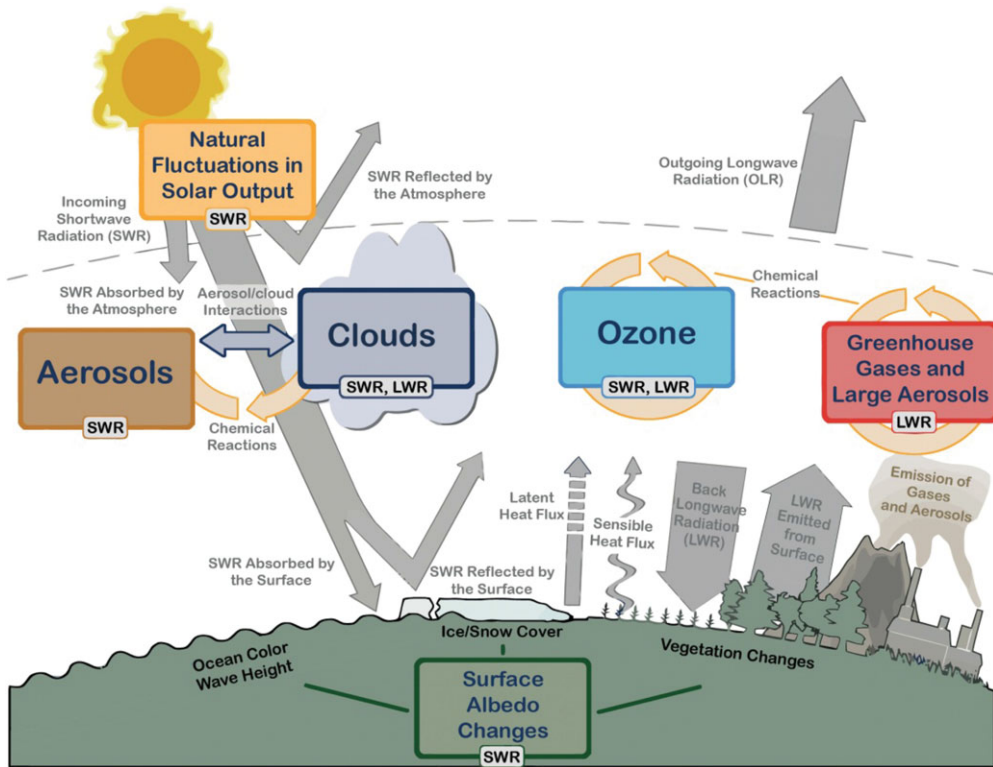
**Figure 1.2.** Observed CO<sub>2</sub> concentrations through 2005 and future CO<sub>2</sub> concentrations consistent with four representative concentration pathways (RCPs). NPCC2 climate projections are based on RCP 4.5 and RCP 8.5. Carbon dioxide and other GHG concentrations are driven by a range of factors, including carbon intensity of energy used, population and economic growth, and diffusion and adoption of new technologies including green energy and energy efficiency.

radiation and the incoming solar radiation. Without the presence of naturally occurring GHGs in the atmosphere, this balance would be achieved at temperatures of approximately  $-33^{\circ}\text{F}$  ( $-18^{\circ}\text{C}$ ). An atmosphere containing GHGs is relatively opaque to terrestrial radiation. Such a planet achieves radiative balance at a higher surface temperature than it would without GHGs. On Earth, the increase in GHG concentrations due to human activities such as fossil fuel combustion, cement making, deforestation, and land use changes has led to a surface warming of almost  $1.8^{\circ}\text{F}$  ( $1^{\circ}\text{C}$ ) and a range of climate changes including upper ocean warming, and loss of land and sea ice. Key components of Earth's radiative balance are illustrated in Figure 1.3.

In the 2013 Fifth Assessment Report (IPCC AR5), the IPCC documented a range of observed climate trends. Global surface temperature has increased about  $1.5^{\circ}\text{F}$  ( $0.85^{\circ}\text{C}$ ) since 1880. Both hemispheres have experienced decreases in net snow and ice cover, and global sea level has risen by approximately 0.5 to 0.7 inches (1.3 to 1.7 cm) per decade over the past century (Hay *et al.*, 2015). More recently,

since the 1990s, the global sea level rise rate has accelerated to approximately 1.3 inches (3.2 cm) per decade (see Chapter 2, NPCC, 2015, for New York metropolitan region sea level rise observations and projections). Droughts (in regions such as but not limited to the Mediterranean and West Africa) have grown more frequent and longer in duration. In the United States, Canada, and Mexico (as well as other regions), intense precipitation events have become more common. Hot days and heat waves have become more frequent and intense, and cold events have decreased in frequency. The upper oceans have warmed and become more acidic (IPCC, 2013). As temperatures have warmed in the atmosphere and ocean, biological systems have responded as well; for example, spring has been arriving earlier, and fall has been extending later into the year, in many mid- and high-latitude regions (IPCC, 2014).

The IPCC AR5 states that there is a greater than 95% chance that warming temperatures since the mid-20th century are primarily due to human activities. Atmospheric concentrations of the major GHG carbon dioxide ( $\text{CO}_2$ ) are now approximately



**Figure 1.3.** The main drivers of climate change. Source: IPCC, 2013.

40% higher than in preindustrial times. Concentrations of other important GHGs, including methane ( $\text{CH}_4$ ) and nitrous oxide ( $\text{N}_2\text{O}$ ), have increased by close to 150% and close to 20%, respectively, since preindustrial times. The warming that occurred globally over the 20th century cannot be reproduced by GCMs unless human contributions to historical GHG concentrations are taken into account (Fig. 1.4).

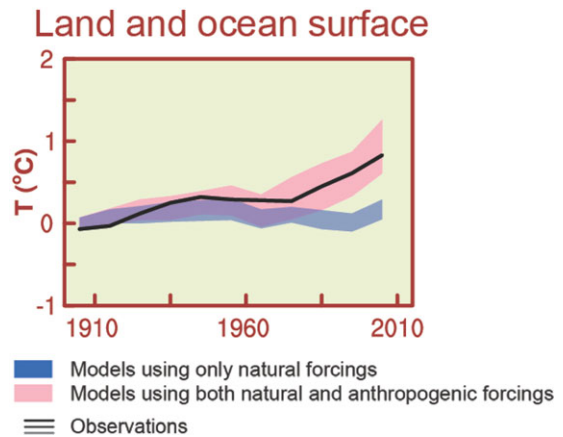
Further increases in GHG concentrations are extremely likely to lead to accelerated temperature increases. Depending on these future emissions and concentrations, by the 2081 to 2100 time period, global average temperatures are projected to increase by 2.0°F to 4.7°F (1.1°C to 2.6°C) or as high as 4.7°F to 8.6°F (2.6°C to 4.8°C)<sup>c</sup> (IPCC, 2013). The large range is due to uncertainties both in future GHG concentrations and the sensitivity<sup>d</sup> of the climate system to GHG concentrations. Warming is projected to be greatest in the high latitudes of the northern hemisphere. Throughout the globe, land areas are generally expected to warm more than ocean regions.

High-latitude precipitation is projected to increase in both hemispheres, while many dry regions at subtropical latitudes, such as the Mediterranean region, are projected to become drier.

Globally, it is virtually certain that the hottest temperatures will increase in frequency and magnitude, and the coldest temperatures will decrease in frequency and magnitude, although there could be regional exceptions (IPCC, 2012). Both land ice and sea ice volumes are projected to decrease. Ocean acidification is projected to increase as  $\text{CO}_2$  concentrations rise.

## 1.2 Observed local climate

This section describes the critical climate hazards related to temperature and precipitation in the New York metropolitan region. For sea level and coastal storms, see Chapters 2 and 4 (NPCC, 2015). Both



**Figure 1.4.** Twentieth-century observations and global climate model results. Source: IPCC, 2013.

mean (e.g., annual averages) and extreme (e.g., heavy downpours) quantities are presented. Observations for New York City are placed in a broader context because trends over large spatial scales (regional, national and global) are an important source of predictability with respect to New York City's future climate.

### Temperature

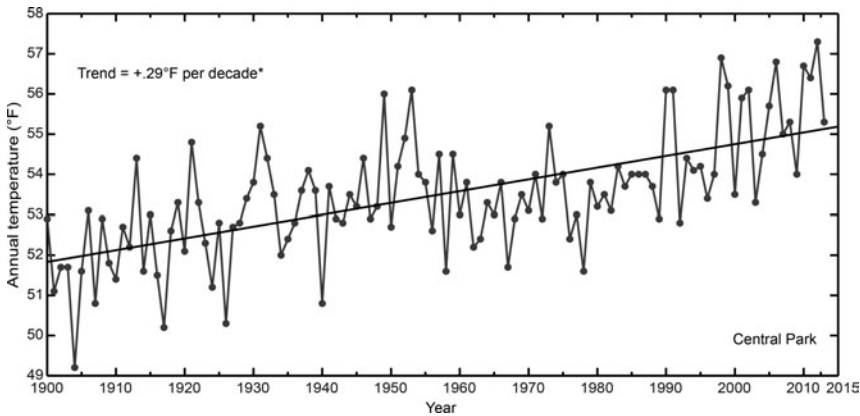
Summers in New York City are warm, with cool winters. Annual mean air temperature in New York City (using data from the Central Park weather station) was approximately 54°F from 1971 to 2000. Mean annual temperature has increased at a rate of 0.3°F per decade over the 1900 to 2013 period in Central Park, although the trend has varied substantially over shorter periods (Fig. 1.5). For example, the first and last 30-year periods were characterized by warming (0.38°F per decade and 0.79°F per decade, respectively), whereas the middle segment experienced negligible cooling (−0.04°F per decade). This absence of warming in the middle of the 20th century is evident nationally and globally as well and has been linked to a combination of high sulphate aerosol emissions (a cooling factor) and natural variability.

The temperature trend since 1900 for the New York metropolitan region is broadly similar to the trend for the northeast United States (Fig. 1.6).<sup>e</sup> Specifically, most of the Northeast has experienced

<sup>c</sup>Estimates based on RCP 4.5 and RCP 8.5.

<sup>d</sup>Climate sensitivity is defined by the IPCC (IPCC, 2007) as the equilibrium or final increase in global temperature associated with a doubling of  $\text{CO}_2$  from preindustrial levels. More generally, sensitivity refers to how much climate change is associated with a given climate-forcing agent, such as  $\text{CO}_2$ .

<sup>e</sup>The Northeast as defined in the U.S. National Climate Assessment consists of Connecticut, Delaware, Maine,



**Figure 1.5.** Observed annual temperature trend in New York City (Central Park) for 1900 to 2013. Data are from NOAA United States Historical Climatology Network (USHCN) Version 2.5 (Menne *et al.*, 2013). \*Trend is significant at the 99% level.

a trend toward higher temperatures, especially in recent decades. This trend is present in both rural and urban weather stations, so it cannot be explained by the urban heat island effect.<sup>f</sup>

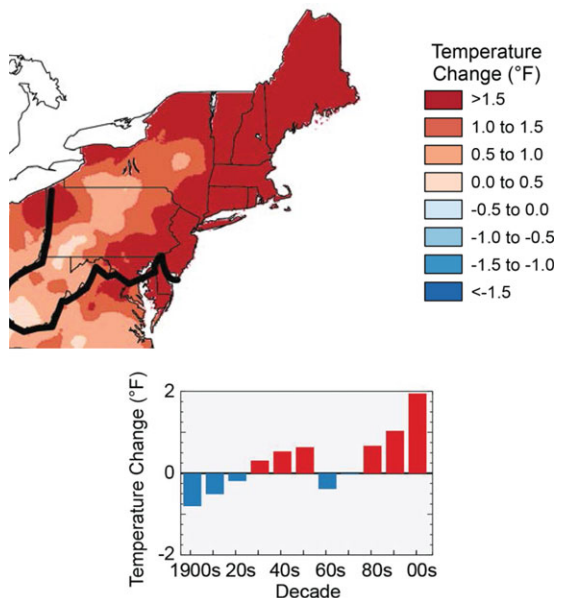
**Precipitation**

New York City experiences significant precipitation throughout the year, with relatively little variation from month to month in the typical year. Annual average precipitation ranges between approximately 43 and 50 inches, depending on the location within the city. Precipitation has increased at a rate of approximately 0.8 inches per decade from 1900 to 2013 in Central Park (Fig. 1.7).

Year-to-year (and multiyear) variability of precipitation has also become more pronounced,

especially since the 1970s. The standard deviation, a measure of variability, increased from 6.1 inches from 1900 to 1956 to 10.3 inches from 1957 to 2013.

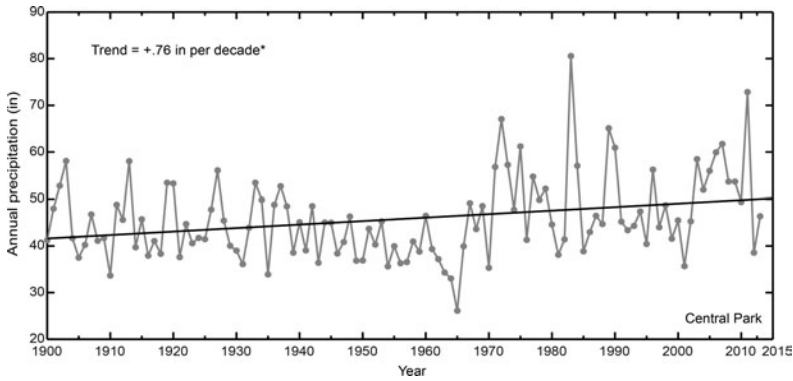
Precipitation in many parts of the larger Northeast region has also increased since the 1900s



**Figure 1.6.** Observed temperature changes in the Northeast. The map shows temperature changes over the past 22 years (1991–2012) compared to the 1901–1960 average. The bars on the graph show the average temperature change by decade for 1901–2012 (relative to the 1901–1960 average). The far right bar (2000s decade) includes 2011 and 2012. Source: Melillo *et al.*, 2014; Horton *et al.*, 2014.

Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and West Virginia (NCA; Melillo *et al.*, 2014; Horton *et al.*, 2014).

<sup>f</sup>Urbanization is often associated with elevated surface air temperature, a condition referred to as the urban heat island (UHI). Urban centers and cities are often several degrees warmer than their surrounding areas. Because of the low albedo (reflectivity) of urban surfaces (such as dark rooftops and asphalt roadways) and reduced evapotranspiration, cities “trap” heat (Blake *et al.*, 2011, and references therein). The future projections described in this chapter primarily reflect the influences of global processes. New York City’s long-term baseline surface temperature is higher than those of surrounding areas in part due to the urban heat island effect, but the UHI cannot explain New York City’s long-term warming trend.



**Figure 1.7.** Observed annual precipitation trend in New York City (Central Park) for 1900 to 2013. Data are from NOAA United States Historical Climatology Network (USHCN) Version 2.5 (Menne *et al.*, 2013). \*Trend is significant at the 99% level.

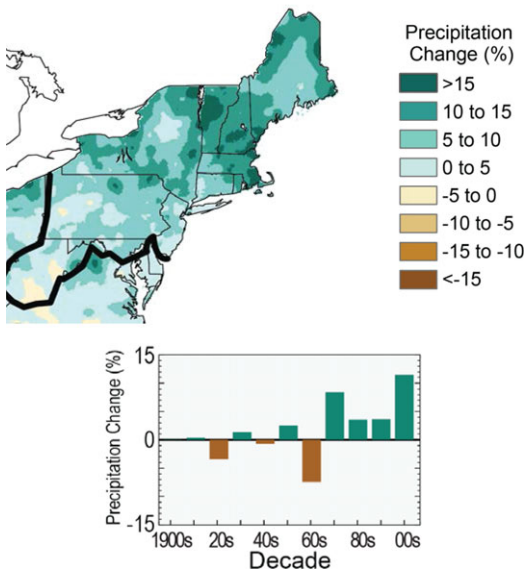
(Fig. 1.8). However, this long-term trend in the Northeast generally cannot be distinguished from natural variability.

**Extreme events**

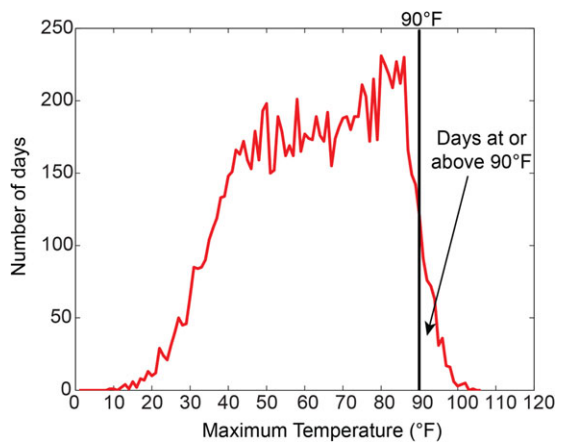
Both temperature and precipitation extremes have significant impacts on New York City. When a single climate variable or combinations of variables approach the tails of their distribution, this

is referred to as an extreme event (see Fig. 1.9 for an example of how an extreme is defined). Extreme precipitation timescales are highly asymmetrical: heavy precipitation events generally range from less than an hour to a few days, whereas meteorological droughts can range from months to years. With its location in the midlatitudes, New York City frequently experiences heat waves in summer and periods of cold weather in winter.

Trends in extreme events at local scales such as the New York metropolitan region are often not statistically significant due to high natural variability and limited record length (Horton *et al.*, 2011). However, some changes in extreme events (such as daily maximum and minimum temperatures and



**Figure 1.8.** Observed precipitation changes in the Northeast. The map shows annual total precipitation changes (%) for 1991–2012 compared to the 1901–1960 average. The bars on the graphs show average precipitation changes (%) by decade for 1901–2012 (relative to the 1901–1960 average). The far right bar is for 2001–2012. Source: Melillo *et al.*, 2014; Horton *et al.*, 2014.



**Figure 1.9.** Distribution of observed cumulative daily maximum temperatures in Central Park from 1971 to 2000 with an extreme event threshold of days with maximum temperature at or above 90°F. Source: NCDC

extreme precipitation) at large spatial scales can be attributed to human influences on global climate (IPCC, 2012). The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) report concluded that it is very likely that there have been an overall decrease in the number of cold days and cold nights and an overall increase in the number of warm days and warm nights globally for most land areas with sufficient data, including North America, Europe, and Asia. The SREX also found that there have been statistically significant trends in the number of heavy precipitation events in some regions around the world (e.g., Canada and Mexico).

Hurricane Sandy has focused attention on the significant effects that extreme climate events have on New York City (see Chapter 2, Box 2.1). Other recent events in the United States, such as the widespread drought of 2012 or the “polar vortex” winter of 2013/2014 (see Box 1.2), also raised awareness of the impacts of weather and climate extremes. Although it is not possible to attribute any one extreme event such as Hurricane Sandy to climate change, sea level rise already occurring in the New York metropolitan region, in part due to climate change, increased the extent and magnitude of coastal flooding during the storm (see also Chapter 2, NPCC, 2015). This is an example of how long-term trends in climate variables can modify the risk of extremes.

**Extreme temperature.** Extreme temperature events can be defined in several ways using daily data from New York City (Central Park weather station) since 1900.<sup>g</sup> Here, we use the following metrics:

- Individual days with maximum temperatures at or above 90°F
- Individual days with maximum temperatures at or above 100°F
- Heat waves, defined as three consecutive days with maximum temperatures at or above 90°F
- Individual days with minimum temperatures at or below 32°F

<sup>g</sup>Temperatures from the meteorological station in Central Park tend to be lower than those in some other parts of New York City. This is due to the close proximity of the weather station to extensive vegetation.

From 1971 to 2000, New York City averaged 18 days per year with maximum temperatures at or above 90°F, 0.4 days<sup>h</sup> per year at or above 100°F, and two heat waves per year.

The number of extreme events in a given year is highly variable. For example, New York City recently recorded three consecutive years (2010–2012) with at least one day with maximum temperatures at or above 100°F. Prior to 2010, the last day at or above 100°F was in 2001, and there has only been one other time on record (1952–1955) where New York City experienced more than two years in a row with maximum temperatures at or above 100°F.

From 1971 to 2000, Central Park averaged 71 days per year with minimum temperatures at or below 32°F. As is the case for hot days, the number of cold days in a given year also varies from one year to the next. In the cool season of 2013/2014, there were 92 days at or below 32°F, whereas in 2011/2012, there were only 37 days. The former is the greatest number of cool season days at or below 32°F since 1976/1977.

**Extreme precipitation.** Extreme precipitation events are defined here as the number of occurrences per year of precipitation at or above 1, 2, and 4 inches per day for New York City (at the weather station in Central Park) since 1900. Between 1971 and 2000, New York City averaged 13 days per year with 1 inch or more of rain, 3 days per year with 2 inches or more of rain, and 0.3 days per year with 4 inches or more of rain. As with extreme temperatures, year-to-year variations in extreme precipitation events are large.

There has been a small but not statistically significant trend toward more extreme precipitation events in New York City since 1900. For example, the four years with the greatest number of events with 2 inches or more of rain have all occurred since 1980 (1983, 1989, 2007, and 2011). Because extreme precipitation events tend to occur relatively infrequently, long time-series of measurements over large areas are needed to identify trends; there is a relatively large burden of proof required to distinguish a significant trend from random variability. Over the larger Northeast region, intense precipitation events (defined as the heaviest 1% of all daily

<sup>h</sup>For extreme events, decimal places are shown for values less than 1, although this does not indicate higher precision/certainty.



events) have increased by approximately 70% over the period from 1958 to 2011 (Horton *et al.*, 2014).

### 1.3 Climate projections

This section presents New York City–specific climate projections for the 21st century along with the methods used to develop the projections. Quantitative global climate model–based projections are provided for means and extremes of temperature and precipitation. This section also describes the potential for changes in other variables (e.g., heat indices and heavy downpours) qualitatively because quantitative projections are either unavailable or considered less reliable. See Appendices I and IIA (NPCC, 2015) for infographics of the projections and further details.

#### *Uncertainty and risk management*

Scientific understanding of climate change and its impacts has increased dramatically in recent years. Nevertheless, there remain substantial uncertainties that are amplified at smaller geographical scales (Box 1.3) (IPCC, 2007; 2012).

The NPCC2 seeks to present climate uncertainties clearly in order to facilitate risk-based decision-making for the use of policy tools such as incentives, regulations, and insurance. The goal is to make New York City and the surrounding metropolitan region more resilient to mean changes in climate and to future extreme events (e.g., Lempert *et al.*, 1996; Kunreuther *et al.*, 2013).

#### *Methods*

The NPCC2 generates a range of climate model-based outcomes for temperature and precipitation from GCM simulations based on two representative concentration pathways (Moss *et al.*, 2010). The RCPs represent a range of possible future global concentrations of GHGs, other radiatively important agents such as aerosols, and land use changes over the 21st century. Simulation results from 35 GCMs are used to produce temperature and precipitation projections for the New York metropolitan region.

For some variables, climate models do not provide results, the model results are too uncertain, or there is not a long-enough history of observations to justify quantitative model-based projections. For these variables, a qualitative projection of the likely direction of change is provided on the basis of expert judgment. Both the quantitative and qualitative

approaches parallel methods used in the IPCC AR5 report (IPCC, 2013).

**Global climate models.** GCMs are mathematical representations of the behavior of the Earth’s climate system over time that can be used to estimate the sensitivity of the climate system to changes in atmospheric concentrations of GHGs and aerosols. Each model simulates physical exchanges among the ocean, atmosphere, land, and ice. Over the past several decades, climate models have increased in both complexity and computational power as physical understanding of the climate system has grown.

The GCM simulations used by the NPCC2 are from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor *et al.*, 2011) and were developed for the IPCC AR5. Compared to the previous climate model simulations from CMIP3 used in the first NPCC (NPCC, 2010), the CMIP5 models generally have higher spatial resolution and include more diverse model types (Knutti and Sedlacek, 2013).

The CMIP5 global climate models include some Earth system models that allow interactions among chemistry, aerosols, vegetation, ice sheets, and biogeochemical cycles (Taylor *et al.*, 2011). For example, warming temperatures in an Earth system model lead to changes in vegetation type and the carbon cycle, which can then “feed back” on temperature, either amplifying (a positive feedback) or damping (a negative feedback) the initial warming. There have also been a number of improvements in model-represented physics and numerical algorithms. Some CMIP5 models include better treatments of rainfall and cloud formation that can occur at small “subgrid” spatial scales. These and other improvements have led to better simulation of many climate features, such as Arctic sea ice extent (Stroeve *et al.*, 2012).

**Local projections.** Local projections are based on GCM output from the single land-based model grid box<sup>i</sup> covering the New York metropolitan region.

<sup>i</sup> GCMs divide the Earth into a series of grid boxes, which represent the finest spatial resolution of the climate model. In each grid box, physical equations (e.g., of motion and moisture conservation) are solved to determine the evolution of the climate in space and time.

### Box 1.2. The polar vortex and climate change

The winter of 2013/2014 serves as a timely reminder that unusually cold conditions can still be expected to occur from time to time as the climate warms, especially at regional and local scales. Cold conditions extended throughout the Eastern United States, where the Great Lakes reached their second highest ice cover amount in the 41-year satellite record. However, averaged over the continental United States, cold conditions in the East were largely canceled out by warm conditions in the Western United States, where a few states experienced their warmest winter on record. Globally, 2013 tied for the fourth warmest year on record (NOAA, 2013). The planet has not experienced a month with below-normal temperatures since February 1985.

The fact that global temperatures continue to climb as GHG concentrations continue to rise does not rule out the possibility that individual regions could cool or that weather could become more extreme in either direction. An emerging body of observational and modeling studies (e.g., Liu *et al.*, 2012) is investigating whether rapid reduction in Arctic sea ice could be producing a wavier jet stream characterized by more, and more persistent, weather extremes. This is an active research topic [counterarguments have been made by Screen and Simmonds (2013) and Wallace *et al.* (2014), for example]. However, the potential consequences are large, given the expected continued retreat of Arctic sea ice (Liu *et al.*, 2013) and the high societal vulnerability to climate extremes.

The precise coordinates of the grid box vary from GCM to GCM because GCMs differ in spatial resolution (i.e., the unit area over which calculations are made). These spatial resolutions range from as fine as ~50 miles by ~40 miles (80 by 65 km) to as coarse as ~195 miles by ~195 miles (315 by 315 km), with an average resolution of approximately 125 miles by 115 miles (200 by 185 km). The changes reported by the NPCC2 in temperature and precipitation through time (e.g., 3 degrees of warming by a given future time period) are specific to the New York metropolitan region.

The spatial area of applicability of the NPCC2 projections is larger for mean changes in temperature and precipitation than for the number of days exceeding extreme event thresholds. The mean changes in temperature and precipitation generally apply across at least a 100-mile land radius. For example, the precise quantitative mean temperature and precipitation change projections for Philadelphia (approximately 78 miles from Manhattan) and New Haven (approximately 70 miles from Manhattan) differ only slightly from those for New York City (i.e.,  $\pm 4\%$ ).<sup>j</sup> These small differences are well within the bounds

of the climate uncertainty in any long-term projections.

Similarly, the qualitative projections for changes in extreme events (such as heat indices and extreme winds) are expected to be generally applicable across an approximately 100-mile radius. However, the quantitative projections of changes in the frequency of extreme event thresholds (e.g., days over 90°F) can be highly variable spatially, even within the confines of a city itself. For example, there is large spatial variation in the number of days over 90°F across the region as a result of factors such as the urban heat island and the distance from the Atlantic Ocean. The percentage change in the number of days over 90°F is variable as well (Meir *et al.*, 2013).

Although the NPCC2 projections for total sea level change are applicable for the New York metropolitan region (see Chapter 2, NPCC, 2015), projected changes in flood extent will vary substantially within the 100-mile radius, and within the city itself, as shown in the NPCC2 coastal flood maps (Chapter 3, NPCC, 2015). This is primarily because coastal topography differs throughout the region;

comparison of the 35-GCM ensemble for RCP 8.5. The climate projections described here illustrate changes for the 2050s relative to the 1980s base period.

<sup>j</sup> Spatial variation in mean temperature and precipitation projections across these three cities is based on the com-

for example, the relatively flat south shores of Brooklyn and Queens are in contrast to the steep shorelines where northern Manhattan and the Bronx meet the Hudson River.

**Time slices.** Although it is not possible to predict future temperature or precipitation for a particular day, month, or year, GCMs are valuable tools for projecting the likely range of changes over multi-decadal time periods. The NPCC2 projections use time slices of 30-year intervals, expressed relative to the baseline period 1971 to 2000, for temperature and precipitation. The NPCC uses three time slices (the 2020s, 2050s, and 2080s) centered around a given decade. For example, the 2050s time slice refers to the period from 2040 to 2069.<sup>k</sup>

The NPCC2 has also provided climate projections for 2100. Projections for 2100 require a different methodological approach from the 30-year time slices discussed above. The primary difference is that because the majority of climate model simulations end in 2100, it is not possible to make a projection for the 30-year time slice centered on the year 2100. Projections for 2100 are an average of two methods that involve adding a linear trend to the final time slice (2080s) and extrapolating that trend to 2100 (see Appendix IIA).

Uncertainties grow over the timeframe of the NPCC projections toward the end of the century (Box 1.3). For example, the RCPs do not sample all the possible carbon and other biogeochemical cycle feedbacks associated with climate change. The few Earth system models in CMIP5 used by the NPCC2 could possibly underestimate the potential for increased methane and carbon release from the thawing Arctic permafrost under extreme warming scenarios. More generally, the potential for surprises, such as technological innovations that could remove carbon from the atmosphere, increases the further into the future one considers.

**Model-based probability.** The combination of 35 GCMs and two RCPs produces a 70 (35 × 2)-member matrix of outputs for temperature and precipitation. For each time period, the results con-

stitute a climate model-based range of outcomes, which can be used in risk-based decision-making. Equal weights were assigned to each GCM and to each of the two selected RCPs.

The results for future time periods are compared to the climate model results for the baseline period (1971 to 2000). Mean temperature change projections are calculated via the delta method, a type of bias-correction<sup>l</sup> whereby the difference between each model's future and baseline simulation is used, rather than "raw" model outputs. The delta method is a long-established technique for developing local climate-change projections (Gleick, 1986; Arnell, 1996; Wilby *et al.*, 2004; Horton *et al.*, 2011). Mean precipitation change is similarly based on the ratio of a given model's future precipitation to that of its baseline precipitation (expressed as a percentage change<sup>m</sup>).

**Methods for projecting changes in extreme events.** The greatest impacts of extreme temperature and precipitation (with the exception of drought) occur on daily rather than monthly timescales. Because monthly output from climate models is considered more reliable than daily output (Grotch and MacCracken, 1991), the NPCC2 uses a hybrid projection technique for extreme events.

Modeled changes in monthly temperature and precipitation are based on the same methods described for the annual data. Monthly changes through time in each of the GCM-RCP combinations are then applied (added in the case of degrees of temperature change and multiplied in the case of percentage change in precipitation) to the observed daily 1971 to 2000 temperature and precipitation data from Central Park to generate 70 time-series of daily data. This simplified approach to projections of extreme events does not account for possible changes in

<sup>k</sup>Thirty-year time slices are required to minimize the effects of natural variability, which is largely unpredictable. For sea level rise (see Chapter 2), 10-year time slices are sufficient due to smaller natural variability.

<sup>l</sup>Bias correction is a standard practice when climate model outputs are used because long-term changes through time are considered more reliable than actual values, especially when an area like the New York metropolitan region, that is smaller than the size of a climate model grid box, is assessed.

<sup>m</sup>The ratio approach is used for precipitation because it minimizes the impact of climate model biases in average baseline precipitation, which can be large for some models at monthly scales.

### Box 1.3. Sources of uncertainty in climate projections

Sources of uncertainty in climate projections include:

*Future concentrations of GHGs, aerosols, black carbon, and land use change.* Future GHG concentrations will depend on population and economic growth, technology, and biogeochemical feedbacks (e.g., methane release from permafrost in a warming Arctic). Multiple emissions scenarios and/or RCPs are used to explore possible futures.

*Sensitivity of the climate system to changes in GHGs and other “forcing” agents.* Climate models are used to explore how much warming and other changes may occur for a given change in radiatively important agents. The direct temperature effects of increasing CO<sub>2</sub> are well understood, but models differ in their feedbacks (such as changes in clouds, water vapor, and ice with warming) that determine just how much warming ultimately will occur. A set of climate models is used to sample the range of such outcomes.

*Regional and local changes* that may differ from global and continental averages. Climate model results can be statistically or dynamically downscaled (e.g., using regional models embedded within global models), but some processes may not be captured by existing downscaling techniques. Examples include changes in land–sea breezes and the urban heat island effect on a warming planet.

*Natural variability* that is largely unpredictable, especially in midlatitude areas such as the New York metropolitan region. As a result, even as increasing GHG concentrations gradually shift weather and climate, random elements will remain important, especially for extreme events and over short time periods (e.g., a cold month). Chaos theory has demonstrated that natural variability can be driven by small initial variations that amplify thereafter. Other sources of natural variability include the El Niño Southern Oscillation and solar cycles. Averaging short-term weather over long periods of time (e.g., 30 years) can average out much of the natural variability, but it does not eliminate it entirely.

*Observations* include uncertainties as well. Sources of observational uncertainty include poor siting of weather stations, instrument errors, and errors involved in the processing of data using models.

submonthly variability over time, which are not well understood.

#### *Projections for the New York metropolitan region*

This section presents climate projections for the 2020s, 2050s, 2080s, and 2100 for temperature, precipitation, and extreme events.

**Mean annual changes.** Higher temperatures are extremely likely for the New York metropolitan region in the coming decades. All simulations project continued increases through the end of this century. Most GCM simulations indicate small increases in precipitation, but some do not. Natural precipitation variability is large; thus, precipitation projections are less certain than temperature projections.

*Future temperature.* The projected future temperature changes shown in Table 1.1 and Figure 1.10 indicate that by the 2080s, New York City’s mean

temperatures throughout a “typical” year may bear similarities to those of a city like Norfolk, Virginia, today. The middle range of projections show temperatures increasing by 2.0°F to 2.8°F by the 2020s, 4.0°F to 5.7°F by the 2050s, and 5.3°F to 8.8°F by the 2080s. By 2100, temperatures may increase by 5.8°F to 10.3°F. Temperature increases are projected to be comparable for all months of the year.

The two RCPs project similar temperature changes up to the 2020s; after the 2020s, temperature changes produced by RCP 8.5 are higher than those produced by RCP 4.5. It takes several decades for the different RCPs to produce large differences in climate due to the long lifetime of GHGs in the atmosphere and the inertia or delayed response of the climate system and the oceans especially.

*Future precipitation.* Table 1.1 indicates that regional precipitation is projected in the middle range to increase by approximately 1–8% by the

**Table 1.1. Mean annual changes**

a. Temperature			
Baseline (1971–2000) 54°F	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
2020s	+1.5°F	+2.0–2.9°F	+3.2°F
2050s	+3.1°F	+4.1–5.7°F	+6.6°F
2080s	+3.8°F	+5.3–8.8°F	+10.3°F
2100	+4.2°F	+5.8–10.4°F	+12.1°F
b. Precipitation			
Baseline (1971–2000) 50.1 in	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
2020s	–1 percent	+1–8%	+10%
2050s	+1 percent	+4–11%	+13%
2080s	+2 percent	+5–13%	+19%
2100	–6 percent	–1% to +19%	+25%

NOTE: Based on 35 GCMs and two RCPs. Baseline data cover the 1971–2000 base period and are from the NOAA National Climatic Data Center (NCDC). Shown are the low estimate (10th percentile), middle range (25th percentile to 75th percentile), and high estimate (90th percentile). These estimates are based on a ranking (from most to least) of the 70 (35 GCMs times 2 RCPs) projections. The 90th percentile is defined as the value that 90 percent of the outcomes (or 63 of the 70 values) are the same or lower than. Like all projections, the NPCC climate projections have uncertainty embedded within them. Sources of uncertainty include data and modeling constraints, the random nature of some parts of the climate system, and limited understanding of some physical processes. The NPCC characterizes levels of uncertainty using state-of-the-art climate models, multiple scenarios of future greenhouse gas concentrations, and recent peer-reviewed literature. Even so, the projections are not true probabilities and the potential for error should be acknowledged.

2020s, 4–11% by the 2050s, and 5–13% by the 2080s. By 2100, projected changes in precipitation range from –1 to +19%. In general, the projected changes in precipitation associated with increasing GHGs in the global climate models are small relative to year-to-year variability. Figure 1.11 shows that precipitation is characterized by large historical variability, even with 10-year smoothing. One example is the New York metropolitan region’s multi-year drought of record in the 1960s.

Precipitation increases are expected to be largest during the winter months. Projections of precipitation changes in summer are inconclusive, with approximately half the models projecting precipitation increases and half projecting decreases (see Appendix IIA for seasonal projections).

**Future extreme events.** Despite their brief duration, extreme events can have large impacts on New York City’s infrastructure, natural systems, and population. This section describes how the frequencies of heat waves, cold events, and intense precipitation in the New York metropolitan

region are projected to change in the coming decades. The extreme event projections shown in Table 1.2 are based on observed data for Central Park.

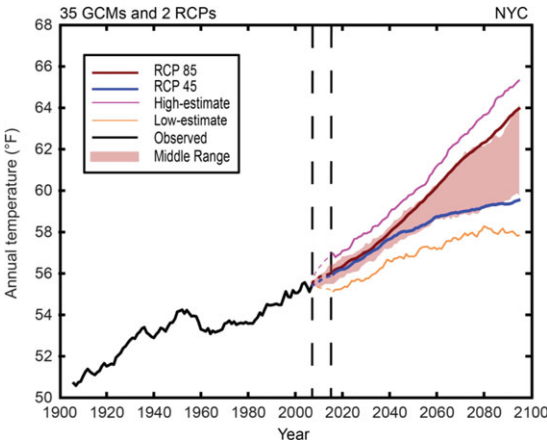
*Future heat waves and cold events.* The total number of hot days, defined as days with a maximum temperature at or above 90°F or 100°F, is expected to increase as the 21st century progresses (Table 1.2). By the 2020s, the frequency of days at or above 90°F may increase by more than 50% relative to the 1971 to 2000 base period; by the 2050s, the frequency may more than double; by the 2080s, the frequency may more than triple. Although 100°F days are expected to remain relatively rare, the percentage increase in their frequency of occurrence is projected to exceed the percentage change in days at or above 90°F.

The frequency and duration of heat waves, defined as three or more consecutive days with maximum temperatures at or above 90°F, are very likely to increase. In contrast, the frequency of extreme cold events, defined as the number of days per year with minimum temperatures at or below 32°F, is projected to decrease approximately 25% by the

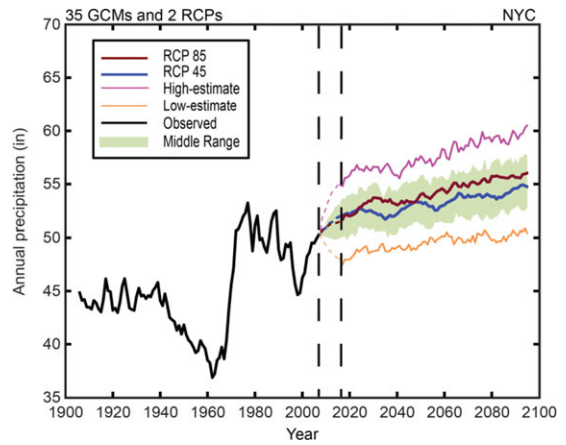
**Table 1.2. Extreme events**

	Baseline (1971–2000)	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
<b>a. 2020s</b>				
Numbers of heat waves per year	2	3	3–4	4
Average heat wave duration (days)	4	5	5	5
Number of days per year with				
Maximum temperature at or above 90°F	18	24	26–31	33
Maximum temperature at or above 100°F	0.4	0.7	1–2	2
Minimum temperature at or below 32°F	71	50	52–58	60
Rainfall at or above 1 inch	13	13	14–15	16
Rainfall at or above 2 inches	3	3	3–4	5
Rainfall at or above 4 inches	0.3	0.2	0.3–0.4	0.5
<b>b. 2050s</b>				
	Baseline	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
Numbers of heat waves per year	2	4	5–7	7
Average heat wave duration (days)	4	5	5–6	6
Number of days per year with				
Maximum temperature at or above 90°F	18	32	39–52	57
Maximum temperature at or above 100°F	0.4	2	3–5	7
Minimum temperature at or below 32°F	71	37	42–48	52
Rainfall at or above 1 inch	13	13	14–16	17
Rainfall at or above 2 inches	3	3	4–4	5
Rainfall at or above 4 inches	0.3	0.3	0.3–0.4	0.5
<b>c. 2080s</b>				
	Baseline	Low estimate (10th percentile)	Middle range (25th to 75th percentile)	High estimate (90th percentile)
Numbers of heat waves per year	2	5	6–9	9
Average heat wave duration (days)	4	5	5–7	8
Number of days per year with				
Maximum temperature at or above 90°F	18	38	44–76	87
Maximum temperature at or above 100°F	0.4	2	4–14	20
Minimum temperature at or below 32°F	71	25	30–42	49
Rainfall at or above 1 inch	13	14	15–17	18
Rainfall at or above 2 inches	3	3	4–5	5
Rainfall at or above 4 inches	0.3	0.2	0.3–0.5	0.7

NOTE: Projections for temperature and precipitation are based on 35 GCMs and 2 RCPs. Baseline data are for the 1971 to 2000 base period and are from the NOAA National Climatic Data Center (NCDC). Shown are the low estimate (10th percentile), middle range (25th to 75th percentile), and high estimate (90th percentile) 30-year mean values from model-based outcomes. Decimal places are shown for values less than one, although this does not indicate higher precision/certainty. Heat waves are defined as three or more consecutive days with maximum temperatures at or above 90°F. Like all projections, the NPCC climate projections have uncertainty embedded within them. Sources of uncertainty include data and modeling constraints, the random nature of some parts of the climate system, and limited understanding of some physical processes. The NPCC characterizes levels of uncertainty using state-of-the-art climate models, multiple scenarios of future greenhouse gas concentrations, and recent peer-reviewed literature. Even so, the projections are not true probabilities and the potential for error should be acknowledged.



**Figure 1.10.** Combined observed (black line) and projected temperature (colored lines). Projected model changes through time are applied to the observed historical data. The two thick lines (blue and red) show the average for each representative concentration pathway across the 35 GCMs. Shading shows the middle range. The bottom and top lines respectively show each year’s low-estimate and high-estimate projections across the suite of simulations. A smoothing procedure/10-year filter has been applied to the observed data and model output to remove unpredictable short-term natural variability and highlight longer-term signals associated with climate and climate change. The dotted area between 2007 and 2015 represents the time period that is not covered due to the smoothing procedure.



**Figure 1.11.** Combined observed (black line) and projected precipitation (colored lines). Projected model changes through time are applied to the observed historical data. The two thick lines (blue and red) show the average for each representative concentration pathway across the 35 GCMs. Shading shows the middle range. The bottom and top lines respectively show each year’s low-estimate and high-estimate projections across the suite of simulations. A smoothing procedure/10-year filter has been applied to the observed data and model output to remove unpredictable short-term natural variability and highlight longer-term signals associated with climate and climate change. The dotted area between 2007 and 2015 represents the time period that is not covered due to the smoothing procedure.

2020s, more than 33% by the 2050s, and approximately 50% by the 2080s.

**Future extreme precipitation.** Although the percentage increase in annual precipitation is expected to be relatively small, larger percentage increases are expected in the frequency, intensity, and duration of extreme precipitation (defined in this report as at least 1, 2, or 4 inches) at daily timescales (Table 1.2). Because some parts of New York City, including parts of coastal Brooklyn and Queens, currently experience significantly fewer extreme precipitation days than does Central Park, they may experience fewer extreme precipitation days than those shown in the table for Central Park in the future as well.

**Qualitative extreme events.** For some of the extreme climate events, future changes are too uncertain at local scales to allow quantitative projections. For example, the relationships between short duration extreme precipitation events and different types of storms, and between droughts and temperature/precipitation, are complex. For these, the NPCC makes qualitative projections based on scientific literature and expert judgment (Table 1.3).

By the end of the century, heat indices<sup>7</sup> are very likely to increase, both directly due to higher temperatures and because warmer air can hold more moisture. The combination of high temperatures and high humidity can produce severe additive effects by restricting the human body’s ability to cool itself and thereby induce heat stress (see Chapter 5, NPCC, 2015).

Downpours, defined as intense precipitation at subdaily, and often subhourly, timescales, are very likely to increase in frequency and intensity. Changes in lightning are currently too uncertain to support even qualitative statements.

By the end of the century, it is more likely than not that late-summer short-duration droughts will increase in the New York metropolitan region (Rosenzweig *et al.*, 2011). It is unknown how multiyear drought risk in the New York metropolitan region may change in the future.

<sup>7</sup>The heat index (HI) or “apparent temperature” is an approximation of how hot it “feels” for a given combination of air temperature and relative humidity (American Meteorological Society, 2013).

**Table 1.3. Qualitative changes in extreme events**

	Spatial scale of projection	Direction of change by the 2080s	Likelihood	Sources
Heat index	New York metropolitan region	Increase	Very likely	NPCC, 2010; IPCC, 2012; Fischer and Knutti, 2012
Short-duration drought	New York metropolitan region	Increase	More likely than not	Rosenzweig <i>et al.</i> , 2011
Multi-year drought	New York metropolitan region	Unknown	—	Dai, 2013
Seasonal snowfall	New York metropolitan region	Decrease	Likely	IPCC, 2007; 2012; Liu <i>et al.</i> , 2012
Ice storms/freezing rain	New York metropolitan region	Unknown	—	NPCC, 2010; Rosenzweig <i>et al.</i> , 2011
Downpours	New York metropolitan region	Increase	Very likely	IPCC, 2012; Melillo <i>et al.</i> , 2014
Lightning	New York metropolitan region	Unknown	—	Melillo <i>et al.</i> , 2014; Price and Rind, 1994

As the century progresses, snowfall is likely to become less frequent, with the snow season decreasing in length (IPCC, 2007). Possible changes in the intensity of snowfall per storm are highly uncertain. It is unknown how the frequency and intensity of ice storms and freezing rain may change.

#### 1.4 Conclusions and recommendations

Projections for the New York metropolitan region from the current generation of global climate models indicate large climate changes and thus the potential for large impacts. In the coming decades, the NPCC projects that climate change is extremely likely to bring warmer temperatures to New York City and the surrounding region. Heat waves are very likely to increase. Total annual precipitation is likely to increase, and brief, intense rainstorms are very likely to increase. It is more likely than not that short-duration, end-of-summer droughts will become more severe. Although there remain significant uncertainties regarding long-term climate change, these projections would move the city's climate outside what has been experienced historically.

This chapter offers critical information that can be used to support resiliency, but a central message is that the high-end scenarios of extreme warming may challenge even a great city like New York's adaptive capacity. The best steps to avoid extreme warming are to ramp up the reductions in GHG emissions already undertaken in New York City (City of New York, 2014). Although GHG emissions are a global issue, New York City's leadership on emissions reduction in the United States and internationally is crucially important.

Although the NPCC has a growing understanding of how the city as a whole may be affected by climate change, more research is needed on neighborhood-by-neighborhood impacts. Neighborhood- and building-level indicators and monitoring (see Chapter 6, NPCC, 2015) of temperature, precipitation, air quality, and other variables will be critical in the era of "big data." High-resolution regional climate modeling will also illuminate how projected changes vary throughout the city due to factors including coastal breezes, topography, and different urban land surfaces.



The NPCC risk-based approach emphasizes a range of possible outcomes and lends itself to updated projections as new information and climate model results become available. Such updates are essential as the science of climate change advances.

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