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

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Issue: *New York City Panel on Climate Change 2010 Report*

Chapter 3: Climate observations and projections

Lead authors
Radley Horton,[1] Vivien Gornitz,[1] and Malcolm Bowman[2]

[1]Columbia University Center for Climate Systems Research, New York, New York. [2]School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, New York

Contributing author
Reginald Blake[3]

[3]Physics Department, New York City College of Technology, Brooklyn, New York

Address for correspondence: Radley Horton, Associate Research Scientist, NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025. Voice: 212-678-5640. Rmhorton@giss.nasa.gov

Introduction

Climate change is extremely likely (see Fig. 3.1 for definitions of uncertainty terms and Box 3.1 for additional definitions) to bring warmer temperatures to New York City and the surrounding region (see CRI, Appendix A, for further information on all the material presented in this chapter). Heat waves are very likely to become more frequent, intense, and longer in duration. Total annual precipitation will more likely than not increase, and brief, intense rainstorms are also likely to increase, with concomitant flooding. Toward the end of the 21st century, it is more likely than not that droughts will become more severe. Additionally, rising sea levels are extremely likely, and are very likely to lead to more frequent and damaging flooding related to coastal storm events in the future.

The treatment of likelihood related to the New York City Panel on Climate Change (NPCC) climate change projections is similar to that developed by the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4, 2007), with six likelihood categories. The assignment of climate hazards to these categories is based on global climate simulations, published literature, and expert judgment.

3.1 The climate system and the impact of human activities

This section describes the climate system and how human activities are leading to climate change. Terminology used throughout the chapter is also defined.

The global climate system is comprised of the atmosphere, biosphere, hydrosphere, cryosphere, and lithosphere as shown in Figure 3.2. The components of the climate system interact over a wide range of spatial and temporal scales.

The earth's climate is inextricably linked to the energy received from the sun. This incoming solar radiation is partly absorbed, partly scattered, and partly reflected by gases in the atmosphere, by aerosols, and by clouds. The oceans, lithosphere, and biosphere absorb most of the radiation that reaches the surface.[1] Some of the absorbed energy is used to heat the earth. The earth re-emits some of 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 radiation and the incoming solar radiation. Without the presence of naturally occurring

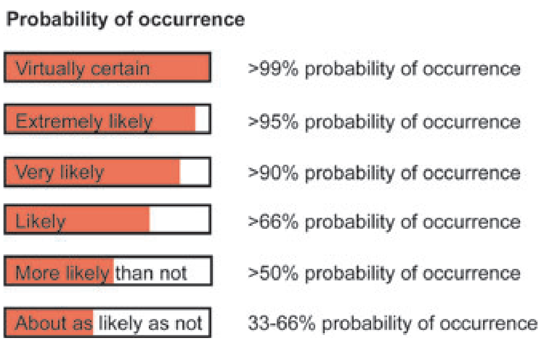

Figure 3.1. Probability of occurrence. Source: IPCC WG1 2007.

greenhouse gases (GHGs) in the atmosphere (i.e., mostly water vapor, but some carbon dioxide), this balance would be achieved at temperatures of approximately −33°F (−18°C). An atmosphere containing GHGs, however, is relatively transparent to solar radiation, but relatively opaque to terrestrial radiation. Such a planet achieves radiative balance at a higher surface and lower atmospheric temperature than a planet totally without GHGs. 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 radiative imbalance and rising surface temperature.

In its 2007 Fourth Assessment Report, the IPCC documented a range of observed climate trends. Global surface temperature has increased about 1.3°F (0.7°C) over the past century. During that time, both hemispheres have experienced decreases in net snow and ice cover, and global sea level has risen by approximately 0.7 inches (1.8 cm) per decade over the past century. More recently, the global sea level rise rate has accelerated to approximately 1.2 inches (3.1 cm) per decade. In terms of extreme events, droughts have grown more frequent and longer in duration, and over most land areas 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 IPCC AR4 states that there is a greater than 90% chance that warming temperatures are *primarily* due to human activities. Atmospheric concentrations of the major GHG carbon dioxide (CO_2) are now more than one-third higher than in pre-industrial times. Concentrations of other important GHGs, including methane (CH_4) and nitrous oxide (N_2O), have increased by more than

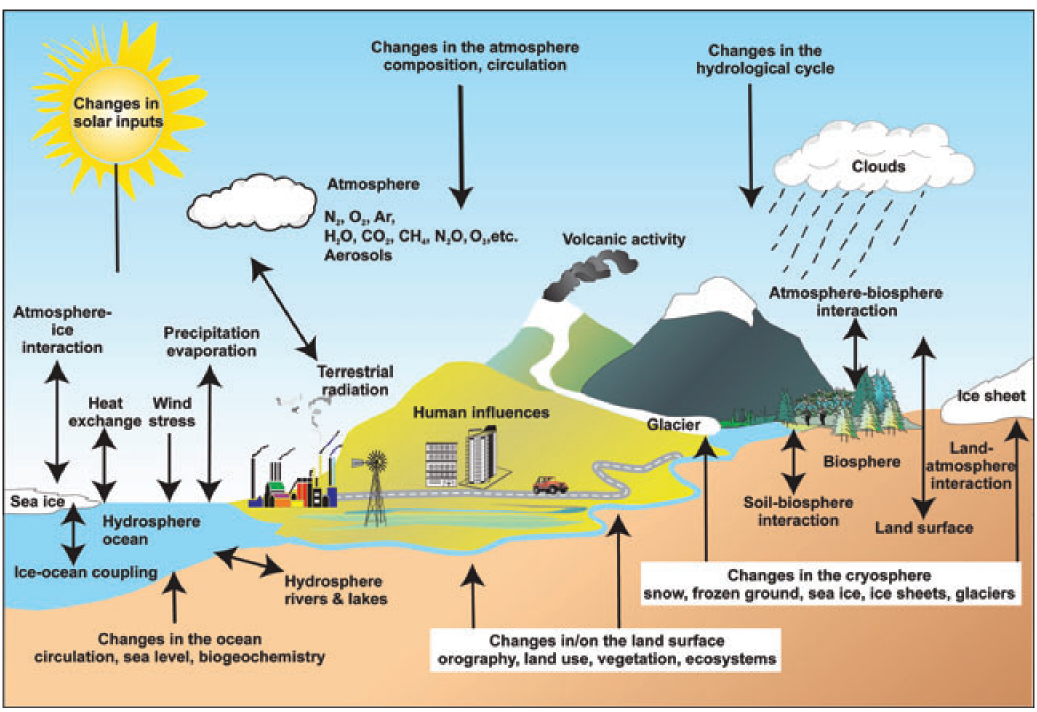

Figure 3.2. The global climate system. Adapted from IPCC WG1 2007.

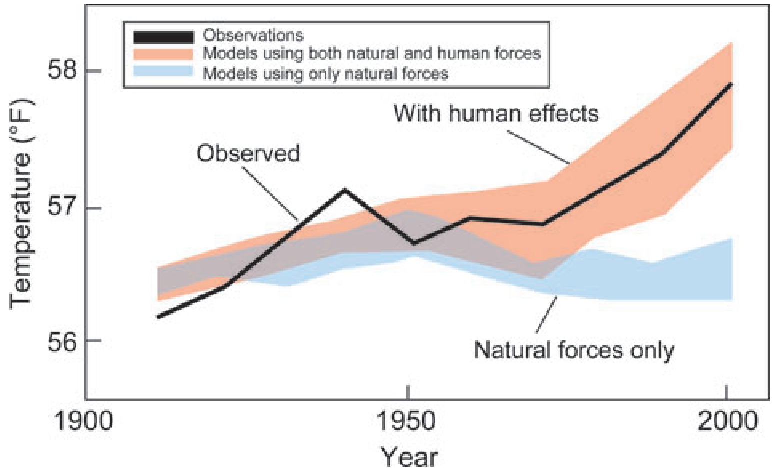

Figure 3.3. **20th century observations and GCM results. Adapted from IPCC WG1 2007 and United States Global Change Research Program.**

100% and close to 20%, respectively, since pre-industrial times. The warming that occurred over the 20th century cannot be reproduced by global climate models (GCMs) unless human contributions to historical GHG concentrations are taken into account (Fig. 3.3). Further increases in GHG concentrations are extremely likely to lead to accelerated temperature increases.

According to the IPCC, global average temperature over the 21st century is expected to increase by between 3.2 and 7.2°F (1.8–4.0°C). The large range is due to uncertainties both in future GHG concentrations and the sensitivity[2] of the climate system to GHG emissions. Globally averaged temperature projections mask a range of regional variations. The greatest warming is expected over land and in the high latitudes of the northern hemisphere where local warming may exceed 15°F (8.3°C). In these regions, winter warming is expected to be greatest. Precipitation, mostly as rain, is expected to increase in the high latitudes and decrease in the subtropical latitudes in both hemispheres. Hot extremes are very likely to increase, and cold extremes are very likely to decrease. Snow cover and sea ice extent are very likely to decrease this century. As CO_2 continues to be absorbed by the oceans, both seawater pH and availability of carbonate ions will be further reduced.

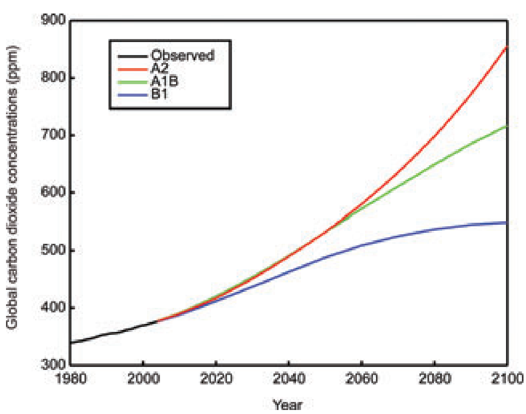

Figure 3.4. **Observed CO_2 concentrations through 2003, and future CO_2 concentrations in the A2, A1B, and B1 scenarios (2004–2100). Adapted from IPCC AR4.**

Box 3.1 Definitions and terms

The NPCC uses observed local climate and climate model simulations to develop regional climate change projections for the New York City region. Definitions and basic descriptions are provided below.

Scenarios

Climate change scenarios provide coherent and plausible descriptions of possible future conditions (Parson *et al.*, 2007). The IPCC Special Report on Emissions Scenarios (SRES) (IPCC, 2000) provides multiple future "storylines," each with different assumptions about population and economic growth, and technological and land-use changes, that lead to GHG emissions and atmospheric concentration trajectories. These GHG profiles are then used as input drivers in climate model simulations.

Three GHG emissions scenarios that were used as drivers for many GCMs and available from the World Climate Research Program (WCRP) and the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (see section 3.3 for further description) were selected for use by the NPCC (Fig. 3.4). The A2, A1B, and B1 emissions scenarios provide GHG concentrations determined by particular developmental storylines. While it is unlikely than any single emissions scenario or GCM projection will occur exactly as described, a suite of GCM simulations and GHG emissions profiles provides a range of possible climate outcomes that reflects the current level of expert knowledge. This approach to climate change scenarios was developed by the IPCC and provided the basis for its 2007 Assessment.

Local climate change information

On the basis of a selection of these three scenarios of GHG emissions and 16 (seven for sea level rise) GCM simulations, *local climate change information* is developed for the key climate variables—temperature, precipitation, and sea level and associated extreme events. These results and projections reflect a range of potential outcomes for New York City and the surrounding region.

The NPCC uses this approach to make regional temperature, precipitation, and sea level projections. For some variables, climate models do not provide results, the model results are too uncertain, or there is not a long enough history of model variable evaluation to justify a quantitative model-based projection. 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 follow the methods used in the IPCC AR4 report.

Climate risk factors

Climate risk factors are the subset of climate hazards that are of most consequence for New York City's infrastructure. They are selected on the basis of interactions with stakeholders who are responsible for managing the critical infrastructure of the region and expert judgment using the quantitative and qualitative climate-hazard information. The climate risk factors are then used by the stakeholders to follow the Adaptation Assessment Guidebook (AAG) to develop climate change Adaptation Plans (see AAG, Appendix B).

The "risk factors" identified in this report are not complete statements of "risk," traditionally defined as "magnitude of consequence times likelihood" (Chapter 2). Rather, the risk factors are generalized climate variables prioritized by considerations of their potential importance for the region's infrastructure. Qualitative statements of the likelihood of occurrence of these tailored climate risk factors are presented as well as potential impacts and consequences of the climate risk factors. Figure 3.5 summarizes the process of translating global climate information into localized risk factors.

Sources of uncertainty

Climate change projections are characterized by large uncertainties. At the global scale, these uncertainties can be divided into two main categories:

- *Uncertainties in future GHG concentrations* and other climate drivers that alter the global energy balance, such as aerosols and land-use changes. These are uncertain because they depend on future population and economic growth, as well as technological innovation and technology sharing; and
- *Uncertainties in how sensitive the climate system will be* to changes in GHG concentrations and other climate drivers, and how rapidly the climate will respond.

When planning adaptations for local and regional scales, uncertainties are further increased for two additional reasons:

- *Climate variability* (which is mostly unpredictable in the midlatitudes) can be especially large over small regions, partially masking more uniform effects of climate change; and
- *Local physical processes* that operate at fine scales, such as land/sea breezes and urban heat island effects, are not captured by the GCMs used to make projections.

By providing projections for the region that span a range of GCMs and GHG emissions scenarios, these uncertainties may be reduced, but they are not eliminated. Presenting climate projections as average changes over 30-year time slices, rather than absolute climate values, reduces the local- and regional-scale uncertainties, although it does not address the possibility that local climate processes may change with time.

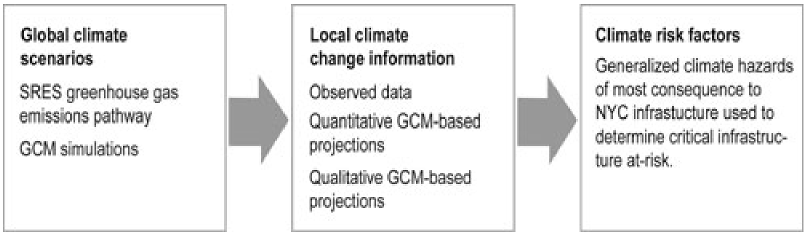

Figure 3.5. **Framework for translating global information into local climate risk factors.**

3.2 Observed climate

This section describes the New York City regional climate, including historical trends and variability of key climate variables.

Temperature

New York City has a temperate, continental climate, with hot and humid summers and cold winters. Records show an annual average air temperature from 1971–2000 of approximately 55°F (12.8 °C). The annual mean temperature in New York City has risen 2.5°F (1.4 °C) since 1900 (Fig. 3.6A), although the rate has varied substantially. For example, the first and last 30-year periods were characterized by warming, while the middle segment, from 1930 to the late 1970s, was not. The absence of a warming trend during the middle of the 20th century may have been due in part to the cooling effects of large regional emissions of sulfate aerosols associated with industrial activity. However, natural variability can also explain local temperature variations at multi-decadal timescales.

The temperature trends in the New York City region over the past century are broadly similar to trends in the northeast United States. In particular, most of the Northeast has experienced a trend toward higher temperatures, especially in recent decades.

Precipitation

The city's climate is characterized by substantial precipitation in all months of the year. Thirty-year annual average precipitation from 1971–2000 ranged between 43 and 50 inches (1090–1270 mm) depending on the location within the City. As mean annual precipitation levels have increased over the course of the past century, inter-annual variability of precipitation has also become more pronounced (Fig. 3.6B). For the 20th century, the rate of increase for precipitation in the New York City area was 0.72 in (18 mm) per decade.

Precipitation in the Northeast also increased in the 20th century, although the trend reversed slightly in the last decades of the 20th century.

Sea level rise

Prior to the Industrial Revolution's onset in the 18th century, sea level had been rising along the East Coast of the United States at rates of 0.34–0.43 inches (0.86–1.1 cm) per decade, mostly due to land subsidence. The land subsidence in the New York City area is primarily the result of ongoing adjustments of the earth's crust to the removal of the ice sheets, a process that began around 20,000 years ago. While areas once under ice sheets to the north and west of the New York metropolitan region continue to rise in response to the removal of the weight of the ice sheets, New York City and the surrounding region is sinking because it resides in a peripheral zone to the south and east. Within the past 100 to 150 years, as global temperatures have increased, regional sea level has been rising more rapidly than over the last thousand years (Gehrels *et al.*, 2005; Donnelly *et al.*, 2004; Holgate and Woodworth, 2004).

Currently, rates of sea level rise in New York City range between 0.86 and 1.5 inches (2.2–3.8 cm) per decade as measured by tide gauges, with a long-term rate since 1900[3] averaging 1.2 inches (3.0 cm) per decade, as seen in Figure 3.6C. The sea level rise rates shown in Figure 3.6C include both the effects of recent global warming and the residual crustal adjustments to the removal of the ice sheets. Most of the observed current climate-related rise in sea level over the past century can be attributed to the thermal expansion of the oceans as they warm, although melting of land-based ice may become the

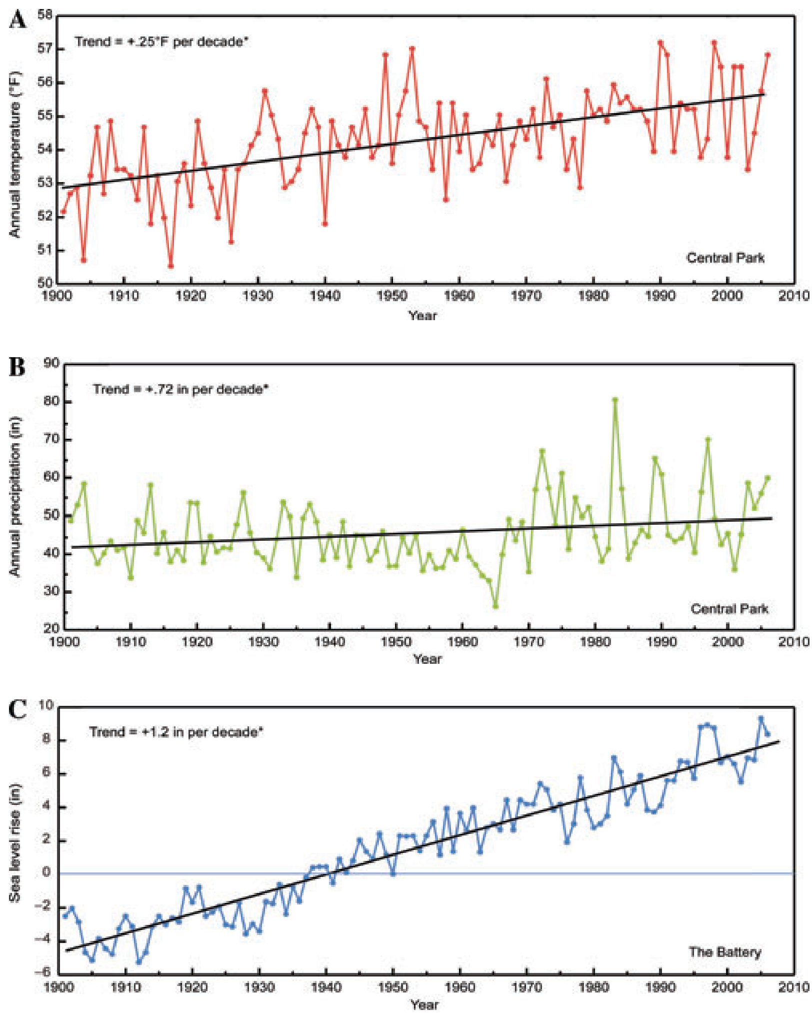

Figure 3.6 **Observed climate in New York City. Temperature data are not adjusted for bias due to urbanization effects. *All trends are significant at the 95% level.**
Source: Columbia University Center for Climate Systems Research.

dominant contributor to sea level rise during the current century.

Extreme events

Extreme events are intense climate events often of short duration, such as heat waves, cold air events, extreme rainfall, and storm surges. However, timescales of extreme events can be asymmetric: heavy precipitation events generally range from less than one hour to a few days, whereas droughts can range from months to years. Temperature and precipitation-based extreme events are defined here using daily meteorological data from Central Park; storm surge data are based on hourly tide-gauge data from the Battery since 1960 and on US Army Corps of Engineers hydrodynamic storm surge models (see CRI, Appendix A).

Extreme temperature and heat waves

The NPCC calculated hot days as the number of individual days with maximum temperatures above 90°F and 100°F per year, and defined heat waves as three or more consecutive days with maximum temperatures above 90°F.

During the 1971–2000 period, New York City averaged 14 days per year over 90°F, 0.4 days per year over 100°F, and two heat waves per year. The number of events in any given year is highly variable.

For example, in 2002 New York City experienced temperatures above 90°F on 33 different days. In 2004, temperatures above 90°F occurred only twice. Although the post-1900 trends for these heat events cannot be distinguished statistically from random variability, 7 of the 10 years with the most days over 90 degrees in the 107-year record have occurred since 1980.

Extreme precipitation

Between 1971 and 2000, New York City averaged 13 days per year with over 1 inch of rain, 3 days per year with over 2 inches of rain, and 0.3 days per year with more than 4 inches of rain. As with extreme temperatures, extreme precipitation events vary widely from year to year. Since extreme precipitation events tend to occur relatively infrequently, long time series are needed to identify trends; thus there is a relatively large "burden of proof" required to distinguish a meaningful trend from random variability. The 3 years with the most occurrences of days per year with greater than 2 inches of rainfall in the region have all occurred during the last three decades, roughly coinciding with the period of increased inter-annual variability.

Coastal storms and storm surge

The two types of storms with the largest influence on the region are hurricanes and nor'easters. Hurricanes strike New York City and the surrounding region infrequently, but can produce large storm surges and wind damage. They generally occur between July and October, and are usually of short duration, as they tend to move rapidly by the time they reach midlatitude locations, such as New York.

Nor'easters, in contrast, occur more frequently than hurricanes in the region and tend to take place during cooler parts of the year. While nor'easters generally produce smaller surges and weaker winds than hurricanes, their impacts can nevertheless be large. They often remain in the region for multiple days, bringing an extended period of high winds and high water that often coincides with high tides.

While sea level rise is a gradual process, storm surges are short-term, high-water events superimposed onto mean sea height. In New York City and the surrounding region, both nor'easters and hurricanes cause storm surges. The surges are primarily due to wind-induced piling up of water along the shore. The strong winds associated with nor'easters and hurricanes can also generate large waves that exacerbate coastal flooding.

A significant fraction of New York City and the surrounding region lies less than 10 feet (3 meters) above mean sea level, and infrastructure in these areas is vulnerable to flooding during major storm events, both from coastal storm surges and inland (rainfall-induced) flooding. The current 1-in-100 year coastal flood, the storm with approximately a 1% chance of occurring in a given year, produces approximately an 8.6-foot (2.6 meters) surge at the Battery in lower Manhattan.[4]

Documenting historical coastal flood events is challenging. More complete and accurate documentation of recent events may make it appear that damaging storms are increasing, even though they may not be (CRI, Appendix A). Although no trend in observed storms is evident in the region, characterizing historical storms is a critical step in understanding future storms and their impacts. The CRI workbook (Appendix A) presents a description of key hurricane events in the New York City region over the past two centuries.

3.3 Future projections

Building on historical climate information, this section presents climate projection methods and projections for the 21st century for New York City and the surrounding region. Climate model-based quantitative projections are given for temperature, precipitation, sea level rise, and extreme events. This section also describes the potential for changes in other variables in a more qualitative way, because quantitative projections are either unavailable or considered less reliable. These variables include heat indices, frozen precipitation (snow), intense precipitation of short duration, lightning, and storms (hurricanes, nor'easters, and associated wind events).

Creating regional projections from global climate models

The projected changes in temperature and precipitation through time (for example, three degrees of warming by the 2050s) are New York City region specific. The regional projections are based on GCM output from the single land-based model gridbox covering New York City and its surrounding area,

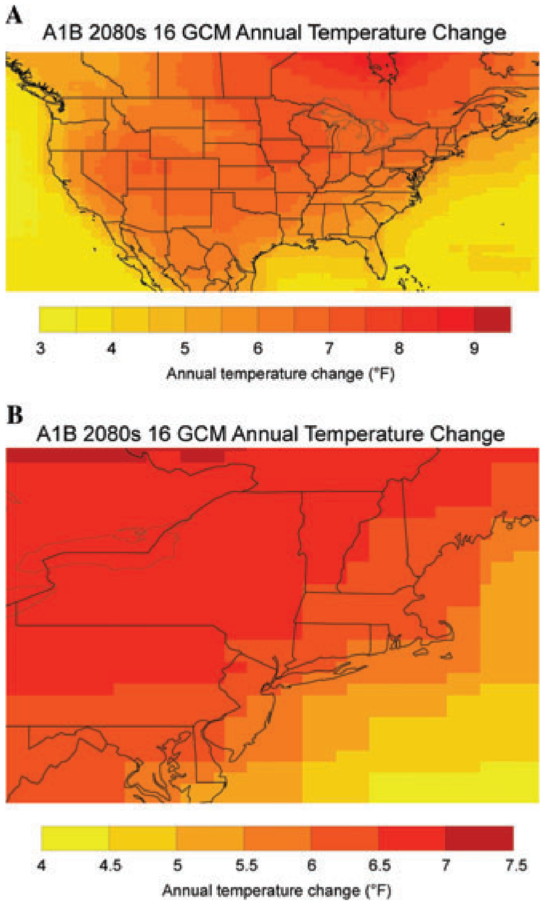

Figure 3.7 Annual temperature changes in the 2080s, relative to the 1971–2000 base period. Source: Columbia University Center for Climate Systems Research.

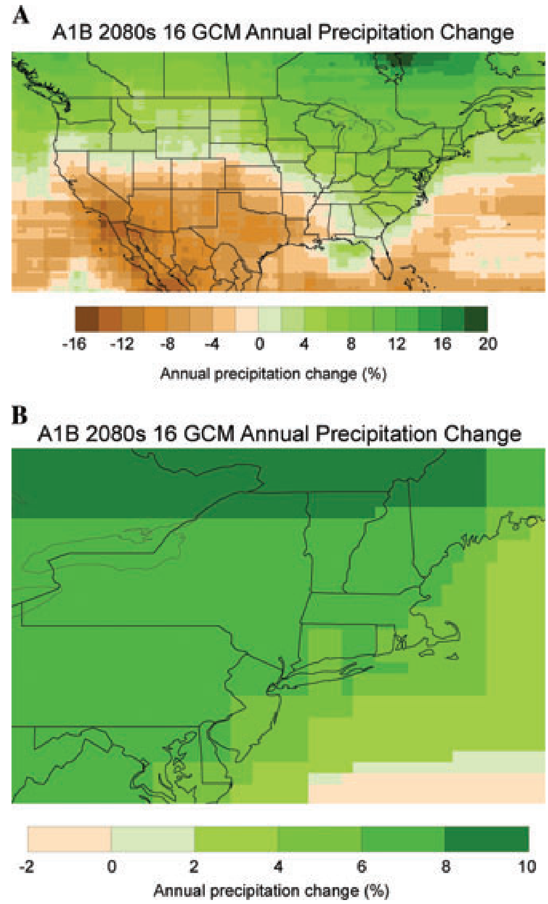

Figure 3.8 Annual precipitation changes in the 2080s, relative to the 1971–2000 base period. Source: Columbia University Center for Climate Systems Research.

which are then applied to observed data from the region. The precise coordinates of the gridbox differ since each GCM has a different spatial resolution. The resolutions range from as fine as ∼75 × ∼100 miles to as coarse as ∼250 × ∼275 miles, with an average resolution of approximately 160 × 190 miles.

In general, the projections apply roughly out to ∼100 miles from New York City. The applicability of the projections decreases with distance from New York City, and this decrease in applicability is more pronounced for extreme events than for mean annual changes.[5]

Comparisons to results from nearby land-based grid boxes reveal similar climate changes for neighboring areas, as shown in Figures 3.7 and 3.8 (see Box 3.2 for discussion). By applying the projected changes from the relevant gridbox to observed data, the projections become location specific. For example, although Poughkeepsie's projected change in temperature through time is similar to New York City's, the number of current and projected days per year with temperatures above 90°F is lower because it is cooler in the present climate. The spatial variation in baseline climate is much larger than the spatial variation of projected climate changes.

Box 3.2 New York City temperature and precipitation projections in a broader geographical context

The maps in Figures 3.7 and 3.8 reveal that the mean changes described for New York City are consistent over the entire northeastern United States. They place the mean temperature and precipitation projections for the New York City region in a broader geographical perspective. Shown are the mean changes in temperature and precipitation for the A1B scenario in the 2080s relative to 1971–2000 averaged across 16 GCMs. The spatial pattern is similar for the two other emissions scenarios. The spatial consistency of the projected changes over the broader area lends support to the New York City results.

While the overall patterns are consistent across the northeastern United States, there are differences. Ocean regions are expected to warm less than interior regions. Since New York is a coastal city, it may experience slightly less warming (∼0.5°F) than more inland regions by the 2080s. Generally speaking, more southerly latitudes than New York City's are expected to experience less warming, while more northerly latitudes are expected to experience more warming.

Precipitation projections are very consistent spatially across the northeastern United States. Near the Canadian border, precipitation is projected to increase somewhat more than in the Northeast as a whole. There is also an ocean region of projected slight decrease in precipitation approximately 200 miles to the southeast. The proximity of this region to New York City indicates that the possibility of slightly decreased mean precipitation for New York City, although less likely than not, cannot be ruled out.

Time slices

Although it is not possible to predict the temperature, precipitation, or sea level for a particular day, month, or even specific year because of fundamental uncertainties and natural variability in the changing climate system, GCMs are a valuable tool for projecting the likely range of changes over decadal to multidecadal time periods (see Box 3.3 for a description of GCMs). These projections, known as time slices, are expressed relative to the baseline period, 1971–2000 (2000–04 for sea level rise). The time slices are centered around a given decade, for example, the 2050s time slice refers to the period from 2040–69.[6] Thirty-year time slices (10-year for sea level rise) are used to provide an indication of the climate "normals" for those decades; by averaging over this period, much of the random year-to-year variability, or "noise," is cancelled out, while the long-term influence of increasing greenhouse gases, or "signal," remains. Thirty-year averaging is a standard used by meteorological and climate scientists (Guttman, 1989; WMO, 1989). This method can be used to estimate the climate change signal on both mean annual values and the frequency and intensity of extreme events.

Box 3.3 Global climate models

GCMs are mathematical representations of climate system interactions through time. Because the earth is a complicated system, fluxes of heat, momentum, and moisture, as well as feedbacks among the land, ocean, and atmosphere and other components of the earth system must be considered. These processes are simulated by means of detailed computer programs that solve sets of coupled partial differential equations based on the general principles of conservation of mass, momentum, and energy.

As shown in the Figure 3.9, GCMs divide the earth's surface into a series of gridboxes. For a point within each gridbox, equations are solved to calculate elements of the climate system, for example, the motion of the air, heat transfer, radiation, moisture content, and surface hydrology (precipitation, evaporation, snow melt, and runoff).

Climate models are sophisticated enough to handle the interactions of the ocean, the atmosphere, the land, hydrologic and cryospheric processes, terrestrial and oceanic carbon cycles, and atmospheric chemistry. Clouds and water vapor are included as well. While the mathematical representation of climate processes still need refinement and improvement, these model simulations now skillfully capture many aspects of the current climate and its variability.

For example, recent integrated climate model simulations, conducted for the IPCC Fourth Assessment Report (2007), were run at higher spatial resolution than earlier models and, due to improved physical understanding, incorporated more accurately complex physical processes, such as cloud formation and destruction. These models are also able to reproduce some of the key climate characteristics of paleoclimates that were far different than today's climate, such as the relatively warm mid-Holocene (approximately 6000 years ago) and the relatively cool last glacial maximum (approximately 21,000 years ago). Skillful simulation of a range of past climate periods helps to build confidence in the general realism of future simulations.

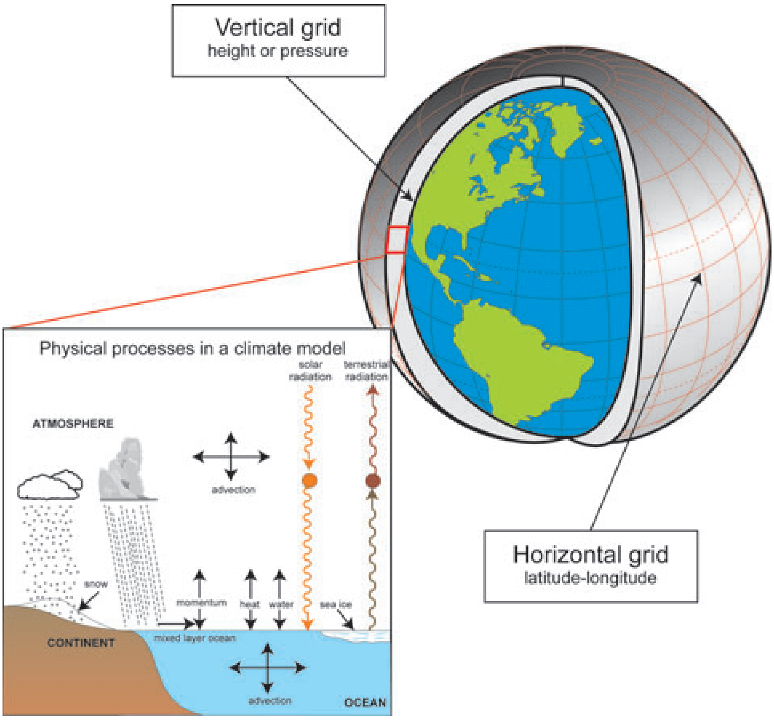

Figure 3.9. GCM processes and gridboxes. Adapted from NOAA.

The large number of available GCMs makes possible model-based probabilistic assessment of future climate projections across a range of climate sensitivities (defined as the mean equilibrium temperature response of a GCM to doubling carbon dioxide (CO_2), relative to pre-industrial levels).

Although GCMs are the primary tool used for long-range climate prediction, they have limitations. They simplify some complex physical processes, such as convective rainfall. In addition, the spatial and temporal scales of some climate processes, such as thunderstorms, are finer than the resolutions of GCMs. Further, they do not fully include other relevant local climate forcings, including black carbon, land-cover changes and urban heat island effects, and solar variability. For these and other reasons, it is possible that the regional climate of New York City may change in ways not captured by the models, leading to temperature, precipitation, and sea level rise changes outside the model-based range presented.[7]

Model-based probability

The NPCC used IPCC-based methods (IPCC AR4) to generate model-based probabilities for temperature, precipitation, and sea level rise from GCM simulations based on three GHG emission scenarios (A2, A1B, and B1; see Fig. 3.4, and CRI for a description of each scenario). Simulation results from 16 GCMs have been used for the temperature and precipitation projections, and results based on seven GCMs are used to project sea level rise.

The combination of 16 GCMs and three emissions scenarios produces a 48 (16 × 3)-member matrix of outputs for temperature and precipitation. For each scenario time period and variable, the results constitute a “model-based” probability function. The results for the future time periods are compared to the model results for the 1971–2000[8] baseline period. Mean temperature change projections are calculated as the difference between each model’s future simulation and the same model’s baseline simulation, whereas mean precipitation is based on the ratio of a given model’s future precipitation to the same model’s baseline precipitation (expressed as a percentage change). Sea level rise methods are more complex, since sea level rise is not a direct output of most GCMs.

The model-based frequency distributions represent subsets of the possible future range of the climate variables. Neither the global climate models nor the emissions scenarios fully sample the range of possible climate change outcomes. Actual results could fall outside the range simulated by the models. This approach is based on the assumption, used by the IPCC, that each GCM and emission scenario is equally valid; this may not be true. Despite these caveats, the model-based quantitative approach provides valuable information for many projected climate variables by providing the range and central tendency of possible outcomes based on the leading global climate models and a set of emissions scenarios, both developed by the worldwide scientific community.

Sea level rise methods

For sea level rise, the NPCC produced two sets of projections using a combination of approaches. The first is similar to the IPCC model-based method used for temperature and precipitation described above, with seven GCMs contributing available results. The projections include both global and local components. The global components include thermal expansion and meltwater from glaciers, ice caps, and ice sheets; and the local components include local land subsidence and local water surface elevation (CRI, Appendix A).

The IPCC estimates may be too low in large part because they do not fully consider the potential for land-based ice sheets to melt owing to dynamic (motion-related) processes (Horton *et al.*, 2008). Therefore, the NPCC also developed an alternative "rapid ice-melt" approach for regional sea level rise projections because of extensive discussion within the scientific community of the possibility that the GCMs used in the IPCC AR4 sea level rise projections may underestimate the range of possible increases. The NPCC "rapid ice-melt" scenarios, therefore, are based on observed trends in melting of the West Antarctic (Velicogna and Wahr, 2006) and Greenland ice sheets (Rignot and Kanagaratnam, 2006) and paleoclimate studies of ice-melt rates during the most recent postglacial period (Fairbanks, 1989). Starting around 20,000 years ago, global sea level rose 394 feet (120 meters) and reached near present-day levels around 7000–8000 years ago. Paleoclimate data show that the average rate of sea level rise during this period of about 10,000–12,000 years was on the order of 3.9–4.7 in (9.9–11.9 cm) per decade. This information is incorporated into the rapid ice-melt scenario projections. More information on the rapid ice-melt scenario and its integration with GCM-based projections, can be found in the CRI workbook (Appendix A).

Extreme events methods

Extremes of temperature and precipitation (with the exception of drought) tend to have their largest impacts at daily rather than monthly timescales. Because monthly output from climate models is considered more reliable than daily output, the NPCC used a hybrid technique to project how extreme events may change in the future because of increasing greenhouse gas emissions. Simulated changes in monthly temperature and precipitation were calculated on the basis of the same methods described for the annual data; monthly changes through time from each of the 16 GCMs and three emissions scenarios were then applied to the observed daily Central Park record from 1971–2000 to generate 48 time series of daily data.[9] This is a simplified approach to projections of extreme events, since it does not allow for possible changes in the patterns of climate variability through time. However, because changes in variability for most climate hazards are considered highly uncertain, the approach provides an initial evaluation of how extreme events may change in the future. This level of information with appropriate caveats can assist long-term planners as they begin to prepare adaptation strategies to cope with future extreme events.

Projections for the New York City region

Future climate change for the New York City region is projected for mean annual temperature and precipitation, heat waves, intense downpours and droughts, sea level rise, and coastal flooding events.

Mean annual changes

Regional projections show that higher temperatures and sea level rise are extremely likely to occur in the coming decades. For temperature and sea level rise, all simulations project continuing increases over the century, with the central range (defined as the values occurring in 67% of the simulations) projecting more rapid temperature and sea level rise than occurred over the 20th century.

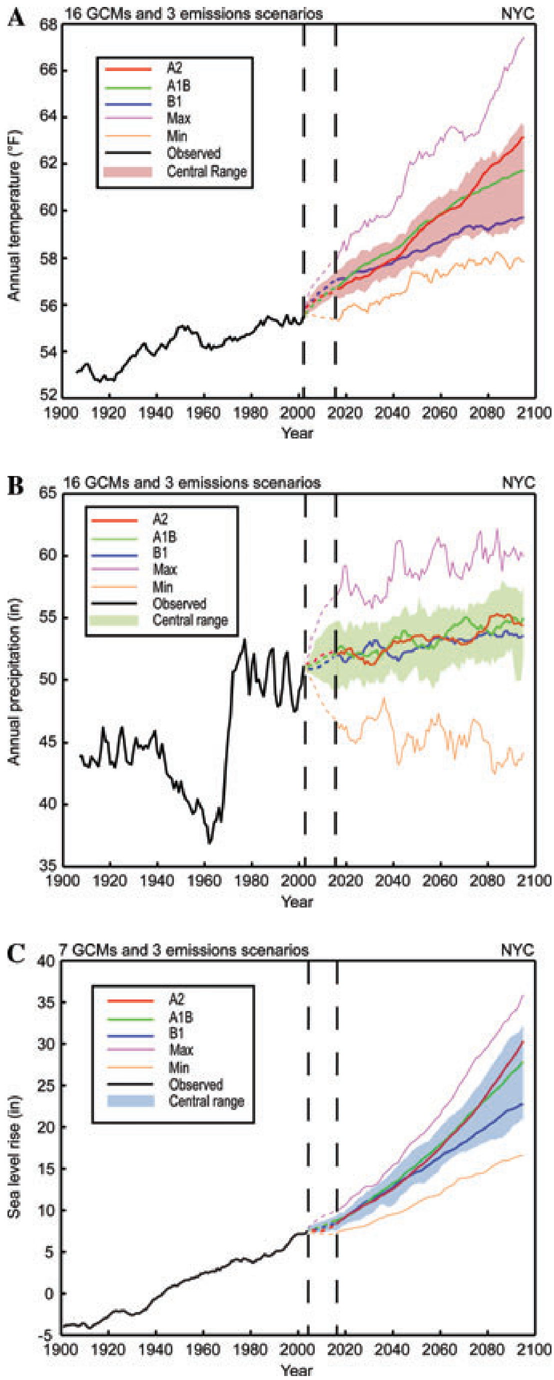

Figure 3.10. Combined observed (*black line*) and projected temperature, precipitation and sea level rise. Projected model changes through time are applied to the observed historical data. The three thick lines (green, red, and blue) show the average for each emissions scenario across the 16 GCMs (7 in the case of sea level). Shading shows the central range. The *bottom* and *top lines*, respectively, show each year's minimum and maximum projections across the suite of simulations. A ten-year filter has been applied to the observed data and model output. The *dotted area* between 2003 and 2015 (2002–2015 for sea level rise) represents the period that is not covered due to the smoothing procedure.
Source: Center for Climate Systems Research, Columbia University.

Precipitation projections are less certain than temperature projections, in part owing to large multidecadal variability. Although most projections for the region indicate at least small increases in precipitation, some do not. Further, projections later in the century relative to earlier in the century are characterized by larger uncertainty (i.e., the ranges of outcomes become larger through time), because of uncertainties in the climate system and the possible pathways of the greenhouse gas emission scenarios. This increasing uncertainty through time is not unique to precipitation; it applies to all climate variables.

Figure 3.10 presents observed data from 1900 to the present and projected changes up to 2100 for temperature, precipitation, and sea level rise. These graphs provide context on how projected changes in the region compare to historical trends and long-term variability; the black line on the left-hand side of the figures shows the historic values, and the right-hand side of the graphs shows the range of projections across the GCMs over the course of the 21st century.

Table 3.1 shows the baseline climate and projected changes in temperature, precipitation, and sea level rise relative to the baseline for the 2020s, 2050s, and 2080s. In order to highlight where the various GCM and emissions scenario projections agree, the values in rows two through four indicate the central 67% range of the projected model-based changes; the highest and lowest 16.7% of values are not shown on the table. The maximum and minimum values of the projections, as well as the entire distributions, are shown in CRI (Appendix A).

Future temperature

The projected future temperature changes shown in Figure 3.10A and Table 3.1 indicate that by the

Table 3.1. Baseline climate and mean annual changes[a]

	Baseline 1971–2000	2020s	2050s	2080s
Air temperature				
Central range[b]	55° F	+ 1.5 to 3.0° F	+ 3.0 to 5.0° F	+ 4.0 to 7.5° F
Precipitation				
Central range[b]	46.5 in^3	+ 0 to 5%	+ 0 to 10%	+ 5 to 10%
Sea level rise[c]				
Central range[b]	NA	+ 2 to 5 in	+ 7 to 12 in	+ 12 to 23 in
Rapid ice-melt scenario[d]	NA	∼ 5 to 10 in	∼ 19 to 29 in	∼ 41 to 55 in

Source: Columbia University Center for Climate Systems Research.
[a]Based on 16 GCMs (7 GCMs for sea level rise) and 3 emissions scenarios. Baseline is 1971–2000 for temperature and precipitation and 2000–04 for sea level rise. Data from National Weather Service (NWS) and National Oceanic and Atmospheric Administration (NOAA). Temperature data are from Central Park; precipitation data are the mean of the Central Park and La Guardia Airport values; and sea level data are from the Battery at the southern tip of Manhattan (the only location in New York City for which comprehensive historic sea level rise data are available).
[b]Central range = middle 67% of values from model-based probabilities; temperatures ranges are rounded to the nearest half-degree, precipitation to the nearest 5%, and sea level rise to the nearest inch.
[c]The model-based, sea level rise projections may represent the range of possible outcomes less completely than the temperature and precipitation projections.
[d]"Rapid ice-melt scenario" is based on acceleration of recent rates of ice melt in the Greenland and West Antarctic ice sheets and paleoclimate studies.

2080s, New York City's mean temperatures throughout a "typical" year may bear similarities to a city like Raleigh, North Carolina, or Norfolk, Virginia, today, increasing by 1.5–3°F by the 2020s, 3–5°F by the 2050s, and 4–7.5°F by the 2080s. The growing season could lengthen by approximately a month, with summers becoming hotter and winters more mild. The climate model simulations suggest that the amount of warming may be relatively consistent for each of the four seasons. Because year-to-year temperature variability is larger in winter than in summer, the summer changes may produce relatively larger deviations from what has been experienced historically during individual years.

The three emissions scenarios project similar temperature in the near-term decades. Only beginning around the 2030s do the three emissions scenarios produce temperature patterns that are distinguishable from each other. This is due to both (1) the large inertia of the climate system—it takes centuries to millennia for the full climate effects of greenhouse gas emissions to be felt—and, (2) the fact that it takes time for the different emissions scenarios to produce large differences in greenhouse gas concentrations.

Future precipitation

Table 3.1 indicates that regional precipitation is projected to increase by approximately 0–5 % by the 2020s, 0–10 % by the 2050s, and 5–10 % by the 2080s. While seasonal projections are less certain than annual results, the climate models tend to distribute much of this additional precipitation during the winter months. During the autumn months of September and October, in contrast, total precipitation for the region is slightly reduced in many climate models. Monthly and seasonal breakdowns of both temperature and precipitation projections are included in CRI (Appendix A).

Figure 3.10B shows that precipitation is characterized by large historical variability, even with 10-year smoothing. The GCMs project similar levels of increased precipitation through the 2030s. Only from the 2040s on does the lower-concentration B1 scenario produce smaller increases in precipitation than the A1B and A2 scenarios. Even after the 2040s, there are occasional periods where B1 precipitation exceeds A2. At no point in the coming century are the A2 and A1B scenario-based precipitation projections consistently distinguishable.

Future sea level rise

The GCM-based sea level rise projections in Figure 3.10C and Table 3.1 indicate that sea level may rise by 2–5 inches in the 2020s, 7–12 inches in the 2050s, and 12–23 inches in the 2080s. Sea level projections for the three emissions scenarios agree through the 2040s. Figure 3.10C shows that the B1 scenario produces smaller increases in sea level than the A1B and A2 scenarios beginning in the 2050s, and only around 2080 does the A2 scenario produce larger values than A1B. The separation of A2 from A1B occurs approximately 10 years earlier for temperature than for sea level rise, in part reflecting the large inertia of the ocean and ice sheets relative to the atmosphere.

Sea level rise projections for the New York City region are higher than global sea level rise projections (by approximately 6 inches for 21st century projections) (IPCC, 2007). One reason is that New York City and the surrounding region are subsiding by approximately 3–4 inches per century. The climate models also have a tendency to produce accelerated sea level rise along the northeast U.S. coast, associated in large part with a projected weakening of the Gulf Stream (Yin *et al.*, 2009).

The model-based sea level rise projections shown in Figure 3.10 and Table 3.1 are characterized by greater uncertainty than the temperature projections, due to the possibility that dynamic processes in polar ice sheets not captured by the GCMs may accelerate melting beyond currently projected levels. This uncertainty is weighted toward the upper bound of the GCM projections: that is, the probability of future sea level rise being lower than that described in the third row of Table 3.1 is very low, and the probability of sea level rise exceeding the GCM projections is relatively high.

The rapid ice melt sea level rise scenario shown in the fourth row of Table 3.1 addresses this possibility. It is based on extrapolation of recent accelerating rates of ice melt from the Greenland and West Antarctic ice sheets and on paleoclimate studies that suggest sea level rise on the order of ∼3.9–4.7 inches (9.9–11.9 cm) per decade may be possible. The potential for rapid ice melt needs to be included in the regional projections for New York City because of the large magnitude of consequence should it occur. (As described in Chapter 2 on risk management, rapid ice melt leading to accelerated sea level rise is the kind of catastrophe of which the consequences may be so severe that policy makers need to take it into consideration, despite uncertainties.) More information on the development of the rapid ice-melt scenario can be found in the CRI (Appendix A). To assess the risk of accelerated sea level rise and climate change for the New York City region over the coming years, climate experts need to monitor rates of polar ice melt, as well as other key indicators of global and regional climate change.

Future extreme events

Despite their brief duration, extreme events can have large impacts on infrastructure and people, so they are a critical component of climate change impact assessment. Table 3.2 indicates how the frequency of heat waves, cold events, intense precipitation, drought, and coastal flooding in New York City and the surrounding region are projected to change in the coming decades. The average number of extreme events per year for the baseline period is shown, along with the central 67% of the range of the model-based projections. The full range of results can be found in CRI (Appendix A). Uncertainties associated with extreme events are discussed in Box 3.4.

a. Future heat waves and cold events

The total number of hot days, defined by the NPCC as days with a maximum temperature over 90 or 100°F, is expected to increase as the 21st century progresses. The frequency and duration of heat waves, defined as three or more consecutive days with maximum temperatures above 90°F, are also expected to increase. In contrast, extreme cold events, defined as the number of days per year with minimum temperature at or below 32°F, are expected to become rarer. The extreme event temperature projections shown in Table 3.2 are based on observed data from the weather station located in Central Park. Because some parts of New York City, including the south shore of Brooklyn and Queens, currently experience significantly fewer extreme heat days, they will probably experience fewer heat events than those shown in the corresponding column of the table for Central Park in the future as well.

b. Future intense precipitation and droughts

Although the percentage increase in annual precipitation is expected to be relatively small, larger percentage increases are expected in the frequency of

Table 3.2. **Quantitative changes in extreme events**

	Extreme event	Baseline (1971–2000)	2020s	2050s	2080s
Heat waves and cold events	# of days/year with maximum temperature exceeding:				
	90°F	14	23 to 29	29 to 45	37 to 64
	100°F	0.4[a]	0.6 to 1	1 to 4	2 to 9
	# of heat waves/year[b]	2	3 to 4	4 to 6	5 to 8
	Average duration (in days)	4	4 to 5	5	5 to 7
	# of days/year with minimum temperature at or below 32°F	72	53 to 61	45 to 54	36 to 49
Intense precipitation and droughts	# of days per year with rainfall exceeding:				
	1 inch	13	13 to 14	13 to 15	14 to 16
	2 inches	3	3 to 4	3 to 4	4
	4 inches	0.3	0.2 to 0.4	0.3 to 0.4	0.3 to 0.5
	Drought to occur, on average[c]	∼once every 100 yrs	∼once every 100 yrs	∼once every 50 to 100 yrs	∼once every 8 to 100 yrs
Coastal floods and storms[d]	1-in-10 yr flood to recur, on average	∼once every 10 yrs	∼once every 8 to 10 yrs	∼once every 3 to 6 yrs	∼once every 1 to 3 yrs
	Flood heights (in ft) associated with 1-in-10 yr flood	6.3	6.5 to 6.8	7.0 to 7.3	7.4 to 8.2
	1-in-100 yr flood to recur, on average	∼once every 100 yrs	∼once every 65 to 80 yrs	∼once every 35 to 55 yrs	∼once every 15 to 35 yrs
	Flood heights (in ft) associated with 1-in-100 yr flood	8.6	8.8 to 9.0	9.2 to 9.6	9.6 to 10.5
	1-in-500 yr flood to recur, on average	∼once every 500 yrs	∼once every 380 to 450 yrs	∼once every 250 to 330 yrs	∼once every 120 to 250 yrs
	Flood heights (in ft) associated with 1-in-500 yr flood	10.7	10.9 to 11.2	11.4 to 11.7	11.8 to 12.6

Source: Columbia University Center for Climate Systems Research.
Note: Extreme events are characterized by higher uncertainty than mean annual changes. The central range (middle 67% of values from model-based probabilities) across the GCMs and GHG emissions scenarios is shown.
[a]Decimal places shown for values less than 1 (and for all flood heights), although this does not indicate higher accuracy/certainty. More generally, the high precision and narrow range shown here are due to the fact that these results are model based. Owing to multiple uncertainties, actual values and range are not known to the level of precision shown in this table.
[b]Defined as three or more consecutive days with maximum temperature exceeding 90°F.
[c]Based on minima of the Palmer Drought Severity Index (PDSI) over any 12 consecutive months. More information on the PDSI and the drought methods can be found in the CRI.
[d]Does not include the rapid ice-melt scenario.

extreme precipitation (defined as more than 1, 2, and 4 inches per day). This projection is consistent both with physical climate theory that a warmer atmosphere is expected to hold more moisture and that precipitation tends to be concentrated in extreme events; the projection is also consistent with observed trends nationally over the 20th century (Karl and Knight, 1998). Because some parts of New York City, including parts of coastal Brooklyn and Queens, currently experience significantly fewer extreme warm-season precipitation events than Central Park because of the cooling effect of the nearby ocean, they may experience fewer extreme warm-season precipitation days than Central Park in the future as well.

Twenty-first century drought projections reflect the competing influences of greater total precipitation as well as greater evaporation due to higher temperatures. By the end of the 21st century the effect of higher temperatures, especially during the warm months, on evaporation is expected to outweigh the increase in precipitation, leading to more droughts, although the timing and levels of drought projections are marked by relatively large uncertainty. Changes in the distribution of precipitation throughout the year and timing of snowmelt could potentially make drought more frequent as well. According to the IPCC, snow season length is very likely to decrease over North America (IPCC, 2007).

Severe drought frequency, as defined by the 12-month average Palmer Drought Severity Index (PDSI; Palmer, 1965) based on global climate model results, is essentially unchanged for the 2020s, but increases thereafter. For the 2050s, the projected frequency of severe drought is approximately doubled, and by the 2080s the frequency is approximately five times greater. The rapid increase in drought risk through time is reflective of a nonlinear response in the PDSI, because as temperature increases in summer become large, potential evaporation increases dramatically. See CRI (Appendix A) for more information on the PDSI and its applicability. Because New York City and the surrounding region has experienced severe multiyear droughts during the 20th century, most notably the "drought of record" in the 1960s, any increase in drought frequency, intensity, or duration could have serious implications for water resources in the region.

c. Future coastal floods and storms

As sea level rises, coastal flooding associated with storms will very likely increase in intensity, frequency, and duration. The changes in coastal floods shown in Table 3.2 are solely due to the IPCC model-based projections of gradual changes in sea level through time. Any increase in the frequency or intensity of storms themselves would result in even more frequent future flood occurrences. By the end of the 21st century, projections based on sea level rise alone suggest that coastal flood levels that currently occur on average once per decade may occur once every 1-to-3 years.

The projections for flooding associated with more severe storms (e.g., the 1-in-100 year storm) are less well characterized than those for less severe storms (e.g., the 1-in-10 year events). The historical record is not sufficiently long to allow precise estimates of the flood level associated with the once-per-century storm. Furthermore, the storm risk may vary on multidecadal to centennial ocean circulation-driven timescales that are currently not well understood. Keeping these uncertainties in mind, the NPCC estimates that owing to sea level rise alone the 1-in-100 year flood may occur approximately four times as often by the 2080s. The current 1-in-500 year flood height is even more uncertain than the 1–in-100 year flood since the historical record is shorter than 500 years. However, on the basis of the available information, by the end of the century, the current 1-in-500 year flood event may occur on the order of once every 200 years.

The flood heights shown in Table 3.2 are based on the tide gauge located at the Battery in lower Manhattan and on surge models. Some parts of New York City, such as the northernmost points where the Bronx Borough and the Hudson River meet, experience lower flood heights than the Battery.

Qualitative extreme event projections

For some extreme climate events—such as heat indices, heavy downpours, and lightning—that have large impacts on infrastructure, future changes are too uncertain at local scales to allow quantitative projections. Therefore, qualitative information for some of these factors is provided in Table 3.3.

By the end of the century, *heat indices* that combine temperature and humidity are very likely to

Table 3.3. **Qualitative changes in extreme events**
Probable direction of change over the 21st century, as well as likelihood associated with the qualitative projection. For these variables, which can have large impacts on infrastructure, quantitative projections are not possible because of insufficient information.

Extreme event	Probable direction throughout 21st century	Likelihood[a]
Heat index[b]	⇑	Very likely
Ice storms/freezing rain	⇑	About as likely as not
Snowfall frequency and amount	⇓	Likely
Downpours (precipitation rate/hour)	⇑	Likely
Lightning	Unknown	
Intense hurricanes	⇑	More likely than not
Nor'easters	Unknown	
Extreme winds	⇑	More likely than not

Source: Columbia University Center for Climate Systems Research.
[a]Likelihood definitions given in Figure 3.1. See CRI Appendix A for more information.
[b]The National Weather Service uses a heat index related to temperature and humidity to define the likelihood of harm after "prolonged exposure or strenuous activity" (http://www.weather.gov/om/heat/index.shtml).

increase, both directly owing to higher temperatures and because warmer air can hold more moisture and the resulting humidity exacerbates the effects of heat. The combination of high temperatures and high humidity can produce severe additive effects by restricting the human body's ability to cool itself. The National Weather Service Heat Index definition is based on the combination of these two climate factors.

Ice storms can have large effects on infrastructure. Greater warming of the lower atmosphere than surface layer could potentially lead to more ice storms in the near term by allowing snow to more frequently melt on descent and then refreeze near (or at) the surface, but any such changes are highly uncertain. By the second half of the century, overall warming may be large enough to reduce the threat of ice storms below current levels. *Snowfall* is likely to become less frequent in a warmer climate, with the snow season decreasing in length. Possible changes in the intensity of snowfall per storm are highly uncertain.

Intense hurricanes and associated extreme wind events will more likely than not become more frequent due to expected warming of the upper ocean in the tropical cyclone genesis regions (IPCC AR4, 2007). That is, once formed, the fraction of hurricanes that become intense is expected to increase, along with the overall destructive power. However, because future changes in other critical factors for tropical cyclones, including wind shear, the vertical temperature gradient in the atmosphere, and patterns of variability including the El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO)[10] are not well known, it is unclear whether the total number of tropical storms will increase. There is the possibility that intense hurricanes and their extreme winds will not become more frequent or intense, should there be a decrease in the total number of tropical storms. It is also unknown whether the most probable tracks or trajectories of hurricanes and intense hurricanes may change in the future.

Regional downpours, defined as intense precipitation at subdaily (often subhourly) timescales, are likely to increase in frequency and intensity in a warmer climate due to the greater capacity of warmer air to hold water vapor. Future changes in *nor'easters* and *lightning* are currently too uncertain to support even qualitative statements.[11]

Box 3.4 Uncertainties related to extreme events

Because the climate processes affecting extreme events, such as hurricanes and nor'easters, may change in the future, prediction of future extremes is generally characterized by higher uncertainty than the annual averages described in the previous section. The NPCC projections are based on the assumption that the distributions of the extreme events will remain unchanged while mean temperature, precipitation, and sea level rise shift. Changes in the distribution of extreme events could have large effects on the results shown here. Given the uncertainty, the direction and relative magnitudes of changes, rather than the precise projections, should be emphasized.

While Table 3.2 provides an estimate of how the occurrence of extreme events may change for the average future year, extreme events in individual years will continue to be characterized by high variability. In some cases, only when many years, or even decades, are averaged will the pattern of changes in extreme events become evident. For example, New York City's drought of record was a multiyear event that occurred four decades ago in the 1960s; no drought since that time in New York has approached it in severity. Droughts usually affect entire regions; the 1960s drought of record affected New York City's entire watershed and had implications for water sharing with other regional metropolises. Generally speaking, changes in variability are considered very uncertain, although there are exceptions. For example, precipitation at daily timescales is likely to increase in variability owing to the intensification of the hydrological cycle that is associated with a warming climate.

Uncertainties, high-end scenarios, and longer-term projections

Climate changes in New York City and the surrounding region in the 21st century may extend beyond the ranges projected by global climate models for several reasons. Actual greenhouse gas emissions may exceed the range encompassed by the scenarios used here. Indeed current emissions are beyond the highest scenario used in these projections. Ultimately, greenhouse gas emissions directly related to human activities could be either higher or lower than the projected range. Changes in the earth's carbon and methane cycles brought on by a changing climate could further modify greenhouse gas concentrations and climate through feedback effects (IPCC, 2007).

Additionally, the climate system's sensitivity to increasing greenhouse gases may fall outside the range of the 16 climate models used to produce the NPCC projections. Other possible types of climate changes that could have large impacts on the region also cannot be ruled out. These could include shifts in the average latitudes and tracks of moisture-laden storms traversing eastern North America, and/or changes in ocean circulation in the North Atlantic.

High-end scenarios and rapid ice melt

The rapid ice-melt scenario was developed by the NPCC to address the possibility of more rapid sea level rise in the region than the IPCC model-based approach projects (see Box 3.5 for more information). The motivation to consider sea level rise exceeding IPCC-based estimates is due to several factors, including:

- Recent accelerated ice melt in Greenland and West Antarctica, which may indicate the potential for high sea level rise over multiple centuries;[12]
- Paleoclimatic evidence of rapid sea level rise;
- Ice sheet dynamics not properly simulated by global climate models; and
- Potentially large implications for a coastal city of more rapid sea level rise.

Additionally, recent well-documented decreases in summer and fall Arctic sea ice area and volume, although not a significant direct cause of sea level rise, are also raising concern. Declines in sea ice could indicate that polar climate sensitivity to greenhouse gases, and increasing temperatures is higher than predicted by global climate models. The warming effect of decreasing sulfate aerosols, along with atmospheric and ocean circulation patterns may also be partially responsible for recent accelerated melting. The sea ice declines could also modify atmospheric and oceanic conditions over the high latitudes, with implications for Greenland's ice sheet. For example, since air over water is warmer than air over ice, sea ice melting would generally result in warmer air in polar regions. If this warmer air were transported out of the Arctic to Greenland, Greenland's coastal and low-elevation glaciers might receive more moisture in the form of rain, and less as snow, leading to accelerating melting of the land ice that does contribute directly to sea level rise.

Box 3.5 Sea level rise—past, present, and future

Starting around 20,000–21,000 years ago, global sea level began to rise from a low of 394 feet (120 meters) below present-day sea level, when water on the planet was locked up in ice, to close to present levels by 7000–8000 years ago (Peltier and Fairbanks, 2006; Fairbanks, 1989). Most of the rise was accomplished in a 10,000- to 12,000-year period; the average rate of sea level rise over this period ranged between 3.9 and 4.7 inches (9.9–11.9 cm) per decade depending on length of period used to calculate the average rate of rise.

In the course of this long period of melting, shorter periods of more rapid rise lasting several centuries, known as meltwater pulses, occurred in which maximum rates of sea level rise ranged between 16 and 24 inches (40–60 cm) per decade. It is highly unlikely that such high meltwater pulse sea level rise rates will be matched during the 21st century, since they occurred after the ice sheets had already been weakened and undermined by centuries to millennia of prior warming. Furthermore, the meltwater pulses often occurred as abrupt intervals associated with catastrophic events (e.g., ice dams breaking) at a time when total ice extent was much greater than today. Vast ice sheets covered much of North America, northern Europe and adjacent Russia, the British Isles, and high mountain ranges at the peak of the last Ice Age. The ice on Antarctica was also much thicker than at present.

In the NPCC rapid ice-melt scenario, we assume that glaciers and ice sheets melt at a rate comparable to that of the average rate during the last deglaciation (i.e., total ice melt rises linearly at 3.9–4.7 inches (9.9–11.9 cm) per decade until 2100). We use the average present-day ice rate of 0.4 inches (1.1 cm) per decade 2000–04 as a base period. This is the sum of observed mountain glacier melt (IPCC, 2007) and ice sheet melt (Shepherd and Wingham, 2007) during this period. For 2100, the total rise in sea level attributed to ice melt from all sources including mountain glaciers is estimated to be 39–47 inches (99–119 cm). Since the melting is likely to accelerate through time as warming occurs, we then fit an exponential curve to three points: 2000, 2002 (the mid-point of 2000–04), and 2100. We then add the other three components from the IPCC-based sea level rise projection approach (thermal expansion, local ocean dynamics, and subsidence) to this exponential meltwater estimate for three time slices.

Longer-term projections

Climate change projections for the 22nd century are beyond most current infrastructure planning horizons. However, planning for some long-lived infrastructure, which hypothetically could include, for example, new aqueducts and subway lines, would justify consideration of climate in the 22nd century. Furthermore, many types of infrastructure intended only to have a useful lifespan within the 21st century may remain operational beyond their planned lifetime. Future projects aimed specifically at climate change adaptation might benefit during their planning stages from consideration of long-term climate change.

Projections of 22nd century climate are highly uncertain, largely because greenhouse gas emissions and concentrations cannot be projected with any confidence that far into the future. Additionally, the possibility that geo-engineering techniques designed to cool the planet may be employed at multicentury timescales cannot be ruled out. Despite uncertainties, the large inertia of the climate system suggests that the current directional trends in two key climate variables, sea level rise and temperature, will probably continue into the 22nd century (Solomon *et al.*, 2009).

The biggest climate uncertainties surround the issue of whether abrupt climate changes may occur as the system moves further from pre-industrial conditions. Given the large inertia of the ice sheets on Greenland and West Antarctica, continuing evidence during the next decade of acceleration of dynamically induced melting would greatly increase the probability that these ice sheets would contribute significantly to sea level rise in the 22nd century, even if greenhouse gas concentrations, and perhaps even global temperatures, were to stabilize in the coming decades.

3.4 Conclusions and recommendations

State-of-the art global climate models now enable climate change projections at scales relevant to decision makers creating initial adaptation plans in New York City. Climate change is extremely likely to bring warmer temperatures to New York City and the surrounding region. Heat waves are very likely to become more frequent, intense, and longer in duration. Total annual precipitation will more likely than not increase, and brief, intense rainstorms are likely to increase as well. Toward the end of the 21st century, it is more likely than not that droughts will become more severe. Additionally, rising sea levels are extremely likely and are very likely to lead to more frequent and damaging flooding related to coastal storm events in the future.

New York City has the good fortune to include within its boundaries some of the world's leading practitioners of climate science. This local resource can be invaluable for city and state officials as they grapple with climate change adaptation. Thus city and state officials should continue to work with these scientists to maximize the value of this local knowledge base. At the same time, scientists can learn a great deal about climate change adaptation on an empirical level by working closely with New York City's infrastructure workers, managers, and other professionals.

There is a need for enhanced regional modeling capability to improve the skill and plausibility of climate projections. The scientific community is working on refining existing climate models, at both global and regional scales, and this work should be monitored for developments that can be applied locally.

While improved model resolution will depend in part on improvements in processing power, perhaps no less important are improved and extended local and regional observational datasets to provide indicators and monitoring (as discussed in Chapter 7). Such data sets will help to improve understanding and simulation of key climate change and impact processes in the complex urban environment of New York City and its surrounding region. Such data sets will also facilitate one of the major climate initiatives of the next decade: the seamless integration of weather and climate prediction by bridging the weekly, seasonal, and decadal timescales.

A key recommendation is the need to update climate change projections on an ongoing and regular basis. Updates are necessary because understanding of the climate system and climate models improves through time, and New York City needs to have an ongoing set of science-based climate scenarios to continue to develop effective Flexible Adaptation Pathways.

Endnotes

[1]The cryosphere (which includes ice sheets, glaciers, sea ice, seasonal snow cover, and permafrost), in contrast, generally reflects far more radiation than it absorbs.

[2]Climate sensitivity is defined by the IPCC as the equilibrium or final increase in global temperature associated with a doubling of CO_2 from preindustrial levels. More generally sensitivity refers to how much climate change is associated with a given climate forcing agent, such as CO_2.

[3]Records are available beginning in 1856; however, the 19th century values are not included here because of large gaps in the record.

[4]Relative to NAVD88. The surge level may vary from one location to another.

[5]Projections of extreme events are conditioned on historical data (which has large spatial variation), whereas projections of mean annual changes are conditioned only on model changes through time (which have less spatial variation).

[6]For sea level rise, the multidecadal approach is not necessary owing to lower inter-annual variability; the 2050s time slice for sea level (for example) therefore refers to the period from 2050–2059.

[7]Regional climate models, similiar to GCMs but run at a higher resolution over a limited area, are increasingly being used to address issues of spatial scale.

[8]For drought, the entire 20th century was used as a baseline, and 2000 to 2004 data were used for sea level rise.

[9]Because they are rare, the coastal storm projections were based on longer time periods. See CRI for more information.

[10]ENSO and the AMO are coupled ocean-atmosphere phenomena centered in the tropical Pacific and Atlantic Oceans, respectively.

[11]Although some research does suggest that lightning may become more frequent with warmer temperatures and more moisture in the atmosphere (Price and Rind, 1994).

[12]Neither the Greenland nor West Antarctic ice sheet has yet to significantly contribute to global

and regional sea level rise, but because potential sea level rise would be large should current melt patterns continue to accelerate, their statuses should be monitored on a regular basis.

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