Chapter 1

Climate Risks

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Introduction

This chapter describes New York State's climate and the climate changes the state is likely to face during this century. The chapter contains: 1) an overview; 2) observed climate trends in means and extremes; 3) global climate model (GCM) validation, methods, and projections (based on long-term average changes, extreme events, and qualitative descriptions); and 4) conclusions and recommended areas for further research. To facilitate the linking of climate information to impacts in the eight ClimAID sectors, the state is divided into seven regions. Three appendices describe the projection methods, outline a proposed program for monitoring and indicators, and summarize the possible role of further downscaling climate model simulations for future assessments.

The climate hazards described in this chapter should be monitored and assessed on a regular basis. For planning purposes, the ClimAID projections focus on the 21st century. Although projections for the following centuries are characterized by even larger uncertainties and are beyond most current infrastructure planning horizons, they are briefly discussed in Appendix A because climate change is a multi-century concern.

Observed Climate Trends

- Annual temperatures have been rising throughout the state since the start of the 20th century. State-average temperatures have increased by approximately 0.6ºF per decade since 1970, with winter warming exceeding 1.1ºF per decade.
- Since 1900, there has been no discernable trend in annual precipitation, which is characterized by large interannual and interdecadal variability.
- Sea level along New York's coastline has risen by approximately 1 foot since 1900.
- Intense precipitation events (heavy downpours) have increased in recent decades.

Climate Projections

These are the key climate projections for mean changes and changes in extreme events.

Mean Changes

- Mean temperature increase is extremely likely this century. Climate models with a range of greenhouse gas emissions scenarios indicate that temperatures across New York State[1] may increase 1.5–3.0ºF by the 2020s,[2] 3.0–5.5ºF by the 2050s and 4.0–9.0ºF by the 2080s.
- While most climate models project a small increase in annual precipitation, interannual and interdecadal variability are expected to continue to be larger than the trends associated with human activities. Projected precipitation increases are largest in winter, and small decreases may occur in late summer/early fall.
- Rising sea levels are extremely likely this century. Sea level rise projections for the coast and tidal Hudson River based on GCM methods are 1–5 inches by the 2020s, 5–12 inches by the 2050s, and 8–23 inches by the 2080s.
- There is a possibility that sea level rise may exceed projections based on GCM methods, if the melting of the Greenland and West Antarctic Ice Sheets continues to accelerate. A rapid ice melt scenario, based on observed rates of melting and paleoclimate records, yields sea level rise of 37–55 inches by the 2080s.

Changes in Extreme Events[3]

- Extreme heat events are very likely to increase and extreme cold events are very likely to decrease throughout New York State.
- Intense precipitation events are likely to increase. Short-duration warm season droughts will more likely than not become more common.
- Coastal flooding associated with sea level rise is very likely to increase.

A Note on Potential Changes in Climate Variability

Climate variability refers to temporal fluctuations about the mean at daily, seasonal, annual, and decadal timescales. The quantitative projection methods in ClimAID generally assume climate variability will remain unchanged as long-term average conditions shift. As a result of changing long-term averages alone, some types of extreme events are projected to become more frequent, longer, and intense (e.g., heat events), while events at the other extreme (e.g., cold events) are projected to decrease.

In the case of brief intense rain events (for which only qualitative projections can be provided), both the mean and variability are projected to increase, based on a combination of climate model simulations, theoretical understanding, and observed trends. Both heavy precipitation events and warm season droughts (which depend on several climate variables) are projected to become more frequent and intense during this century. Whether extreme multi-year droughts will become more frequent and intense than at present is a question that is not fully answerable today. Historical observations of large interannual precipitation variability suggest that extreme drought at a variety of timescales will continue to be a risk for the region during the 21st century.

1.1 Climate Change in New York State

Global average temperatures and sea levels have been increasing for the last century and have been accompanied by other changes in the Earth's climate. As these trends continue, climate change is increasingly being recognized as a major global concern. An international panel of leading climate scientists, the Intergovernmental Panel on Climate Change (IPCC), was formed in 1988 by the World Meteorological Organization and the United Nations Environment Programme to provide objective and up-to-date information regarding the changing climate. In its 2007 Fourth Assessment Report, the IPCC states that there is a greater than 90 percent chance that rising global average temperatures, observed since 1750, are primarily due to human activities. As had been predicted in the 1800s (Ramanathan and Vogelman, 1997; Charlson, 1998), the principal driver of climate change over the past century has been increasing levels of atmospheric greenhouse gases associated with fossil-fuel combustion, changing land-use practices, and other human activities. Atmospheric concentrations of the greenhouse gas carbon dioxide are now more than one-third higher than in pre-industrial times. Concentrations of other important greenhouse gases, including methane and nitrous oxide, have increased as well (Trenberth et al., 2007). Largely as a result of work done by the IPCC and the United Nations Framework Convention on Climate Change (UNFCCC), efforts to mitigate the severity of climate change by limiting levels of greenhouse gas emissions are under way globally.

Some impacts from climate change are inevitable, because warming attributed to greenhouse gas forcing mechanisms is already influencing other climate processes, some of which occur over a long period of time. Responses to climate change have grown beyond a focus on mitigation to include adaptation measures in an effort to minimize the current impacts of climate change and to prepare for unavoidable future impacts. Each ClimAID sector used the climate-hazard information described in this chapter to advance understanding of climate change impacts within the state, with the goal of helping to minimize the harmful consequences of climate change and leverage the benefits.

New York State was divided into seven regions for this assessment (**Figure 1.1**). The geographic regions are grouped together based on a variety of factors, including type of climate and ecosystems, watersheds, and dominant types of agricultural and economic activities. The broad geographical regions are: Western New York and the Great Lakes Plain, Catskill Mountains and the West Hudson River Valley, the Southern Tier, the coastal plain composed of the New York City metropolitan area and Long Island, the East Hudson and Mohawk River Valleys, the Tug Hill Plateau, and the Adirondack Mountains.

Climate analysis was conducted on data from 22 meteorological observing stations (**Figure 1.1**; **Table 1.1a**). These stations were selected based on a combination of factors, including length of record, relative absence of missing data and consistency of station observing procedure, and the need for an even

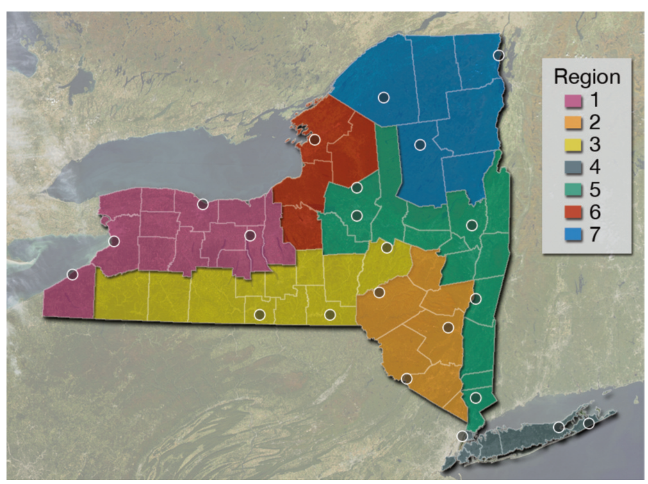


Figure 1.1 ClimAID climate regions. Circles represent meteorological stations used for the climate analysis

spatial distribution of stations throughout the regions and state.

Global climate model-based quantitative projections are provided within each region for:

- temperature,
- precipitation,
- sea level rise (coastal and Hudson Valley regions only), and
- extreme events.

The potential for changes in other variables is also described, although in a more qualitative manner because quantitative information for them is either unavailable or considered less reliable. These variables include:

- heat indices,
- frozen precipitation,
- lightning,
- intense precipitation of short duration, and
- storms (hurricanes, nor'easters, and associated wind events).

Station	Location	NYSERDA region	Data source	Length of coverage	Time-scale
Buffalo/Niagara International Airport	Buffalo	Region 1	COOP	1970–2008	Daily
Rochester International Airport	Rochester	Region 1	COOP	1970–2008	Daily
Geneva Research Farm	Geneva	Region 1	COOP	1970–2008	Daily
Fredonia	Fredonia	Region 1	COOP	1970–2008	Daily
Mohonk Lake	Mohonk Lake	Region 2	COOP	1970–2008	Daily
Port Jervis	Port Jervis	Region 2	COOP	1970–2008	Daily
Walton	Walton	Region 2	COOP	1970–2008	Daily
Binghamton Link Field	Binghamton	Region 3	COOP	1970–2008	Daily
Cooperstown	Cooperstown	Region 3	COOP	1970–2008	Daily
Elmira	Elmira	Region 3	COOP	1970–2008	Daily
Bridgehampton	Bridgehampton	Region 4	COOP	1970–2008	Daily
Central Park	New York	Region 4	COOP	1970–2008	Daily
Riverhead Research Farm	Riverhead	Region 4	COOP	1970–2008	Daily
Saratoga Springs 4 S	Saratoga Springs	Region 5	COOP	1970–2008	Daily
Yorktown Heights 1 W	Yorktown Heights	Region 5	COOP	1970–2008	Daily
Utica - Oneida Country Airport	Utica	Region 5	COOP	1970–2008	Daily
Hudson Correctional	Hudson	Region 5	COOP	1970–2008	Daily
Boonville 4 SSW	Boonville	Region 6	COOP	1970–2008	Daily
Watertown	Watertown	Region 6	COOP	1970–2008	Daily
Indian Lake 2 SW	Indian Lake	Region 7	COOP	1970–2008	Daily
Peru 2 WSW	Peru	Region 7	COOP	1970–2008	Daily
Wanakena Ranger School	Wankena	Region 7	COOP	1970–2008	Daily

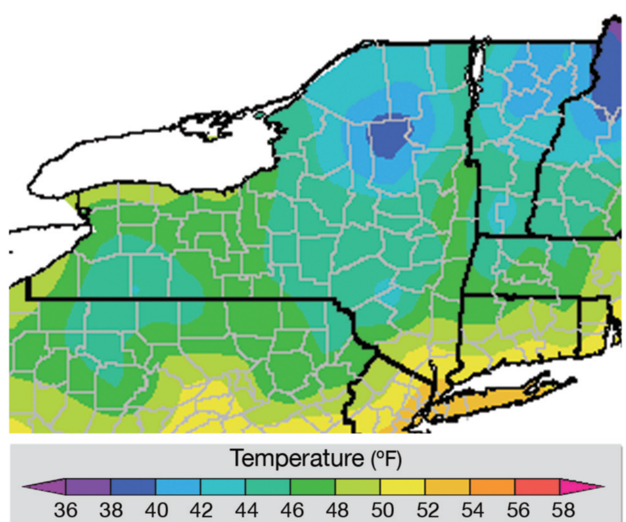
Table 1.1a The 22 New York State stations used in regional baseline averages and extreme events

1.2 Observed Climate

This section describes New York State's mean climate, trends, and key extreme events since 1900. The climate and weather that New York State has experienced historically provides a context for assessing the climate changes for the rest of this century (Section 1.3.3 and Section 1.3.4).

1.2.1 Average Temperature and Precipitation

New York State's climate can be described as humid continental. The average annual temperature varies from about 40°F in the Adirondacks to about 55°F in the New York City metropolitan area (**Figure 1.2**). The wettest parts of the state—including parts of the Adirondacks and Catskills, the Tug Hill Plateau, and portions of the New York City metropolitan area—average approximately 50 inches of precipitation per year (**Figure 1.3**). Parts of western New York are relatively dry, averaging about 30 inches of precipitation per year. In all regions, precipitation is relatively consistent in all seasons, although droughts and floods are nevertheless not uncommon.



Source: Northeast Regional Climate Center

Figure 1.2 Normal average temperature in New York State

1.2.2 Sea Level Rise

Prior to the Industrial Revolution, sea level had been rising along the East Coast of the United States at rates of 0.34 to 0.43 inches per decade (Gehrels, et al., 2005; Donnelly et al., 2004), primarily because of regional subsidence (sinking) as the Earth's crust continues to slowly re-adjust to the melting of the ice sheets since the end of the last ice age. Since the Industrial Revolution, regional sea level has been rising more rapidly than over the last thousand years (Holgate and Woodworth, 2004). Currently, rates of sea level rise on New York State's coastlines have ranged across the region from 0.86 to 1.5 inches per decade, averaging 1.2 inches per decade since 1900. Sea level rise rates over this time period, measured by tide gauges, include both the effects of global warming since the onset of the Industrial Revolution 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 expansion of the oceans as they warm, although melting of glaciers and ice sheets may become the dominant contributor to sea level rise during this century (Church et al., 2008).

1.2.3 Snowfall

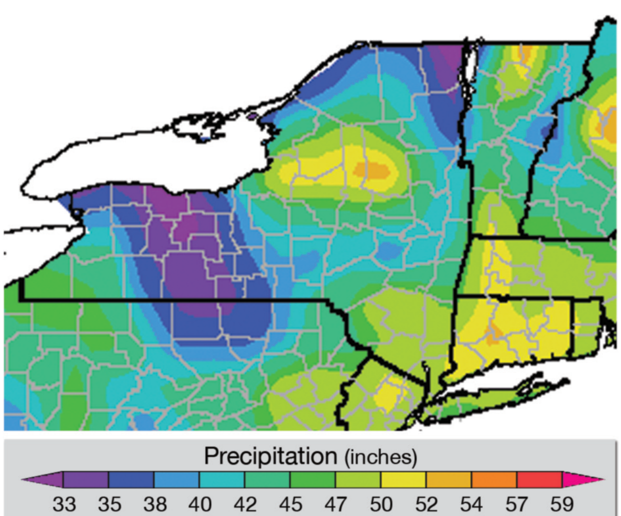
New York State averages more than 40 inches per year of snow. Snowfall varies regionally, based on topography and the proximity to large lakes and the Atlantic Ocean (**Figure 1.4**). Maximum seasonal snowfall is more than 175 inches in parts of the Adirondacks and Tug Hill Plateau, as well as in the westernmost parts of the state. The warming influence of the Atlantic keeps snow in the New York metropolitan region and Long Island below 36 inches per year. Heavy snow squalls frequently occur near the Great Lakes, generating as much as 48 inches of snow in a single storm. In southern parts of the state, snowfall amounts occasionally exceed 20 inches during nor'easters. New York City, for example, experiences snow storms that exceed 20 inches about once every 30 years (New York State Climate Office, 2003).

1.2.4 Extreme Events

New York State is affected by extremes of heat and cold, intense rainfall and snow, and coastal flooding caused by tropical storms and nor'easters. Due to the large regional variations in the state's climate, no single extreme event metric is appropriate for the entire state. For example, in the northern parts of the state 0°F may be an appropriate metric for some stakeholder applications, whereas 32°F is more appropriate in the southern coastal plain, where maritime air from the Atlantic Ocean moderates temperatures.

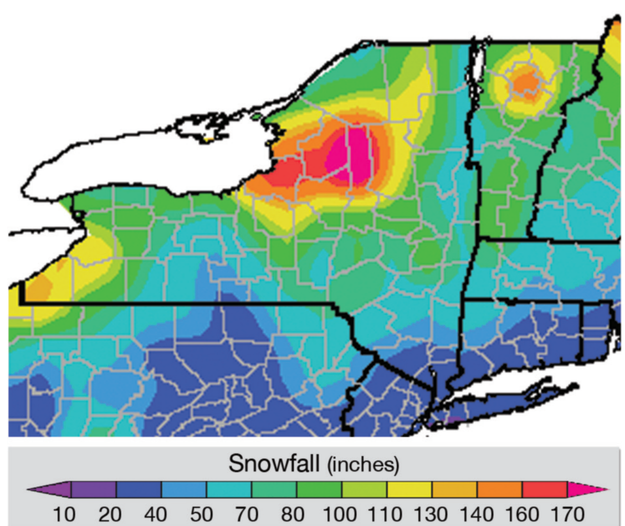
Extreme Temperature and Heat Waves

Extreme hot days and heat waves are thus defined in several ways to reflect the diversity of conditions experienced across New York State:



Source: Northeast Regional Climate Center

Figure 1.3 Normal average precipitation in New York State



Source: Northeast Regional Climate Center

Figure 1.4 Normal average snowfall in New York State

- Individual days with maximum temperatures at or above 90°F
- Individual days with maximum temperatures at or above 95°F
- Heat waves, defined as three consecutive days with maximum temperatures above 90°F

Extreme cold days are also defined to reflect the state's regional climate variations:

- Individual days with minimum temperatures at or below 32°F
- Individual days with minimum temperatures at or below 0°F

In all locations, the number of extreme events from year to year is highly variable. For example, in 2002, Port Jervis experienced temperatures of 90°F or higher on 31 different days; in 2004 days with temperatures of 90°F or higher only occurred four times.

Extreme Precipitation and Flooding

Throughout New York State, heavy rainfall can lead to flooding in all seasons. Urban areas (due to impermeable surfaces, including roads and buildings), steep slopes, and low-lying areas are particularly vulnerable. In much of central and northern New York State, flooding is most frequent in spring, when rains and rapid snowmelt lead to runoff. Ice jams sometimes contribute to serious flooding in very localized areas during spring and winter as well. Farther south, inland floods are more frequent during the summer.

Across the state, mechanisms responsible for producing heavy rainfall vary and are generally more common near the coasts. Intense precipitation can be associated with small-scale thunderstorms, most common in the warmer months. Large-scale coastal storms (see Coastal Storms), including cold/cool-season nor'easters (which can produce snow and ice in addition to rain) and warm-season tropical cyclones, can also produce intense precipitation.

Another extreme precipitation event experienced in regions of New York State is lake-enhanced snow events. These snowfall events, which can last anywhere from an hour to a few days, affect places downwind of the Great Lakes (and, to a lesser extent, the Finger Lakes) in western New York. Parts of Western New York (including Buffalo) receive snowfall from Lake Erie, while the Tug Hill region (including Watertown and Oswego) experiences snowfall from Lake Ontario. Lake-enhanced snowfall is localized; areas within miles of each other can experience large differences in snowfall totals. For example, an October 2006 lake-effect snow event produced as much as 2 feet of snow in parts of the Buffalo metropolitan area, while just 20 miles away, Niagara Falls received approximately an inch of snow (Hamilton, 2007).

Destructive winds, lightning strikes, and hail are common during severe thunderstorms, but tend to affect small areas. Freezing rain events are more rare, but can affect larger areas.

Coastal Storms

The two types of storms with the largest impact on the coastal areas of the state are tropical cyclones and nor'easters. Tropical cyclones strike New York State very infrequently (generally between July and October), can produce large storm surges along the coast, and can cause wind damage and intense precipitation throughout the entire state. Nor'easters are far more frequent and of longer duration; they generally do not occur during the warmest months. Nor'easters are generally associated with smaller surges and weaker winds along the coast than tropical cyclones. Nevertheless, nor'easter flood effects can be large, since their long duration can extend the period of high winds, high water, and wave action over multiple tidal cycles.

A large fraction of New York City and coastal Long Island, especially the south shore, is less than 10 feet above average sea level and is vulnerable to coastal flooding during major storm events, both from inland flooding and from coastal storm surges. The current

Station	NYSERDA region	Data source	Length of coverage	Timescale
Rochester	Region 1	USHCN	1900–2008	Monthly
Port Jervis	Region 2	USHCN	1910–2008	Monthly
Elmira	Region 3	USHCN	1900–2008	Monthly
New York City (Central Park)	Region 4	USHCN	1900–2008	Monthly
Albany	Region 5	USHCN	1900–2008	Monthly
Watertown	Region 6	USHCN	1900–2008	Monthly
Indian Lake	Region 7	USHCN	1900–2008	Monthly

Table 1.1b Seven New York State stations used for temperature and precipitation analysis, including drought

100-year flood event (see Appendix A for a description of how return periods are defined and calculated) can produce an 8.6-foot storm surge across much of New York City.

1.2.5 Historical Analysis

An analysis of historical trends in seasonal and annual average temperature and precipitation was conducted at one station with a long data record in each of the seven regions (**Table 1.1b**).[4] The observed monthly data source is Version 2 of the United States Historical Climatology Network (USHCN) product (http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html). The data are corrected for time of observation and change in observation practice through time. Missing data are filled in using optimized spatial interpolation; these interpolations have been shown not to affect trends (Menne et al., 2009). This data product is not specifically adjusted for urbanization (Menne et al., 2009).

For extreme event projections, daily data came from the NOAA Cooperative Observer Program (COOP) data set (http://www7.ncdc.noaa.gov/IPS/coop/coop.html), with missing data filled in using spatial interpolation (Menne et al., 2009).[5]

Average annual and seasonal temperature and precipitation trends were calculated for three time periods: 1901–2000 (**Table 1.2a**), 1970–2008 (**Table 1.2b**) and 1970–1999 (**Table 1.2c**). The 1900s and 30-year time periods are frequently used for analysis (see Trenberth et al., 2007 and Hayhoe, 2007 for local application). By analyzing a full century, the role of unpredictable decade-to-decade variability can be reduced. The 30-year timeslice is referred to as the "climate normal" and has wide application in the meteorological and climate communities (for example, Guttman, 1989; WMO, 1989). The 30-year trend has strong appeal to stakeholders since it is deemed more representative of the experienced climate than is the 100-year trend; the 30-year trend also better reflects the global carbon dioxide forcing associated with warming at the end of the 20th century. However, at such short timescales, regional trends can be dominated by climate variability. The analysis is extended through 2008 to reduce this problem.

Temperature

The well-documented warming trend in New York State (Hayhoe, 2007 and 2008) from 1970 through 1999 is even more robust when extended through 2008

	Annual (°F/decade)	Spring (°F/decade)	Summer (°F/decade)	Fall (°F/decade)	Winter (°F/decade)
Albany	0.18**	0.25**	0.13*	0.06	0.29**
Elmira	0.01	-0.02	-0.09	0.00	0.17
Indian Lake	0.15**	0.13	0.05	0.14*	0.29*
NYC	0.39**	0.45**	0.33**	0.28**	0.53**
Port Jervis	0.06	0.09	0.02	-0.08	0.20*
Rochester	0.20**	0.26**	0.19**	0.10	0.25*
Watertown	0.17**	0.17*	0.15**	0.08	0.31**

Temperature in ºF per decade
* Significant at the 95% level. ** Significant at the 99% level.

	Annual (in/decade)	Spring (in/decade)	Summer (in/decade)	Fall (in/decade)	Winter (in/decade)
Albany	1.13**	0.33	0.34	0.36**	0.10
Elmira	0.30	0.01	-0.08	0.26	0.11
Indian Lake	-0.06	-0.01	-0.04	0.08	-0.10
NYC	0.47	0.24	-0.05	0.25	0.04
Port Jervis	0.11	0.15	-0.21	0.12	0.04
Rochester	0.29	0.01	0.15	0.20*	-0.07
Watertown	0.35	-0.01	0.05	0.23*	0.09

Precipitation in inches per decade
* Significant at the 95% level. ** Significant at the 99% level.
Source: Columbia University Center for Climate Systems Research. Data are from NOAA NCDC USHCN

Table 1.2a Observed climate trends in New York State (1901–2000)

	Annual (°F/decade)	Spring (°F/decade)	Summer (°F/decade)	Fall (°F/decade)	Winter (°F/decade)
Albany	0.64**	0.23	0.69**	0.47	1.23**
Elmira	0.61**	0.31	0.71**	0.44	1.04*
Indian Lake	0.70**	0.36	0.38	0.73**	1.39**
NYC	0.60**	0.43	0.31	0.47*	1.23**
Port Jervis	0.43**	0.05	0.51**	0.45*	0.78
Rochester	0.49**	0.27	0.23	0.36	1.18**
Watertown	0.57**	0.21	0.39	0.60*	1.15*

Temperature in ºF per decade
* Significant at the 95% level. ** Significant at the 99% level.

	Annual (in/decade)	Spring (in/decade)	Summer (in/decade)	Fall (in/decade)	Winter (in/decade)
Albany	1.33	0.16	0.50	0.62	-0.15
Elmira	1.68	0.52	0.77	0.36	-0.08
Indian Lake	0.43	0.26	0.06	-0.10	0.06
NYC	-0.16	-0.48	0.41	0.31	-0.62
Port Jervis	0.47	-0.53	0.07	0.91	-0.22
Rochester	0.30	0.08	0.11	0.20	-0.15
Watertown	0.73	0.30	-0.03	0.42	-0.04

Precipitation in inches per decade
* Significant at the 95% level. ** Significant at the 99% level.
Source: Columbia University Center for Climate Systems Research. Data are from NOAA NCDC USHCN

Table 1.2b Observed climate trends in New York State (1970–2008)

(**Table 1.2**). The annual temperature trends for all seven stations are significant at the 99 percent level over the 1970–2008 period, whereas only three of seven are significant at that level for the 1970–1999 period. The seven-station average warming trend has decreased slightly from 0.63°F per decade over the 30-year period to 0.58°F per decade from 1970 through 2008. The seven-station, 100-year warming trend can be attributed almost entirely to the warming in recent decades.

Winter warming (the average over December, January, and February) contributes most strongly to the trends. Winter warming trends for 1970–2008 from four of the seven stations are significant at the 99 percent level as compared to three of the 1970–1999 trends. However, the seven-station average winter warming trends decrease from 1.63°F per decade to 1.14°F per decade, indicating that the winters of the past decade have not been particularly warm. When the 1970–2008 record is used in place of the 1970–1999 record, summer and to a lesser extent fall warming trends become more evident; three of the seven stations show summer warming that is significant at the 99 percent level for the 1970–2008 period. Averaged across the seven stations over the 1970–2008 period, summer warming trends are 0.46°F and fall warming trends are 0.50°F per decade.

	Annual (°F/decade)	Spring (°F/decade)	Summer (°F/decade)	Fall (°F/decade)	Winter (°F/decade)
Albany	0.58*	0.23	0.52	-0.02	1.64**
Elmira	0.76**	0.52	0.88*	0.21	1.51*
Indian Lake	0.87**	0.70	0.33	0.48	2.02**
NYC	0.67**	0.47	0.33	0.22	1.69**
Port Jervis	0.53*	0.25	0.38	0.19	1.35*
Rochester	0.43	0.30	0.07	-0.14	1.54
Watertown	0.59	0.24	0.35	0.18	1.65*

Temperature in ºF per decade
* Significant at the 95% level.
** Significant at the 99% level.

	Annual (in/decade)	Spring (in/decade)	Summer (in/decade)	Fall (in/decade)	Winter (in/decade)
Albany	-0.59	-0.01	-0.73	0.55	-0.56
Elmira	0.03	0.72	-0.23	-0.08	-0.53
Indian Lake	-1.76	-0.24	-0.56	-0.36	-0.6
NYC	-2.27	-0.47	-0.73	-0.68	-0.55
Port Jervis	-0.61	-0.17	-0.62	0.46	-0.37
Rochester	0.15	0.16	0.21	0.34	-0.56
Watertown	-1.36	-0.01	-1.04	0.15	-0.35

Precipitation in inches per decade
* Significant at the 95% level. ** Significant at the 99% level.Source: Columbia University Center for Climate Systems Research. Data are from NOAA NCDC USHCN

Table 1.2c Observed climate trends in New York State (1970–1999)

Precipitation

Few precipitation trends at these seven stations are significant at even the 95 percent confidence level for any of the three time periods analyzed. Over the entire 1900s, annual precipitation (averaged across the seven stations) increased by 0.37 inches per decade, with weak increasing trends during each of the four seasons. The well-documented decreasing annual precipitation trend from 1970 through 1999 (-0.92 inches per decade in the seven-station average) reverses and increases (0.68 inches per decade in the seven-station average) when the 2000–2008 period is included. For the 1970–2008 period, only the winter trend decreases, at a negligible -0.17 inches per decade for the seven-station average. These results point to the dominant influence of natural variability at decade-to-decade timescales on precipitation, and suggest that average precipitation changes over the region's observed historical record cannot be attributed to climate change.

Extreme Events

For each of the seven stations, extreme event trends for the 1970–1999 and 1970–2007 periods were also calculated based on daily data. Due to large year-to-year variability in extreme events, the available temporal coverage of the daily data is lower than optimal for trend analysis. As a result, shifting of the years analyzed can produce a large change in the trends shown here. The trends analyzed were: number of days per year with maximum temperatures above 85°F;[6] numbers of days per year with minimum temperatures below 32°F; heating and cooling degree days;[7] length of growing season (defined as duration of period with temperatures above 32°F); number of days with precipitation exceeding 1 inch; and annual snowfall and snow depth.

Four of the seven stations showed a statistically significant (95 percent) decreasing trend in the number of days with minimum temperatures at or below 32°F over the 1970–2007 period (**Table 1.3**, top). At Saratoga Springs, there were 7.1 fewer days per decade. Consistent with this trend, all seven stations showed a decrease in heating degree days, although the trend was only significant at the 99 percent level at two of the seven stations (**Table 1.3**, middle). Most of the stations showed decreased annual snowfall and snow depth between 1970 and 2007; however, given the large year-to-year variability, none

Station	Number of days below 32ºF (days/decade)***
Rochester	-2.32
Port Jervis	-1.21
Elmira	-3.21*
New York City (Central Park)	-2.73
Saratoga Springs	-7.10**
Watertown	-3.90**
Indian Lake	-5.14**

Station	Heating degree days (degree days/decade)***
Rochester	-109.9
Port Jervis	-46.3
Elmira	-137.4*
New York City (Central Park)	-91.5
Saratoga Springs	-278.4**
Watertown	-163.2*
Indian Lake	-204.0**

Station	Annual snowfall (inches/decade)***
Rochester	0.94
Port Jervis	-0.43
Elmira	0.7
New York City (Central Park)	2.37
Saratoga Springs	-1.63
Watertown	0.13
Peru	-5.38

* Significant at the 95% level. ** Significant at the 99% level.
*** Negative values indicate that these events have been occurring less frequently over approximately the last 40 years. Source: Columbia University Center for Climate Systems Research. Data are from NOAA NCDC USHCN

Table 1.3 Trends in extreme events (1970–2007)

of the snow trends is statistically significant (**Table 1.3**, bottom).

1.3 Climate Projections

Global climate models are mathematical representations of the behavior of the Earth's climate system through time. Each model couples the ocean, atmosphere, and land and ice surfaces. Climate models have increased in complexity as computational power has increased. Recent integrated climate model simulations, done for the IPCC 2007 report, were run at higher spatial resolution than earlier models and, due to improved physical understanding, incorporated complex physical processes more accurately such as cloud physics. Current climate models are generally able to reproduce the warming that occurred over the last century at global and continental scales (Hegerl et al., 2007) but not regional scales (Christensen et al., 2007) when they run in a hindcast mode, which uses accurate historical greenhouse gas concentrations. These models are also able to reproduce some of the key climate characteristics of paleoclimates that were far different than today's climate, which lends additional confidence that global climate models' future simulations are generally realistic. Of the IPCC simulations, the 16 state-of-the-art global climate models that had available output for each of three emissions scenarios (only seven global climate models are available for sea level rise) were selected to develop the projections for the New York State ClimAID assessment. A full description of these emissions scenarios can be found in section 1.3.3.

The large number of available global climate models allows future climate projections to be made using model-based probabilistic assessment across a range of climate sensitivities (the average equilibrium temperature response of a global climate model to doubling the atmospheric carbon dioxide concentration relative to preindustrial levels). The global climate model results used here were calculated from outputs from the World Climate Research Program and the Program for Climate Model Diagnosis and Intercomparison. The outputs of recent simulations of these models are collected by these programs (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php) at the Lawrence Livermore Laboratory in Berkeley, California.

Although global climate models are the primary tool used for long-range climate prediction, they do have limitations. For example, they simplify some complex physical processes, such as convective rainfall (rain events accompanied by instability often associated with thunderstorms and heavy rain). In addition, the spatial and temporal scales of some climate variables, such as thunderstorms, are finer than the resolutions of global climate models. Furthermore, they do not fully include all relevant local climate forcings, including some aerosols, black carbon (which increases warming by absorbing heat in the atmosphere and reducing snow and ice's ability to reflect sunlight), land-cover changes, urban heat island effects, and changes in the amount of solar radiation.[8] For these and other reasons, local climate may change in ways not captured by the models, leading to temperature, precipitation, and sea level rise changes outside the ranges presented here.

1.3.1 Climate Model Validation

Because the 16 coupled climate models (IPCC AR4) were run with observed time-varying 20th century carbon dioxide concentrations and other forcings, results can be compared to the observed data for the same period. Evaluation of climatology/averages and long-term trends are standard metrics used in many studies (for example, Randall et al., 2007; Hegerl et al., 2007; Brekke et al., 2008) of global climate model historical performance. While validation can be conducted on a range of climate variables, this analysis focuses on the two long-term average surface variables from global climate models that are of most interest to stakeholders: temperature and precipitation. Because long-term temperature and precipitation trends have minimal spatial variation in the Northeast in current-generation global climate models (Horton et al., 2010), this analysis focuses exclusively on single gridbox (see Section 1.3.2, Regional Projections for more information) results from the three geographical extremes of the state: the Adirondack region, Western New York, and the coastal plain. The assessment was conducted on 1900s (**Table 1.4a**) and 1970–1999 periods (**Table 1.4b**) of the hindcast global climate model simulations conducted for the IPCC Fourth Assessment Report. These hindcasts closely approximate the greenhouse gas concentrations that were present in the atmosphere over the time period represented by the simulation.

Station	Observed 100-year temperature (ºF)	Global climate model ensemble 100-year temperature (ºF)
Rochester	47.51	42.57
New York City	54.18	49.78
Indian Lake	40.40	40.82

Station	Observed 100-year precipitation (in)	Global climate model ensemble 100-year precipitation (in)
Rochester	29.83	40.06
New York City	45.25	46.62
Indian Lake	39.84	44.46

Source: Columbia University Center for Climate Systems Research. Data are from USHCN and PCMDI

Table 1.4a Observed and modeled temperature and precipitation for the 1900s

Station	Observed 30-year temperature (ºF)	Global climate model ensemble 30-year temperature (ºF)
Rochester	47.89	42.83
New York City	55.06	50.35
Indian Lake	40.18	41.17

Station	Observed 30-year precipitation (in)	Global climate model ensemble 30-year precipitation (in)
Rochester	33.25	40.26
New York City	50.76	46.79
Indian Lake	39.97	44.93

Source: Columbia University Center for Climate Systems Research. Data are from USHCN and PCMDI

Table 1.4b Observed and modeled temperature and precipitation 1970–1999

Mean Climate

For the New York City region, the average temperature for the 1970–1999 period, according to the models, is 50.3ºF. The observed temperature at Central Park was 55.0ºF. While observations exceed the global climate models in all months, the departure is largest in July at 6.8ºF degrees, and smallest in January at 2.3ºF, indicating that the annual temperature cycle is damped in the global climate models. Both observed temperatures and modeled average temperatures are lowest in January and highest in July. The discrepancy between the observed and modeled temperatures is due, in part, to the urban heat island, which is not simulated by global climate models, and to a tendency for the selected grid boxes to be centered in the cooler zone north of the coastal plain (since ocean-dominated grid boxes were not included in the analysis).

The global climate models' average annual precipitation from 1970 through 1999 for the Coastal Plain also falls below observations for Central Park by 8 percent. However, the modeled average is comparable to New York City as a whole (La Guardia airport's average, for example, is only 3 inches lower than the modeled mean). Most of the global climate models are able to capture the relatively even distribution of precipitation throughout the year.

For the Western New York region, the average temperature for the 1970–1999 period, according to the models, is 42.9ºF. This is approximately 5ºF colder than the corresponding observed temperature at Rochester. The hindcast average precipitation is approximately 7 inches higher than the observed value of 33 inches at Rochester.

In the Adirondack region, the average temperature for the 1970–1999 period, according to the models, is 41.2ºF. The observed temperature at Indian Lake was 40.2ºF. The hindcast average precipitation is approximately 5 inches (12 percent) higher than the observed values at Indian Lake, but is representative of the region as a whole, which includes areas that receive more than 50 inches of precipitation per year.

Trends

Historical trend analysis is challenging for multiple reasons. First, over the historical period, the climate change signal from greenhouse gases was not as strong as it is expected to be during this century. Additionally, because the ocean and atmosphere in the climate models interact, the oceans in the models evolve independently from the real ocean through time. As a result, the global climate model historical simulations do not feature the same ocean temperatures and forcing that actually occurred at multi-year to decadal timescales. Thus, the role of natural variability relative to climate change in generating a trend in the models—or in the models relative to observations—cannot be easily assessed. Trends and statistical significance are therefore calculated independently for observations and models.

In Western New York, annual observed temperatures increased 0.2°F per decade over the 20th century. Only the fall trends were not significant at the 95 percent level. Modeled temperatures have warmed by 0.13°F per decade since 1900. The annual and seasonal model trends are all significant at the 99 percent level, with the greatest seasonal warming(0.17°F) present in winter. For the 1970–1999 period, the observed warming increased to 0.43°F per decade. No trends for the 1970–1999 observed period were significant. Over the same period, modeled annual warming was 0.34°F; both the modeled annual trend and the fall trend of 0.53°F per decade are significant at the 99 percent level.

The only significant trend in Rochester's observed average precipitation was for the fall season over the 20th century, at 0.20 inch per decade. The global climate models ensemble precipitation for the 20th century was significant annually and for all seasons but the summer. While the observed trends were not significant for the 1970–1999 period, the global climate model ensemble showed a significant increase in annual average precipitation.

For the Adirondack region (**Table 1.5**, Indian Lake station), the observed warming trend of 0.15°F per decade for the 1900s is well simulated by the global climate model hindcast of 0.14°F per decade. In the observations, approximately half of the warming is due to winter warming; in the global climate models, winter warming exceeds warming in other seasons, but each of the four modeled seasonal trends is similar and significant at the 99 percent level. Over the 1970–1999 period, the global climate model ensemble underestimates the observed annual temperature trend (0.34°F modeled versus 0.87°F observed per decade), although both trends are significant at the 99 percent level. While the observed warming during that time period is primarily in the winter, the global climate model ensemble warming is only significant at the 99 percent level in the summer and fall, when the warming trend in the model is also the largest.

1900–1999 Annual and Seasonal Temperature Trends (°F/decade)
Region 7 – Indian Lake***

100-year average temperature	17%	83%	ENS	Observed
December–February	0.05	0.29	0.16**	0.29*
March–May	0.00	0.26	0.12**	0.13
June–August	0.05	0.24	0.12**	0.05
September–November	0.07	0.21	0.15**	0.14*
Annual	0.04	0.27	0.14**	0.15**

1970–1999 Annual and Seasonal Temperature Trends (°F/decade)
Region 7 – Indian Lake

30-year average temperature	17%	83%	ENS	Observed
December–February	-0.48	0.84	0.16	2.02**
March–May	-0.36	0.67	0.22	0.70
June–August	0.17	0.56	0.40**	0.33
September–November	0.19	0.96	0.55**	0.48
Annual	0.1	0.59	0.34**	0.87**

1900–1999 Annual and Seasonal Precipitation Trends (inches/decade)
Region 7 – Indian Lake***

100-year average precipitation	17%	83%	ENS	Observed
December–February	-0.05	0.16	0.40*	-0.10
March–May	0.02	0.15	0.01	-0.01
June–August	-0.16	0.07	0.03**	-0.04
September–November	-0.02	0.12	0.06*	0.08
Annual	-0.01	0.41	0.14**	-0.06

1970–1999 Annual and Seasonal Precipitation Trends (inches/decade)
Region 7 – Indian Lake

30-year average precipitation	17%	83%	ENS	Observed
December–February	-0.15	0.42	0.15	-0.60
March–May	-0.35	0.29	-0.08	-0.24
June–August	-0.45	0.28	-0.02	-0.56
September–November	-0.22	0.40	0.13	-0.36
Annual	-0.44	0.80	0.10	-1.76

* Significant at the 95% level. ** Significant at the 99% level.
*** Observed data set came from Indian Lake, New York, 1901–2000.
Shown are the observed values for Indian Lake, the GCM ensemble average (ENS), and two points on the GCM distribution (17th and 83rd percentiles) representing the central range. Source: Columbia University Center for Climate Systems Research. Data are from WCRP and PCMDI

Table 1.5 Indian Lake validation

Indian Lake's observed average precipitation trends are not significant in any seasons for both the 1900s and 1970–1999 periods (**Table 1.5**). The same is true of the global climate ensemble for the 1970–1999 period; however for the 1900–1999 period, the ensemble shows statistically significant (99 percent) increases in precipitation both annually and during the summer.

In the coastal plain, the modeled annual temperature increases by 0.13°F per decade during the 1900s. This can be attributed to the 0.32°F per decade trend from 1970 through 1999. The observed 1970–1999 trend is greater at 0.67°F per decade. Observed per-decade temperature increases over the entire 1900s, however, are nearly triple that of the models, at 0.39°F. The 1900s model ensemble trend is similar in each season, while the 1970–1999 model ensemble shows the most temperature increase in the fall and summer. Observed temperature increases during the 1900s, by contrast, were largest in the winter and the smallest during the fall, though all seasons showed significant warming in all seasons. The entire observed warming trend during the past three decades can be attributed to winter warming.

The ensemble average model precipitation trend for the coastal plain is negligible over the 100-year record. The 1970–1999 30-year record shows a small increase of 0.18 inch per decade, due almost entirely to a small increase in winter precipitation. Nevertheless, in all four seasons, the central range of global climate models span from decreasing to increasing values. Over the 1970–1999 period, observed precipitation patterns show a small decrease in precipitation, which is due to decreases in summer and fall precipitation that outweigh increases in spring precipitation. This trend, however, is highly dependent on the selection of years, suggesting that 100-year trends for precipitation are more appropriate, given precipitation's high year-to-year and decade-to-decade variability in the region.

Validation Summary

While the global climate models are able to reproduce the state's climatology with limited biases, departures from observations over the hindcast period (due largely to spatial scale discontinuities between point data and GCM gridboxes)—are large enough to necessitate the use of climate change factors—future global climate model departures from global climate model baseline values—rather than direct model output. This finding provides a rationale for bias-correction such as the change factors or delta-method approach used for the ClimAID assessment (see section 1.3.3 for a description of this method).

The picture regarding trend validation is more complex. Ideally the global climate change factors from each model could be trained using historical trends, but this is not advisable for several reasons. While the 30-year modeled trends deviate from observations, these deviations do not necessarily indicate that global climate model sensitivity and regional response to

Climate Model Acronym	Institution	Atmospheric Resolution (latitude x longitude)	Oceanic Resolution (latitude x longitude)	References
BCCR	Bjerknes Center for Climate Research, Norway	1.9 x 1.9	0.5 to 1.5 x 1.5	Furevik et al., 2003
CCSM	National Center for Atmospheric Research, USA	1.4 x 1.4	0.3 to 1.0 x 1.0	Collins et al., 2006
CGCM	Canadian Center for Climate Modeling and Analysis, Canada	2.8 x 2.8	1.9 x 1.9	Flato 2005
CNRM	National Weather Research Center, METEO-FRANCE, France	2.8 x 2.8	0.5 to 2.0 x 2.0	Terray et al., 1998
CSIRO	CSIRO Atmospheric Research, Australia	1.9 x 1.9	0.8 x 1.9	Gordon et al., 2002
ECHAM5	Max Planck Institute for Meteorology, Germany	1.9 x 1.9	1.5 x 1.5	Jungclaus et al., 2005
ECHO-G	Meteorological Institute of the University of Bonn, Germany	3.75 x 3.75	0.5 to 2.8 x 2.8	Min et al., 2005
GFDL-CM2.0	Geophysical Fluid Dynamics Laboratory, USA	2.0 x 2.5	0.3 to 1.0 x 1.0	Delworth et al., 2006
GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory, USA	2.0 x 2.5	0.3 to 1.0 x 1.0	Delworth et al., 2006
GISS	NASA Goddard Institute for Space Studies	4.0 x 5.0	4.0 x 5.0	Schmidt et al., 2006
INMCM	Institute for Numerical Mathematics, Russia	4.0 x 5.0	2.0 x 2.5	Volodin and Diansky, 2004
IPSL	Pierre Simon Laplace Institute, France	2.5 x 3.75	2.0 x 2.0	Marti, 2005
MIROC	Frontier Research Center for Global Change, Japan	2.8 x 2.8	0.5 to 1.4 x 1.4	K-1 Developers, 2004
MRI	Meteorological Research Institute, Japan	2.8 x 2.8	0.5 to 2.0 x 2.5	Yuikimoto and Noda, 2003
PCM	National Center for Atmospheric Research, USA	2.8 x 2.8	0.5 to 0.7 x 1.1	Washington et al., 2000
UKMO-HadCM3	Hadley Center for Climate Prediction, Met Office, UK	2.5 x 3.75	1.25 x 1.25	Johns et al., 2006

Table 1.6 Global climate models used in the ClimAID assessment

greenhouse gas forcing is incorrect in the models. For example, observed trends, especially for precipitation, also vary substantially based on the time period selected due to high year-to-year and decade-to-decade variability, which the models are not expected to experience concurrently with their freely evolving climate system. The fact that some important, regionally varying external forcings, including some aerosols, are not included in all the global climate models would be expected to further lead to departures from observations over the historical period. Finally, the models are missing local features that may have influenced the trends, including the urban heat island and precipitation island in those stations that are urban centers. In the New York metropolitan region, the heat island effect has been substantial (Rosenzweig et al., 2009; Gaffin et al., 2008). While these missing forcings may contribute to errors in the future, these errors are expected to become relatively less important as the warming role of increasing greenhouse gas concentrations becomes more and more dominant.

1.3.2 Projection Methods

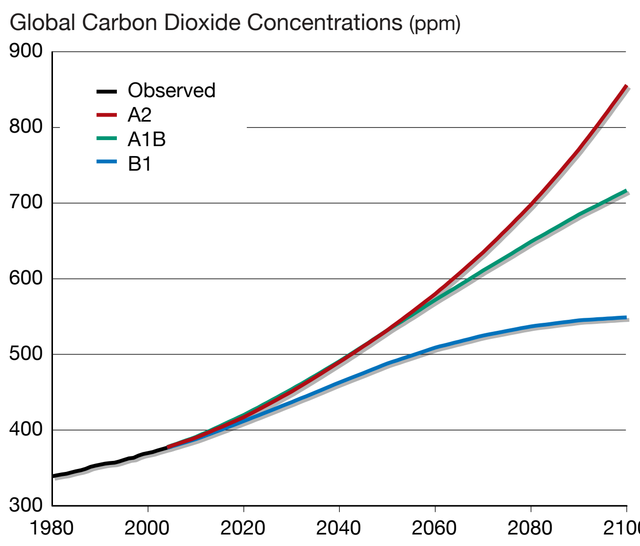
For the ClimAID assessment, global climate models were used to develop a set of climate projections for New York State. Projections were made for changes in mean annual climate (Section 1.3.3) and extreme events (Section 1.3.4). Model-based probabilities for temperature, precipitation, sea level rise, and extreme events are created based on global climate model simulations (see **Table 1.6** for more information about the global climate models) and greenhouse gas emissions scenarios (IPCC, 2000) used in the IPCC Fourth Assessment Report (IPCC, 2007). This approach has been applied to many regions, including locally for New York City as part of the New York City Panel on Climate Change activities in support of New York City's Climate Change Adaptation Task Force (New York City Panel on Climate Change, 2010; Horton et al., 2010).

Emissions Scenarios

To produce future climate scenarios, global climate model simulations are driven with projected greenhouse gas emissions scenarios (**Figure 1.5**). Each emissions scenario represents a unique blend of demographic, social, economic, technological, and environmental assumptions (IPCC, 2000). The following three scenarios are used for this analysis:

> **A2:** Relatively rapid population growth and limited sharing of technological change combine to produce high greenhouse gas levels by the end of this century, with emissions growing throughout the entire century.
>
> **A1B:** Effects of economic growth are partially offset by introduction of new technologies and decreases in global population after 2050. This trajectory is associated with relatively rapid increases in greenhouse gas emissions and the highest overall carbon dioxide levels for the first half of this century, followed by a gradual decrease in emissions after 2050.
>
> **B1:** This scenario combines the A1 population trajectory with societal changes tending to reduce greenhouse gas emissions growth. The net result is the lowest greenhouse gas emissions of the three scenarios, with emissions beginning to decrease by 2040.

Additional IPCC-based scenarios, such as the high-end A1FI scenario, yield moderately higher greenhouse gas concentrations (and therefore climate response) by the end of this century than the three scenarios indicated



Based on IPCC emissions scenarios. Observed carbon dioxide concentrations through 2003 and future carbon dioxide concentrations in the A1B, A2, and B1 scenarios (2004 to 2100). Source: Columbia University Center for Climate Systems Research. Data are from WCRP and PCMDI

Figure 1.5 Future carbon dioxide concentrations used in the ClimAID assessment above. High-end climate change scenarios along the lines of A1FI are discussed qualitatively, especially with regard to the rapid ice melt scenario. Such trajectories should continue to be monitored and reassessed over time. The A1FI scenario was not included in the model-based approach described here due to few available corresponding global climate model simulations.

Model-based Probability

The combination of 16 global climate models and three emissions scenarios produces a matrix with 48 scenarios for temperature and precipitation;[9] 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 1970–1999 baseline period. Average temperature change projections for each month are calculated as the difference between each model's future simulation and the same model's baseline simulation, whereas average monthly 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).[10] Sea level rise methods are more complex since sea level rise is not a direct output of most global climate models.

Sea Level Rise

The GCM-based methods used to project sea level rise for the coastal plain and Hudson River include both global components (global thermal expansion, or sea level rising as a result of increases in water temperature, and meltwater from glaciers, ice caps, and ice sheets) and local components (local land subsidence, i.e., sinking, and local water surface elevation).

Within the scientific community, there has been extensive discussion of the possibility that the GCM approach to sea level rise may substantially underestimate the range of possible increases. For this reason, an alternative rapid ice melt approach has been developed based on paleoclimate studies. Starting around 20,000 years ago, global sea level rose 394 feet; present-day sea level was reached about 8,000 to 7,000 years ago. The average rate of sea level rise during this 10,000 to 12,000-year period was 0.39–0.47 inch per year. This information is incorporated into the rapid ice melt scenario projections. More information on this method, including how it is integrated with the global climate model-based methods, can be found in Appendix A, "Rapid Ice Melt Sea Level Rise Scenario."

Extreme Events

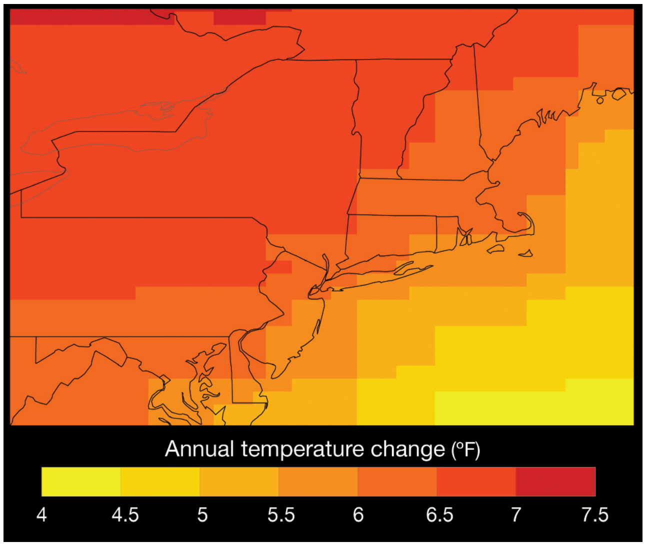
Extremes of temperature and precipitation (with the exception of drought) tend to have their largest impacts at daily rather than monthly timescales. However, monthly output from climate models has more observational fidelity than daily output (Grotch and MacCracken, 1991), so a hybrid projection technique was employed for these events. The modeled mean changes in monthly temperature and precipitation for each of the 16 global climate models and three emissions scenarios were applied to each region's observed daily data from 1971 to 2000 to generate 48 time series of daily data.[11]

This is a simplified approach to projections of extreme events, since it does not allow for possible changes in variability through time. While changes in variability are generally highly uncertain (rendering the precise changes in extreme event frequency highly uncertain as well), changes in frequency associated with average monthly shifts alone are of sufficient magnitude to merit consideration by long-term planners as they develop adaptation strategies that prepare for extreme events.

Regional Projections

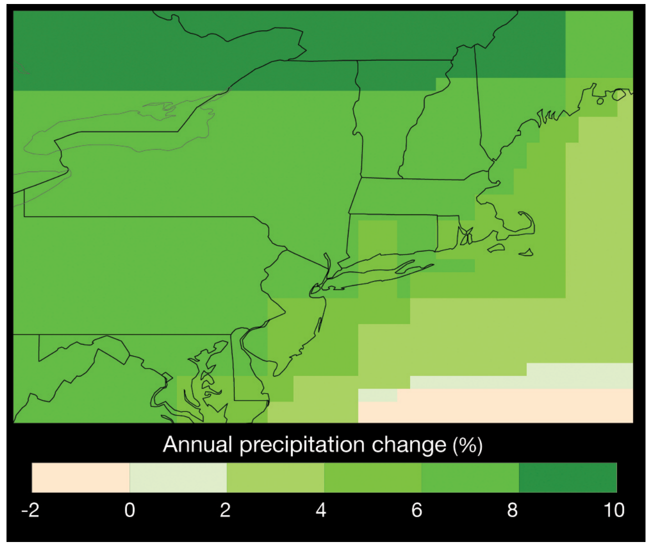
The projections for the seven regions of New York State are based on global climate model output from each model's single land-based model gridbox covering the center of each region. The precise coordinates of each model's gridboxes differ since each global climate model has a different spatial resolution. These resolutions range from as fine as about 75 by 100 miles to as coarse as about 250 by 275 miles, with an average resolution of approximately 160 by 190 miles. Changes in temperature (**Figure 1.6a**) and precipitation (**Figure 1.6b**) through time are region-specific (for example, 3°F degrees of warming by a given timeframe for a particular region). Neighboring regions, however, exhibit similar average changes in climate. This spatial similarity indicates that the average change results shown here are not very sensitive to how the region was defined geographically.

By applying the projected changes from the relevant gridbox to observed data, the projections become specific to the region. For example, although Rochester'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 below 32°F degrees differs between the two locations because they have different baseline temperatures. Thus, the spatial variation in baseline climate is much larger than the spatial variation of projected climate changes.



Source: Columbia University Center for Climate Systems Research. Data are from WCRP and PCMDI

Figure 1.6a Projected change in annual temperature for the 2080s in the Northeast relative to the 1980s baseline period



Source: Columbia University Center for Climate Systems Research. Data are from WCRP and PCMDI

Figure 1.6b Projected change in annual precipitation for the 2080s in the Northeast relative to the 1980s baseline period

		Baseline[1] 1971–2000	2020s	2050s	2080s
Region 1					
Stations used for Region 1 are Buffalo, Rochester, Geneva and Fredonia.	Air temperature[2]	48ºF	+1.5 to 3.0ºF	+3.0 to 5.5ºF	+4.5 to 8.5ºF
	Precipitation	37 in	0 to +5%	0 to +10%	0 to 15%
Region 2					
Stations used for Region 2 are Mohonk Lake, Port Jervis, and Walton.	Air temperature[2]	48ºF	+1.5 to 3.0ºF	+3.0 to 5.0ºF	+4.0 to 8.0ºF
	Precipitation	48 in	0 to +5%	0 to +10%	+5 to 10%
Region 3					
Stations used for Region 3 are Elmira, Cooperstown, and Binghamton.	Air temperature[2]	46ºF	2.0 to 3.0ºF	+3.5 to 5.5ºF	+4.5 to 8.5ºF
	Precipitation	38 in	0 to +5%	0 to +10%	+5 to 10%
Region 4					
Stations used for Region 4 are New York City (Central Park and LaGuardia Airport), Riverhead, and Bridgehampton.	Air temperature[2]	53ºF	+1.5 to 3.0ºF	+3.0 to 5.0ºF	+4.0 to 7.5ºF
	Precipitation	47 in	0 to +5%	0 to +10%	+5 to 10%
Region 5					
Stations used for Region 5 are Utica, Yorktown Heights, Saratoga Springs, and the Hudson Correctional Facility.	Air temperature[2]	50ºF	+1.5 to 3.0ºF	+3.0 to 5.5ºF	+4.0 to 8.0ºF
	Precipitation	51 in	0 to +5%	0 to +5%	+5 to 10%
Region 6					
Stations used for Region 6 are Boonville and Watertown.	Air temperature[2]	44ºF	+1.5 to 3.0ºF	+ 3.5 to 5.5ºF	+4.5 to 9.0ºF
	Precipitation	51 in	0 to +5%	0 to +10%	+5 to 15%
Region 7					
Stations used for Region 7 are Wanakena, Indian Lake, and Peru.	Air temperature[2]	42ºF	+1.5 to 3.0ºF	+3.0 to 5.5ºF	+4.0 to 9.0ºF
	Precipitation	39 in	0 to +5%	0 to +5%	+5 to 15%

[1] The baselines for each region are the average of the values across all the stations in the region.
[2] Shown is the central range (middle 67%) of values from model-based probabilities; temperature ranges are rounded to the nearest half-degree and precipitation to the nearest 5%.
Source: Columbia University Center for Climate Systems Research. Data are from USHCN and PCMDI

Table 1.7 Baseline climate and mean annual changes for the 7 ClimAID regions

Projections for extreme events use baseline climate and projected changes in temperature, precipitation, and sea level rise relative to the given baseline for the timeslices, which are defined by averaging all 22 stations within a given region (**Table 1.7**).

Timeslices

Although it is not possible to predict the temperature, precipitation, or sea level for a particular day, month, or even specific year due to fundamental uncertainties in the climate system, global climate models can project the likely range of changes over decadal to multi-decadal time periods. These projections, known as timeslices, are expressed relative to the given baseline period, 1970–1999 (2000–2004 for sea level rise). The timeslices are centered around a given decade. For example, the 2050s timeslice refers to the period from 2040–2069.[12] Thirty-year timeslices (10 years 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,[13] while the long-term influence of increasing greenhouse gases—or signal—remains (Guttman, 1989; WMO, 1989).

1.3.3 Average Annual Changes

Higher temperatures and sea level rise are extremely likely for New York State. For temperature and sea level rise, all simulations project continued increases over the century, with the entire central range of the projections indicating more rapid temperature and sea level rise than occurred during the last century. Although most projections indicate small increases in precipitation, some do not. Natural precipitation variability is large; thus, precipitation projections are less certain than temperature projections. There is a distinct possibility that precipitation will decrease over both 10-year and 30-year timescales. For all variables, the numerical projections for later in this century are less certain than those for earlier in the century (i.e., the ranges of outcomes become larger through time), due to uncertainties in the climate system and the differing possible pathways of the greenhouse gas emission scenarios.

Comparing observed data with projected changes for temperature and precipitation provides context with regard to how projected changes in the region compare to historical trends and long-term variability (**Figure 1.7**). To emphasize the climate signal and deemphasize the unpredictable year-to-year variability, a 10-year filter has been applied to the observed data and model output.

Temperature

Average annual temperatures are projected to increase across New York State by 1.5–3.0ºF in the 2020s, 3.0–5.5ºF in the 2050s, and 4.0–9.0ºF in the 2080s (**Table 1.7**; **Figure 1.6a**). By the end of the century, the greatest warming may be in the northern parts of the state. The state's growing season could lengthen by about a month, with summers becoming more intense and winters milder. The climate models suggest that each season will experience a similar amount of warming relative to the baseline period.

Beginning in the 2030s, the emissions scenarios diverge, producing temperature patterns that are distinguishable from each other (**Figure 1.7**). This is because it takes several decades for the climate system to respond to changes in greenhouse gas concentrations. It also takes several decades for different emissions scenarios to produce large differences in greenhouse gas concentrations.

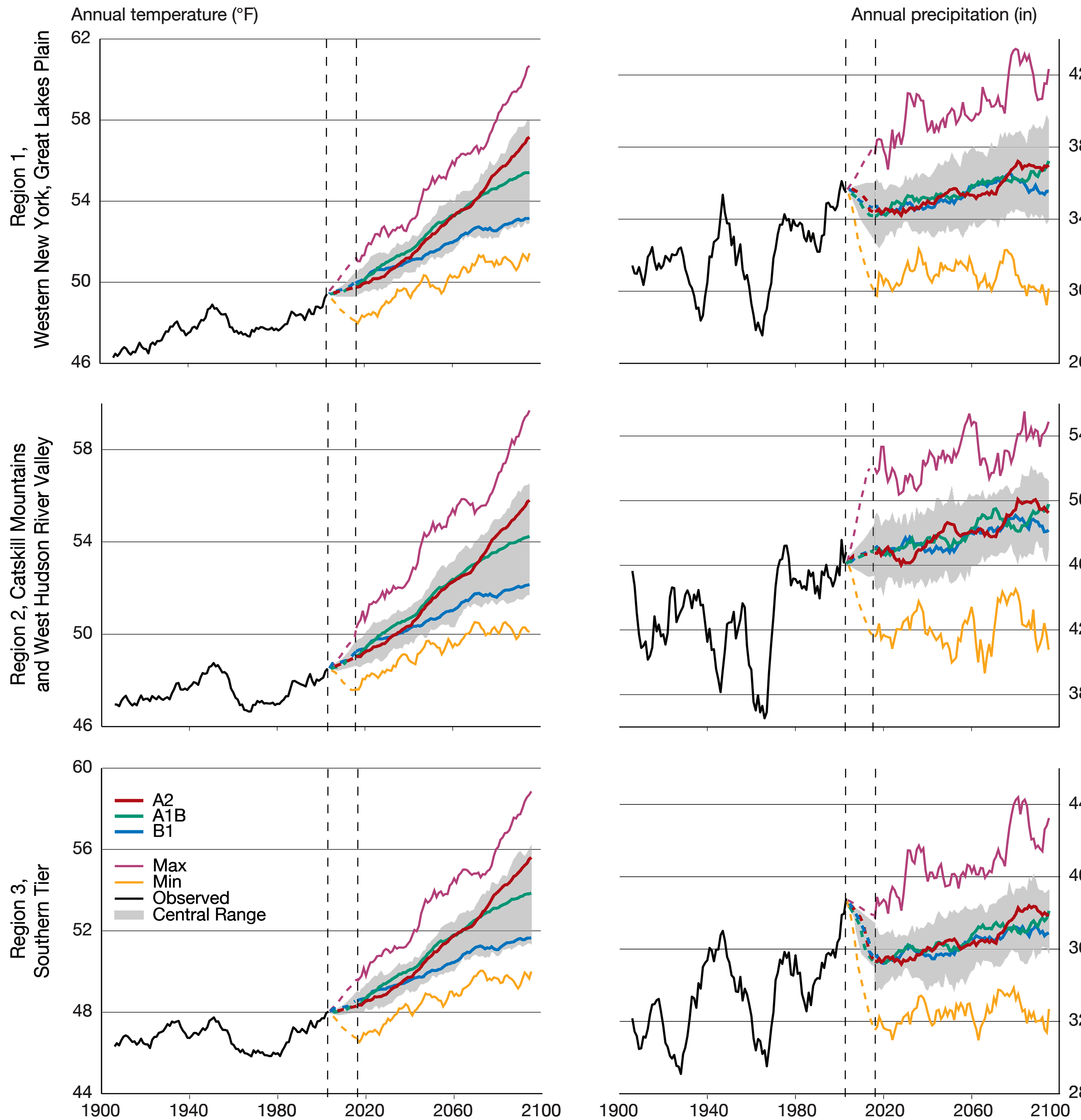
Precipitation

Regional precipitation across New York State may increase by approximately 0–5 percent by the 2020s, 0–10 percent by the 2050s, and 5–15 percent by the 2080s (**Table 1.7**; **Figure 1.6b**). By the end of the century, the greatest increases in precipitation may be in the northern parts of the state. While seasonal projections are less certain than annual results, much of this additional precipitation may occur during the winter months. During September and October, in contrast, total precipitation is slightly reduced in many climate models.

Precipitation is characterized by large historical variability, even with 10-year smoothing (**Figure 1.7**). Beginning in the 2040s, the climate models diverge, with the lower-emission B1 scenario producing smaller increases in precipitation than the high-emission A1B and the mid-emission A2 scenarios. However, even after the 2040s there are occasional periods where the B1 scenario projects more precipitation than that of A2. At no point in the century are the A2 and A1B scenario-based precipitation projections consistently distinguishable.

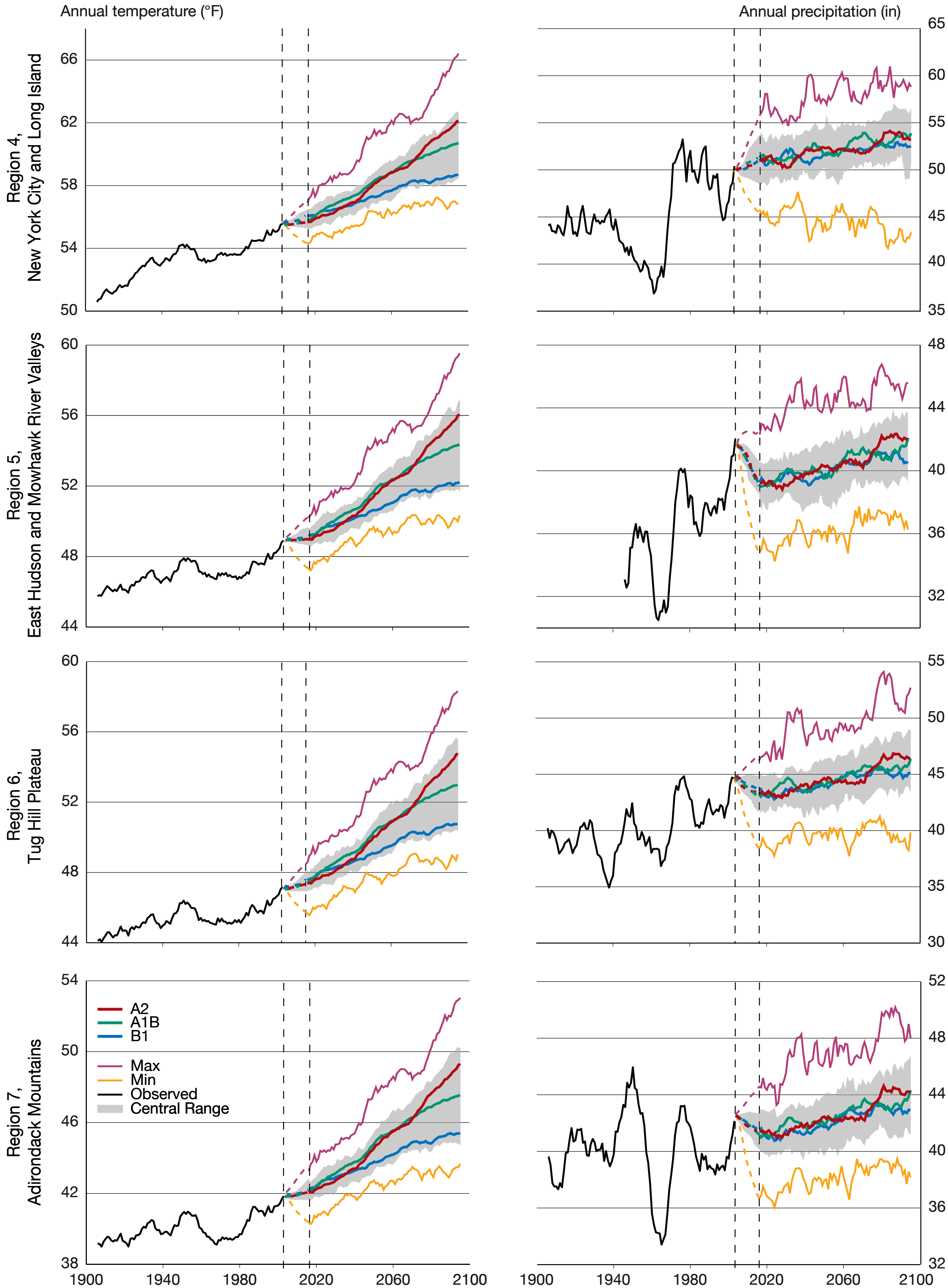
Sea Level Rise

Sea level is projected to rise along the coast and in the tidal Hudson by 1–5 inches in the 2020s, 5–12 inches in the 2050s, and 8–23 inches in the 2080s, using the



Observed (black line) and projected temperature (left) and precipitation (right). Projected model changes through time are applied to the observed historical data. The green, red, and blue lines show the average for each emissions scenario across the 16 global climate models. The shaded area indicates the central range. The bottom shows the minimum projection across the suite of simulations, and the top line shows the maximum projections. A 10-year filter has been applied to the observed data and model output. The dotted area between 2004 and 2015 represents the period that is not covered as a result of 10-year filter. Note different scales for temperature and precipitation.
Source: Columbia University Center for Climate Systems Research. Data are from USHCN, WCRP and PCMDI

Figure 1.7 Observed and projected temperature (left) and precipitation (right) for the ClimAID regions of New York State. Note that the y-axis is specific to each graph (continues on next page)


Annual temperature (°F)
Annual precipitation (in)
Region 4, New York City and Long Island
Region 5, East Hudson and Mowhawk River Valleys
Region 6, Tug Hill Plateau
Region 7, Adirondack Mountains
A2
A1B
B1
Max
Min
Observed
Central Range
1900
1940
1980
2020
2060
2100

GCM-based model projections (**Table 1.8**). Beginning in the 2050s, the low-emissions B1 scenario produces smaller increases in sea level than the higher-emissions A1B and A2 scenarios, and in the 2080s, the A2 scenario projects more sea level rise than A1B. The A2 scenario diverges from A1B approximately 10 years earlier for temperature than it does for sea level rise, in part reflecting the large response time of the ocean and ice sheets relative to the atmosphere.

The model-based sea level rise projections are characterized by greater uncertainty than the temperature projections, largely due to the possibility that future changes in polar ice sheets may accelerate melting beyond currently projected levels; this possible change is not captured by global climate models. This uncertainty is weighted toward the upper bound; that is, the probability that sea level rise will be lower than the GCM-based projection is very low, but the probability that sea level rise will exceed the GCM-based projection is higher.

The rapid ice melt sea level rise scenario addresses the possibility of the ice sheets melting more rapidly. This scenario is based on extrapolating the 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 0.39–0.47 inch per year may be possible. This scenario projects a sea level rise of 37 to 55 inches by the 2080s. The potential for rapid ice melt should be considered, in part, because of its potential for large consequences. It is also uncertain how rapid ice melt might indirectly influence sea level in the New York region through second-order effects, including gravitational, glacial isostatic adjustments, and rotational terms (e.g., Mitrovica et al., 2001, 2009).

Region 4: New York City and Long Island	2020s (inches)	2050s (inches)	2080s (inches)
GCM-based[1]	+2 to +5	+7 to +12	+12 to +23
Rapid ice-melt scenario[2]	~5 to +10	~19 to +29	~41 to +55
Region 5: East Hudson and Mohawk River Valleys	**2020s** (inches)	**2050s** (inches)	**2080s** (inches)
GCM-based[1]	+1 to +4	+5 to +9	+8 to +18
Rapid ice-melt scenario[2]	~4 to +9	~17 to +26	~37 to +50

[1] Shown is the central range (middle 67%) of values from global climate model-based probabilities rounded to the nearest inch.
[2] The 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.

Table 1.8 ClimAID Assessment sea level rise projections

To assess the risk of accelerated sea level rise over the coming years, scientific understanding as well as many key indicators should be monitored and reassessed on an ongoing basis (Appendix B).

1.3.4 Changes in Extreme Events

Despite their brief duration, extreme climate events can have large impacts, so they are a critical component of this climate change impact assessment. The frequencies of heat waves, cold events, intense precipitation, drought, and coastal flooding in the seven regions are projected to change in the coming decades, based on average global climate model shifts (**Table 1.9**). The average number of extreme events per year for the baseline period is shown, along with the middle 67 percent and full range of the model-based projections. Because the model-based probability does not represent the actual probability distribution, and shifts in extreme event distributions are not constrained to the types of average shifts described above, the relative magnitude of projected changes, rather than the actual projected number of events, should be emphasized.

Heat Waves and Cold Events

The total number of hot days in New York State is expected to increase as this century progresses. The frequency and duration of heat waves, defined as three or more consecutive days with maximum temperatures at or above 90°F, are also expected to increase (**Table 1.9**). In contrast, extreme cold events, defined both as the number of days per year with minimum temperature at or below 32°F, and those at or below 0°F, are expected to decrease. Some parts of each region, such as cold high-altitude zones, are likely to experience fewer heat events and more cold events in the future than regional averaging would suggest, because of the cold tendency in their baseline climates.

Intense Precipitation and Droughts

Although the increase in total annual precipitation is projected to be relatively small, larger increases are projected in the frequency, intensity, and duration of extreme precipitation events (defined as events with more than 1, 2, or 4 inches of rainfall) at daily timescales. The projection for New York State is

Table 1.9 Extreme events projections

Rochester (Region 1): Full range of changes in extreme events: minimum, (central range*), and maximum					
	Extreme event	Baseline	2020s	2050s	2080s
Heat Waves & Cold Events	Number of days per year with maximum temperature exceeding				
	90°F	8	8 (10 to 17) 23	12 (17 to 30) 44	16 (22 to 52) 68
	95°F	0.8	0.9 (2 to 4) 6	2 (3 to 9) 17	3 (6 to 22) 38
	Number of heat waves per year[2]	0.8	0.9 (1 to 2) 3	2 (2 to 4) 6	2 (3 to 7) 8
	average duration	4	4 (4 to 4) 5	4 (4 to 5) 5	4 (4 to 5) 7
	Number of days per year with min. temp. at or below 32°F	133	99 (104 to 116) 126	76 (90 to 103) 108	53 (75 to 97) 106
Intense Precipitation	Number of days per year with rainfall exceeding:				
	1 inch	5	3 (4 to 5) 6	3 (4 to 6) 7	3 (4 to 6) 7
	2 inches	0.6	0.4 (0.5 to 0.7) 0.9	0.3 (0.5 to 0.8) 1	0.2 (0.5 to 1) 1

Port Jervis (Region 2): Full range of changes in extreme events: minimum, (central range*), and maximum					
	Extreme event	Baseline	2020s	2050s	2080s
Heat Waves & Cold Events	Number of days per year with maximum temperature exceeding				
	90°F	12	13 (14 to 24) 34	16 (22 to 40) 53	21 (28 to 65) 75
	95°F	2	2 (2 to 5) 10	3 (5 to 12) 20	4 (7 to 28) 39
	Number of heat waves per year[2]	2	2 (2 to 3) 5	2 (3 to 5) 7	3 (4 to 9) 10
	average duration	4	4 (4 to 5) 5	5 (5 to5) 6	5 (5 to 6) 8
	Number of days per year with min. temp. at or below 32°F	138	101 (111 to 121) 128	70 (91 to 111) 115	57 (70 to 101) 112
Intense Precipitation	Number of days per year with rainfall exceeding:				
	1 inch	12	10 (11 to 13) 14	10 (12 to 14) 14	10 (12 to 14) 15
	2 inches	2	1 (2 to 2) 3	1 (2 to 3) 3	1 (2 to 3) 3

Elmira (Region 3): Full range of changes in extreme events: minimum, (central range*), and maximum					
	Extreme event	Baseline	2020s	2050s	2080s
Heat Waves & Cold Events	Number of days per year with maximum temperature exceeding				
	90°F	10	11 (14 to 19) 25	15 (21 to 33) 45	19 (26 to 56) 70
	95°F	1	2 (2 to 4) 7	2 (4 to 10) 18	4 (7 to 24) 38
	Number of heat waves per year[2]	1	1 (2 to 3) 3	2 (3 to 4) 6	2 (3 to 8) 9
	average duration	4	4 (4 to 5) 5	4 (4 to 5) 5	4 (5 to 5) 7
	Number of days per year with min. temp. at or below 32°F	152	116 (122 to 124) 145	86 (106 to 122) 168	68 (87 to 114) 124
Intense Precipitation	Number of days per year with rainfall exceeding:				
	1 inch	6	5 (6 to 7) 8	5 (6 to 7) 8	5 (6 to 8) 10
	2 inches	0.6	0.5 (0.6 to 0.9) 1	0.5 (0.6 to 1) 1	0.4 (0.7 to 1) 2

New York City (Region 4): Full range of changes in extreme events: minimum, (central range*), and maximum					
	Extreme event	Baseline	2020s	2050s	2080s
Heat Waves & Cold Events	Number of days per year with maximum temperature exceeding				
	90°F	19	20 (23 to 31) 42	24 (31 to 47) 58	31 (38 to 66) 80
	95°F	4	4 (6 to 9) 15	6 (9 to 18) 28	9 (12 to 32) 47
	Number of heat waves per year[2]	2	3 (3 to 4) 6	3 (4 to 6) 7	4 (5 to 8) 9
	average duration	4	4 (5 to 5) 5	5 (5 to 5) 6	5 (5 to 7) 8
	Number of days per year with min. temp. at or below 32°F	72	48 (53 to 62) 66	31 (45 to 54) 56	22 (36 to 49) 56
Intense Precipitation	Number of days per year with rainfall exceeding:				
	1 inch	14	11 (13 to 15) 16	11 (14 to 16) 16	11 (14 to 16) 17
	2 inches	3	2 (3 to 4) 5	3 (3 to 4) 5	2 (4 to 5) 5

Saratoga Springs (Region 5): Full range of changes in extreme events: minimum, (central range*), and maximum					
	Extreme event	Baseline	2020s	2050s	2080s
Heat Waves & Cold Events	Number of days per year with maximum temperature exceeding				
	90°F	10	11 (14 to 20) 28	17 (20 to 35) 49	18 (26 to 60) 75
	95°F	1	1 (2 to 4) 7	3 (3 to 10) 18	3 (6 to 25) 42
	Number of heat waves per year[2]	2	2 (2 to 3) 4	3 (3 to 5) 7	3 (4 to 8) 9
	average duration	4	4 (4 to 5) 5	4 (4 to 5) 6	4 (5 to 6) 9
	Number of days per year with min. temp. at or below 32°F	134	121 (128 to 139) 147	92 (111 to 127) 135	78 (90 to 120) 131
Intense Precipitation	Number of days per year with rainfall exceeding:				
	1 inch	10	8 (10 to 11) 12	9 (10 to 11) 12	10 (10 to 12) 14
	2 inches	1	1 (1 to 2) 2	1 (1 to 2) 2	1 (1 to 2) 2

Watertown (Region 6): Full range of changes in extreme events: minimum, (central range*), and maximum					
	Extreme event	Baseline	2020s	2050s	2080s
Heat Waves & Cold Events	Number of days per year with maximum temperature exceeding				
	90°F	3	2 (4 to 7) 11	5 (8 to 17) 27	8 (12 to 36) 52
	95°F	0	0 (0.1 to 0.9) 2	0.2 (0.6 to 3) 7	0.8 (2 to 11) 23
	Number of heat waves per year[2]	0.2	0.2 (0.4 to 0.9) 1	0.6 (0.8 to 2) 4	0.6 (1 to 4) 6
	average duration	4	3 (4 to 4) 5	3 (4 to 4) 5	4 (4 to 5) 7
	Number of days per year with min. temp. at or below 32°F	147	114 (120 to 130) 140	93 (108 to 121) 126	78 (91 to 114) 122
Intense Precipitation	Number of days per year with rainfall exceeding:				
	1 inch	5	5 (6 to 8) 9	6 (6 to 8) 9	5 (7 to 10) 11
	2 inches	0.8	0.4 (0.6 to 0.9) 1	0.5 (0.6 to 1) 1	0.3 (0.6 to 1) 2

Indian Lake (Region 7): Full range of changes in extreme events: minimum, (central range*), and maximum					
	Extreme event	Baseline	2020s	2050s	2080s
Heat Waves & Cold Events	Number of days per year with maximum temperature exceeding				
	90°F	0.3	0.3 (0.5 to 1) 2	0.5 (1 to 5) 7	1 (2 to 13) 23
	95°F	0	0 (0 to 0.1) 0.2	0.1 (0.1 to 0.3) 0.6	0.1 (0.2 to 2) 6
	Number of heat waves per year[2]	0	0 (0 to 0.1) 0.2	0 (0.1 to 0.6) 0.7	0.1 (0.2 to 2) 3
	average duration	3	3 (3 to 3) 4	3 (3 to 4) 4	3 (4 to 4) 5
	Number of days per year with min. temp. at or below 32°F	193	155 (166 to 177) 184	125 (146 to 163) 173	108 (124 to 156) 166
Intense Precipitation	Number of days per year with rainfall exceeding:				
	1 inch	7	6 (7 to 8) 10	6 (7 to 9) 10	6 (7 to 10) 11
	2 inches	0.8	0.4 (0.7 to 1) 1	0.6 (0.7 to 1) 2	0.6 (0.8 to 1) 2

The values in parentheses in rows two through four indicate the central 67% range of the projected model-based changes to highlight where the various global climate model and emissions scenario projections agree. The minimum values of the projections are the first number in each cell and maximum values of the projections are last numbers in each cell.

* The central range refers to the middle 67% of values from model-based probabilities across the global climate models and greenhouse gas emissions scenarios.

1 Decimal places shown for values less than 1, although this does not indicate higher precision/certainty. The high precision and narrow range shown here are due to the fact that these results are model-based. Due to multiple uncertainties, actual values and ranges are not known to the level of precision shown in this table.

2 Defined as three or more consecutive days with maximum temperature exceeding 90°F.

3 NA indicates no occurrences per 100 years.

Source: Columbia University Center for Climate Systems Research. Data are from USHCN and PCMDI

consistent with global projections (Meehl et al., 2007) and with trends observed nationally (Karl and Knight, 1998; Kunkel et al., 2008).

Drought projections for this century reflect the competing influences of more total precipitation and more evaporation due to higher temperatures. By the end of this century, the number of droughts is likely to increase, as the effect of higher temperatures on evaporation is likely to outweigh the increase in precipitation, especially during the warm months. Drought projections, however, are marked by relatively large uncertainty. Drought in the Northeast has been associated with local and remote modes of multi-year ocean-atmosphere variability, including sea surface temperature anomalies in the North Atlantic (e.g., Namias, 1966; Bradbury et al., 2002) that are currently unpredictable and may change with climate change. Changes in the distribution of precipitation throughout the year and the timing of snowmelt could potentially make drought more frequent as well. The length of the snow season is very likely to decrease throughout North America (IPCC, 2007).

Coastal Floods and Storms

As sea levels rise, coastal flooding associated with storms will very likely increase in intensity, frequency, and duration. The changes in coastal flood intensity shown here are solely due to gradual changes in sea level through time. Any increase in the frequency or intensity of storms themselves would result in even more frequent large flood events. By the end of this century, sea level rise alone may contribute to a significant increase in large coastal floods; coastal flood levels that currently occur once per decade on average may occur once every one to three years.

Due to sea level rise alone, flooding at the level currently associated with the 100-year flood may occur about four times as often by the end of the century, based on the more conservative IPCC-based sea level rise scenario. The rapid ice melt scenario, should it occur, would lead to more frequent flood events. It should be noted that the more severe, current 100-year flood event is less well characterized than the less severe, current 10-year flood, due to the limited length of the historical record.

The relative flood vulnerability between locations is likely to remain similar in the future. Thus, portions of the state that currently experience lower flood heights than those described here (for reasons including coastal bathymetry and orientation of the coastline relative to storm trajectories) are likely to experience lower flood heights in the future than these projections indicate.

Uncertainties Related to Extreme Events

Because extreme events are by definition rare, they are characterized by higher uncertainty than the annual averages described previously. The climate risks described in each sector chapter in the ClimAID assessment reflect the combination of the climate hazard probability and the related impacts. The method used with GCM projections assumes that the distribution of the extreme events described quantitatively will remain the same, while average temperature, precipitation, and sea level rise change (**Table 1.9**). A change in the distribution of extreme events could have a large effect on these results.

The occurrence of extreme events in a given year will continue to be characterized by high variability; in some cases, the pattern of changes will only become evident after many years, or even decades, are averaged. For example, much of New York State's record of significant drought was a multiyear event that occurred four decades ago in the 1960s; no drought since that time in the state has approached it in severity. Generally speaking, changes in variability in future climate are considered very uncertain, although there are exceptions. For example, precipitation at daily timescales is likely to increase in variability since the warming atmosphere can hold more moisture (Emori and Brown, 2005; Cubasch et al., 2001; Meehl et al., 2005).

Other Extreme Events

Some of the extreme events that have a large impact throughout the state cannot be quantitatively projected into the future at local scales due to the high degree of uncertainty. Qualitative information for some of these factors is provided, including:

- heat indices, which combine temperature and humidity,
- frozen precipitation (snow, ice, and freezing rain),
- large-scale storms (tropical storms/hurricanes and nor'easters) and associated extreme wind,
- intense precipitation of short duration (less than one day), and
- lightning.

By the end of the century, heat indices (which combine temperature and humidity) 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 moisture content in the air can produce severe 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.

Seasonal ice cover has decreased on the Great Lakes at a rate of 8 percent per decade over the past 35 years; models suggest this will lead to increased lake-effect snow in the next couple of decades through greater moisture availability (Burnett et al., 2003). By mid-century, lake-effect snow will generally decrease as temperatures below freezing become less frequent (Kunkel et al., 2002).

Intense mid-latitude, cold-season storms, including nor'easters, are projected to become more frequent and take a more northerly track (Kunkel et al., 2008).

Intense hurricanes and associated extreme wind events may become more frequent (Bender et al., 2010) as sea surface temperatures rise in the areas where such storms form and strengthen (Meehl et al., 2007; Emanuel, 2008). However, other critical factors in the formation and intensity of these storms are not well known, including changes in wind shear, the vertical temperature gradient in the atmosphere, and patterns of variability such as the El Niño Southern Oscillation climate pattern and large-scale ocean circulation (for example, the meridional overturning circulation). As a result, there is the possibility that intense hurricanes and their extreme winds will not become more frequent or intense. It is also unknown whether the tracks or trajectories of hurricanes and intense hurricanes will change in the future. Thus, the impacts of future changes in hurricane behavior in the New York State coastal region are difficult to assess given current understanding.

Downpours, with intense precipitation occurring over a period of minutes or hours, are likely to increase in frequency and intensity as the state's climate warms. Thunderstorm and lightning projections are currently too uncertain to support even qualitative statements.[14]

1.4 Conclusions and Recommendations for Future Research

Climate change is extremely likely to bring higher temperatures to New York State, with slightly larger increases in the north of the state than along the coastal plain. Heat waves are very likely to become more frequent, intense, and longer in duration. Total annual precipitation will more likely than not increase; brief, intense rainstorms are likely to increase as well. Additionally, rising sea levels are extremely likely and are very likely to lead to more frequent and damaging flooding along the coastal plain and Hudson River related to coastal storm events in the future.

Climate hazards are likely to produce a range of impacts on the rural and urban fabric of New York State in the coming decades. The risk-management adaptation strategies described in this report will be useful in reducing these impacts in the future, but are also likely to produce benefits today, since they will help to lessen impacts of climate extremes that currently cause damages. However, given the scientific uncertainties in projecting future climate change, monitoring of climate and impacts indicators is critical so that flexible adaptation pathways for the region can be achieved.

Region-specific climate projections are only a starting point for impact and adaptation assessments. For some sectors, climate changes and their impacts in regions outside New York may rival the importance of local climate changes, by influencing, for example, migration, trade, ecosystems, and human health. Furthermore, some of the hazards described here (such as drought), are often regional phenomena with policy implications (such as water-sharing) that extend beyond state boundaries. Finally, since climate vulnerability depends on many factors in addition to climate (such as poverty and health), some adaptation strategies can be initiated in the absence of region-specific climate change projections.

Given the existing uncertainties regarding the timing and magnitude of climate change, monitoring and reassessment are critical components of any climate change adaptation plan. A dense network of sustained observations with resolutions that allow more accurate projections on a decade-to-decade basis will improve understanding of regional climate, extreme events, and long-term trends. Monitoring climate indicators can also play a critical role in refining future projections and reducing uncertainties. In order to successfully monitor future climate and climate impacts, specific indicators must be identified in advance. For example, to assess the significant risk of accelerated sea level rise and climate change for the coastal regions over the coming years, polar ice sheets and global sea level should be monitored. These uncertainties of timing and magnitude point to the need for flexible adaptation strategies that optimize outcomes by repeatedly revisiting climate, impacts, and adaptation science rather than committing to static adaptations. Frequent science updates will help to reduce these uncertainties.

Future projections can also be refined with greater use of regional climate models (see Appendix C for a description of regional climate models), which can capture changes in local processes as climate changes, such as the difference in magnitude of temperature increases on land versus that of the ocean. Advanced statistical downscaling techniques (see Appendix D) that allow projections at more localized levels than those described here may be of use as well; such techniques tend to be more effective when they use predictor variables that are well simulated by global climate models and that are policy relevant.

There is also a need for improved simulation of future climate variability at year-to-year and decade-to-decade scales, a need that may be met by future generations of climate models. Even the background rates of climate variation and extremes such as the 100-year drought and coastal flood will be better understood as a wide range of approaches, such as long-term tree-ring and sediment records, are increasingly used.

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Appendix A. Uncertainty, Likelihoods, and Projection of Extreme Events

Uncertainty and Likelihoods

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

- *Uncertainties in future greenhouse gas concentrations* and other climate drivers, which alter the global energy balance, such as aerosols and land-use changes; and
- *Uncertainties in how sensitive the climate system will be* to greenhouse gas concentrations and other climate drivers.

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

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

By providing projections that span a range of global climate models and greenhouse gas emissions scenarios, the global uncertainties may be reduced, but they cannot be fully eliminated. Averaging projections over 30-year timeslices and showing changes in climate through time, rather than absolute climate values, reduces the local- and regional-scale uncertainties, although it does not address the possibility that local processes may change with time.

The treatment of likelihood is similar to that developed and used by the IPCC. The six likelihood categories used here are as defined in the IPCC WG I Technical Summary (2007). The assignment of climate hazards to these categories is based on global climate simulations, published literature, and expert judgment.

Droughts

Droughts reflect a complex blend of climate and non-climate factors that operate at a number of timescales and are fundamentally different from other extreme events in that they are of longer duration. The drought timescale can last from a few months to multiple years. For this analysis, an intermediate timescale of 24 consecutive months was selected. In addition to precipitation, the other critical drought component is potential evaporation, which has a more complex relationship to drought. High temperatures, strong winds, clear skies, and low relative humidity all increase evaporative potential. Actual evaporation will generally be less than potential evaporation, however, since water is not always present for evaporation. For example, there will be little evaporation from dry soils, and as plants become water stressed under drought conditions, they become more effective at restricting their water loss to the atmosphere. Drought is also driven by water demand, so water-management decisions and policies can influence the frequency, intensity, and duration of droughts.

The Palmer Drought Severity Index (PDSI) uses temperature and precipitation to generate region-specific measures of drought and soil water excess. Because the calculation is strongly influenced by conditions in prior months, the PDSI is a good indicator of long-term phenomena like droughts. Potential limitations of the PDSI as used in this analysis include, but are not limited to, the exclusion of the water-demand component and the challenge of accurately capturing how potential evaporation changes with time. This analysis also does not consider water supplies stored on the ground as snow and ice.

The drought analysis conducted included two phases. First, the monthly PDSI was calculated for each observed data station from 1901 to 2000. Based on this calculation, the lowest consecutive 24 month-averaged PDSI value was defined as the 100-year drought. It should be noted that: 1) the drought record over the last 100 years can only provide a very rough estimate of the true 100-year drought; and 2) drought over a 24-month interval is only one possible definition.

In the second phase, the monthly changes in temperature and percentage changes in precipitation through time for each global climate model and emissions scenario were applied to the observed station data. The number of times that the 100-year, 24-month drought threshold (as defined in the paragraph above) was exceeded was then recalculated. Only events that did not overlap in time were counted.

Coastal Flood and Storm-related Extreme Events

The quantitative analyses of changes in coastal flooding are based on changes in sea level only, not in storm behavior. Projections were made by superimposing future changes in average sea level onto the historical dataset. The sea level rise projections are for the decade-to-decade averages of the 2020s, 2050s, and 2080s relative to the average sea level of the 2000–2004 base period. For coastal flooding, the critical thresholds were the 10-year, 100-year and 500-year flood events.

The 10-year event was defined using historical hourly tide data from the Battery. Forty years' worth of hourly sea level data were available from a period spanning 1960 to 2006 (nearest-neighbor interpolation was used to fill in missing data points for those years with little missing data). The Battery tide gauge was used to assess the frequency and duration of extreme coastal flood events. The raw tidal data are accessible from the NOAA website (http://tidesandcurrents.noaa.gov).

Average sea level was used as the reference datum. For the purposes of the storm analysis, additional calculations were made. First, data were de-trended (to remove the linear sea level trend) and normalized by dividing the data by the long-term average. This procedure gives water levels that include the influence of astronomical tides. To calculate surge levels, which more directly reflect the strength of the storm itself than do water levels, the difference between the actual flood level and the predicted level (the astronomical tide) was calculated. This approach allows assessment of the frequency and duration of extreme flood events. The ClimAID assessment defines the 10-year event as the storm surge thresholds corresponding to the fourth-largest surge over the 40-year period of tide data. Once the 10-year threshold was identified, the final procedure involved adding sea level rise projections for this century to the historical storm data as modified above to assess how frequently these flood levels would occur during this century.

Inasmuch as hourly data are unavailable from tide gauges prior to 1960, different methods were applied for estimating the 100-year and 500-year floods. The 100- and 500-year storms were analyzed using flood return interval curves (stage-frequency relationships) that provide a correlation between the water elevation by coastal storms versus the likelihood of occurrence. These curves include both surge and tidal components. An increase in sea level results in a higher flood height for a storm of a given return interval. The alternative approach taken here is to calculate the decrease in the return period for a given flood height with sea level rise (e.g., what will be the change in return period for the current 100-year flood if sea level rises 2 feet by 2080?). The 500-year estimate especially must be considered highly uncertain.

The surge data for the 100-year and 500-year storm calculations are based on data provided by the U.S. Army Corps of Engineers for the Metro East Coast Regional Assessment (MEC, 2001). In that study, the Army Corps used the USACE Waterways Experiment Station (WES) Implicit Flood Model (WIFM) developed in the 1980s as the hydrodynamic storm surge model. This time-dependent model includes sub-grid barriers and allows grid cells to become flooded during a simulation. The surge data were calculated relative to the National Geodetic Vertical Datum of 1929 (NGVD29) at high tide (thus a storm-flood level), excluding the effects of waves, for combined nor'easters and hurricanes. The flood height data were converted to the North American Vertical Datum of 1988 (NAVD88) by subtracting 0.338 meters (1.11 feet) from the flood heights given by the Army Corps. The conversion factors can be obtained from the National Geodetic Survey.

As research continues to advance, it may become possible to better estimate the surges associated with the 100-year and especially the 500-year historical storms, which are currently not well known.

High-end Scenarios and Longer-term Projections

This section describes 1) the possibility that climate changes in this century may deviate beyond the ranges projected by global climate models, 2) the rapid ice melt sea level rise scenario, and 3) potential climate change beyond this century.

There are several reasons why future climate changes may not fall within the model-based range projected for the ClimAID assessment. Actual greenhouse gas emissions may not fall within the envelope encompassed by the three emissions scenarios used here (A2, A1B, B1). This could be due either to changes in greenhouse gas concentrations directly related to changes in human activities or indirectly due to changes in the Earth's carbon and methane cycles brought on by a changing climate. The simulations used here all have known deficiencies regarding carbon cycle feedbacks, and some global climate models do not include volcanic forcings, for example.

Additionally, the climate's sensitivity to increasing greenhouse gases during this century may fall outside the range of the 16 climate models used. Possible types of climate changes exceeding model-based estimates that could have large impacts on the region include shifts in the average latitudes or tracks of moisture-laden storms traversing eastern North America and/or changes in ocean circulation in the North Atlantic.

Rapid Ice Melt Sea Level Rise Scenario

The rapid ice melt scenario addresses the possibility of more rapid sea level rise than the IPCC-based approach yields. The motivation to consider sea level rise exceeding IPCC-based estimates is based on several factors, including:

- recent accelerated ice melt in Greenland and West Antarctica, which may indicate the potential for high levels of sea level rise over multiple centuries if ice melt rates continue to accelerate;[15]
- paleoclimatic evidence of rapid sea level rise;
- the fact that not all sea level rise components are properly simulated by global climate models, increasing uncertainty about global climate model-based sea level rise projections; and
- the potentially large implications for a coastal city of more rapid sea level rise.

While not a significant direct cause of sea level rise, recent well-documented decreases in summer and fall Arctic sea-ice area and volume are also raising concern, since the decreases point to polar climate sensitivity higher than predicted by models. This could potentially modify atmospheric and oceanic conditions over a broader region, with implications for Greenland's ice sheet. For example, if 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.

Around 21,000 to 20,000 years ago, sea level began to rise from its low of about 394 feet below current levels. It approached present-day levels about 8,000 to 7,000 years ago (Peltier and Fairbanks, 2006; Fairbanks, 1989). Most of the rise was accomplished within a 12,000–10,000 year period; thus, the average rate of sea level rise over this period ranged between 0.39 and 0.47 inch per year. During shorter periods of more rapid rise, known as meltwater pulses, lasting several centuries, maximum rates of sea level rise ranged between 1.6 and 2.4 inches per year. These meltwater pulse sea level rise rates are considered too high to be matched during this century, since they occurred 1) after the ice sheets had already been undermined by thousands of years of forcing and 2) as abrupt intervals associated with singular events (e.g., ice dams breaking) at a time when total ice extent was much greater than today.

The rapid ice melt scenario assumes that glaciers and ice sheets melt at an average rate comparable to that of the last deglaciation (i.e., total ice melt increases linearly at 0.39 to 0.47 inch per year until 2100). However, the ice melt rate is more likely to be exponential. Thus, the average present-day ice melt rate of 0.04 inch per year (sum of observed mountain glacier melt [Bindoff et al., 2007] and ice sheets [Shepherd and Wingham, 2007]) during the 2000–2004 base period is assumed to increase to 0.39 to 0.47 inch per year (all ice melt) by 2100. An exponential curve is then fitted to three points: 2000, 2002 (midpoint of the 2000–2004 base period), and 2100. The other components—thermal expansion, local ocean dynamics, and subsidence—are added from the global climate model-based simulations and local information to this exponential meltwater estimates for the three timeslices. The rapid ice melt values combine the central range of the global climate model components and the range of estimates of rapid ice melt from the paleoclimate literature for multi-millennia timescales.

Longer-term Projections

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 considering the climate during the next century. Furthermore, many pieces of infrastructure intended only to have a useful lifespan within this century may remain operational beyond their planned lifetime. It is also possible that future projects aimed specifically at climate change adaptation might benefit during their planning stages from long-term climate guidance.

Because next century's climate is characterized by very high uncertainty, only qualitative projections are possible, especially at a local scale. 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 next century (Solomon et al., 2009). Given the large inertia of the ice sheets on Greenland and West Antarctica, continued 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 next century, even if greenhouse gas concentrations, and perhaps even global temperatures, were to stabilize at some point during this century.

Appendix B. Indicators and Monitoring

Monitoring and reassessment are critical components of any climate change adaptation plan. Adaptation plans should account for changes in climate science, impacts, technological advancements, and adaptation strategies.

In order to successfully monitor future climate and climate impacts, specific indicators to be tracked must be identified in advance. These indicators are of two types. First, climate indicators, such as extreme precipitation, can provide an early indication of whether climate changes are occurring outside the projected range.[16] Given the large uncertainties in climate projections, monitoring of climate indicators can play a critical role in refining future projections and reducing uncertainties. Second, climate-related impact indicators provide a way to identify consequences of climate change as they emerge. For example, lower water quality may be a climate-related impact of extreme precipitation.

Regional climate indicators to monitor include, but are not limited to the following:[17]

Temperature-related
- average annual temperatures
- degree days in the hot and cold seasons
- temperature extremes
- coastal and inland water temperatures

Precipitation-related
- average annual precipitation
- extreme precipitation events
- droughts

Sea level rise and coastal flood-related
- average sea level
- high water levels
- extreme wind events

Additional larger-scale climate indicators should include:

- nor'easter frequency and intensity,
- tropical storms over the entire North Atlantic basin, as well as climatic conditions (including upper-ocean temperatures) that support tropical cyclones,
- variability patterns that influence the region, such as the North Atlantic Oscillation (large-scale ocean circulation patterns) and the El Niño Southern Oscillation climate pattern, and
- evidence of changes in the Earth's carbon cycle.

The possibility of rapid climate change in general and sea level rise in particular are two areas where the importance of monitoring and reassessment is well documented. Indicators of rapid ice melt to monitor could include, but should not be limited to:

- status of ice sheets,
- changes in sea-ice area and volume,
- global and regional sea level, and
- polar upper-ocean temperatures.

Climate variables cause certain climate-related impacts, which will also need to be monitored. These impacts include, but are not limited to:

- shoreline erosion,
- localized inland flooding,
- biological and chemical composition of waters, and
- changes in vegetation.

In addition to monitoring climate changes and their impacts, advances in scientific understanding, technology, and adaptation strategies should also be monitored. Technological advances, such as those in material science and engineering, could influence design and planning, and potentially result in cost savings. Monitoring adaptation plans in the region should be done both to determine if they are meeting their intended objectives and to discern any unforeseen consequences of the adaptation strategies. Some adaptation strategies will also have to be reassessed in the context of non-climate factors that are based on uncertain projections. For example, by monitoring trends in population, economic growth, and material costs, managers can tailor future climate change adaptation strategies to ensure they remain consistent with broader statewide objectives. Monitoring and reassessment of climate science, technology, and adaptation strategies will no doubt reveal additional indicators to track in the future.

Appendix C. Regional Climate Models

Additional downscaling methods have been employed in the ClimAID case studies including all or portions of New York State. These downscaling initiatives include both regional climate modeling and statistical downscaling (see Appendix D).

Regional climate models (RCMs) are similar to the models used for global modeling, except they run at higher spatial resolution and use different physics parameters for some processes such as convective precipitation (rain events accompanied by instability often associated with lightning, thunder, and heavy rain). Higher resolution improves the depiction of land and water surfaces as well as elevation. Because the domain is not global, information from outside the domain must be provided by a global climate model. Regional climate model simulations depend on high-quality global climate model boundary conditions; global climate model biases may thus be inherited by regional climate models. Additionally, regional climate models cannot provide feedbacks to the global climate models, so important observed local factors that impact the global scale may be missing from these experiments. Because regional climate model resolutions are generally no finer than three to four times the lateral resolution of the driving global climate models, more complex double-nesting (essentially running a high-resolution RCM inside a lower-resolution RCM) computations may also be needed to achieve policy-relevant resolutions, which leads to further uncertainty in the regional climate models. Even at such fine scales, there are uncertainties regarding how the parameters of subgrid-scale processes (such as convective rainfall) are defined. Furthermore, even the most high-resolution regional climate model simulations generally require some corrections for bias.

Because regional climate modeling is computationally demanding, historically only a limited number of short-duration simulations have been performed, potentially limiting their value for climate change assessment. For example, in New York State, the New York City Department of Environmental Protection and Columbia University funded short-duration regional climate model simulations using both the Pennsylvania State University/National Center for Atmospheric Research mesoscale model (MM5) and the International Center for Theoretical Physics Regional Climate Model (ReGCM3) (Taylor et al., 2008). While validation of these proof-of-concept studies demonstrated that regional climate models can simulate historical average climate, the applicability of these results was limited by the fact that the experiments were limited to single-year runs. To be useful for climate change assessment, simulations over multiple decades driven by a number of climate models are needed.

An advantage of regional climate modeling relative to statistical downscaling techniques is that regional climate models do not depend on the assumption that historical relationships between predictors (the information provided by the global climate models) and predictands (the local information needed for impact analysis, e.g., daily precipitation) will continue in the future. Because regional climate models are physics-based, they do not need to rely on the assumption that relationships will remain the same, which may not be valid as the climate moves further from its present state. For example, regional climate models may be able to provide reliable information about how changes in land/sea temperature gradients may modify coastal breezes in the future.

The North American Regional Climate Change Assessment Program (NARCCAP) is an ongoing project designed to address stakeholders' need for high-resolution climate projections. The program is a repository for multi-decade simulations, based on pairings of six regional climate models and four global climate models (**Table 1.10**). For validation purposes, all six regional climate models were also driven by a global climate model from 1980–2004 (the National Centers for Environmental Prediction/Department of Energy Atmospheric Model Intercomparison Project II (NCEP/DOE AMIP-II) Reanalysis) (**Table 1.10**). These reanalysis simulations represent the best estimate of observed conditions as simulated by a combination of observations and short-term global model simulation. Long-term climate change simulations over the northeastern United States are currently available from NARCCAP (http://www.narccap.ucar.edu/) for 2041 to 2070 for the A2 emissions scenario from two regional-climate-model/global-climate-model combinations, at an approximately 50-kilometer resolution. These combinations are the Canadian Centre for Climate Modeling and Analysis (CCCma) Coupled Global Climate Model (CGCM3) with the Canadian Regional Climate Model (CRCM) and the Geophysical Fluid Dynamics Laboratory (GFDL) 2.1 global climate model with the International Centre for Theoretical Physics regional climate model (RegCM3). These same two regional-climate-model/global-climate-model pairings have been hindcast for the 1970–1999 period based on coupled global climate model simulations.

Climate Model	Full Name	Modeling group
CRCM	Canadian Regional Climate Model	OURANOS / UQAM
ECPC	Experimental Climate Prediction Center Regional Spectral Model	University of California, San Diego / Scripps
HRM3	Hadley Regional Model 3 / Providing Regional Climates for Impact Studies	Hadley Centre
MM5I	MM5 – PSU/NCAR mesoscale model	Iowa State University
RCM3	Regional Climate Model version 3	University of California, Santa Cruz
WRFP	Weather Research and Forecast Model	Pacific Northwest National Lab

Driver GCM	Full Name
CCSM	Community Climate System Model
CGCM3	Third Generation Coupled Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory GCM
HadCM3	Hadley Centre Coupled Model, version 3
NCEP	NCEP/DOE AMIP-II Reanalysis

Table 1.10 North American Regional Climate Change Assessment Program (NARCCAP) models

Regional Climate Model Validation

Because the Reanalysis product is the best estimate of the actual chronological order of the boundary conditions for the 1980–2004 period, the Reanalysis-driven simulations are used to estimate regional climate model biases and strengths. The RegCM3 and CRCM NCEP-driven simulations are compared here to the observed data for the Northeast from the University of Delaware (also available from NARCCAP/not shown here). Temperature and precipitation are evaluated for the winter and summer seasons.

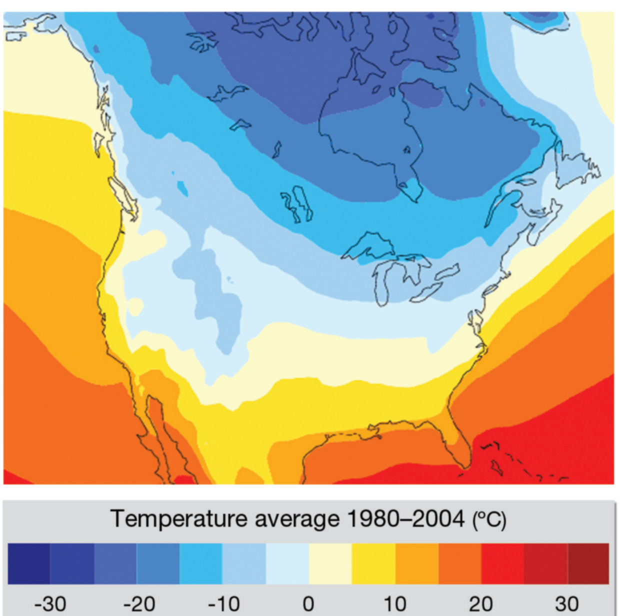
The National Centers for Environmental Prediction (NCEP) Reanalysis simulation with RegCM3 has a cold bias in both winter and summer over New York State, indicating lower temperatures than the historical observations. The RegCM3 does not capture the observed pattern of increasing temperatures from west to east of the Great Lakes (**Figure 1.8**). This cold bias east of the Great Lakes is also present in the CRCM regional climate model in winter, but not in summer (not shown). In both winter and summer, cool biases are more prevalent than warm biases across the six regional climate models.

The NCEP-RegCM3 pairing captures eastern New York's tendency to receive more winter precipitation than the western part of the state. It also captures the precipitation maximum (the state's highest precipitation area) downwind of Lakes Ontario and Erie (**Figure 1.9**). However, winter precipitation is overestimated by approximately 1 millimeter per day in the RegCM3 model. The summer precipitation minimum in western New York is also simulated; like the winter, summer precipitation is also overestimated by approximately 1 millimeter per day. The NCEP/CRCM pairing does not produce the overestimated precipitation bias seen with RegCM3 over New York State (not shown). Across the entire six regional climate models, winter precipitation biases span from strongly underestimating to strongly overestimating precipitation, while summer precipitation biases tend towards overestimates.

In general, the RCM results vary significantly among models. The majority of models show cool biases over the region, and there is a tendency for summer precipitation to be overestimated.

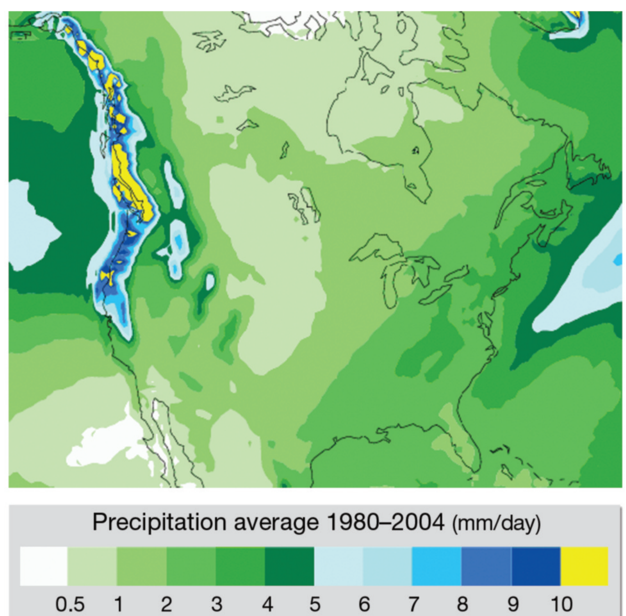
Regional Climate Model Projections

By comparing projected climate change from a global climate model only to projected changes from a regional climate model forced by the same global climate model, the effects of higher resolution can be emphasized. Discussed here are winter and summer temperature and precipitation results from the two



Source: NARCCAP

Figure 1.8 NCEP/RegCM3 winter (December, January, February) temperatures for 1980–2004



Source: NARCCAP

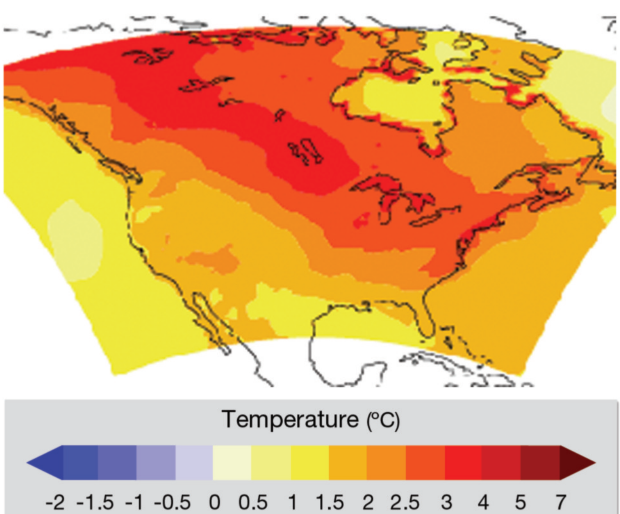
Figure 1.9 NCEP/RegCM3 winter (December, January, February) precipitation for 1980–2004 available global-climate-model/regional-climate-mode pairings described above.

Over northeast North America, the winter spatial pattern of warming in RegCM3 driven by the GFDL global climate model is quite different than the GFDL model warming pattern alone (**Figure 1.10**). Whereas GFDL features the characteristic pattern of greater warming moving north (not shown), the GFDL-RegCM3 pairing features a local minimum east of Hudson Bay. As a consequence, while both models indicate that southeastern New York will warm by approximately 5.4°F, the GFDL/RegCM3 produces less warming to the north than the GFDL global climate model. The CRCM regional climate model driven by CGCM3 over New York State produces a warming trend of 4.5–5.4°F by the 2050s relative to the base period and is also less than the CGCM3 global climate model's results (not shown).

In summer, GFDL global climate model warming over much of the central United States is 1.8–3.6°F higher than the paired GFDL/RegCM3 regional climate model warming over the same region. Both the GFDL global climate model and the GFDL/RegCM3 regional climate model simulations produce the greatest New York warming in the western portions of the state that are farthest from the coast, with the global climate model indicating slightly higher temperatures than the regional climate model in western New York (**Figure 1.11**). By contrast, for most of the United States including New York State, the CRCM regional climate model driven by the CGCM3 global climate model produces approximately 1.8°F more warming than the CGCM3 global climate model alone (**Figure 1.12**). The CRCM regional climate model indicates that summer temperatures over the state will increase by 5.4–7.2°F.

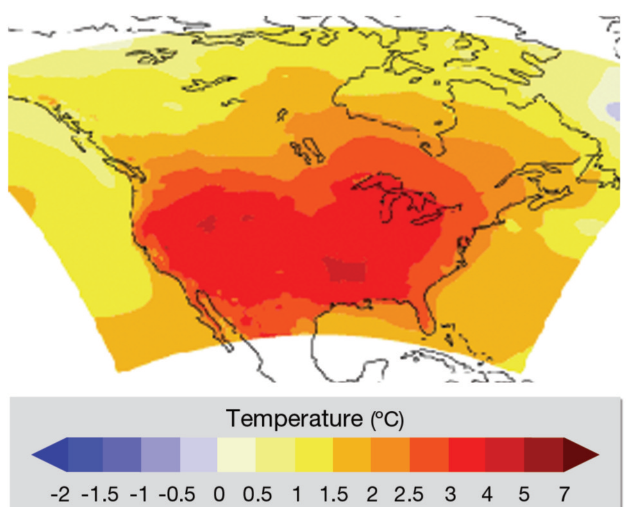
The GFDL global climate model produces large increases in winter precipitation—greater than 20 percent—in New York State, whereas the RegCM3 regional climate model driven by GFDL indicates a precipitation increase between 10 and 20 percent. Both the CGCM3 global climate model alone and the CGCM3/CRCM pairing indicate a 10–20 percent precipitation increase (not shown).

In summer the GFDL global climate model produces precipitation patterns that range from no change (0 percent) in southeastern New York to a greater than 10 percent decrease in precipitation in southwestern New York. Regional climate model precipitation changes have a fine spatial scale; precipitation increases by approximately 10 percent in much of the southern part of the state. The far west of the state shows precipitation decreases of approximately 10 percent. The CGCM3 global climate model produces slight decreases in precipitation ranging from 0 to 5 percent across the entire state (**Figure 1.13**). The CRCM regional climate model simulation driven by CGCM3



Source: NARCCAP

Figure 1.10 GFDL/RegCM3 modeled winter (December, January, February) temperature change for the A2 scenario in the 2050s



Source: NARCCAP

Figure 1.11 GFDL/RegCM3 modeled summer (June, July, August) temperature change for the A2 scenario in the 2050s indicates even more drying throughout New York State, with precipitation decreases approaching 20 percent in New York's northern and western regions.

These two global climate model-regional climate model pairings demonstrate that a range of uncertainties persist in regional climate projections. Over New York State, the largest discrepancy is in summer precipitation.

Downscaling Extreme Events

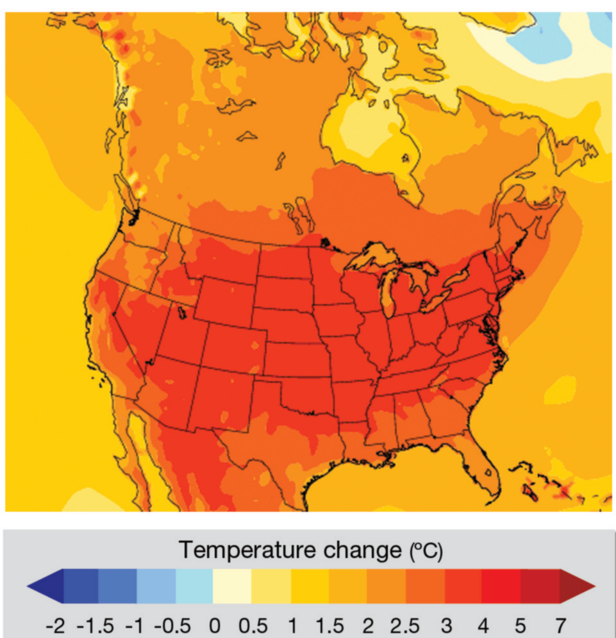
Regional climate model simulations hold promise for the simulation of changes in climate extremes, since many extreme events occur at smaller spatial scales than global climate model gridboxes.

Regional climate model simulations have also been conducted for the ecosystems sector. Specifically, Weather Research and Forecasting (WRF) regional climate model sensitivity experiments were conducted at Cornell University on the effects of changing Great Lake and atmospheric temperatures on lake-effect snow (see Chapter 6, "Ecosystems").

Future work by the climate team will evaluate 3-hour outputs from NARCCAP, to assess how the climate model projections of extremes such as intense precipitation, heat waves, and cold events described in this chapter could be augmented by regional climate model output.

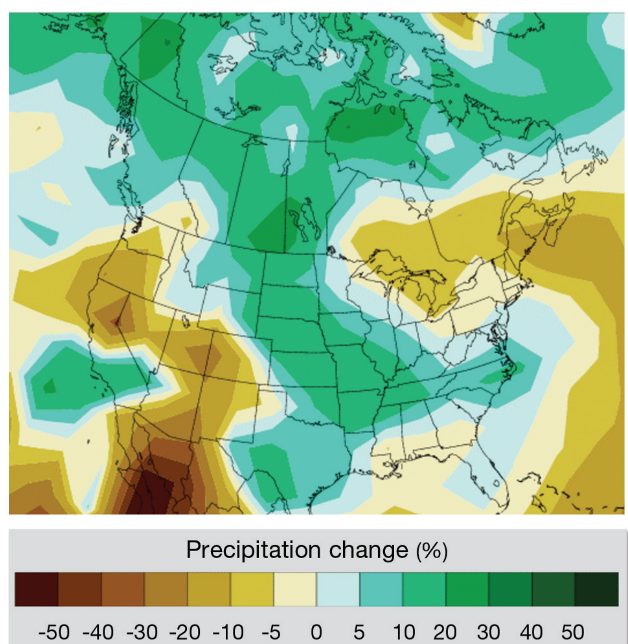
Appendix D. Statistical Downscaling in the ClimAID Assessment

An additional downscaling approach used in the ClimAID report to show potential changes in extremes to the end of the century is to utilize The Statistical DownScaling Model[18] (SDSM) Version 4.2 of Wilby et al. (2002, 1999). SDSM is described as a hybrid of a stochastic weather generator and regression-based methods. Large-scale circulation patterns and atmospheric moisture variables are used to linearly condition local-scale weather generator parameters (e.g., precipitation occurrence and intensity) for the predictand series. This approach is potentially better for estimating extremes, as it attempts to bridge the gap between dynamical and statistical downscaling.



Source: NARCCAP

Figure 1.12 CGCM3/CRCM modeled summer (June, July, August) temperature change for the A2 scenario in the 2050s



Source: NARCCAP

Figure 1.13 Summer precipitation change (June, July, August), from the CGCM3 model for the A2 scenario in the 2050s

Downscaling using SDSM in the ClimAID report was completed for extreme precipitation events (see Chapter 4, "Water Resources" and Chapter 7, "Agriculture") and winter snow cover (see Chapter 6, "Ecosystems"). In both cases, observed climate data were linked to large-scale predictor variables derived from the National Centers for Environmental Prediction (NCEP) reanalysis data set (Kalnay et al., 1996). For both projections in rainfall and snow cover, a dataset with an ensemble of 20 daily simulations was created using model output from the United Kingdom Meteorological Office Hadley Centre Climate Model version 3 (HadCM3; Pope et al., 2000).

For the precipitation events, the simulated daily data were used to construct extreme value series consisting of the annual maximum rainfall event for 30-year periods beginning in 1961. The first of these series included data from 1961–1990 and the last of these encompassed the 2071–2100 period. Additional statistical analysis was then conducted on these daily series (see Tryhorn and DeGaetano, 2011a). For snowfall, the two datasets were then combined by adding up the increases and decreases over time to give an estimate of the snow cover over the winter (Tryhorn and DeGaetano, 2011b).

1 The range of temperature projections is the lowest and highest of values across the middle 67% of projections for all regions of New York State.
2 The temperature and precipitation timeslices reflect a 30-year average centered around the given decade, i.e., the time period for the 2020s is from 2010–2039. For sea level rise, the timeslice represents a 10-year average.
3 Probability of occurrence is defined as follows: Very likely (>90% probability of occurrence), Likely (>66% probability of occurrence), and More likely than not (>50% probability of occurrence).
4 Preliminary analysis of those stations with lengthy records indicated that one station per region was generally sufficient to characterize each region's overall trends.
5 The USHCN data are a selected group of stations that come from the COOP data set.
6 Lower thresholds were used for the historical analysis than the projections, since warming is expected.
7 A degree day is defined as the difference between the daily mean temperature and 65ºF. Heating degree days occur when the daily mean temperature is below 65ºF, while cooling degree days occur when the daily mean temperature is above 65ºF.
8 Changes in these additional factors are expected to have a smaller influence on climate change than increases in greenhouse gases during this century.
9 Due to limited availability of model outputs, sea level rise projections are based on seven GCMs.
10 The ratio approach is used for precipitation because it minimizes the impact of model biases in average baseline precipitation, which can be large for some models/months.
11 Because they are rare, the drought and coastal storm projections were based on longer time periods.
12 For sea level rise, the multidecadal approach is not necessary due to lower inter-annual variability; the 2050s timeslice for sea level (for example) therefore refers to the period from 2050–2059.
13 The influence of interdecadal variability cannot be eliminated with 30-year timeslices, however. While longer timeslices would reduce the influence of interdecadal variability, it would be at the expense of information about the evolution of the climate change signal through time.
14 Some research does suggest that lightning may become more frequent with warmer temperatures and more moisture in the atmosphere (Price and Rind, 1994, for example).
15 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 is large, should current melt patterns continue to accelerate, their status should be monitored.
16 One potential pitfall of monitoring over short timescales, especially for small regions, is that it is easy to mistake natural variability for a long-term trend.
17 Many of these indicators are already tracked to some degree by agencies within New York State.
18 Available for download at http://www.sdsm.org.uk