PNNL-24868 Rev. 1

Potential Impacts of Accelerated Climate Change

Annual Report of Work for NRC Agreement Number NRC-HQ-60-14-D-0025

June 2019

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Contract DE-AC05-76RL01830

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Abstract

This research project is part of the U.S. Nuclear Regulatory Commission's (NRC's) Probabilistic Flood Hazard Assessment (PFHA) research plan in support of developing a risk-informed licensing framework for flood hazards and design standards at proposed new facilities and significance determination tools for evaluating potential deficiencies related to flood protection at operating facilities. The PFHA plan aims to build upon recent advances in deterministic, probabilistic, and statistical modeling of extreme precipitation events to develop regulatory tools and guidance for NRC staff with regard to PFHA for nuclear facilities. The tools and guidance developed under the PFHA plan will support and enhance the NRC's capacity to perform thorough and efficient reviews of license applications and license amendment requests. They will also support risk-informed significance determination of inspection findings, unusual events, and other oversight activities.

For Year 1, Pacific Northwest National Laboratory (PNNL) staff specifically focused on the following:

- Prepared an annual report that summarizes recent scientific findings, reports on activities of federal agencies with direct responsibility for climate change science, and provides a qualitative assessment of these findings relevant to NRC concerns on a regional level (i.e., increasing air and water temperatures, decreasing water availability, increasing frequency and intensity of storms and flooding, and rising sea levels).
- Participated in annual webinars with NRC staff at NRC Headquarters in Rockville, Maryland.
- Presented updates summarizing recent scientific findings at the NRC PFHA Workshop Headquarters in Rockville, Maryland.

PNNL staff have identified neither technical nor programmatic issues in proceeding with Year 2 activities. PNNL staff updated this Year 1 report during the spring of 2019. Subsequent reports prepared during Years 2, 3, and 4 summarized the recent scientific findings related to climate change and its impacts for various regions of the U.S.; the Year 2 report focuses on the Southeast U.S., Year 3 report focuses on the Midwest U.S., and the Year 4 report focuses on the Northeast U.S.

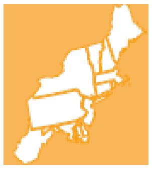
Executive Summary

This report summarizes Pacific Northwest National Laboratory (PNNL) staff efforts over the first year of the U.S. Nuclear Regulatory Commission's (NRC) Probabilistic Flood Hazard Assessment research project. NRC safety and environmental reviews are fundamentally different processes and have substantially different needs. The environmental reviews directly reference climate research published in the U.S. Global Change Research Program National Assessment. From the NRC safety perspective, climate research is unlikely to provide direct information at annual exceedance probability level of 0.001 or less in the near future. However, an improved understanding of large-scale climate pattern changes (e.g., the occurrence of extreme precipitation events such as atmospheric rivers, rain on snow overlying frozen soil, etc.) can help inform the probabilistic characterization (i.e., the likelihood) of extreme events. Hence, this report includes a literature review of recent studies that improve understanding of the mechanisms of how the climate parameters relevant to the NRC may change in a warmer climate, including discussions of the robust and uncertain aspects of the changes and future directions for reducing uncertainty in projecting those changes. The literature review is followed by a summary of key findings from two recent reports that synthesize analyses of historical climate changes from observational records and projected regional climate changes from ensembles of regional and global climate models for the United States. Finally, an assessment of current climate modeling and federal agency activities related to climate change is presented.

Overall, surface temperature is projected to increase as greenhouse gas emissions continue in the future. This will be accompanied by increases in heat wave intensity and frequency and reductions in cold extremes. As atmospheric water vapor holding capacities increase with increasing temperatures, global precipitation is expected to increase, with regional differences. Extreme precipitation is projected to increase more than the mean precipitation, and extreme snowfall is expected to increase, despite a general reduction of mean snowfall in warmer climates. In the western United States, atmospheric rivers, which are the dominant flood producers, are projected to increase in frequency by 50 to 600 percent primarily because of increasing moisture in the atmosphere. In regions where heavy precipitation originates primarily from summer convective storms (e.g., the Great Plains), data from observations suggest a 7 percent increase in convective extreme precipitation per degree of warming. Aridity will generally increase simultaneously because of increasing saturation deficit over land, with robust drought risks projected for the southwestern and central United States. Increases in ocean heat content in a warmer climate will generally increase hurricane intensity, but climate models do not project robust Atlantic tropical cyclone frequency changes. In a warmer and moister atmosphere under global warming, hazardous convective weather that generates strong, damaging winds is generally projected to increase, although a reduction in wind shear due to polar amplification may offset some of the changes. Projections of sea-level rise in the 21st century show the largest increase in the Gulf Coast, followed by the eastern United States, where uncertainty is the largest. Selected regional climate changes are highlighted in the table below for each conterminous U.S. region.

By providing a high-level review of recent advances in climate change science and synopsis of regional climate change in the United States from recent assessments, this first annual report aims to build the foundation for a more comprehensive review of the current level of understanding and an assessment of climate changes relevant to NRC needs over the duration of the project. Subsequent reports prepared during Years 2, 3, and 4 summarized the recent scientific findings related to climate change and its impacts for various regions of the U.S.; the Year 2 report focuses on the Southeast U.S., Year 3 report focuses on the Midwest U.S., and the Year 4 report focuses on the Northeast U.S.

Table ES-1. Summary of Climate Change Impacts by U.S. Regions. (Source: Melillo et al. 2014, Overview)

	**Northeast**	• Largest increase in very heavy precipitation historically among all U.S. regions • More extreme rainfall and snowfall, influenced by storm surge and sea-level rise (i.e., 0.75 –1 m by the end of the 21st century)
	Southeast	• Increased risks of more intense hurricanes • Sea-level rise in the 21st century projected to be larger than 1 meter • Sea-level rise and increased hurricane risks increase vulnerability to storm surge and coastal inundation
	**Midwest**	• Increased occurrence of heat waves and droughts • More intense convective extreme precipitation • Increased flood risks
	**Great Plains**	• Robust increased drought risks • Higher likelihood of hazardous convective weather • Sea-level rise in the Gulf Coast
	**Southwest**	• Robust increased drought risks • Increased frequency of atmospheric rivers and associated heavy precipitation
	**Northwest**	• Increased frequency of atmospheric rivers and associated heavy precipitation • Changes in streamflow timing due to warming-induced early snowmelt

Glossary

Atmospheric rivers: Atmospheric rivers are narrow filaments of enhanced atmospheric water vapor extending from the tropics to the mid-latitudes. Commonly known as the "pineapple express," they are responsible for over 90 percent of the poleward moisture transport in the atmosphere, although on average only 4 to 5 atmospheric rivers occupying less than 10 percent of the zonal circumference are present at any time. Upon landfall, atmospheric rivers often produce heavy precipitation because of the large moisture flux convergence produced as they encounter mountains (e.g., the coastal ranges and the cordillera of western North and South America and the mountains in Western Europe).

Blocking: When large-scale atmospheric circulation patterns are nearly stationary, migratory extratropical cyclones or synoptic disturbances can be "blocked" or redirected by the stationary high-pressure fields, leading to an extended period of clear or stormy weather in different regions influenced by the circulation patterns. In the northern hemisphere, blocking occurs most frequently over the North Pacific and northeastern Atlantic Oceans during the cold season. Cold air outbreaks can develop on the eastern side of blocking anticyclones that direct Arctic air mass to the mid-latitudes.

Clausius-Clapeyron relation: The Clausius-Clapeyron relation characterizes the discontinuous phase transition between two phases of a single constituent. The Clausius-Clapeyron equation for atmospheric water vapor is given by:

$$\frac{\mathrm{d}e_s}{\mathrm{d}T} = \frac{L_v(T)e_s}{R_v T^2}$$

where e_s is saturation vapor pressure, T is temperature, L_v is the specific latent heat of vaporization, and R_v is the gas constant of water vapor. In typical atmospheric conditions, the above equation can be approximated by:

$$e_s(T) = 6.1094 \exp\left(\frac{17.625T}{T + 243.04}\right)$$

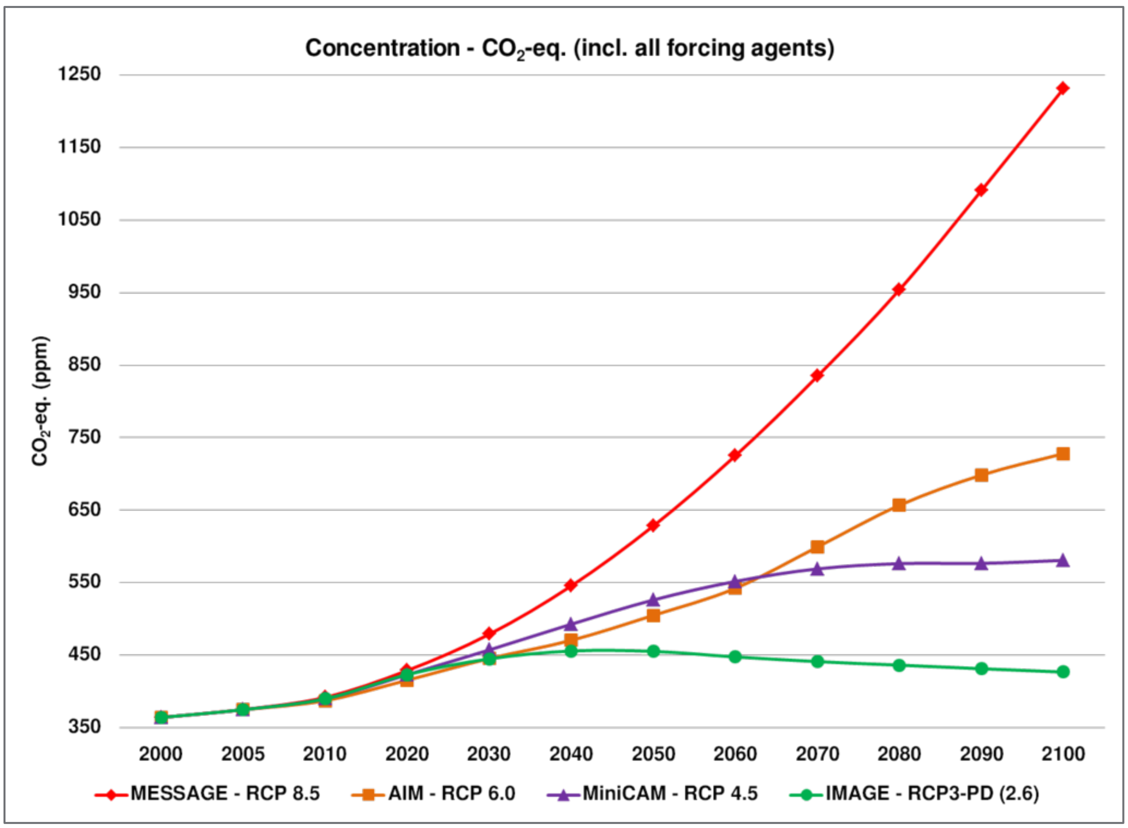
Hence, e_s changes approximately exponentially with temperature, so the water-holding capacity of the atmosphere increases by about 7 percent per degree K of temperature rise. In climate simulations, global mean precipitable water (i.e., vertically integrated water vapor) increases with global mean surface temperature at a rate of ~ 7.5 percent per degree K of warming.

CMIP5: The Coupled Model Intercomparison Project (CMIP) is a framework for coordinated climate change experiments. The fifth phase of CMIP (CMIP5) provided simulations for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). Modeling centers that participated in CMIP5 performed climate simulations following a common experimental protocol and archived their model outputs using a common data format to facilitate access and analysis of the multimodel ensemble for improving understanding of the drivers of climate change, projecting future climate change, and characterizing uncertainties due to model and scenario differences.

Hazardous convective weather: Hazardous convective weather (HCW) is produced by severe convection that generates tornadoes, hail, and damaging winds. HCW can cause damage to property and loss of life. Three ingredients are essential to support HCW: (1) vertical wind shear contributes to the organization and longevity of severe convection, (2) thermodynamics that support development of updraft, and (3) an initiation process for convection. Hence the seasonality of HCW favorable environments correlates quite well with the seasonality of HCW occurrence.

Mesoscale convective systems: Mesoscale convective systems (MCS) are the largest convective clouds that can be identified by satellite infrared imagery of a large, contiguous precipitation area ~100 km or more in at least one direction. The MCS rain area can be divided into convective and stratiform regions. MCSs often are found downwind of mountain ranges, so they occur frequently in spring and summer in the Great Plains when deep convection initiated in the Rocky Mountain in the late afternoon propagates eastward. With moisture supplied by the southerly flow from the Gulf of Mexico, the convective cells organize into large MCSs that produce nocturnal precipitation in the Great Plains. MCSs are responsible for ~60 percent of summer rainfall in the Great Plains.

RCP: Representative Concentration Pathways (RCP) are four trajectories of greenhouse gas concentration used in IPCC AR5 for projection of future climate by global climate models (see the following graphic). The RCPs are developed by integrated assessment models (MESSAGE, AIM, MiniCAM, and IMAGE) that consider the interactions among climate, energy economics, land cover and land use, and socio-economics to limit the radiative forcing in 2100 to 2.6, 4.5, 6.0 and 8.5 Wm^{-2} relative to pre-industrial values. RCP8.5 is commonly known as the 'business-as-usual' scenario, while RCP2.6, RCP4.5, and RCP6 represent different mitigation scenarios to curb the radiative forcing.



Acronyms and Abbreviations

AEP	annual exceedance probability
AR	atmospheric rivers
CAO	cold air outbreaks
CAPE	convective available potential energy
CC	Clausius-Clapeyron
CMIP	Coupled Model Intercomparison Project
DOE	U.S. Department of Energy
ECB	Engineering and Construction Bulletin
EPA	U.S Environmental Protection Agency
ETCCDI	Expert Team on Climate Change Detection and Indices
GCM	global climate model
HCW	hazardous convective weather
IPCC	Intergovernmental Panel on Climate Change
IT	information technology
MAPE	mean available potential energy
MCS	mesoscale convective systems
NASA	National Aeronautics and Space Administration
NCA	National Climate Assessment
NOAA	National Oceanic and Atmospheric Administration
NRC	U.S. Nuclear Regulatory Commission
PFHA	Probabilistic Flood Hazard Assessment
PI	potential intensity
PNNL	Pacific Northwest National Laboratory
RCP	representative concentration pathways
TC	tropical cyclone
USACE	U.S. Army Corps of Engineers
USGCRP	U.S. Global Change Research Program

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1.0 Characterization of NRC Need

This research project is part of the U.S. Nuclear Regulatory Commission's (NRC) Probabilistic Flood Hazard Assessment (PFHA) research plan that supports development of a risk-informed licensing framework for flood hazards and design standards at proposed new facilities and significance determination tools for evaluating potential deficiencies related to flood protection at operating nuclear facilities. The PFHA plan aims to build upon recent advances in deterministic, probabilistic, and statistical modeling of extreme precipitation events to develop regulatory tools and guidance for NRC staff with regard to PFHA for nuclear facilities. The tools and guidance developed under the PFHA plan will support and enhance the NRC's capacity to perform thorough and efficient reviews of license applications and license amendment requests. They will also support risk-informed significance determination of inspection findings, unusual events, and other oversight activities.

To focus consideration of processes and mechanisms that may be impacted by climate change, Mr. Lance Vail, a Pacific Northwest National Laboratory (PNNL) staff member with extensive experience in NRC safety and environmental reviews, developed a preliminary characterization of the nexus of NRC needs and climate change parameters, while Dr. L. Ruby Leung, a PNNL climate scientist, synthesized scientific understanding and findings on NRC-relevant climate change parameters in the United States. Mr. Vail's characterization is summarized in a matrix that represents his perspective and is considered an ongoing way of characterizing and focusing this project to align with NRC needs.

The matrix, shown in Table 1.1, shows NRC's assessment topics for safety and environmental reviews and prioritized climate change information needs for each review topic. The characterization as 'primary,' 'secondary,' and 'tertiary' needs does not imply that the other areas are of no interest, rather they are lower priority needs. For instance, for Local Intense Precipitation, without substantial reduction in uncertainty of precipitation, any reduction of uncertainty in temperature would likely be of limited interest.

Table 1.1. Matrix of NRC's Assessment Topics and Prioritized Climate Change Information Needs

	NRC Need		Climate Change Information Needs					
Topic	Safety (1)	Environmental (2)	Sea Level Rise	Precipitation	Temperature	Wind	Hurricane	Humidity
Local Intense Precipitation	1	3	3	1	2	3		
River Flooding	1	2	3	1	2	3		3
Drought	3	1		1	2	3		3
Tsunami	1		1					
Storm Surge	1	2	1				1	
Alternative Cooling Systems		2			1			2
Cooling System Performance	2	2			1			2
Stream Temperature		2			1	2		3
Alternative Energy		3			1	1		
Energy Demand		3	2	2	1			3
Forecasting	2	3	2	1	1	2	2	3
Water Quality		1	1	1	1			
Wind Load	1					1		

1 Primary
2 Secondary
3 Tertiary

The NRC's safety reviews and environmental reviews are fundamentally different processes and have substantially different needs. Certain topics are only considered in one or the other. However, some topics (e.g., Local Intense Precipitation) are of interest to both reviews but have substantially different considerations. Mr. Vail documented his preliminary characterizations in a Microsoft Excel™ workbook. Separate sheets were used to elaborate on each topic. Table 1.2 is a current example of the sheet for Local Intense Precipitation.

Table 1.2. NRC and Climate Information Needs Related to Local Intense Precipitation

Local Intense Precipitation		
NRC Need	Definition	Local Intense Precipitation is an intense, relatively small-area event where the concern is onsite and adjacent offsite flooding.
	Safety	Protection of safety-related structures, systems, and components from flooding during a local intense precipitation event generally considers an event with a mean exceedance frequency of 10^{-3} or lower per year.
	Environmental	Typical standard engineering design for stormwater runoff systems requires designing structures and systems (e.g., culverts, retention ponds) for a rainfall event with a mean exceedance frequency of about 5×10^{-2} without causing adverse impacts to adjacent waterways. Erosion is a primary concern with runoff discharged through a concentrated release point that drains the site and adjacent area with impervious surfaces. Since this is a well-developed design question and is typical of any large commercial facility, it is usually a tertiary concern in environmental licensing reviews.
Climate Info Need	Sea Level Rise	For coastal sites, sea level rise may result in a change in backwater-related boundary conditions. Consideration of concurrent storm surge (for instance, local intense precipitation with hurricane) is typically greater than sea level rise. Additionally, sea level rise is projected to occur gradually.
	Precipitation	Primary interest is in a detectable shift in precipitation magnitude for the respective frequencies for safety and environmental reviews (10^{-3} and lower per year and about 5×10^{-2} per year, respectively).
	Temperature	Temperature during antecedent precipitation and event precipitation can result in snow and ice accumulation that can transform the drainage landscape and clog ditches, drains, and culverts.
	Wind	Wind can cause water surfaces to increase in downwind directions and trigger wind waves and associated wave runup onto the site.
	Hurricane	Hurricanes as manifest extreme events can result in storm surge. However, this is considered separately in the storm surge topic.
	Evaporation	The relatively limited extent of local intense precipitation events makes evaporation of insignificant interest.

The primary difference in environmental reviews and safety reviews is the degree of conservatism involved. Environmental reviews consider what is reasonably foreseeable over the license period (i.e., 40 years of operation). Therefore, considering a 20-year rainfall event (equivalent annual exceedance probability [AEP] of 5×10^{-2} or mean exceedance frequency of about 5×10^{-2} per year) for the design of a detention pond is reasonable. However, the time scales in safety reviews are significantly more onerous. Safety systems can be designed to be protected from events that may occur, on average, only once in 10,000 years (equivalent annual exceedance probability of 10^{-4} or mean exceedance frequency of 10^{-4} per year). The uncertainty in 20-year estimates is far smaller than the uncertainty in a 10,000-year estimate. It is critical to keep in mind the difference in the definition of an 'extreme event' between an environmental review and a safety review. Moreover, the terminology used in the broad climate research community is

not aligned with that used in the NRC permitting and licensing context. For example, Kunkel et al. (2013, Figure 18) describe trends in ‘extreme’ precipitation events using the 24-hour, 2×10^{-1} annual exceedance probability precipitation events. In contrast, NRC’s interest in extreme events spans a much lower range of annual frequencies of exceedance; that is, 10^{-3} and lower (NRC 2016). The flood events of interest to the NRC, particularly in safety reviews, may be generated by precipitation at a range of timescales—from 5 minutes to several days. Therefore, research results developed by the climate community should be carefully evaluated and interpreted for use in the NRC permitting and licensing context.

Climate research published in the U.S. Global Change Research Program (USGCRP) National Assessment is directly referenced in NRC environmental reviews. The NRC’s environmental review staff has developed an environmental impact statement appendix and associated spreadsheets that correlate NRC environmental assessment needs per Regulatory Guide 4.2 with USGCRP National Assessment findings. The appendix and spreadsheets are used to disclose NRC staff beliefs about the anticipated change in operational impacts over the license period from the current baseline affected environment to the reasonably foreseeable new affected environment consistent with climate change. Inasmuch as this project is related to PFHA (a safety perspective), environmental topics are not pursued further outside of preliminary characterization.

Currently, NRC hydrology safety analyses are deterministic, stylized, and conservative. With PFHA on the horizon, the climate change information must be embedded in the distributions of hydrometeorological parameters used in PFHA (Monte Carlo simulations). The distributions reflect both aleatory and epistemic uncertainty with climate change an element of the uncertainty. Currently, distributions for events with annual exceedance probabilities in excess of once in 1,000 years (equivalent annual exceedance probability of 10^{-3}) do not exist for precipitation and other hydrometeorological parameters. Wide error bands are expected, commensurate with the large aleatory and epistemic uncertainties, without regard to climate change. Climate change may or may not be a significant contributor to the overall uncertainty. However, it is likely that the improved climate system understanding being developed with climate change research models will help develop better conceptual models of climate systems that will be critical to developing exceedance curves for events of annual exceedance probabilities of interest to NRC safety reviews. The existing deterministic hydrology and hydraulic models are likely to be used in the PFHA framework. However, the overall input to PFHA will be probability distributions with associated uncertainties and not the current deterministic approach.

Recent advances in deterministic hydrologic modeling have been predominately driven by advances in information technology (IT) resources and the need to support assessments of impacts of climate change on water resources. Enhanced data management infrastructure and new spatial data products (including remotely sensed information) have allowed more rapid and automated data assimilation into hydrologic models. To assimilate products provided by the climatological community as inputs to hydrologic analyses, the hydrologic community has recently developed capabilities to provide meteorological records with multivariate coherence in space and time. With these capabilities, the current suite of hydrologic simulation models is able to generate meaningful flow records based on the climate results. In addition, grid development for many one- and multi-dimensional hydrological models is now fully automated in front-ends to many standard simulation software. Thus the time and cost associated with model setup have been greatly reduced. This setup efficiency, along with improved IT resources, allows for ensemble runs with deterministic models to develop probabilistic outcomes more consistent with the NRC’s probabilistic, risk-informed regulations.

From the NRC safety perspective, climate research is unlikely to provide direct information at annual exceedance probability level of 10^{-3} and less in the near future. However, an improved understanding of large-scale climate pattern changes (e.g., the occurrence of extreme precipitation events such as atmospheric rivers, rain on snow overlying frozen soil) can help inform the probabilistic characterization (i.e., likelihood) of extreme events.

2.0 Recent Scientific Findings on Climate Change

Spanning the Pacific and Atlantic coasts with mountains and plains in between, the United States is marked by diverse climate regimes that exhibit large variability ranging from sub-daily to decadal time scales. Figure 2.1 highlights some key climatic features relevant to the climate information needs identified in Table 1.1. In the west, California and the Pacific Northwest receive most of their precipitation during the cold season, with orographic forcing from mountains playing a key role in amplifying precipitation from Pacific storms and producing snowpack at high elevations that becomes a natural reservoir of water released during the spring and summer. Atmospheric rivers (i.e., narrow filaments of abundant moisture transported across the subtropics to the mid-latitudes) are the main producers of heavy precipitation and floods. Despite frequent winter storms, California is prone to droughts as the storm tracks are influenced by large-scale circulation patterns that vary on interannual to decadal time scales. Further inland in the intermountain west, both winter and summer storms may be responsible for flooding. The complex terrain has a strong influence on precipitation seasonality and flood characteristics. The Southwest is influenced by the North American monsoon that brings warm moist air and convective storms in the summer. This region, however, is generally arid as it is under the influence of the subtropical high-pressure system; thus, seasonal and multi-year droughts are of concern.

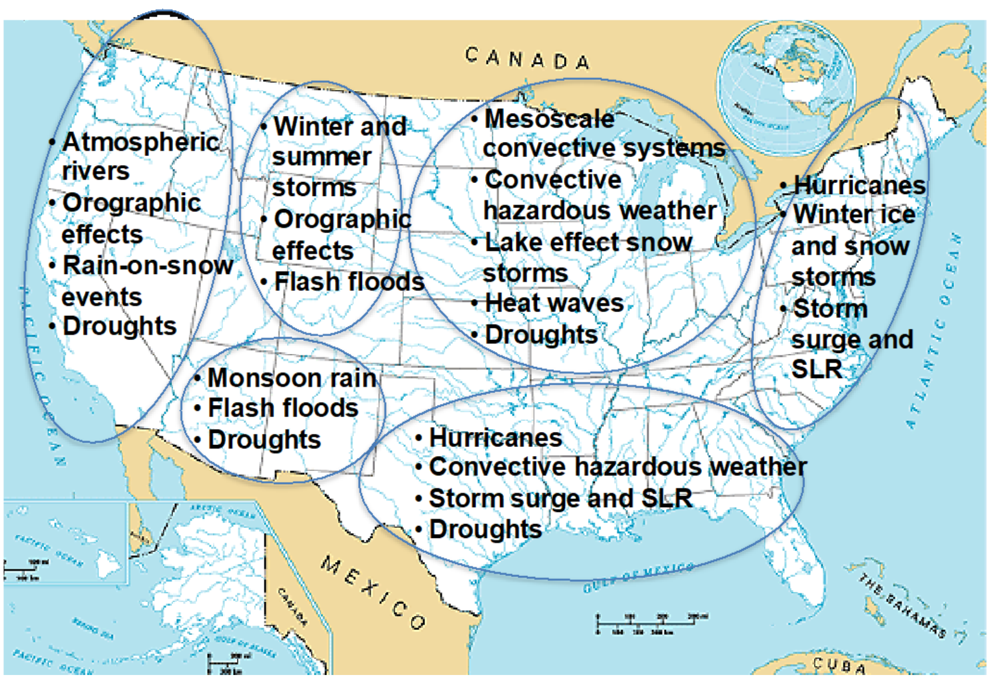

Figure 2.1. Regional Climatic Features in the Conterminous United States Relevant to NRC's Climate Information Needs

In the central United States, abundant moisture is supplied by a low-level southerly flow from the Gulf of Mexico, which helps maintain mesoscale convective systems (MCS) propagating from Rocky Mountains across the Great Plains, producing heavy precipitation. The moist environment and the wind shear are conducive to hazardous weather (e.g., tornadoes). In the northern Great Plains, lake-effect snow storms can generate heavy snowfall in the Great Lakes region. However, the Midwest also is prone to heat waves and droughts in the summer when high-pressure systems stagnate for prolonged periods. In the Gulf Coast region and eastern United States, storm surges associated with hurricanes are significant threats to coastal inundation. Severe winter ice and snow storms are important climatic factors along the Atlantic coast.

Since the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5), important advances in understanding and projecting future climate changes have been made using theories and modeling. Climate model outputs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012) that feature historical and future climate simulations by a large ensemble of multiple climate models continue to be used extensively in climate research, while new modeling experiments specifically designed by individual researchers or modeling centers supplement the standard CMIP5 simulations to investigate specific mechanisms of regional impacts of climate change. In the remainder of this chapter, we summarize key findings from recent literatures, with a focus on the extremes for different climate variables relevant to NRC's climate information needs.

2.1 Temperature

Temperature Changes

- Projected larger increases in daily minimum temperature that daily maximum temperature.
- Greater warming in the "business-as-usual" scenario than in mitigation scenarios.
- Shifts in daily maximum surface temperatures can lead to increases in heat wave intensity and frequency in the future.
- Hot extremes are projected to intensify over much of the United States, with drying amplifying the severe hot and dry conditions.
- Although cold extremes still may occur in the future, models project robust reduction in frequency of cold air outbreaks as polar amplification reduces cold air advection into the mid-latitudes.

Projections indicate that surface air temperatures will increase in the future as greenhouse gases continue to accumulate in the atmosphere from past emissions and future emission scenarios. Extreme temperatures have been investigated using the Expert Team on Climate Change Detection and Indices (ETCCDI) (Alexander et al. 2006). The ETCCDI indices are designed to be used for detecting and attributing human effects on extreme weather, but they do not represent particularly rare events. For example, many indices are defined based on monthly lowest/highest daily minimum/maximum temperature and precipitation or 10^{th} and 90^{th} percentile values. Extreme value statistical methodologies can be applied to quantify the behavior of the tails of the distribution of certain ETCCDI indices and provide insights on truly rare events (e.g., >98.5 or <1.5 percentile) (Brown et al. 2008; Peterson et al. 2013). Climate models projected larger increases in daily minimum temperature than daily maximum temperature, and the warming is larger for the "business-as-usual" emission scenario RCP8.5 than the emission scenario RCP4.5 with mitigation. The northern high latitude regions show the strongest increase in lowest daily minimum temperature, while changes in the highest daily maximum temperature tend to be evenly distributed globally (Sillmann et al. 2013).

For North America, the winter increase in cold nights has significant changes in northern United States, corresponding to snow covered areas in the present climate. Cool nights in the summer show warming that increases from the coast towards the continental interior. Winter increases in warm days are projected to be significantly less than winter cold nights, with an apparent poleward gradient. Summer hot days are projected to warm slightly more than summer cool nights (Figure 2.2). Seasonality in the projected changes reflects the complex mechanisms affecting changes in extreme and mean temperatures. For example, changes in snow cover affect the future winter mean and extreme temperatures, and decreases in soil moisture affect the future summer mean and extreme temperatures, thus creating warming patterns reflecting the modulating effects of the land surface on air temperatures.

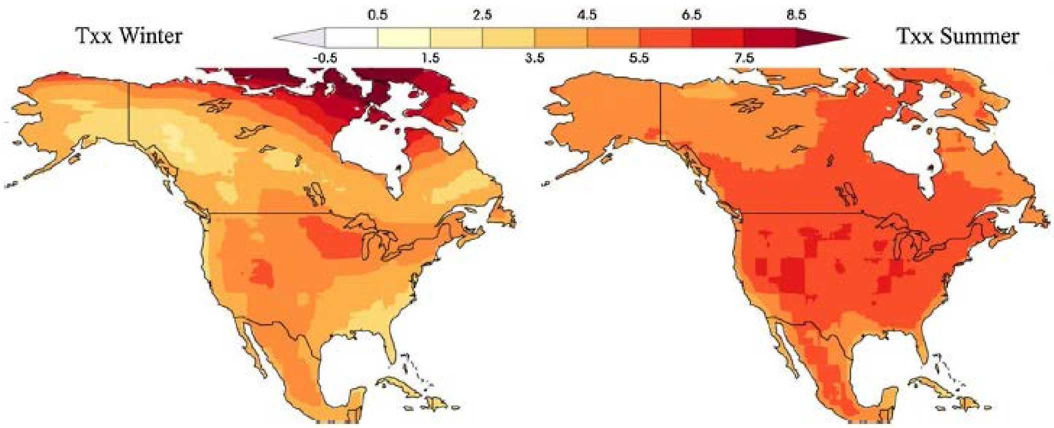

Figure 2.2. Changes in Temperature of Extreme Hot Days (i.e., seasonal maximum of maximum daily temperature [Txx]) for Winter (left) and Summer (right) Comparing 2080–2100 and 1985–2005 from the CMIP5 Model Projections following the RCP8.5 (business-as-usual) Scenario (Grotjahn et al. 2015)

Changes in large-scale circulation (e.g., a shift towards a more westerly circulation or changes in the frequency or patterns of blocking events) may influence extreme temperature (van Oldenborgh et al. 2009; Sillmann and Croci-Maspoli 2009). In the United States, Lau and Nath (2012) noted that the probability distribution functions for the current and future climate over most regions that experience heat waves have a similar shape except for a shift by the mean warming in the daily maximum temperature. For skewness, the probability distribution functions exhibited only minor changes from the current to future climate. Hence, the increase in heat wave intensity and frequency in the future is primarily associated with a shift in the daily maximum surface temperature, with changes in large-scale circulation likely playing only a minor role. However, Diffenbaugh and Ashfaq (2010) found that hot extremes will intensify over much of the United States in association with a summer anticyclonic circulation anomaly in the future, which will reduce precipitation and soil moisture, thereby amplifying severe hot and dry conditions. These changes were more prominently simulated in regional models that better resolve climatological variations.

For cold air outbreaks (CAOs), Schneider et al. (2015) and Gao et al. (2015a) both found that the mean warming and the reduced temperature variance due to polar amplification account for most of the decrease in CAOs in a warmer climate. For North America, Gao et al. (2015a) further found that changes in temperature skewness associated with changes in blocking frequency and thermodynamical modulation by melting of snow and sea ice along the 0°C isotherm contribute to regional differences in CAO changes.

Overall, some robust changes in temperature extremes have emerged from analysis of the CMIP3 and CMIP5 multimodel ensembles. In general, model projections indicate increased frequency, intensity, and duration of heat waves and that despite global warming, cold extremes may still occur in some regions due potentially to changes in blocking events and thermodynamic effects of snowmelt (Vavrus et al. 2006; Gao et al. 2015a). Some believe that CAOs may become more extreme because of the weakened jet stream that allows high-amplitude eddies and increases the likelihood of blocking episodes (Francis and Vavrus 2012; Cohen et al. 2014). However, recent studies based on model simulations and theory showed no signs of more frequent or extreme CAOs, as polar amplification reduces the meridional temperature gradient and hence, significantly reduces cold air advection into the mid-latitudes. Analysis of northern hemisphere blocking in climate simulations using three blocking identification methods also showed no clear increase in blocking frequency due to polar amplification, as suggested to be the mechanism for increasing CAOs in the future (Barnes et al. 2014).

To reduce uncertainty in projecting extreme temperature changes in the future, more detailed analyses using multimodel ensembles may provide further insights on the mechanisms of heat wave changes associated with land-atmosphere coupling. In the Great Plains, well-known large warm biases exist in model simulations of summer temperatures; these biases have been linked to model a deficiency in simulating precipitation associated with mesoscale organized convection (Klein et al. 2006). Hence, improving model simulations of convection and regional precipitation may be key to constraining the role of land-atmosphere interactions on extreme warm temperature changes in the future. Finally, some uncertainty remains in potential changes in large-scale circulation patterns (e.g., blocking) that affect both heat waves and CAOs. Well-designed climate modeling experiments combined with observational analyses that target specific mechanisms and hypotheses may help isolate different factors and provide constraints for more robust projections of extreme temperature changes.

2.2 Precipitation (and Humidity)

Precipitation Changes

- Globally, precipitation is projected to increase ~2% per K warming.
- Extreme precipitation is projected to increase more than mean precipitation. In the extratropics, the increase will be ~5–6% per K warming.
- In the western United States, flooding primarily is associated with atmospheric rivers, which are projected to increase by 50 to 600% in frequency on the west coast of North America.
- Changes in extreme precipitation associated with warm season convection are more uncertain, but analysis of observational records provided some evidence of extreme convective precipitation increasing by more than 7% per K warming.
- Although warmer temperatures in the future will reduce mean snowfall in general, extreme snowfall should increase due to competition between increasing saturated specific humidity and decreasing snowfall fraction with warmer temperature.
- Increasing saturation deficit over land should drive a general increase in aridity over land in a warmer climate. More specifically, climate models robustly projected a significant increase in draught risks in the southwestern and central United States driven primarily by increase evaporation.

Climate models have projected warmer temperatures in the future as a result of increasing concentrations of greenhouse gases. Following the Clausius-Clapeyron (CC) relationship, the atmosphere can hold about 6 to 7 percent more moisture for each degree K of warming, or more precisely, the saturation vapor pressure increases by 6 to 7 percent per degree K of warming. Changes in evaporation are energetically constrained by changes in processes related to near-surface relative humidity. By relating the fractional change in relative humidity to the fractional change in saturation-specific humidity and fractional change in evaporation, it can be inferred that near-surface relative humidity changes very little with temperature (Schneider 2010). As precipitation is balanced by evaporation globally, the increase in precipitation is constrained by the change in evaporation, which relates directly to surface latent heat flux that is energetically constrained by the radiative forcing. Hence, unlike water vapor or precipitable water, which increases by 6 to 7 percent per degree K of warming, climate models projected only an approximately 2 percent increase per degree K warming for global precipitation and evaporation (Held and Soden 2006). Regionally, precipitation changes can vary significantly depending on the changes in the large-scale

circulation. For example, climate models projected expanded drying in the subtropics associated with the subsiding branch of the Hadley circulation, which is projected to weaken and expand poleward (Vecchi and Soden 2007; Lu et al. 2007). Climate models also projected poleward shifts of the storm tracks in response to the meridional temperature gradient change (Chang et al. 2012), giving rise to dipole changes in extratropical precipitation on the poleward and equatorward sides of the storm tracks.

Extreme precipitation is projected to increase more than mean precipitation because extreme precipitation is not energetically constrained as precipitation by evaporation from the surface. Several factors could contribute to changes in extreme precipitation in the future. These include dynamical contributions from changes in vertical motion, thermodynamical contributions from changes in saturation-specific humidity, and microphysical contributions from changes in precipitation efficiency. In the extratropics, vertical motion in non-convective environments (e.g., frontal systems) is constrained by planetary rotation, so its changes are relatively small. Hence, thermodynamical contributions play a dominant role and extreme precipitation increases by approximately 5 to 6 percent per degree K of warming in the extratropics (Figure 2.3). Similar to mean precipitation, however, regional changes in extreme precipitation vary by season and location. In the cold season, poleward shifts in the storm tracks appear to shift both the mean and extreme precipitation poleward (O'Gorman and Schneider 2009; Lu et al. 2014).

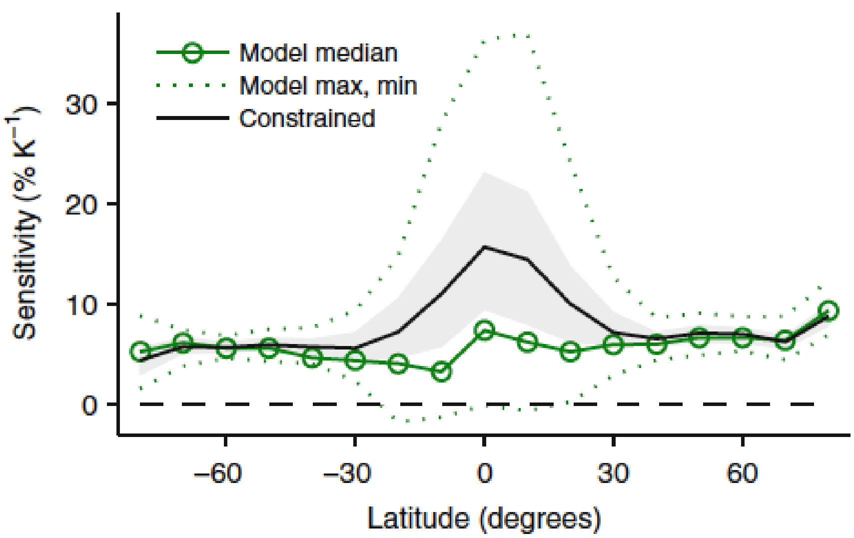

Figure 2.3. Changes in 99.9th Percentile Daily Extreme Precipitation from CMIP5 Models, showing a General Increase of about 7 Percent per Degree K of Warming in the Extratropics but Larger Uncertainty in the Tropics (O'Gorman 2015)

Extreme precipitation in the western United States is dominated by atmospheric rivers (AR), which are narrow corridors responsible for over 90 percent of the poleward transport of water vapor globally (Zhu and Newell 1998). When ARs from the North Pacific make landfall at the coastal western United States, they can bring record-setting precipitation that leads to floods (Dettinger 2011; Ralph et al. 2006; Leung and Qian 2009, Neiman et al. 2011). On the other hand, ARs also can have benevolent impacts by relieving droughts (Dettinger 2013). Following the CC relationship, AR frequency could increase as climate warms. Using CMIP3 results, Dettinger (2011) found that the number and intensity of winter ARs making landfall in California were roughly unchanged, but the number of ARs with water vapor transport much larger than historical amounts increased. Warner et al. (2015) found an almost threefold increase in the number of days with vertically integrated vapor transport above the historical 99th percentile along the west coast of North America. Consistent with these results, Gao et al. (2015b) revealed a strikingly large increase (i.e., between 50 and 600 percent) of AR days by the end of the 21st century in the RCP8.5

scenario. Gao et al. (2015b). They further quantified the dynamical and thermodynamical contributions associated with winds and water vapor, respectively, to the change in AR frequency and found that the latter contributes predominantly to the increase in AR frequency, while wind changes limit the increase in AR days (Figure 2.4). The negative effect of wind changes on AR days in spring and fall is linked to the robust poleward shift of the subtropical jet in the North Pacific basin. Overall, these results consistently point to the likelihood of increasing frequency of ARs in the future. Following the discussion of extreme precipitation changes, the enhanced water vapor with warming may increase extreme precipitation associated with ARs following roughly the CC rate.

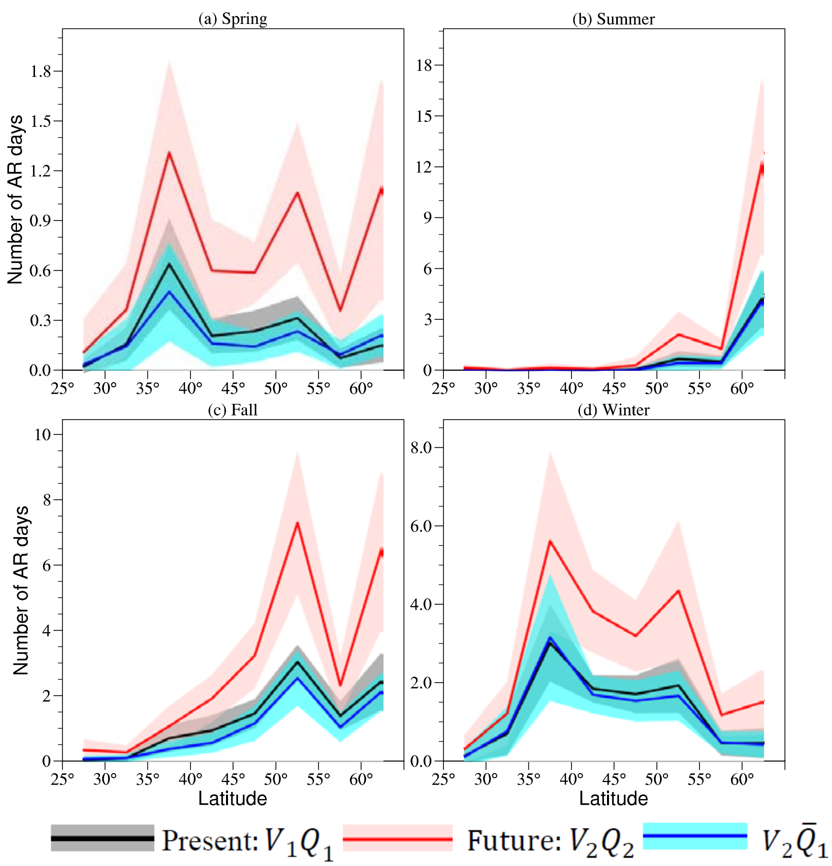

Figure 2.4. Number of AR Days from CMIP5 Simulations for the Present (grey), Future (pink), and for AR Detected by Scaling the Future Simulations with the Present Day Atmospheric Moisture (blue) Comparing the Two Decades Near the End of the 21st and 20th Centuries in the RCP8.5 Scenario (Gao et al. 2015)

Despite improved understanding of extreme precipitation changes in the extratropics during the cold season, significant uncertainty remains in projecting changes in extreme precipitation in the tropics or during the warm season in the extratropics dominated by convection. Uncertainty in parameterizing convection in climate models is a main reason for this uncertainty. This issue is particularly acute in the central United States where MCSs are dominant mechanisms for producing heavy precipitation. Climate models that rely on convective parameterizations are known to be highly deficient in simulating the propagating MCSs that produce nocturnal precipitation peaks in the Great Plains. A few studies (e.g., Kendon et al. 2014) that downscaled global climate projections using regional models at convection permitting resolution (i.e., at 1 to 4 km that explicitly resolves rather than parameterizes convection) suggest that convective extreme precipitation may increase at a super-CC rate (i.e., greater than approximately 7 percent per degree K of warming) due to enhanced moisture combined with more

vigorous convection in a warmer climate. Analysis of observed hourly precipitation data in Europe (Lenderink and van Meijgaard 2008; Berg et al. 2013) and the United States (Lepore et al. 2014) supports the super-CC increase in extreme convective precipitation in contrast to extreme stratiform precipitation that roughly follows the CC rate (Figure 2.5).

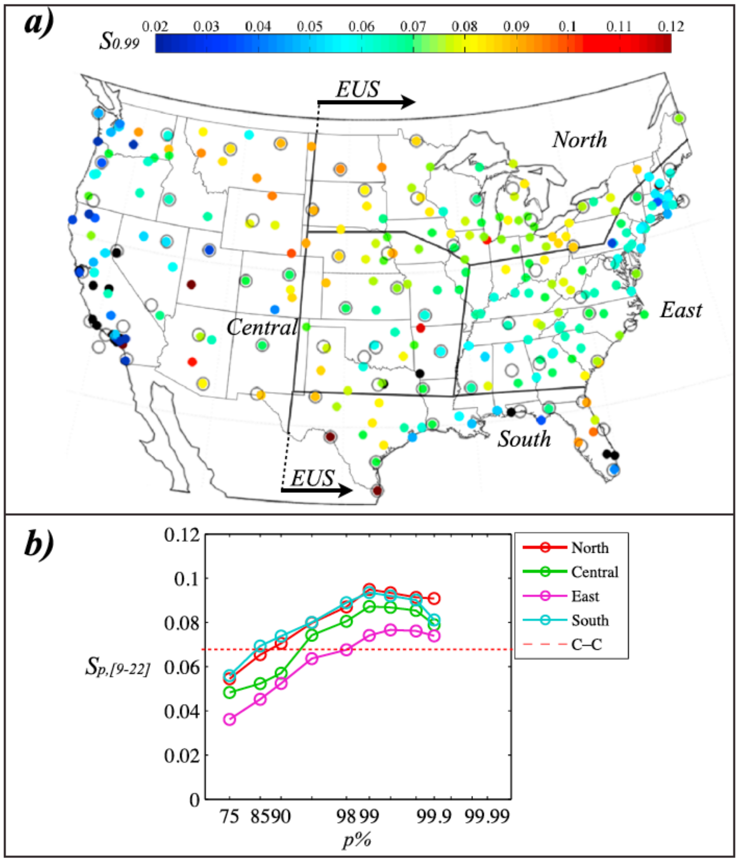

Figure 2.5. Sensitivity of the 99th Percentile Hourly Precipitation per Degree K of Warming ($S_{0.99}$) in the United States (upper) and the Sensitivity for Different Percentile Values ($S_{p[9\text{-}22]}$) for Four U.S. Sub-Regions Showing Increasing Sensitivity with Increasing Percentile Values (bottom) (Lepore et al. 2014).

In addition to modeling, theories have been developed to estimate an upper bound for how storm intensity may vary as a function of climate. For example, Agard and Emanuel (2017) investigated how the peak convective available potential energy (CAPE) scales with warming. Theoretically, higher values of CAPE correspond to more intense storms, as CAPE provides an upper bound for the theoretical maximum updraft speed. Agard and Emanuel (2017) argued that it is the peak values of time-dependent CAPE rather than the time-averaged background levels of CAPE that are relevant to the severe storm environments. Using a system of equations to describe the evolution of the surface boundary layer with a dry adiabatic column of air that comes into contact with a moist land surface, they found that the value of peak CAPE scales with the CC relation of ~7 percent increase per each degree of warming.

Regarding convection in the extratropics, a decrease in the meridional temperature gradient in a warmer climate weakens the cyclone activity (measured by the eddy kinetic energy). However, an increase in moisture and decrease in static stability may increase the growth rates of eddies to oppose the weakening of eddy activities due to changes in the meridional temperature gradient. Furthermore, changes in the mean thermal structure and moisture may increase the energy available for convection, so it is not clear

how cyclone activities and the associated convection may change in a warmer climate. Gertler and O'Gorman (2019) addressed this question using the framework of mean available potential energy (MAPE) in the northern hemisphere summer. Calculating the trends of MAPE for the northern hemisphere summer using reanalysis data for 1979–2017 and decomposing MAPE into convective and nonconvective components, they found that the nonconvective MAPE decreased over this period, which is consistent with decreases in eddy kinetic energy due to weakening of the meridional temperature gradient. However, convective MAPE was found to increase, implying an increase in the energy available to convection. Their analysis suggests that despite a weakening of extratropical cyclones, their associated convection can become more energetic because the convective MAPE is more sensitive to increases in surface temperature than weakening of the meridional temperature gradient.

Taken together, observational analysis, modeling, and theoretical considerations all suggest that convection intensity may increase in a warmer climate, with the peak CAPE (maximum updraft) increasing at the CC rate and extreme precipitation increasing at a super-CC rate.

Snowfall events are expected to decrease in a warmer climate due to changes in the precipitation phase with warmer temperatures. However, O'Gorman (2014) found that changes in extreme snowfall would be more muted compared to snowfall events. This is because extreme snowfall occurs at an optimal temperature (approximately -2.3^{o}C) that is determined by the competition between increasing saturation-specific humidity and decreasing snowfall fraction with increasing temperature. This optimal temperature is insensitive to warming. Hence extreme snowfall is projected to decrease by only 8 percent compared to 65 percent for mean snowfall by the end of the 21st century in the RCP8.5 scenario (Figure 2.6). This muted response of extreme snowfall suggests that extreme snowfall events, such as those that occur in the eastern United States, may continue in the future and that reduction in extreme snowfall may not be used as early signs to detect warming, as would be inferred from the sensitivity of snowfall to temperature.

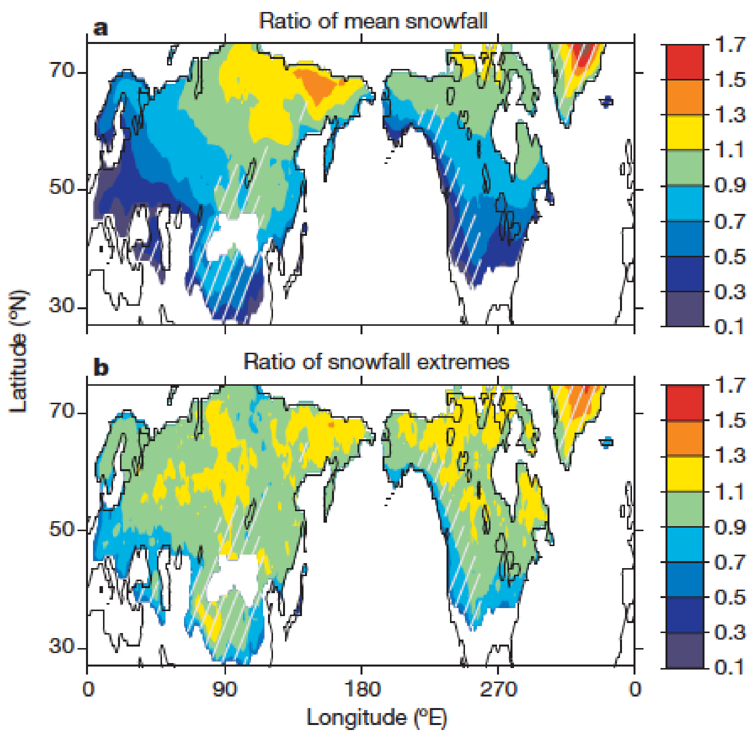

Figure 2.6. The Ratio of Future to Present Mean Snowfall (upper) and Snowfall Extremes (bottom) showing a Much Larger Reduction from the Present to the Future for Mean Snowfall than Snowfall Extremes (O'Gorman 2014).

Climate change may alter precipitation characteristics on both ends of the extreme through increases in frequency and intensity of extreme precipitation and droughts (Trenberth et al. 2004). While an increase in atmospheric water-holding capacity plays a major role in enhancing extreme precipitation in a warmer climate, an increase in evaporation is an important factor in amplifying and prolonging droughts in the future. Land surface warms on average 50 percent more than ocean surface, but water vapor content over land does not increase fast enough to meet the evaporative demand. This is because water vapor over land is mostly supplied by the ocean, which increases at the CC rate corresponding to the smaller warming over the ocean (Sherwood and Fu 2014). Hence, the increasing saturation deficit over land should drive a general increase in aridity over land in a warmer climate.

Historically, droughts in the United States have been largely attributed to interannual and interdecadal variations of sea surface temperature patterns in the Pacific and Atlantic Oceans that shift storm tracks and anticyclonic pressure centers through teleconnections (Hoerling and Kumar 2003), with the land surface amplifying the response through soil moisture-precipitation feedbacks. Global climate models projected an imminent transition to more arid conditions comparable to mega-droughts of the past in the southwestern United States (Seager et al. 2007), largely driven by the mean circulation of the subtropical high diverging more moisture from the warmer temperature away. Strengthening/expansion of the subtropical high pressure over the Pacific Ocean (Li et al. 2012) also contributes to the drying (Seager et al. 2010), and an additional role of poleward storm track shifts in enhancing drying in the Southwest has been suggested (Gao et al. 2012; Gao et al. 2014). Using paleoclimate records to benchmark global climate models simulations of historical droughts, Cook et al. (2015) showed that the Palmer Drought Severity Index simulated by global climate models for the historical period of 1931–1990 is indistinguishable from observations, despite some significant deviations in some models. Cook et al. (2015) further showed that despite the diverse response of the models in their ability to capture atmosphere-ocean dynamics and teleconnections, they consistently projected significant drought risks in southwestern and central United States in the future (Figure 2.7), driven primarily by increased evaporation in conjunction with reduced precipitation or overcompensating the increased precipitation.

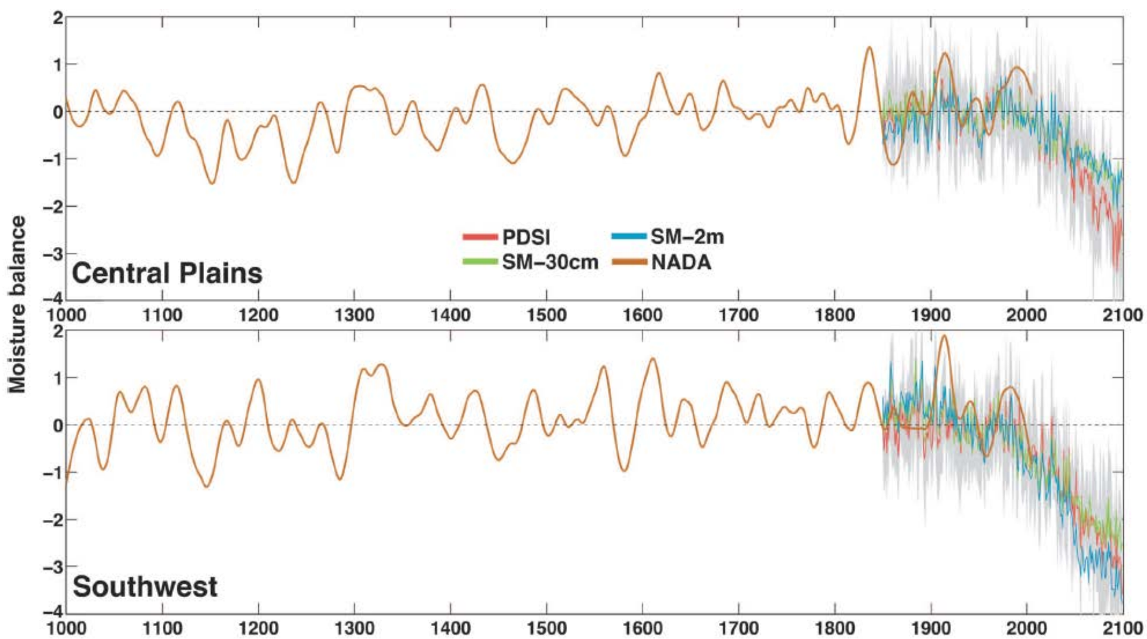

Figure 2.7. PDSI from North American Drought Atlas (brown) and CMIP5 Models (red), and Soil Moisture at 30 cm (green) and 2 m (blue) from CMIP5 Models for the Central Plains and Southwest Regions of North America (Cook et al. 2015)

Overall, understanding of the changes in mean and extreme precipitation has progressed in the last decade based on analysis of multimodel simulations to determine the robust changes, combined with theoretical understanding aiming at explaining the robust changes. In the climate science literature, extreme precipitation is typically defined as the 95th and 99th percentile daily precipitation value. Some studies also have investigated the changes in 99.9th and 99.99th percentile daily precipitation based on idealized simulations (e.g., aqua-planet simulations) (e.g., O'Gorman and Schneider 2009; Lu et al. 2014). In these simulations, zonal and hemispheric symmetry allows more robust statistical estimates of the 99.9th and 99.99th percentile values by constructing a space-time cumulative distribution function of daily precipitation (e.g., Sugiyama et al. 2010) to increase sample size from climate simulations, or by fitting the Generalized Extreme Value distribution to time series of annual maxima from climate simulations using probability-weighted moments instead of maximum-likelihood estimation because of the relatively short time samples (e.g., Kharin and Zwiers 2000).

As larger uncertainty in projecting changes in extreme precipitation is associated with extreme convective precipitation in the tropics and warm season events in the extratropics, regional models, global variable resolution models, and the multiscale modeling frameworks that explicitly resolve convection as well as development of scale aware parameterizations for convection are promising venues for advancing understanding and modeling of extreme precipitation in the warmer climate. These models may also produce more credible simulations of hourly and sub-hourly precipitation for studying higher temporal frequency extreme precipitation changes beyond daily extremes. As aridity and drought in the future may be driven more strongly by changes in evaporation than precipitation, and evaporation depends on temperature that models consistently project to increase, uncertainty in projecting drought risks tends to be smaller than uncertainty in projecting changes in extreme precipitation. However, uncertainty in the role of the land surface in amplifying droughts and uncertainty in large-scale circulation changes still need to be addressed to further constrain the projections of drought intensity and regional differences.

2.3 Hurricanes

Hurricane Changes

- Increases in ocean heat content in a warmer climate will general increase hurricane intensity and, hence, the frequency of high-intensity storms.
- Climate models do not project robust signals of Atlantic tropical cyclone frequency changes, but some consistent changes in storm intensity are projected.
- A poleward migration of the meridional position of lifetime-maximum intensity has been found in historical track data, which is consistent with the poleward shifts in vertical wind shear and potential intensity found in global reanalysis data.
- Model predictions of hurricane changes are uncertain. Continued improvements in linking tropical cyclone activity to large-scale environments and statistical-dynamical downscaling are important for advancing insights on hurricane changes.

Hurricanes draw energy primarily from the ocean. In a warmer climate, hurricane intensity is projected to increase because the ocean heat content generally increases, thus increasing the frequency of the high-intensity storms (Elsner et al. 2008, Knutson et al. 2010). Despite this general finding, model projections of changes in hurricane intensity and frequency are uncertain because of uncertainty in projecting changes in the ocean heat content; uncertainty in projecting changes in atmospheric environments (e.g., vertical wind shear, sea-level pressure, and vorticity) that influence hurricane intensity, tracks, and genesis; and

model deficiency in simulating tropical cyclones (TC), partly because of the low resolution and limitations in defining the physics parameters.

Three methods can be used to investigate changes in hurricane activities simulated by climate models. In the first method, TC detection and tracking algorithms are applied directly to model outputs to identify and track TC-like storms simulated by the models. These algorithms, which use dynamical and thermodynamical thresholds (e.g., thresholds for vorticity, wind speed, and local temperature anomaly), are adjusted based on statistics of the 6-hourly model outputs from the historical simulations to provide a reasonable climatology of TC activity for each model. The same thresholds for each model are then applied to the simulations of the future climate by the same model. The second method relates TC activity with large-scale environments resolved by climate models. The third method involves dynamical or statistical-dynamical downscaling to improve simulations of higher intensity TCs.

Applying TC detection and tracking algorithms to CMIP5 model outputs showed that models generally simulate too few TCs in the historical period (Camargo 2013). Although no robust signal of Atlantic Ocean TC activity changes was observed across models—consistent with projections using statistical downscaling methods (Villarini and Vecchi 2012)—dynamical downscaling suggested decreasing storm frequency (Knutson et al. 2013). However, CMIP5 models projected a statistically significant increase (decrease) in the percentage of storms for the subtropical (tropical) cluster, suggesting changes in tracks that may influence the likelihood of U.S. landfall. In general, the models projected increases in potential intensity (PI)—one indicator of TC activity based on the large-scale environment—in the northern hemisphere, with model differences at regional scale. Many models also projected an increase in vertical wind shear in the eastern North Atlantic Ocean and Caribbean Sea regions, but the eastern part of the Atlantic is marked by a reduction in wind shear.

Despite uncertainty in projecting changes in the number of TCs, there are some consistent changes in TC intensity. Hence, an important question is how TC tracks have changed in the past and may change in the future and influence the frequency of hurricanes that make landfall on U.S. coasts. Analysis of observed track data for 1982–2012 showed a poleward migration of the meridional position of lifetime-maximum intensity, which is consistent with the poleward shifts in vertical wind shear and potential intensity found in global reanalysis data (Kossin et al. 2014) (Figure 2.8 and Figure 2.9). An assessment of future track changes is not likely to yield robust results as TC tracks are not reliably simulated by models. However, changes in large-scale environments may provide some insights on the likelihood of unusual tracks occurring again in the future. This question was investigated by Barnes et al. (2013) using the unusual track of Hurricane Sandy as an example. Sandy was steered onto the U.S. coast almost perpendicular to the coastline by unusual atmospheric conditions including an equatorward jet shift, a blocking anticyclone in the Atlantic, and associated Rossby wave breakings that steered Sandy along the anomalously cyclonic vorticity contour. Changes in the large-scale circulation projected by CMIP5 models (e.g., the poleward shift of the jet stream) suggest reduced likelihood for the atmospheric environment to steer another storm along Sandy's path, should a storm of similar intensity and genesis location occur in the future.

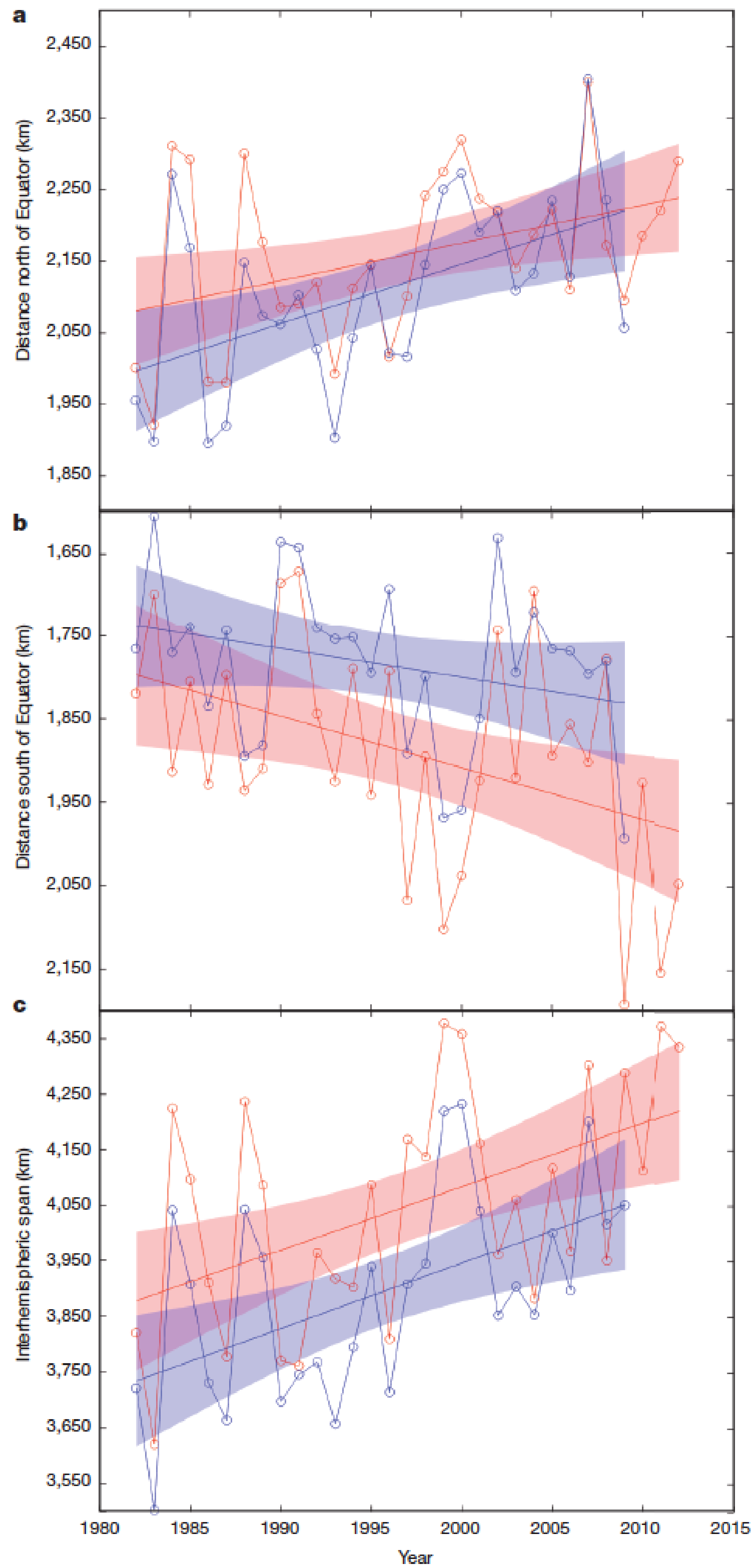

Figure 2.8. Poleward Migration of the Latitude of Lifetime-Maximum Intensity Away from the Tropics from the Best-Track Historical Data (red) and the ADT-HURSAT Reanalysis (blue) in the Northern (a) and Southern (b) Hemispheres, and Their Annual Mean Difference (c) (Kossin et al. 2014).

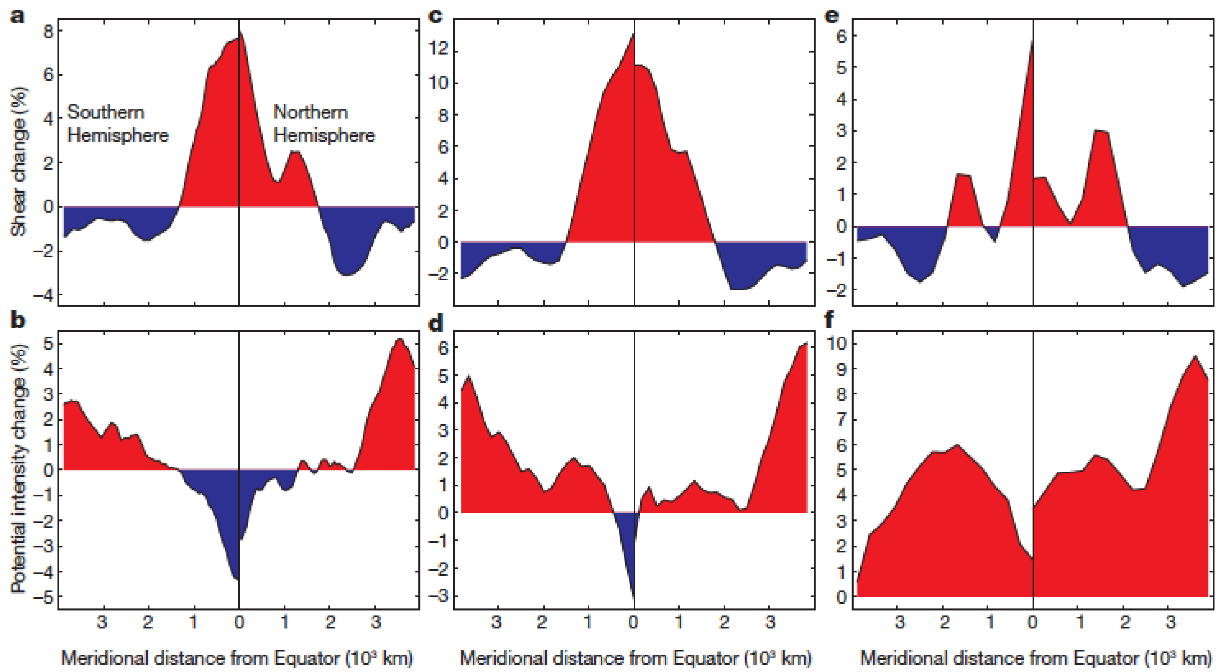

Figure 2.9. Observed Changes from 1980–1994 to 1995–2010 in the Mean Vertical Wind Shear (a, c, e) and Potential Intensity (b, d, f) where TCs Form and Track. Results are from three different reanalysis products (Kossin et al. 2014).

As model resolution increases, climate models could simulate TCs more realistically to provide a more robust assessment of future TC changes. However, models in CMIP6 will not reach a resolution for significant improvement in TC simulations. Hence, continued improvements of all approaches in linking TC activity to the large-scale environment and dynamical and statistical-dynamical downscaling are important for advancing insights on hurricane changes. These methods also represent a more viable approach for providing TC information needed for modeling storm surge associated with TCs (e.g., Lin et al. 2012).

2.4 Wind

Wind Changes

- Hazardous convective weather (HCW) is not resolved in current climate models, so projecting its changes has been advanced through understanding the atmospheric environments that are favorable for its occurrence.
- Three ingredients are important to support HCW that generates strong, damaging winds: 1) vertical wind shear, 2) strong updraft, and 3) convection initiation.
- Climate models generally have projected an environment more favorable for HCW because of warmer and moister atmosphere, but a reduction in wind shear due to polar amplification may offset some of the changes.

Strong, damaging winds that occur in the United States are most commonly associated with hurricanes and HCW (i.e., weather that produces tornadoes, hail, and damaging winds). Fundamental challenges in understanding and predicting HCW are related to limitations imposed by observational data that lack sufficient spatial and temporal resolution, and models that do not adequately resolve severe convection due partly to the coarse model resolution. Hence, research on projecting HCW changes in the future

climate has advanced mainly through understanding the atmospheric environments that are favorable for HCW occurrence and how such environments may change in a warmer climate. Three ingredients in the atmosphere are important to support HCW. First, vertical wind shear is an important control of the organization and longevity of severe convection. Second, the development of strong updraft requires energy governed by the thermodynamics of the atmosphere. Finally, a process for convection initiation must be present to trigger severe convective events. The first two elements can be described by the bulk vertical wind shear between the surface and ~6 km and the CAPE, respectively. However, characterizing convective initiation is more difficult because a variety of mechanisms can trigger convection, and they are influenced by mesoscale to large-scale atmospheric environment as well as surface conditions. Indices based on wind shear and CAPE or similar thermodynamical parameters have some utility in capturing the seasonal and spatial variability of HCW occurrences (e.g., tornadoes) (Brooks et al. 2007; Tippett et al. 2012).

Analysis of historical data of atmospheric environments showed increasing trends in the frequency of the most extreme HCW in the United States over the last three decades (Sander et al. 2013). Climate model projections of HCW changes in a warmer climate generally indicate an increase in the atmospheric environment favorable for HCW (Trapp et al. 2007; Brooks 2013; Diffenbaugh et al. 2013; Tippett 2014; Seeley and Romps 2015), largely because of an increase in the CAPE due to warmer temperatures (Del Genio et al. 2007) and associated increased saturation-specific humidity. Increasing the CAPE is offset somewhat by a reduction of vertical wind shear due to the weaker meridional temperature gradient resulting from the polar amplification. In the United States, for example, Diffenbaugh et al. (2013) found the largest increase of 2 days per model grid point in favorable HCW by the end of the 21st century occurring during the spring due to the weaker reduction in wind shear compared to other seasons (Figure 2.10).

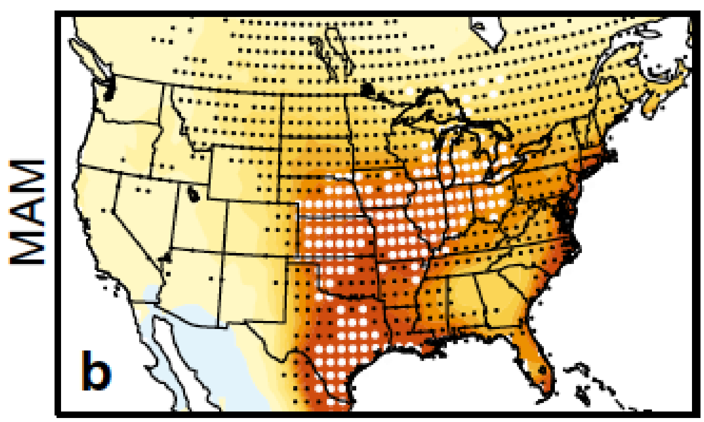

Figure 2.10. Changes in Number of Days with the Spring (March-April-May) Severe Thunderstorm Environment Comparing 2070–2099 with 1970–1999 from CMIP5 Models in the RCP8.5 Scenario (Diffenbaugh et al. 2013)

A major source of uncertainty in projecting changes in HCW in a warmer climate is the reliance on relating HCW to the atmospheric large-scale environment, which does not explain all of the variance in HCW in the historical records. Ignoring convection initiation and other factors (e.g., land-surface conditions) that also influence HCW creates a significant gap. With global climate models far from being able to resolve HCW in the near future, improving projections of HCW changes will rely on further advancing understanding of what controls HCW and improving simulations of the large-scale environments and other factors by climate models. There is also a potential for using regional climate models to advance both understanding of HCW and resolving HCW in dynamical downscaled projections of future climate (Gensini and Mote 2014).

2.5 Sea-Level Rise

Sea-Level Changes

- Between 1992 and 2013, the global mean sea level has increased at a linear trend of 3.3 mm/yr.
- Regional sea level can differ significantly from the global sea level, with wind-driven and buoyancy-flux-driven changes dominating regional sea level changes since the 20th century.
- For the United States, the median sea-level rise in the 21st century following the RCP8.5 scenario is highest at the Gulf Coast (>1 m), followed by the eastern United States (0.75–1 m) where uncertainty is the greatest because of the uncertainty in atmosphere and ocean dynamics in climate models.

The global mean sea level is governed by the change in the volume of water in the global ocean and the change in the shape of the ocean basin related to terrestrial land motion. On decadal time scales, changes in the volume of water are related to changes in density, which are produced by (1) changes in temperature and salinity and (2) water exchange between the ocean and reservoirs of continental hydrology including ice sheets, glaciers, ice caps, groundwater, and inland surface waters. Since 1992, sea levels has been monitored continuously by satellite radar altimeters with sufficient accuracy to monitor regional and global trends. Based on information from satellites, the estimated linear trend of global mean sea level between 1993 and 2009 is 3.3 mm/yr (Nicholls et al. 2010).

Regional sea level can differ significantly from the global sea level due to regional differences in geological processes, the fingerprint effects of ice and ocean mass redistribution, and atmospheric and oceanic dynamics. The latter has been a dominant driver of regional sea-level changes, referred as dynamic sea-level changes, since the 20th century. Atmospheric and oceanic processes responsible for dynamic sea-level changes are either wind driven (i.e., mass redistribution by winds) or buoyancy-flux driven (i.e., changes in temperature, salinity, and freshwater fluxes).

Projections of future changes in global mean sea level are based on either a bottom-up assessment of different contributing factors or a top-down method based on a semi-empirical relationship between temperature and the rate of global mean sea level change. Projecting regional sea level requires a bottom-up approach as different contributing processes can change very differently in the future. Global coupled atmosphere-ocean models are used to project dynamic sea-level changes. Kopp et al. (2014) reported projections of regional sea-level rise in the 21st century following the RCP8.5 scenario. For the United States, the median sea-level rise is highest in the Gulf Coast, with projected increases >1 m except along the Florida coast (Figure 2.11). This is followed by the eastern United States, with projected increases generally between 0.75 m and 1 m. The west coast sea level is projected to increase between 0.25 and 0.6 m. Uncertainty in projected sea-level changes is by far the largest along the East Coast. Globally, uncertainty in projecting sea-level rise is largely related to uncertainty in ice sheet changes, as climate models are only beginning to represent ice sheet dynamics. In the eastern United States, uncertainty in projecting sea-level rise is mainly associated with uncertainty in atmosphere-ocean processes.

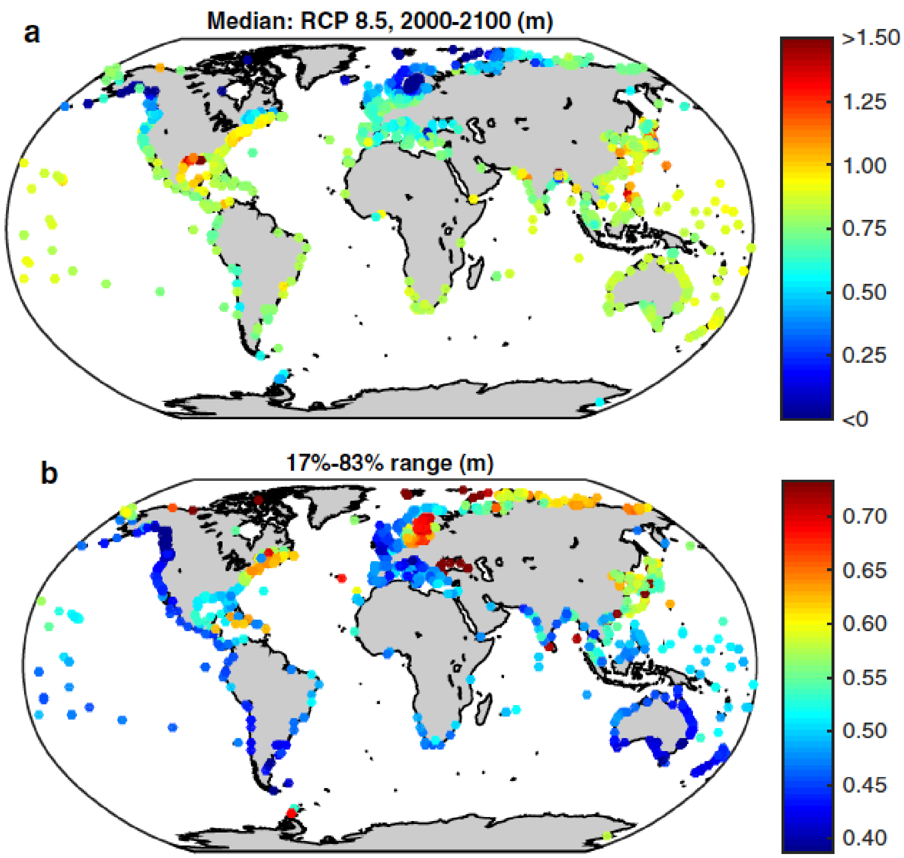

Figure 2.11. Inter-Model Median (upper) and 17–83 Percent Range (bottom) of Sea-Level Rise Projected by a Multimodel Ensemble in Meters (Kopp et al. 2014)

To reduce uncertainty in projecting sea-level changes, future research needs to be more attentive to improving understanding of key processes such as ice sheet dynamics and their interactions. While ocean models driven by observed atmospheric states reasonably reproduced dynamic sea-level changes in the past (Griffies et al. 2014), large biases still exist in coupled atmosphere-ocean models, particularly in the equatorial and southern oceans (Landerer et al. 2014). Numerical models of geological driven sea-level changes have advanced, but complex three-dimensional models are rarely used to project future sea-level changes. Improvements in projecting sea-level changes in the near future may come from modeling of process interactions that have not been incorporated to an extent possible in the past.

3.0 Summary of Climate Change Projections for the United States

In 2013, U.S. Department of Energy (DOE) produced a report entitled *U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather*.[1] To support national climate change adaptation planning and advance the DOE's goal of promoting energy security, the report examines current and potential future impacts of climate trends in air and water temperatures, regional water availability, and storm event intensities and frequencies, flooding, and sea-level rise, which are relevant to the U.S. energy sector. In 2014, the U.S. Global Change Research Program (USGCRP) published the Third National Climate Assessment (NCA3) Report that assesses the science of climate change and its impacts across the United States (Melillo et al. 2014). The USGCRP published the two volume NCA4 report in 2017 and 2018 (USGCRP 2017, 2018). These reports summarize observed climate changes based on a wide range of observational records and projected climate changes for the United States from available regional and global climate model simulations. In sections 3.1, 3.2, and 3.3 (Figure 3.1 through Figure 3.15), we reproduce summary figures of observed and projected climate changes from these two reports that are relevant for NRC's planning. In section 3.4, the results by region are presented in Figure 3.18.

3.1 Temperature

Temperature Changes

- Observed annual average temperature over the contiguous United States. increased by 1.2°F for the 1986–2016 period compared to the 1901–1960 period and by 1.8°F based on a linear regression for the 1895–2016 period. NCA4 states these trends with very high confidence.
- Annual average temperature over the contiguous United States is projected to rise by about 2.5°F for the 2021–2050 period compared to the 1976–2005 period in all RCP scenarios. For 2071–2100 period, annual average temperature is projected to increase by 2.8–7.3°F in RCP4.5 scenario and by 5.8–11.9°F in RCP8.5 scenario. NCA4 states these results with high to very high confidence.
- The coldest and warmest daily temperatures of the year are projected to increase at least 5°F by the 2036–2065 period in most areas of the contiguous United States and by 10°F or more by late-21st century.

3.1.1 Observed Changes

In NCA3 and NCA4, changes in annual average temperatures over the contiguous United States are described using the nClimGrid and nClimDiv datasets (Vose et al. 2014; Vose et al. 2017). The annual average temperature in the contiguous United States has increased since the start of the 20th century and rapidly since about 1970. The increase was estimated to be 1.2°F between the annual average temperature for 1986–2016 and that for 1901–1960. The estimate for the increase from a fitted linear trend for the period 1895–2016 was 1.8 °F. All NCA regions experienced increases in annual average temperatures (Table 3.1, column 2).

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[1] http://energy.gov/sites/prod/files/2013/07/f2/20130716-Energy%20Sector%20Vulnerabilities%20Report.pdf

Table 3.1. Observed Changes in Annual Average Temperatures (°F) for the NCA Regions. The differences are between the annual average temperatures for the 1986-2016 and 1901–1960 periods for the contiguous United States and between those for the 1986–2016 and 1925–1960 periods for Alaska, Hawaii, and the Caribbean. (Source: USGCRP 2017, Table 6.1)

NCA Region	Change in Annual Average Temperature	Change in Annual Average Maximum Temperature	Change in Annual Average Minimum Temperature
Contiguous U.S.	1.23°F	1.06°F	1.41°F
Northeast	1.43°F	1.16°F	1.70°F
Southeast	0.46°F	0.16°F	0.76°F
Midwest	1.26°F	0.77°F	1.75°F
Great Plains North	1.69°F	1.66°F	1.72°F
Great Plains South	0.76°F	0.56°F	0.96°F
Southwest	1.61°F	1.61°F	1.61°F
Northwest	1.54°F	1.52°F	1.56°F
Alaska	1.67°F	1.43°F	1.91°F
Hawaii	1.26°F	1.01°F	1.49°F
Caribbean	1.35°F	1.08°F	1.60°F

Figure 3.1 shows the observed changes in annual, summer, and winter average temperatures between the 1986–2016 and 1901–1960 periods for the contiguous United States, and between the 1986–2016 and 1925–1960 periods for Alaska and Hawaii. More than 95 percent of the contiguous United States experienced an increase in annual average temperature. Small parts of southeastern United States and Southern Great Plains experienced cooling. Warming was greatest and more widespread in winter.

Figure 3.2 shows changes in the coldest and warmest daily temperatures of the year between 1986–2016 and 1901–1960 time periods over the contiguous United States. All NCA regions experienced increases as shown in Table 3.1 (columns 3 and 4). Apart from some locations in the southeast, most of the contiguous United States experienced increases in the coldest daily temperature with the largest increases occurring in the northern Great Plains and the northwest (Table 3.2). The changes in warmest daily temperature of the year shows increases in some parts of western United States but decreases in almost all areas east of Rocky Mountains (Table 3.2, column 3 and Figure 3.2 top-right panel). The decreases in warmest daily temperature of the year in the eastern United States may be related to the effects of the 1930s Dust Bowl which resulted in unprecedented summer heat in the Great Plains (USGCRP 2017).

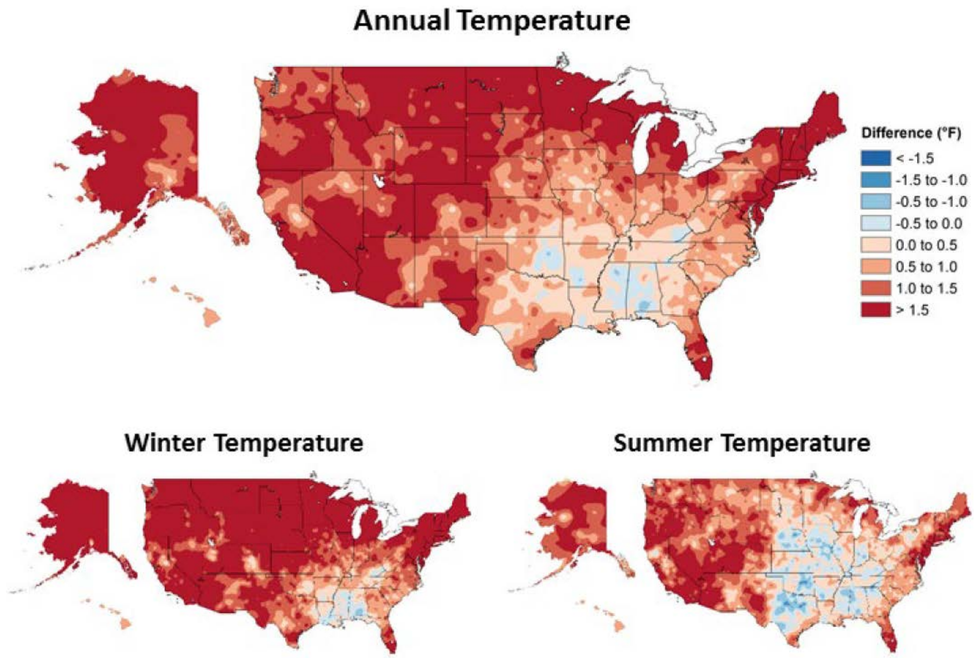

Figure 3.1. Observed Changes in Annual, Winter, and Summer Temperatures Averaged Over 1986–2016 Compared to the 1901–1960 Average for the Continental United States, and Compared to the 1925–1960 Average for Alaska and Hawaii. The estimates were derived from Vose et al. (2014) and Vose et al. (2017) nClimDiv dataset. (Source: USGCRP 2017, Figure 6.1)

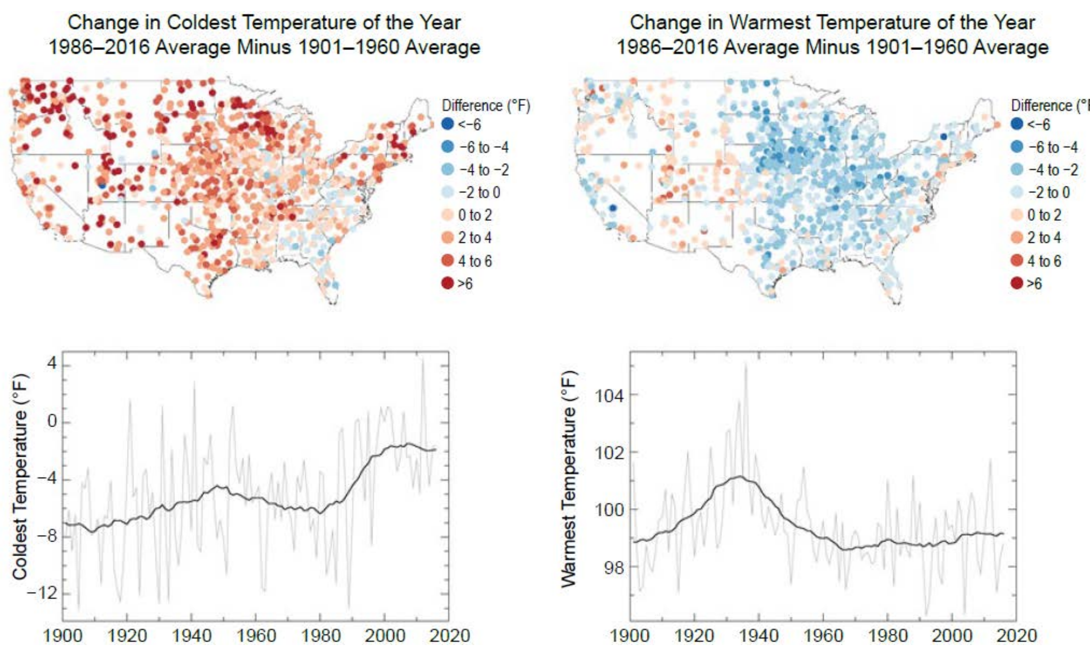

Figure 3.2. Observed Changes in Annual Coldest (left panels) and Warmest (right panels) Daily Temperatures (°F) Over the Contiguous United States. The maps in the top row show at-station difference between the 1986–2016 averages and the 1901–1960 averages. The

bottom time series plots show the area-weighted averages for the contiguous United States (Source: USGCRP 2017, Figure 6.3)

Table 3.2. Changes in Coldest and Warmest Daily Temperatures of the Year for the NCA Regions Expressed as the Difference in Respective Quantities Between the Periods 1986–2016 and 1901–1960. Estimates were derived from long-term Global Historical Climatology Network stations with minimal missing data. (Source: USGCRP 2017, Table 6.2)

NCA Region	Change in Coldest Day of the Year	Change in Warmest Day of the Year
Northeast	2.83°F	−0.92°F
Southeast	1.13°F	−1.49°F
Midwest	2.93°F	−2.22°F
Great Plains North	4.40°F	−1.08°F
Great Plains South	3.25°F	−1.07°F
Southwest	3.99°F	0.50°F
Northwest	4.78°F	−0.17°F

3.1.2 Projected Changes

In NCA4, temperature projections are based on CMIP5 global climate model runs, associated downscaled products, and model weighting[1] to refine projections (USGCRP 2017). The annual average temperature in the contiguous United States is projected to increase throughout the 21st century (about 2.5°F and 2.9°F corresponding to RCP4.5 and RCP8.5, respectively, for 2021–2050 compared to 1976–2005; and 5.0°F and 8.7°F for 2071–2100). The projected increases are statistically significant (Figure 3.3).

The coldest and warmest daily temperatures of the year are projected to increase at least 5°F by the mid-21st-century (2036–2065) in most areas of the contiguous United States (Figure 3.4; USCGRP 2017) and the increase rises to 10°F or more by late 21st-century (USGCRP 2017). Increases in coldest temperature of the year are projected to be larger, especially in northern United States, whereas increases in the warmest temperature of the year is more uniform across the United States (Figure 3.4).

The number of days that will exceed selected temperature thresholds are projected to increase significantly across the contiguous United States (Figure 3.5; USGCRP 2017). By mid-21st-century under the RCP8.5 scenario, there are projected to be about 20 to 30 more days per year with a maximum temperature above 90°F in most of the contiguous United States. In southeastern United States, the number rises to 40 to 50 more days. By mid-21st-century under the RCP8.5 scenario, there are projected to be about 20 to 30 fewer days per year with a minimum temperature below freezing in most of the

[1] Models are weighted based on model independence (accounting for dependencies arising from common parameterizations and/or tuning practices) and skill over North America for seasonal and annual coldest and warmest temperatures (USGCRP 2017, Appendix B). USGCRP (2017) stated that model weighting results in refined confidence and likelihood statements about projections; however, projections of U.S. surface air temperatures remained very similar to those in NCA3.

contiguous United States. In the northern and western United States, the number increases to 40 to 50 days.

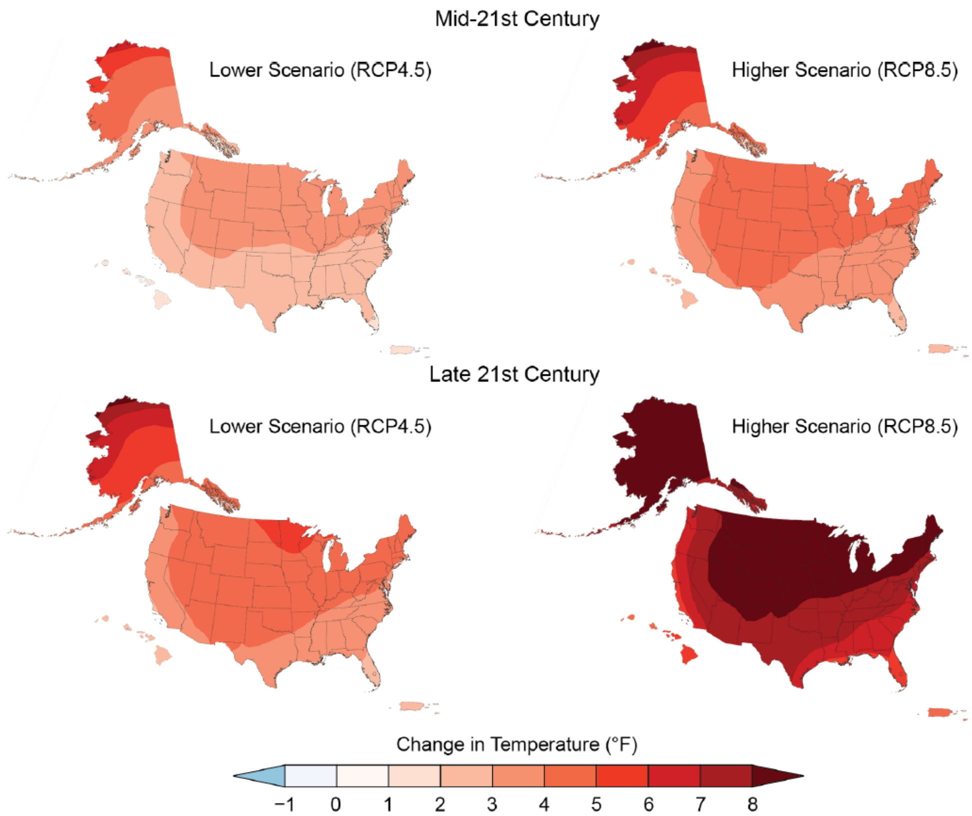

Figure 3.3. Projected Changes in Annual Average Temperatures (°F) Based on CMIP5 Weighted Multimodel Mean. The changes are differnces between the annual averate temperature for 2036–2065 (top panels) or 2070–2099 (bottom panels) periods relative to 1986–2015 period. The increases are statistically significant (more than half of the models show a statistically significant change and more than two-thirds of the models agree on the sign of the change). Warming at higher elevation may be underestimated because resolutions of CMIP5 models do not capture detailed orography. (Source: USGCRP 2018, Figure 2.4)

Table 3.3. Projected Changes in Annual Average Temperatures (°F) for the NCA Regions Relative to the 1976–2005 Period. The estimates were derived from 32 global climate models that were statistically downscaled using the Localized Constructed Analogs technique (Pierce et al. 2014). The increases are statistically significant for all regions (more than half of the models

show a statistically significant change and more than two-thirds of the models agree on the sign of the change).

NCA Region	RCP4.5 Mid-Century (2036–2065)	RCP8.5 Mid-Century (2036–2065)	RCP4.5 Late-Century (2071–2100)	RCP8.5 Late-Century (2071–2100)
Northeast	3.98°F	5.09°F	5.27°F	9.11°F
Southeast	3.40°F	4.30°F	4.43°F	7.72°F
Midwest	4.21°F	5.29°F	5.57°F	9.49°F
Great Plains North	4.05°F	5.10°F	5.44°F	9.37°F
Great Plains South	3.62°F	4.61°F	4.78°F	8.44°F
Southwest	3.72°F	4.80°F	4.93°F	8.65°F
Northwest	3.66°F	4.67°F	4.99°F	8.51°F

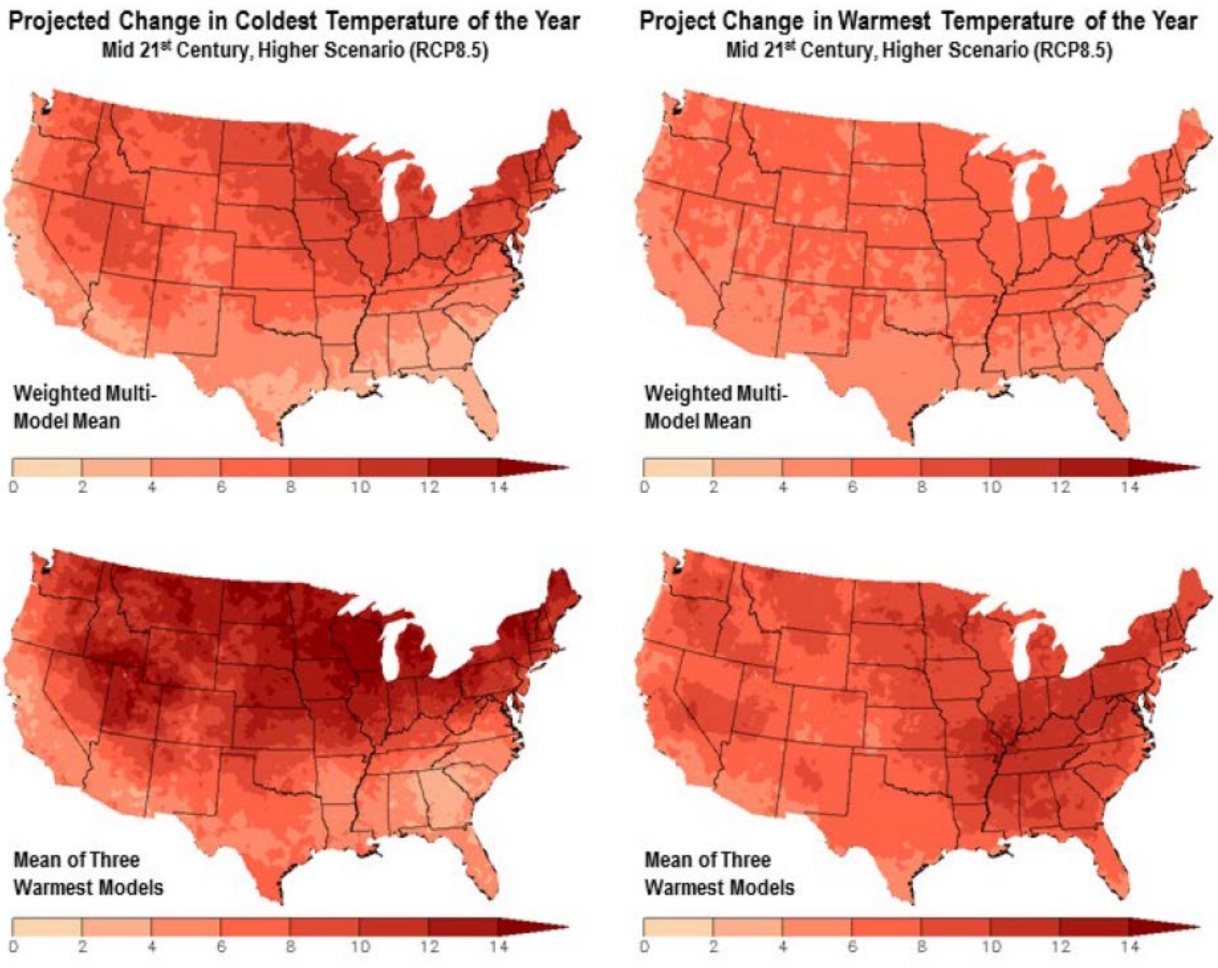

Figure 3.4. Projected Changes in the Coldest and Warmest Daily Temperatures (°F) of the Year in the Contiguous United States. The changes are differnces between the average for 2036–2065 period and the average for 1976–2005 period under RCP8.5 scenario. Top panels show the weighted multimodel means where the botton panels show the mean of the models that predict the three warmest scenarios. The estimates were derived from 32 global climate models that were statistically downscaled using the Localized Constructed Analogs technique (Pierce et al. 2014). The increases are statistically significant for all regions (i.e.,

more than half of the models show a statistically significant change and more than two-thirds of the models agree on the sign of the change). (Source: USGCRP 2017, Figure 6.8)

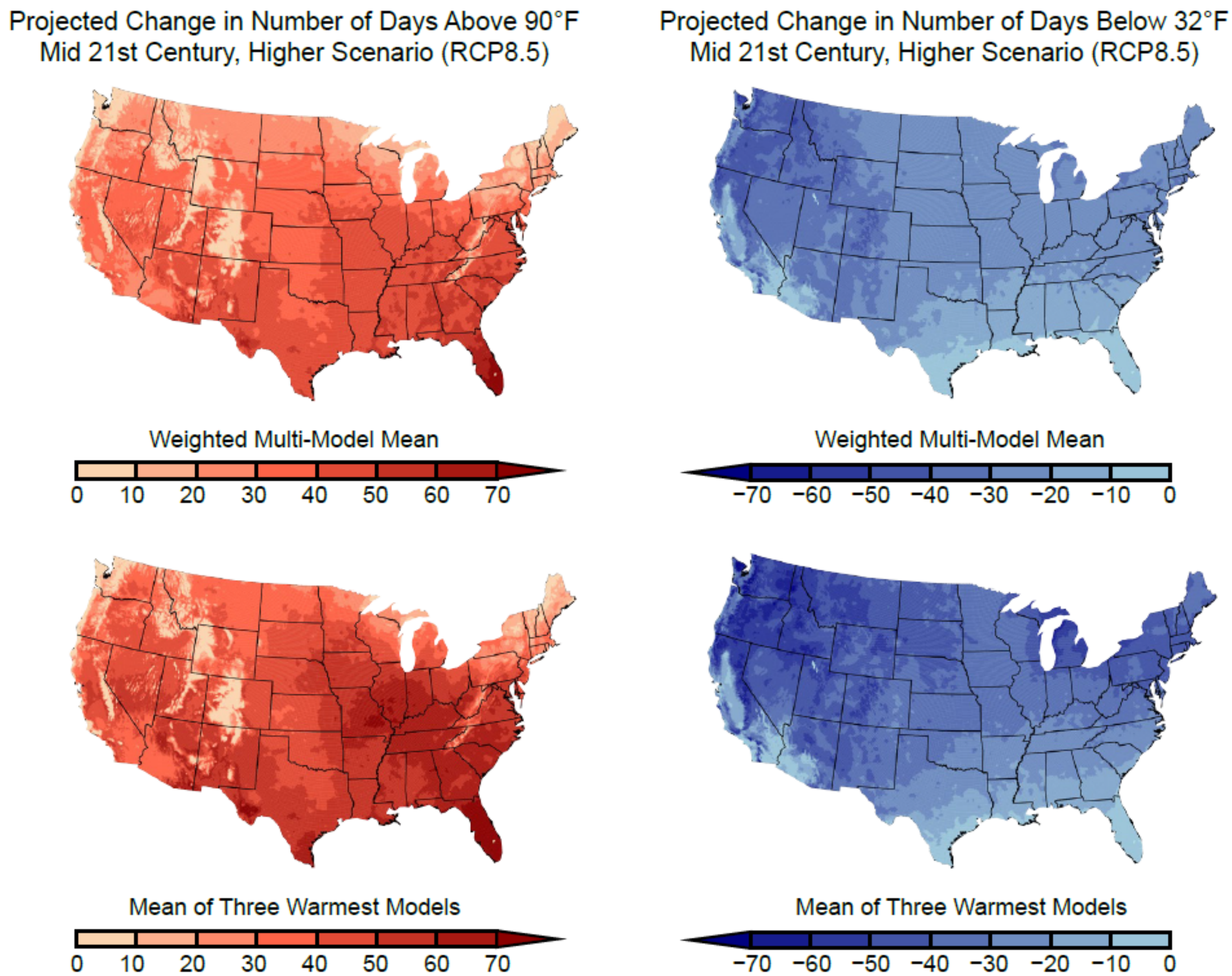

Figure 3.5. Projected Changes in the Number of Days Per Year with Maximum Temperature Above 90°F and Minimum Temperature Below 32°F in the Contiguous United States. The changes are differnces between the average for 2036–2065 period and the average for 1976–2005 period under the RCP8.5 scenario. Top panels show the weighted multimodel means where the botton panels show the mean of the models that predict the three warmest scenarios. The estimates were derived from 32 global climate models that were statistically downscaled using the Localized Constructed Analogs technique (Pierce et al. 2014). The increases are statistically significant for all regions (more than half of the models show a statistically significant change and more than two-thirds of the models agree on the sign of the change). (Source: USGCRP 2017, Figure 6.9)

3.2 Precipitation and Floods

- Observed annual average precipitation has increased 4 percent since 1901 nationally, mostly as a result of increases in the fall season. Annual average precipitation increased in the Great Plains and the Midwest and Northeast regions. NCA4 states these trends with medium confidence.
- Heavy precipitation (e.g., 1-day precipitation depth at AEP 0.05) has increased in most parts of contiguous United States with largest increases in the Northeast region. The frequency of 2-day precipitation events exceeding depth corresponding to AEP 0.2 has been increasing since 1901 and particularly since 1970. NCA4 states these trends with high confidence.
- Heavy precipitation (e.g., 2-day precipitation events exceeding depth corresponding to AEP 0.2) is projected to increase in frequency and intensity over the 21st century. MCSs in the central United States are expected to in number and intensity in the future. NCA4 states these trends with high confidence.
- In the northern United States., in the early to middle 21st century, snowfall is likely to increase as precipitation increases while in the latter half of the 21st century, snowfall is likely to change to rainfall as temperatures increase. NCA4 states these trends with high confidence.
- Some analyses of historical flood records have shown spatial patterns across the United States—flood magnitudes have increased in the Midwest and Northeast regions of the United States whereas they have decreased in the Southwest region. An analysis of stream gauges in the central United States indicated significant increases in flood frequency but not in flood magnitudes.
- Because changes in streamflow depend on factors both human and natural, including climate change, NCA4 noted that projections of future changes in flood is a complex multivariate problem. While influences of climate change on some factors are known—e.g., increasing intensity and frequency of atmospheric rivers—translating the increases in atmospheric river frequency to flood frequency requires a detailed representation of western U.S. topography in the GCMs or estimation via dynamic downscaling using regional models, still an evolving field of research.

3.2.1 Observed Changes in Precipitation

NCA4 reported an increase of 4 percent in annual average precipitation across the United States over the 1901–2015 period (USGCRP 2017). Nationally, largest increases are in the fall while winter shows little change (Figure 3.6). There is considerable spatial and seasonal variability in the observed changes. The Northeast, Midwest, and Great Plains regions show increases while parts of Southwest and Southeast regions show decreases. Over the contiguous United States, fall shows the largest (10 percent) and most widespread increases—the northern Great Plains, Southeast, the Northeast regions show increases exceeding 15 percent. Winter precipitation decreased over much of the western and parts of the southeastern United States. Spring and summer show about a 3.5 percent increase nationally but have substantially different spatial patterns. The northern half of the contiguous United States shows increases in average spring precipitation while the southern half shows decreases. Average summer precipitation shows mixed increases and decreases over the contiguous United States.

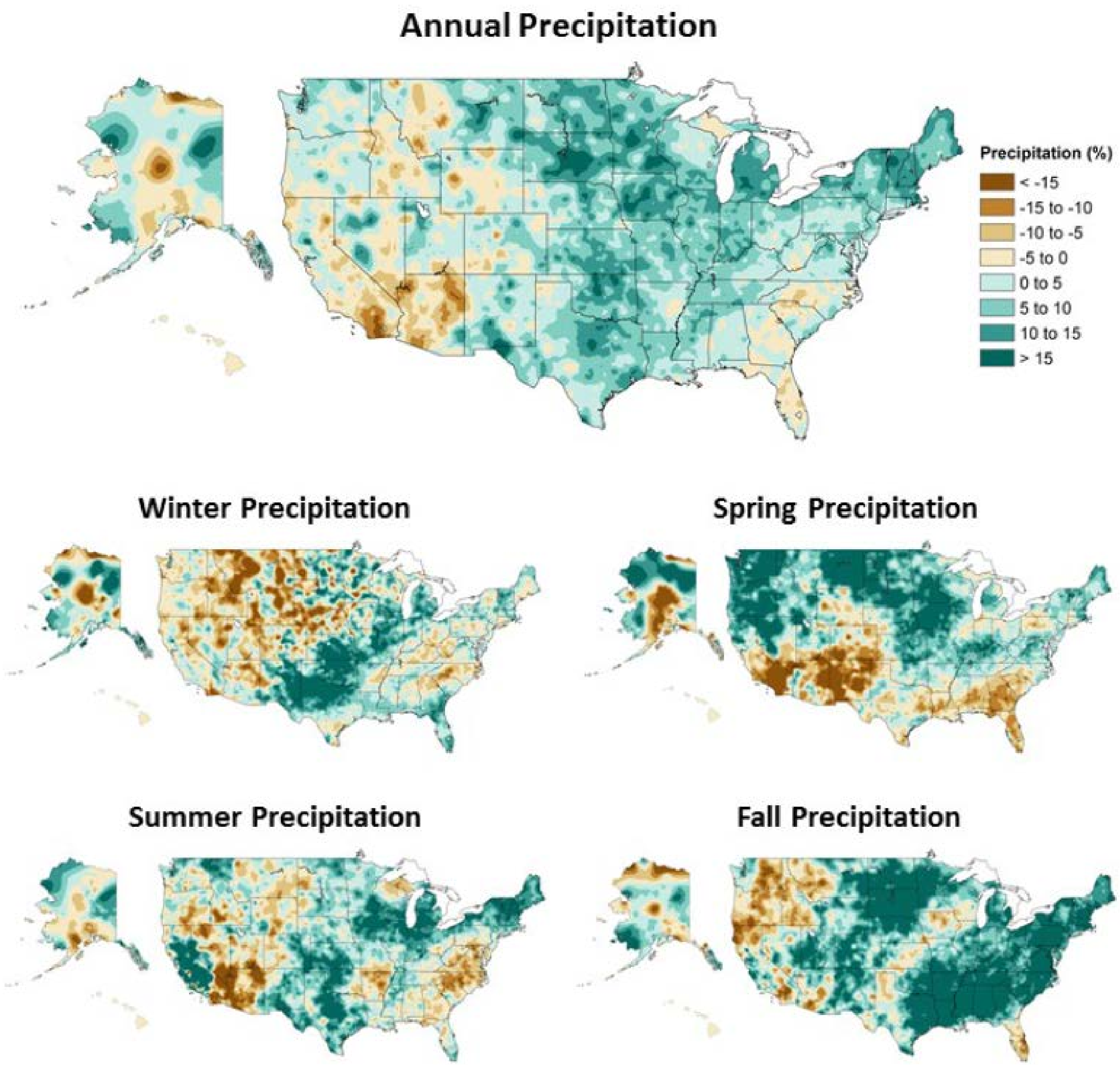

Figure 3.6. Observed Precipitation Changes over the United States. Changes are the difference between annual (or seasonal) average precipitation for the 1986–2015 period compared to the 1901–1960 baseline period for the contiguous United States or the 1925–1960 baseline period for Alaska and Hawaii, expressed as a percentage change from the baseline period. (Source: USGCRP 2017, Figure 7.1)

Figure 3.7 shows observed changes in 1-day precipitation depth at the 0.05 AEP for the contiguous United States. While the Northwest region shows little change in all seasons, the Southern Great Plains shows a large increase in the winter and the Southeast region shows a large increase in the fall.

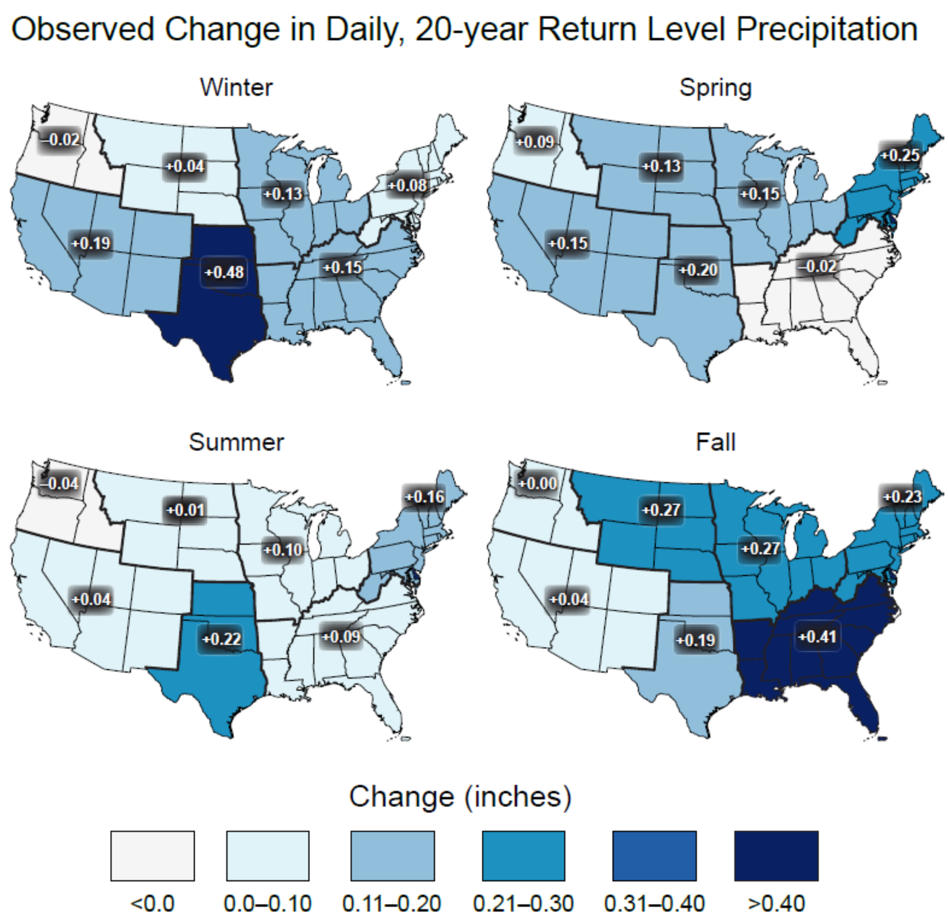

Figure 3.7. Observed Changes in 1-Day Precipitation Depth (in.) at 0.05 AEP for the Contiguous United States. Changes were estimated over the 1948–015 period using the Global Historical Climatology Network dataset. (Source: USGCRP 2017, Figure 7.2)

3.2.2 Projected Changes in Precipitation

NCA4 stated that projected changes in seasonal average precipitation varies across the contiguous United States with a mix of increases, decreases, or minor changes depending both on location and season (USGCRP 2017). Spatial variations in projected precipitation is a result of variations in locally available water vapor and shifts in weather systems. Figure 3.8 shows the CMIP5 weighted multimodel average seasonal changes for the 2070–2099 period compared to the 1976–2005 averages under the RCP8.5 scenario. Precipitation in the northern United States is projected to increase in winter and spring; in the early to middle 21st century, snowfall is likely to increase as precipitation increases. In the latter half of 21st century, temperatures are projected to be too warm in many places and precipitation would be mostly rainfall (USGCRP 2017). Spring precipitation is projected to decrease in southwestern United States but only a little more than natural variations. Many portions of the contiguous United States would not experience significant changes in summer and fall precipitation (Figure 3.8, bottom panels).

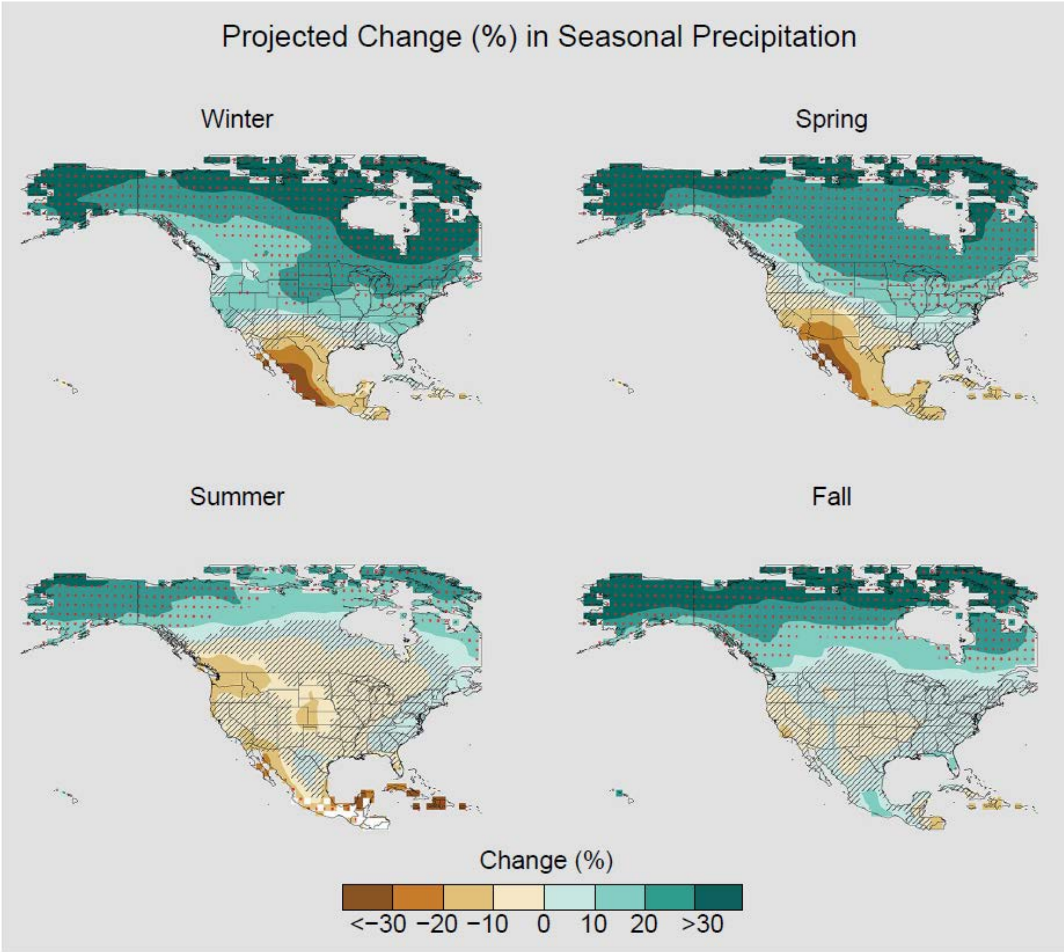

Figure 3.8. Projected Changes in Seasonal Total Precipitation from CMIP5 Models Using the RCP8.5 Emission Scenario for 2070–2099 Period. Changes are between the weighted multimodel mean for the 2070–2099 period relative to 1976–2005 averages. Stippling indicates large changes compared to natural variations, and hatching indicates small changes compared to natural variations. (Source: USGCRP 2017, Figure 7.5)

NCA3 had projected reductions of up to 40 percent in annual snowpack in the western United States based on *Special Report on Emissions Scenarios* A2 emission scenario, which also are supported by more recent research using CMIP5 projections statistically downscaled for the western United States under the RCP8.5 scenario (USGCRP 2017). Lute et al. (2015) describe decreases in various snow-related metrics including snowfall water equivalent, number of snowfall events exceeding 90th percentile historical snowfall, and number of snow days. By the end of the 21st century, snowpack at lower elevations are projected to virtually disappear under both the RCP4.5 and RCP8.5 scenarios (USGCRP 2017).

Heavy precipitation events (e.g., 2-day precipitation at AEP 0.2) are projected to increase even in regions where total precipitation is projected to decrease (USGCRP 2017; Figure 3.9). Under the RCP8.5 scenario, the number of heavy precipitation events is projected to increase two to three times by the end of the 21st century. Under the RCP4.5 scenario, increases are 50 to 100 percent of historical baseline. Figure 3.10 shows projected changes in the 1-day precipitation depth at AEP 0.05 for the contiguous United States. Under RCP4.5, 1-day precipitation depth at AEP 0.05 is projected to increase up to 10 percent for mid-21st-century and up to 14 percent for late 21st-century. Projected increases for RCP8.5 are

even larger
(Figure 3.10, bottom panels).

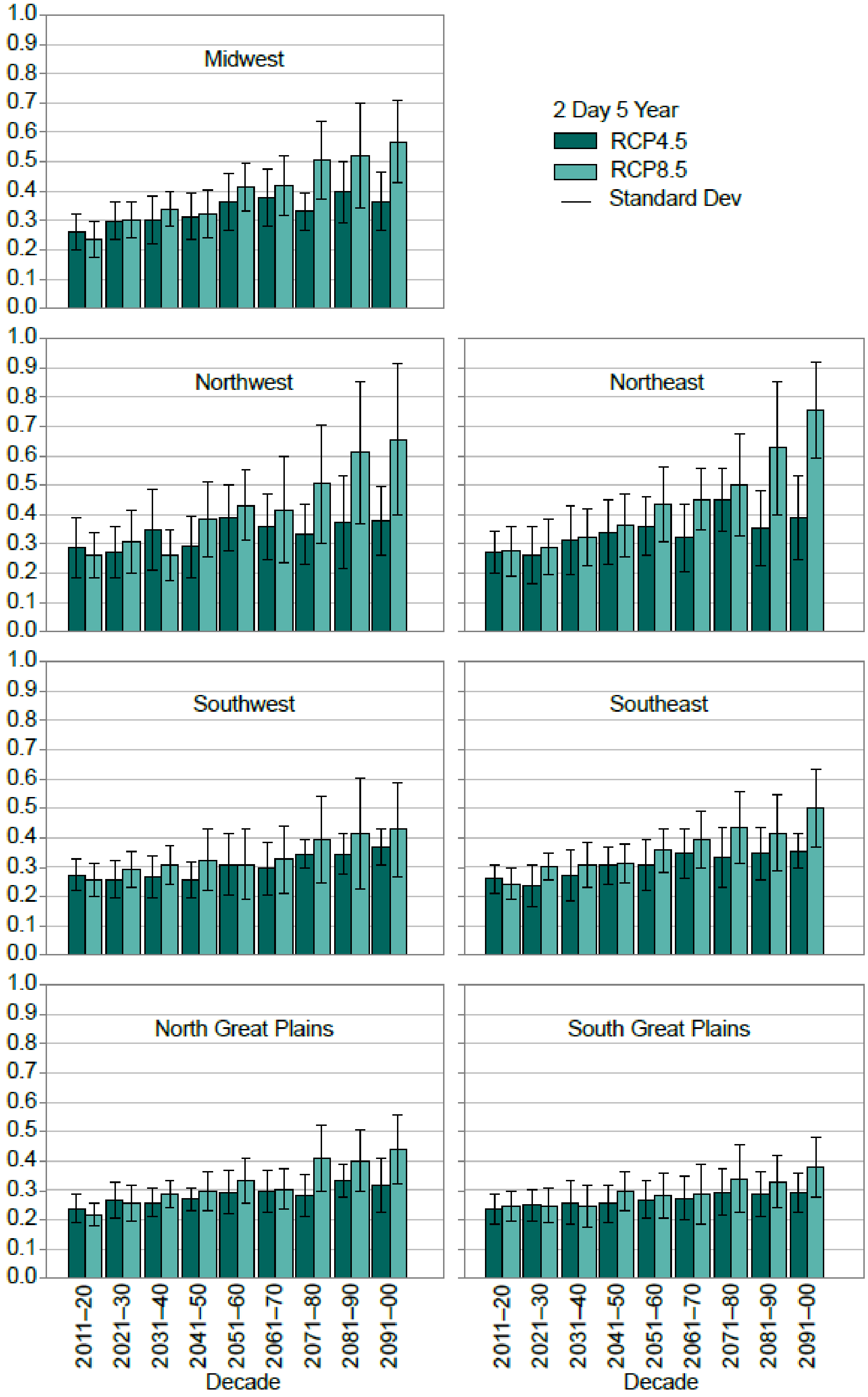

Figure 3.9. Changes in 2-Day, AEP 0.2 Precipitation Frequency as Measured by Extreme Precipitation Index (Vertical Axes) During the 21st Century Compared to Historical 2-Day, AEP 0.2 Precipitation. (Source: USGCRP 2017 Figure 7.6 and Janssen et al. 2014)

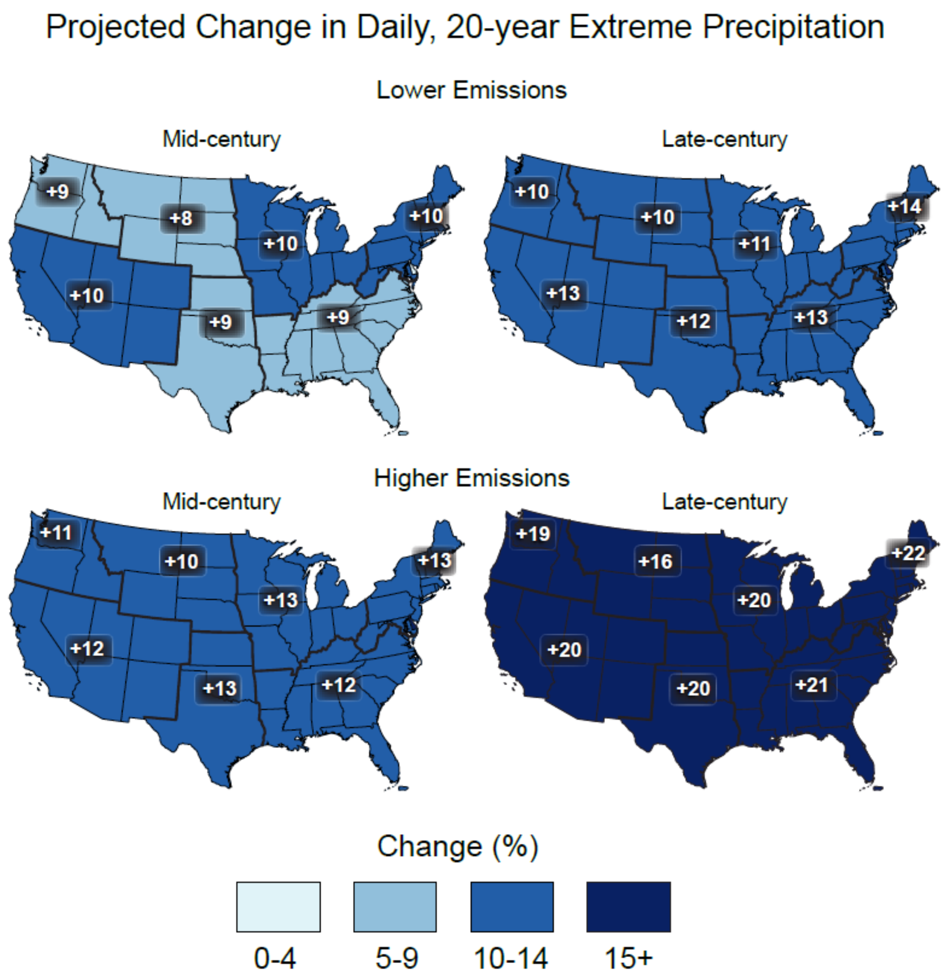

Figure 3.10. Projected Changes in the 1-Day Precipitation Depth at 0.05 AEP over the Contiguous United States for Two Emission Scenarios (Top: RCP4.5, and Bottom: RCP8.5). Estimates were derived from downscaled CMIP5 outputs. (Source: USGCRP 2017, Figure 7.7)

3.2.3 Observed Changes in Floods

NCA3 stated that while some floods are closely tied to climate factors (e.g., heavy precipitation for flash floods or sea-level rise for coastal and storm surge floods), other floods result from more complex set of causes (Melillo et al. 2014). For example, riverine floods are catchment-specific and depend not only on precipitation amount but also on pre-existing conditions like soil moisture, topography, and human-induced changes to catchments. Peterson et al. (2013) analyzed peak annual floods with records of the order of 100 years in watersheds that experienced little or no land-use or water-management changes (Hirsch and Ryberg 2012). While most of the contiguous United States showed minor changes in annual peak flood, some areas have spatially coherent patterns particularly the Midwest and Northeast regions where flood magnitudes are increasing and the Southwest region where flood magnitudes are decreasing (Figure 3.11).

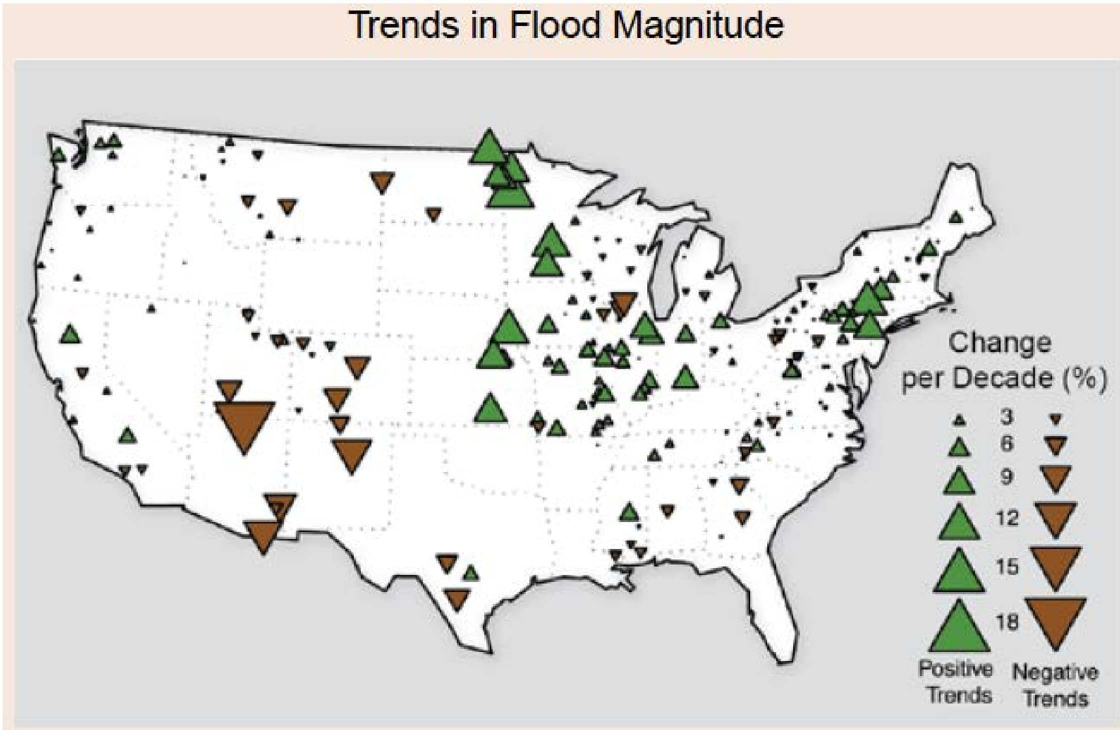

Figure 3.11. Trends of Annual Flood Magnitude from 1920s through 2008. (Source: Melillo et al. 2014, Figure 2.21 and Peterson et al. 2013)

NCA4 stated that floods in the United States can result from multiple mechanisms; for example, flash flooding in smaller rivers and creeks in response to heavy precipitation, flooding in major rivers in response to rapid snowmelt (substantial winter snow accumulations followed by rapid temperature rise or rain-on-snow events) or heavy seasonal rainfall or ARs, urban flooding not associated with proximity to a river, coastal flooding from storm surges potentially exacerbated by sea-level rise, and combination of coastal and inland flooding during hurricanes (USGCRP 2017).

NCA4 also noted that the IPCC Fifth Assessment Report did not report detectable changes in flood magnitudes, durations, or frequencies (USGCRP 2017). Analysis of stream gauges in the central United States indicated significant increases in flood frequency in about one-third of the gauges but not in flood magnitudes (Mallakpour and Villarini 2015).

3.2.4 Projected Changes in Floods

Because changes in streamflow depend on factors both human (e.g., deforestation, urbanization, dams, floodwater management, agriculture) and natural, including climate change, NCA4 noted that projections of future changes in flood is a complex multivariate problem (USGCRP 2017).

Najafi and Moradkhani (2015) performed a multimodel ensemble analysis of seasonal maximum runoff simulated by the Variable Infiltration Capacity model driven by 1/8° historical and the North American Regional Climate Change Assessment Program datasets for the Pacific Northwest region. They estimated seasonal runoffs at AEP 0.01 over the region and concluded that the magnitude of future (2041–2070) runoff at AEP 0.01 decreased in summer in Washington, Oregon, Idaho, and western Montana but increased during other seasons. They noted that the results suggested a substantial shift in seasonality of peak streamflow, from summer to spring, for several regions in the Pacific Northwest.

USGCRP (2017) noted that for the west coast United States, precipitation from atmospheric river-generated storms is an important factor in flood magnitude and frequency. Climate projections indicate greater frequency of ARs in the future (Dettinger et al. 2011; Warner et al. 2015; Gao et al. 2015b). USGCRP (2017) stated that translating increases in atmospheric river frequency to flood frequency requires a detailed representation of western U.S. topography in the GCMs or estimation via dynamic downscaling using regional models.

A report for the Federal Emergency Management Agency that used a regression-based approach for scaling stream-gauge data based on commonly used climate change indices (see Tebaldi et al. 2006) from the CMIP3 dataset concluded that by the end of the 21st century, the 1-percent annual chance riverine floodplain area would increase by about 45 percent nationally, with large regional variations (AECOM 2013). The report estimated that the corresponding increase in the coastal floodplain would be about 55 percent, again with wide regional variations.

3.3 Hurricanes and Sea-Level Rise

- Although historical data for TCs have considerable uncertainty prior to the start of satellite-based observations, the intensity, frequency, and duration of North Atlantic hurricanes have increased since the 1980s. The frequencies of Saffir-Simpson Category 4 and 5 hurricanes also have increased.
- Locations where TCs reach their maximum intensities has migrated poleward.
- While globally the frequency of TCs would change little, globally there would be increases in tropical cyclone intensity (medium confidence), precipitation rate (high confidence), and frequency of Saffir-Simpson Category 4 and 5 TCs (low confidence).
- NCA4 stated with very high confidence that the global mean sea level has risen 7–8 in. since 1900, with approximately 3 in. of the increase occurring since 1993.
- Although the trend signal for sea-level changes is large compared to its natural variability, at interannual timescales, changes in ocean dynamics, density, and wind can cause substantial within-region variability. A suppression of sea-level rise off the U.S. Pacific coast since 1993 may be tied to a change in wind stress pattern. A record 2-year sea-level rise on the northeastern coast of North America may be tied to combined effects of ocean circulation and North Atlantic Oscillation index.

3.3.1 Observed Tropical Cyclone Activity

USGCRP (2017) noted that historical data for TCs are highly heterogeneous both in time and among regions, leading to low confidence in estimation of long-term trends in tropical cyclone activity. Historic records of Atlantic hurricanes have considerable uncertainty prior to the satellite-based observations (pre-1970s; Mellillo et al. 2014). However, the intensity, frequency, and duration of North Atlantic hurricanes have increased since the 1980s (Figure 3.12; Melillo et al. 2014). The frequencies of category 4 and 5 hurricanes also have increased.

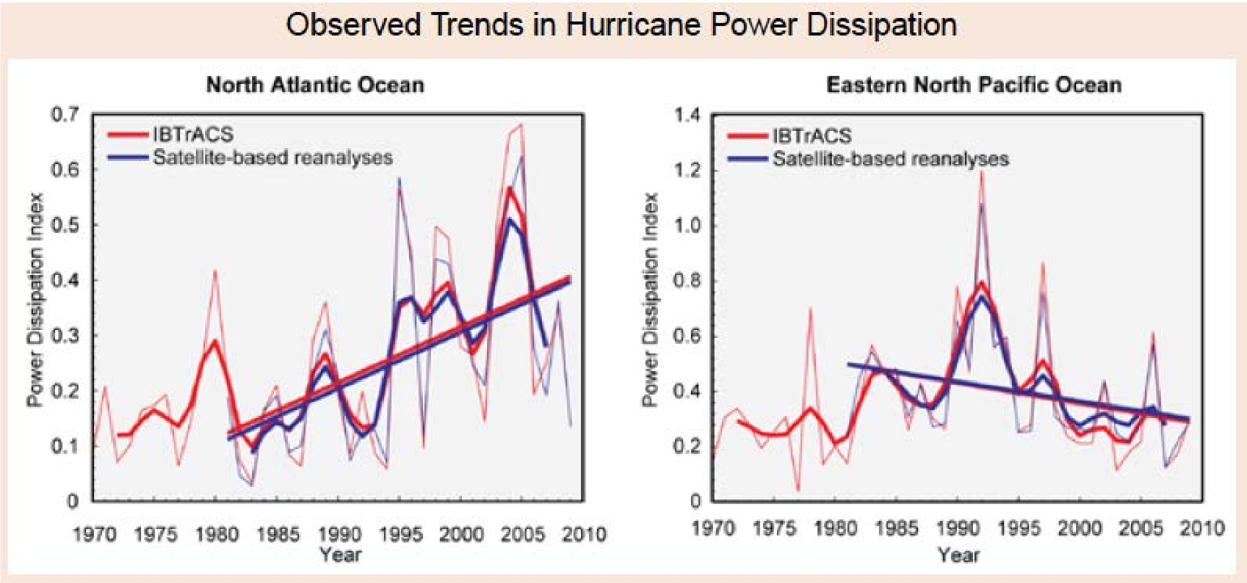

Figure 3.12. Recent Variations of the Power Dissipation Index in the North Atlantic and Eastern North Pacific Oceans. Power dissipation index is an aggregate measure of storm intensity, frequency, and duration and provides a measure of total hurricane power over a hurricane season. (Source: Melillo et al. 2014, Figure 2.23)

There is also evidence that locations where TCs reach their peak intensity have migrated poleward over the last 30 years (Figure 3.13; USGCRP 2017).

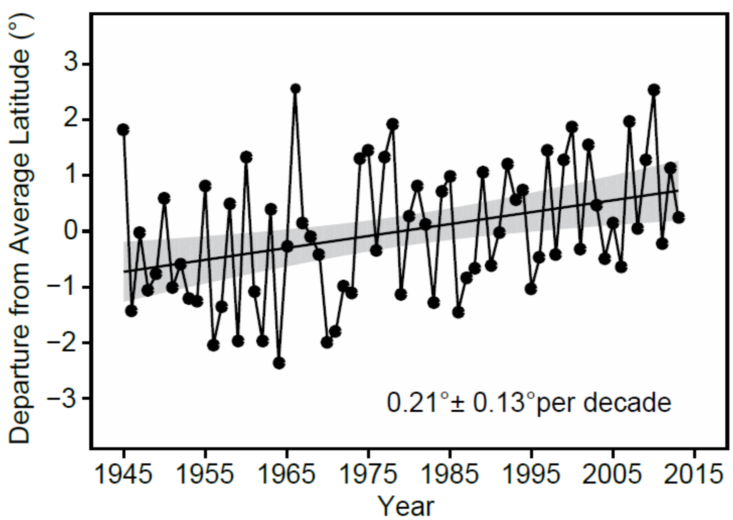

Figure 3.13. Poleward Migration (in Degrees of Latitude) of the Location of Annual Mean Tropical Cyclone Peak Lifetime Intensity in the Western North Pacific Ocean, after Accounting for the Known Regional Modes of Interannual (El Niño–Southern Oscillation) and Interdecadal (Pacific Decadal Oscillation) Variability. (Source: USGCRP 2017, Figure 9.1)

3.3.2 Projected Tropical Cyclone Activity

NCA4 stated that according to the IPCC AR5 consensus, while globally the frequency of TCs would change little, globally there would be increases in tropical cyclone intensity, precipitation rate, and frequency of Saffir-Simpson Category 4 and 5 TCs (USGCRP 2017). Since IPCC AR5, more research has focused on the statement made about TCs. Knutson et al. (2015) described an increase in tropical cyclone intensity in North Atlantic and other basins, but not in all basins. They also described significant increases in occurrences of Saffir-Simpson Category 4 and 5 TCs, particularly in the northeastern Pacific basin (Figure 3.14). While some studies also have shown increases in tropical cyclone frequency globally under the RCP8.5 scenario, others have concluded that it is more likely than not that the global frequency of TCs will decrease or remain the same in the future (USGCRP 2017).

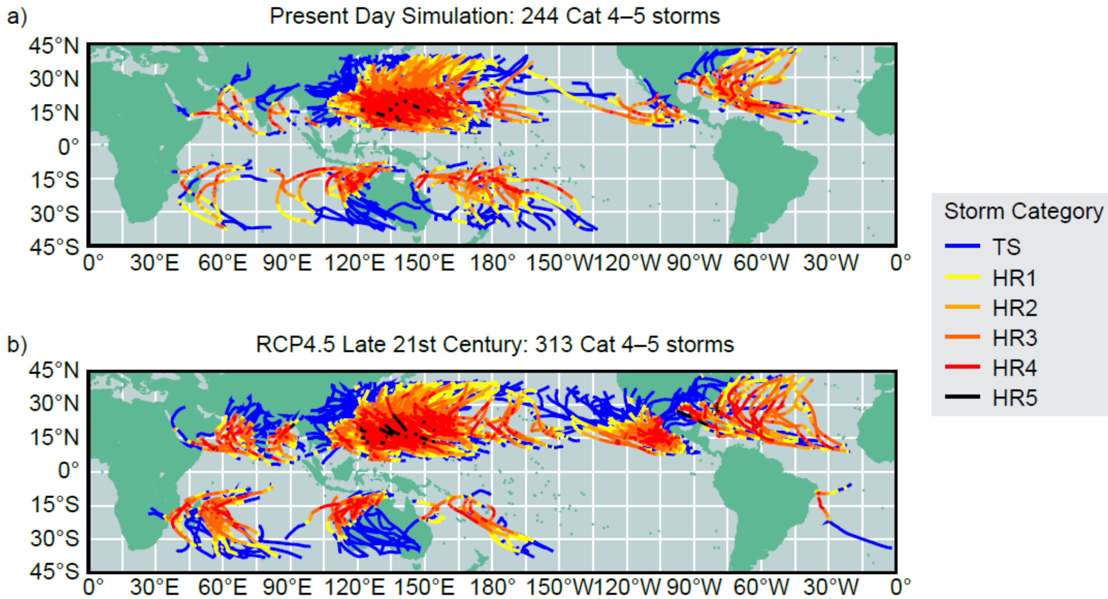

Figure 3.14. Tracks of Simulated TCs for the Present Day (top panel) and Late 21st-Century (bottom panel). The results shows are for the RCP4.5 scenario CMIP5 multimodel ensemble. (Source: USGCRP 2017, Figure 9.2)

3.3.3 Sea-Level Rise

Since the late 1800s, tide gauges have shown that global sea level has risen by about 8 in. (Melillo et al. 1014). Since 1992, the rate of sea-level rise as measured by satellites has been twice that observed over the last century. NCA4 stated with very high confidence, that the global mean sea level has risen 7–8 in. since 1900, with about 3 in. of the increase occurring since 1993 (USGCRP 2017). Global sea-level changes result from a variety of factors; the two primary factors being (1) change in seawater volume because of thermal expansion and (2) increase in mass of seawater because of melting ice from glaciers and ice sheets. However, sea-level changes are not uniform globally for the following reasons:

- Differences in height of the sea surface in response to ocean circulation, winds, and other oceanic dynamics
- Differences in density from the spatial distribution of heat and salinity
- Differences in locations of melting ice and associated gravitational, rotational, and crustal deformation effects (Figure 3.16)

- Ongoing glacial isostatic adjustments from the last ice age
- Differences in local, vertical land movement including those from sediment compaction, compaction due to groundwater or fossil fuel extraction, plate tectonics, and gradual seismic creep.

USGCRP (2017) stated that although the trend signal for sea-level changes is large compared to its natural variability, at interannual timescales, changes in ocean dynamics, density, and wind can cause substantial within-region variability. For example, there has been a suppression of sea-level rise off the U.S. Pacific coast based on both tide gauge measurements and satellite altimetry since 1993. This suppression is tied to a change in wind stress pattern (Bromirski et al. 2011). While there is a general upward trend in sea levels along the northeastern coast of North America, significant year-to-year fluctuations are observed in tide gauge records (Goddard et al. 2015). During the 2-year period 2009–2010, the coastal sea level north of New York City increased by 5 in. (128 mm), which is estimated to have an AEP of 1.2×10^{-3}. Goddard et al. (2015) attributed this event to a combination of two factors: (1) a 30-percent downturn in the Atlantic meridional overturning circulation and (2) a significant negative North Atlantic Oscillation index.

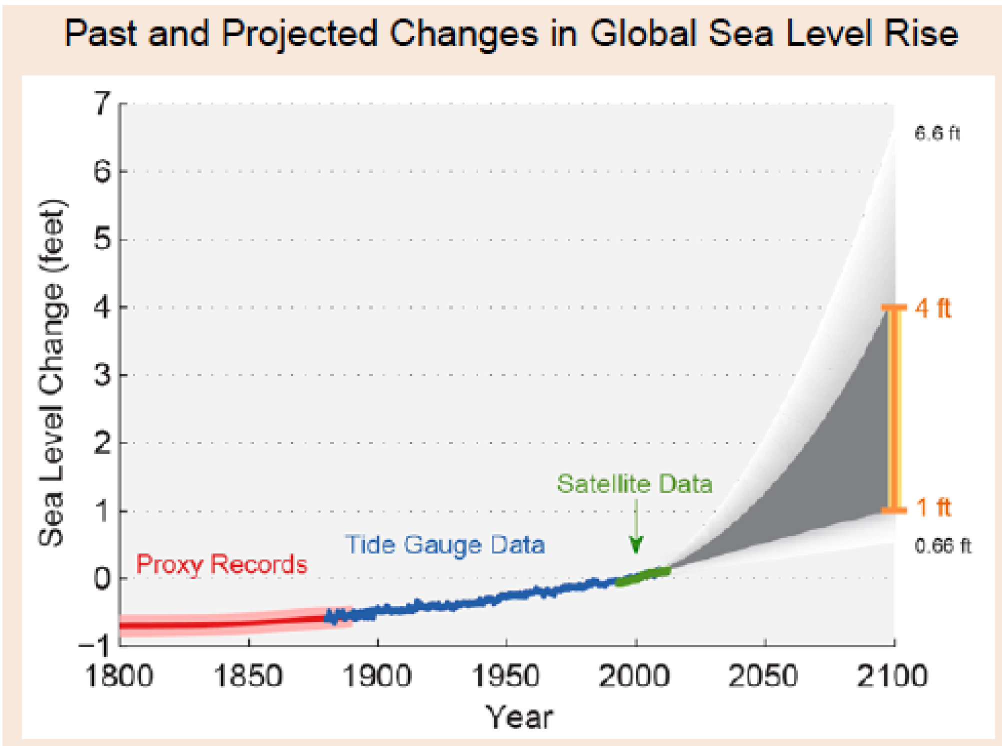

Figure 3.15. Estimated, Observed, and Possible Future Amounts of Global Sea-Level Rise from 1800–2100 Relative to the Year 2000. Proxy data in red (e.g., from sediment records) spans 1800-1890, tide gauge data in blue span 1880-2009, and satellite observations in green span 1993-2012. (Source: Melillo et al. 2014, Figure 2.26)

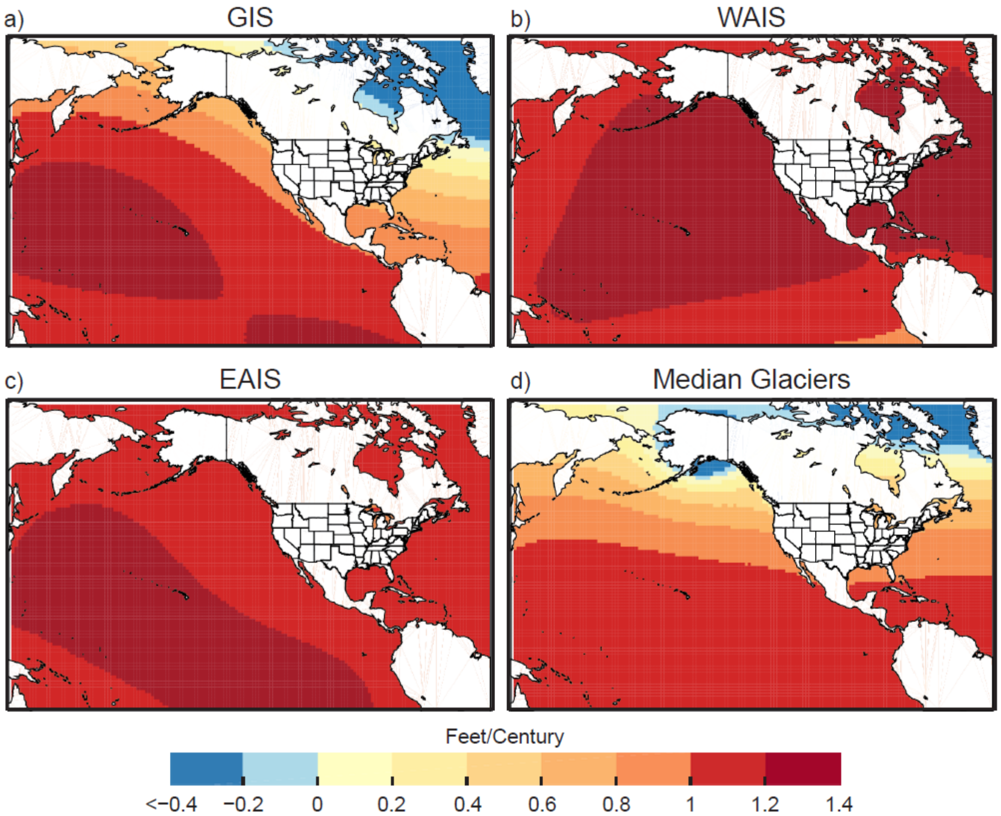

Figure 3.16. Relative Sea-Level Change per foot of Global Mean Sea Level Change (ft/century) from Regional Differences in Locations of Melting Ice and Associated Gravitational, Rotational, and Crustal Deformation Effects. Effect of mass loss from (a) Greenland, (b) West Antarctica, (c) East Antarctica, and (d) median projected combination of melting glaciers. (Source: USGCRP 2017, Figure 12.1)

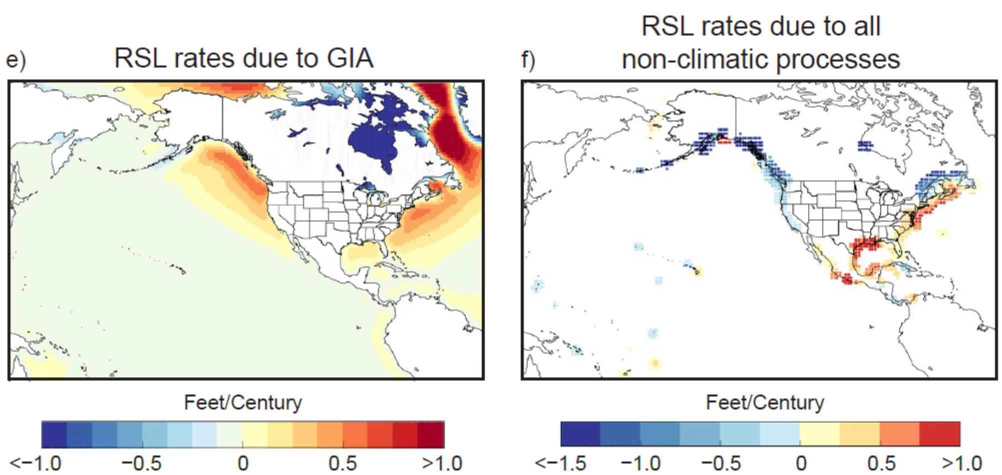

Figure 3.17. Relative Sea-Level Change (ft/century) Based on (left panel) Model Projections of Relative Sea-Level Rise from Glacial Isostatic Adjustments and (right panel) Tide-Gauge Based Estimates of Non-Climatic, Long-Term Contribution to Relative Sea-Level Rise Including the Effects of Glacial Isostatic Adjustments, Tectonics, and Sediment Compaction. (Source USGCRP 2017, Figure 12.1)

3.4 Summary of Climate Impacts

Region	Impacts
Northeast	Communities are affected by heat waves, more extreme precipitation events, and coastal flooding due to sea level rise and storm surge.
Southeast and Caribbean	Decreased water availability, exacerbated by population growth and land-use change, causes increased competition for water. There are increased risks associated with extreme events such as hurricanes.
Midwest	Longer growing seasons and rising carbon dioxide levels increase yields of some crops, although these benefits have already been offset in some instances by occurrence of extreme events such as heat waves, droughts, and floods.
Great Plains	Rising temperatures lead to increased demand for water and energy and impacts on agricultural practices.
Southwest	Drought and increased warming foster wildfires and increased competition for scarce water resources for people and ecosystems.
Northwest	Changes in the timing of streamflow related to earlier snowmelt reduce the supply of water in summer, causing far-reaching ecological and socioeconomic consequences.
Alaska	Rapidly receding summer sea ice, shrinking glaciers, and thawing permafrost cause damage to infrastructure and major changes to ecosystems. Impacts to Alaska Native communities increase.
Hawai‘i and Pacific Islands	Increasingly constrained freshwater supplies, coupled with increased temperatures, stress both people and ecosystems and decrease food and water security.
Coasts	Coastal lifelines, such as water supply infrastructure and evacuation routes, are increasingly vulnerable to higher sea levels and storm surges, inland flooding, and other climate-related changes.
Oceans	The oceans are currently absorbing about a quarter of human-caused carbon dioxide emissions to the atmosphere and over 90% of the heat associated with global warming, leading to ocean acidification and the alteration of marine ecosystems.

Figure 3.18. Summary of Climate Impacts by U.S. Regions. (Source: Melillo et al. 2014, Overview)

4.0 Status in Climate Modeling and Federal Agency Activities

Climate models are the primary tools for projecting climate change because they encapsulate the complex processes that govern the forcing and response of Earth systems to human perturbations. Advances in improving model representations of Earth-system processes and missing processes and increasing model resolution enabled by high-performance computing have improved model utility in simulating climate over the past decades (National Research Council 2012). Most climate modeling centers participate in the CMIP, which generates multimodel ensembles of present and future climate used in the IPCC. The most recent results (i.e., CMIP5) were used in the IPCC Fifth Assessment Report (Stocker et al. 2013). A collection of papers on climate changes in North America from CMIP5 was published in a *Journal of Climate* special issue (Volume 26, December 2013). The multimodel ensemble framework of CMIP5 has enabled more advanced assessment of uncertainty in projecting future changes and evaluation of model utility. The North American Regional Climate Change Assessment Program (Mearns et al. 2012, 2013) represents another multimodel framework that uses multiple regional climate models to dynamically downscale multiple global climate simulations of current and future climate. Results from the program have been used prominently in the U.S. National Assessment of Climate Change and facilitated numerous studies of regional climate change and assessments of climate change impacts on water resources, wind energy, agriculture, extreme events, etc. (Mearns et al. 2015). In addition to the multimodel ensemble, Kay et al. (2015) developed a large ensemble (32 members) of climate simulations using a single global climate model to enable better quantification of internal variability and evaluate the robustness of regional climate change signals in the presence of noise. The climate modeling community has begun to plan and coordinate modeling experiments and simulations for the next phase of CMIP6 (Meehl et al. 2014).

In addition to improvements in climate model fidelity and development of multimodel ensemble and single-model large ensemble of climate change simulations to quantify uncertainty of climate change, the use of hierarchical modeling has advanced our understanding of and advanced theories regarding climate change. In hierarchical modeling (Leung et al. 2013), simulations from idealized configurations (e.g., aqua-planet) to a realistic configuration from a single component (e.g., atmosphere-only) to a coupled system of the real world are performed to facilitate analysis and interpretations of the model response to global warming (O'Gorman and Schneider 2009). Modeling experiments have further revealed the potential for key climatic features (e.g., the jet stream) to converge as models reach a horizontal resolution of ~50 km (Demory et al. 2014; Lu et al. 2015). If these findings are confirmed by multiple models, a potential implication is that models at ~50 km resolution may be able to more robustly project climate changes in the future as model sensitivity to resolution is a major source of uncertainty in climate modeling.

A report entitled *A National Strategy for Advancing Climate Modeling* (National Research Council 2012) recommended a strategy that includes:

1. Evolution towards a common national software infrastructure to support a diverse hierarchy of different models aimed at improving the performance of climate models on extreme-scale computing architectures

2. Convening an annual climate modeling forum that promotes tighter coordination among climate modeling centers

3. Nurturing a unified weather-climate modeling effort to better exploit synergies among weather forecasting, data assimilation, and climate studies

4. Developing training, accreditation, and continuing education for "climate interpreters" who will act as a two-way interface between modeling advances and diverse user needs.

Since 2012, some progress has been made to realize the strategy recommended by the report. For example, the National Oceanic and Atmospheric Administration (NOAA) recently began funding a major model development effort to develop the Next Generation Global Prediction System that will adopt a unified weather-climate modeling framework. The first U.S. Climate Modeling Summit was held in February 2015. This summit brought together six premier U.S. climate modeling centers (NOAA Geophysical Fluid Dynamics Laboratory, NOAA National Centers for Environmental Prediction, National Aeronautics and Space Administration [NASA] Goddard Institute for Space Studies, NASA Global Modeling and Assimilation Office, Community Earth System Model, and DOE Accelerated Climate Modeling for Energy) to strategize priorities of national interest and coordinate research activities. There are ongoing efforts among different agencies to advance high-performance computing and discussion of model interoperability that may support a common software infrastructure for diverse modeling frameworks. However, it remains unclear whether or how the U.S. government may support a national climate service to better support the climate change information needs of diverse users of climate information (e.g., for planning and management of resources).

Changes in extreme events are high priority climate change information for NRC's safety and environment reviews (Table 1.1). Research in extreme event attribution has advanced rapidly over the last decade to understand and quantify the extent to which climate change influences the magnitude or probability of occurrence of an individual extreme weather or climate event. A report entitled *Attribution of Extreme Weather Events in the Context of Climate Change* explores the framing and attribution methods used in extreme event attribution (National Academies of Sciences, Engineering, and Medicine 2016). The report also provides a synopsis of attribution of nine specific types of extreme events (extreme heat events, extreme cold events, droughts, wildfires, extreme rainfall, extratropical cyclones, extreme snow and ice storms, TCs, and severe convective storms). Two classes of event attribution approaches that (1) determine the change in magnitude or probability of events based on observational record and (2) use climate simulations to compare how an event would manifest in a world with and without human-caused climate change were broadly discussed. The report noted that event attribution based on "sound physical principles, consistent evidence from observations, and numerical models that can replicate the event" are more reliable. However, non-meteorological factors such as wildfires can limit the accuracy of model simulations of extreme events. The overall assessment of the state of event attribution science for different event types are summarized in Table 4.1 and Figure 4.1. The table summarizes the estimate of confidence (high, medium, and low) in the capabilities of climate models to simulate an event class, the quality of the length of the observational record from a climate perspective, and understanding of the physical mechanisms that lead to changes in extremes as a result of climate change. The climate model capabilities apply to models with spatial resolutions of 100 km or coarser that are representative of the majority of models that participated in CMIP5. In Figure 4.1, bubbles below the 1:1 line indicate the potential for improvement in attribution capability for the specific event types.

Based on the above criteria, the report concluded that confidence in attributing extreme events that are related to an aspect of temperature (e.g., extreme heat and cold events) is greatest because the anthropogenic influence on regional and global warming trends is already well established. There also is confidence in attributing hydrological drought and heavy precipitation, but attribution of severe convective storms and extratropical cyclones has little or no confidence. Furthermore, it cannot be claimed that climate change caused a specific event in a deterministic sense because natural variability also influences extreme events. The report recommended (1) a focused effort to improve understanding of specific aspects of weather and climate extremes to improve the ability to perform extreme event attribution through advances in modeling and understanding and (2) efforts to extend the historical record.

Table 4.1. Assessment of the Capabilities of Climate Models, Quality, and Length of the Observational Record, and Understanding of the Physical Mechanisms that Lead to Changes in Extremes as a Results of Climate Change for Different Event Types. (Source: NASEM 2016)

● = high **O** = medium ○ = low	Capabilities of Climate Models to Simulate Event Class	Quality/Length of the Observational Record	Understanding of Physical Mechanisms that Lead to Changes in Extremes as a Result of Climate Change
Extreme cold events	●	●	●
Extreme heat events	●	●	●
Droughts	**O**	**O**	**O**
Extreme rainfall	**O**	**O**	**O**
Extreme snow and ice storms	**O**	○	**O**
Tropical cyclones	○	○	**O**
Extratropical cyclones	**O**	○	○
Wildfires	○	**O**	○
Severe convective storms	○	○	○

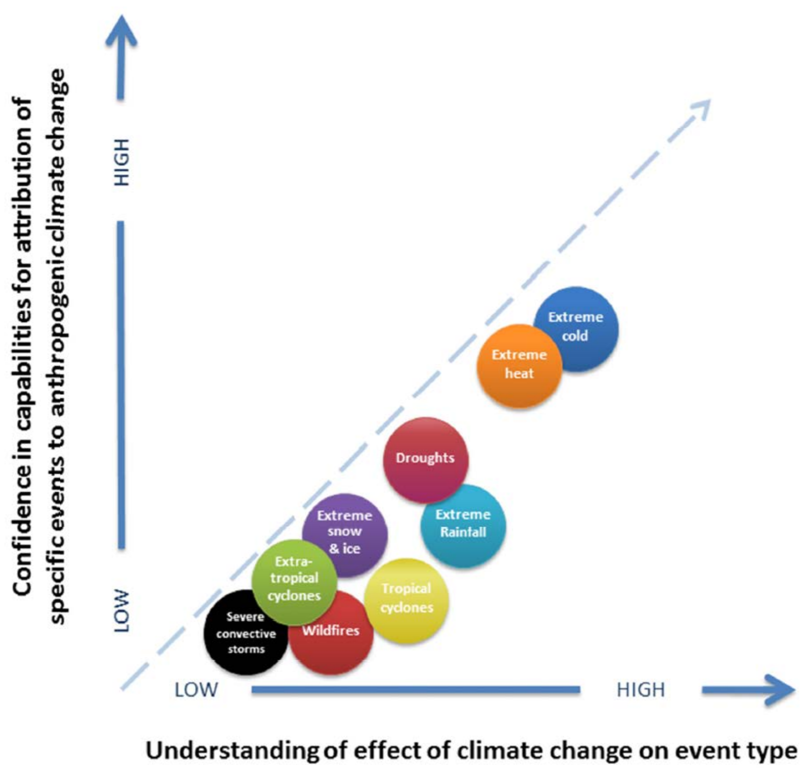

Figure 4.1. Schematic Depiction of the State of Attribution Science for Different Event Types. (Source: NASEM 2016)

The following sections provide an overview of recent climate assessment and modeling activities, as well as guidance developed by federal agencies and interagency initiatives. This overview focuses on information with potential relevance to NRC's mission.

4.1 U.S. Global Change Research Program

The USGCRP was established by Presidential Initiative in 1989 and mandated by Congress in the Global Change Research Act of 1990 (Pub.L. 101-606) to "… assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." The act established a committee on Earth and Environmental Sciences, under the umbrella of the pre-existing Federal Coordinating Council for Science, Engineering, and Technology, to carry out functions relating to global change research, for the purpose of increasing the overall effectiveness and productivity of federal global change research efforts. The committee includes at least one representative from the National Science Foundation, NASA, NOAA, U.S. Environmental Protection Agency (EPA), DOE, U.S. Department of Defense, Department of Interior, Department of Agriculture, Department of Transportation, Office of Management and Budget, Office of Science and Technology Policy, Council on Environmental Health Sciences of the National Institutes of Health, and such other agencies and departments of the federal government as the President or the Chairman of the Council considers appropriate. The USGCRP performs its mandated functions primarily though working groups of this interagency committee. The USGCRP has a legal mandate to conduct a National Climate Assessment every 4 years. The third assessment, NCA3 (Melillo et al. 2014), released in May 2014, provides an important basis for this annual report that focuses on climate change in the Midwest region. NCA4 was released on November 23, 2018. An author of this report (Leung) served on a committee organized by the National Academies of Science, Engineering, and Medicine (NASEM 2018) to review a draft of the report. This NRC Climate Change Annual Report also has incorporated significant information from the Climate Science Special Report (Volume 1 of NCA4; USGCRP 2017), which was developed to inform the fourth National Climate Assessment. More specifically, the Climate Science Special Report provides an update of the physical climate science presented in NCA3, including updated climate science findings and projections important to the authors of NCA4.

To improve the coordination and communication of national climate modeling goals and objectives, USGCRP's Interagency Group on Integrative Modeling has convened an annual U.S. Climate Modeling Summit since 2015. The fourth annual summit was convened on April 4–5, 2018. The summit brought together representatives from the six U.S. "CMIP-class" climate model development centers and from operational climate-prediction programs. Specifically, two representatives—one lead and one additional delegate—from each of the following groups were invited to participate in the summit: Geophysical Fluid Dynamics Laboratory (Climate Model/Earth System Model), Climate Forecast System, Goddard Institute for Space Studies (Model E), Goddard Earth Observing System (GEOS-5), Community Earth System Model, and Energy Exascale Earth System Model (E3SM). A workshop on "Land-Atmosphere Interactions and Extremes" was held on the first day of the summit. Land-surface processes are increasingly being recognized as providing important information for weather and climate predictions, and the land surface represents an important intersection between human activities and the Earth system. The workshop provided a forum for discussions to prioritize research and development for the modeling centers. The subjects addressed included land-atmosphere interactions and extremes, hydrological extremes, and coastal, land, and human interactions.

4.2 Federal Climate Change and Water Working Group

The federal Climate Change and Water Working Group provides engineering and scientific collaborations in support of water management under a changing climate. Participating agencies include U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation, NOAA, U.S. Geological Survey (USGS), EPA, Federal Emergency Management Agency, NASA and the U.S. Department of Agriculture. This collaborative working group informs and coordinates with higher-level interagency activities such as the U.S. Global Change Research Program's Adaptation Science Interagency Working Group, Council of Environmental Quality's Climate Preparedness and Water Resources Work Group, the Office of Science and Technology Policy Committee on Environment and Natural Resources' Subcommittee on Water Availability and Quality, and the Advisory Committee on Water Information's Water Resources Adaptation to Climate Change Workgroup.

The USACE Works Program recently published Engineering and Construction Bulletin (ECB) No. 2016-25, "Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects" (USACE 2016). The ECB recognizes that in some geographical locations and for some impacts that are relevant to the USACE, climate change may be shifting, not only the climatological baseline, but also the natural variability about that baseline (USACE 2016). ECB 2016-25 noted that projections of climate change and impacts at local scales can be highly uncertain and proposed a qualitative assessment that may assist in future project modifications and consideration of alternatives (examples of the qualitative assessment were included). It also required the qualitative analysis to be performed for all hydrologic studies at inland watersheds at the time of its issuance. Figure 4.2 is the flow chart included in ECB No. 2016-25; it lays out the elements of the qualitative analysis.

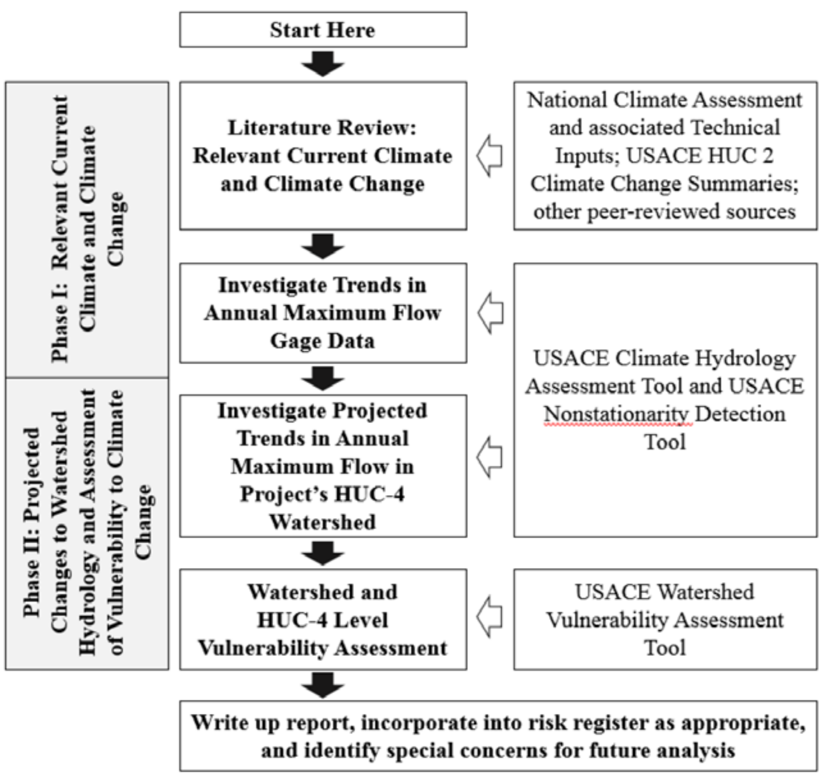

Figure 4.2. Flow Chart for Qualitative Assessment of the Impacts of Climate Change in Hydrologic Analyses. (Source: USACE 2016)

USACE also has developed a web-based qualitative Climate Hydrology Assessment Tool that is available publicly at http://corpsclimate.us/ptcih.cfm. However, the ECB 2016-25 cautions that the climate hydrology output may be limited in precision, may not adequately represent watershed complexities including snowmelt and regulation, and may only be suitable for watershed-scale decisions. At the time of ECB No. 2016-25 publication, USACE did not require qualitative assessment of climate change impacts on probable maximum floods because the existing body of research in this area is insufficient.

4.2.1 USACE Responses to Climate Change Program

USACE also has implemented a Responses to Climate Change Program to understand the potential impacts of climate change on natural and human-made systems (USACE 2017). As part of this program, USACE is preparing 21 regional climate syntheses. These regions are at the scale of a two-digit Hydrologic Unit Code across the continental United States, Alaska, Hawaii, and Puerto Rico (Figure 4.3). USACE noted that outputs from climate models are coherent and useful at the scale of 2-digit Hydrologic Unit Codes and that confidence in climate model outputs declines for areas smaller than 4-digit Hydrologic Unit Codes. The regional syntheses summarize observed and projected climate and hydrological patterns as reported in national and regional reports and peer-reviewed literature. The syntheses for Regions 5, 10, and 11 were published in January 2015; that of Region 4 in April 2015; that of Region 9 in May 2015; and that of Region 7 in June 2015. The syntheses assess the vulnerability of each region to USACE business lines, including navigation, flood risk management, water supply, ecosystem restoration, hydropower, recreation, emergency management, regulatory mission, and military programs against several climate variables, including increased ambient temperatures, increased maximum temperatures, increased storm intensity and frequency, and sea-level rise.

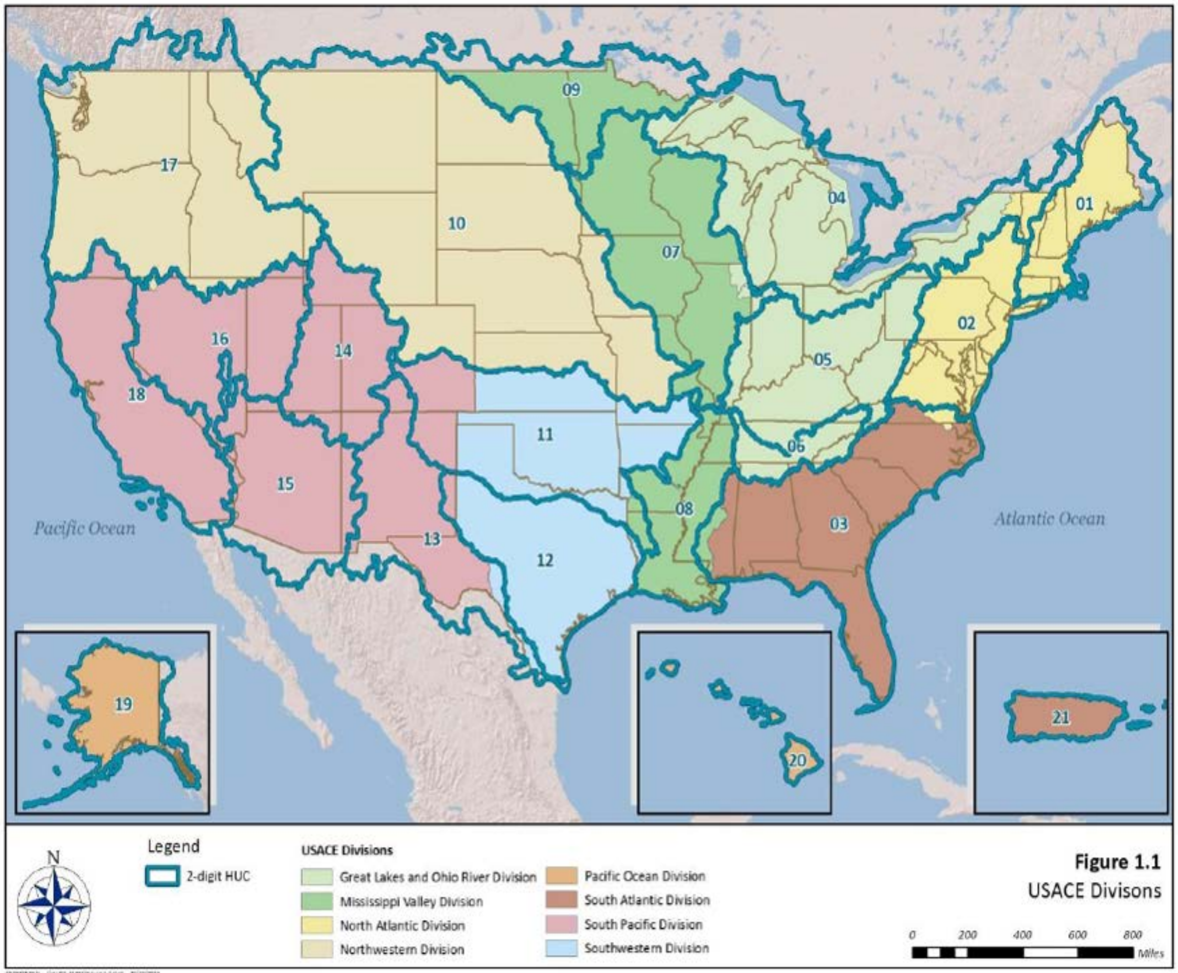

Figure 4.3. Regions used in USACE Responses to Climate Change Program. (Source: USACE 2017)

4.3 NOAA State Climate Summaries

The NOAA National Centers for Environmental Information has released a set of state climate summaries containing information on historical climate variations and trends, future climate model projections of climate conditions, and past and future sea-level and coastal-flooding conditions. These state climate summaries build on information provided in the 2014 National Climate Assessment (NCA3) and contain three types of information: (1) key messages, (2) narrative summaries, and (3) downloads. Downloads include state summaries, high-resolution figures suitable for use in reports or presentations, and supplemental web graphics.

The description of historical climate conditions for each state are based on an analysis of core climate data (the data sources are described in the supplementary online material). However, to help understand, prioritize, and describe the importance and significance of different climate conditions, additional input was derived from climate experts in each state, some of whom are authors on these state climate summaries. In particular, input was sought from NOAA Regional Climate Centers and from State Climatologists. The historical climate conditions are meant to provide a perspective on what has been happening in each state and what types of extreme events have historically been noteworthy, to provide a context for assessment of future impacts.

The future climate scenarios are intended to provide an internally consistent set of climate conditions that can inform analyses of potential impacts of climate change. The scenarios are not intended as projections as there are no probabilities for their future realization attached. They simply represent an internally consistent climate picture under certain assumptions about the future pathway of greenhouse gas emissions. The future climate scenarios are based on well-established sources of information. No new climate model simulations or downscaled datasets were produced for use in these state climate summaries. State climate summaries can be found at https://statesummaries.ncics.org.

4.4 EPA Report on Climate Change Indicators in the United States

The EPA has released an externally peer-reviewed report that describes a variety of climate change indicators in the United States as of 2016. The information provided gives a good national overview, with some regions highlighted for particular variables. The resources page lists other good sources of information. This report is available at https://www.epa.gov/sites/production/files/2016-08/documents/climate_indicators_2016.pdf.

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