CHAPTER 1: CLIMATE CHANGE IN THE NORTHEAST AND MIDWEST UNITED STATES

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CHAPTER 1: CLIMATE CHANGE IN THE NORTHEAST AND MIDWEST UNITED STATES

Summary Points

The climate is changing rapidly in ways that have already impacted wildlife and their habitats. Here, we present a summary of the observed past and projected future climate changes in the region that are relevant to wildlife and ecosystems, as well as what we know and don't know in order to raise managers' confidence in their planning. A number of large-scale regional changes affect the overall terrestrial landscape within the Northeast and Midwest United States:

- Warming is occurring in every season, particularly in winter, at higher latitudes, at higher elevations, and inland (i.e. away from the ocean and lake coasts).
- Heatwaves may become more frequent, more intense, and last longer.
- Precipitation amounts are increasing, particularly in winter and with respect to high-intensity events in summer.
- Snow is shifting to rain, leading to reduced snowpacks and extent of snow cover, as well as harder, crustier snowpacks.
- Atmospheric moisture content is likely to increase.
- Wind speeds are declining, though wind gusts may be intensifying.
- Streamflows are intensifying.
- Streams are warming.
- Thunderstorms may become more severe.
- Floods are intensifying, yet droughts are also on the rise as dry periods between events get longer.
- Blizzards and ice storms are occurring more often in some areas, though most areas experiencing milder winters (i.e., warmer and with less snow).
- Growing seasons are getting longer, with more growing degree days accumulating earlier in the season.

In addition, localized climate change is occurring in specific regions:

- U.S. Atlantic coast

    - Sea level is rising at an accelerating rate.
    - Tropical cyclones and hurricanes may be intensifying and storm tracks have been shifting northward along the coast.
    - Oceans are warming and becoming more acidic.
- Great Lakes
    - The lakes are warming.
    - Winter maximum lake ice extent is shrinking.
    - Lake evaporation rates are increasing.
    - Lake-effect snow events are becoming more severe, longer lasting, and shifting to rain, but occurring less often.
    - Water levels have decreased, but may not be linked to anthropogenic climate change.
- Appalachians
    - Warming may be occurring more rapidly at higher elevations.
    - Greater intensification of heavy rainfall events may be occurring.

In the short term (i.e., over the next 5-20 years), the direction and magnitude of warming in the global climate are mostly consistent across all emissions scenarios and with strong agreement across models. Accordingly, we are certain that the Northeast and Midwest will see longer growing seasons. We are likely to see shifts from snow to rain, though shifts in the amount of total precipitation (rain and snow) are less certain. Severe weather events (e.g., thunderstorms, tornadoes) are challenging to detect. Soil moisture and evapotranspiration trends are neither robustly observed nor consistent amongst modeling studies.

I. INTRODUCTION

There is abundant evidence that the climate is warming (Hartmann et al. 2013; Kennedy et al. 2010), and that the global atmosphere has warmed faster over the past century than any point in at least the last millennium (Masson-Delmotte et al. 2013). Global average temperature has risen by slightly under one degree Celsius since the industrial revolution with the vast majority of this change due to human emissions of carbon dioxide and other greenhouse gases (Christensen et al. 2013; Cook et al. 2013; Fischer & Knutti 2015). Under a "business as usual" scenario of rapid emissions growth throughout the 21st century, global temperature is projected to rise by 3-5 degrees Celsius; under a scenario where emissions are aggressively reduced, temperature rise could likely be held in the 2-3 degree Celsius range (Collins et al. 2013). Global temperatures are expected to rise beyond the range of natural variability (Rawlins et al. 2012).

The Northeast and Midwest Regions of the United States (hereafter referred to as the Northeast and Midwest) are vulnerable to a range of climate threats including extreme temperatures, heavy precipitation, sea level rise, and warming lake waters in the Great Lakes. These changes are likely to cause widespread ecosystem disruption in the region (Kopp et al. 2014), resulting in adverse effects on wildlife, as discussed in subsequent chapters. Extreme temperatures may rise faster than the mean in the region (Kodra & Ganguly 2014; Horton et al. 2014). As a result, the frequency, magnitude, and duration of heat waves are expected to dramatically increase (Meehl & Tebaldi 2004). Winter minimum temperatures are projected to rapidly rise, reducing the frequency of extremely cold days by an order of magnitude by mid-century (Sillmann et al. 2013). Changes in the frequency and magnitude of some extreme events (e.g., extreme heat and cold, drought, and heavy rainfalls) resulting from climatic warming are also anticipated (Alexander et al. 2006; Walsh et al. 2014).

This synthesis is provided by the Northeast Climate Science Center (NE CSC) and partners to help guide the 22 states within its geographical footprint (**Figure 1**) in their efforts to incorporate climate change information into their State Wildlife Action Plans (SWAP) revisions. While management planning typically operates on 5- to 20-year planning horizons, it is important to anticipate longer-term future conditions and offer some end-of-century projections. In addition, management actions typically occur on a local level (e.g., watershed, county, or smaller), yet there are many challenges in gleaning reliable information from models at small spatial scales, as described in the next section.

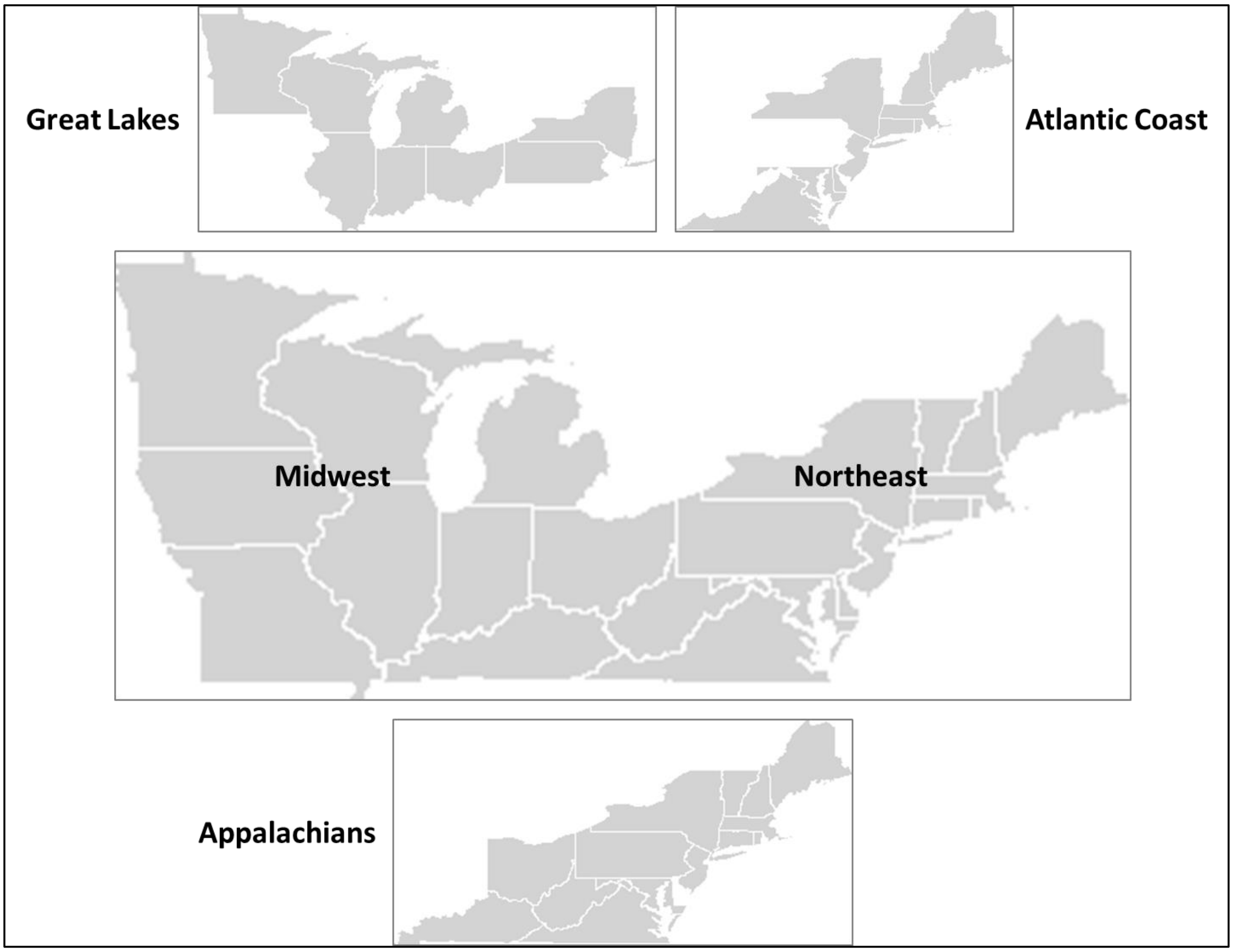


Figure 1: Geographical footprint and subregions of the DOI Northeast Climate Science Center (NE CSC), represented by this guide.

The goals of this section are to:

1. Characterize the greatest climate changes across the region;
2. Identify climate variables that are particularly difficult for many non-climate scientists to interpret and explain why;
3. Outline potential recommendations for managers in interpreting and taking action under these uncertainties; and

4. Identify where and when extreme climate conditions and intense storms have already occurred and are most likely to occur in the future.

We begin with some considerations for managers on how to interpret the information presented in this document, including discussions about uncertainty and approaches for coping with uncertainty. Next, we provide a summary of many of the climate trends that have been observed or are projected to occur in the region, particularly those relevant to wildlife and their habitats. Our discussion of climate trends begins with the widespread changes affecting the terrestrial landscape across the entire NE CSC region (e.g., long-term climatic warming, heavier rain events, and shifts in terrestrial surface hydrology). We conclude our synthesis with some regionally-specific changes pertaining to states along the Atlantic coast (e.g., sea level rise, storm surge, coastal flooding, and changing ocean acidification), surrounding the Great Lakes (e.g., lake levels, temperature, and quality, ice coverage, and lake-effect precipitation), and along the Appalachian Mountains (e.g., elevation-dependent warming, snowline, mountain hydrology).

II. MANAGING IN AN UNCERTAIN FUTURE: GUIDELINES FOR INTERPRETING THIS DOCUMENT

The climate is changing and already having visible consequences on our wildlife and their habitats (see **Chapters 2 and 3**). Emissions of carbon dioxide from human activity, particularly fossil fuel combustion, are largely responsible for the recent warming (Christensen et al. 2013; Cook et al. 2013; Fischer & Knutti 2015). Continued carbon emissions over the course of the 21st century will lead to further shifts in climate (Sillmann et al. 2013). Even if all carbon emissions ceased today, warming is very likely to continue (Frölicher et al. 2014). The Earth is currently warming faster than wildlife and ecosystems often are able to adapt, and thus climate change adaptation approaches are necessary to facilitate transitions of many climate-sensitive species if they are to be conserved. At the same time, climate change is still very much an area of active research, and thus many uncertainties and gaps in our knowledge exist. While these uncertainties and knowledge gaps pose challenges for planning, they can often prevent planners from attempting to plan and act. Amidst the uncertainty, there are many things that are certain for the Northeast and Midwest: the climate is warming, resulting in longer growing seasons, more extreme events, and many related impacts on wildlife and habitats (e.g., increased pests and disease, vegetation shifts). For these more certain aspects of climate change, plans and actions can be made with a high degree of confidence. For areas that are less certain (e.g., local scale changes in precipitation and its impact on surface hydrology, such as terrestrial drought, river and stream flows, vernal pool formation, etc.), planners can consider the actions they might take and whether they have the tools in place for the full range of projected outcomes.

This document presents observed and projected trends and our confidence in said trends for many climate variables that are relevant to wildlife and their habitats. When possible, we try to discuss variability across the Northeast and Midwest and time of year, as well as any other useful information, such as important considerations about uncertainty or results from particular case studies. All information presented here (unless noted otherwise) derives from the published scientific literature and has thus been thoroughly scrutinized for accuracy and legitimacy through the peer review process.

When discussing climate models and their output, we use terms that can be confusing to distinguish: projection, prediction, forecast, and scenario. *Projections* show a range of what *could* happen based on a range of future *scenarios*. In contrast, *predictions* describe what *will* happen assuming one particular scenario plays out. A *forecast* is a prediction used exclusively in predicting short-term (i.e., days to weeks) weather and thus not used in this report. Model projections (i.e., what could happen) are *not* predictions (i.e., what will happen) because the final outcome depends on how greenhouse gas emissions change over time as policies and human activities shift. Climate change projections are based on a standard set of 4-5 "emissions scenarios," ranging from a worst-case scenario, in which emissions continue at present magnitudes (i.e., "business-as-usual"), to a low-emissions scenario under which global policies lead to major reductions in emissions (Nakićenović et al. 2000; Moss et al. 2010). Each scenario results in proportional differences in global climatic warming. In the short term (i.e., over the next 5-20 years), the direction and magnitude of warming in the global climate are mostly consistent across all emissions scenarios and with strong agreement across models. After approximately 20 years, the trends in global-scale warming from the different emissions scenarios begin to diverge. Models are run with each scenario, producing a suite of projected future conditions.

Climate models can produce varying results within the same emissions scenario. Several climate models have been developed out of many different institutions around the world. Although these models are built off of similar fundamental physical principles, they can predict different future conditions due to differences in how they represent more complex atmospheric processes (e.g., convection, cloud physics, surface-atmosphere interactions). Models also vary in resolution. Global models, used to simulate large-scale atmospheric motions, including the movement of air masses and jet streams, are run at a coarse spatial resolution (1-3° horizontal grid spacing; Flato et al. 2013). These models do not adequately capture local-scale climate features, as is necessary for most management planning applications, and thus fine scale (1-50 km) models have been developed for a subset of the globe using a variety of “downscaling” techniques. The downscaling approach used can also yield different model results. While downscaling is a necessary step for adequately representing the local climate, the technique does not necessarily reduce the uncertainty in the global projections, and may, in fact, introduce new uncertainties due to differences in how models capture fine-scale atmospheric processes.

When describing projected trends, we try to convey the approximate likelihood of possible future conditions using the terms defined in **Table 1**. Trends are considered likely (or greater) if model projections agree with each other, are supported by observed trends, or stand up to expert judgement. We use an assortment of phrases to elaborate on these sources of likelihood. For instance, an event “is projected to” occur if models consistently show a particular trend. If model projections are both consistent and supported by past observations, we say a trend *is* occurring (e.g., temperatures are increasing, rainfall is becoming more intense). We express the likelihood of future events through a variety of other terms. For instance, something that “may” happen means the outcome is plausible but about equally likely to occur as it is to not occur or see the opposite trend (33 – 66% probability). This applies most often to precipitation projections, which can show equal magnitudes of wetter or drier conditions in the future.

Table 1: Numerical definitions of terms used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) to convey the likelihood of a given outcome (Adapted from Mastrandrea et al. 2010).

Term	Likelihood of the Outcome
Very likely	90 – 100% probability
Likely	66 – 100% probability
About as likely as not	33 – 66% probability
Unlikely	0 – 33% probability
Very unlikely	0 – 10% probability

Though many aspects of future climate are uncertain, there are approaches managers can take to cope with these uncertainties, such as scenario planning, structured decision-making, and adaptive management. **Chapter 4** of this document discusses how these and other tools can aid planning and decision-making in the face of uncertainty. If you wish to obtain guidance on how to interpret outputs and uncertainties related to climate model projections relative to your specific planning efforts, consult a qualified climatologist (e.g., the authors of this report).

III. WIDESPREAD CHANGES IN THE NORTHEAST AND MIDWEST

A) SURFACE AIR TEMPERATURE

Warming is occurring in all states and seasons.

Over the last century, mean temperature in the Midwest and Northeast regions has been observed to increase by approximately 1.4 and 1.6 °F, respectively (Hayhoe et al. 2007; Hayhoe et al. 2008; Kunkel 2013). In the Northeast, annual temperature has increased 0.16°F per decade during the period 1895-2011. Warming has been more pronounced during winter (0.24°F/decade), but statistically significant increasing trends are observed in all seasons. Over the Midwest states, the trend in annual temperature is positive over the period 1900-2010 with an increased rate of warming in the recent time period. However, only the spring season shows statistically significant increasing trends. Several studies suggest that the rate of climatic warming has been faster at higher elevations, though the availability of long-term meteorological data at high elevations is limited (Diaz et al. 2014; Pepin et al. 2015).

Future projections consistently show continued warming over the next century across the entire region, as shown in **Figure 2** (Hayhoe et al. 2007; 2008; Rawlins et al. 2012; Kunkel 2013; Ning et al. 2015). All models agree on the sign of the change, but vary in magnitude toward the end of the century depending on emissions scenario. The Midwest and Northeast are projected to see average temperature increases that exceed the global average, with potential warming of 4 – 5 °F annually by mid-century under a high emissions scenario (Kunkel 2013; Coffel & Horton 2015). The simulated annual changes increase with latitude and inland due to the regulating effects of the Atlantic Ocean and Great Lakes on air temperatures over the surrounding landscapes (Hayhoe et al. 2008; Notaro et al. 2013).

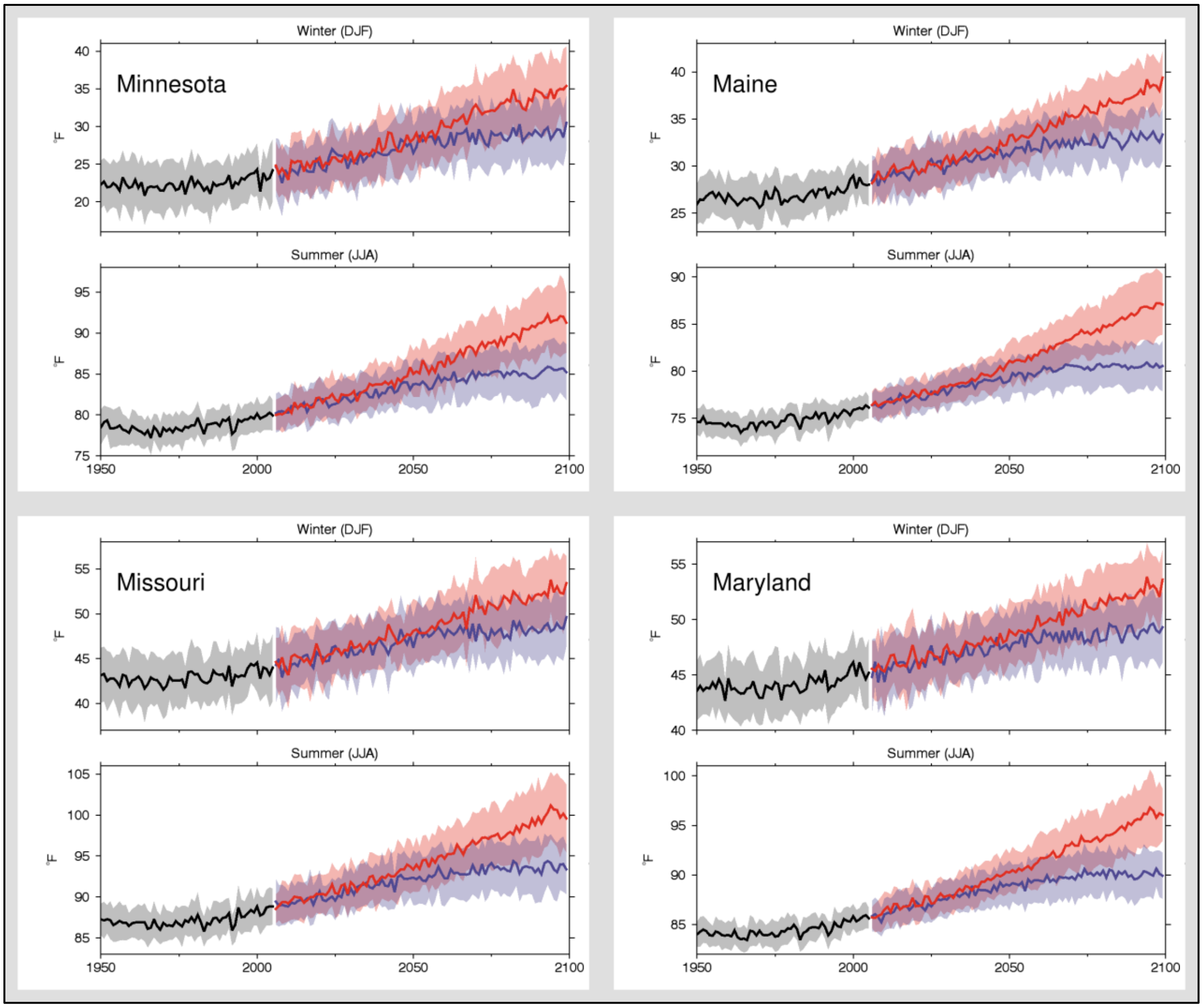


Figure 2: Trends in winter (December, January, and February) and summer (June, July, and August) average temperature from 1950 to 2100, courtesy of the USGS National Climate Change Viewer (Alder & Hostetler 2013). Both historical (black line with grey shading) and projected (colored lines and shading) trends derive from the NASA NEX-DCP30 data set (Thrasher et al. 2013), which includes 33 GCMs downscaled to a resolution of 800 meters. The solid line represents the mean of the 33 models. The red and blue curves represent the high and low emissions scenarios, respectively. The shading represents the range of one standard deviation.

Seasonal changes show more spatial variability (**Figure 3**, Kunkel 2013), with winter and spring showing higher increases in the north compared to the southern Midwest. The greatest warming is projected to occur in northwestern Minnesota and upper New England in winter (6°F) and in the Northeastern states in spring (4-4.5°F). Summer and fall show a reversed spatial pattern, with the greatest simulated increases to be in the southwestern part of the region and a north-south gradient ranging from 4.0 to 6.0°F.

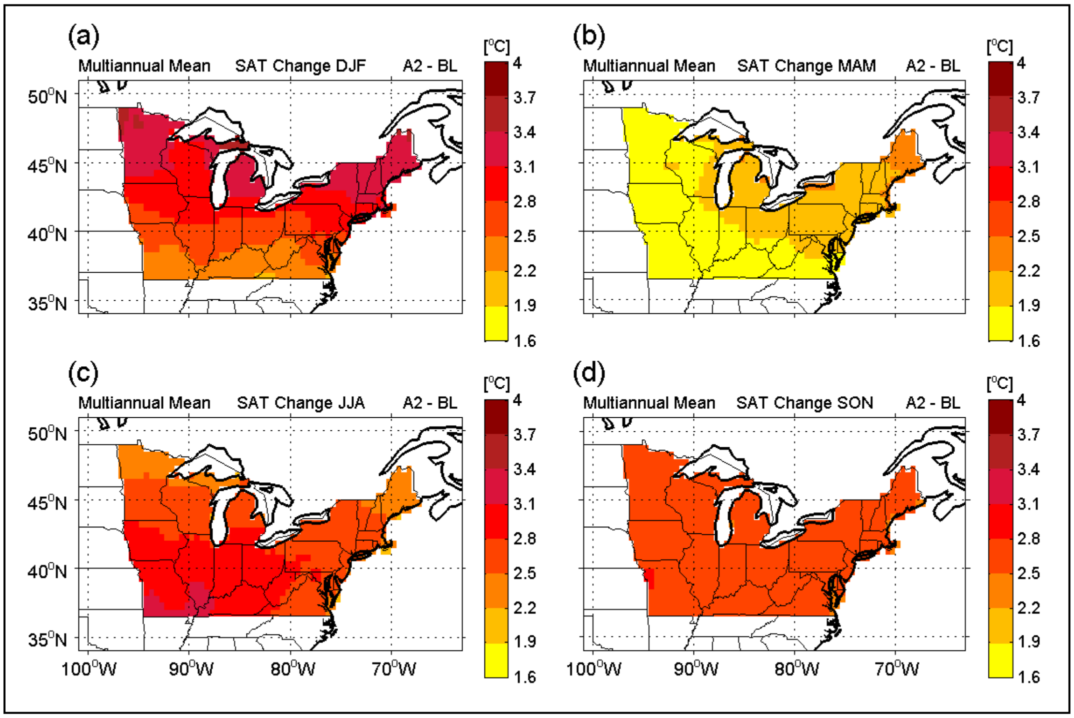


Figure 3: Projected warming across the NE CSC region by season: (a) winter (December, January, and February), (b) spring (March, April, and May), (c) summer (June, July, and August), and (d) autumn (September, October, and November). Values represent the differences between the 1979 – 2004 and 2041 – 2070 average temperatures for each season. Multi-model means from the North American Regional Climate Change Assessment Program (NARCCAP), based on a high emissions scenario, are used (Data and map for Northeast published by Rawlins et al. (2012); maps extended by F. Fan, written communication).

Heatwaves may become more frequent, more intense, and last longer.

Anthropogenic warming has led to more extreme heat events globally (Fischer & Knutti 2015). However, several studies point to a distinct "warming hole" over the past half century across the eastern U.S., where the number of warm days have been either stagnant or slightly decreasing (Alexander et al. 2006; Perkins et al. 2012; Donat et al. 2013). In addition, linear trends over the past half century indicate more cool days, albeit slight. While daytime extremes show cooler trends, nights have been getting warmer, with fewer cold nights and more warm nights. Long warm spells early in the spring season are particularly threatening to vegetation as such spells can trigger premature leaf-out and flowering (Cannell & Smith 1986; Inouye 2000), leaving the plant vulnerable to frost damage later in the season. Frost damage can affect the overall productivity of the plant for the entire growing season (Gu et al. 2008; Hufkens et al. 2012). However, recent analyses of trends over the past century indicate the last spring freeze is getting earlier at a faster rate than leaf-out, suggesting that damaging late-season spring freezes are becoming less likely (Peterson & Abatzoglou 2014).

Heatwave intensity, frequency, and duration are expected to increase over the U.S. in the 21st century, with the greatest increases projected toward the southwest portion of the Northeast and Midwest region (Meehl & Tebaldi 2004). Fewer cold days and nights, and more warm days and nights are expected over the next century (Sillman et al. 2013; Ning et al. 2015). Southern states in the region are projected to experience more additional warm days (days with maximum temperatures exceeding 90th percentile) than northern states, although the Great Lakes region is likely to see the greatest reductions in cold days (days with maximum temperatures below 10th percentile; Ning et al. 2015). The greatest increases in nighttime minimum temperatures are expected for inland areas and areas at higher latitudes due to reduced snow cover associated with warmer winters (Sillman et al. 2013; Thibeault & Seth 2014). The minimum temperature on the coldest night of the year is expected to increase by 11 °C by the end of the century from the Great Lakes northward, more than triple the expected increase for areas south of the Great Lakes (Sillman et al. 2013). Projected increases in the daily maximum temperatures are generally greatest inland (Sillman et al. 2013), with the exception of major urban centers along the coast due to heat island effects (Thibeault & Seth 2014). Higher elevations are also likely to see larger increases in the summer daily maximum temperatures, though past observations suggest greater increases in daily minimum temperatures (Diaz & Bradley 1997; Pepin & Lundquist 2008; Diaz et al. 2014; Thibeault & Seth 2014; Pepin et al. 2015). An increase in the inter-annual variability (in addition to the frequency) of extremes heat events is also anticipated under future climate (Ning et al. 2015).

B) PRECIPITATION

Annual precipitation is increasing, particularly in winter, though with less certainty in future projections than with temperature.

Annual total precipitation has increased over the past century on a global scale (Zhang et al. 2007). In the Midwest and Northeast, the last two decades (1991-2012) were wetter than the first 60 years of the twentieth century by about 10-15% (Walsh et al. 2014). According to a dense network of station observations from the National Climatic Data Center (NCDC), annual precipitation amounts across the NE CSC region have increased at a rate of over 1 inch per decade since 1895, with the greatest increases of nearly 2.5 inches per decade in Maine (NCDC 2015).

Over the next century, overall annual precipitation amounts are expected to increase over the NE CSC region (Schoof 2015), largely due to greater intensity in precipitation events (Thibeault & Seth 2014; see below). Further, precipitation events are expected to become less frequent (i.e., more consecutive dry days, or extreme dry spells), but last longer (i.e., more persistent; Schoof 2015; Guilbert et al. 2015). Heavy rainfall events occurring at a reduced frequency raises the risk for both flooding and drought (Horton et al. 2014).

Projections consistently predict wetter winters (**Figure 4**; Hayhoe et al. 2007; Rawlins et al. 2012; Kunkel 2013; Alder & Hostetler 2013; Schoof 2015), though with more rain than snow. Drier summers are projected, particularly for the southern Midwest, with some areas seeing little change or some increasing. Rainfall events in the summer are anticipated to become more intense and shorter with longer dry periods between events, hence little change in the seasonal total. More frequent severe thunderstorm activity may mean more frequent hail events in summer (Gensini & Mote 2015). In the Northeast, precipitation may become more persistent in summer and more intense in winter (Guilbert et al. 2015). For spring and fall, model projections agree on small positive changes in the Northeast, which are significant over much of the region in spring and within the level of natural variability in the fall (Rawlins et al. 2012).

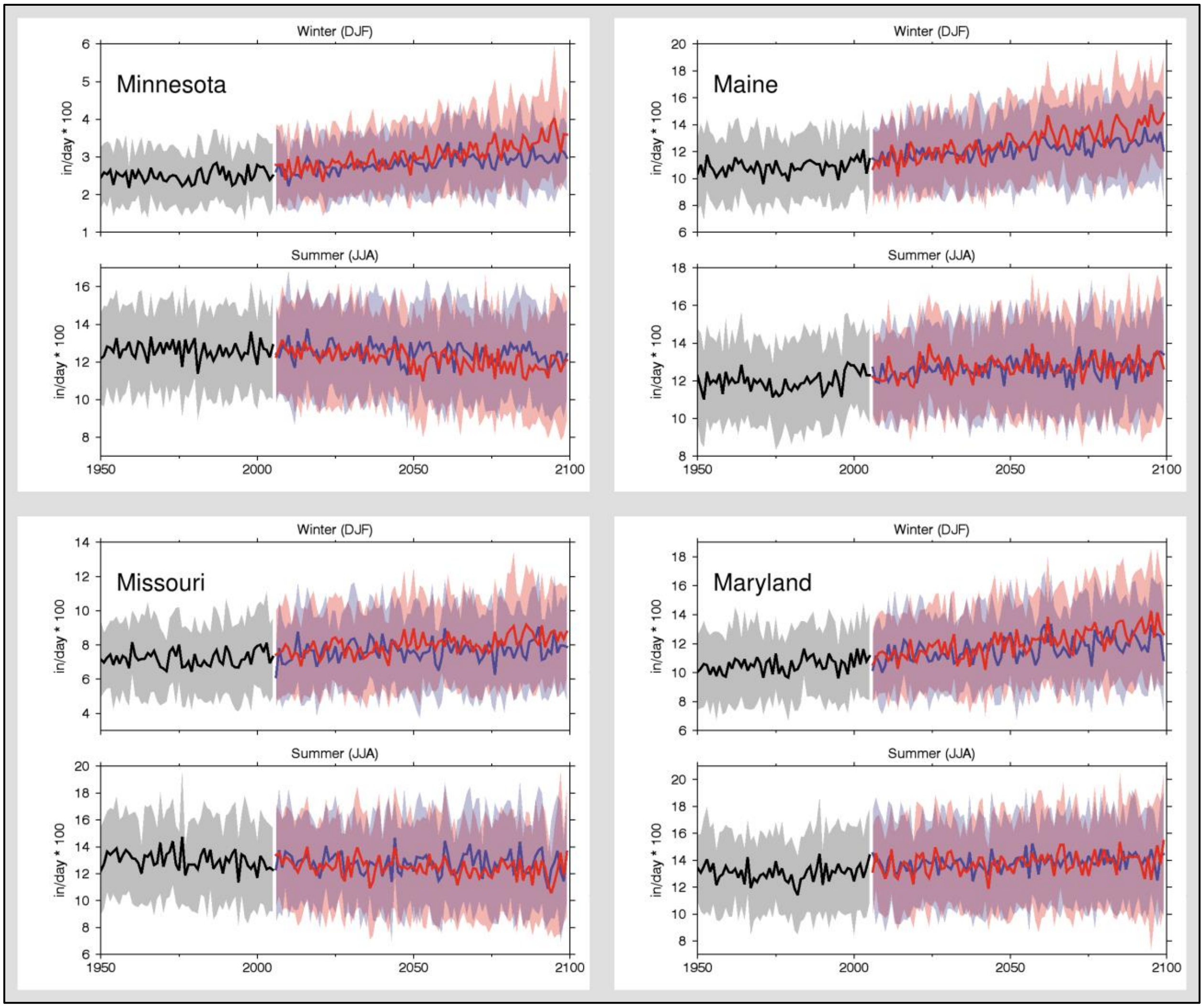


Figure 4: Simulated trends in winter (December, January, and February) and summer (June, July, and August) average precipitation, courtesy of the USGS National Climate Change Viewer (Alder & Hostetler 2013). Both historical (black line with grey shading) and projected (colored lines and shading) trends derive from the NASA NEX-DCP30 data set (Thrasher et al. 2013), which includes 33 GCMs downscaled to 800 meters. The solid line represents the mean of the 33 models, and the shading represents the range of one standard deviation. The red and blue curves represent the high and low emissions scenarios, respectively.

Changes in seasonal precipitation amounts vary regionally (**Figure 5**). Wetter conditions are projected for the Northeast and Midwest in winter, spring, and fall, with significant drying projected for the southern Midwest in summer. However, some projections show significant summertime drying in the upper Great Plains, as well, over the next century (Swain & Hayhoe 2015). In spring and fall, the largest increases are in the northern Midwest. Winter increases do not show a distinct regional gradient. We emphasize, however, the lack of confidence in the regional distribution of precipitation, as discussed below (Collins et al. 2013).

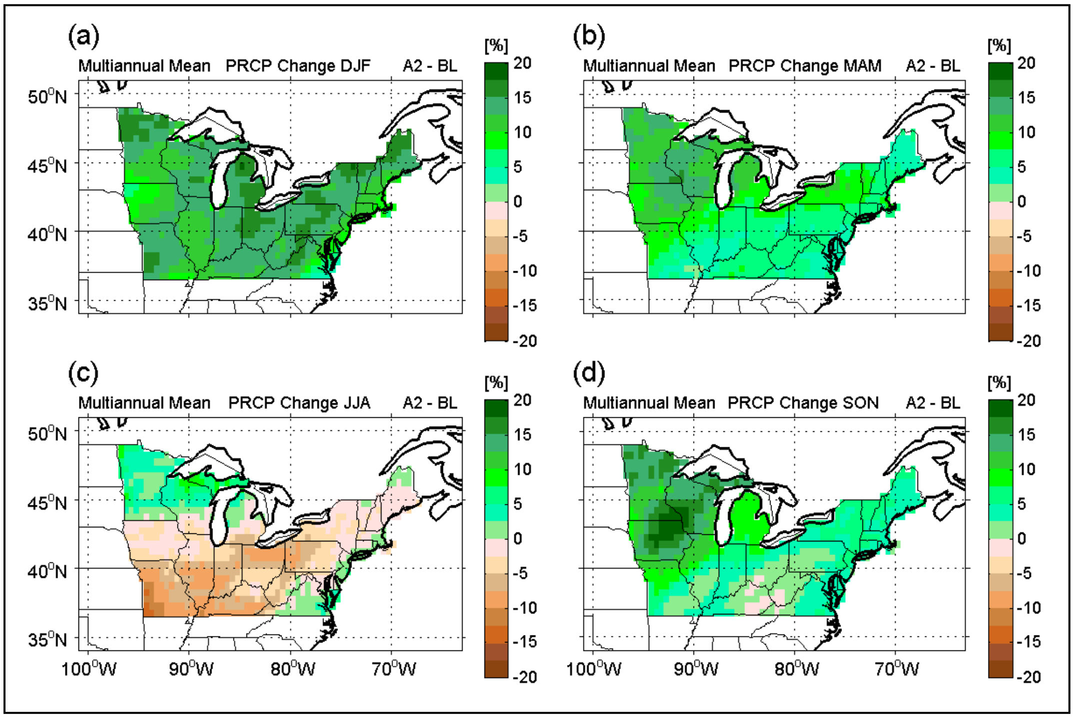


Figure 5: Projected precipitation changes across the NE CSC region by season: (a) winter (December, January, and February), (b) spring (March, April, and May), (c) summer (June, July, and August), and (d) autumn (September, October, and November). Percent change is calculated as (future – baseline) / (baseline) × 100% between the 1979 – 2004 and 2041 – 2070 average precipitation for each season. Multi-model means from the North American Regional Climate Change Assessment Program (NARCCAP), based on a high emissions scenario, are used (Data and map for Northeast published by Rawlins et al. (2012); maps extended by F. Fan, written communication).

Projections of changes in precipitation patterns are less robust than for temperature (Hawkins & Sutton 2011; Collins et al. 2013; Knutti & Sedláček 2013), particularly with respect to annual and seasonal totals (**Figure 4**). Not all models agree on the sign of the change for certain sub-regional averages. Part of the discrepancy comes down to challenges simulating cloud formation and convection due to the complex nature of these processes and difficulties representing them in the model. Additionally, not all models adequately capture large-scale climatic drivers of precipitation in the region, such as the Great Plains low-level jet or lake-effect precipitation. Consequently, models vary widely in the placement of precipitation maxima and minima. Therefore, planners should use caution when interpreting spatial distributions of precipitation in future projections. While one model may show more rainfall in one part of a state over another, another model may show the reverse. In conclusion, at present model projections are insufficiently reliable to be able to identify which part of a state or region may experience the most or least precipitation in the future.

Heavy rainfall events are intensifying, particularly in the Northeast.

The Northeast and Midwest have seen a pronounced increase in the frequency and intensity of extreme precipitation events in the past several decades (Groisman et al. 2005; 2013; Kunkel 2013; Schoof 2015; Guilbert et al. 2015), a trend which appears robustly simulated by the latest suite of GCMs (Scoccimarro et al. 2013; Toreti et al. 2013; Kendon et al. 2014; Wuebbles et al. 2014). Anthropogenic climate change is almost certainly a contributor of heavier precipitation events (Min et al. 2011; Fischer & Knutti 2015). The Northeast has seen the largest increases in heavy precipitation events over the rest of the country (a 74% increase in the heaviest 1% of all events since 1958; Groisman et al. 2013), with increases as high as 240% in the Connecticut River basin over the past 60 years (Parr & Wang 2014). Increases in the Midwest states are the second highest in the country at 46% (Groisman et al. 2013). The amount of rainfall falling in very heavy precipitation events in these states has increased by more than 20-30% in recent decades relative to 1901-1960 average. Over 30% of annual total precipitation at most stations in the Midwest occurs during the ten wettest days of the year. Therefore, changes in the magnitude and frequency of extreme precipitation events are of great importance.

Over the region as a whole, the occurrence of these intense precipitation events has risen substantially in recent decades. For example, the number of 24-hour storms with a 20% chance of occurrence in a given year has increased by about 4% per decade since the beginning of the 20th century. About 85% of the events occur during the warm season period of May through September. About 90% of the annual trend is due to increases during this warm season period. In other words, what would be expected to be a 100-year event based on 1950-1979 data occurs with an average return interval of 60 years when data from the 1978-2007 period are considered (DeGaetano 2009). Similarly, the amount of rain that constituted a 50-year event during 1950- 1979 is expected to occur on average once every 30 years based on the more recent data.

Intensity increases are projected for all seasons (Toreti et al. 2013), at a rate faster than the increase in annual mean precipitation (Kharin et al. 2013). The greatest increase in the number of heavy precipitation events are projected for northern latitudes, higher elevations, and coastal areas (Thibeault & Seth 2014). The Northeast, particularly along the Atlantic coast and Appalachians, should see the largest increase in number, intensity, and inter-annual variability of extreme precipitation events (Ning et al. 2015). Total wet-day precipitation amounts and the number of days with precipitation greater than 10mm are projected to increase in the Northeast, with models agreeing on the sign of the change (Sillman et al. 2013).

Less snow expected as events occur less frequently and shift to rain, though more intense snowfall events may lead to local increases in snowpack and totals.

Snowfall trends in response to climate change are complex and vary regionally. Climatic warming is resulting in a shift from snow to rain, leading to decreases in snow. However, areas that will remain cold enough for snow (e.g., northern latitudes and high elevations) may see localized increases in snowfall due to more intense precipitation events. For instance, lake-effect snow has increased in recent decades over the Great Lakes states due to warmer lake waters (Andresen et al. 2012) and is projected to continue to increase, particularly over Lake Superior where temperatures are likely to remain cold enough for snow (Notaro et al. 2015; see Great Lakes section below). In addition, increases in the amplitude of the jet stream in winter may have led to the observed increases in winter storms affecting the southeastern United States (Thompson et al. 2013).

Snowpacks are thinning and melting earlier, and thus shorter lived; the snowline may be retreating northward and upslope.

Climatic warming is expected to reduce snowpack depth across the Northeast and Midwest and lead to earlier snow melt (Mahanama et al. 2012). Climate projections for the 21st century indicate decreases in snow depth and the number of days with snow cover, as have already been observed (Hayhoe et al. 2007). Snow cover retreat is projected to occur earlier, shifting from spring to winter (Pierce & Cayan 2013; Maloney et al. 2014). Observed reductions in snow cover extent over the 2008 – 2012 period exceeded the decrease predicted by global climate model projections (Derksen and Brown 2012).

Snowpack textures may harden more often in many areas.

Some studies have observed changes in snow quality and characteristics of the snow pack, namely harder, crustier snow conditions (Klein et al. 2005; Chen et al. 2013). As the climate warms, temperatures are likely to cross above the freezing line more often during the winter. This will lead to more rain and freezing rain events, which alter the quality of the existing snowpack when the rain freezes upon the snow, resulting in an ice-like texture.

C) ATMOSPHERIC MOISTURE

More atmospheric moisture, higher cloud bases, and more frequent fog events are expected.

Climatic warming will increase the capacity of the atmosphere to hold water, yet future projections do not show substantial change in relative humidity. This implies that the amount of atmospheric water vapor will increase with warming temperatures in order to maintain a constant relative humidity (Shi & Durran 2014). There is some evidence that cloud base heights have increased in the northeast over the last 30 years (Richardson et al. 2003) and that fog cover has become more frequent in spring and fall on Mt. Washington in New Hampshire (1934-2004; Seidel et al. 2007).

D) WIND

Wind speeds are declining, though stronger wind gusts are possible.

Winds can be described in terms of sustained winds (long-lasting winds that occur in the background with little fluctuation over time) and wind gusts (short bursts of high-speed winds). Past observations and future projections both indicate decreases in overall wind speed (sustained plus gusts) under climate change cross the country (Pilson 2008; Pryor et al. 2009; 2012). Modeling studies over the continental U.S. indicate no change in extreme wind events with climate change (Pryor et al. 2012). However, one modeling study simulating Ontario, Canada, projected increases in the number of 45-mph wind gusts by up to 20-30% (Cheng et al. 2014). High winds often accompany severe weather, such as thunderstorms, tornadoes, and hurricanes, which are expected to increase in intensity with climate change (Holland & Bruyère 2014; Gensini & Mote 2015; see **Section F**) .

E) SURFACE HYDROLOGY

This section discusses changes in hydrology on the terrestrial surface (e.g., soil moisture, evapotranspiration, streamflow and temperature, surface runoff, and groundwater levels). Changes in hydrology pertaining to the Atlantic Ocean and Great Lakes are discussed in later sections.

Soil moisture trends are uncertain.

Observations over the Connecticut River Basin indicate wetter soils since 1950 due to more extreme precipitation events (Parr & Wang 2014). However, many habitats across the U.S. are predicted to experience net drying during the next 50 years, even in areas where precipitation is predicted to increase (Brooks 2009; Wuebbles et al. 2014). Trends in soil moisture are difficult to predict given that rainfall events are both becoming less frequent (suggesting drier soils), yet more intense and longer lasting (suggesting wetter soils). The Northeast and Midwest are especially problematic given that the increases in annual precipitation and heavy precipitation events predicted for them are stronger than any other region in the country.

Evapotranspiration rates are also inconclusive.

Many studies indicate increasing trends in evapotranspiration as the climate warms and is thus able to contain more water vapor, and as precipitation increases moisture availability (Hayhoe et al. 2007; Wuebbles et al. 2014; Pan et al. 2015). Some trends in the Northeast are statistically significant (Hayhoe et al. 2007). However, there is generally a lot of uncertainty about how the hydrologic environment will shift and impact evapotranspiration rates. There is also debate as to whether precipitation increases or decreases will feed back to increased evapotranspiration (Abtew & Melesse 2013; Wuebbles et al. 2014). Higher carbon dioxide concentrations may lead plants to close their stomata, resulting in less transpiration, whereas increased leaf temperature increases transpiration rates. No trend has been seen in evapotranspiration measurements in the Connecticut River Basin since 1950 (Parr & Wang 2014), though there appears to be wide spatial variability in trends (Abtew & Melesse 2013).

Streamflow is intensifying, but varies by season and sub-region, and is not proportional to increases in extreme rainfall.

Climate change will have significant impacts on the flows of rivers and streams throughout the Northeast and Midwest. The most direct sources of these changes are projected shifts in temperature, rainfall, and evapotranspiration. These changes are unlikely to be uniform across the region and will be altered by the specific characteristics of the individual basins. Basin characteristics that are very likely to have particular impacts include the basin's vegetation, degree of urbanization, underlying geology, longitude, latitude, elevation, the contribution of groundwater, and basin slope.

Annual flows have increased during the last part of the 20th century in the Northeast (Collins 2009; Hodgkins et al. 2005; McCabe & Wolock 2011). However, despite recent intensification of precipitation events, observed maximum annual flows have not increased (Douglas et al. 2000; Lins & Slack 1999; 2005; Villarini & Smith 2010; Villarini et al. 2011). More precipitation during the summer in New England and during the fall in the upper Mississippi basin and upper Midwest have been linked to positive trends in low flows linked to groundwater contribution (Hodgkins et al. 2005; Small et al. 2006). Low flows play a crucial role in maintaining aquatic ecosystems since they provide a minimum flow during the warm summer months and control stream water temperatures.

Step changes in the mean and variance of observed mean and minimum annual streamflows around the year 1970 have been documented for the continental U.S. by McCabe & Wolock (2002). Similarly, step changes in maximum annual values were identified around the same time in 23 (out of 28) basins in New England and attributed to the natural variability of the North Atlantic Oscillation (Collins 2009). Conversely, step changes in the mean and variance of flood peaks were observed in 27% and 40% of the stations in the Eastern and Midwest states, respectively, and linked to changes in land use-land cover practices in the region and not to external climatic conditions (Villarini & Smith 2010; Villarini et al. 2011).

Projected warmer summers along with reduced precipitation may impact soil moisture conditions in the region if evapotranspiration increases. Additionally, diminished groundwater reserves, linked to declining snow pack, will impact base flows in streams (Hayhoe et al. 2008).

Earlier winter-spring peak flows in the range of 6-8 days have also been observed in the Northeast and Midwest and thought to be linked to increased snowmelt and rain-on-snow episodes (Hodgkins & Dudley 2006). This trend is projected to continue during the 21st century (Campbell et al. 2011). A shift toward higher winter flows and lower spring flows has been documented for two Northeastern watersheds (Connecticut River Basin, and a small forest site in New Hampshire) using climate-driven streamflow simulations (Campbell et al. 2011; Marshall & Randhir 2008). Changes in the timing and the magnitude of spring snowmelt in eastern U.S. are crucial to maintain ecosystem functions since some aquatic species rely on the time and volume of streamflows for vital life cycle transitions (Comte et al. 2013; Hayhoe et al. 2007). Larger peak flows can contribute to increases in river scour magnitude and frequency and affect egg burial depths of some salmon species (Goode et al. 2013). Additionally, larger flow velocities in river channels can impede the natural displacement of some small fish (Nislow & Armstrong 2012).

Stream temperatures are rising.

Warming has been observed in many streams across the continent (Webb 1996; Bartholow 2005), as also seen in future projections (Mohseni et al. 1999). Warming stream temperatures seem to be more a function of warmer nights than warmer days or daily averages (Diabat et al. 2013).

F) EXTREME EVENTS

Severe thunderstorms may become more severe, whereas tornadoes may decrease in annual number and increase in daily number.

Only a few studies have attempted to examine observed and projected trends in severe weather, and with much difficulty due to a limited observational record and inconsistent metrics to describe weather events (e.g., structural damage, storm reports; Walsh et al. 2014). Studies reporting reliable estimates in observed trends in severe thunderstorm activity could not be located. One study reported increases in damage costs from storms over recent decades; however, this trend was not statistically significant and may owe more to population and wealth increases than severe activity (Kunkel 2013). The number of tornadoes per year has not changed since 1970; however, one study found that the number of days with tornadoes is decreasing while the number of tornadoes per day is increasing (Brooks et al. 2014). Some studies suggest that climatic warming may increase the frequency of severe storms (Del Genio et al. 2007). Some future projections indicate an increase in the occurrence of hazardous events, such as tornadoes, damaging wind, and hail (Gensini & Mote 2015), with the greatest increases estimated for the Great Plains in March, and southern Illinois and Indiana in April. Brooks (2013) projected more severe thunderstorms due to increased available convective energy, though lower probability of tornadoes due to decreased wind shear. Little change in severe activity is projected for the Northeast; however, trends show an increase in Atlantic hurricanes making landfall in the northern coastal states (see U.S. Atlantic Coast section below).

Floods are becoming more intense.

Increasing trends in floods have been observed in the Northeast and the Midwest, associated with increases in annual precipitation (Peterson et al. 2013; Wuebbles et al. 2014). Across the United States, the NE CSC region is most susceptible to increases in flood events (Wuebbles et al. 2014). It is expected that overall annual precipitation totals will increase over the Northeast region throughout the century, but that precipitation events will become less frequent. As a consequence, the events that do occur are projected to be more intense, raising the risk for both flooding and drought (Horton et al. 2014).

Droughts are becoming more frequent.

The average number of consecutive dry days over the region is projected to increase by 1-5 additional days (Sillman et al. 2013; Ning et al. 2015), suggesting a potential increase in drought frequency. However, simultaneous increases in annual precipitation (Schoof 2015), particularly extreme rain events, may help minimize the severity of droughts. Thus, statistically significant increases in the frequency of short-term (lasting 1-3 months) droughts are projected with minimal threat of increased long-term droughts (Hayhoe et al. 2007).

More frequent droughts are expected in the future for all states in the Northeast and Midwest. Maine, New Hampshire, Vermont, western Massachusetts, Connecticut, Rhode Island, and the Adirondacks may see the greatest increases in short-term (lasting 1-3 months) droughts (one every year, up from one every 2-3 years), while more long-term (lasting 6+ months) droughts are expected predominantly in western New York. We note again, however, that projections are not very reliable at capturing regional distributions in precipitation, and that long-term trends in drought events have yet to be observed (Hayhoe et al. 2007; Karl et al. 2012). In fact, droughts may be occurring less frequently than in the past in the Northeast (Peterson et al. 2013) due to amplifications in precipitation, particularly in extreme events. Nonetheless, warming and less frequent precipitation events favor an increase in drought intensity.

Blizzards and ice storms are occurring more frequently.

Severe snow and ice storms have more than doubled over the last 55 years relative to the previous 60 years (Kunkel 2013). This suggests that, while most areas are seeing reduced snow pack due to warming and shifts in precipitation from snow to rain, some localized areas that experience severe storms may exhibit an increase in annual total snowfall.

G) BIOLOGICAL INDICES

Growing seasons are getting longer.

Growing season length is generally defined as the number of days between the dates of the last spring frost and the first autumn frost. Frosts occur when the minimum daily temperature drops below freezing (32 °F). Over the entire time period of 1895-2011, there is a statistically significant upward trend in freeze-free season length in the Northeast (Hayhoe et al. 2007; Kunkel 2013), indicative of shorter winters and longer summers. The average freeze-free season length in the Northeast during 1991-2010 was about 10 days longer than during 1961-1990 (Kunkel 2013). The average date of the last frost in spring has been getting earlier each year, and the date of the first frost in autumn has been getting later across the Northeast (Hayhoe et al. 2007), though the magnitude of change varies spatially. In Vermont over the past half century, the average date of the last spring freeze has been getting earlier by 2.3 days every decade, while the first autumn freeze has gotten later by only 1.5 days per decade (Betts 2011). This finding suggests the impact of climate change is greatest during the early growing season when vegetation is most vulnerable to extreme climate (e.g., extreme heat and cold, drought). For example, late-season spring freezes following an early leaf-out can damage leaves and decrease their productivity for the remainder of the warm season (Norby et al. 2003; Inouye 2008; Gu et al. 2008; Martin et al. 2010; Hufkens et al. 2012). While the average date of the last spring freeze is getting earlier, fluctuations in temperature in a given season are getting wider (Rigby & Porporato 2008; Augspurger 2013), implying that climate change is likely to result in more frequent frost damage on plants.

Projections show continued lengthening of the freeze-free season across the Northeast by at least 19 days by 2055 relative to 1980-2000 for the high emissions scenario (Kunkel 2013). By the end of the century, the growing season may lengthen by as much as 1-2 months depending on the emissions scenario (Hayhoe et al. 2007; Ning et al. 2015). In the Midwest, increases of up to 26 more days in the length of the annual freeze-free season are simulated across most of the Midwest by 2055 relative to 1980-2000 for the high emissions scenario (Kunkel 2013). Anticipated increases are greatest from 40-50 °N, the latitude band covering the Great Lakes region, and along the Appalachian Mountains (**Figure 6**).

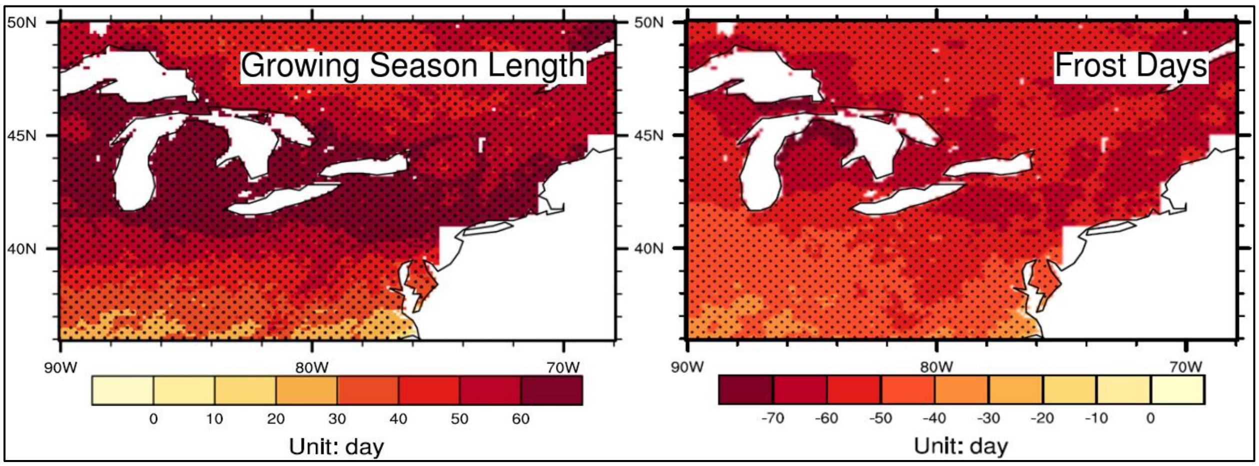


Figure 6: Change in the number of days in the growing season (left) and number of frost days (right) by the end of century (2050-2099) relative to the 1950-1999 average, following a "business-as-usual" greenhouse gas emissions scenario (Used with permission from Ning et al. 2015).

More growing degree days are expected.

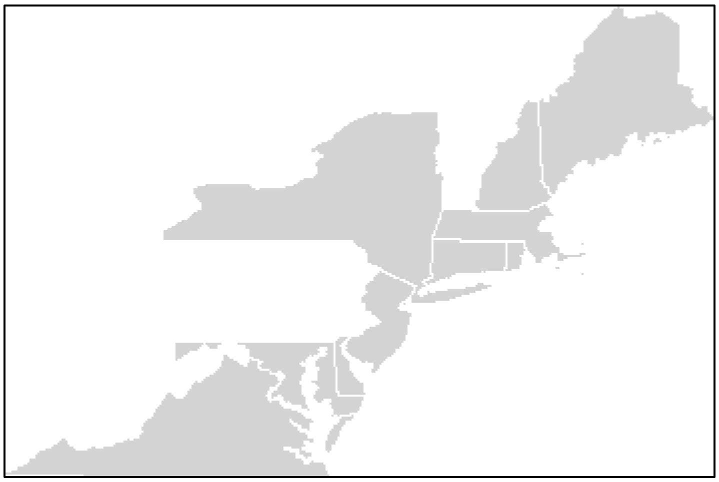
Growing degree days (GDD) is an index that is used to estimate the timing of certain events in the phenology of plants and animals, such as leaf-out and pest invasions. GDD for a given day is the average of the daily minimum and maximum temperature minus some base temperature above which biological events (e.g., blooming, leaf-out) are triggered. For example, a high of 70 °F and a low of 40 °F with a base temperature of 50 °F indicate a daily yield of 5 GDDs. An average temperature below the base temperature yields 0 GDDs. GDDs are additive, and so they accumulate day after day throughout the growing season. GDDs begin accumulating on March 1 each year. GDDs eventually reach a certain threshold that has biological significance. Though the base temperature varies by species, a standard reference temperature (often either 50 °F or 65 °F) is generally used in weather reports. Projections estimate an increase in GDD of over 32-33% and 35-41% in the Midwest and Northeast, respectively, over the next half century, with strong agreement among the models (Kunkel 2013). More important than the increase in GDD is the shift in timing of when GDD becomes large enough to trigger certain events. As the climate warms, the date at which GDD begins accumulating is very likely to be earlier. This may provide opportunities for some warm climate vegetation while negatively impacting cold-adapted species.

Winters are becoming less severe.

The Winter Severity Index (WSI) is a measure of the combined influence of the intensity and duration of severe cold and snow cover (Notaro et al. 2014). This indicator is a useful metric for tracking wildlife populations (e.g., deer expansion or waterfowl migration). For instance, Schummer et al. (2010) found that southward migration of ducks generally begins when WSI exceeds 7.2. Notaro et al. (2014) estimate a 20-40% decrease in the probability of a 7.2 or greater WSI in December across the Northeast and Midwest, suggesting that waterfowl migration may occur later in the winter. Changing WSI patterns are largely attributed to a 40-50% decrease in snowfall. Severe winters, with heavy snow and extreme cold, also negatively impact deer (Verme 1968), and thus deer populations and some other wildlife populations are likely to expand northward as decreases in WSI allow regions that were unsuitable for deer to become suitable.

IV. SUB-REGIONAL ANALYSES

A) U.S. ATLANTIC COAST



Sea level is rising at an accelerating rate.

The coastal region of the Northeast has high, and growing, vulnerability to coastal flooding (Horton et al. 2014). It combines low slope coastal areas, especially in southern parts of the region, with the potential for faster regional sea level rise than the global average (Yin et al. 2009). While global sea levels have risen by about 8 inches since 1900, much of the Northeast has experienced approximately 1 foot, whereas the Mid-Atlantic states have experienced approximately 1.5 feet during that same time period (Horton et al. 2014) of sea level rise. Sea level rise threatens coastal environments, through more frequent coastal erosion, flooding, and salt water intrusion (Kane et al. 2015), as well as more severe flooding during storms (Horton et al. 2014). Storms are likely to become more destructive in the future as sea level rise contributes to higher storm surges (Anthes et al. 2006).

Sea level rise is uniquely threatening to the U.S. Atlantic coast, both due to the more rapid than average rate of increase expected in the area as well as the particular vulnerability of developed coastal areas, including New York City (NYC). Sea level rise is much less responsive to emissions reductions than temperature (Solomon et al. 2009); therefore, even under an aggressive climate change mitigation policy, sea level will continue to rise for the rest of the 21st century and beyond. Due to the near certainty of continued sea level rise, coastal adaptation is essential if society is to prevent increasing damage from flooding events.

Sea level rise is projected to accelerate in the future. By mid-century, much of the region could see between 8 inches and 2.5 feet of sea level rise relative to 2000-2004 levels; by the end of the century, anywhere between 1.5 and 6 feet of sea level rise is possible (Collins et al. 2013; Horton et al. 2015). While the worst case projections would require rapid acceleration of land-based ice melt in Greenland and West Antarctica, such rapid melting cannot be ruled out (Joughin et al. 2014). Faster-than-expected slowdown in the Atlantic meridional overturning circulation also contributes to high-end projections in sea level rise (Rahmstorf et al. 2015). Even at the mid-range of the projections for late in the century—say 2.5 feet—coastal flood frequency would increase dramatically, even if storms remain unchanged. In the NYC region, for example, the current 1 in 100 year flood level could become a 1 in 20 year event under such a sea level scenario (Horton et al. 2015). We note high uncertainties in projections of the magnitude of future sea level rise, particularly in the high emissions scenario. However, there is no uncertainty that the sea level has risen and will continue to rise.

Coastal storms, such as tropical cyclones, hurricanes, and Nor'easters, may be intensifying.

Changes in the frequency and intensity of tropical cyclones (warm season coastal storms) or Nor'easters (cool/cold season coastal storms) would modify coastal flood risks. The balance of evidence suggests that the strongest tropical cyclones may become more intense due to climate change and warming of the upper oceans (Knutson et al. 2010; Christensen et al. 2013), as has already been observed over the past 40-45 years (Emanuel 2005; Webster et al. 2005). In addition, tropical cyclones may track further north toward the poles over the course of the 21st century (Yin 2005). However, confidence in how tropical cyclones may change is relatively low, due to high natural variability, short observed record, and uncertainty in how other climate variables that are important for tropical cyclones may change (e.g., wind shear, vertical temperature gradients in the atmosphere, and warming in the tropical Atlantic ocean relative to the tropical oceans as a whole). Hurricane intensity is also projected to increase (Emanuel et al. 2008; Ting et al. 2015). It is also unclear how Nor'easters may change (Horton et al. 2015), although some research suggests growing risk for the northern-most parts of the U.S. Atlantic coast, and decreasing risk for southern parts (Colle et al. 2010).

While it is unclear exactly how storms may change in the future, it is certain that our coasts are highly vulnerable today. Sea level rise, even at the low end of the projections, are very likely to dramatically increase flood risk. It should be noted that sea level rise impacts can penetrate far inland in our tidal estuaries. Saltwater intrusion into coastal ecosystems and aquifers are very likely to be an issue of increasing concern. Furthermore, in low lying areas, rainfall flooding may become worse due not only to heavier rain events, but because high sea levels will reduce drainage to the ocean (Horton et al. 2014). This may enhance pollution issues, especially in (formerly) industrial sites.

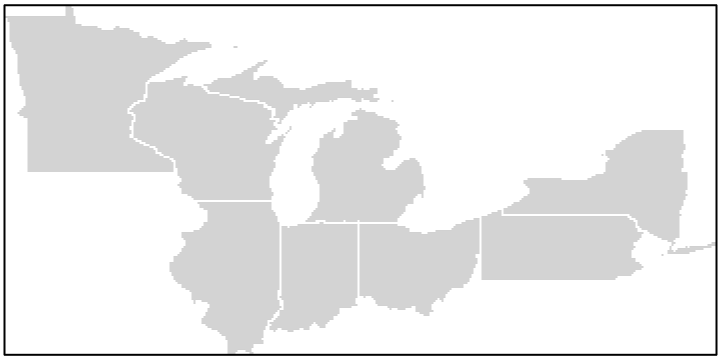
Oceans are warming.

Warming of the ocean waters has been observed in recent decades, with many of the records collected within the last 10 years (Mann & Emanuel 2006; Holland & Webster 2007; Domingues et al. 2008; Rhein et al. 2013). This suggests a direct link with anthropogenic climate change. Changes in coastal water ecology have been observed along the northern Atlantic coast (Oviatt 2004; Nixon et al. 2009). Other examples of how warming ocean waters will impact marine species and ecosystems are presented in **Chapter 3**.

The ocean is becoming more acidic.

With more carbon in the atmosphere from human activity (Sabine et al. 2004), and thus greater absorption of carbon by the Earth’s oceans (Feely et al. 2004; Canadell et al. 2007; Cooley & Doney 2009), the oceans and coastal waters are becoming more acidic (Walsh et al. 2014). The pH level of the oceans and coastal waters will continue to drop as atmospheric carbon continues to rise (Rhein et al. 2013). Ocean acidity has not changed in the last 300 million years with the exception of a few rare events (Caldeira & Wickett 2003), highlighting the impact of recent anthropogenic climate change. More importantly, these changes in ocean acidity are irreversible over the next several thousand years and thus will have prolonged impacts on marine and aquatic ecosystems.

B) GREAT LAKES



Like other parts of the NE CSC region, warmer conditions and more extreme temperature and precipitation events are expected for the Great Lakes basin (Bartolai et al. 2015). However, there are a number of changes that specifically impact the states that are adjacent to the lakes.

The lakes are warming.

Warming of water in the Great Lakes has already been observed (McCormick & Fahnenstiel 1999; Jones et al. 2006; Austin & Colman 2007; Dobiesz & Lester 2009), and is expected to continue (Trumpickas et al. 2009; Music et al. 2015). Observations indicate warming by 1-3 °C over the past 40 years (Dobiesz & Lester 2009). Lake Erie is warming, but at a slower rate than the other lakes (Dobiesz & Lester 2009). Lake temperatures are warming faster than surrounding air due to reductions in ice cover (Austin & Colman 2007). Given the influence of the lakes on regional climate, particularly their role in moderating air temperatures (Notaro et al. 2013), warming of the Great Lakes is very likely to lead to warmer air over the surrounding landscape compared to areas far away from the lakes. Since ice cover reduces the ability of the lakes to regulate temperatures, reductions in ice cover due to warmer lake temperatures may lead to faster warming of air temperatures immediately surrounding the lakes than other parts of the adjacent states.

Lake ice is decreasing in areal extent.

Long-term decreases in ice cover extent have already been observed (Assel 2005; Austin & Colman 2007; Wang et al. 2012; Bartolai et al. 2015) and are likely to continue to decline dramatically as a result of long-term climatic warming (Notaro et al. 2015). Ice cover extent varies interannually associated with the phases of large-scale climatic phenomena, such as the El Niño/La Niña cycle (Bai et al. 2015). Specifically, low ice cover tends to occur under strong positive phases of the North Atlantic Oscillation (NAO) and the La Niña phase of the El Niño-Southern Oscillation pattern. It is uncertain how climate change will impact these oceanic oscillations, let alone their influence on Great Lakes ice cover.

Lake evaporation rates are increasing.

Lake ice acts as a barrier that inhibits evaporation from the lakes. As ice cover extent decreases and waters warm, enhancements in lake evaporation are expected. Increases in lake evaporation rates have already been observed over the past 50 years due to warmer waters and decreasing ice coverage (Gronewold et al. 2013). Future projections anticipate continued increases in evaporation from the lakes as ice cover extent continues to decrease (Notaro et al. 2015). Due to the enormous size of the lakes and the ability of water to store heat, lake temperatures, and thus evaporation rates, have an offset seasonal cycle relative to land surface temperatures and evapotranspiration (Bryan et al. 2015). Specifically, most lake evaporation tends to occur in the winter when waters heated from the previous summer are much warmer than the overlying air. Accordingly, warmer lakes under a changing climate may lead to proportionally greater enhancement of evaporation in the winter season.

Lake-effect snow events are likely to shift to rain, become more severe, last longer, but occur less often.

During winter lake-effect snow is driven by intense evaporation from the lakes which occurs when lake waters are significantly warmer (by 13 °C or more, typically) than the overlying air (Wright et al. 2013). As lake waters warm, this temperature gradient between the lake and air may become stronger, leading to shifts in lake-effect snow. Ice cover inhibits lake-effect snow (Vavrus et al. 2013; Wright et al. 2013), so decreases in ice cover extent may also contribute to more intense lake-effect snow events. Given projected increases in future global temperature, areas downwind of the Great Lakes may experience increased lake-effect snowfall for the foreseeable future.

Lake-effect snow has been observed to increase in the twentieth century (Andresen et al. 2012), and model projections indicate continued increases in the future (Notaro et al. 2015). In particular, lake-effect events are expected to become more intense and longer lasting, but less frequent than at present. As the climate warms, however, lake-effect snow is likely to transition to lake-effect rain, which is predicted for four of the five Great Lakes (Notaro et al. 2015). Given its high latitude, Lake Superior is expected to be cold enough over the next century to support lake-effect snow. However, as warming continues into the next century, lake-effect rain may occur as far north as the Lake Superior region.

Water levels have been decreasing slightly, but future projections and the link to anthropogenic climate change is uncertain.

Slight decreases in lake levels in the Great Lakes have been observed over the past 30 years (Gronewold et al. 2013), coinciding with increased warmer waters, increased evaporation, and decreased areal ice coverage. Decreases have varied in magnitude depending on the lake (**Figure 7**). Future projections indicate slight decreases to no change over the next century (Angel & Kunkel 2010; Hayhoe et al. 2010). However, lake-level predictions are not very robust, and the hydrological drivers of lake levels are quite complex, thus the impact of climate change on lake levels is not fully understood or well predicted (Gronewold et al. 2013).

Higher evaporation rates from warmer lake waters implies a loss of water from the lakes resulting in lower lake levels. However, a net reduction in lake water requires evaporated water to escape the Great Lakes watershed basin before precipitating back to the surface; additionally, the entry of new water transported from long distances must not make up for the loss of water evaporated from the lake (Bryan et al. 2015). It is unclear how these various aspects of the Great Lakes hydrologic budget will change with climate change (i.e., whether there will be a net loss or gain to the system). It is also unclear how much the slight decrease in water levels observed recently is due to anthropogenic climate change or more natural, longer-term causes. As shown in **Figure 7**, lake levels in Lakes Michigan and Huron have been decreasing since before anthropogenic warming began. Even if the net water content remains constant and lake levels remain unchanged with climate change, it is likely the hydrologic cycle in the region will manifest more intense evaporation and convection combined with more intense precipitation events (Grover 2015).

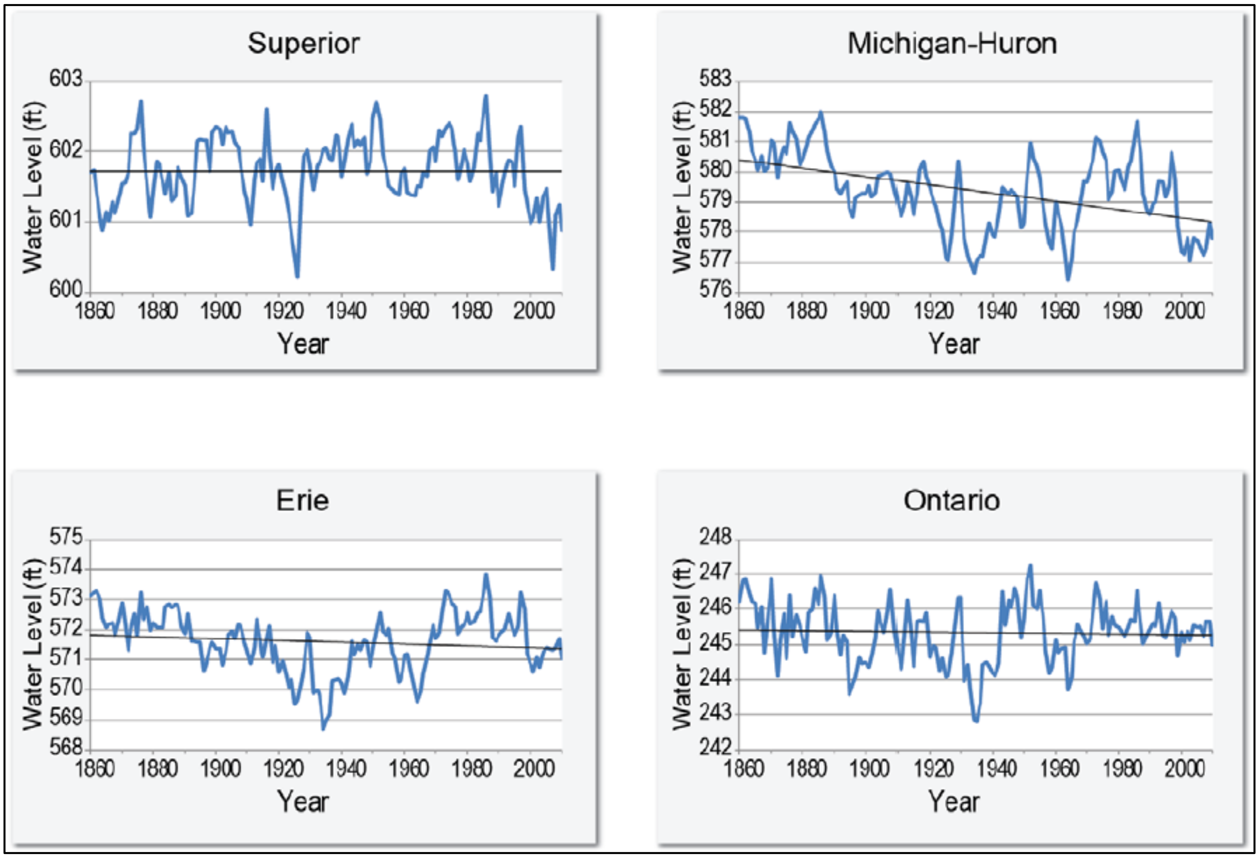
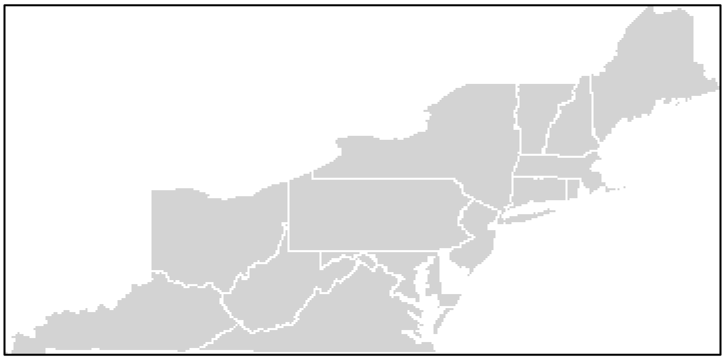


Figure 7: Recent trends in Great Lakes water levels (Used with permission from Kunkel 2013). Linear regressions for the 1860 – 2010 period are shown in black.

C) APPALACHIANS



Warming may be occurring at a faster rate at higher elevations.

Though the observational networks at the tops of mountains are limited, there is evidence on several mountain peaks around the world that temperatures are increasing at a faster rate at the top of mountains than at the bases (Diaz & Bradley 1997; Pepin & Lundquist 2008; Rangwala & Miller 2012; Diaz et al. 2014; Pepin et al. 2015). Based on model simulations, under future warming, the magnitudes of temperature increases over mountain regions are also larger than over low-elevation regions (Bradley et al. 2004; Bradley et al. 2006; Diaz et al. 2014). The potential physical mechanisms that contribute to elevation-dependent warming include: a) snow albedo and surface-based feedbacks; b) water vapor changes and latent heat release; c) surface water vapor and radiative flux changes; d) surface heat loss and temperature change; and, e) aerosols (Pepin et al. 2015).

Consistent with these model results, future projections indicate a more rapid increase in summer daily highs (Thibeault & Seth 2014) and lengthening of the growing season (**Figure 6**; Ning et al. 2015) in the Appalachians than for the surrounding landscape. A further consequence of this warming may be an accelerating decrease in snow pack and upslope regression of the snowline (Cohen et al. 2012). No matter the variability in rate with elevation, warming in general will likely lead to decreased depths and earlier melting of snow in mountain regions (Barnett et al. 2005), as have already been observed since the start of the century (Dedieu et al. 2014). Wildlife or habitats that depend on specific timing and magnitude of snow melt and thicknesses of winter snow cover will be most vulnerable to these changes. For example, some species rely on snow cover for camouflage, and as snow packs melt away earlier, there may be a mismatch in timing with changes in seasonal coat (e.g., snowshoe hare; Mills et al. 2013). Additionally, upslope progression of the temperate-boreal transition zone may accelerate with future warming.

The Appalachians may see greater intensification of extreme precipitation.

The precipitation environment along mountain slopes is distinct from flat terrain due to the influence of orographic lift on the windward side and subsidence on the leeward side (Roe 2005). Overall, precipitation amounts and frequency of extreme events on mountain slopes are likely to increase and the shift from snow to rain under warming climate points to heavier runoff and flooding (Shi & Durran 2015). Projections suggest that the Appalachians, in addition to the U.S. Atlantic coast, may see greater increases in the number, intensity, and inter-annual variability of extreme precipitation (Ning et al. 2015). The windward side of mountains is particularly sensitive to climatic warming due to the influence of orographic lift in producing high amounts of precipitation in that region (Shi & Durran 2014). Warming may increase both the intensity and duration of orographic precipitation due to elevation-varying changes in the moist adiabatic lapse rate, winds along the slope, and orographic lift. Changes in the progression of mid-latitude storms may also impact precipitation on the slopes of the Appalachians.

V. LITERATURE CITED

Abtew, W. and A. Melesse. 2013. Climate Change and Evapotranspiration. Evaporation and Evapotranspiration. Springer:197-202.

Alder, J. R. and S. W. Hostetler. 2013. USGS National Climate Change Viewer. Available at: http://www.usgs.gov/climate_landuse/clu_rd/nccv.asp (accesssed May 2015)

Alexander, L. V., et al. 2006. Global observed changes in daily climate extremes of temperature and precipitation. Journal of Geophysical Research **111**:D05109.

Andresen, J., S. Hilberg, and K. Kunkel. 2012. Historical climate and climate trends in the Midwestern USA. U.S. National Climate Assessment Midwest Technical Input Report.:1-18.

Angel, J. R. and K. E. Kunkel. 2010. The response of Great Lakes water levels to future climate scenarios with an emphasis on Lake Michigan-Huron. Journal of Great Lakes Research **36**:51-58.

Anthes, R. A., R. W. Corell, G. Holland, J. W. Hurrell, M. C. MacCracken, and K. E. Trenberth. 2006. Hurricanes and global warming-Potential linkages and consequences. Bulletin of the American Meteorological Society **87**:623-628.

Armstrong, W. H., M. J. Collins, and N. P. Snyder. 2012. Increased Frequency of Low-Magnitude Floods in New England. Journal of the American Water Resources Association **48**:306-320.

Assel, R. A. 2005. Classification of Annual Great Lakes Ice Cycles: Winters of 1973-2002. Journal of Climate **18**:4895-4905.

Augspurger, C. K. 2013. Reconstructing patterns of temperature, phenology, and frost damage over 124 years: Spring damage risk is increasing. Ecology **94**:41-50.

Austin, J. A. and S. M. Colman. 2007. Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. Geophysical Research Letters **34**:L06604.

Bai, X., et al. 2015. A record-breaking low ice cover over the Great Lakes during winter 2011/2012: combined effects of a strong positive NAO and La Niña. Climate Dynamics **44**:1187-1213.

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature **438**:303-309.

Bartholow, J. M. 2005. Recent water temperature trends in the lower Klamath River, California. North American Journal of Fisheries Management **25**:152-162.

Bartolai, A. M., L. He, A. E. Hurst, L. Mortsch, R. Paehlke, and D. Scavia. 2015. Climate change as a driver of change in the Great Lakes St. Lawrence River basin. Journal of Great Lakes Research **41**:45-58.

Betts, A. K. 2011. Vermont climate change indicators. Weather, Climate, and Society **3**:106-115.

Bradley, R. S., F. T. Keimig, and H. F. Diaz. 2004. Projected temperature changes along the American cordillera and the planned GCOS network. Geophysical Research Letters **31**:L16210.

Bradley, R. S., M. Vuille, H. F. Diaz, and W. Vergara. 2006. Threats to water supplies in the tropical Andes. Science **312**:1755-1756.

Brooks, R. T. 2009. Potential impacts of global climate change on the hydrology and ecology of ephemeral freshwater systems of the forests of the northeastern United States. Climatic Change **95**:469-483.

Brooks, H. E. 2013. Severe thunderstorms and climate change. Atmospheric Research **123**:129-138.

Brooks, H. E., G. W. Carbin, and P. T. Marsh. 2014. Increased variability of tornado occurrence in the United States. Science **346**:349-352.

Brown, R. D. 2000. Northern hemisphere snow cover variability and change, 1915-97. Journal of Climate **13**:2339-2355.

Brown, P. J. and A. T. DeGaetano. 2011. A paradox of cooling winter soil surface temperatures in a warming northeastern United States. Agricultural and Forest Meteorology **151**:947-956.

Brown, R. D. and D. A. Robinson. 2011. Northern Hemisphere spring snow cover variability and change over 1922-2010 including an assessment of uncertainty. The Cryosphere **5**:219-229.

Bryan, A. M., A. L. Steiner, and D. J. Posselt. 2015. Regional modeling of surface-atmosphere interactions and their impact on Great Lakes hydroclimate. Journal of Geophysical Research: Atmospheres **120**:1044-1064.

Burnett, A. W., M. E. Kirby, H. T. Mullins, and W. P. Patterson. 2003. Increasing Great Lake-Effect Snowfall during the Twentieth Century: A Regional Response to Global Warming? Journal of Climate **16**:3535-3542.

Caldeira, K. and M. E. Wickett. 2003. Oceanography: anthropogenic carbon and ocean pH. Nature **425**:365-365.

Campbell, J. L., S. V. Ollinger, G. N. Flerchinger, H. Wicklein, K. Hayhoe, and A. S. Bailey. 2011. Past and projected future changes in snowpack and soil frost at the Hubbard Brook Experimental Forest, New Hampshire, USA. Hydrological Processes **24**:2465-2480.

Canadell, J. G., C. Le Quéré, M. R. Raupach, C. B. Field, E. T. Buitenhuis, P. Ciais, T. J. Conway, N. P. Gillett, R. A. Houghton, and G. Marland. 2007. Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the national academy of sciences **104**:18866-18870.

Cannell, M. G.R. and R. I. Smith. 1986. Climatic warming, spring budburst and forest damage on trees. Journal of Applied Ecology **23**:177-191.

Cheng, C. S., E. Lopes, C. Fu, and Z. Huang. 2014. Possible Impacts of Climate Change on Wind Gusts under Downscaled Future Climate Conditions: Updated for Canada. Journal of Climate **27**:1255-1270.

Chen, W., et al. 2013. Monitoring habitat condition changes during winter and pre-calving migration for Bathurst Caribou in northern Canada. Biodiversity **14**:36-44.

Christensen, J. H., et al. 2013. Climate Phenomena and their Relevance for Future Regional Climate Change. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA:1217-1308.

Coffel, E. and R. Horton. 2015. Climate change and the impact of extreme temperatures on aviation. Weather, Society, and Climate **7**:94-102.

Cohen, S. J., et al. 2012. Downscaling and visioning of mountain snow packs and other climate change implications in North Vancouver, British Columbia. Mitigation and Adaptation Strategies for Global Change **17**:25-49.

Colle, B. A., K. Rojowsky, and F. Buonaito. 2010. New York City Storm Surges: Climatology and an Analysis of the Wind and Cyclone Evolution. Journal of Applied Meteorology and Climatology **49**:85-100.

Collins, M. J. 2009. Evidence for changing flood risk in New England since the late 20th century. Journal of the American Water Resources Association **45**:279-290.

Collins, M., et al. 2013. Long-term Climate Change: Projections, Commitments and Irreversibility. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T. F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA:1029-1136.

Comte, L., L. Buisson, M. Daufresne, and G. Grenouillet. 2013. Climate-induced changes in the distribution of freshwater fish: observed and predicted trends. Freshwater Biology **58**:625-639.

Cook, J., D. Nuccitelli, S. A. Green, M. Richardson, B. Winkler, R. Painting, R. Way, P. Jacobs, and A. Skuce. 2013. Quantifying the consensus on anthropogenic global warming in the scientific literature. Environmental Research Letters **8**:024024.

Cooley, S. R. and S. C. Doney. 2009. Anticipating ocean acidification's economic consequences for commercial fisheries. Environmental Research Letters **4**:024007.

Dedieu, J. P., A. Lessard-Fontaine, G. Ravazzani, E. Cremonese, G. Shalpykova, and M. Beniston. 2014. Shifting mountain snow patterns in a changing climate from remote sensing retrieval. Science of The Total Environment **493**:1267-1279.

DeGaetano, A. T. 2009. Time-dependent changes in extreme-precipitation return-period amounts in the continental United States. Journal of Applied Meteorology and Climatology **48**:2086-2099.

Del Genio, A. D., M.S. Yao, and J. Jonas. 2007. Will moist convection be stronger in a warmer climate? Geophysical Research Letters **34**:L16703.

Derksen, C. and R. Brown. 2012. Spring snow cover extent reductions in the 2008-2012 period exceeding climate model projections. Geophysical Research Letters **39**:L19504.

Diabat, M., R. Haggerty, and S. M. Wondzell. 2013. Diurnal timing of warmer air under climate change affects magnitude, timing and duration of stream temperature change. Hydrological Processes **27**:2367-2378.

Diaz, H. F. and R. S. Bradley. 1997. Temperature variations during the last century at high elevation sites. Climatic Change at High Elevation Sites. Springer:21-47.

Diaz, H. F., R. S. Bradley, and L. Ning. 2014. Climatic changes in mountain regions of the American Cordillera and the tropics: historical changes and future outlook. Arctic, Antarctic, and Alpine Research **46**:735-743.

Dobiesz, N. E. and N. P. Lester. 2009. Changes in mid-summer water temperature and clarity across the Great Lakes between 1968 and 2002. Journal of Great Lakes Research **35**:371-384.

Domingues, C. M., J. A. Church, N. J. White, P. J. Gleckler, S. E. Wijffels, P. M. Barker, and J. R. Dunn. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature **453**:1090-1093.

Donat, M. G., et al. 2013. Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. Journal of Geophysical Research: Atmospheres **118**:2098-2118.

Douglas, E. M. and C. A. Fairbank. 2010. Is precipitation in northern New England becoming more extreme? Statistical analysis of extreme rainfall in Massachusetts, New Hampshire, and Maine and updated estimates of the 100-year storm. Journal of Hydrologic Engineering **16**:203-217.

Douglas, E. M., R. M. Vogel, and C. N. Kroll. 2000. Trends in floods and low flows in the United States: impact of spatial correlation. Journal of Hydrology **240**:90-105.

Easterling, D. R., G. A. Meehl, C. Parmesan, S. A. Changnon, T. R. Karl, and L. O. Mearns. 2000. Climate extremes: observations, modeling, and impacts. Science **289**:2068-2074.

Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature **436**:686-688.

Emanuel, K., R. Sundararajan, and J. Williams. 2008. Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations. Bulletin of the American Meteorological Society **89**:347-367.

Fan, F., R. S. Bradley, and M. A. Rawlins. 2014. Climate change in the northeastern US: regional climate model validation and climate change projections. Climate Dynamics **43**:145-161.

Feely, R. A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, and F. J. Millero. 2004. Impact of anthropogenic CO2 on the CaCO3 system in the oceans. Science **305**:362-366.

Fischer, E. M. and R. Knutti. 2015. Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. Nature Climate Change: doi:10.1038/nclimate2617.

Flato, G., et al. 2013. Evaluation of Climate Models. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA:741-866.

Frölicher, T. L., M. Winton, and J. L. Sarmiento. 2014. Continued global warming after CO2 emissions stoppage. Nature Climate Change **4**:40-44.

Frumhoff, P. C., J. J. McCarthy, J. M. Melillo, S. C. Moser, and D. J. Wuebbles. 2007. *Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions*. Union of Concerned Scientists (UCS), Cambridge, Massachusetts.

Gan, J. 2004. Risk and damage of southern pine beetle outbreaks under global climate change. Forest Ecology and Management **191**:61-71.

Gensini, V. A. and T. L. Mote. 2015. Downscaled estimates of late 21st century severe weather from CCSM3. Climatic Change **129**:307-321.

Goode, J. R., J. M. Buffington, D. Tonina, D. Isaak, R. F. Thurow, S. Wenger, D. Nagel, C. Luce, D. Tetzlaff, and C. Soulsby. 2013. Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. Hydrological Processes **27**:750-765.

Groisman, P. Y., R. W. Knight, D. R. Easterling, T. R. Karl, G. C. Hegerl, and V. N. Razuvaev. 2005. Trends in intense precipitation in the climate record. Journal of Climate **18**:1326-1350.

Groisman, P. Y., R. W. Knight, and O. G. Zolina. 2013. Recent Trends in Regional and Global Intense Precipitation Patterns. Climate Vulnerability: Understanding and Addressing Threats to Essential Resources. Academic Press:25-55.

Gronewold, A. D., V. Fortin, B. Lofgren, A. Clites, C. A. Stow, and F. Quinn. 2013. Coasts, water levels, and climate change: A Great Lakes perspective. Climatic Change **120**:697-711.

Grover, V. I. 2015. Impact of Climate Change on the Water Cycle. Managing Water Resources under Climate Uncertainty. S. Shrestha, A. K. Anal, P. A. Salam, and M. van der Valk (eds.). Springer International Publishing:3-30.

Gu, L., P. J. Hanson, W. Mac Post, D. P. Kaiser, B. Yang, R. Nemani, S. G. Pallardy, and T. Meyers. 2008. The 2007 Eastern US spring freeze: Increased cold damage in a warming world? BioScience **58**:253-262.

Guilbert, J., A. K. Betts, D. M. Rizzo, B. Beckage, and A. Bomblies. 2015. Characterization of increased persistence and intensity of precipitation in the northeastern United States. Geophysical Research Letters **42**:1888-1893.

Hartmann, D. L., et al. 2013. Observations: Atmosphere and Surface. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.). Cambridge University Press, United Kingdom and New York, NY, USA:159-254.

Hawkins, E. and R. Sutton. 2009. The potential to narrow uncertainty in regional climate predictions. Bulletin of the American Meteorological Society **90**:1095-1107.

Hawkins, E. and R. Sutton. 2011. The potential to narrow uncertainty in projections of regional precipitation change. Climate Dynamics **37**:407-418.

Hayhoe, K., J. VanDorn, T. Croley II, N. Schlegal, and D. Wuebbles. 2010. Regional climate change projections for Chicago and the US Great Lakes. Journal of Great Lakes Research **36**:7-21.

Hayhoe, K., C. Wake, B. Anderson, X.Z. Liang, E. Maurer, J. Zhu, J. Bradbury, A. DeGaetano, A. M. Stoner, and D. Wuebbles. 2008. Regional climate change projections for the Northeast USA. Mitigation and Adaptation Strategies for Global Change **13**:425-436.

Hayhoe, K., C. P. Wake, T. G. Huntington, L. Luo, M. D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, and A. DeGaetano. 2007. Past and future changes in climate and hydrological indicators in the US Northeast. Climate Dynamics **28**:381-407.

Hidalgo, H. G., et al. 2009. Detection and attribution of streamflow timing changes to climate change in the western United States. Journal of Climate **22**:3838-3855.

Hodgkins, G. A. and R. W. Dudley. 2006. Changes in the timing of winter-spring streamflows in eastern North America, 1913-2002. Geophysical Research Letters **33**:L06402.

Hodgkins, G. A., R. W. Dudley, and T. G. Huntington. 2005. Summer low flows in New England during the 20th Century. Journal of the American Water Resources Association **41**:403-411.

Holland, G. and C. L. Bruyère. 2014. Recent intense hurricane response to global climate change. Climate Dynamics **42**:617-627.

Holland, G. J. and P. J. Webster. 2007. Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend? Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **365**:2695-2716.

Horton, R., C. Little, V. Gornitz, D. Bader, and M. Oppenheimer. 2015. Chapter 2: Sea Level Rise and Coastal Storms. New York City Panel on Climate Change 2015 Report. Annals of the New York Academy of Sciences, New York, NY:36-44.

Horton, R., G. Yohe, W. Easterling, R. Kates, M. Ruth, E. Sussman, A. Whelchel, D. Wolfe, and F. Lipschultz. 2014. Ch. 16: Northeast. Climate Change Impacts in the United States: The Third National Climate Assessment. J. M. Melillo, T. (.C.). Richmond, and G. W. Yohe (eds.). U.S. Global Change Research Program:371-395.

Hufkens, K., M. A. Friedl, T. F. Keenan, O. Sonnentag, A. Bailey, J. O'Keefe, and A. D. Richardson. 2012. Ecological impacts of a widespread frost event following early spring leaf-out. Global Change Biology **18**:2365-2377.

Inouye, D. W. 2008. Effects of climate change on phenology, frost damage, and floral abundance of montane wildflowers. Ecology **89**:353-362.

Jones, M. L., B. J. Shuter, Y. Zhao, and J. D. Stockwell. 2006. Forecasting effects of climate change on Great Lakes fisheries: models that link habitat supply to population dynamics can help. Canadian Journal of Fisheries and Aquatic Sciences **63**:457-468.

Joughin, I., B. E. Smith, and B. Medley. 2014. Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica. Science **344**:735-738.

Kane, H. H., C. H. Fletcher, L. N. Frazer, T. R. Anderson, M. M. Barbee, and H. H. Kane. 2015. Modeling sea-level rise vulnerability of coastal environments using ranked management concerns. Climatic Change: doi:10.1007/s10584-015-1377-3.

Karl, T. R., et al. 2012. U.S. temperature and drought: Recent anomalies and trends. Eos, Transactions American Geophysical Union **93**:473-474.

Kendon, E. J., N. M. Roberts, H. J. Fowler, M. J. Roberts, S. C. Chan, and C. A. Senior. 2014. Heavier summer downpours with climate change revealed by weather forecast resolution model. Nature Climate Change **4**:570-576.

Kennedy, J. J., P. W. Thorne, T. C. Peterson, R. Ruedy, P. A. Stott, D. E. Parker, S. A. Good, H. Titchner, and K. Willett. 2010. How do we know the world has warmed? Bulletin of the American Meteorological Society **91**:S26--S27.

Kharin, V. V., F. Zwiers, X. Zhang, and M. Wehner. 2013. Changes in temperature and precipitation extremes in the CMIP5 ensemble. Climatic Change **119**:345-357.

Klein, D. R., et al. 2005. Management and conservation of wildlife in a changing. Arctic climate impact assessment. C. Symon, L. Arris, and B. Heal (eds.). Cambridge University Press, Cambridge:597-648.

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi. 2010. Tropical cyclones and climate change. Nature Geoscience **3**:157-163.

Knutti, R. and J. Sedláček. 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change **3**:369-373.

Kodra, E. and A. R. Ganguly. 2014. Asymmetry of projected increases in extreme temperature distributions. Scientific Reports **4**:5884.

Kopp, R., S. Hsiang, R. Muir-Wood, M. Delgado, K. Larsen, and T. Hauser. 2014. American Climate Prospectus: Economic Risks in the United States. New York, NY.

Kunkel, K. E. 2013. Regional climate trends and scenarios for the US National Climate Assessment. US Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service.

Kunkel, K. E., et al. 2013. Monitoring and Understanding Trends in Extreme Storms: State of Knowledge. Bulletin of the American Meteorological Society **94**:499-514.

Lins, H. F. and J. R. Slack. 1999. Streamflow trends in the United States. Geophysical Research Letters **26**:227-230.

Lins, H. F. and J. R. Slack. 2005. Seasonal and regional characteristics of US streamflow trends in the United States from 1940 to 1999. Physical Geography **26**:489-501.

Mahanama, S., B. Livneh, R. Koster, D. Lettenmaier, and R. Reichle. 2012. Soil moisture, snow, and seasonal streamflow forecasts in the United States. Journal of Hydrometeorology **13**:189-203.

Maloney, E. D., et al. 2014. North American Climate in CMIP5 Experiments: Part III: Assessment of Twenty-First-Century Projections. Journal of Climate **27**:2230-2270.

Mann, M. E. and K. A. Emanuel. 2006. Atlantic hurricane trends linked to climate change. Eos, Transactions American Geophysical Union **87**:233-241.

Marshall, E. and T. Randhir. 2008. Effect of climate change on watershed system: a regional analysis. Climatic Change **89**:263-280.

Martin, M., K. Gavazov, C. Koerner, S. Haettenschwiler, and C. Rixen. 2010. Reduced early growing season freezing resistance in alpine treeline plants under elevated atmospheric CO2. Global Change Biology **16**:1057-1070.

Masson-Delmotte, V., et al. 2013. Information from Paleoclimate Archives. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA:383-464.

McCabe, G. J. and D. M. Wolock. 2002. A step increase in streamflow in the conterminous United States. Geophysical Research Letters **29**:2185.

McCabe, G. J. and D. M. Wolock. 2011. Independent effects of temperature and precipitation on modeled runoff in the conterminous United States. Water Resources Research **47**:W11522.

McCormick, M. J. and G. L. Fahnenstiel. 1999. Recent climatic trends in nearshore water temperatures in the St. Lawrence Great Lakes. Limnology and Oceanography **44**:530-540.

Meehl, G. A. and C. Tebaldi. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science **305**:994-997.

Miller-Rushing, A. J. and R. B. Primack. 2008. Global warming and flowering times in Thoreau's Concord: a community perspective. Ecology **89**:332-341.

Mills, L. S., M. Zimova, J. Oyler, S. Running, J. T. Abatzoglou, and P. M. Lukacs. 2013. Camouflage mismatch in seasonal coat color due to decreased snow duration. Proceedings of the National Academy of Sciences **110**:7360-7365.

Min, S.K., X. Zhang, F. W. Zwiers, and G. C. Hegerl. 2011. Human contribution to more-intense precipitation extremes. Nature **470**:378-381.

Mishra, V. and D. P. Lettenmaier. 2011. Climatic trends in major U.S. urban areas, 1950–2009. Geophysical Research Letters **38**:L16401.

Mohseni, O., T. R. Erickson, and H. G. Stefan. 1999. Sensitivity of stream temperatures in the United States to air temperatures projected under a global warming scenario. Water Resources Research **35**:3723-3733.

Moss, R. H., et al. 2010. The next generation of scenarios for climate change research and assessment. Nature **463**:747-756.

Music, B., A. Frigon, B. Lofgren, R. Turcotte, and J.F. Cyr. 2015. Present and future Laurentian Great Lakes hydroclimatic conditions as simulated by regional climate models with an emphasis on Lake Michigan-Huron. Climatic Change **130**:603-618.

Nakićenović, N., et al. 2000. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge, U.K.

NCDC. 2015. *Climate at a Glance*. [online]. [Accessed 1 May 2015]. Available at: http://ncdc.noaa.gov/cag/ (accessed May 2015)

Ning, L., E. E. Riddle, and R. S. Bradley. 2015. Projected Changes in Climate Extremes over the Northeastern United States. Journal of Climate **28**:3289-3310.

Nislow, K. H. and J. D. Armstrong. 2012. Towards a life-history-based management framework for the effects of flow on juvenile salmonids in streams and rivers. Fisheries Management and Ecology **19**:451-463.

Nixon, S. W., R. W. Fulweiler, B. A. Buckley, S. L. Granger, B. L. Nowicki, and K. M. Henry. 2009. The impact of changing climate on phenology, productivity, and benthic-pelagic coupling in Narragansett Bay. Estuarine, Coastal and Shelf Science **82**:1-18.

Norby, R. J., J. S. Hartz-Rubin, and V. M. J. 2003. Phenological responses in maple to experimental atmospheric warming and CO2 enrichment. Global Change Biology **9**:1792-1801.

Notaro, M., V. Bennington, and S. Vavrus. 2015. Dynamically Downscaled Projections of Lake-Effect Snow in the Great Lakes Basin. Journal of Climate **28**:1661-1684.

Notaro, M., K. Holman, A. Zarrin, E. Fluck, S. Vavrus, and V. Bennington. 2013. Influence of the Laurentian Great Lakes on Regional Climate. Journal of Climate **26**:789-804.

Notaro, M., D. Lorenz, C. Hoving, and M. Schummer. 2014. Twenty-First-Century Projections of Snowfall and Winter Severity across Central-Eastern North America. Journal of Climate **27**:6526-6550.

Oviatt, C. A. 2004. The changing ecology of temperate coastal waters during a warming trend. Estuaries **27**:895-904.

Pan, S., H. Tian, S. R. Dangal, Q. Yang, J. Yang, C. Lu, B. Tao, W. Ren, and Z. Ouyang. 2015. Responses of global terrestrial evapotranspiration to climate change and increasing atmospheric CO2 in the 21st century. Earth's Future **3**:15-35.

Parr, D. and G. Wang. 2014. Hydrological changes in the U.S. Northeast using the Connecticut River Basin as a case study: Part 1. Modeling and analysis of the past. Global and Planetary Change **122**:208-222.

Peng, S., S. Piao, P. Ciais, P. Friedlingstein, L. Zhou, and T. Wang. 2013. Change in snow phenology and its potential feedback to temperature in the Northern Hemisphere over the last three decades. Environmental Research Letters **8**:014008.

Pepin, N., et al. 2015. Elevation-dependent warming in mountain regions of the world. Nature Climate Change **5**:424-430.

Pepin, N. C. and J. Lundquist. 2008. Temperature trends at high elevations: Patterns across the globe. Geophysical Research Letters **35**:L14701.

Perkins, S. E., L. V. Alexander, and J. R. Nairn. 2012. Increasing frequency, intensity and duration of observed global heatwaves and warm spells. Geophysical Research Letters **39**:L20714.

Peterson, A. G. and J. T. Abatzoglou. 2014. Observed changes in false springs over the contiguous United States. Geophysical Research Letters **41**:2156-2162.

Peterson, T. C., et al. 2013. Monitoring and Understanding Changes in Heat Waves, Cold Waves, Floods, and Droughts in the United States: State of Knowledge. Bulletin of the American Meteorological Society **94**:821-834.

Petkova, E. P., R. M. Horton, D. A. Bader, and P. L. Kinney. 2013. Projected heat-related mortality in the US urban northeast. International Journal of Environmental Research and Public Health **10**:6734-6747.

Pierce, D. W., et al. 2008. Attribution of Declining Western U.S. Snowpack to Human Effects. Journal of Climate **21**:6425-6444.

Pierce, D. W. and D. R. Cayan. 2013. The uneven response of different snow measures to human-induced climate warming. Journal of Climate **26**:4148-4167.

Pilson, M. E.Q. 2008. Narragansett Bay amidst a globally changing climate. Science for ecosystem-based management. Springer:35-46.

Primack, D., C. Imbres, R. B. Primack, A. J. Miller-Rushing, and P. Del Tredici. 2004. Herbarium specimens demonstrate earlier flowering times in response to warming in Boston. American Journal of Botany **91**:1260-1264.

Pryor, S. C., R. J. Barthelmie, and J. T. Schoof. 2012. Past and future wind climates over the contiguous USA based on the North American Regional Climate Change Assessment Program model suite. Journal of Geophysical Research: Atmospheres **117**:D19119.

Pryor, S. C., R. J. Barthelmie, D. T. Young, E. S. Takle, R. W. Arritt, D. Flory, W. J. Gutowski, A. Nunes, and J. Roads. 2009. Wind speed trends over the contiguous United States. Journal of Geophysical Research: Atmospheres **114**:D14105.

Rahmstorf, S., J. E. Box, G. Feulner, M. E. Mann, A. Robinson, S. Rutherford, and E. J. Schaffernicht. 2015. Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nature Climate Change **5**:475-480.

Rangwala, I. and J. R. Miller. 2012. Climate change in mountains: a review of elevation-dependent warming and its possible causes. Climatic Change **114**:527-547.

Rawlins, M. A., R. S. Bradley, and H. F. Diaz. 2012. Assessment of regional climate model simulation estimates over the northeast United States. Journal of Geophysical Research: Atmospheres **117**:D23112.

Rhein, M., et al. 2013. Observations: Ocean. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA:255-315.

Richardson, A. D., E. G. Denny, T. G. Siccama, and X. Lee. 2003. Evidence for a Rising Cloud Ceiling in Eastern North America. Journal of Climate **16**:2093-2098.

Rigby, J. R. and A. Porporato. 2008. Spring frost risk in a changing climate. Geophysical Research Letters **35**:L12703.

Roe, G. H. 2005. Orographic precipitation. Annual Review of Earth and Planetary Sciences **33**:645-671.

Rupp, D. E., P. W. Mote, N. L. Bindoff, P. A. Stott, and D. A. Robinson. 2013. Detection and attribution of observed changes in Northern Hemisphere spring snow cover. Journal of Climate **26**:6904-6914.

Sabine, C. L., et al. 2004. The Oceanic Sink for Anthropogenic CO2. Science **305**:367-371.

Schoof, J. T. 2015. High resolution projections of 21st century daily precipitation for the contiguous US. Journal of Geophysical Research: Atmospheres: doi:10.1002/2014JD022376.

Schummer, M. L., R. M. Kaminski, A. H. Raedeke, and D. A. Graber. 2010. Weather-Related Indices of Autumn-Winter Dabbling Duck Abundance in Middle North America. The Journal of Wildlife Management **74**:94-101.

Scoccimarro, E., S. Gualdi, M. Zampieri, A. Bellucci, and A. Navarra. 2013. Heavy precipitation events in a warmer climate: results from CMIP5 models. Journal of Climate **26**:7902–7911.

Seidel, T. M., A. N. Grant, A. A. Pszenny, and D. J. Allman. 2007. Dewpoint and humidity measurements and trends at the summit of Mount Washington, New Hampshire, 1935-2004. Journal of Climate **20**:5629-5641.

Sheffield, J., et al. 2013. North American Climate in CMIP5 Experiments. Part I: Evaluation of Historical Simulations of Continental and Regional Climatology. Journal of Climate **26**:9209-9245.

Shi, X. and D. R. Durran. 2014. The response of orographic precipitation over idealized midlatitude mountains due to global increases in CO2. Journal of Climate **27**:3938-3956.

Shi, X. and D. Durran. 2015. Estimating the Response of Extreme Precipitation. Journal of Climate In Press: doi:10.1175/JCLI-D-14-00750.1.

Sillmann, J., V. Kharin, X. Zhang, F. Zwiers, and D. Bronaugh. 2013. Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. Journal of Geophysical Research: Atmospheres **118**:1716-1733.

Sillmann, J., V. Kharin, F. Zwiers, X. Zhang, and D. Bronaugh. 2013. Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. Journal of Geophysical Research: Atmospheres **118**:2473-2493.

Small, D., S. Islam, and R. M. Vogel. 2006. Trends in precipitation and streamflow in the eastern U.S.: Paradox or perception? Geophysical Research Letters **33**:L03403.

Solomon, S., G.K. Plattner, R. Knutti, and P. Friedlingstein. 2009. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences **106**:1704-1709.

Swain, S. and K. Hayhoe. 2015. CMIP5 projected changes in spring and summer drought and wet conditions over North America. Climate Dynamics **44**:2737-2750.

Thibeault, J. M. and A. Seth. 2014. Changing climate extremes in the Northeast United States: observations and projections from CMIP5. Climatic Change **127**:273-287.

Thompson, P. R., G. T. Mitchum, C. Vonesch, and J. Li. 2013. Variability of winter storminess in the eastern United States during the twentieth century from tide gauges. Journal of Climate **26**:9713-9726.

Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis, and R. Nemani. 2013. Downscaled climate projections suitable for resource management. Eos, Transactions American Geophysical Union **94**:321-323.

Ting, M., S. J. Camargo, C. Li, and Y. Kushnir. 2015. Natural and Forced North Atlantic Hurricane Potential Intensity Change in CMIP5 Models. Journal of Climate: doi:10.1175/JCLI-D-14-00520.1.

Toreti, A., P. Naveau, M. Zampieri, A. Schindler, E. Scoccimarro, E. Xoplaki, H. A. Dijkstra, S. Gualdi, and J. Luterbacher. 2013. Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models. Geophysical Research Letters **40**:4887-4892.

Trần, J. K., T. Ylioja, R. F. Billings, J. Régnière, and M. P. Ayres. 2007. Impact of minimum winter temperatures on the population dynamics of Dendroctonus frontalis. Ecological Applications **17**:882-899.

Trumpickas, J., B. J. Shuter, and C. K. Minns. 2009. Forecasting impacts of climate change on Great Lakes surface water temperatures. Journal of Great Lakes Research **35**:454-463.

Vavrus, S., M. Notaro, and A. Zarrin. 2013. The role of ice cover in heavy lake-effect snowstorms over the Great Lakes Basin as simulated by RegCM4. Monthly Weather Review **141**:148-165.

Verme, L. J. 1968. An Index of Winter Weather Severity for Northern Deer. The Journal of Wildlife Management **32**:566-574.

Villarini, G. and J. A. Smith. 2010. Flood peak distributions for the eastern United States. Water Resources Research **46**:W06504.

Villarini, G., J. A. Smith, M. L. Baeck, R. Vitolo, D. B. Stephenson, and W. F. Krajewski. 2011. On the frequency of heavy rainfall for the Midwest of the United States. Journal of Hydrology **400**:103-120.

Walsh, J., et al. 2014. Chapter 2: Our Changing Climate. Climate Change Impacts in the United States: The Third National Climate Assessment. J. M. Melillo, T. (.C.). Richmond, and G. W. Yohe (eds.). U.S. Global Change Research Program:19-67.

Wang, J., X. Bai, H. Hu, A. Clites, M. Colton, and L. Brent. 2012. Temporal and Spatial Variability of Great Lakes Ice Cover, 1973–2010. Journal of Climate **25**:1318-1329.

Webb, B. 1996. Trends in stream and river temperature. Hydrological Processes **10**:205-226.

Webster, P. J., G. J. Holland, J. A. Curry, and H.R. Chang. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science **309**:1844-1846.

Wi, S., F. Dominguez, M. Durcik, J. Valdes, H. F. Diaz, and C. L. Castro. 2012. Climate change projection of snowfall in the Colorado River Basin using dynamical downscaling. Water Resources Research **48**:W05504.

Wright, D. M., D. J. Posselt, and A. L. Steiner. 2013. Sensitivity of lake-effect snowfall to lake ice cover and temperature in the Great Lakes region. Monthly Weather Review **141**:670-689.

Wuebbles, D., et al. 2014. CMIP5 Climate Model Analyses: Climate Extremes in the United States. Bulletin of the American Meteorological Society **95**:571-583.

Yin, J. H. 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate. Geophysical Research Letters **32**:L18701.

Yin, J., M. E. Schlesinger, and R. J. Stouffer. 2009. Model projections of rapid sea-level rise on the northeast coast of the United States. Nature Geoscience **2**:262-266.

Zhang, X., F. W. Zwiers, G. C. Hegerl, F. H. Lambert, N. P. Gillett, S. Solomon, P. A. Stott, and T. Nozawa. 2007. Detection of human influence on twentieth-century precipitation trends. Nature **448**:461-465.