Recent and Near-future Climate Trends Important to Tree Fruit Production in the Northeastern U.S.

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Contents

Introduction

Unless noted otherwise, graphics and text in this document are adapted from original content in Wolfe et al., 2018.

David W. Wolfe, Arthur T. DeGaetano, Gregory M. Peck, Mary Carey, Lewis H. Ziska, John Lea-Cox, Armen R. Kemanian; Michael P. Hoffmann; David Y. Hollinger. 2018. Unique Challenges and Opportunities for Northeastern U.S. Crop Production in a Changing Climate. Climatic Change (2018) 146: 231. https://doi.org/10.1007/s10584-017-2109-7

The intention of this document is to combine content from Wolfe et al. 2018 with selected graphics and text from Janowiak et al., 2018 and other recent publications into a comprehensive, yet concise and accessible overview of recent climate trends and projections for the next 30-40 years. Text from original sources was edited for brevity while attempting to preserve meaning, and to increase focus on those points of greatest use to tree fruit growers and other farmers. The primary source, Wolfe et al., 2018, was distributed under the terms of the Creative Commons Attribution 4.0 International License: http://creativecommons.org/licenses/by/4.0/.

Where values are based on a range of years, for simplicity the middle year of the period is used as the date indicator, with the actual year range shown in parentheses. Values from Albany, NY are highlighted to exemplify several variables. Note that Albany NY is not necessarily representative for the Northeast region as a whole.

In order to provide a comprehensive review from multiple perspectives, but still remain concise, this document include extended text excerpts adapted from several recent national and regional climate assessments. Those excerpts are not quoted verbatim because in adapting them for use in this context, small changes to wording have been made to remove extraneous text, focus on topics specific to climate in the Northeastern U.S. relevant to tree fruit production, and provide graceful page breaks. These extended text excerpts are identified by a dashed line at the beginning and end of each except, by a slight indentation, by a vertical line along the left side of the page, and by a dark blue instead of black font.

The text below is adapted from Wolfe et al. 2018. References in the original were excluded for clarity.

> **Summary:** Climate change may both exacerbate the vulnerabilities and open up new opportunities for farming in the Northeastern USA. Among the opportunities are double-cropping and new crop options that may come with warmer temperatures and a longer frost-free period. However, prolonged periods of spring rains in recent years have delayed planting and offset the longer frost-free period.
>
> Water management will be a serious challenge for Northeast farmers in the future, with projections for increased frequency of heavy rainfall events, as well as projections for more frequent summer water deficits than this historically humid region has experienced in the past.

Adaptations to increase resilience to such changes include expanded irrigation capacity, modernized water monitoring and irrigation scheduling, farm drainage systems that collect excess rain into ponds for use as a water source during dry periods, and improved soil water holding capacity and drainage.

Among the greatest vulnerabilities over the next several decades for the economically important perennial fruit crop industry of the region is an extended period of spring frost risk associated with warmer winter and early spring temperatures. Improved real-time frost warning systems, careful site selection for new plantings, and use of misting, wind machine, or other frost protection measures will be important adaptation strategies.

Increased weed, insect, and disease pest pressure associated with longer growing seasons and warmer winters is another increasingly important challenge. Proactive development of non-chemical control strategies, improved regional monitoring, and rapid response plans for targeted control of altered pest threats will be necessary.

Methods: To estimate future trends, a subset of ten global climate models (from CMIP5) that perform well in simulating solar radiation, temperature, precipitation and wind were used to create regional projections using two future climate scenarios called RCP8.5 and RCP4.5. (RCP stands for "Representative Concentration Pathway"). RCP8.5 represents future conditions under a continued trend of increasing human-generated greenhouse gas emissions. RCP4.5 represents expected conditions if there is a rapid reduction in global greenhouse emissions by mid-century. Since 2010, when the RCP scenarios diverge from each other, global CO2 emissions have closely tracked the high (RCP8.5) scenario, and have been higher than the estimates used in moderate (RCP4.5) scenario. Therefore, for planning purposes, the prudent assumption is that the high emissions scenario is currently a more realistic basis for estimating future conditions.

End of text adapted from Wolfe et al. 2018.

Average vs. variability and extremes, Abrupt vs. gradual change.

The projections for future temperature and precipitation shown in this document are the most likely midpoint estimates from a range of possible outcomes under moderate and high future greenhouse gas emission scenarios. Less extreme and more extreme outcomes above or below the midpoint estimate are possible, but with lower probability. Seasonal and year-to-year variability caused by the El Nino - Southern Oscillation and other natural cycles will continue to cause fluctuations around long-term trends, and unpredictable factors such as a large volcanic eruption can influence temperature and other climatic features for multiple sequential years (Birkel and Mayewski, 2018).

In addition to change in annual or seasonal average values, the patterns and degree of variability of weather and climate can also change. For example, even without a change in total seasonal rainfall, the rain may occur more erratically, with greater swings between wet and dry conditions. Similarly, a gradual increase in warming temperature can be accompanied by an increase in the frequency or intensity of heat waves. In addition, synergistic compound effects can lead to outcomes that are unexpected in their intensity or direction of change. For example, despite an increase in precipitation, there can be a simultaneous increase in drought caused by higher temperatures that accelerate plant evapotranspiration and soil moisture losses that exceed the precipitation increase (Hao et al., 2018).

There are also “reinforcing feedbacks” and “tipping points” in the climate system (National Research Council, 2013). Exact prediction for the timing or intensity for these mechanisms is not possible. Some reinforcing feedbacks, such as increased solar energy absorption due to Arctic sea ice decline are known to already to be affecting the climate. Reinforcing feedbacks become more intense or more likely, or both, with increasing degree of climate disruption.

If one of a dozen or more known or suspected tipping points in the climate system is exceeded, that could lead to abrupt and radical shift in temperature, precipitation, or other components of the climate system that far exceed the rates of gradual incremental change. The possibility of one or more tipping point thresholds being exceeded is thought to greatly increase if global average surface temperature increases by 2 degrees Celsius (3.6 degrees Fahrenheit) above the preindustrial average (Drijfhout et al., 2015). As of 2018, the Earth has already warmed 1.1 degree C, and continues to warm at a rate at almost 0.2 degree C per decade (NASA, 2018), with the highest warming rate in the most recent decade.

“The climate change resulting from human-caused emissions of carbon dioxide will persist for decades to millennia. Self-reinforcing cycles within the climate system have the potential to accelerate human-induced change and even shift Earth’s climate system into new states that are very different from those experienced in the recent past. Future changes outside the range projected by climate models cannot be ruled out, and due to their systematic tendency to underestimate temperature change during past warm periods, models may be more likely to underestimate than to overestimate long-term future change,” (USGCRP, 2018).

“Although agriculture has a long history of successful adaptation to climate variability, the accelerating pace of climate change and the intensity of projected climate change represent new and unprecedented challenges to the sustainability of U.S. agriculture,” (Melillo et al., 2014).

TEMPERATURE

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Observed average annual temperature increase from 1988 to 2017.

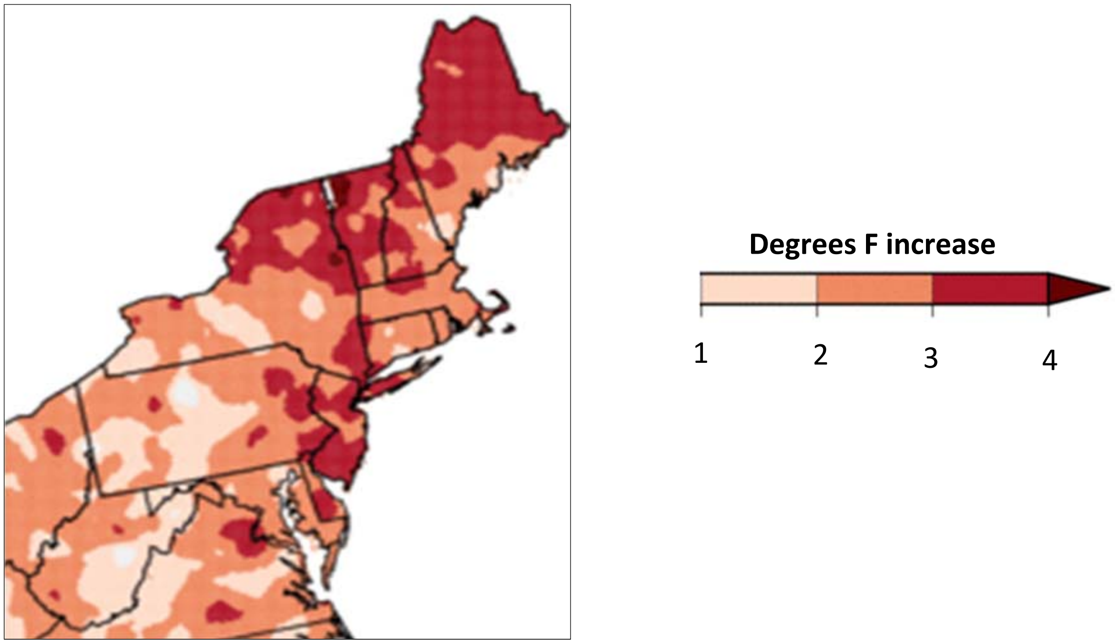


Figure 1. Annual average temperature change from 1988 to 2017. Adapted from NOAA 2018a.

Observed Northeastern U.S. average annual temperature, 1988 to 2018.

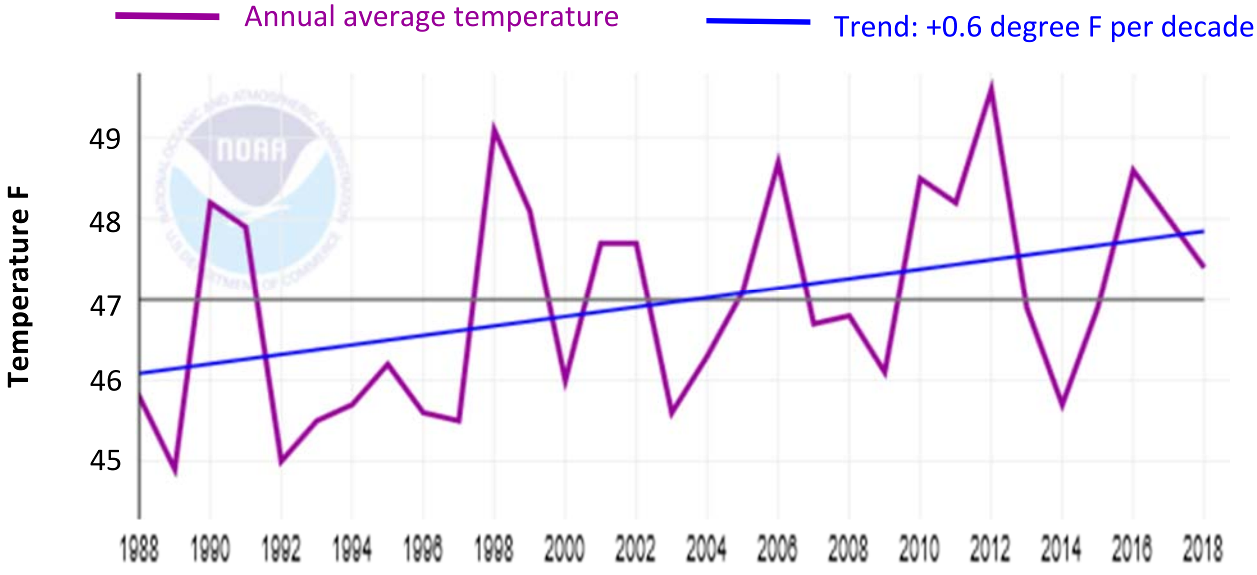


Figure 2. Average annual temperature for the Northeastern U.S. from 1988 to 2018. The annual average increased by 0.6 degree F per decade, and a total of 1.9 degrees F across 30 years. Trends for individual states ranged from 0.6 to 0.8 F per decade. Even with the upward trend, the average rises and falls between individual years. Adapted from NOAA, 2018b.

Observed warming relative to the global average land rate, 1975 to 2018.

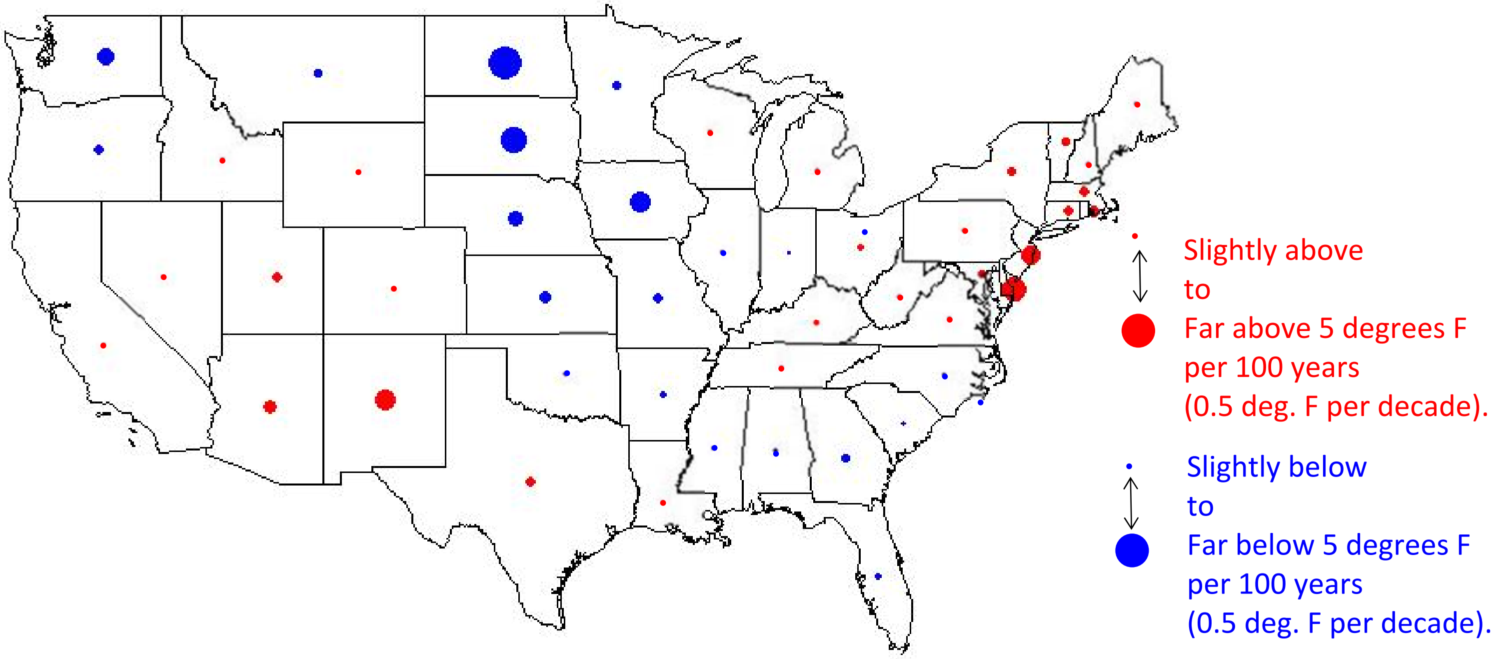
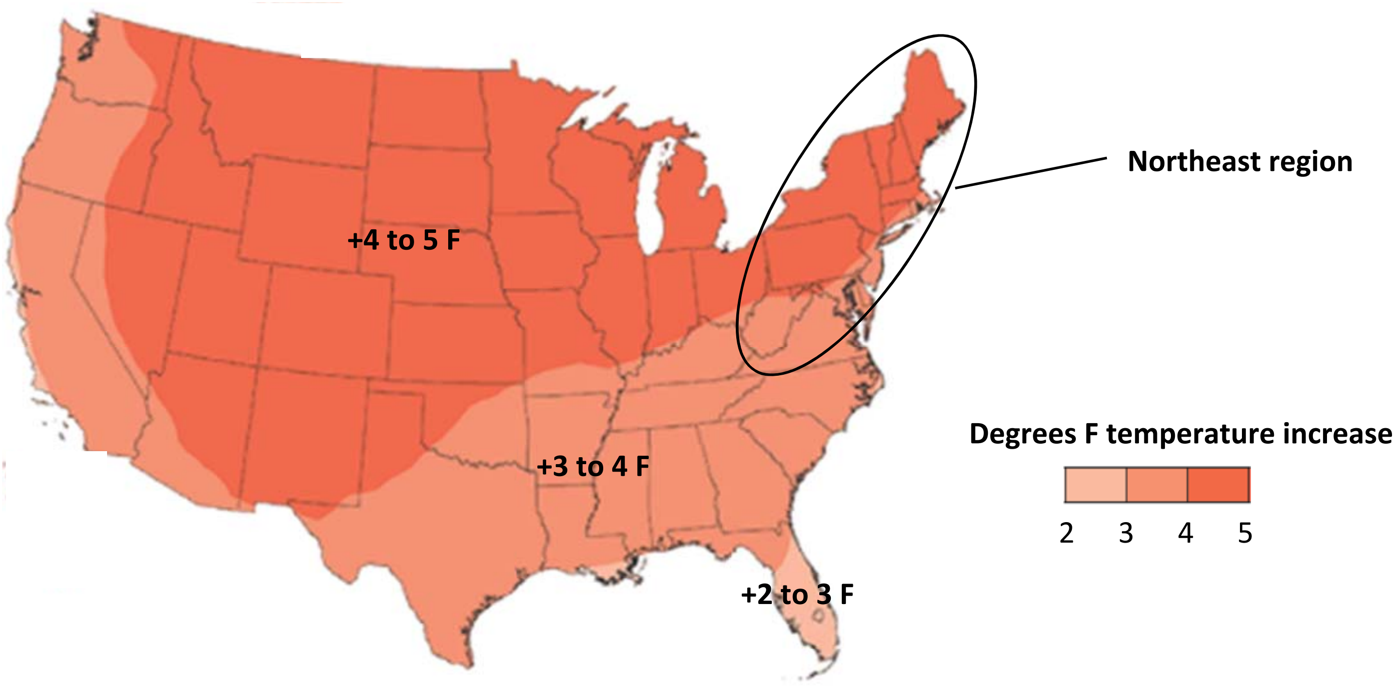


Figure 3. Rate of temperature increase for the lower 48 U.S. states from 1975 to 2018, relative to the global land average rate of 5 degrees F per 100 years. All of the states are warming. Those with blue dots are warming at <u>less</u> than 5 degrees F per 100 years, those with red dots at <u>more</u> than 5 degrees F per 100 years. Size of the dots indicates relative rate. Adapted from Foster, 2019.

Contrary to some climate model simulations and projections, observed temperature variability in the Northeast, and the U.S. overall, did not become more variable as of 2012 (Kunkel, 2015). This conclusion is based on monthly average maximum and minimum temperatures for the seven U.S. climate regions (Melillo et al., 2014), as well as for the 344 NOAA U.S. climate divisions, by comparing temperature data across four 27-year-long periods between 1901 and 2012.



Projected warming from 2001 to 2050.

Figure 4. Projected increase in annual average temperature from 2001 (1986–2016) to 2050 (2036–2065) under the RCP8.5 high future greenhouse gas emission scenario. Adapted from USGCRP, 2018.

Observations show that annual average temperature in the Northeast increased by 1.2 F from 1990 (1975–2005) to 2007 (1998–2017), (NOAA 2018b). Under the moderate emissions scenario (RCP4.5), the Northeast region is projected to warm by 4 F between 2001 and 2050. Under the high emissions scenario (RCP8.5), the Northeast is projected to warm by 5.1 F between 2001 and 2050.

This report defines the Northeast region as Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Washington D.C., West Virginia, and Vermont. Even though much of Virginia is enclosed in the oval in Figure 4, it is not included in the Northeast region for this report.

Observed 30-year average annual temperature from 1981 to 2010

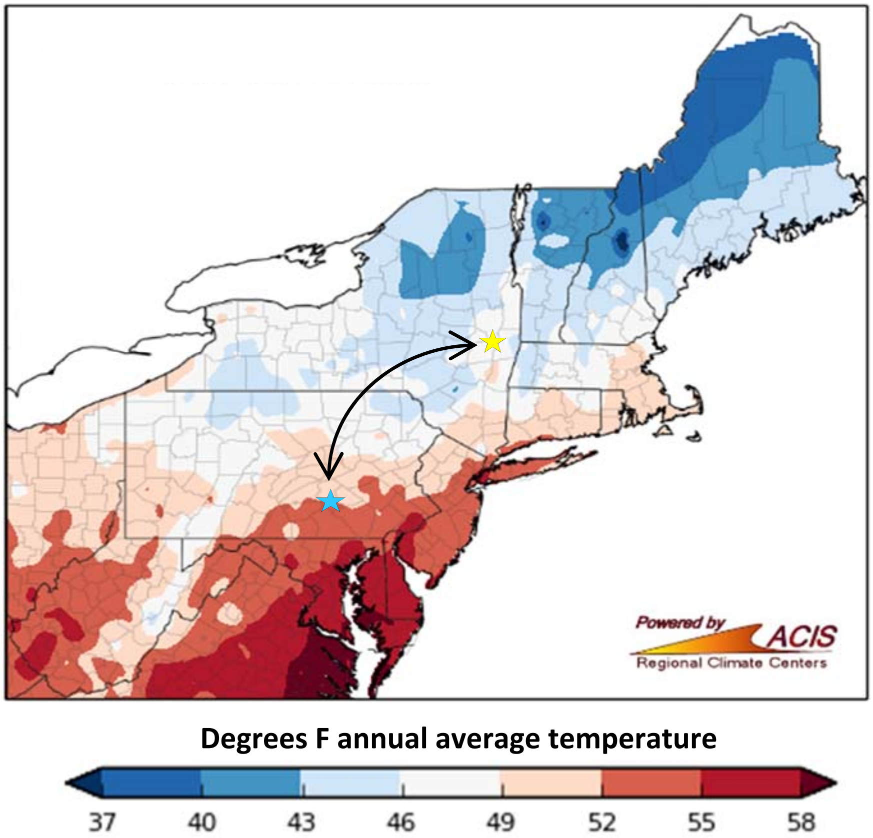


Figure 5. Average annual temperature, 1981–2010. Adapted from Northeast Regional Climate Center, 2018.

This figure provides geographic interpretation for projected future increases in annual average temperature. The projected increase of 4.5F between 1996 (1981–2010) and 2050 (average of moderate and high emission scenario estimates, USGCRP 2017) would be like a location changing one and a half color categories on this map.

For example, Albany NY (★ on map), had an average annual temperature of 48.2 F in 1981–2010, and is in the white zone of Figure 5. With a 4.5 F temperature increase, Albany NY would have an average annual temperature of 52.7 F, warmer than the 1981-2010 annual average of 51.9 F at Harrisburg PA (★ on map), which is located on the border between the light and dark peach-colored zones. 1981-2010 average temperatures for Albany and Harrisburg from NOAA, 2013.

Figure 6. Pairings for locations with similar daily average temperature and precipitation in 2001 (1986–2015) (solid white text) and projected values (gray text) for 2050 (2036–2065) under the RCP8.5 high emissions scenario. For example, by 2050 Syracuse NY is projected to have similar temperature and precipitation as Lorane PA had in 2001. Adapted from Zarracina and Northrop, 2018.

Projected geographic shift in average May temperature, from 1996 to 2055.

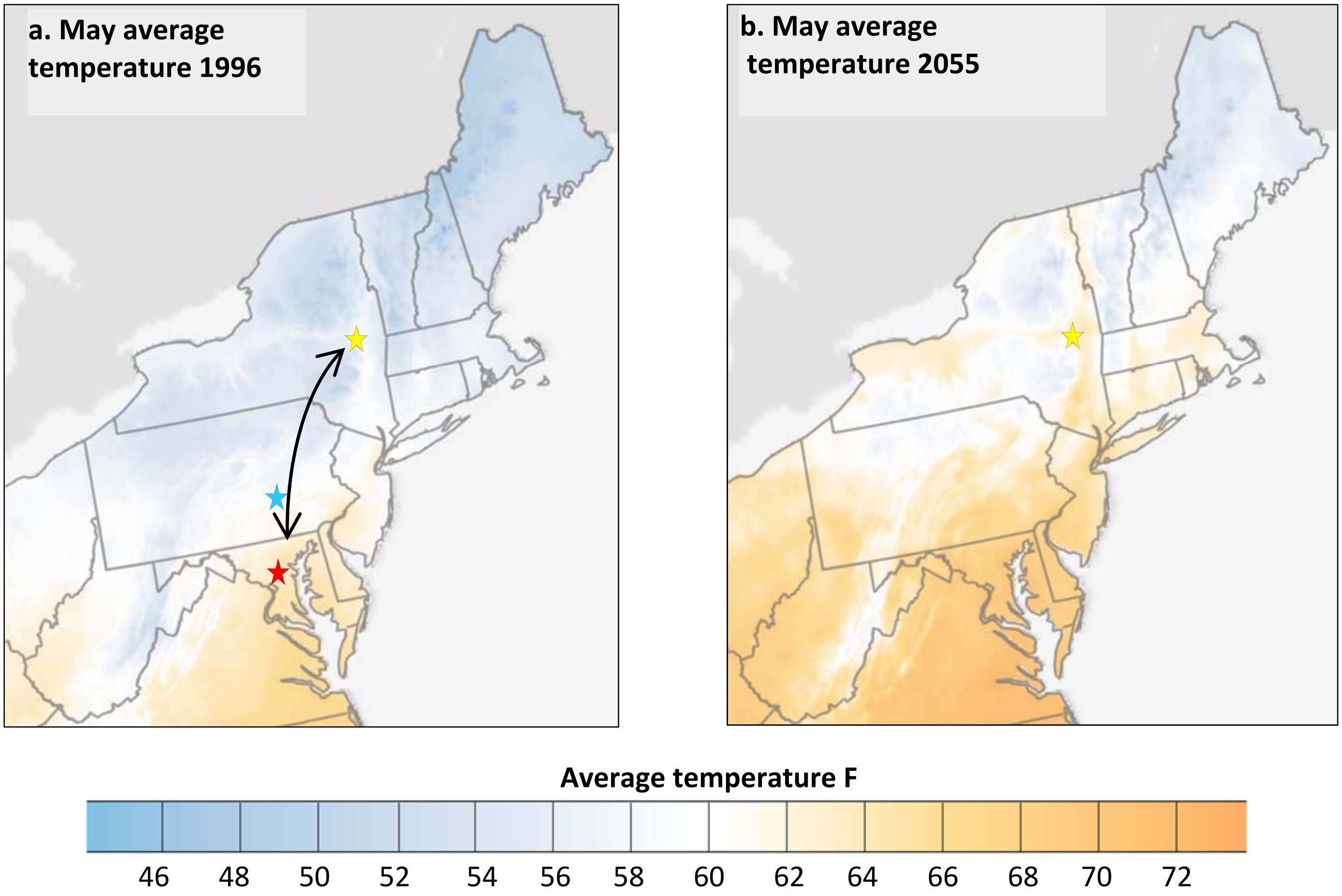


Figure 7a. May average temperature in 1996 (1981–2010).

Figure 7b. May average temperature in 2055 (2050–2059) under a high emissions scenario, RCP8.5. Figures 7a and 7b adapted from NOAA, 2018c.

Comparing the two maps gives an indication how spring temperatures projected for 2055 would compare with recent (1981–2010) observations. The 1981–2010 average May temperature for Albany NY (★ on map) was 58.3 F. An increase of 4.5F (average of moderate and high emission scenario estimates, USGCRP 2017) would result in a May average of 62.8 F. At Harrisburg PA (★) the average May temperature in 1981-2010 was 61.0 F, at Beltsville MD (★) the average was 63.4 F (NOAA, 2013). Thus, the projected 2055 May temperature for Albany NY under the high emissions scenario is between the 1981–2010 averages for Harrisburg PA and Beltsville MD.

By 2055, the average May temperature in southern interior Maine could be similar to the 1981-2010 average May temperature in western Massachusetts; western MA in 2055 could be similar to south-central PA 0n 1981-2010; and south-central PA could be match the 1981-2010 May average of the warmest locations in VA.

The precision of future temperature estimates varies between locations, timeframe, and methodology. For example, an estimate of a 5.4 F increase in average annual temperature between 1985 (1971–2000) and 2054 (2050–2059) for Saratoga NY (40 miles north of Albany) had an 80% confidence interval of +/- 1.8 degrees F (Horton et al., 2014).

Projected increase in winter minimum and summer maximum temperatures, from 1994 to 2055.

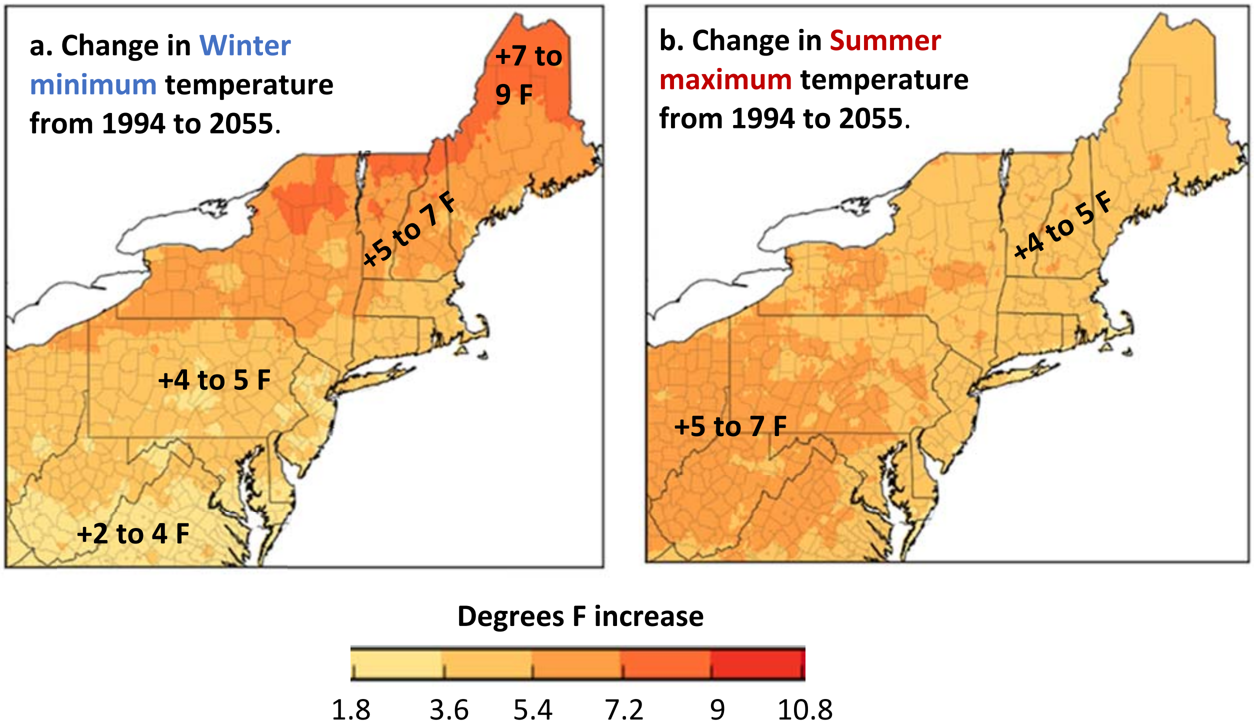


Figure 8a. Difference in winter minimum temperature from 1994 to 2055 (1979–2008 vs. 2040–2069) under the RCP8.5 high emissions scenario.

Figure 8b. Difference in summer maximum temperature (degrees F) from 1994 to 2055 (1979–2008 vs. 2040–2069) under the RCP8.5 scenario. Values in Figures 8a and 8b rounded to nearest whole number, and adapted from Wolfe et al., 2018.

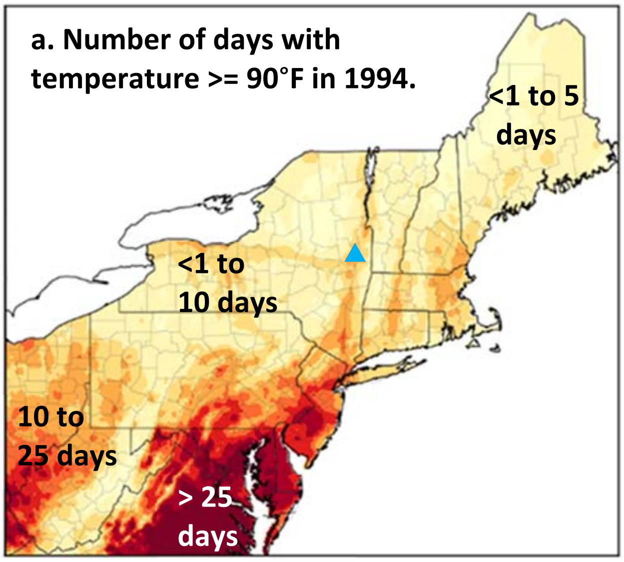
With the high emissions scenario, the mid-century increase in Northeastern U.S. winter **minimum** temperature is projected to be 2°F to 6°F greater than the increase in summer **maximum** temperature. The Fourth National Climate Assessment (USGCRP 2017) estimated that under the high greenhouse gas emission scenario (RCP8.5), the coldest temperature of the year in the Northeast would increase by 9.5°F from 1990 (1976-2005) to 2050 (2036-2065), while the warmest temperature of the year would increase by 6.5°F.

Future Summer Heat Stress

Daytime temperatures in the Northeast have not changed as much in recent decades as nighttime temperatures. Warm nighttime temperatures increase carbon loss through plant respiration and can have a negative impact on carbohydrate accumulation and crop yield. Summer heat stress (day or night) during critical plant growth stages can lead to significant yield reductions in many grain, vegetable, and field crops. Even when production quantity is not affected, short duration summer heat stress can reduce crop quality and therefore marketable yield of high-value fruits and vegetables.

(text continues after graphs on next two pages)

Projected increase in number of days with temperature >= 90°F, from 1994 to 2055, and from 1994 to 2085



a. Number of days with temperature >= 90°F in 1994.

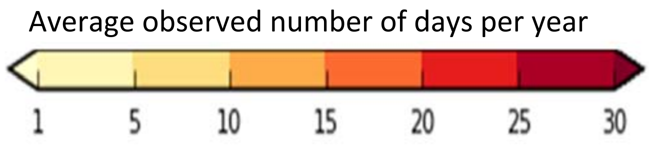
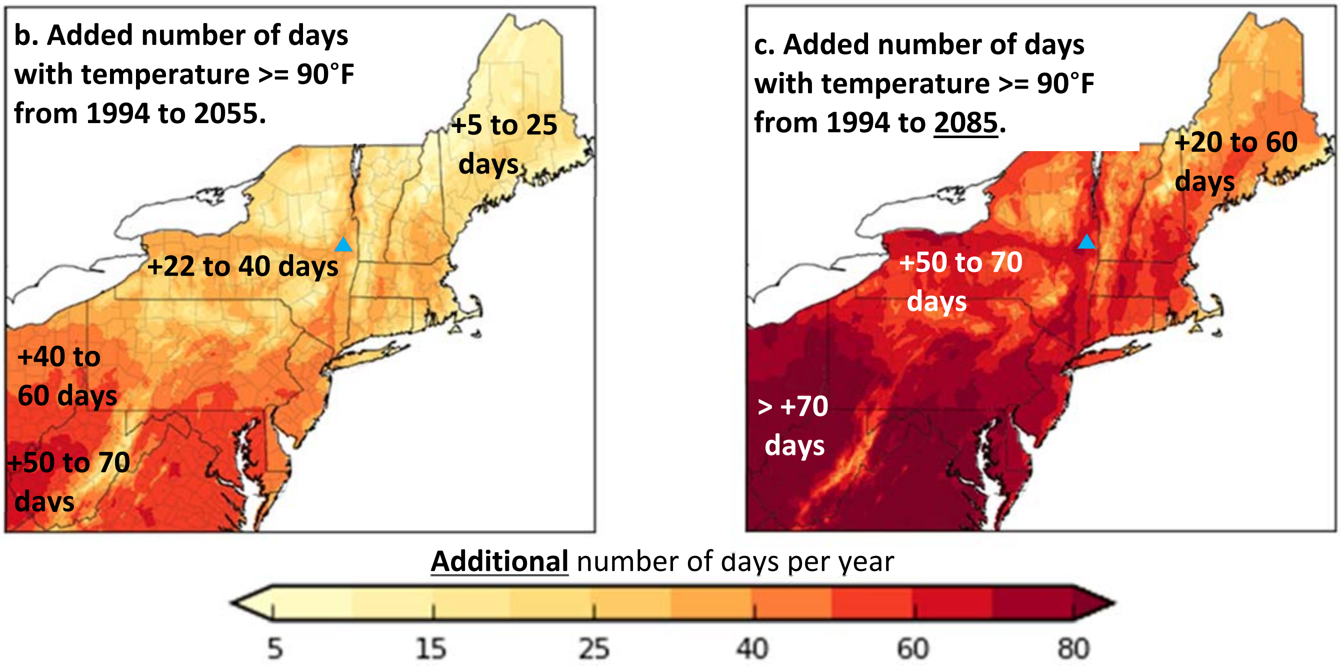


Figure 9a. Model simulated number of days per year with temperature >=90°F in 1994 (1979–2008 average). At Saratoga Springs NY, (▲ on map), there were an average of 8.1 days per year with a temperature >= 90F in 1981–2010 (NOAA, 2013a).



b. Added number of days with temperature >= 90°F from 1994 to 2055.

c. Added number of days with temperature >= 90°F from 1994 to 2085.

Figure 9b. Number of days with maximum temperatures >=90°F added from 1994 to 2055 (1979–2008 vs. 2040–2069) under the RCP8.5 high emissions scenario. Under a combination of moderate and high future emission scenarios (RCP4.5, RCP8.5), the number of days per year >=90F at Saratoga NY, (▲ on map) is projected to average 34 (80% confidence interval 22 to 50 days) in 2054 (2050–2059) (Horton et al., 2014).

Figure 9c. Number of days with maximum temperatures >=90°F added from 1994 to 2085 (1979–2008 vs. 2070–2099) under the RCP8.5 high emissions scenario. Under a combination of moderate and high future emissions scenarios, the number of days per year >=90F at Saratoga NY (▲ on map) is projected to average 53 (80% confidence interval 27 to 82 days) in 2054 (2050–2059) (Horton et al., 2014). Figures 9a-c adapted from Wolfe et al., 2018.

Projected increase in number of days with temperature over 95°F, from 1994 to 2055, and from 1994 to 2085.

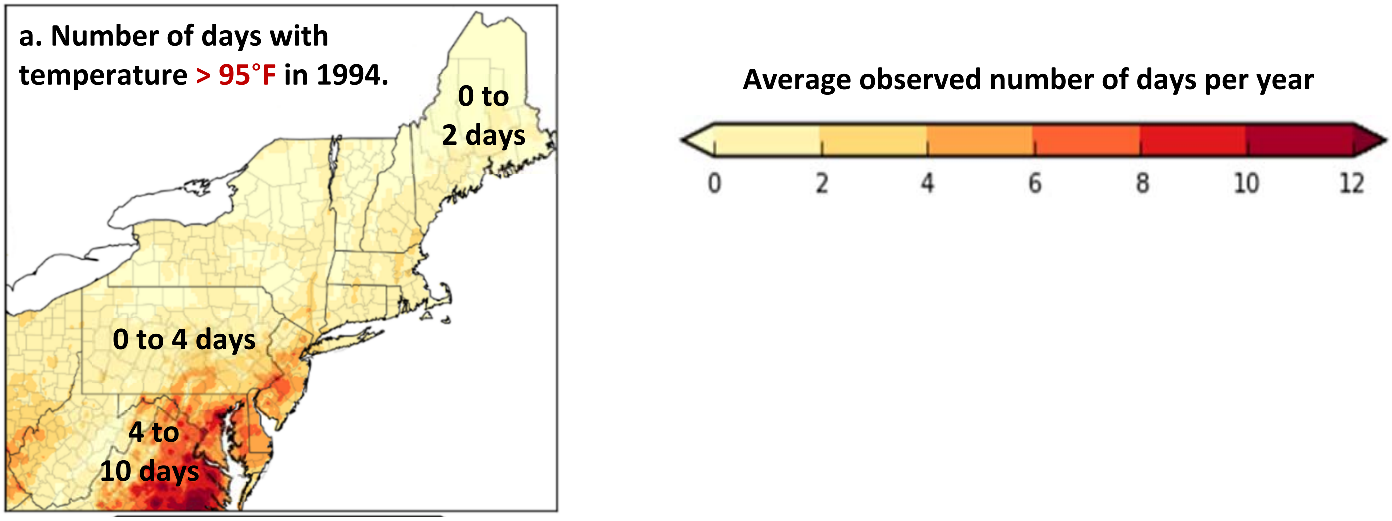


Figure 10a. Model simulated number of days per year with maximum temperatures >=95°F in 1994 (1979–2008 average).

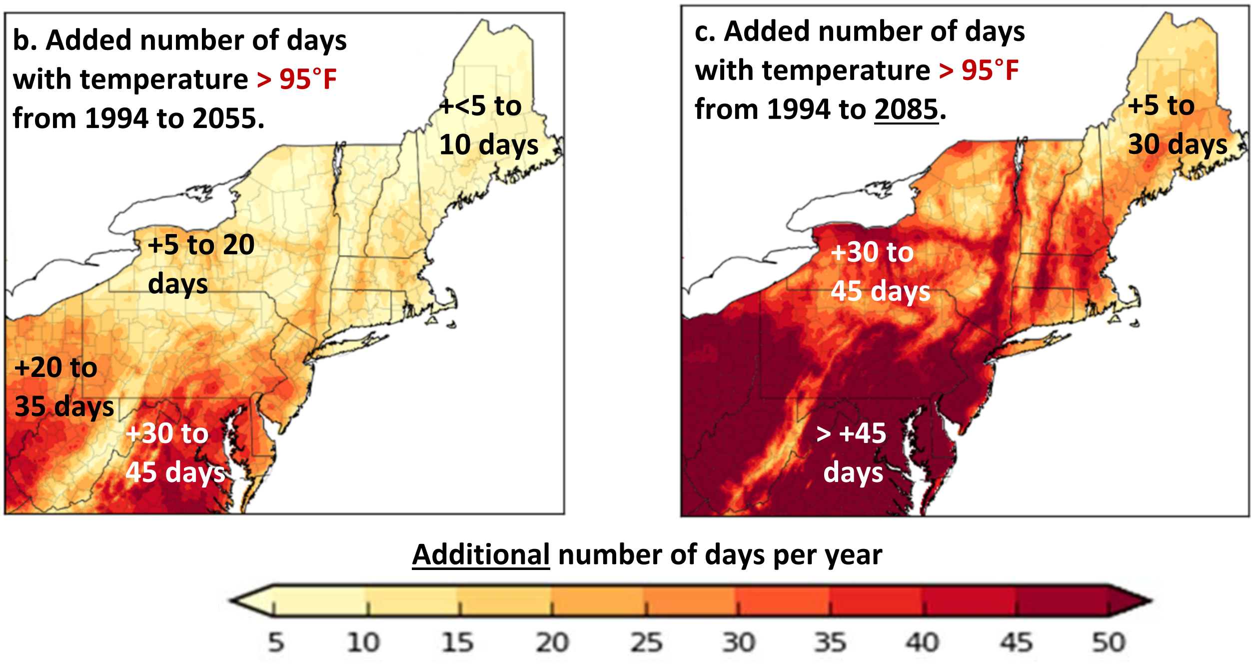


Figure 10b. Number of days with temperatures >=95°F added from 1994 to 2055 (1979–2008 vs. 2040–2069) under the RCP8.5 high emissions scenario. Under the moderate emissions scenario (RCP4.5), the number of days >=95°F added from 1994 to 2085 is similar to Figure 10b.

Figure 10c. Number of days with temperatures >=95°F added from 1994 to 2085 (1979–2008 vs. 2070–2099) under the RCP8.5 high emissions scenario. Figures 10a-c adapted from Wolfe et al., 2018.

Future Summer Heat Stress (cont.)

Recent research (Budikova et al. 2019) indicates that reduction of summer ice in the Arctic is associated with an increased frequency of summer heat waves in the continental U.S., including the east coast.

Climate projections suggest that there will be a significant increase in both day and night temperatures over the next 80 years. Cool season adapted crops currently grown in the Northeast would be particularly susceptible to an increase in the number of days with high temperatures sufficient to decrease crop yield or quality.

The text below is adapted from Wolfe et al. 2018.

> Areas south of Philadelphia are projected to experience up to 70 additional days with a maximum temperature of 90°F or above by 2055 (2040–2069) under the RCP8.5 scenario high emissions scenario. Results were similar for the moderate emissions RCP4.5 scenario, not shown). This region currently experiences 15-30 such days.
>
> Areas of central New York and New England, which currently experience fewer than 10 days with temperatures of 90°F or above, are projected to experience up to 25 additional days above this threshold by 2055 (2040–2069) under the high emissions scenario.
>
> More than two-thirds of all summer days will have daily high temperature over 90°F at locations south of New York City by 2100 under the RCP8.5 scenario, with the exception of extreme coastal locations and high elevation inland locations.
>
> Under the RCP4.5 moderate greenhouse gas emissions scenario, the increase in the number of days with temperature ≥ 90°F by 2070–2099 is projected to be about half that of the RCP8.5 high emissions scenario.

End of text adapted from Wolfe et al. 2018.

Observed increase in the length of the frost-free season.

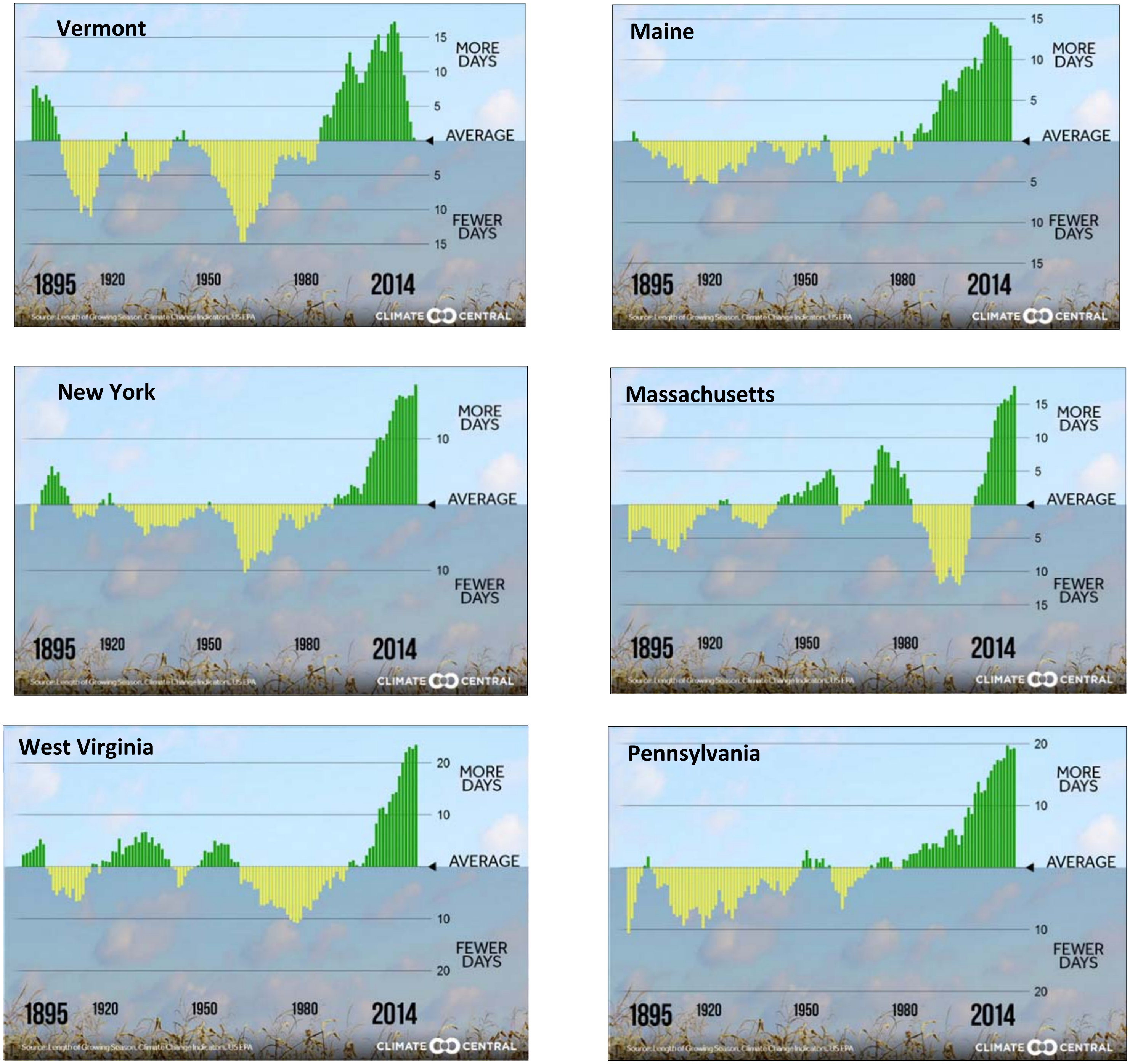


Figure 11. The average frost-free season in the Northeast region is now at least 10 days longer than the 1950-1980 average. Adapted from Climate Central (2015), which also has 1895 to 2014 frost-free growing season graphs for each of the other Northeast states.

Projected change in final spring, and first fall, frost dates from 1994 to 2055.

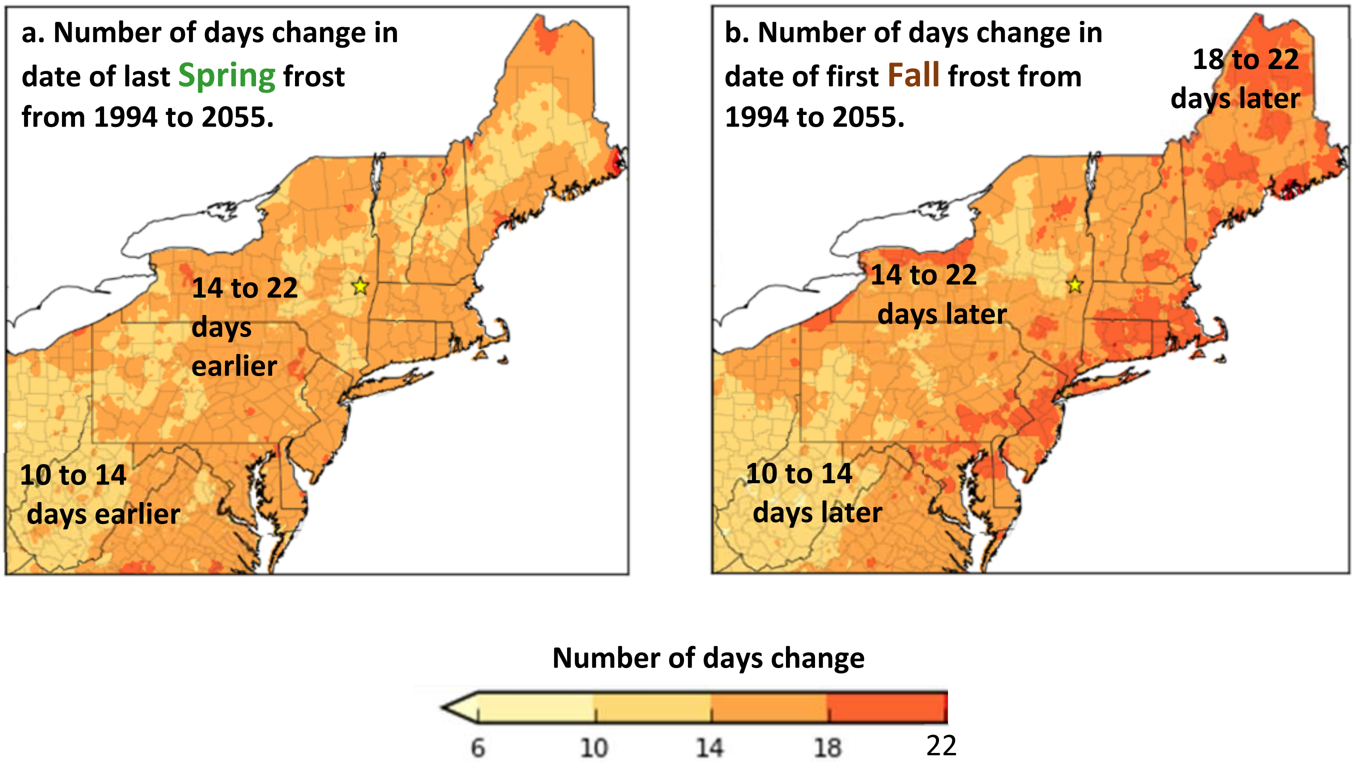


Figure 12a. Change in model-simulated date of last Spring 32°F frost from 1994 to 2055 (1979–2008 vs. 2040–2069) under the RCP8.5 high emissions scenario. At Albany NY, (☆on map), the average last Spring 32°F frost date in 1981–2010 was April 28 (NOAA, 2015). At 14 days earlier, the average final spring frost date in Albany could shift to April 14.

Figure 12b. Change in model-simulated date of first Fall 32°F frost from 1994 to 2055 (1979–2008 vs. 2040–2069) under the RCP8.5 high emissions scenario. At Albany NY, (☆on map), the average first Fall 32°F frost date in 1981–2010 was October 10. By 2055 the average first fall frost date in Albany could shift to October 24. Figures 12a and 12b adapted from Wolfe et al., 2018.

The average spring to fall frost-free interval in Albany in 1981–2010 was 163 days (NOAA, 2013b). With a 14-day extension for both the spring and fall frost dates, the average frost-free interval in Albany would become 191 days. At Beltsville MD, the average interval between spring and fall dates with temperatures below 32 F in 1981–2010 was 195 days (NOAA, 2013b).

Not shown: Under the RCP4.5 moderate emissions scenario the projected change in spring and fall frost dates between 1994 and 2055 is about 7 days earlier/later on each end, with a total frost-free interval increase of about 14 days. By 2085, under the RCP8.5 high emissions scenario, the last spring frost date is expected to occur 3–4 weeks earlier than in 1994, and the first fall frost date 3–4 weeks later than in 1994, for a total 6–8 weeks (42–56 days) longer frost-free period than in 1994.

Projected increase in annual growing degree-days, from 1994 to 2055, and from 1994 to 2085.

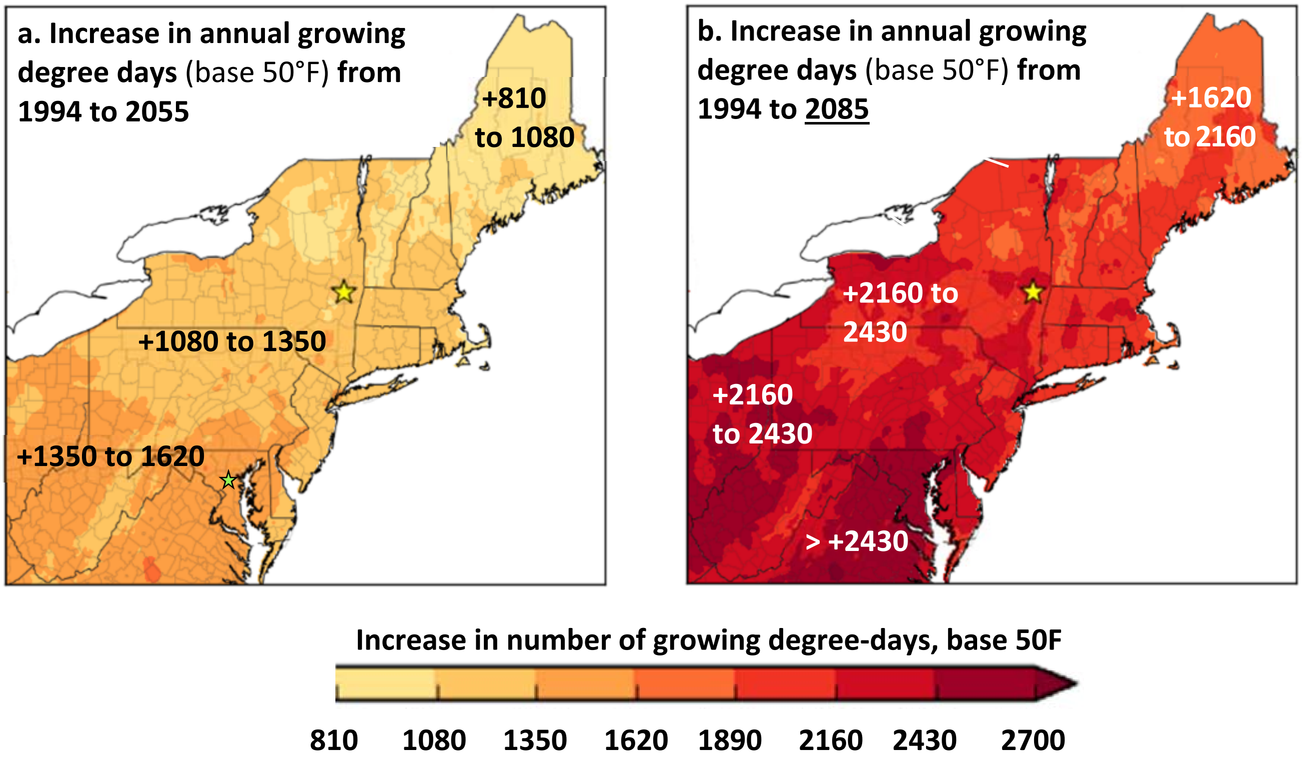


Figure 13a. Increase in total annual base 50°F growing degree-day (DD) accumulation from 1994 (historical 1979-2008 simulations) to 2055 (2040–2069) under the RCP8.5 high emissions scenario.

Figure 13b. Increase in in total annual base 50°F growing degree-day accumulation from 1994 (historical 1979–2008 simulations) to 2085 (2070–2099) under the RCP8.5 high emissions scenario. Figures 13a and 13b adapted from Wolfe et al., 2018.

The 1981–2010 the average annual cumulative growing degree-days (base 50F, DD50F) in Albany NY (☆ on map) was 2,649 (NOAA, 2013a). An additional 1,200 DD by 2055 would be a 45% increase to 3,849, and cumulative DD50F in Albany NY would be slightly larger than the 1981–2010 average of 3,831 DD50F for Beltsville, MD (☆ on map), (NOAA, 2013a).

The projected cumulative DD50F at Augusta ME in 2055 would be about the same as the 1981-2010 average for Harrisburg PA. The projected cumulative DD50F at Harrisburg PA in 2055 would match the 1981–2010 average for Richmond VA (NOAA, 2013a).

A projected increase of 2,160 DD50F in Albany NY between 1994 and **2085** would be an 81% increase over the 1981-2010 average, about the same as the 1981-2010 average at Norfolk VA (almost the warmest location in VA), and almost as high as the 1981-2010 average for Raleigh NC.

The text below is adapted from Wolfe et al., 2018.

> ## Winter freeze damage.
>
> Winter freeze damage can occur when severe cold temperatures are preceded by warm fall or early winter temperatures that delay winter hardening or if warm temperatures occur midwinter, causing the plants to lose hardiness. Such winter cold events caused millions of dollars of losses in the New York Finger Lakes wine region during 2003–2004, and 2013–2014. In the winter of 2015–2016, winter freeze damage to peaches caused a complete crop loss for most of the peach orchards in northern parts of the Northeast region.
>
> ## Future soil temperature and frost.
>
> **The frequency of soil freeze-thaw events is expected to increase** with increasing winter temperatures leading to a reduction in the depth and duration of snowpack. Across much of the Northeast, snow cover insulates the soil surface from changes in air temperature, thereby helping reduce both the number of freeze-thaw cycles and the depth to which frost penetrates the soil. Projections of future soil temperature and frost suggest increased soil frost where snowpack is reduced. Conversely, warming air temperatures may warm soils in southern areas of the Northeast that currently receive less snow and do not typically have a dense snowpack.
>
> ## Fruit tree bud frost and freeze damage.
>
> **Warmer winter and early spring temperatures accelerate leaf-out and bud development in many fruit crops, exposing them to an extended period of vulnerability to frost damage.**
>
> Unusually warm temperatures in late winter and early spring across the Eastern USA in 2012 led to record-breaking early flowering of many plant species. In that year, apples bloomed 3 to 4 weeks earlier than the historical average, which was then followed by a series of spring frost events. Nearly half the New York apple crop was lost, costing growers millions of dollars. Significant damage to apple buds occurred again in spring 2016 after another mild winter, followed by April frost events. An analysis of recent historical data for apple, grapes, and lilac in the Northeast found a trend for earlier bloom of all three species since the 1960s.
>
> Apple spring growth stages of green tip, tight cluster, and full bloom would occur about 15 days earlier in the Northeast by 2100 compared to current dates under the high emissions scenario (RCP8.5).
>
> **However, the relationship between climate effects on bloom date and risk of frost damage is complex.** Successful flowering in most temperate perennial plants is determined by (1) meeting the winter chill requirement (a period of winter low temperatures required to break endodormancy), (2) winter and spring warming and degree-day accumulation to break ecodormancy, and (3) avoiding a spring frost event as buds develop and become vulnerable to cold damage. All three of these factors will be greatly influenced by projected climatic changes.
>
> Studies of spring frost risk to fruit trees have found mixed results, with both increased and decreased risk found for different specific sites and under different climate scenarios. We conducted a modeling study for the Northeast (Figure 14) and found a small increase in frost risk for some apple flower phenological stages (e.g., bloom) within the next three decades (2010–2039), followed by a decline in frost risk after mid-century.
>
> End of text adapted from Wolfe et al. 2018.

Projected changes in frequency of years with apple bud freeze risk.

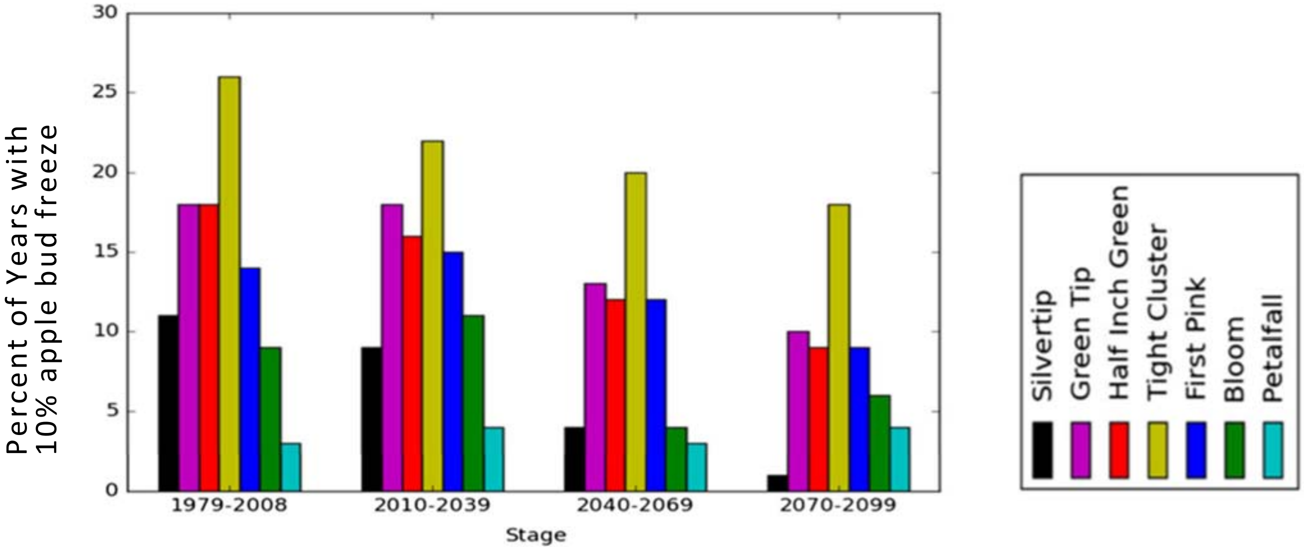


Figure 14. Percentage of years experiencing a lethal frost event resulting in 10% apple flower bud damage from Silvertip to Petal fall in the Northeast. Future periods are based on the RCP8.5 high emissions scenario. Frost risk represents the percentage of 300 model-years (10 models × 30 years each) in which at least one freeze event occurred during each development stage during the 30-year period. Freeze events can occur for multiple stages within a single year. Adapted from Wolfe et al., 2018.

Observed and projected earlier calendar dates for apple budstages.

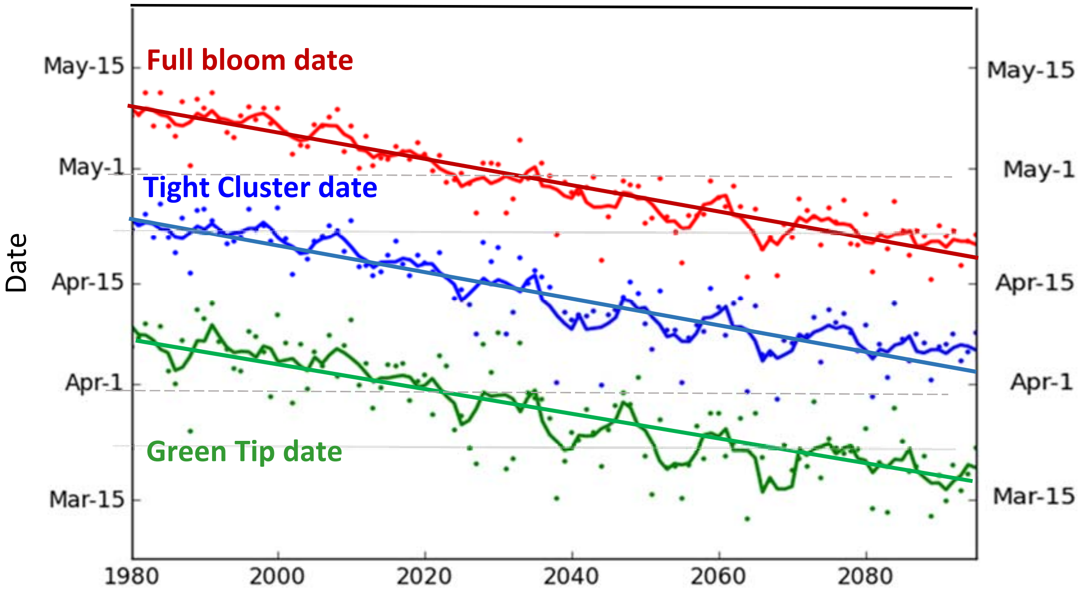


Figure 15. Change in the date of the Green Tip (green); Tight Cluster (blue) and Full Bloom (red) stages of apple development based on the average of 10 downscaled climate model simulations for Geneva, NY. Future (2009–2099) simulations are based on the RCP8.5 emissions scenario. Dots illustrate the year-to-year variation of the modeled dates. The wavy lines show the five-year running average, and the straight lines are a visual estimate of the long-term linear trend. Adapted from Wolfe et al., 2018.

Projected chilling hours in 2025 and 2055.

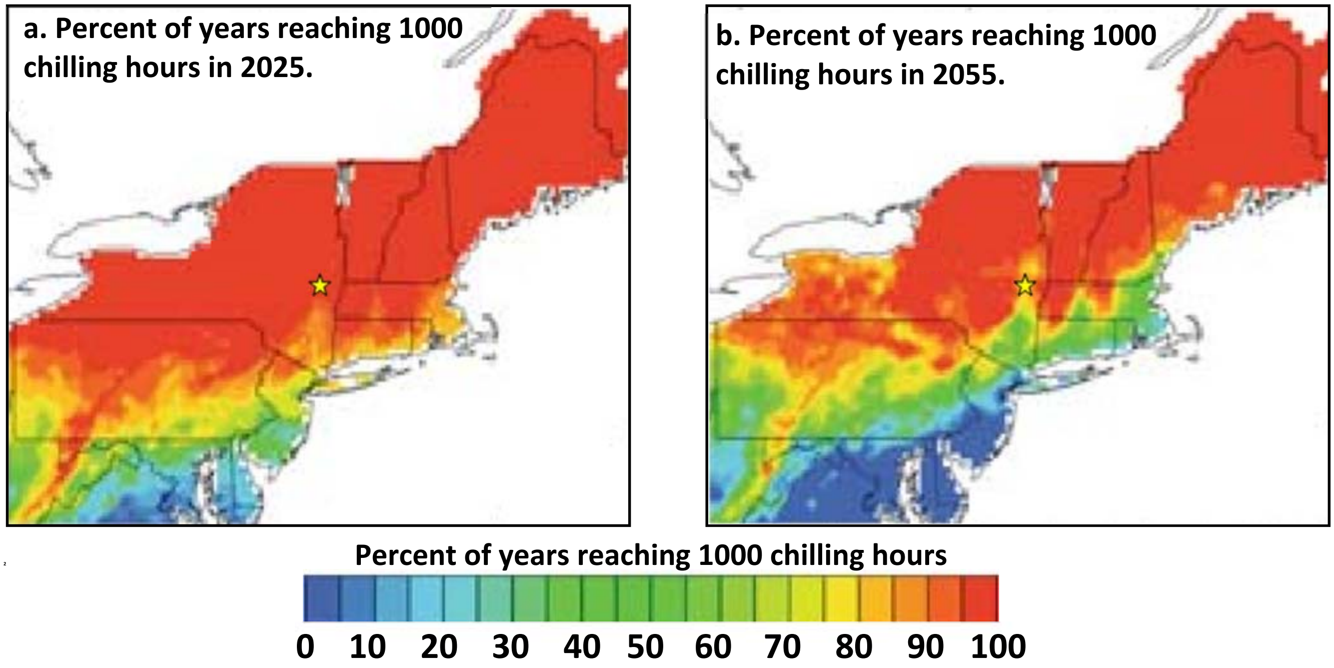


Figure 16a. Projected percentage of years during 2010–2039 when a 1000 hour winter chill requirement (cumulative hours below 45°F threshold) will be met for a high emissions scenario (A1F1 scenario, with warming similar to RCP8.5).

Figure 16b. Same as above but for 2040–2069. Figures 16a and 16b adapted from Wolfe et al. 2008.

The text below is adapted from Wolfe et al., 2008.

> For crops requiring a prolonged “winter chilling” period to flower, yields will be negatively affected if the chilling requirement is not completely satisfied, even if spring and summer temperatures are optimum for growth. Many varieties of agricultural shrubs (e.g., blueberry, *Vaccinium corymbosum*), fruit trees (e.g., apples, grapes), and winter cereal grains (e.g., winter wheat, *T. aestivum*), have a winter chilling requirement of 200 to 2000 cumulative hours within a very narrow temperature range (typically 32–50°F with optimum chill-hour accumulation at 45°F). Temperatures below or above this range are usually ineffective in meeting the chill requirement, and in some cases warm temperatures (e.g., >59°F) can negate previously accumulated chill hours. Chilling hour requirements also vary by variety. For example, native American grapes (*V. labruscana*) have a much longer chilling requirement than *V. vinifera* varieties. Chill requirements for apple range from 400 to 1800 hours, with varieties Gala and Red Delicious at the low end of the scale, and McIntosh and Empire at the high end of the scale.
>
> Currently, most of the Northeast satisfies an 1800-hour chilling requirement in most years. Under a high emissions scenario similar to current emissions, by 2040–2069 much of the southern Northeast could have less than 50% of years meeting an 1800 chill hour requirement. A large portion of the southern and coastal Northeast would accumulate 1000 chilling hours in less than 65% of years. Meeting the chilling threshold in at least 90% of years is considered necessary for profitable tree fruit production. A low chilling requirement threshold of 400 hours is projected to continue to be met for most of the region in most years through mid-century even under the high emissions scenario.
>
> The impact of not completing a chilling hour requirement varies with crop species and variety. Physiological effects include delayed foliation, uneven bloom, reduced fruit set, increased vegetative suckering, and reduced fruit quality.

End of text adapted from Wolfe et al., 2008.

PRECIPITATION

****

Observed change in seasonal average precipitation, 1930 to 2001.

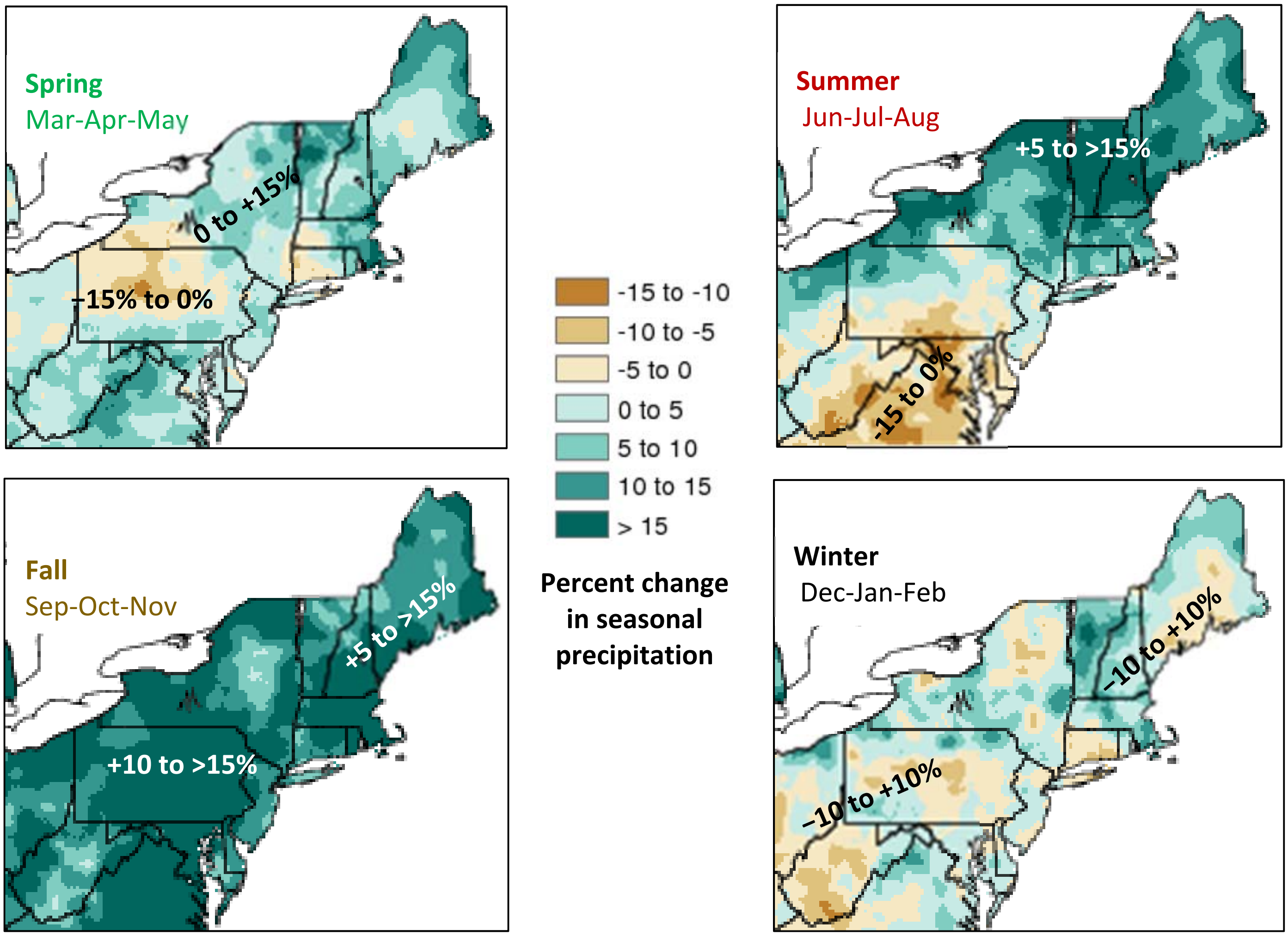


Figure 17. Seasonal average precipitation change from 1931 (1901–1960) to 2001 (1986–2016). Adapted from Easterling et al., 2017.

Annual average precipitation in the Northeast increased by 7.3% between 1931 and 2001, i.e. just over 1% increase per decade on average. But the trend was not consistent.

From 1901 to 1970, the trend was a **decline** of -0.4% per decade. From 1971 to 2016, the trend was an **increase** of +3.0% per decade.

Observed Northeastern U.S. average annual precipitation, 1988 to 2017.

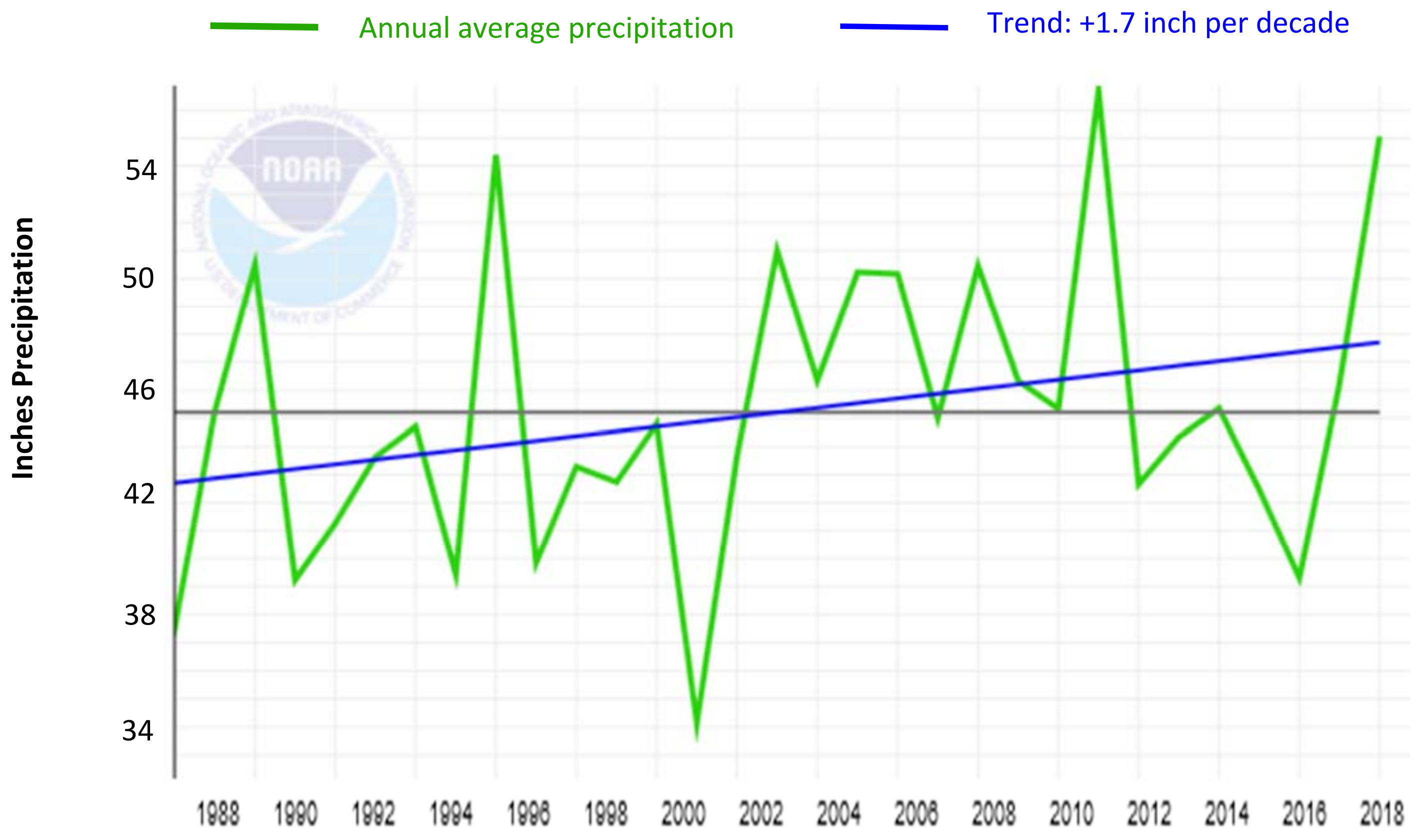


Figure 18. Average annual precipitation for the Northeastern U.S. from 1988 to 2018. The annual average increased by 5 inches (12%) in 31 years. Adapted from NOAA, 2018b.

Within the 30-year upward trend, the annual average rises and falls between individual years. Inter-annual variability will continue and perhaps increase in the coming decades. The increase for 1988 to 2018 in this graph indicates that the seasonal increases shown in Figure 17 have primarily occurred since 1988.

Observed increased intensity of extreme precipitation.

One of the most pronounced changes in climate in the Northeast during the past several decades has been the increase in the intensity of high volume precipitation events. This increase in extreme rainfall is projected to continue through the current century with the largest proportional increases in the north and at higher elevations. New England has had an especially large increase in number of days with heavy precipitation (Kunkel et al. 2013).

In addition to direct crop damage and increased disease pressure, high rainfall events can lead to soil erosion and negative environmental consequences of sediment, agricultural chemicals, or animal manure runoff into surface waterways.

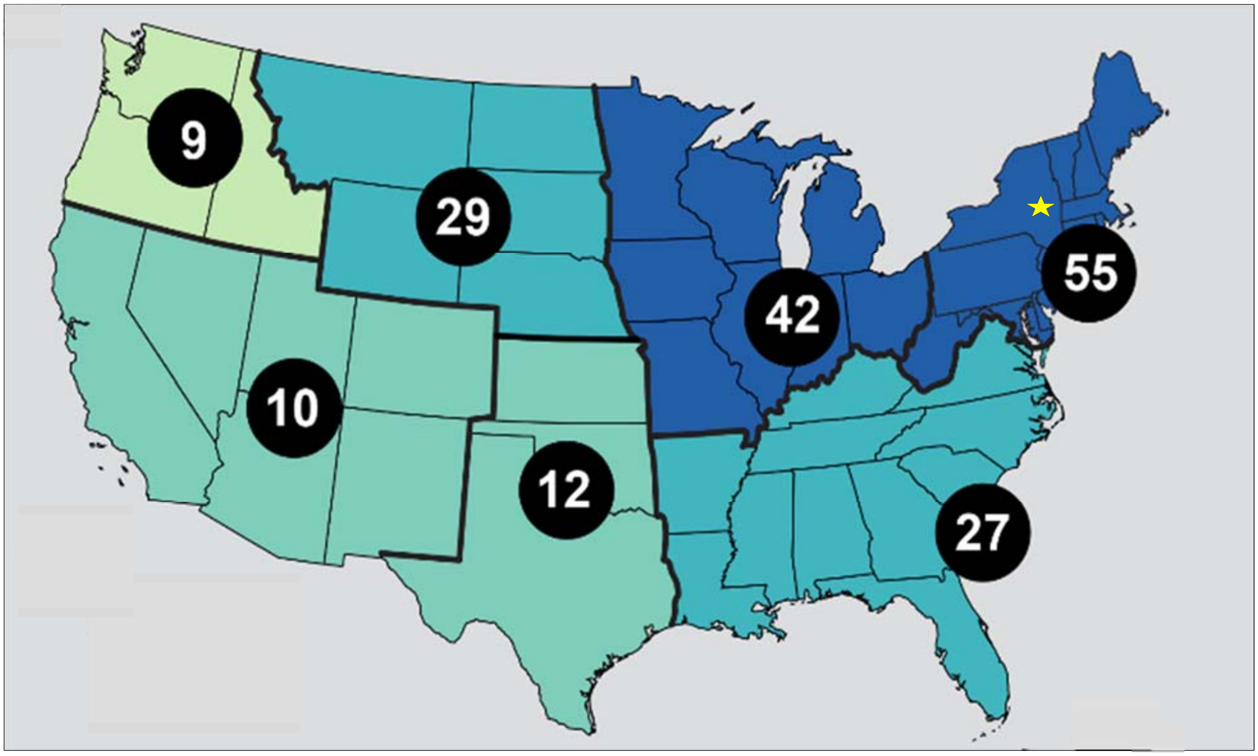


Figure 19. Percent increase in amount of water in the top 1% precipitation events from 1958 to 2016. "Top 1%" events are those that rank within the top 1% for water volume for all precipitation events that year. Adapted from Easterling et al., 2017.

Spierre and Wake (2010) documented change in the number of 1+ inch precipitation events in the Northeast from 1948 to 2007. Most locations showed an increase, but there was not a strong, region-wide trend. Almost 90% of the increase that did occur was in spring and summer**,** with less than 10% of the increase in the number of 1+ inch precipitation events occurring in fall and winter. The increase was highest in the most recent decades.

At Albany NY (★ on map), the average number of days per month with 1 inch or greater precipitation in May through September was 0.72 in 1971–2000, and 0.76 in 1981–2010 (NOAA 2004, NOAA 2013).

Observed increase in frequency of 2+ inch precipitation in 24 hours in Maine.

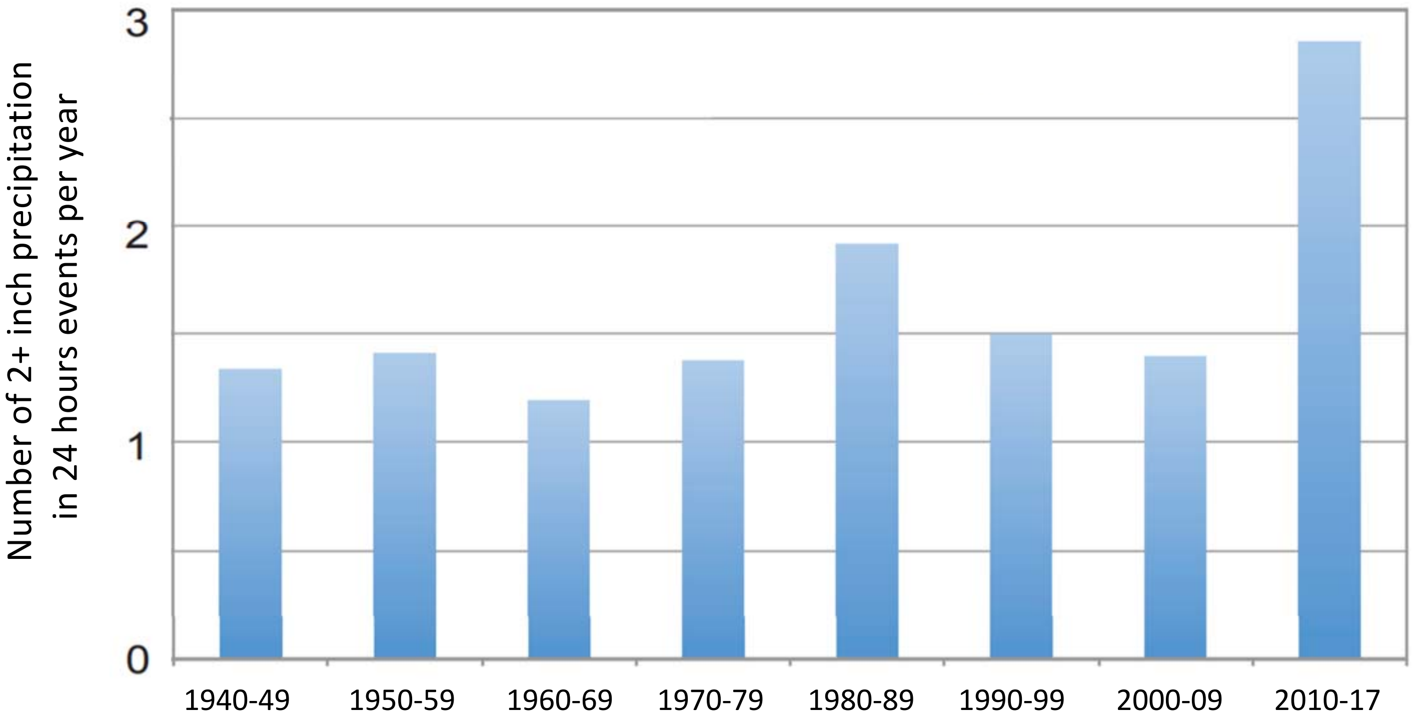


Figure 20. Average number of 2+ inch precipitation within 24 hours events per year at 17 long-term observation sites in Maine. Chart adapted from Birkel and Mayewski, 2018.

The maximum amount of precipitation in 24 hours per year for stations across the Northeast averaged 2.6 inches from 1948 to 2007. The "once per 5 years" maximum 24-hour precipitation average was 3.9 inches. The "once per 10 years" maximum 24-hour precipitation average was 4.5 inches (Spierre and Wake, 2010).

Further increases in rainfall intensity are expected, with increases in precipitation expected during the winter and spring, and less change in the summer and fall (USGCRP, 2018).

Projected change in seasonal precipitation from 1994 to 2055.

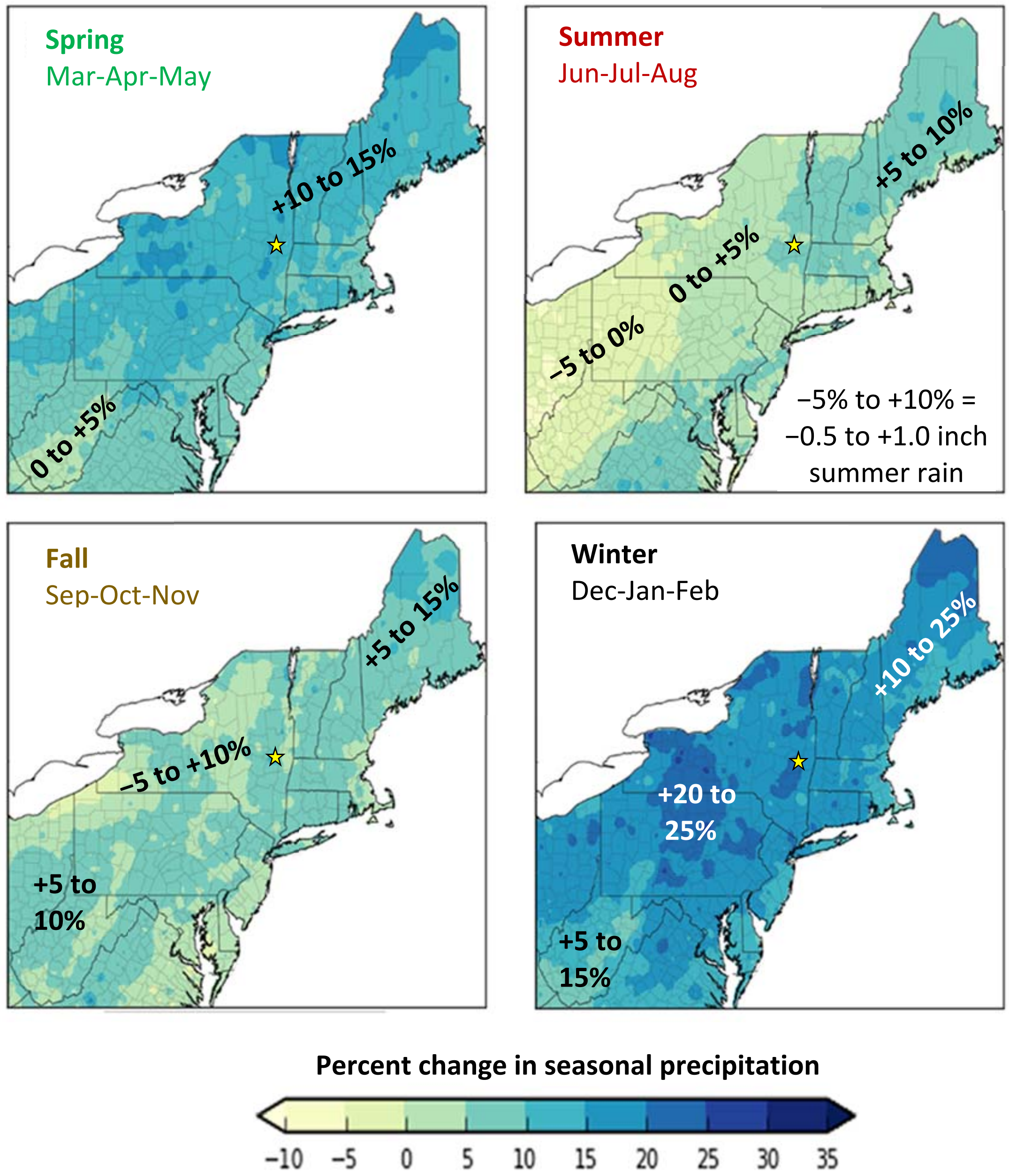
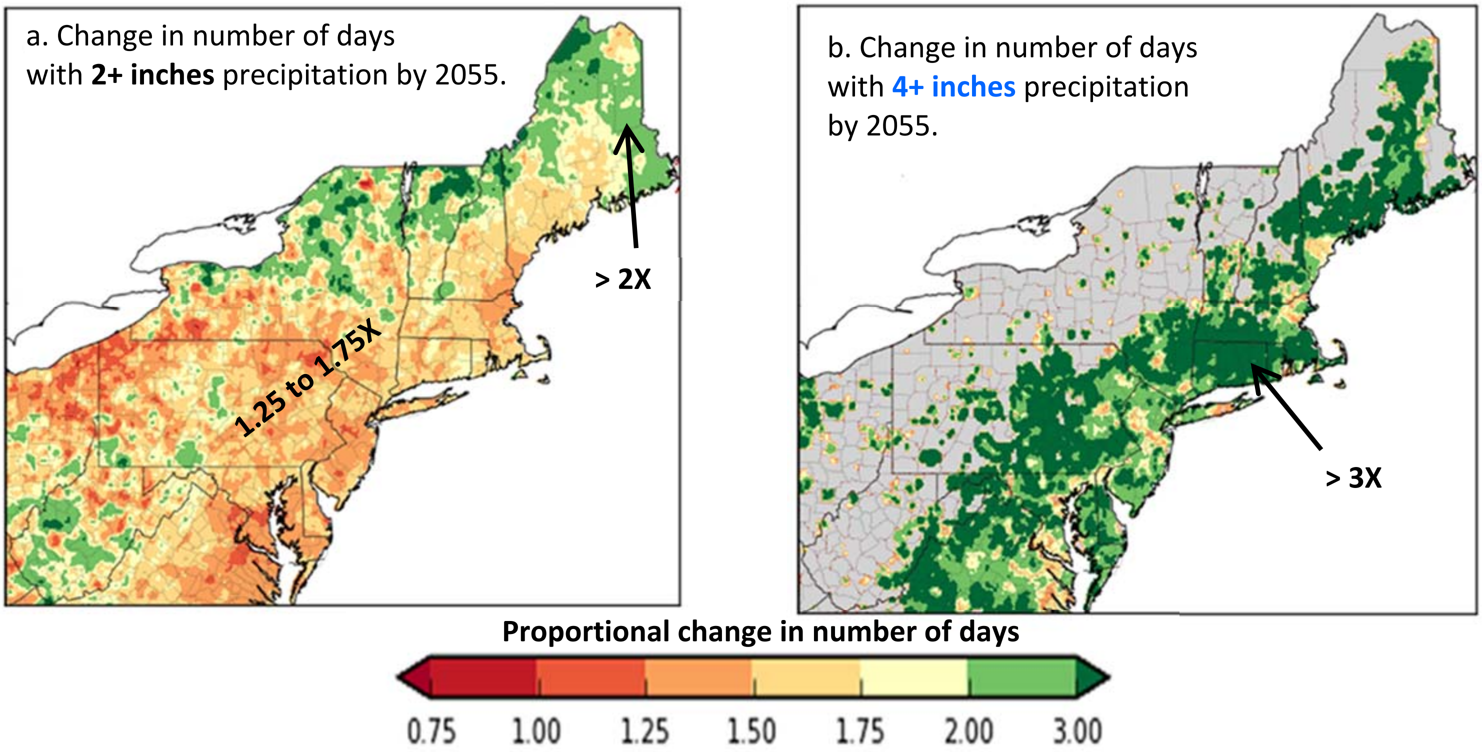


Figure 21. Percent difference in seasonal precipitation amounts from 1994 to 2055 (1979–2008 vs. 2040–2069) under the RCP8.5 high emissions scenario. Adapted from Wolfe et al. 2018.

Based on the seasonal increases, the average annual increase for the region by 2055 would be about 10%. At Albany NY, (☆ on maps), average precipitation in 1981-2010 (NOAA 2013a) was as follows. Spring: 10 inches, Summer: 11.4 inches, Fall: 9.8 inches, Winter: 7.7 inches. Thus, each 10% of relative change at Albany NY represents an absolute change of 0.8 to 1.1 inch.

Projections of future precipitation have much greater uncertainty than temperature projections (Zhuan et al., 2018). For example, an estimated increase of 8% in average annual precipitation at Saratoga NY between 1985 (1971–2000) and 2054 (2050-2059) had an 80% confidence interval of +2% to +15% (Horton et al., 2014). Seasonal projections are less precise than projections for annual average.

Projected increase in number of days with 2+ inch and 4+ inch precipitation, from 1994 to 2055.



1.00 = no change. 1.50 = 50% more days. 2.00 = Twice as many days.

Figure 22a. Proportional change in the average number of days per year with **2+ inches** of precipitation between 1994 and 2055 (1979–2008 vs. 2040–2069) under the RCP8.5 high emissions scenario.

Figure 22b. Proportional change in the average number of days per year with **4+ inches** of precipitation between 1994 and 2055 (1979–2008 vs. 2040–2069) under RCP8.5. Gray areas indicate areas where the annual frequency of 4-inch rainfall has been historically too small to calculate a proportional change. Figures 22a and 22b adapted from Wolfe et al., 2018.

By 2055, the frequency of 2+ inch precipitation events is projected to increase throughout the region under RCP8.5, with such events occurring 1.25 to 2 times more frequently at most locations, and some areas with a three-fold (3X = 300%) increase.

In New York City, the number of days per year with 2+ inches rainfall is projected to increase from an average of about 3 days per year in 1985 (1971–2000) to 4 days per year in 2054 (2050–2059), with an 80% confidence interval of 3 to 5 (Horton et al., 2014), under the moderate or high emissions scenario.

For most locations east of the Appalachians and along the Atlantic coast, the frequency of 4+ inch rainfall events is projected to increase by 2X to 3X by 2055 (2040–2069) under RCP8.5.

The text below refers to northern New York and New England, and was adapted from Janowiak et al., 2018.

> **There is a clear trend toward more frequent and more extreme precipitation events in the Northeast, and this is expected to continue.** It is important to consider this trend in combination with the projected increases or decreases in mean precipitation over the 21st century, because a given increase or decrease in precipitation may not be distributed uniformly across a season or even a month. Additionally, climate change may increase the year-to-year variation of precipitation across the northern United States. Therefore, the Northeast may experience more extremely wet and dry years in the future.
>
> **Under a high emissions scenario (RCP8.5), the Northeast could receive 21% more rainfall events of greater than 1 inch by 2100**, with larger events increasing by progressively larger amounts. The occurrence of events producing more than 1 inch of rain is projected to increase to total of 12 or more additional days per decade by 2100, with coastal areas in southern and central New England projected to have the greatest increases in heavy rainfall.
>
> Warmer temperatures are expected to continue to have dramatic impacts on the winter season. **The total amount of snowfall, and the proportion of precipitation falling as snow, decreased across the Northeast during the 20th century**, and these trends are expected to continue.
>
> **By 2100, total snowfall is projected to decrease by 10 to 50 percent under a low emissions scenario** (RCP4.5)**, and by 30 to 70 percent under a high emissions scenario** (RCP8.5). The most substantial reduction in snowfall amount is expected to occur at the beginning of the winter season, which is December for most of the region and January for southern coastal New England (Notaro et al. 2014). Similarly, the number of days with snow cover is projected to decrease, and southern parts of the region may lose a substantial portion of their current number of days per year with snow cover.
>
> One study projected decreases in **the number of snow-covered days across the region, with decreases up to 30 days per year in northern New York, Vermont, New Hampshire, and Maine by 2100**. Another study projected declines in snow depth of 40 percent or more across the region, with snow depth declining more than 80 percent in localized areas.

End of text adapted from Janowiak et al., 2018.

Observed and projected potential for delayed spring field access due to wet soils.

High rainfall events or prolonged rainy periods can cause delays in planting due to wet or flooded soils. This can effectively shorten the growing season, and may offset the trend for longer frost-free periods in the Northeast.

Projections show an increase in the frequency of years with excessive rainfall prior to last frost date, (defined here as more than 2.7 inches rain in the 21 days just prior to the last frost). Saturated soil in spring can interfere with planting for annual crop growers and for critical pest and horticultural treatments for tree fruit and other perennial crop growers. This counteracts the positive effect for longer growing season, and illustrates why “growing season” and “frost-free period” are not synonymous.

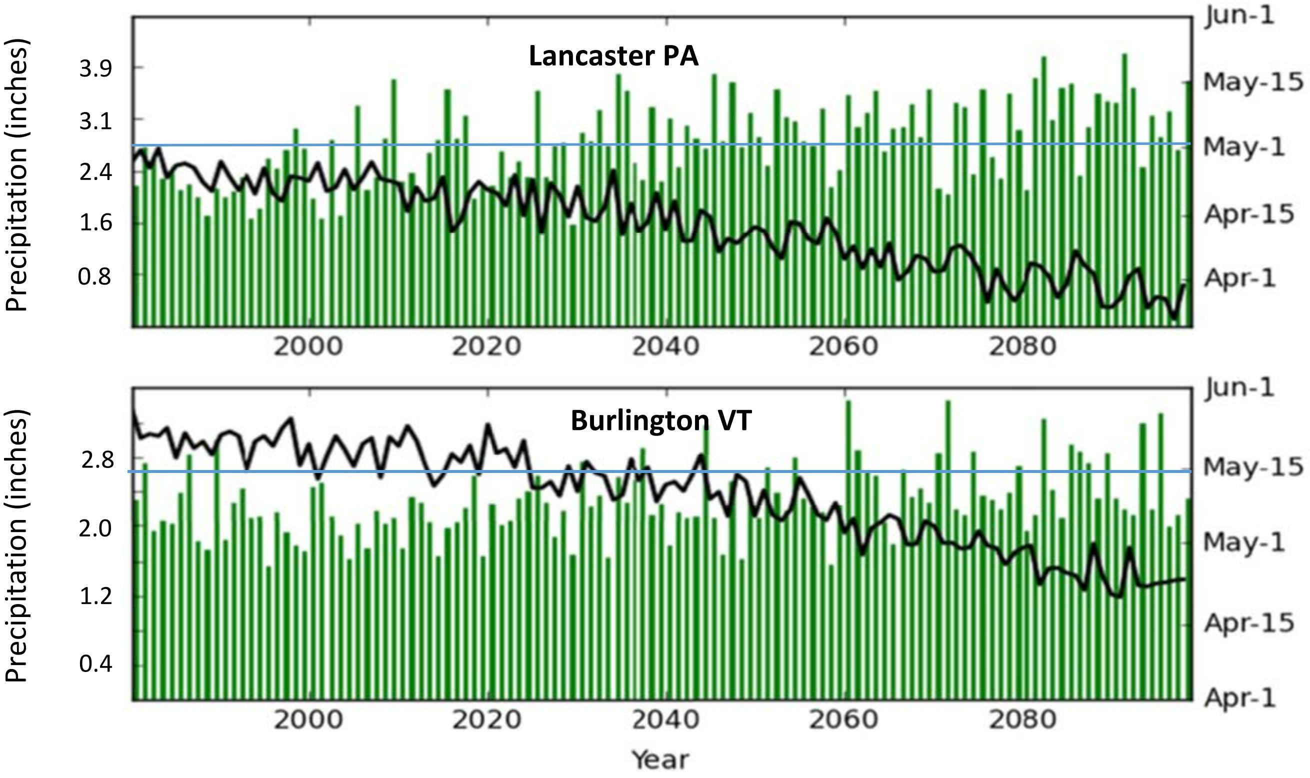


Figure 23a. Rainfall in the 21 days prior to last spring frost (green bars, precipitation amount on left axis), and date of last spring frost (black line, dates on right axis) for 1980–2100 for Lancaster, PA. RCP 8.5 emissions scenario used to project values for years after 2010. The blue horizontal line marks the 2.7 inch hypothetical threshold for wet soil conditions.

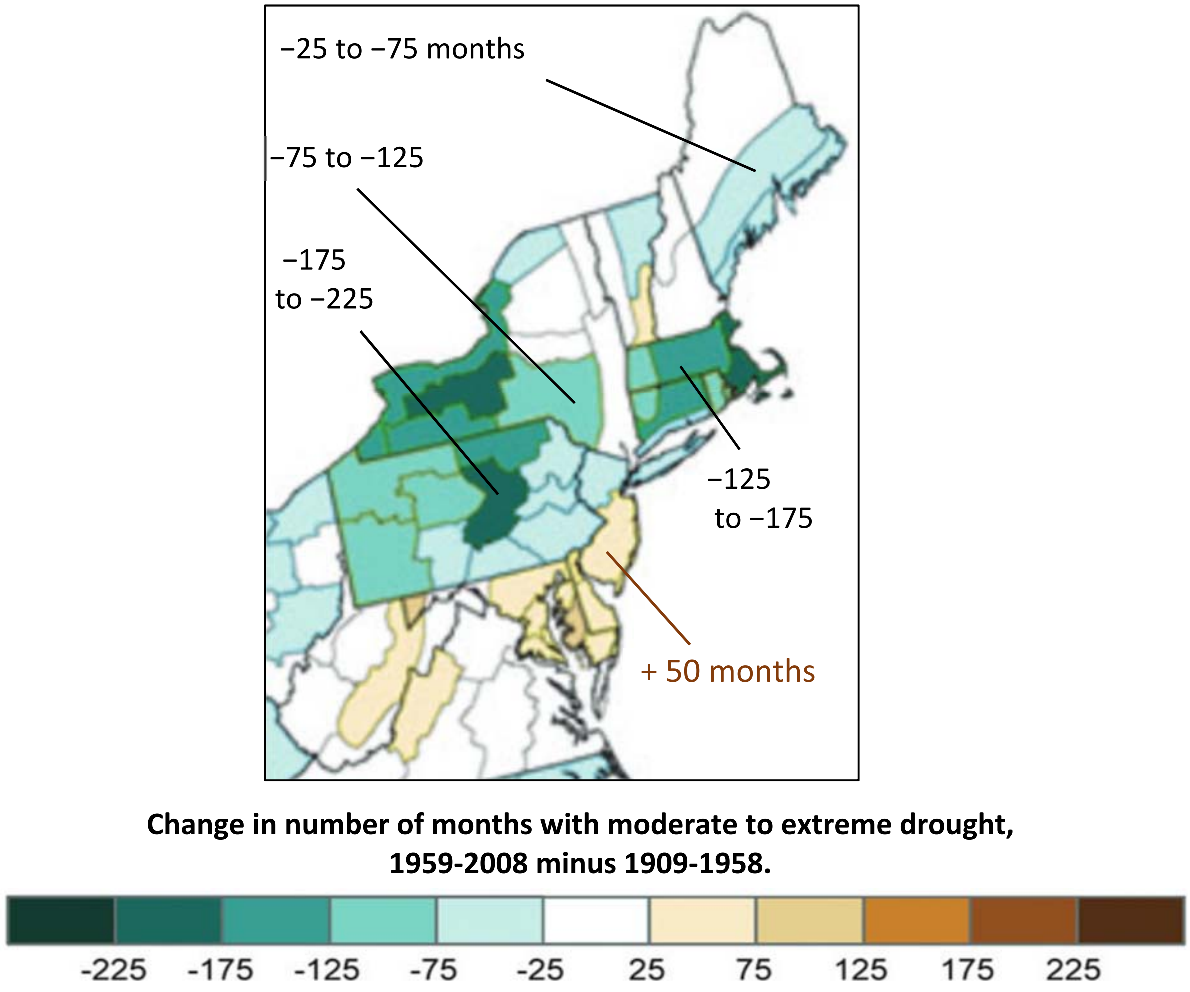
Figure 23b. Same as above, but for Burlington, VT. Note the different scale for precipitation. Figures 23a and 23b adapted from Wolfe et al., 2018.

DROUGHT, EVAPORATION, and SOIL MOISTURE

****

Observed number of drought months.

Over the last century (1909–1958 vs. 1959–2008), different areas across the Northeast vary in with respect to change in the number of months with moderate to extreme drought. The areas with fewer drought months (green shades) are larger in size and intensity than the areas with increased drought months (brown shades). Areas where the change in the number of drought months was less than +/- 25 months over the 49-year periods are shown in white.



Change in number of months with moderate to extreme drought, 1959-2008 minus 1909-1958.

Figure 24. Number of months with moderate to extreme drought during 1959-2008 minus 1900–1958, plotted by climate division. Green values indicate fewer months of drought in 1959–2008. Adapted from Peterson et al., 2013.

A total change of + or − 50 months across the 50 years of 1959–2008 represents a change of 1 month per year on average. Values not shown as average per year because droughts occur as sporadic sequences of consecutive months or years, so stating the change as an average per year would be misleading. Moderate to extreme drought defined as a monthly average Palmer Hydrological Drought Index of less than or equal to -2.0.

Projected increase in summer evaporation, from 1986 to 2055, and from 1986 to 2085.

Projected increases in potential evaporation for the Northeast in summer months (June, July, August) combined with minor change (-5 to +10%) increase in future summer precipitation suggests a potential for increased risk of summer drought. According to the estimate shown below, average summer precipitation would have to increase by 2 inches or more between 1986 and 2055 to maintain the same average soil moisture because of increased evaporation losses.

The expected change in summer precipitation between 1994 and 2055 varies across the region from -0.6 to +1.2 inches. Summer in the Northeast currently has a summer deficit of precipitation minus evaporation (and evapotranspiration). The projected precipitation and evaporation changes by 2055 would cause a net water loss across the 3 summer months of -0.8 inch (from +1.2 inches extra precipitation minus 2 inches extra evaporation) to -2.8 inches (-0.6 inches less precipitation minus 2.2 inches extra evaporation).

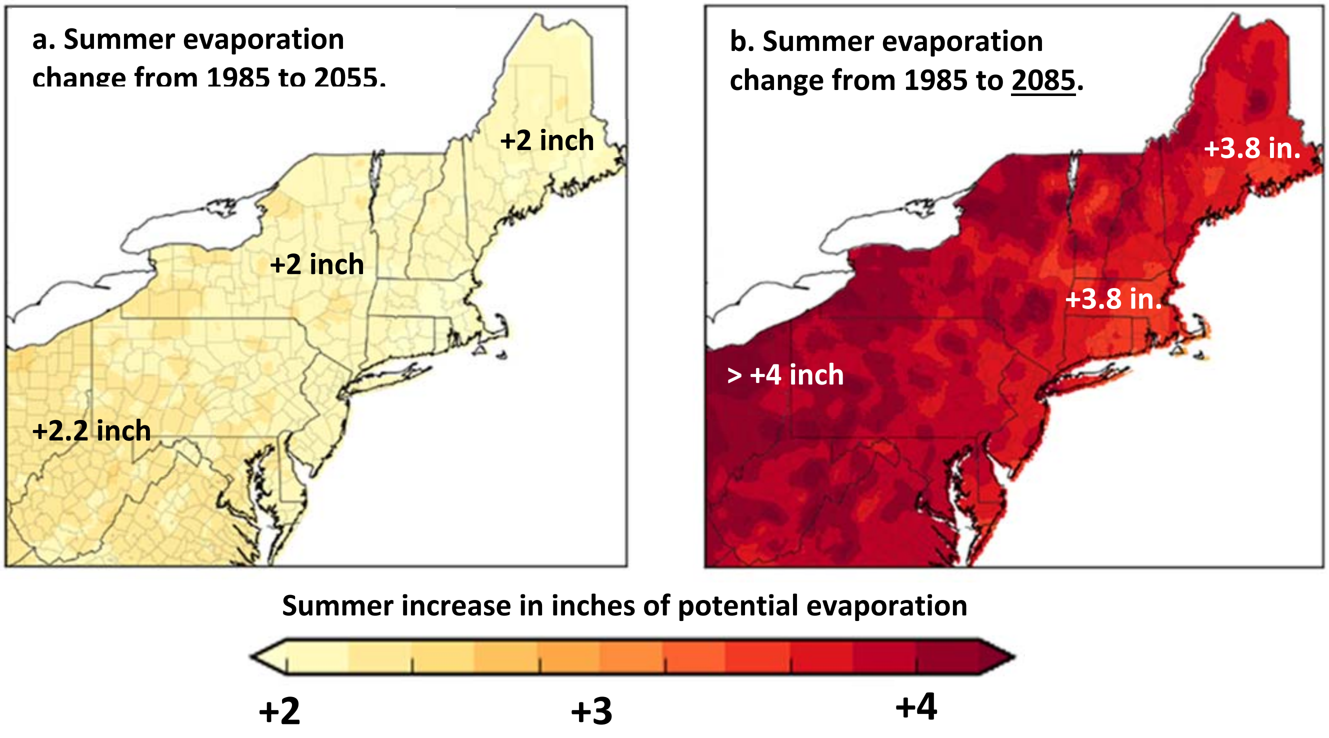


Figure 25a. Difference between model-simulated average summer potential evaporation from 1985 to 2055 (1971–2000 vs. 2040–2069) under the RCP8.5 high emissions scenario.

Figure 25b. Difference between model-simulated average summer potential evaporation from 1985 to 2085 (1971–2000 vs. 2070–2099) under the RCP8.5 high emissions scenario. Figures 25a and 25b adapted from Wolfe et al., 2018.

Projected annual average soil moisture in 2050 under a high emissions scenario.

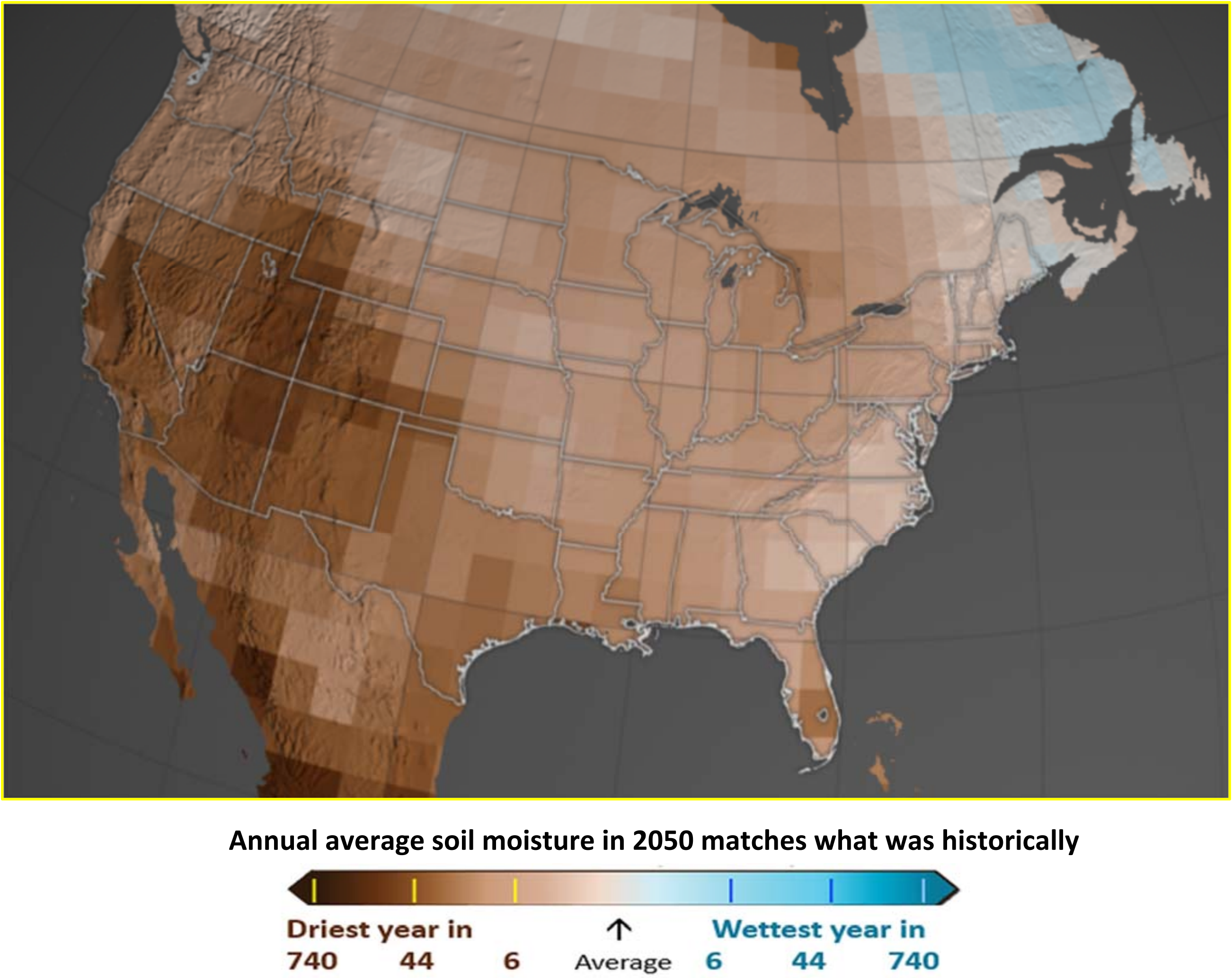


Figure 26. Ten-year average soil moisture (surface to 10 inches below surface) from 2050 to 2060 relative to the driest and wettest years over the previous 740 years. Values are derived from 17 climate models (CMIP5) using a high future emissions scenario (RCP 8.5). New England and eastern NY appear to remain near current average soil moisture. Western NY, PA, NJ, DE, and WV are shifted slightly towards drier average conditions. Adapted from NASA, 2015.

Note that annual average soil moisture does not represent summer drought potential. Relative to other areas of the U.S. and to the world, Naumann et al., 2018 estimated that the Northeastern U.S. is relatively neutral with respect to change in drought magnitude with global surface temperature increases of 1.5 C (2.7 F), 2.0 C (3.6 F), or 3.0 C (5.4 F) above the preindustrial average temperature. However, other more regionally focused studies suggest potential for increased short-term warm season drought stress in the Northeast.

For example, Rosenzweig et al. (2011) estimated that between 1985 (1971–2000) and 2054 (2050–2059) there is greater than 50% chance for an increase in the number of late-summer droughts lasting from a few weeks to a few months in the New York City area.

Similarly, Green et al. (2019) estimated between 1985 (1971-2000) and 2070 (2056-2085), under the high emissions scenario (RCP8.5), variability of soil moisture would increase by 20 to 25% for most locations in the Northeast.

Change in soil moisture variability from 1985 to 2070.

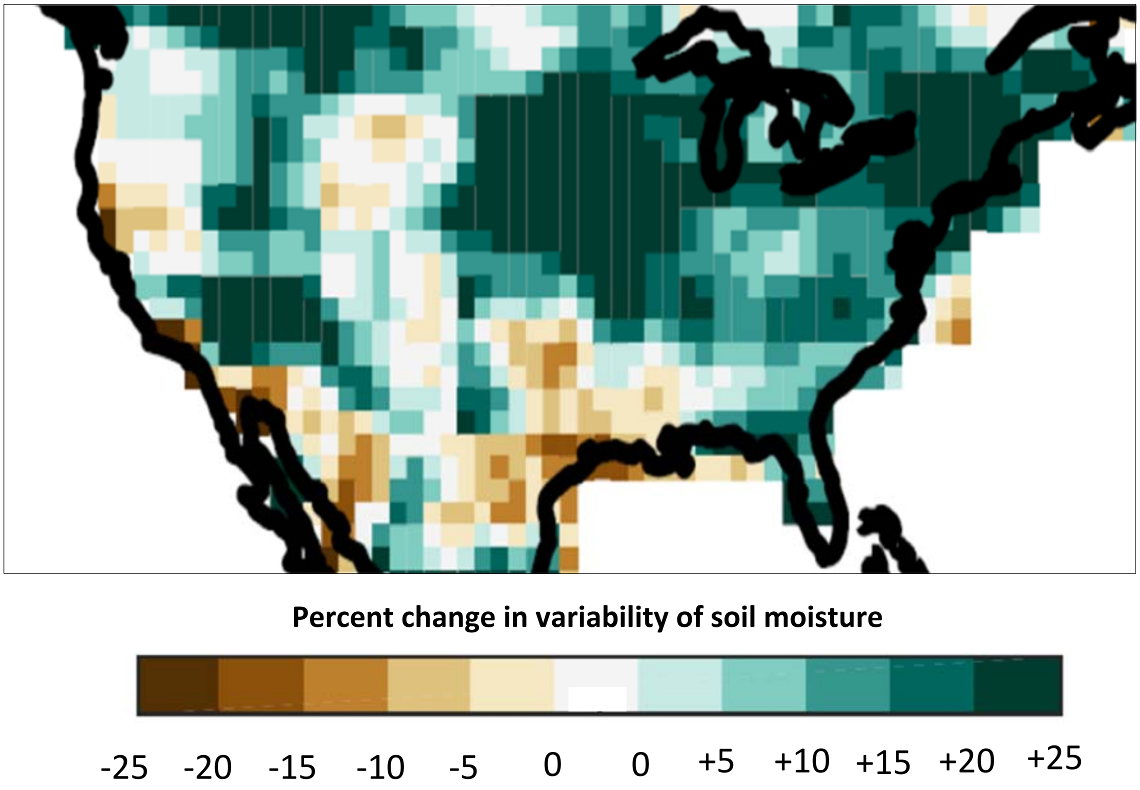


Figure 27. Percent change in soil moisture variability between 1985 (1971-2000) and 2070 (2056-2085) under a high emissions scenario (RCP8.5). Green shades indicate more frequent or intense variation of soil moisture between years. Thus, locations with green shading are likely to see the **frequency of drought and periods of saturated soil increase** from 1985 to 2070. Brown shades indicate locations with less variability, i.e. more consistency, for soil moisture conditions from year to year. Adapted from Green et al., 2019.

The text below refers to northern New York and New England was adapted from Janowiak et al., 2018.

> ### Future water supply and soil moisture.
>
> Summer stream flows in the Northeast are generally projected to decrease. One study in eastern Massachusetts projected that streamflow during the summer months may decline by more than 50% for many watersheds. Projected fall stream flow projections vary and depend on the degree to which scenarios warm the climate and on interactions with vegetation. There is also expected to be greater variation between and within years, with increases in both low-flow and high-flow events throughout the year.
>
> **Changes in soil moisture are largely driven by the balance of temperature, precipitation, runoff, and evapotranspiration** — that is, the combined amount of water lost through evaporation from plant surfaces, litter, and soils as well as through transpiration from plants. As temperatures increase, the atmosphere is able to hold larger quantities of water, which causes evaporation to increase. Plants also transpire more. Moisture stress may occur when increases in evaporation and transpiration are not offset by a corresponding increase in precipitation and soil moisture.
>
> **Precipitation projections have greater uncertainty than temperature projections.** Relatively few studies have projected future changes in soil moisture, making it difficult to make strong conclusions about changes in future drought frequency or severity.
>
> Several modeling studies point to substantially higher temperatures with no more than modest increases in growing season precipitation, and thus increased drought risk in the northeastern United States through the next century.

End of text adapted from Janowiak et al., 2018.

Observed number of 'large hail days' per year, 1979-2015.

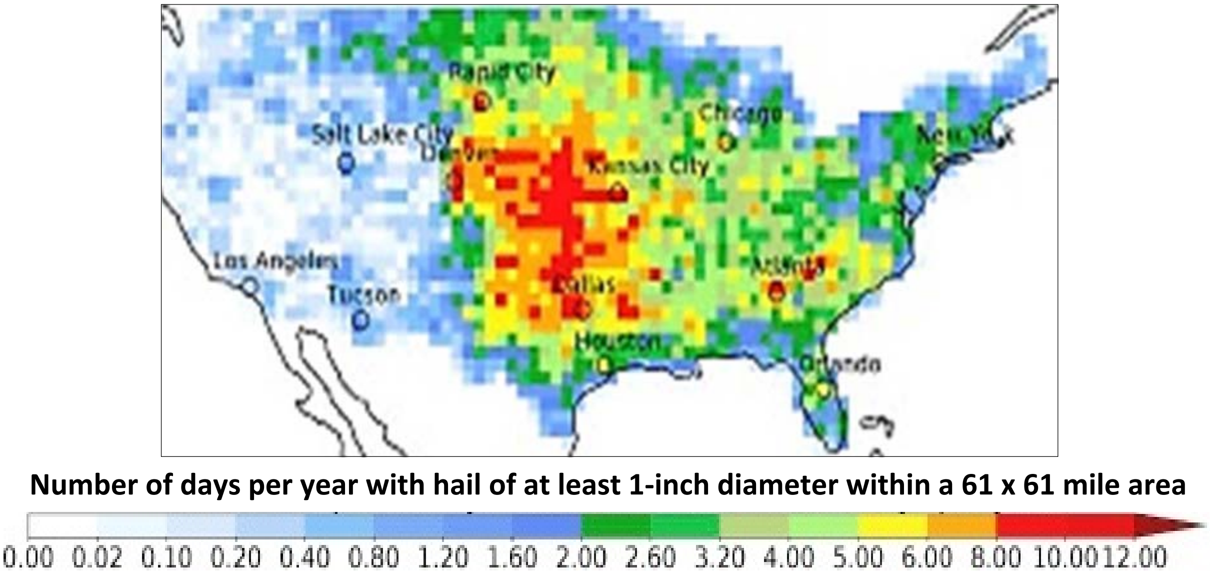
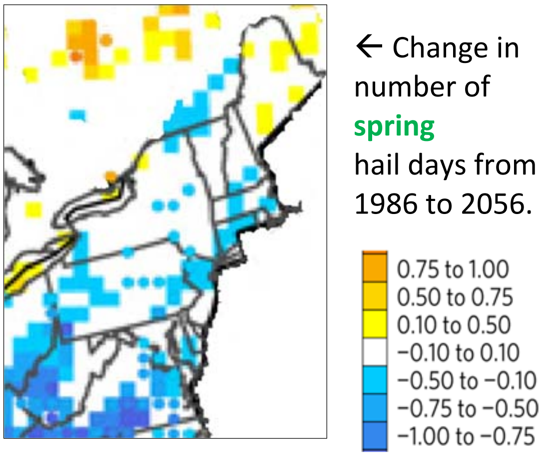
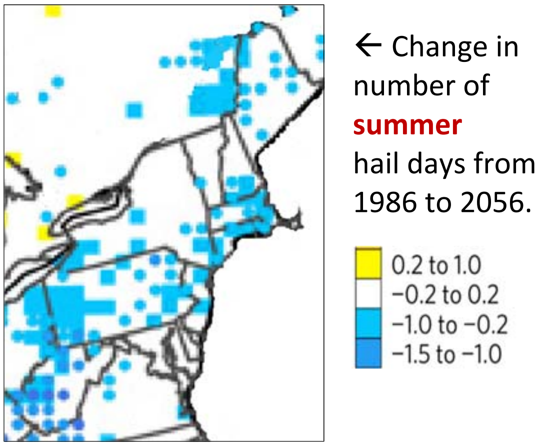


Figure 28. Observed frequency of hail of at least 1 inch diameter within a 61 x 61 mile area, in 1979-2015. While smaller diameter hail is a more frequent cause of damage to tree fruit, the data for larger hail provides an overview for relative hail risk. The larger size hail class was used to reduce variations caused by reporting and sampling methods. Adapted from Prein, 2018. Peak hail frequency was in April or May for DE, MD, WV; June for most of PA; and July-August for the other Northeastern states.

Projected change in number of hail days, from 1986 to 2056.



← Change in number of spring hail days from 1986 to 2056.



← Change in number of summer hail days from 1986 to 2056.

Figure 29a. Change in number of days per Spring (March-April-May) with hail greater than 0.4 inch diameter from 1986 to 2056 (1971–2000 vs. 2041–2070). Colored squares show locations for which all models agreed on the direction of change. Colored circles show locations for which at least two estimates were statistically significant with 90% confidence.

Figure 29b. Same as above, but for change in number of hail days per Summer (June-July-August). Figures 29a and 29b adapted from Brimelow et al., 2017.

The text below was adapted from Janowiak et al. 2018.

> There is some evidence that the strength of Atlantic hurricanes have been increasing since 1970 because of warming sea surface temperatures. As of 2007, there was no evidence of change in the frequency of major hurricanes that make landfall.
>
> There is less confidence in model projections about the magnitude and frequency of extreme events than there is for temperature and precipitation changes. The random nature of extreme events increases the difficulty of detecting trends, but it is likely that the frequency of extreme weather events will increase across the Northeast
>
> Future climate projections are usually done at too coarse a spatial scale to make conclusive statements about ice storms, but some modeling work has investigated potential changes in ice storm risk in the northeastern United States and adjacent areas of Canada. One study projected an 8% to 40% increase in freezing rain events by the 2050s as compared to 1975-2015 in south-central Canada. Another study suggested that all of eastern Canada could experience more freezing rain events late this century during the coldest months (December through February), with the largest increase in the northern part of the area.

End of text adapted from Janowiak et al., 2018.

Observed number and damage costs from extreme weather events in the United States, 1980 to 2017.

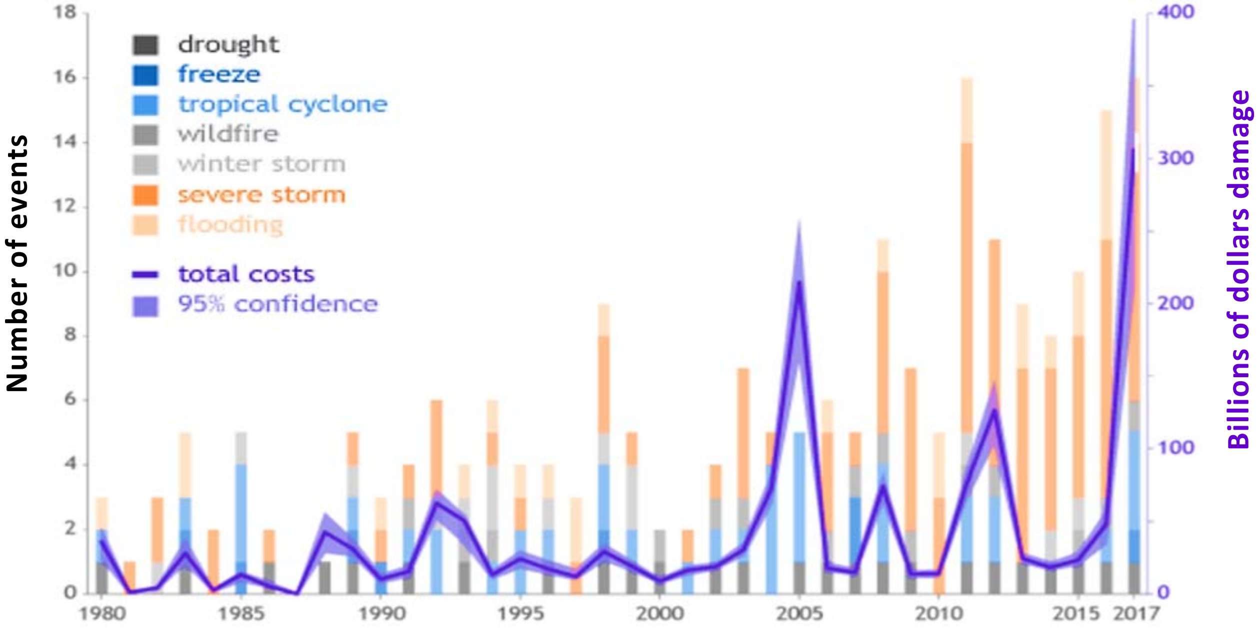


Figure 30. Height of bars shows number of events for each type of extreme weather event (left axis). Purple line shows inflation-adjusted damage per year (right axis). Shading around line shows 95% confidence interval for damage estimate. Adapted from NOAA 2018d.

Damage costs from extreme weather in 2018 in the U.S. from Hurricane Florence, Hurricane Michael, western wildfires and other events is estimated at $91 billion (NOAA 2019).

Well-defined projections for the future frequency and intensity of extreme weather events in the Northeast are not currently available. As shown below in Figure 31, the Northeast appears to have less frequent exposure to many types of extreme weather than other U.S. regions. However, hurricanes, winter storms and inland flooding have each caused damage to Northeast orchards in recent decades, so it is clear that the Northeast is not immune to extreme weather damage. It is reasonable to assume that the Northeast is likely to be affected by the apparent trend of increasing number and severity of extreme weather events.

Regional frequency of different types of extreme weather events causing over $1 billion in the United States, 1980-2017.

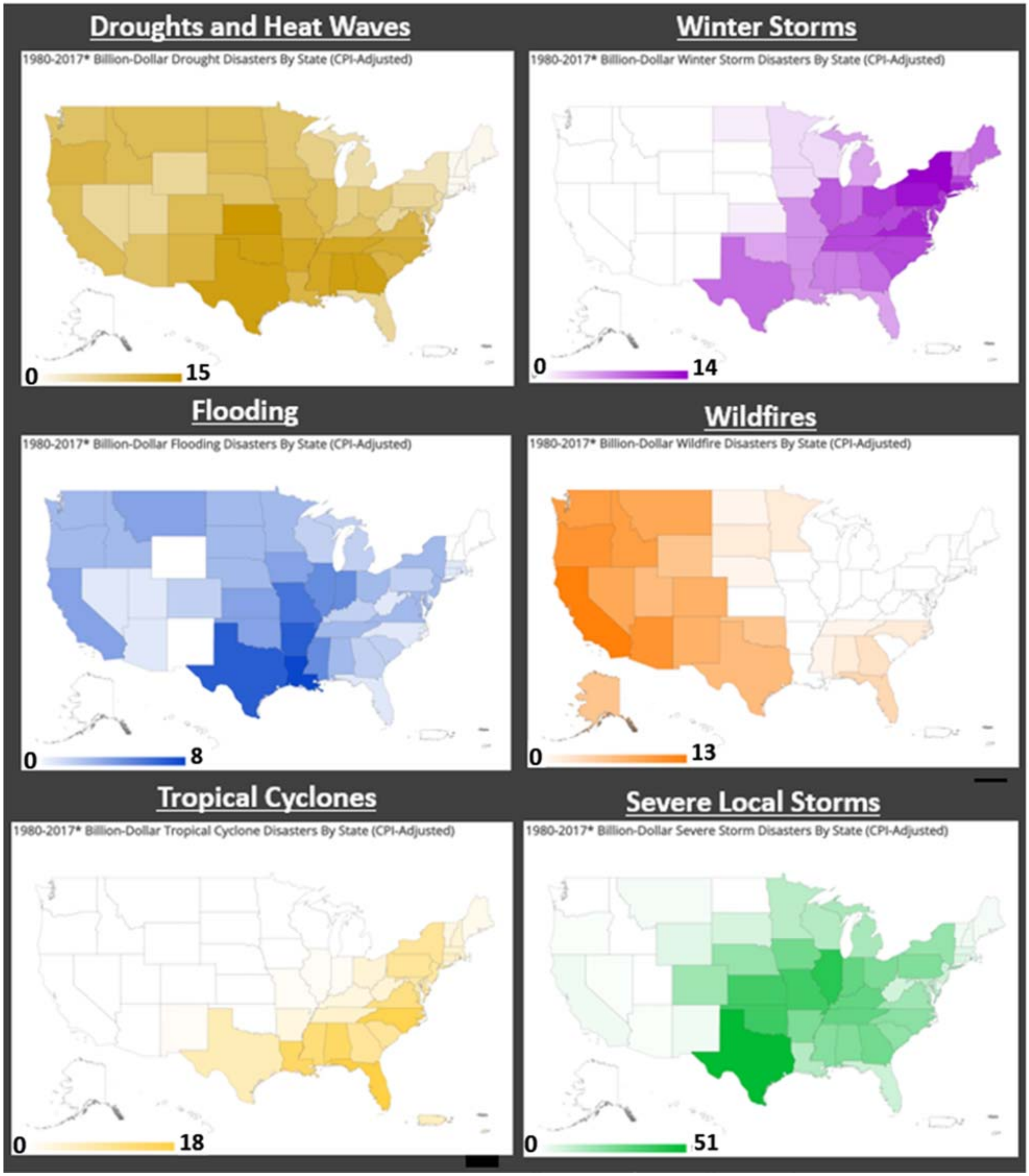
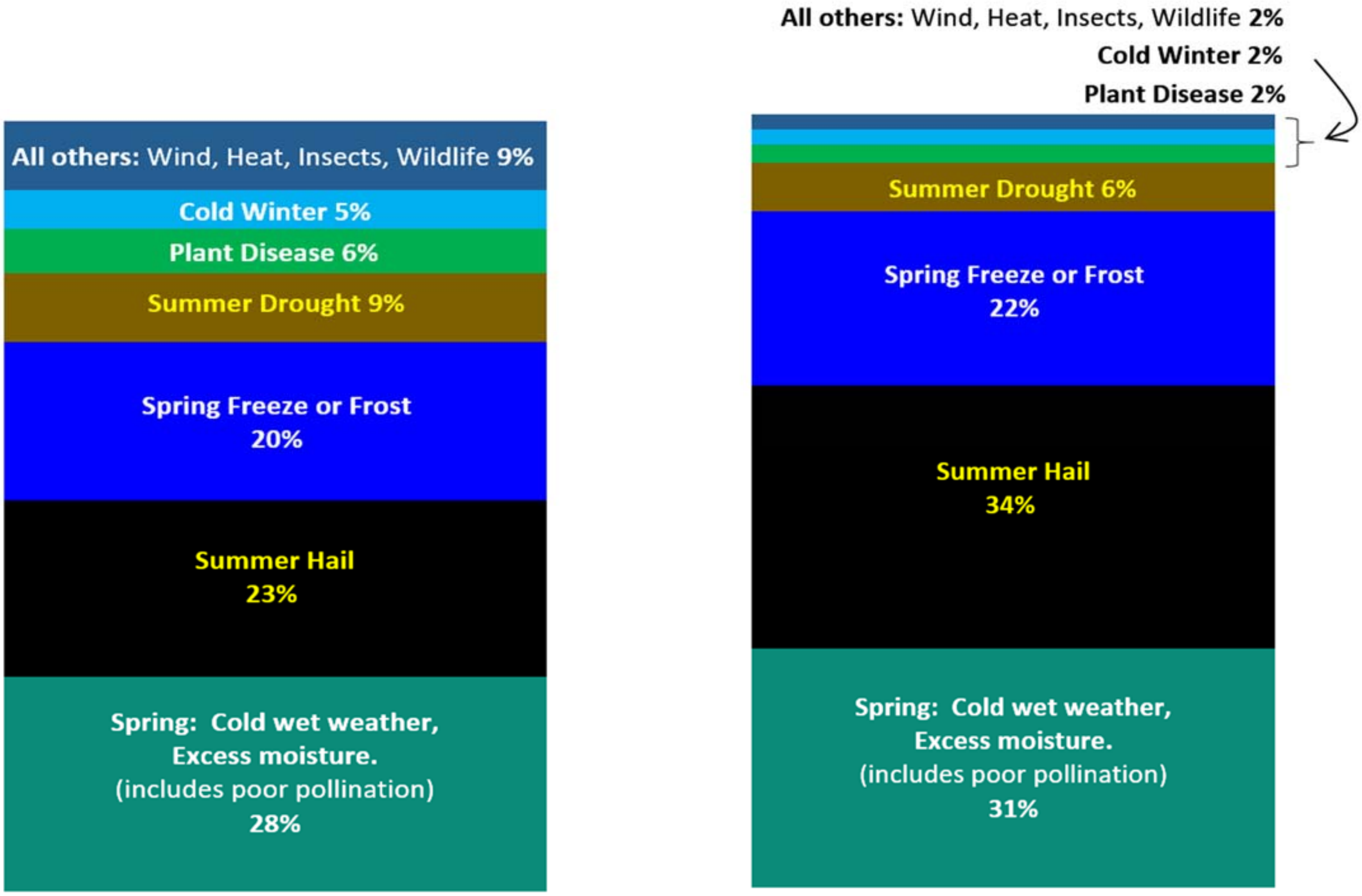


Figure 31. Number of extreme weather events causing over one billion dollars damage (adjusted for inflation, one event can affect multiple states) affecting each state from 1980 to 2017. While these are not agricultural damages, the maps show the geographic pattern and frequency for different types of extreme weather events in the northeastern states relative to the rest of the U.S. Adapted from NOAA, 2018d.

Observed Maine apple crop insurance damage claims, 2001-2017.



a. Frequency of claims

b. Portion of damage claim payments

Figure 32a. Frequency of USDA Risk Management Agency (RMA) apple crop insurance claims in Maine in 2001–2017 categorized by cause of damage. Frequency defined as portion of total number of claim payments.

Figure 32b. Same 2001–2017 RMA crop insurance claim payments to Maine apple growers, but percentages are for portion of total damage payments. Data for Figures 32a and 32b from Erin Roche, University of Maine.

Cold wet weather and excess moisture in spring was the most frequent (28% of claims) cause for reported damage. In many of those cases, the wet spring weather was associated with yield reduction due to poor pollination or fruit set. Even though it was the most common type of damage, cold wet spring weather ranked 2nd for total damage payments because the average payment per acre ($1,420) was relatively low, ranking 7th behind hail, heat, spring freeze or frost, plant disease, drought, and high wind.

Summer hail was the second most frequent type of claim, had the highest average payment per acre ($2,084), and had the highest total damage cost. Hail accounted for 34% of all damage payments.

From 2001 to 2017, an average of 24% of insured Maine apple orchards received a damage claim payment. Total damage payments to Maine apple growers were 3.2 times larger than the total amount of grower-paid crop insurance premiums.

Climate change effects on Northeast agriculture

Northeast Tree Fruit Production

The text on the next five pages was adapted from Walthall et al. 2012. It provides an overview of the expected effects of climate change on tree fruit production in the Northeastern United States in the coming decades.

> Perennial specialty crop production is sensitive to temperature, water availability, solar radiation, air pollution, and CO2. Furthermore, as in other C3 plants, photosynthesis can be limited by CO2 availability when light and other factors are not limiting. Increased atmospheric CO2 generally increases growth rate and yield, resulting in a higher accumulation of biomass, fruit production, and quality in fruit trees. However, growth enhancements in response to increasing CO2 could diminish in the long-term due to acclimation, especially when combined with other limiting factors such as heat stress and nutrient deficiencies.
>
> The value of perennial specialty crops is derived from not only the tonnage but also the quality of the harvested product, for example the size of a peach, the red blush on an apple, or the bouquet of a red wine produced from a particular vineyard. In contrast to annual agronomic crop production, perennial crop production is not easily moved as the climatic nature of a region declines due to many socio-economic factors including long re-establishment periods, nearness to processing plants, availability of labor, and accessible markets. Climate change complicates the problem of food production from perennial crops.
>
> Perennial cropping systems are commonly in place as long as 30 years, and this poses a challenge with a changing climate since the selection of a productive cultivar at planting may not be the most adapted sometime in the future. The development of new cultivars in perennial specialty crops commonly requires 15 to 30 or more years, greatly limiting the opportunity to easily shift cultivars.
>
> In addition to the rise in global temperature, it is expected that some extreme events will increase in frequency and severity as a result of the shift in mean conditions and/or a change in climate variability. Socio-economic factors and inability to rapidly identify adapted cultivars do not necessarily make the perennial specialty cropping systems more vulnerable to climate change, but they do call attention to the needs of the industry for new cultural and genetic tools and research to adapt in a timely and economic manner.
>
> The value of a fruit crop is determined and limited at many points before and during the growing season because the value is based not only on biomass, but on size, color, chemical composition, firmness, and other measurable criteria. Using apple as an example, in the year prior to harvest, floral initiation occurs in June-July and high temperatures reduce the number and vigor of the potential floral buds. During the dormant winter months, extreme cold can kill buds and warming periods can de-acclimate buds, making them susceptible to later winter damage.

In the spring, frost periods can kill flowers. As the fruit are growing in the spring, high temperature can reduce cell division resulting in small fruit. During the summer months, high temperature may cause sunburn damage reducing pack-out at harvest, accelerate maturity, reduce fruit firmness and color development, and/or decrease the suitability of fruit for short- or long-term storage. Modeling of past and future climate changes in the United States has demonstrated that warming in the historical record and future warming will affect perennial specialty cropping systems. (Since 1980, apple mid-bloom dates in the Northeastern United States have advanced 2 days per decade. Since 1988, the rate increased to 0.6 °F/decade, with additional acceleration to >1.0 °F/decade possible from 2020 to 2050. Wolfe et al. 2018).

Enhanced Atmospheric Carbon Dioxide Effects

Experimental studies on perennial specialty crops have reported a sustained stimulation of photosynthesis and growth under elevated CO2. Despite a considerable increase in water-use efficiency at both leaf and crop levels, the actual amount of crop water use remained similar. This is likely because of an increase in tree leaf area in response to elevated CO2.

A rapid increase in tree leaf area during the early season accelerates early growth and biomass accumulation, especially in open canopies. However, this accelerated growth response, such as shown in apple and cherry, is likely to be less pronounced in a dense closed canopy in which the leaf area index is more or less stable, so that competition for light and other resources are high.

Many orchard and other perennial specialty cropping systems are highly managed with ample fertilization, irrigation, spacing, canopy management, thinning and pruning, and other cultural practices to realize high yield and produce quality. With relatively larger sinks for carbohydrates (e.g., fruit load and wood formation) than annual field crops, the CO2 fertilization effect may be amplified and sustained longer for perennial specialty crops if

(1) other resources (e.g., nutrients and water availability) are amply supplied, and

(2) proper management options (e.g., spacing, pruning, thinning) are practiced to facilitate the positive CO2 effects by balancing source-sink relations for carbohydrates.

This will likely require maintaining intensive cropping systems. In addition, the positive CO2 effect may be negated by the detrimental effects of extreme temperatures on phenology, carbon sinks, and reproductive physiology.

While multiple studies examined biomass and allocation response to elevated CO2, few studies report fruit yield response. Even fewer studies have addressed the effects of elevated CO2 on produce and product quality. Produce and product quality measures are likely to reflect different biochemical and physiological pathways of interactions between CO2, nutrients (N in particular), temperature, and pest damage.

Diseases

In the Northeastern United States, the projected increase in short- to medium-term drought will tend to decrease the duration of leaf wetness and reduce some forms of pathogen attack on leaves. However, an increase in humidity and frequency of heavy rainfall events projected for the Northeast will tend to favor some leaf and root pathogens, and the projected increased rainfall frequency may reduce the efficacy of contact fungicides,

Insect pests

A warming trend is likely to lead to increased pesticide use in the Northeast due to earlier arrival of migratory insects, higher winter-time survival of insects that currently are only marginally adapted to the region, and more generations of insects within a single season. In addition, some classes of pesticides (pyrethroids and spinosad), key to protecting perennial specialty cropping systems, have been shown to be less effective in controlling insects at higher temperatures. In addition to increasing numbers and viability of insects, climate change may jeopardize biological control successes.

Effects of Changing Water Constraints

There is a historical trend for increased frequency of high-precipitation events (> 2 inches in 48 hours) in the Northeast, and this trend is expected to continue with a further increase in the number of high-precipitation events of 8% by midcentury and 12% to 13% by the end of the century. More spring rainfall concentrated into high-precipitation events, combined with stable to modest reductions in summer and autumn rainfall and increased temperatures, leads to a projection for more short-term (1- to 3-month) and medium-term (3- to 6-month) droughts for the region, particularly in the northern and eastern parts of the region. One study found that drought frequency is projected to be much greater in higher emissions scenario than in a lower emissions scenario. By the end of the century and with higher emissions, short-term droughts are projected to occur as frequently as once per year for much of the Northeast, and occasional long-term droughts (>6 months) are projected for western, upstate New York, where perennial specialty crops are a major industry.

Increased drought frequency in the Northeast, together with warmer growing season temperatures will result in greater crop water requirements. Perennial specialty crops have reduced yield and quality in association with water deficits, and reduced profits as a result. While many producers of perennial specialty crops in the Northeast have some irrigation equipment, most have not invested in enough equipment to optimize irrigation scheduling and fully meet evapotranspiration requirements of all of their acreage.

Looking beyond the Northeast, reductions in growing season irrigation water will greatly limit perennial specialty crop production in the western U.S. arid and semi-arid production regions unless sufficient water is stored in reservoirs and made available for irrigation. Late season crops will feel this effect most because of the increased water-use later in the growing season due to higher temperatures.

Effects of Higher Temperatures

An extended frost-free period as projected for the Northeast will tend to benefit perennial specialty cropping systems requiring a relatively long growing season such as apples, peaches, and grape varieties. However, projections for an increase in summer heat stress and drought can reduce yield and crop quality. In contrast, Wolfe et al. (2008) found that apple yields for western New York (1971–1982) were lower in years when winters were warmer than average (based on accumulated degree days >41°F from January 1 to budbreak). This was likely related to more variable fruit set following warmer winters.

An increase in winter temperatures will affect the Northeast perennial specialty cropping systems. Mid-winter warming can lead to early bud-burst or bloom of some perennial plants, resulting in frost damage when cold winter temperatures return. Yields will be negatively affected if the chilling requirement is not completely satisfied because flower emergence and viability will be low. All perennial specialty crops have a winter chilling requirement ranging from 200 to 2,000 cumulative hours.

Wolfe et al. (2008) found that a 400-hour chilling requirement will continue to be met for most of the Northeast during this century regardless of emissions scenario. However, crops with prolonged cold requirements (1,000 – 1,200 hours for most apple cultivars) could be negatively affected, particularly in southern sections of the Northeast, and at the higher emissions scenario, where less than 50% of years satisfy the chill requirement by mid-21st century. The effect on crops will vary with species and variety since each species has a range of cultivars with widely varying chill requirements. (Ed. note: Not meeting chill hour requirements can lead to increased spring frost risk and uneven bloom timing within individual trees.)

At a higher emissions scenario, within just the next few decades (2010–2039), a 5 to 10-day increase in the number of July heat stress days is projected for the southern half of the U.S. Northeast (i.e., much of Pennsylvania, New Jersey, Delaware, Connecticut, and southern New York). Under a lower emissions scenario, the climate change effect does not become substantial until midcentury (2040-2069). By the end of the century (2070–2099), with higher emissions, most days in July are projected to exceed the 32°C (90 °F) heat stress threshold for most of the Northeast. Even assuming relatively lower emissions, much of the Northeast is projected to have 10 to 15 more days of heat stress in July by the end of the century, except for some northern areas (e.g., northern Maine and Vermont), where the increase is in the range of 5 to 15 days. The projected increase in summer heat stress will be particularly detrimental to many cool temperature-adapted crops (e.g., apple) that currently dominate the Northeast agricultural economy. For many high value horticultural crops, very short term (hours or a few days), moderate heat stress at critical growth stages can reduce fruit quality by reducing visual or flavor quality even when total tonnage is not reduced.

Adaptation

Development of adapted cultivars is the long-term solution of perennial specialty cropping systems in a changing climate. There is wide variety of adapted cultivars that can be evaluated for new regions. Typical breeding programs require 10 to 30 years to confirm and improve a cultivar. Recent technology demonstrates how this breeding hurdle can be overcome using molecular approaches to reduce perennial crop generation time to months instead of years. Since perennial specialty crops have a chill requirement (the minimum period of cold weather after which a fruit-bearing tree will blossom), it is necessary to induce and end dormancy at times in the growing season that minimize killing frosts both in spring and fall. This requires that the plant react to day length instead of temperature patterns. Research on possible adaptation focused on day length was able to transform apple from temperature-induced dormancy to photoperiod-induced dormancy using a technology that may be adaptable for other perennial specialty crops.

Molecular biology is identifying genes associated with climate change that will benefit perennial specialty crops in the future. While projections of future climate indicate average warmer temperatures will affect crops, in today's environment, increased temperatures already reduce plant productivity. To deal with current temperature issues, technology such as application of reflective particle films (e.g. kaolin clay, Surround) has been developed and commercialized that reduces canopy and fruit temperature, increasing yield and quality in the face of increasing growing-season temperatures.

In addition to these adaptations, perennial specialty crop growers have a wide assortment of management tools that will help them adjust to climate change. These include crop load adjustment, canopy pruning, irrigation, increased use of mechanization, and automation technology. As examples, overhead irrigation effectively reduces canopy temperature and is effective in frost mitigation although it is water-use inefficient.

End of excerpts from Walthall et al. 2012

Northeast Agriculture and Adaptation

The text on the next five pages was adapted from Wolfe et al., 2018. It is less focused on tree fruit but provides different details and perspective from a more recently updated and regionally specific climate change analysis. It covers adaptation topics in greater detail. References in the original were excluded for clarity.

Direct effects of increasing atmospheric CO2.

Plants take up CO2 via photosynthesis to produce sugars for growth, and thus this greenhouse gas has a potential positive effect on both weeds (as discussed above) and on crop plants. Many early studies conducted under optimal conditions in growth chambers or greenhouses found that a variety of plants with the C3 photosynthetic pathway generally increase productivity by 20 to 30% when atmospheric CO2 levels were doubled from current ambient levels and other growth conditions were optimal. Levels of CO2 in 2019 (410 ppm) are projected to increase to 538 and 936 ppm by 2100 under the RCP4.5 and RCP8.5 emission scenarios, respectively.

The magnitude of plant responses to CO2 are complex, however, and are affected by genetic capacity to take advantage of higher CO2 for faster growth or improved water use efficiency, and the degree to which other environmental factors (e.g., temperature) or biotic factors (e.g. insect pests) constrain the photosynthetic and growth response.

Climate change projections for increasing risk of both too much and too little water, as well as increasing pest pressure and heat stress in the Northeast, could offset the potential positive “CO2 fertilization” effect on crops. For example, studies with bean and potato found that doubling CO2 concentration did not compensate for yield losses associated with heat stress.

Longer frost-free period and warmer temperatures.

While climate change will add to the physical and economic challenges of farming in the Northeast, there are likely to be new opportunities as well, such as developing new markets for new crop options that will come with a longer frost-free period and warmer growing season temperatures with greater degree-day accumulation. The expansion of non-native European wine grape production in the Northeast over the past 40 years has benefited from the reduced frequency of severe cold winter temperatures. Additional warming could benefit other crops such as Prunus species (e.g., peaches, plums, cherries, etc.), watermelon, and tomato.

Warmer temperatures and longer growing seasons could enable an intensification of Northeast agriculture if water availability is not limiting, and if excessive rains do not delay planting or in other ways shorten the growing season. One of the simplest adaptations to take advantage of this potential opportunity is to plant longer growing season varieties with higher yield potential. A longer growing period would provide more opportunity for double-cropping. For example, winter barley or winter wheat followed by soybean, a system already practiced with some limitations in southern portions of the Northeast. A longer growing period and milder winters would also expand options for use of non-cash winter cover crops, which provide many ecosystem services, such as reducing soil erosion, nitrogen fixation (with legume species), soil nitrogen capture (e.g., with winter rye), and increasing soil organic matter.

Adaptation strategies

Fruit crop frost protection.

Strategies to avoid damage from spring frost begin with careful site selection, and crop and variety selection and/or diversification. The use of wind machines, helicopters, heaters, irrigation and overhead sprinklers, and covering systems (such as high plastic tunnels) for frost protection has been reviewed by Poling (2008) and others. Decision tools will be required to integrate weather forecasts into early-warning systems for extreme events like winter freeze and spring frost events to help perennial fruit crop growers through a phase of climate change transition that may include increased frequency of winter cold damage risk. For midwinter freezes, approaches might include changes in pruning strategies and mulching to insulate the trunk of young plantings.

Water management.

Climate projections for precipitation suggest that compared to regions where significant decline in precipitation is projected, the Northeast is likely to maintain water supplies sufficient for agriculture. Severe hydrological drought — the drying up of lakes, reservoirs, groundwater and other supplies — is not expected to become a chronic problem in the Northeast region. This could manifest as an opportunity for the region and lead to expansion of agricultural land use. However, the severe drought in the summer of 2016, which led to record-low stream flows, and shallow wells and ponds going dry in some regions, has increased awareness that the Northeast currently lacks an infrastructure for water supply and/or delivery if droughts become longer-term events. The Northeast also lacks a comprehensive rapid-response plan and proactive risk management plans for farmers and surrounding communities for severe drought years.

While many Northeast fruit and vegetable farmers have some capacity to irrigate, few have the available water or equipment to meet water requirements of all of their acreage during prolonged summer droughts. In addition, compared to other regions with historically drier climates, farmer knowledge and use of decision tools for optimized irrigation scheduling is less common in the Northeast. Farming success in the future will require technologies that integrate site specific monitoring with decision tools to adapt to changes in environmental conditions.

Because the Northeast is likely to be vulnerable to increased frequency of both too much and too little water, farmers are faced with complex decisions regarding whether they should adapt by investing in irrigation equipment, a drainage system, or both, and when. Unfortunately, climate model projections for precipitation are less certain than for temperature. In addition to installing irrigation or tile drainage systems, other strategies primarily for annual crops but also relevant for perennial crops such as tree fruit, for dealing with this uncertainty include:

*** Acquire planting or harvesting equipment that can cover acreage more quickly** as a strategy to complete farm operations within smaller windows of opportunity when field access is not compromised by heavy or prolonged rains.

*** Improve farm ditch and drainage systems** to collect water during wet periods and store it in pond systems for use during dry periods.

*** Shift crop production to fields less prone to drought or flooding risk** based on soil type, topography, or prior management.

*** Increase soil organic matter** to maximize water holding capacity (buffering against short-term drought), enhance water infiltration rate, and improve drainage (buffering against flooding damage and maintaining field access). Techniques include reducing tillage, maintaining year-round vegetation coverage, and using manures, composts, and mulches as part of fertility management.

Increasing insect, disease, and weed pressure.

Warmer winters, hotter summers, longer frost-free seasons, less snow cover, and more precipitation events, alone or as interacting factors, are changing the establishment, spread, and competitive ability of insect, disease, and weed pests within the Northeast. Longer, warmer summers can lead to more insect generations per season, greater overwintering survival, and a potential decoupling of insect pests from their natural enemies.

Climate change can affect the incidence and severity of crop diseases by affecting the overwintering, growth, and dispersal of pathogens. Climate change may also indirectly affect disease by impacts on insect vectors of crop disease. In addition, host vulnerability may increase in cases where climate change causes plant environmental stress. Increased frequency of heavy rainfall events and wet soil conditions could favor some root pathogens, and accelerate the spread of foliar diseases such as late blight an important disease in potato production that increases in wet conditions. On the other hand, in years and regions where climate change leads to drier conditions, disease pressure could be reduced.

As winters warm, there is a potential northward expansion of suitable habitat for invasive weedy species such as Kudzu and oriental bittersweet. Northeast weeds that use the C3 photosynthetic pathway, such as lambsquarters, ragweed, and Canadian thistle, have a strong growth response to increasing atmospheric carbon dioxide concentration that exceeds the response observed for most cash crops. In addition, elevated CO2 has been found to reduce the efficacy of glyphosate (the most widely used herbicide in the USA).

Control strategies for new insect, disease, and weed pests.

While we can look to southern regions for control strategies for weeds and other pests moving northward, those methods may not always be directly transferable or desirable for the Northeast, particularly if they involve substantial increases in chemical loads to the environment. New policies and regulatory frameworks may become necessary, involving good communication among farmers, buyers, integrated pest management (IPM) specialists, and state and Federal regulatory agencies. Because specific threats are difficult to project, monitoring of pest populations becomes imperative as the climate changes.

Greater vigilance in tracking emerging pest threats, understanding the risks they pose and effective response once risks become significant, and a rethinking of current management practices will be essential. Integrated pest management to increase resilience in dealing with changes in pest migration, detection, response, and control will be increasingly important.

Farm diversification is a robust strategy to address uncertainties in seasonal weather patterns and climate change projections. A more diversified farm may be less vulnerable to direct weather impacts and weather-related crop losses due to pests. Diversification also provides a pathway for farmers to explore new management options for a changing climate, while minimizing the risks associated with a shift at the whole-farm level.

Unintended consequences of agricultural adaptation and intensification.

While longer frost-free periods, shifts to longer growing season varieties, cropping systems with year-round production, and positive plant responses to increasing CO2 can have yield benefits, there may also be unintended negative impacts on the environment. **A longer growing season and increased plant production may require a corresponding increase in water, nutrient, and chemical inputs,** potentially increasing risk of nutrient or pesticide loading to waterways. Runoff risk could be magnified by increased frequency of heavy rain events, and increased use of herbicides, insecticides, or fungicides to cope with more dynamic weed, insect, and disease pressure.

Adaptation strategies that involve diversifying production systems to cope with temperature and rainfall uncertainty and building resilience by improving soil health and improving IPM strategies to cope with new pest dynamics, can have an overall positive environmental impact.

Crops with increased tolerance to climate stresses.

Varieties with improved stress tolerance, or those adapted to take advantage of a longer growing season for increased yield may already be available for some crop species. Molecular-assisted crop breeding strategies may speed development of new genetic types more tolerant of biotic and abiotic stress. However, to date, many such efforts have focused on a few major world food crops such as corn and wheat, while the high-value fruit and vegetable crops that dominate the Northeast agriculture economy have received less attention.

Breeding perennial fruit crops requires a much longer effort than is required for annual crops. Additionally, it is often more difficult to introduce new varieties of fruit crops because consumers recognize and value specific varieties (i.e., McIntosh apples or Riesling wine grapes). Even for annual crops, changing varieties is not always an easy or low-cost option. New crop and variety introductions must not only be adapted to the new climate, but also adapted to local soils, farming practices, and meet local market preferences for color, size, flavor, and other quality factors.

Knowledge and technology gaps

Real-time weather-based systems for monitoring and forecasting stress.

Current guidelines for many agricultural practices are based on outdated observations and the assumption of a stationary climate. Even experienced irrigation managers often make an incorrect decision. Optimized water, frost, nutrient, and pest management decisions in a changing climate will require site-specific real-time weather forecasts and observations; crop and pest predictive models for interpretation relevant to the vulnerabilities of the particular farm; and monitoring of weather impacts on crops, pest, and soils.

One of the central challenges to adaptive management is how farmers gain access to this site-specific information in a timely and efficient way at a reasonable cost. Farmers will benefit from information only if through education and analysis tools they can translate that information into knowledge that leads to better decisions and actions.

This process can be summarized as:

Information → Knowledge → Decisions → Actions → Outcomes

For example, research on automated irrigation control systems in ornamental plant production indicates that decision support systems can reduce irrigation water applications between 40 and 70%, along with labor and energy use. These systems have also been shown to lower plant mortality, shorten production times, and reduce pesticide applications, significantly increasing crop quality and profitability for growers.

Climate model projections for long-term capital investments.

Regional climate science and modeling research are needed to help farmers identify which adverse weather events are part of normal variability and those that are indicative of a long-term climate shift warranting adaptation investment. Some aspects of climate change, such as increased climate variability and increased frequency and clustering of extreme events, could potentially have severe negative impacts on the Northeast agriculture industry, but our current level of certainty about these climate factors is low. Continuing research to improve climate models may help, but we may be decades away from accurately projecting changes in some climate variables at the local level, so farmer adaptation decisions will have to be made with a degree of uncertainty about future climate-related challenges.

While the immediate concern of farmers tends to be decision tools for day-to-day management, many large capital investments involve complex decisions with a longer time horizon, such as investing in a new irrigation or drainage system, changing varieties of a perennial fruit crop, or potentially even transformative decisions about the nature of the farm enterprise. For these cases, farmers will require tools to evaluate different possible climate change scenarios in relation to costs, risks, benefits, and strategic timing of competing or complementary adaptation options.

End of text adapted from Wolfe et al. 2018.

Weather-based operational decisions vs. Climate-focused planning

Farmers already rely on weather forecasts to make immediate, short- and long-term decisions. That reliance will increase if weather variability or patterns shift, and as new “normals” replace old assumptions. Increased access to and sophistication in use of weather data, including integration into management tools, is already well under way and will become an increasingly important aspect of farm viability.

Fortunately, short and long-range weather forecasting capabilities are increasing with the need. For example, since 2017 NOAA has deployed new satellite and computer systems, and continues to improve forecast models. Temporal and spatial skill in temperature forecasting has gradually increased in recent decades and now extends up to a week ahead for some applications and locations. Long-range temperature trend outlooks can improve upon using the previously observed 30-year climatic average for up to several months in advance (Tian et al., 2017).

Skillful precipitation forecasts and outlooks have much shorter range and spatial specificity than for temperature. However, there is considerable skill in predicting the daily probability and amount of precipitation for several days ahead, and precipitation trend outlooks exceed the skill of climatic average for up to a month or more in advance (Baker et al., 2017, Tian et al., 2017, Sehgal and Sridhar 2018).

Most farmers are fully occupied being profitable in the current growing season and remaining viable for the next three years, thus planning for a 30-year period may seem like an unrealistic ideal. The need and value of long-term planning versus making annual adjustments as needed in response to recent experience varies with the investment timeframe of the enterprise. Foresters have to plan for long timeframes by virtue of the multi-decadal growth cycle for trees. Growers of annual crops have more frequent opportunity and flexibility to change crops, varieties, and management practices between years, or within a single year. Relative to forestry and annual crops, perennial tree fruit crops operate at intermediate time scales.

A ‘wait-and-see’ approach to deal with the challenges brought by changing weather reduces uncertainty about which expenditures are needed, and can reduce the time for investments to return their cost in savings. However, the wait-and-see approach increases the risk of incurring substantial damage before damage-reduction measures are established. If that damage is short-term, incremental or minimal, the risk inherent in the wait-and-see approach may be acceptable. However, if the damage is catastrophic, irreversible, or puts multiple years of returns at risk, then strategic planning to prevent problems before they occur becomes more economical than a wait-and-see approach. Indeed, for long-term viability it could become essential.

Given the relatively low cost for considering different scenarios and response options, a review of the farm enterprise with respect to the challenges and opportunities likely to occur with changing climate is likely to be time well spent. Such a review should include prospects for both changes in average values as well as potential for more frequent or extreme weather events.

Considering options for how best to leverage assets to meet those challenges as within a planning scenario can save much distress compared to waiting dealing with events as they actually occur. Fortunately, many of the methods used to increase resilience to weather risks bring multiple benefits that make economic sense under current conditions, in addition to their role in reducing potential damage from new or altered hazards.

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National and global food system as context

This document is limited to considering the effects of climate change on aspects of weather directly relevant to terrestrial agriculture in the northeastern United States. It does not consider issues such as potential for abrupt shift in weather patterns; changes in ocean chemistry and circulation; sea level rise and other aspects of climate change that will affect the environmental, economic, and social context surrounding a tree fruit production enterprise.

The document also does not account for the effects of climate change on food production at the national and international scales. Changes in the larger food system will likely have profound effects on tree fruit production in the northeastern U.S.

The following pages provide examples of the larger food system context within which Northeast tree fruit agriculture operates. More comprehensive, detailed, and more recently updated information on the global effects of climate change on food production are available in the 2019 special report by the Intergovernmental Panel on Climate Change (IPCC 2019). However, the amount of technical detail published by the IPCC even in their summaries is overwhelming. A lay press article such as Carrington (2019) is often the best way to access the meaning from IPCC reports.

Possible climate change influence on global crop yields between 2000 and 2050.

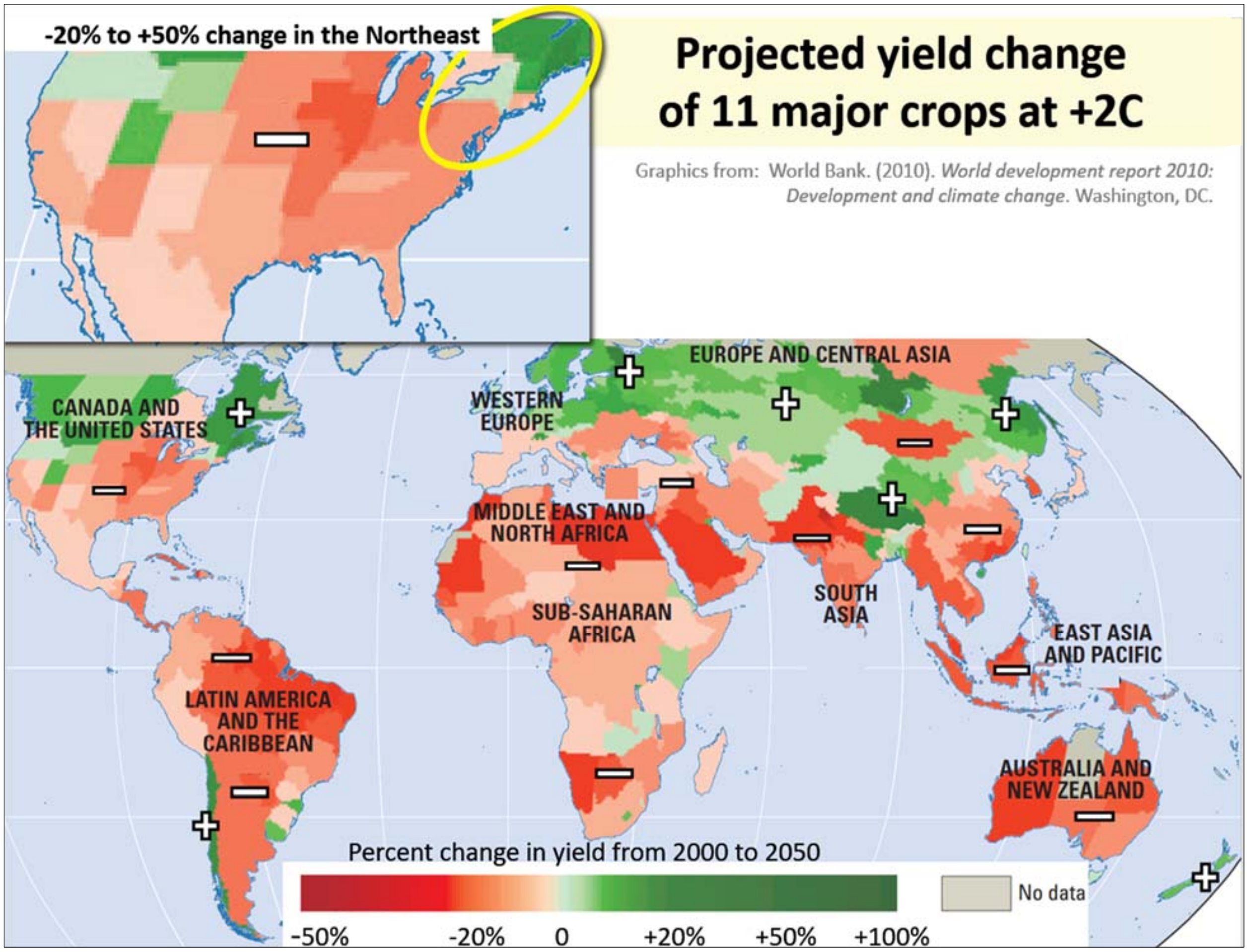

Figure 33. Projected impact of global average surface temperature at 2°C (3.6°F) above the preindustrial average on yield for 11 major agronomic crops (wheat, rice, maize, millet, field pea, sugar beet, sweet potato, soybean, groundnut, sunflower, and canola). Adapted from World Bank, 2010. Yield comparisons are for 2050 (2046–2055) vs. 2000 (1996–2005). These 11 crops account for 64% of human food calories around the world (Tilman et al., 2011).

The yield-change values shown in Figure 33 are the average of three emission scenarios across five global climate models, and assume only basic agricultural adaptation (e.g. adjusting planting date, harvest date, or variety selection for four of the modeled crops - wheat, corn, sunflower, and canola). Additional agricultural adaptations such as crop genetics or relocation to new growing areas are not considered, nor is the potential effect of a CO2 fertilization. If benefits from a CO2 fertilization effect on crop plant growth are realized, that could result in higher yields than indicated. However, fully achieving the potential benefits from a CO2 fertilization effect seems unlikely for most crops at most locations. That is because of constraints on crop productivity imposed by increased temperatures; water supply; insect, disease and weed damage; other management and input requirements; and possible decrease in crop nutrient density.

Observed trends in U.S. agricultural production efficiency, 1951 to 2010, and projected trend 2011 to 2035 due to climate change impacts.

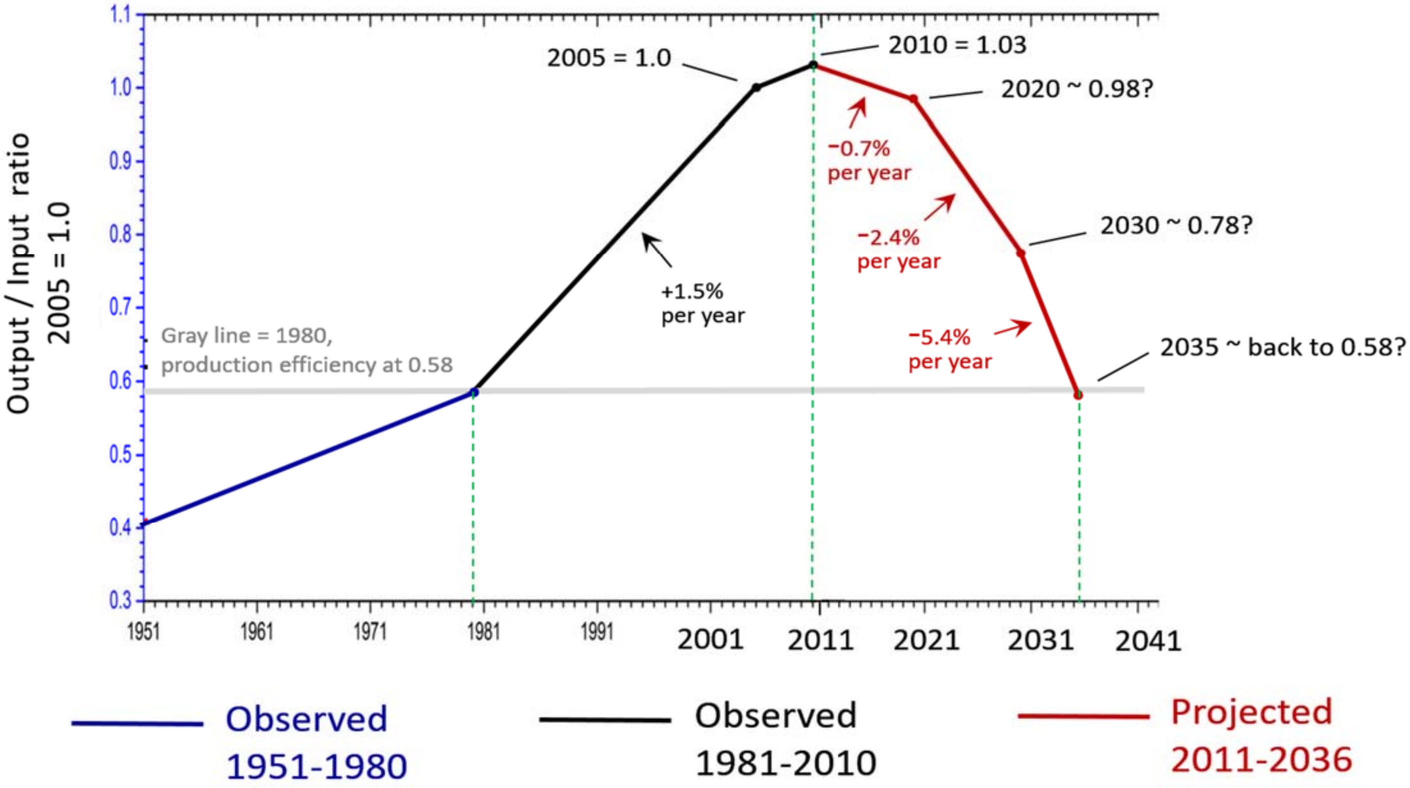

Figure 34. Observed trend of increased U.S. agricultural production efficiency from 1951 to 1980, and from 1981 to 2010, along with projected trend for 2011 to 2035 under a moderate future greenhouse gas emissions scenario. Adapted from Liang et al., 2017.

Production efficiency is the ratio of measured output (such as crop and livestock yield) per unit of combined inputs (such as land, labor, and capital). Increased production efficiency (i.e., output growth not accounted for by increases in inputs) has been a primary driver of the U.S. agricultural economy over the past 70 years. Between 1950 and 2010, total inputs to U.S. agriculture remained relatively constant, while aggregate agricultural output grew at an average rate of 1.5% per year.

The projected values for 2011–2035 were created by combining observed relationships between climate variation and U.S. agricultural output in 1981–2010 with future expected climate variations from a collection of climate models. Under the RCP4.5 moderate greenhouse gas emissions scenario, the average model estimate was that U.S. agricultural production efficiency would revert to the 1980 level during 2035 if projected climate changes occur as expected, with 90% of models estimates finding this drop-off occurring by 2051. Under the RCP8.5 high emissions scenario, the average (i.e. 50%) and 90% probability estimates for the year that U.S. agricultural production efficiency would revert to the 1980 level were 2032 and 2043, respectively.

It is important to acknowledge the limitations inherent to such projections. The correlation between observed weather and production used to define future projections only explained 70% of the variation.

The estimates include an assumption that technological advances and agricultural practices will continue as in the past. The estimates do not account for entirely new climate adaptation measures used to adjust to new conditions, or for the potential for successful climate change mitigation through greenhouse gas emissions and other measures. Extending weather-production relationships based on past observations into unknown and novel future conditions that were not used in defining those relationships is subject to error.

The production efficiency estimates are based on all types of agricultural crop and livestock production in the United States, and are therefore heavily weighted towards large acreage commodity crops such as corn, soybeans, cotton, and wheat. Northeast tree fruit represents only a small fraction of total U.S. agricultural output and thus had little influence on the relationships measured. Obviously, grain production in the central plains and dairy production in California have different weather sensitivities than tree fruit in the Northeast, so estimates for all of U.S. agriculture do not necessarily apply to Northeast tree fruit.

However, horticultural crops such as tree fruit, vegetables, and grapes were included in the observations used to define the weather-production correlation. Spring frosts, summer drought, sunburn, hail, storms and other weather events are frequent causes of damage to tree fruit crops in the Northeast. While there was a range of uncertainty in estimating the exact year that production efficiency would fall to the 1980 level, the results were consistent across many models, with all models estimating efficiency declines after 2020.

Even with the uncertainties involved, the projections indicate strong potential for a reversal in the long-term trend of increasing U.S. agricultural production efficiency unless there are significant and effective adaptation efforts to address increased weather challenges. While Figure 34 is not a definitive prediction of what will happen, it serves as a sobering look at what could happen in the larger context of the U.S. food system in response to plausible climate change trajectories.

Observed and projected trends in U.S. corn production losses due to heat stress.

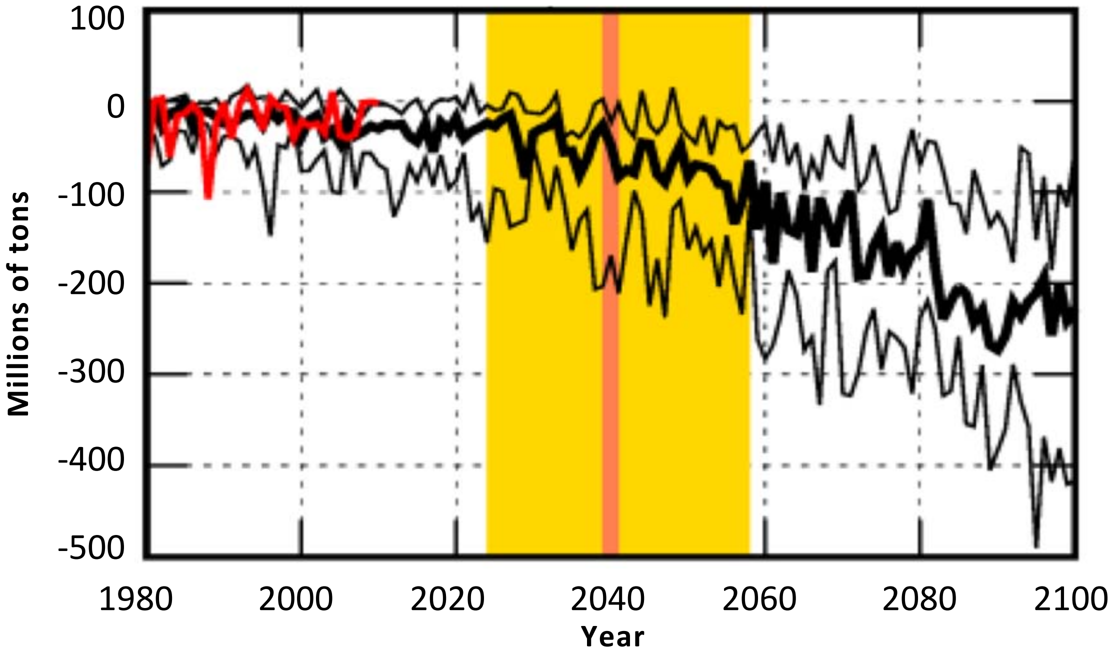

Figure 35. Observed and projected U.S. corn production losses due to heat and drought stresses. The red line shows observed losses in 1980-2010. The thick black line shows the median loss estimated by seven models using a high greenhouse gas emissions scenario (RCP8.5). The thin black lines show the highest and lowest loss estimates from the individual models. The vertical orange bar shows the median estimate for the year in which annual losses match the “worst in 10 year” value from 1980-2010. The vertical yellow bar shows the range of years estimated by the seven individual models. Adapted from Zampieri et al., 2019.

Under the RCP8.5 high emissions scenario, corn production losses in the United States due to climate related stresses could increase dramatically. Zampieri et al. (2019) estimated that by 2040 average annual losses could equal the losses experienced only once in ten years during 1980-2010. Individual model estimates for the year when annual losses would increase to that level ranged from the early 2020s to the late 2050s.

For the U.S., the estimated year by which “worst in 10 year” corn production losses become “normal” (i.e. 2040) matched the year when global average temperature in the climate model projections had increased by 2 degrees Celsius (3.6 degrees Fahrenheit) over the preindustrial average. For most of the other major corn production regions around the world, the estimated year for losses to reach the previous “once in 10 years” level was earlier, and matched the year when global average temperature had increased by 1.5 degrees Celsius. For most corn production areas outside the U.S., by 2040 losses due to heat and drought stress could regularly reach levels worse than the “worst in 10 year” events experienced in 1980-2010.

The production loss estimates were based on a Combined Stress Index (CSI) model that explained 42% of year-to-year variability in the U.S, and 49% globally. The CSI has two components: heat stress and drought stress. The CSI indirectly accounts for the effects of other weather related factors that affect corn yield such as weeds, insect pests, diseases, and crop development timing. The U.S. corn production losses projected in this study were almost entirely due to heat stress, not drought effects. A large increase in irrigation for U.S. corn production in 1980-2010 reduced losses due to drought stress. Due to unsustainable groundwater depletion, the capacity for U.S. corn growers to continue compensating for increasing drought stress by irrigation is questionable.

The study was based on records that show U.S. corn production increasing to about 320 million tons per year in 2010, with an increase of about 44 million tons per decade from 1980 to 2010 due to improved agronomic practices. The corn production losses due to climate stress projected from 2040 to 2080 were about 35−40 million tons per decade.

A study of climate change impact on a grain crop grown in the central plains of the U.S. is not directly relevant for tree fruit production in the Northeast. And any projection based on the high emissions scenario is likely to overestimate impacts if global greenhouse gas emissions after 2020 do not match the climate change potential in that scenario. In addition, corn has been found to be one of the more sensitive crops to climate change (Zampieri et al. 2019).

But within those and other limitations, the corn example demonstrates the potential for average annual losses of a major U.S. crop due to heat stress to annually reach the level that was observed only once per 10 years in 1980-2010. Within that 20-year time frame, heat stress losses could represent a significant portion of current production, and those losses could almost completely negate the trend of production gains observed in 1980-2010.

Relevance of national and global scale to Northeast tree fruit production.

Apart from the direct effects of climate change on tree fruit production and profitability, tree fruit farmers are part of national and international economic and social systems. Changes in basic food calorie availability, cost, and distribution will surely affect demand, pricing, and profitability of tree fruit production, both globally (e.g. Chatzopoulos et al., 2019) and in the Northeast. Predicting those effects is far beyond the scope of this report.

In creating an overview of how climate changes might affect tree fruit production, the fact that indirect socioeconomic impacts on the larger food system will extend far beyond the direct immediate effects of weather on the number of bushels per acre of usable tree fruit yield has to be mentioned. The potential scope and scale of such changes shown indicate that successful farming in the coming decades will require flexibility and resilience to adapt to dynamic changes in the marketing environment that extend far beyond the farm gate.

For example, the sea level projections for Boston shown on the next page may not have direct effects on orchards. However, the effects of sea level rise on the disposable income of millions of people who buy tree fruit, and on the transportation, infrastructure, and other systems needed to market tree fruit, should not be ignored in discussing potential impacts of climate change on tree fruit growers. While it is not possible in this report to identify and discuss such complex and profound changes, an overview of the situation requires at least acknowledging their existence. Budget adjustments required to adapt or move urban centers because of recurrent flooding, as well as policies and technological developments to curtail fossil fuel use and reduce additional climate change, are certainly going to have consequences for the agricultural economy, including tree fruit growers in the Northeast.

Sea level rise.

The northeastern U.S. coastline is among the most vulnerable in the world to sea level rise. The economic and social impacts from increased flooding are already being felt, and are expected to increase greatly by 2050. The effects of climate change on the ocean, including sea level, are likely to continue for centuries along the trajectory set by previous greenhouse gas emissions.

Because of ocean temperature inertia and response lag, the amount and rate of relative sea level rise by 2050 is nearly independent of emissions over the next few decades. The sea level rise is called ‘relative’ because in addition to higher ocean level, it includes sinking land and other local effects. The most likely estimate for relative sea level rise at Boston between 2000 and 2050 is 13 inches, with a 90% confidence interval of 5 to 22 inches (DeConto et al., 2016). The expected sea level rise at New York City between 2002 (2000–2004) and 2054 (2050–2059) is 16 inches, with an 80% confidence interval of 8 to 30 inches (Horton et al., 2014).

Estimates of sea level rise by 2050 and 2100 have increased since research published in 2016 provided better understanding of the potential for accelerated meltwater contributions from Antarctica (e.g. Deconto and Pollard, 2016). The graphs below were made **before** future sea level rise estimates were updated to account for that new research indicating potential for faster increase.

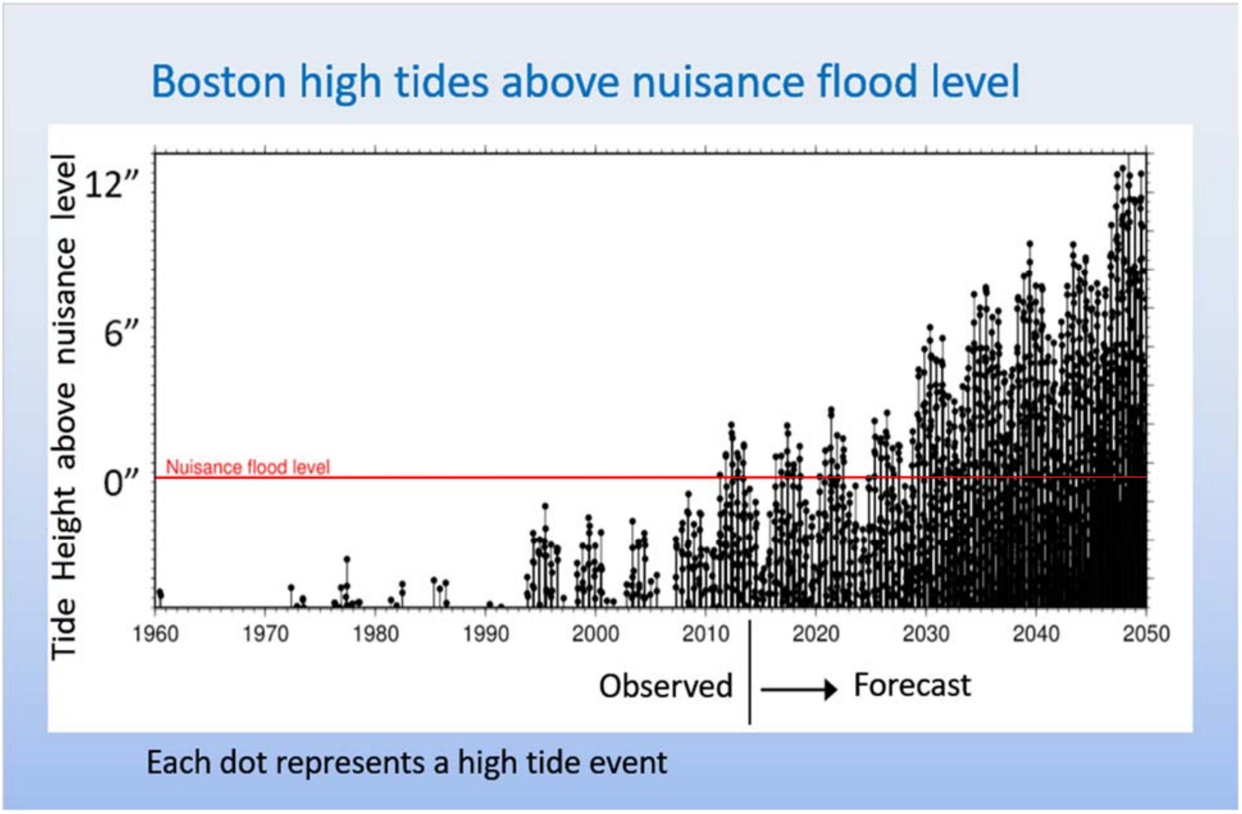

Figure 36. Expected frequency and severity of high tide flooding in Boston MA 1960 to 2050. Adapted from Ray and Foster, 2016.

Figure 37. Areas of Boston MA within 5 feet elevation of the 2015 high tide line. Adapted from Climate Central, 2018a. There is an 83% chance of at least one flood of 5 feet or more between 2016 and 2050, and by 2060 the chance is nearly 100% (Climate Central, 2018b). The blue areas affected by a 5-foot flood would be 4 feet under water with a 9 foot flood above the 2015 high tide line as shown below.

Figure 38. Areas of Boston MA within 9 feet elevation of the 2015 high tide line. Adapted from Climate Central, 2018a. There is an 8% to 14% chance of at least one flood <u>per year</u> with water more than 9 feet above the 2015 high tide line by 2054 (2050–2059) under the moderate and high future greenhouse gas emission scenarios, respectively (DeConto et al., 2016).

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