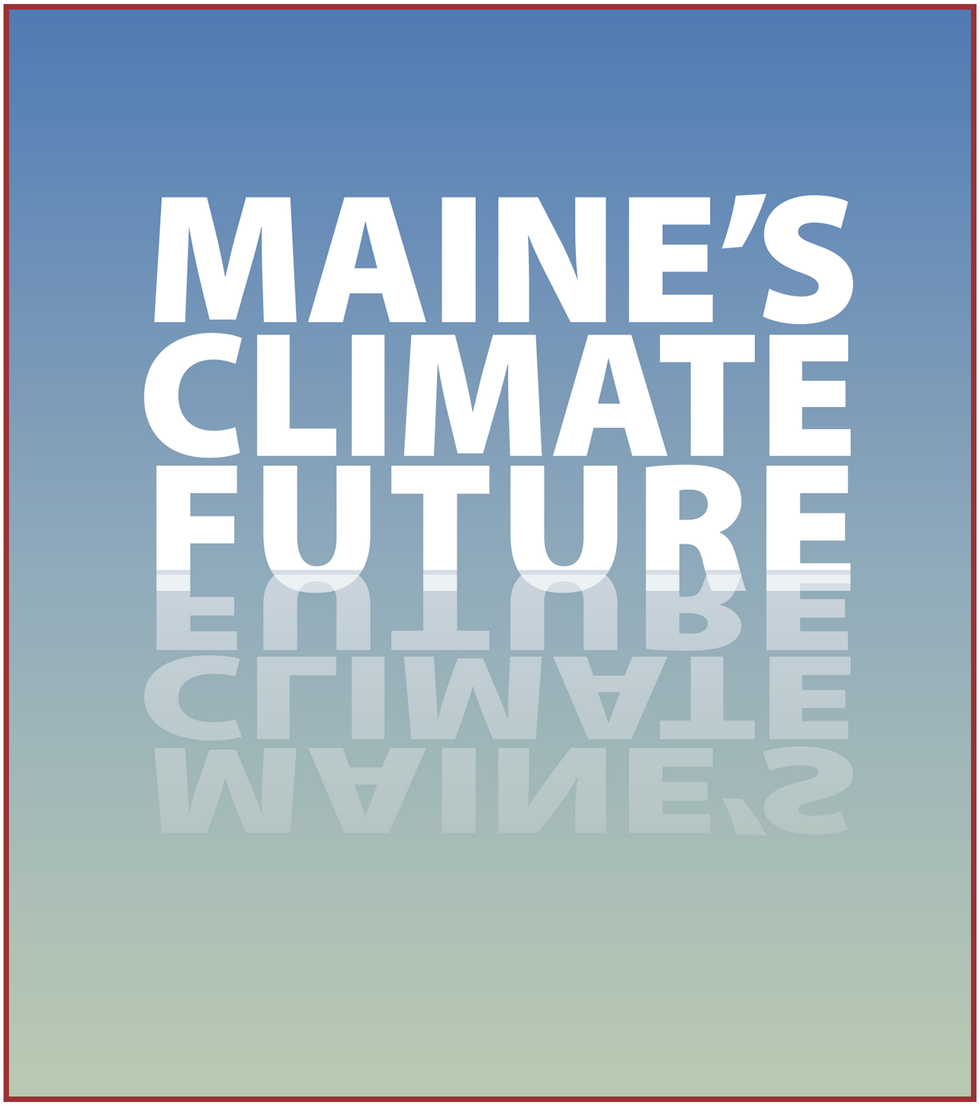
MAINE’S CLIMATE FUTURE—
2020 UPDATE



THE UNIVERSITY OF MAINE

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MAINE'S CLIMATE FUTURE 2020

Introduction

Climate change is a global phenomenon, and its effects in Maine must be understood in the context of changes taking place throughout the world.

Since 1990, the world has learned about the consequences of increasing greenhouse gas concentrations in the Earth's atmosphere for our planetary climate system, most notably through a series of reports from the United Nations Intergovernmental Panel on Climate Change (IPCC). The findings of the most recent IPCC report are summarized in the Synthesis Report released in 2014 (IPCC 2014a). Additionally, "state of the climate" reports produced annually by scientific organizations such as the World Meteorological Organization (WMO 2019a) and the American Meteorological Society (Blunden and Arndt 2019) reinforce the trajectory of change for a warming world and document the accumulation of broken records of atmospheric warming and extreme events from accelerating change in the climate system. The year 2019 was one of exceptional global heat, retreating ice, and record sea level rise, with the most recent five-year and ten-year global temperature averages certain to be the highest on record (WMO 2019b).

The past year has seen the release of notable special reports by the IPCC. Climate Change and Land (IPCC 2019a) details how careful land stewardship is vital for sustaining food systems, freshwater resources, and biodiversity. The worldwide exploitation of land resources is being exacerbated by climate change, as well contributing to the climate crisis. The Ocean and Cryosphere in a Changing Climate (IPCC 2019b) warns of accelerating trends in ocean warming, sea level rise, ocean acidification, and oxygen depletion, along with evidence for accelerating rates of glacial melting around the world. These changes have profound effects on marine fisheries and ecosystems, hurricanes and cyclones, and water supply.

For 2018, the last full year of data available for this report, the American Meteorological Society reported that the planet had an atmospheric carbon dioxide (CO_2) concentration of 407.4 ±0.1 parts per million. This is the highest concentration the earth has seen in 3 to 5 million years (Karlis 2019). The year 2018 was the fourth-hottest globally since records began in the early 1800s. Every year since the start of this century has been hotter than the 1981–2010 average despite the fact that the world oceans have absorbed more than 90 percent of the warming in the past 50 years (Dahlman and Lindsey 2018).

Since 2015 we have witnessed a remarkable escalation in the evidence for a changing planet along with an escalation in the political and social engagement on how to respond. The National Aeronautics and Space Administration reports that, on average worldwide, 18 of the 19 warmest years on record have occurred since 2001, and the five hottest years are the last five years (NASA 2019). Warming rates increase farther north, and are highest over the Arctic and sub-Arctic. Canada's rate of warming is twice that of the global rate, with stark contrasts for the country's future depending on how the world commits to limiting greenhouse gas emissions (Bush and Lemmen 2019).

In the United States, the Global Change Research Program is mandated by Congress to "assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." The Fourth National Climate Assessment focused on observed and projected changes in the physical climate system (Volume 1, USGCRP 2017) and climate-related risks to humans, ecosystems, infrastructure and the economy (Volume II, USGCRP 2018), and concluded that: *the evidence of human-caused climate change is overwhelming and continues to strengthen, that the impacts of climate change are intensifying across the country, and that climate-related threats to Americans' physical, social, and economic well-being are rising.*

While in the past we may have underestimated the rate and severity of climate change, today there is little doubt of the price of unchecked climate change, with the National Climate Assessment estimating a potential cost equal to nearly 10 percent of the U.S. gross domestic product by the end of the century (Berwyn 2018). Since 1980, the U.S. has sustained 241 weather and climate disasters that exceeded $1 billion in damages, with a total cost for these events of $1.6 trillion (Smith 2019). In 2018 alone, there were 14 of these climate disasters with 247 deaths and costs exceeding $1 billion in the U.S. These costs do not include the chronic consequences of a changing climate that we experience every day.

These recent reports on climate change have consistently told us that:

- atmospheric greenhouse gas concentrations are increasing because of human actions,
- they are influencing the climate in unprecedented ways,
- there is increasing evidence that these changes are accelerating,
- we have *not* begun to implement sufficient actions to alter our climate trajectory, and
- we are heading for a planetary condition no humans have ever experienced.

In Maine, we are acutely aware of the importance of our ocean, forests, fields, wetlands, lakes, and rivers to our way of life, our livelihoods, and our economy. All of these characteristics of Maine are shaped, in part, by our climate. We have always dealt with the challenges of weather and the joys of four seasons, but what we are experiencing now is both accelerating change in extremes and long-term averages of weather that reflect fundamental changes in the boundary conditions, or the historical range of conditions, of our climate. While these changes are consistent with the patterns reported in global and national climate assessments, those assessments are not specific to Maine, nor to our unique way of life.

The University of Maine's Climate Change Institute and Maine Sea Grant in 2008 led an initial assessment of climate-related changes in Maine. The resulting comprehensive report, Maine's Climate Future – An Initial Assessment (Jacobson et al. 2009) identified evidence of a changing climate here in Maine. More recently, we published Maine's Climate Future 2015 Update (Fernandez et al. 2015) that described the accumulating evidence of climate change in Maine with clear effects on Maine people and the environment.

The potential to alter our trajectory of impacts on the climate leaves room for optimism about how *significant action today* can avoid the worst-case scenarios for our future and build a sustainable society that we owe to future generations. To do so, we have to use the best available information to understand the changes taking place all around us, particularly where we live.

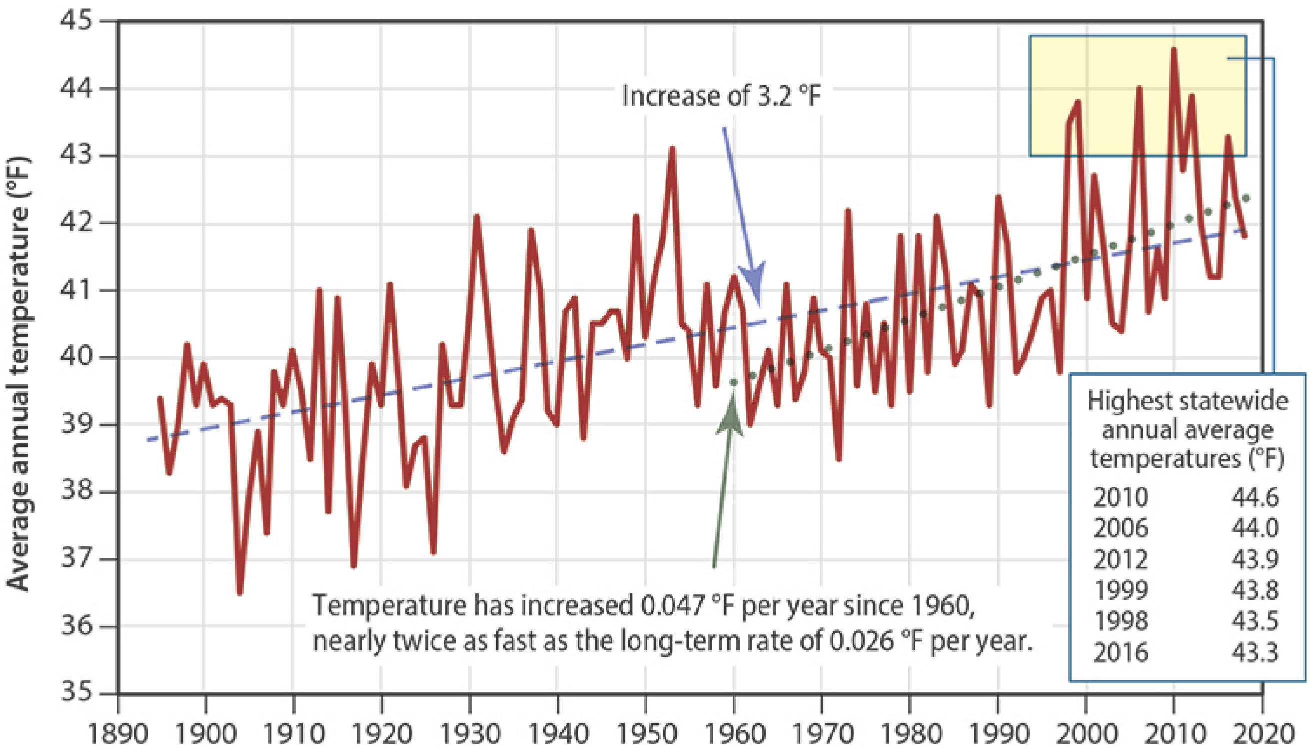
So, what about Maine?

Wiggly Bridge Under the Weather by Wayne Boardman licensed under CC BY-NC 2.0.

Maine's climate continues to change, and fast.

Temperatures are increasing statewide. Average annual temperature has increased 3.2 degrees Fahrenheit (°F) in the last 124 years, and the rate of warming has increased most notably since 1960. The six warmest years on record have occurred since 1998. Indeed, the Northeast is warming faster than any other region in the U.S., and is projected to warm 5.4 °F (3 °C) when the rest of the world reaches 3.6 °F (2 °C) (Karmalkar and Bradley 2017).

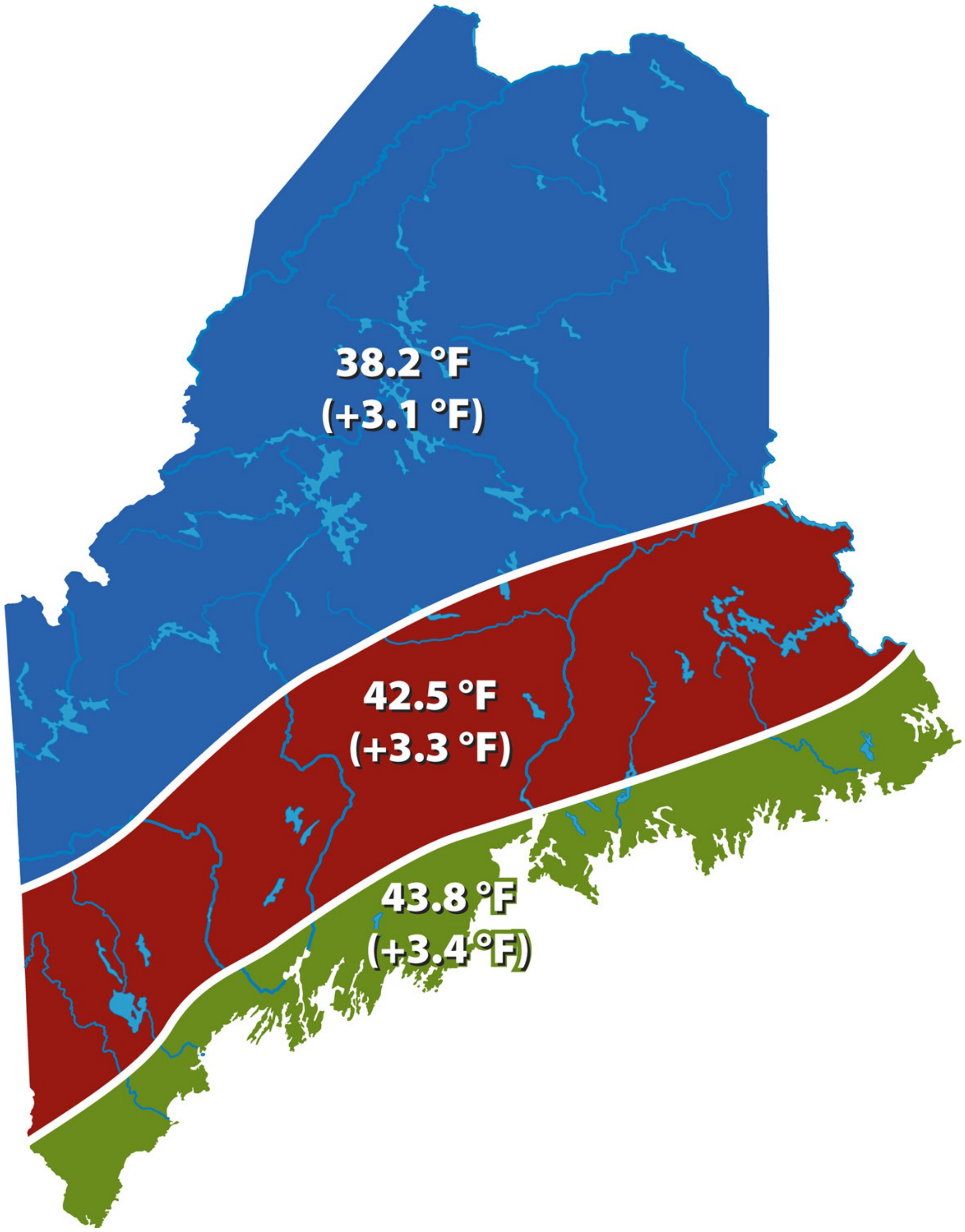
Chart: Maine Average Annual Air Temperature, 1895-2018



Annual temperature, 1895-2018, averaged across Maine based on monthly data from the NOAA U.S. Climate Divisional Database (NOAA CAAG). Linear trends calculated for the entire record (dashed line) and since 1960 (dotted line).

The whole state has warmed, and temperature increases have been greatest in the coastal division.

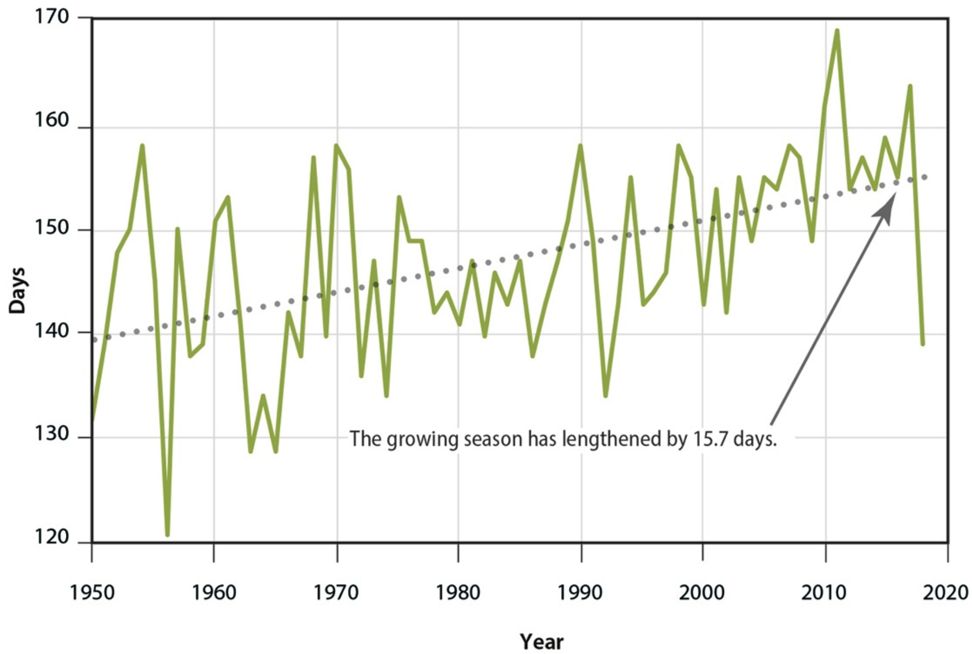
Map: Annual Temperatures by Climate Division



Current average annual temperature and increases in average annual temperature since 1895, calculated from the NOAA U.S. Climate Divisional Database (NOAA CAAG).

The growing season (the period between the last frost and first frost) is more than two weeks longer than it was in 1950, mostly due to later frosts in the fall.

Graph: Growing Season Length, 1950-2018



Average date of last Spring frost is 6.7 days earlier (May 10 ➞ May 4).

Average date of first Fall frost is 9.1 days later (Sept. 27 ➞ Oct 6).

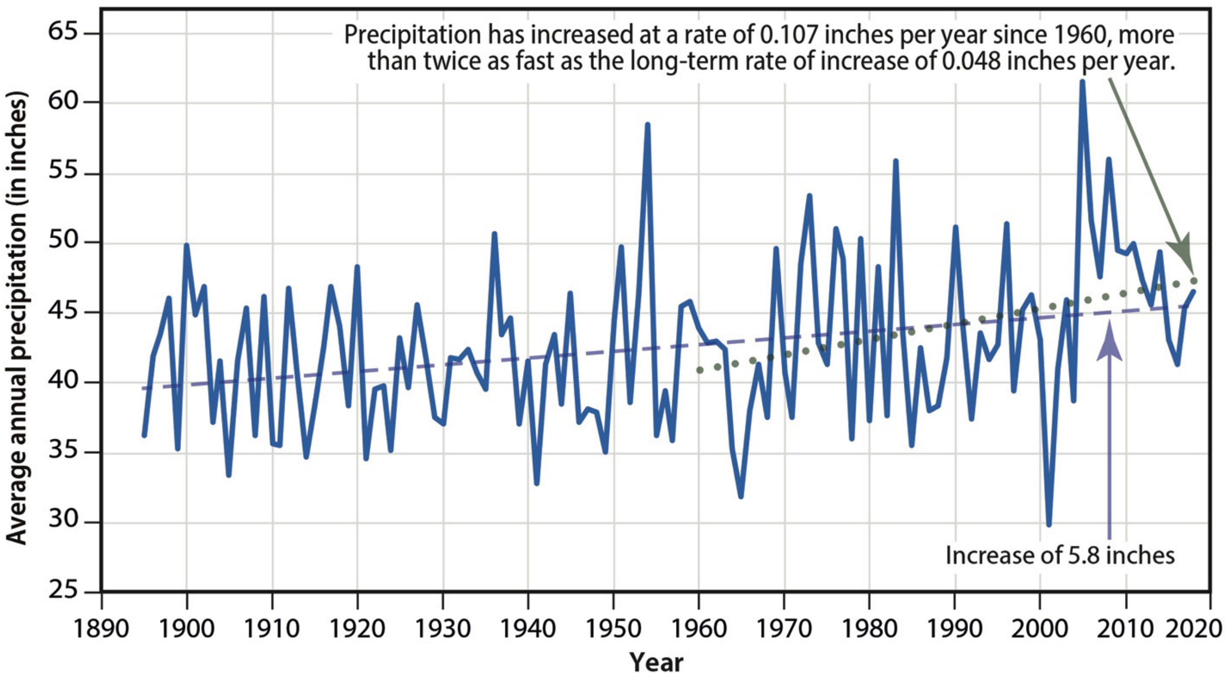
Growing season lengths based on statewide mean of 20 stations with long-term (since 1950) observational records of daily minimum and maximum temperature: Acadia National Park, Augusta, Belfast, Bangor, Bar Harbor, Caribou, Corrina, Eastport, Farmington, Fort Kent, Gardiner, Houlton, Jackman, Jonesboro, Lewiston, Madison, Presque Isle, Portland, Sanford, and Waterville. Data from the NOAA Global Historical Climatology Network (NOAA GHCN)

Longer growing seasons have allowed some farmers to report they could double-crop, and one farmer reported being able to grow watermelon (Mallory and Roche 2018). But unpredictable frost conditions, wetter and cooler springs, more frequent and intense rainfall, drought, and multiple years of weather-related stress are taking an increasing toll on farm viability (Wolf et al. 2018). *Photo courtesy South Paw Farm*

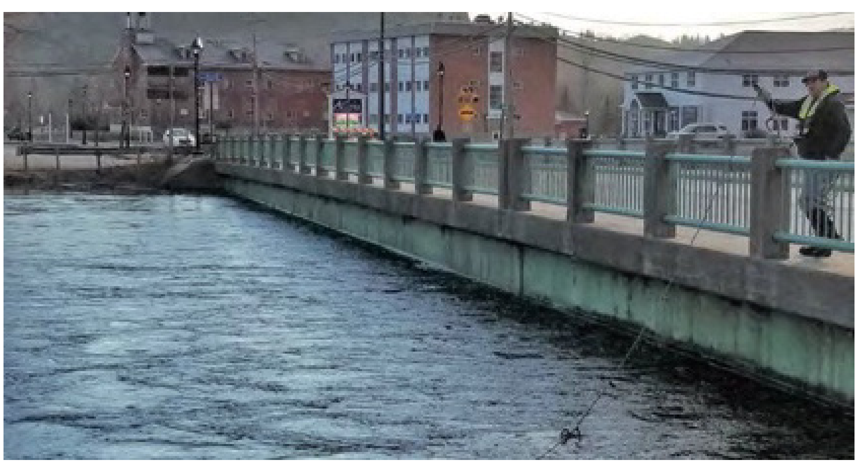
Precipitation is increasing in frequency and intensity.

Average annual precipitation has increased 15 percent (5.8 inches) since 1895, and the increase has come in the form of more rain, and less snow. Since 1895, depth of annual snowfall has decreased 20 percent (2.3 inches). As with temperature, the rate of increase has accelerated in recent decades.

Graph: Maine Average Annual Precipitation, 1895-2018



Total annual precipitation, 1895-2018, averaged across Maine based on monthly data from the NOAA U.S. Climate Divisional Database (NOAA CAAG). Linear trends are depicted for the entire record (dashed) and since 1960 (dotted).



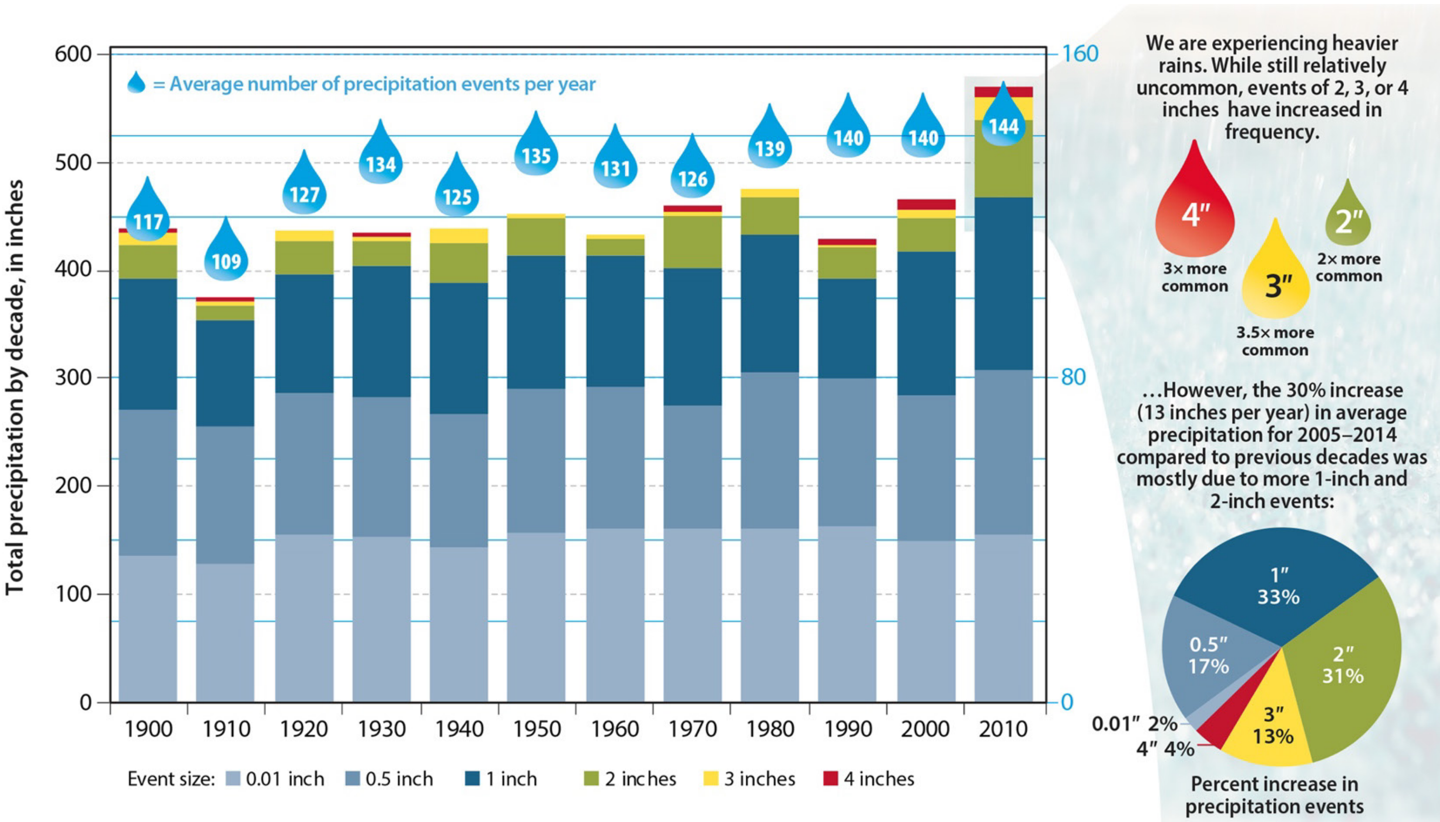
Flooding affected communities in Aroostook County in April 2019 (Lynds 2019). The Maine Emergency Management Agency has information on preparing for threats related to extreme events *(*MEMA 2019*)*. Nationally, flood insurance premiums have been rising between 5 percent and 9 percent a year, and the increase can be as high as 18 percent for individual homeowners, yet many people still aren't covered (Flavelle 2019). *Fort Kent by US Geological Survey*

The spring of 2019 provides evidence of the challenge of wet springs for farmers with delayed planting and crops rotting in the field *(*Sambides Jr. 2019a*).* *Photo by Tori Lee Jackson*

Communities across the state are experiencing more heavy or “intense” precipitation events (Fernandez et al. 2015). In order to gain further insight on storm intensity and frequency, we analyzed the records from Farmington, a precipitation measuring station with a relatively long record. As elsewhere in Maine, precipitation in Farmington has increased, and most dramatically in the last two decades. A closer look at the Farmington data shows that most of the increased volume (30 percent over previous decades) was due to more 1-inch and 2-inch events, although large rain events of three or four inches have also become much more common relative to the past. Intensity of precipitation has increased, *and* it is raining more often. Farmington now experiences 10–15 more precipitation events in a year than during the previous century.

Coastal locations are seeing even greater increases in storm precipitation intensity (Agel et al. 2015). Other studies have found increases in heavy precipitation across the northeastern U.S. in the last two decades, mostly associated with September-October tropical cyclones (hurricanes) and a warming Atlantic Ocean (Frei et al. 2015, Huang et al. 2017, Huang et al. 2018; see also NRCC 2019).

Charts: Precipitation at Farmington, Maine



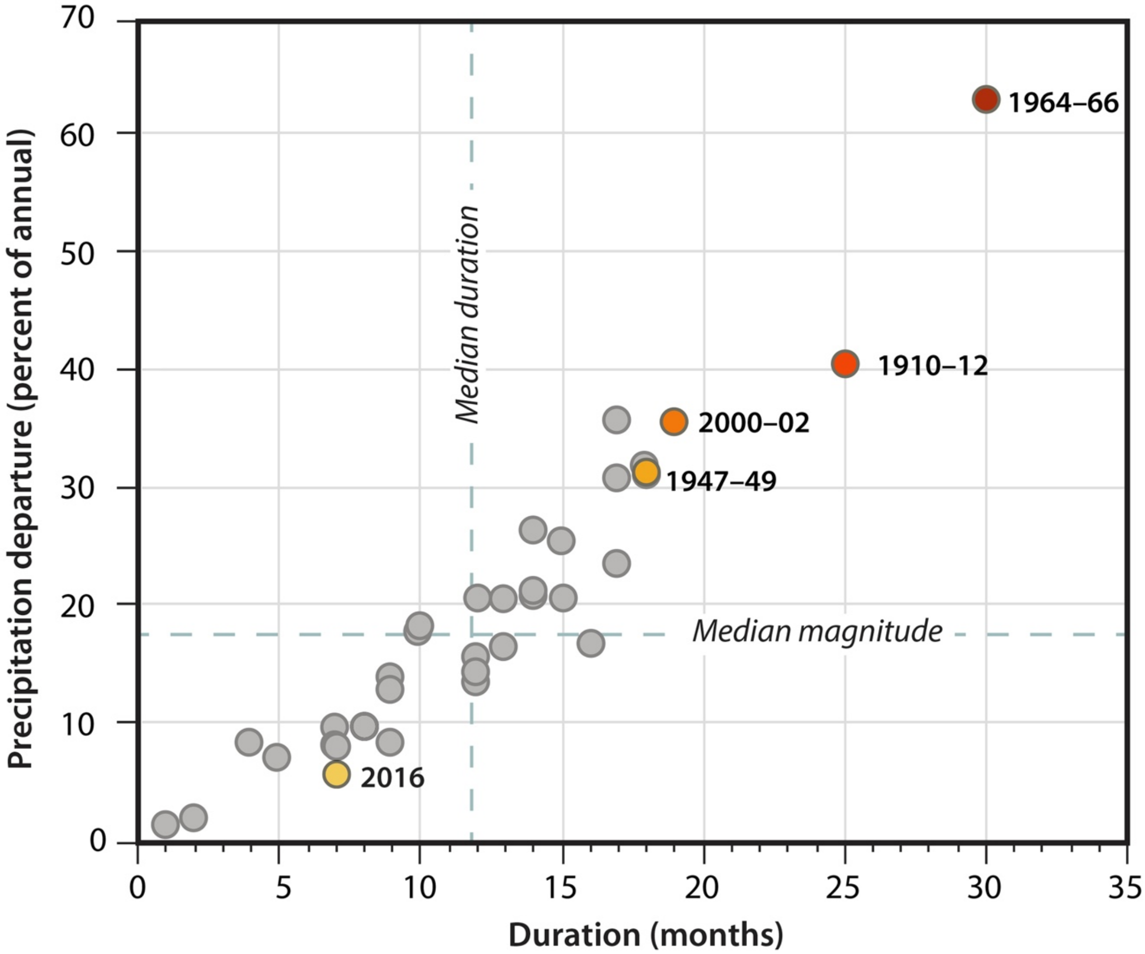
Total decadal precipitation and mean annual number of precipitation events for Farmington, Maine calculated from daily precipitation values, 1895-2014. Precipitation events are defined as days with measurable (>0.01 in) rain or water equivalent snow. Each bin represents a 10-year mean, centered on the year specified (i.e., 1900 represents data from 1895-1904). Data from the NOAA Global Historical Climatology Network (NOAA GHCN).

Increased precipitation means increased volume of runoff to local streams, rivers, and ultimately the Gulf of Maine (Vincent et al. 2015, Huntington et al. 2016). These higher flows and floods can impact drinking water (Warner and Saros 2019) and damage roads, bridges, and properties. Storms often include strong winds, such as the October 2017 event that was the worst wind storm in Maine's history (Jellig 2018). More than half a million people lost electricity due to damaged power lines that cost Central Maine Power Company $69 million (Russell 2018).

What about drought?

With an annual average of more than 45 inches of precipitation a year, Maine is often considered a state with abundant water. However, we do experience dry periods and episodes of drought, sometimes resulting in major impacts to agriculture, water resources, and communities. For example, the multi-year drought that peaked in 1947 was associated with the infamous catastrophic wildfire in Acadia National Park (NPS 2019).

Chart: Statewide Droughts



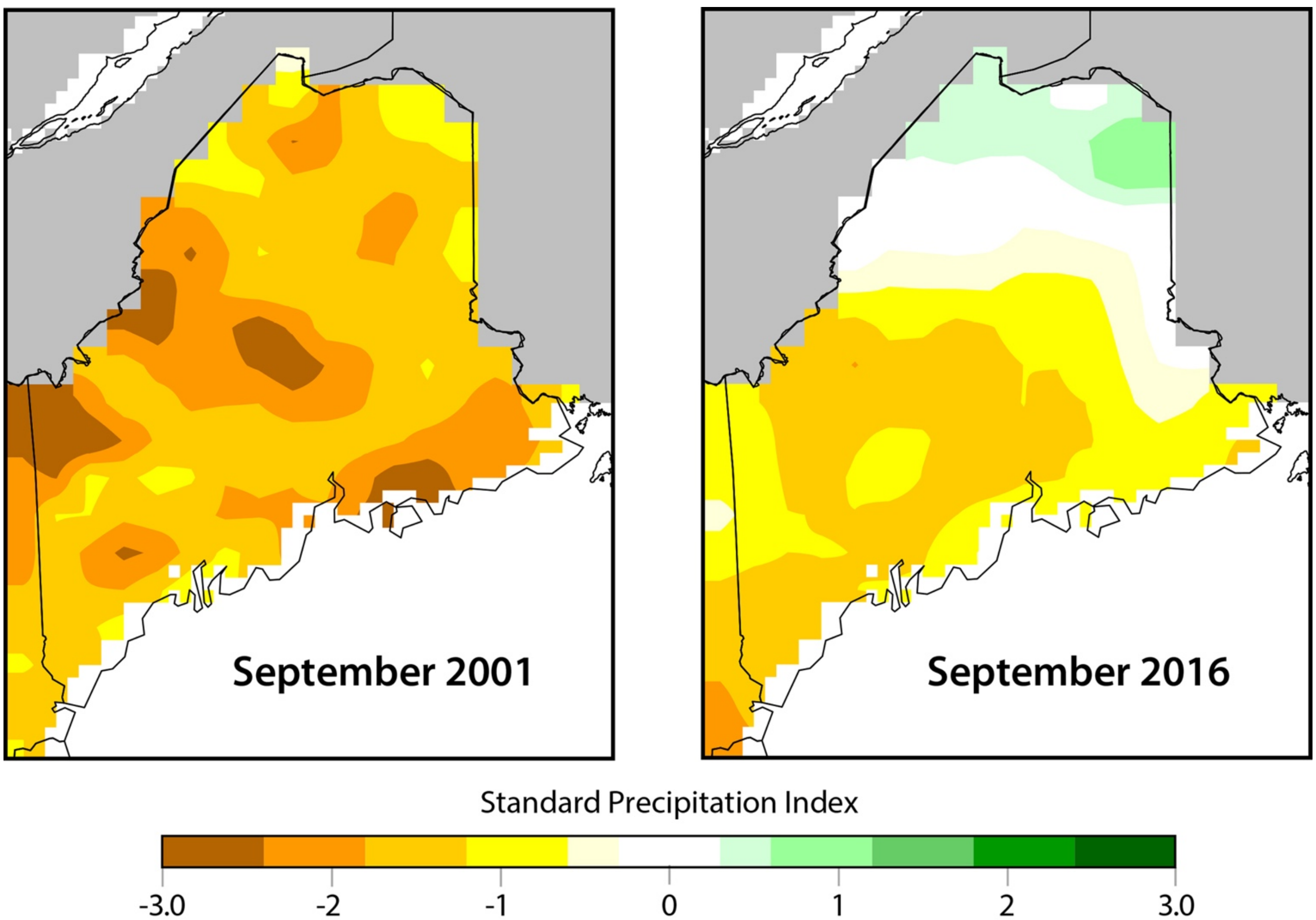
Statewide droughts based on the six-month Standardized Precipitation Index (SPI6), computed from monthly precipitation values averaged across the state of Maine using climate division data, 1900-2018 (NOAA CAAG 2019). An index value of zero indicates average conditions, while negative values indicate drier than average conditions. Drought severity is measured by both drought duration (here, the number of months with SPI6 below 0) and associated cumulative precipitation deficit (the sum of monthly departures of precipitation from average over the course of the drought, displayed here as a percentage of annual average statewide precipitation).

Drought occurs when precipitation is lower than average for a few consecutive months, seasons, or years, and climatologists use different measurements to study drought (Heim 2002). Based on the six-month Standardized Precipitation Index, which compares observed precipitation over the past six months to the average precipitation over the same period, Maine has experienced 35 statewide droughts since 1900. A six-month period relates to water and soil conditions that influence agricultural crops, and captures the slow- developing or "accumulating" nature of drought.

Some droughts are more severe than others. As the duration of a drought increases, so does its associated precipitation deficit.

Drought can also be localized. For example, the recent drought of 2016, which was associated with substantial impacts in southern Maine, appears as a rather modest event when viewed using a statewide index. In contrast, the 2000–2002 drought was clearly more severe in both duration and magnitude, and affected the entire state.

Maps: Local Drought Conditions, 2001 and 2016



Maps of the six-month Standardized Precipitation Index for September 2001 (left) and September 2016 (right) based on gridded precipitation data from NOAA. An index value of zero indicates average conditions, while negative values indicate drier than average conditions. Positive values of the index are associated with wetter than average conditions

When drinking water wells are affected by dry weather, drought can have a direct impact on human health and safety (McGuire 2016). For farmers, dry conditions can cause hay and other forage crops to mature earlier, slow pasture regrowth, increase rodent numbers, and delay reproduction of insect pests, in turn changing monitoring and spray schedules. Drought, along with problems from too much rain, are the leading causes of federal taxpayer-subsidized crop insurance claims (Gustin 2018), costing the nation $74 billion between 2000– 2016. Droughts are among the greatest stressors on forest ecosystems, and can often lead to secondary effects of insect and disease outbreaks on stressed trees and increased fire risk (Clark et al. 2016, Vose et al. 2016).

As the climate warms, future droughts and periods of limited moisture are likely to worsen with higher temperatures favoring increased drying. There is considerable uncertainty whether drought will become more frequent in the future, presenting further challenges to decision-making. More resources for addressing drought are becoming available for the public, such as the National Integrated Drought Information System (NIDIS 2019).

Winter is the fastest changing season.

From north to south, inland to the coast, the most warming has occurred in the winter, with average minimum temperatures increasing 3.7 to 4.3 °F over the long-term.

Table: Temperature Changes by Climate Division, 1895-2018; increases over 100-year average

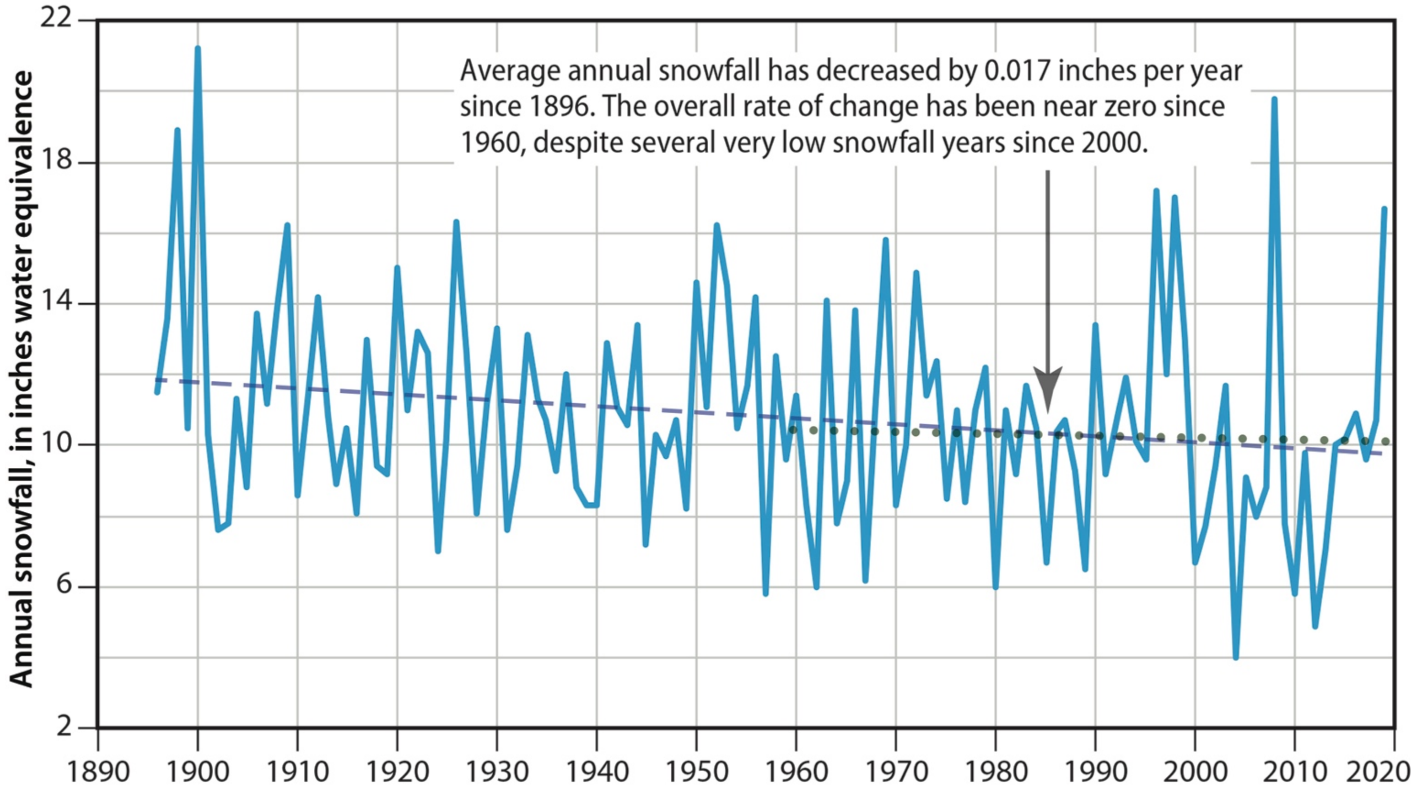
Climate Division	Annual average Temperature	Maximum	Average	Minimum
Northern	38.2°	+2.4″	+3.1″	+3.7″
Interior	42.5°	+2.6″	+3.3″	+4.0″
Coastal	43.8°	+2.5″	+3.4″	+4.3″

Average annual temperature by climate division, with change in maximum, average, and minimum temperature, 1895-2018. Values based on monthly means from the NOAA U.S. Climate Divisional Database (NOAA CAAG).Warming winter temperatures mean that more precipitation is falling as rain instead of snow. Statewide average annual snowfall is estimated to have decreased by about 17 percent over the past century. A lesser downward trend of 3 percent is estimated since 1960, partially attributed to increased moisture availability associated with warmer air.

Since the mid-1990s, there has been considerable variability, with winters of low snowfall (e.g., 2004 and 2010) and high snowfall (e.g., 2008 and 2019). In addition, there can be considerable local variability at specific stations when compared to the statewide trend shown here. Northern Maine in particular diverges from the broader trend: the Caribou station shows that January 2019 was the snowiest month on record (58.9") and 2018–19 winter season as a whole was the third-snowiest on record since record keeping began in 1939 (NWS 2020a).

A recent analysis of temperatures and snow cover across the northeastern U.S. and Canada during winter (November to May) found changes in many seasonal indicators in the region over the last one hundred years, with fewer days of extreme cold, frost, snow, and ice, and more frequent thaws and days with bare ground and mud (Contosta et al. 2019).

Graph: Maine Average Annual Snowfall, 1896-2019



Estimated annual snowfall, 1896-2019, averaged across Maine for the contiguous winter months November-April, with linear trends for the record period (dashed), and since 1960 (dotted). Values derived from monthly temperature and precipitation data from the NOAA U.S. Climate Divisional Database (NOAA CAAG), where snow precipitation is assumed for all months (November through April) with a mean temperature of less than 32 °F.

An erratic frost in the spring, such as the one in June 2018 *(Cooperative Extension 2018)*, can kill flowers that would have become fruit. "We didn't used to have these unpredictable events," wild blueberry specialist with Cooperative Extension Lily Calderwood told *The New York Times*."We could rely on gradual and reliable growing seasons. Now it's all starting to skip around, and these frost events come out of the blue" (Severson 2019). *Photo: Jennifer D'Appollonio*

More and more, we seem to be experiencing "winter weather whiplash," with rapid shifts from freezing to thawing conditions, heat waves and rain in the depths of winter, and cold or snow in spring and fall when the leaves are still on the trees (Casson et al. 2019). Arctic blasts cause cold snaps and can contribute to major snowstorms during otherwise mild winters (Francis and Skific 2015, Cohen 2016, Cohen et al. 2018, Zarzycki 2018, Harvey 2019).

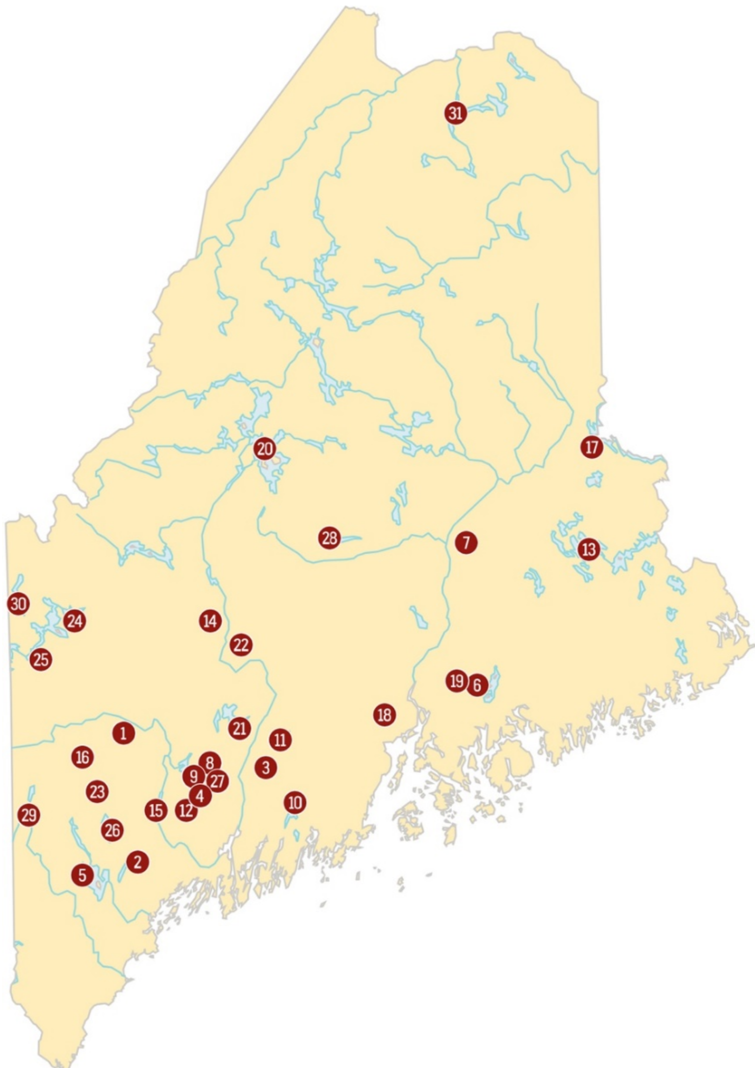
Table: Changes in Winter Indicators

Over the last 100 years, the winter season in the Northern Forest region that includes Maine has changed, as shown by:

Decreased days of:	**Increased days of:**
Ice (max temp < 32): 5 fewer days	Thaw: 5 more days
Frost: 13 fewer days	Bare ground: 9 more days
Snow: 10 fewer days	Mud:10 more days
Snowmaking: 12 fewer days	Insect pest survival: 4–12 more days

Across the state, lakes are experiencing earlier ice-out, ranging from one day earlier at Eagle Lake to more than three weeks earlier at Worthley Pond in western Maine, based on a small subset of lake ice-out dates analyzed here and consistent with the findings of Hodgkins (2013). There does not appear to be a geographic pattern to the changes for this set of lakes, which likely reflects the relative dominance of local climate conditions and individual lake characteristics.

Map and Table: Earlier Ice-Out on Maine Lakes

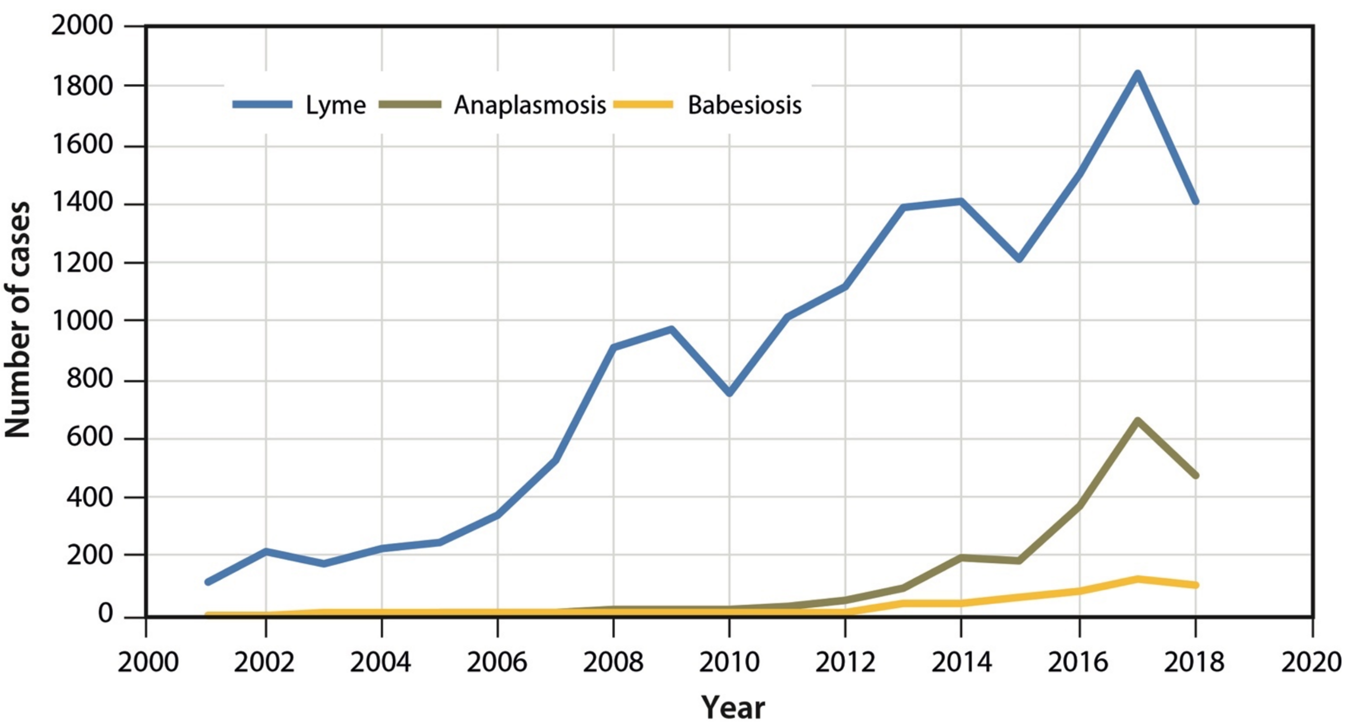


Changes in ice-out date over the period of record for lakes with data beginning 1960 or earlier. Ice-out dates from the Bureau of Parks and Lands, US Geological Survey (Hodgkins and James 2002), and the Lake Stewards of Maine.

Map number	Lake name	Number of days ice-out has shifted earlier
1	Worthley Pond	24.8
2	Crystal Lake	21.3
3	Togus Pond	17.7
4	Sabattus Pond	15.1
5	Sebago Lake	14.1
6	Green Lake	12.4
7	Cold Stream Pond	11.5
8	Maranacook Lake	11.0
9	Cobbosseecontee Lake	10.8
10	Damariscotta Lake	10.6
11	China Lake	10.4
12	Lake Auburn	10.3
13	West Grand Lake	9.5
14	Embden Pond	9.1
15	Cochnewagon Pond	9.1
16	Bryant Pond	8.8
17	East Grand Lake	8.7
18	Swan Lake	8.3
19	Phillips Lake	8.0
20	Moosehead Lake	7.8
21	Messalonkee Lake	7.8
22	Wesserunsett Lake	7.7
23	Pennesseewassee Lake	7.1
24	Rangeley Lake	6.8
25	Richardson Lakes	6.1
26	Thompson Lake	6.1
27	Wilson Pond	5.5
28	Sebec Lake	5.3
29	Kezar Lake	2.4
30	Aziscohos Lake	1.3
31	Eagle Lake	1.0

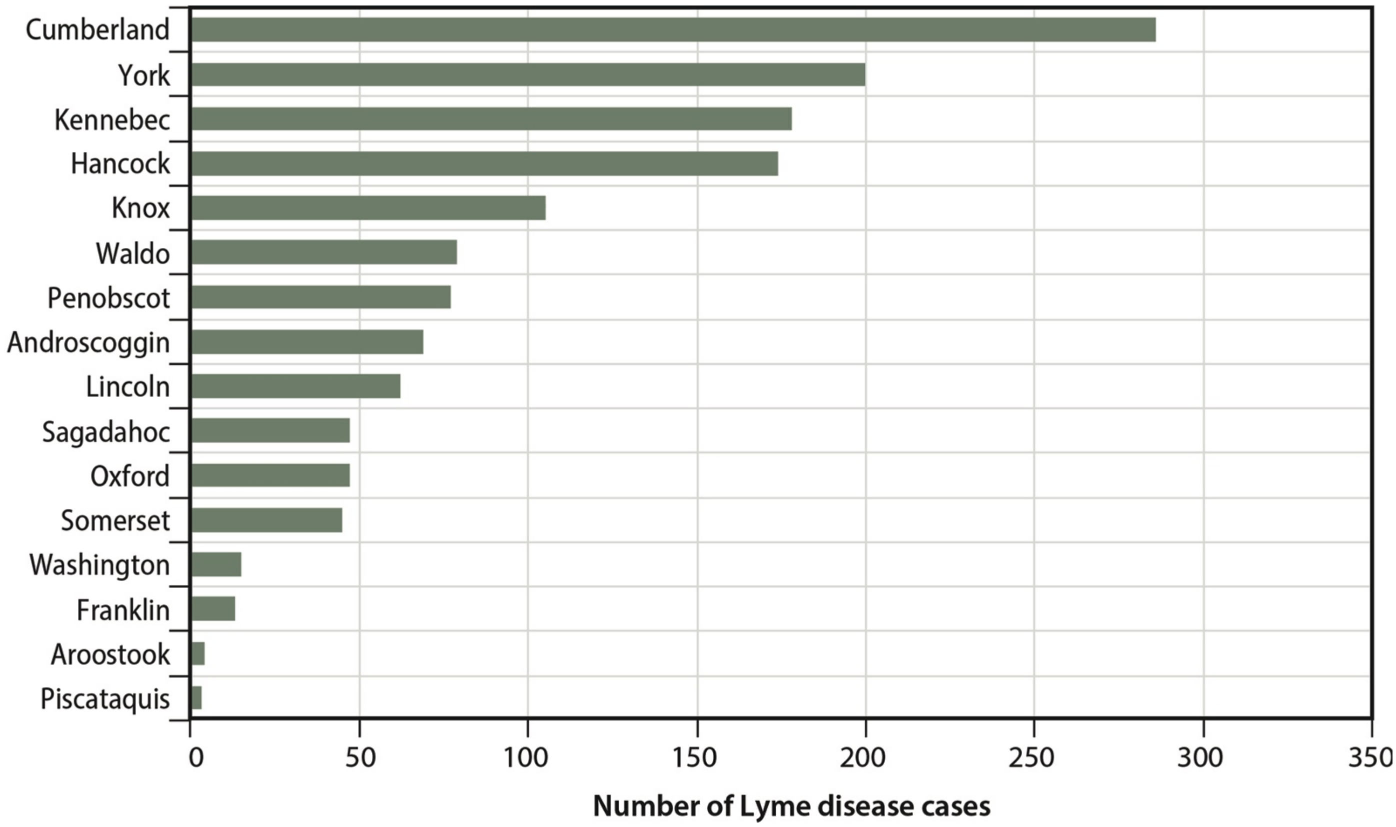
Shorter winters and more extreme rain events are associated with greater tick and mosquito activity and abundance. Lyme disease remains by far the most pervasive problem, and is changing the way Maine people and visitors interact with the outdoors at work and play (Kevin 2018). Data from the Maine Center for Disease Control & Prevention's Maine Tracking Network show mostly a continual rise in the number of reported cases of Lyme and other tick-borne disease (MCDCP 2019a). While the trend is for a clear increase over time, with more cases in southern and coastal Maine, year to year variation exists, with the slight decline in 2018 possibly a reflection of dry summer conditions that year (Lawler 2018). However, experts expect the rates of tick-borne diseases in Maine, including Lyme, anaplasmosis, babisiosis, *Borrelia miyamotoi*, and Powassan encephalitis to continue to increase overall into the future (Sarnacki 2019). The University of Maine Cooperative Extension Tick Lab (Cooperative Extension 2019a) now provides tick testing for disease in Maine and a wealth of information on detection and prevention. As we learn more about the spread of these diseases, we are also learning about the complexity of both the patterns of disease occurrence and reporting over time, and the underlying mechanisms of disease development (Elias 2019, Elias et al. 2019).

Graph: Number of Tick-Borne Disease in Maine



Cases of Lyme disease, Anaplasmosis, and Babesiosis reported to the Maine Center for Disease Control and Prevention, 2000–2018, and distribution of Lyme cases reported for 2018 by Maine county (MCDCP 2019a).

Bar Chart: Number of Lyme disease cases by county



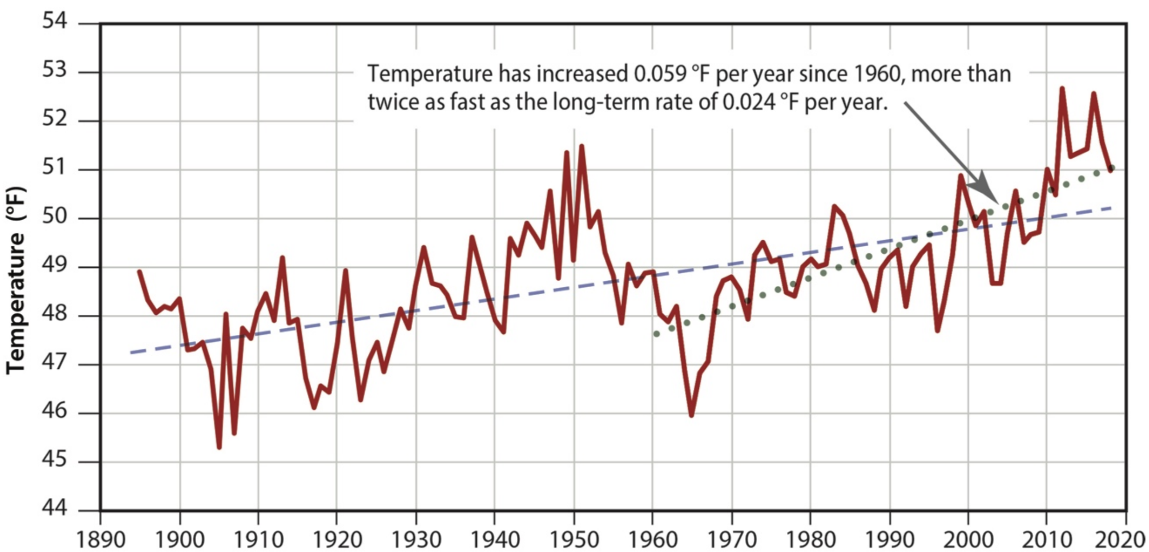
Distribution of Lyme cases reported for 2018 by Maine county (MCDCP 2019a).

Increased winter tick survival is linked to moose population declines (Jones et al. 2019). *Photo by Anne Lichtenwalner*

The Gulf of Maine is getting warmer.

The size and shape of the Gulf of Maine, combined with patterns of currents and circulation, make it especially susceptible to marine heat waves (Mills et al. 2013, Chen and Kwon 2018), which have increased in frequency, duration, and intensity around the world (IPCC 2019b).

Graph: Gulf of Maine Temperature, 1895-2018



Average annual sea surface temperature, 1895-2018, averaged across the Gulf of Maine based on monthly data from the NOAA Extended Reconstructed Sea-Surface Temperature Version 5 gridded dataset (NOAA ERSST5), with linear trends for the periods 1895-2018 (dashed) and 1960-2018 (dotted).

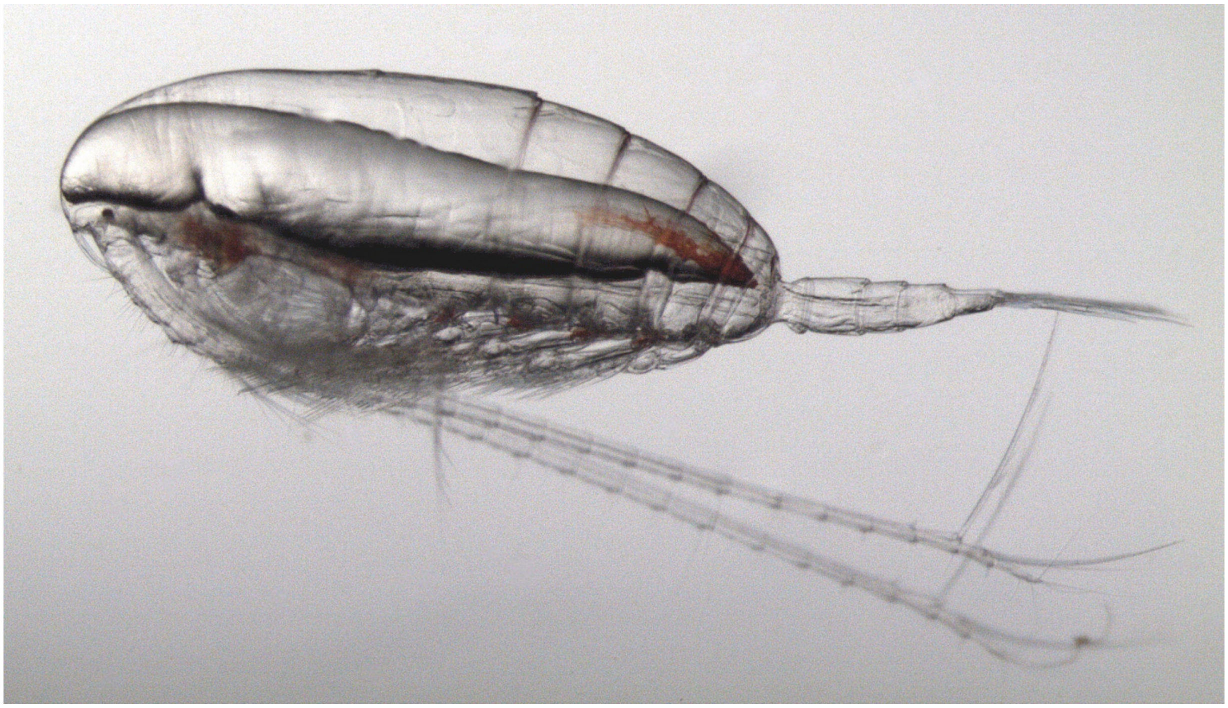
Average annual sea surface temperature of the Gulf of Maine has increased 2.9 °F since 1895. The steepest temperature rise has occurred in recent decades, and “heatwaves” occurred in 2012 and 2016 (Pershing et al. 2018).

The ocean can influence agriculture in the coastal region. Although multiple factors influence crop yield trends over time, Birkel and Mayewski (2018) reported a correlation of blueberry yield increases with increasing sea surface temperatures that resulted in a flow of more warm, moist air onto coastal land. *Photo: Allagash Brewing licensed under CC BY 2.0*

The Gulf of Maine has experienced a rate of warming that few marine ecosystems have encountered (Pershing et al. 2015), and it is expected to continue warming at an above average rate (Saba et al. 2016). There is a seasonality to the warming, with the greatest temperature increase in the summer and early fall months, from June to October. This is in contrast to temperatures on land, which show the greatest change in winter.

Summer conditions in the Gulf of Maine now last about two months longer than in 1982 (Thomas et al. 2017).

The recent warming has been linked to deep flows of warm, salty water into the Northeast Channel (Townsend et al. 2015, Brickman et al. 2018, Record et al. 2019). Warmer temperatures extend the period of stratification. With less mixing, fewer nutrients reach the surface, a trend that could lead to a less productive Gulf of Maine (Balch et al. 2012, Balch et al. 2016). Stratification also affects the timing and intensity of phytoplankton blooms. During the recent warm period, spring blooms have been smaller while phytoplankton abundance has increased in the fall and winter (Runge et al. 2015, Record et al. 2018).

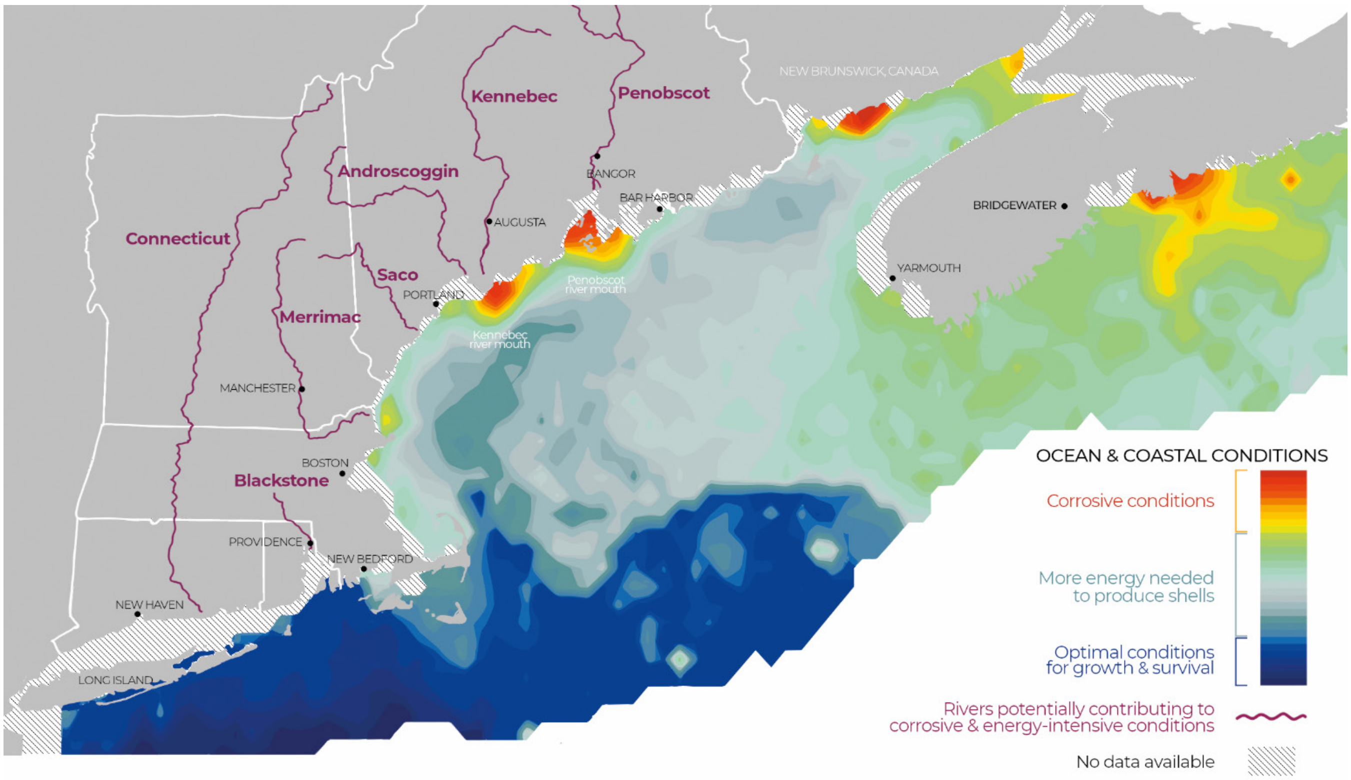


Warming has been linked to declining summer and fall populations of *Calanus finmarchicus*, a tiny crustacean that is a critical part of the ocean food web and an important prey for everything from right whales to larval lobster (Record et al. 2019). *Photo: University of Maine*

The chemistry of the Gulf of Maine is changing.

Carbon dioxide absorbed by the oceans mixes with salt water to form carbonic acid, resulting in "ocean acidification," a condition of reduced pH and carbonate ion concentrations. Acidification is intensified locally in coastal waters ("coastal acidification") from riverine inputs, and when algae blooms die and decompose due to nutrient pollution. Acidic conditions reduce the availability of minerals, particularly calcium, needed by organisms to build healthy shells.

Map: Coastal Acidification in the Northeast Region



Coastal acidification conditions in the Northeast (adapted from Figure 2, Gledhill et al. 2015). This map provides a general illustration of ocean and coastal acidification conditions in the Northeast based on the minimum monthly aragonite saturation state at the sea surface (minimum monthly pixel-by-pixel averages between 2003–2010). Lowest values tend to occur in early spring. During this period, values north of Cape Cod are generally between 1.2 and 1.5 (or frequently lower), levels that are considered harmful to young shellfish.

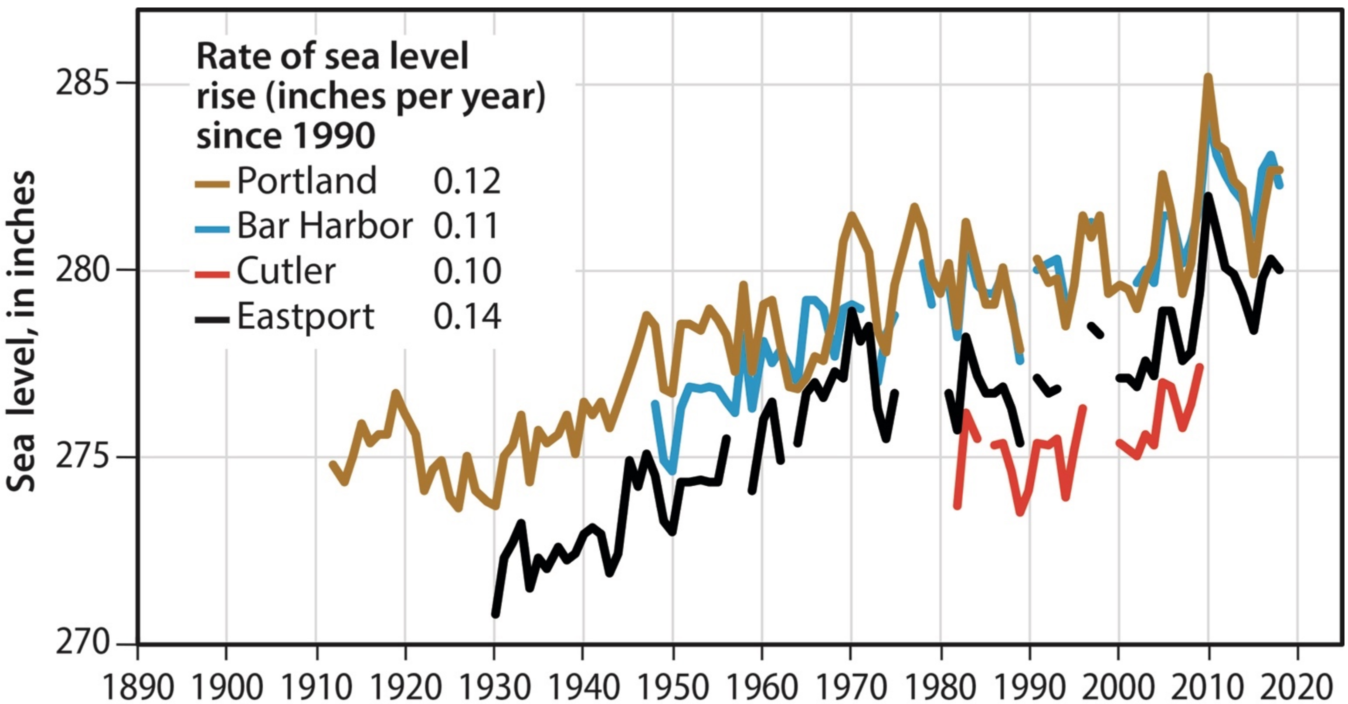
Since 2003, Northeast Coastal Acidification Network (NECAN 2019) partners have measured carbonate chemistry at coastal locations, and offshore from research vessels and NERACOOS buoys (Gledhill et al. 2015). An analysis of data from several buoys in the region adopting assumptions about past atmospheric CO_2 values, concluded that corrosive conditions, which did not exist prior to the industrial period, now occur in the surface waters of the Gulf 11–31 percent of the time from late winter to spring with peak exposure in February and March (Sutton et al. 2016). The complexities of the food web in the Gulf of Maine complicate our ability to forecast the large-scale ecological effects of acidification, which interacts with other stressors such as increasing temperature, decreasing salinity, and depleted oxygen. Changes in temperature and salinity can have substantial effects on acidification in the Gulf of Maine, leading some to conclude that it may take decades of sustained measurements for an acidification-caused drop in pH to emerge from background natural variability, thus highlighting the importance of long-term monitoring (Salisbury and Jönsson 2018). Maine Ocean and Coastal Acidification Partnership (MOCA), formed in 2016, has provided multiple forums for acidification research and information and seeks (1) to implement recommendations of the Ocean Acidification Study Commission authorized by the 126th Legislature, and (2) to coordinate the work of governmental agencies and private organizations and citizens who are studying and implementing means to reduce the impacts of or help adapt to ocean and coastal acidification.

Photo: K Tenga-González

Rising sea levels lead to more frequent flooding.

As warmer ocean temperatures and melting of ice sheets and glaciers cause the ocean to swell and expand at accelerated rates, the water's edge is higher along the coast and is creeping inland (IPCC 2019b). The Gulf of Maine is especially susceptible to fluctuations in sea level due to changes in the strength of the Gulf Stream and seasonal wind patterns. Rates vary geographically due to local geology and topography, but all have accelerated since 1990. For example, at Portland, the station with the longest record, the edge of the water has risen 7.5 inches since record-keeping began in 1912. The overall average rate for the full length of record to the present was 0.07 inches per year, but since 1990 the rate has accelerated to 0.12 inches per year.

Graph: Sea Level Rise in Maine



Annual mean sea level from four long-term observation sites along the Maine coast. Data from the Permanent Service for Mean Sea Level (Holgate et al. 2013, PSMSL 2019).

Higher sea levels mean that regular high tides are also higher, causing more frequent "sunny day" or "nuisance" flooding, when coastal water levels reach or exceed two feet above the long-term average daily high tide. In Portland, such floods historically happened about five times per year, but lately occur 12 or more times a year, especially during winter Nor'easters (Slovinsky 2019; Sweet et al. 2017).

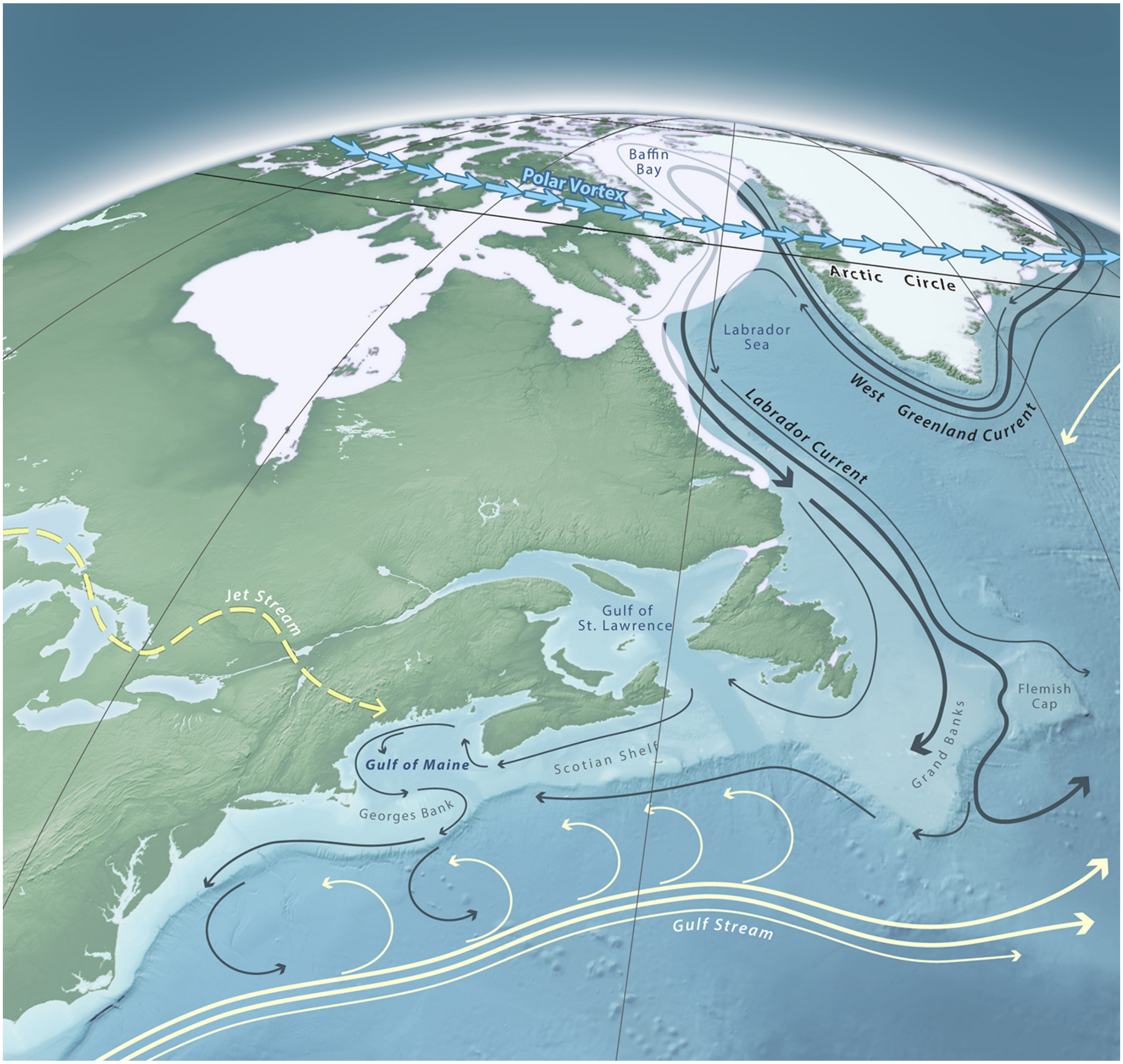
Increased coastal flooding threatens an estimated 198 miles of Maine roadway (Jacobs et al. 2018) and more than 1,200 homes (UCS 2018). Tidal flooding caused by sea level rise already has eroded $70 million in coastal real estate value. Kennebunkport, Saco, Scarborough, Biddeford, and Bath have lost the most value (First Street 2019). All along the coast, communities are confronting rising sea levels and planning for more frequent storms and flooding (Corbin 2017), from evaluating the feasibility of developing a new water supply to avoid salt water intrusion on Monhegan (Maine Coastal Program 2019), to engineering a stronger waterfront in Stonington (Sambides Jr. 2019b), to studying how to reinforce an eroding beach road in Phippsburg (Gates et al. 2018).

When storm waves and tides coincide with high tide, water levels can push the sea even farther inland. The risk of storm surge extends many miles inland from the immediate coastline in some areas. More than 20 percent of flood insurance claims come from outside of high-risk areas, and even people living in "low risk" areas have been advised to obtain flood insurance (UCS 2018).

During the January 4, 2018 Nor'easter, powerful storm waves occurred at the same time as high tide. Water levels in Portland reached 13.8 feet, one of the three highest tides ever recorded. The tide remained above flood stage for nearly three hours, causing millions of dollars in damage statewide (Schmitt and Uteuova 2018). *Photo: Corey Templeton licensed under CC BY-NC-ND 2.0*

Eastport has experienced a 44 percent increase in potential for minor flooding (Ezer and Atkinson 2014). *Photo: K Tenga-González*

Maine's Arctic Connections



Cartography: Margot Dale Carpenter, Hartdale Maps

Rapid warming in the Arctic can affect the weather we experience in Maine and conditions in the Gulf of Maine (Schmitt 2017). As Arctic air warms, there is less of a temperature difference between the North Pole and the continental United States, leading to weaker westerly winds. Recent studies have suggested that weakened westerlies may lead to a more wavy Jet Stream, so called "blocking" storm patterns, and Polar Vortex dips that allow Arctic air, still very cold, to plunge into Maine in winter.

Arctic warming has been associated with increased variability in winter temperatures ("whiplash") across the Northern Hemisphere's middle latitude regions in recent years, including more frequent cold spells and heavy snows in the northeastern U.S. (Cohen 2016, Cohen et al. 2018, Kretschmer et al. 2018). Arctic amplification may be contributing to extreme winter weather, but the mechanisms are complex and remain an active area of scientific study (Cohen et al. 2020).

Melting sea ice in the Arctic and melting glaciers and permafrost on land increase the flow of water into the global ocean. The warm, fresher meltwater tends to stay at the surface. Meltwater also warms and weakens the Labrador Current that flows into the Gulf of Maine (via the Northeast Channel), allowing the Gulf Stream to bring warm water farther north. Warm and cold water masses meet just south of the channel. Interactions between these two currents affect the exchange of deep water, with more frequent pulses of warm salty water, and the surface Gulf of Maine Coastal Current, altering the supply and distribution of nutrients to the Gulf of Maine (Brickman, et al. 2018). The deep water exchange is sensitive to the Atlantic Meridional Overturning Circulation (part of the "ocean conveyor belt") which has been weakening due to Arctic warming (Caesar et al. 2018).

Changes in the distribution of winds and sea-surface temperature across the North Atlantic, and Gulf Stream position, are likely amplifying regional warming and precipitation cycles, and have the potential to further affect seasonal shifts in the environment over the coming decades (Saba et al. 2016, Thomas et al. 2017).

Changes in stratification and circulation cause shifts in phytoplankton and zooplankton, affecting the food web that supports many species in the Gulf of Maine (Perretti et al. 2017, Record et al. 2019).

Our growing weather vocabulary

The weather has always been a subject of interest to Maine people, and we could probably consider ourselves specialists given the importance of the weather in all seasons for our work and play. However, for many of us, climate change is bringing exposure to new terms related to the weather. The use of a particular term in the news media does not necessarily mean the phenomenon is something new, nor necessarily a product of climate change. However, increased variability in the weather, weakening differentials between the rapidly warming Arctic and the equator, warming oceans, and other elements of a changing climate are indeed leading to increasing frequency of extreme events overall. Here is a short list of traditionally uncommon terms that may become more common, and what they mean. In brackets after each is an example from Maine.

Atmospheric Rivers: Long, narrow regions of the atmosphere that transport significant amounts of water vapor into areas outside of the tropics (NOAA 2015). They produce a flow of water equal to a major river, and if they stall in the atmosphere can cause extreme rain and flooding [December 2013, Miller et al. 2018].

Bombogenesis, Bomb Cyclone: A mid-latitude cyclone (rotating system of clouds and thunderstorms) that rapidly intensifies, dropping 24 millibars of atmospheric pressure in 24 hours [October 2017, McCrea 2017; see also NOAA-NOS 2019].

Flash Drought: A drought that develops rapidly, since droughts usually come on slowly [Summer-Fall 2016, NOAA-NCDC 2016; see also Martin 2019].

Heat Index: A measure of how hot it really feels when relative humidity is factored in with the actual air temperature [August 2018, Brogan 2018a; see also NWS 2020c].

Ice Storm: Generally occurs in winter when warm southerly winds from the Gulf of Mexico ride up over cold northerly air masses near the land surface, with precipitation resulting in an accumulation of ice on surfaces of a quarter-inch or more [January 1998, Dolce and Erdman 2017; December 2013, Williams 2013; see also NWS 2020b].

Marine Heat Wave or Blob: Areas of ocean water with temperatures above the 90th percentile for more than five consecutive days [2012, Mills et al. 2013; see also marineheatwaves.org].

Nor'easter: Any significant storm with predominant winds flowing into Maine from the Northeast (NWS 2019). The wind direction is determined by the center of the storm system (low atmospheric pressure = circulating counter-clockwise) tracking to our south. These storms tend to form during the winter and bring with them blizzard conditions of cold and snow, but they can also produce heavy rain [March 2018, NWS 2018; December 1969, Wikipedia 2019].

Polar Express, Arctic Express, Siberian Express, Cold Wave: When very cold polar air plunges into the middle latitudes in a cold wave that may last multiple days. These intense events are typically associated with a weak polar vortex, and can begin with the passage of a strong cold front and abundant snowfall [December 2017-January 2018, Samenow 2017; see also Dolce 2017].

Polar Vortex: Westerly winds circulating around and above the North and South poles (NOAA 2019). The system varies between a strong polar vortex (strong westerlies) and weak polar vortex (wavy jet stream) phases, with the wavy phase often occurring in winter, allowing the intrusion of lobes of bitter cold air mass into Maine [February 2015, Fritz 2015].

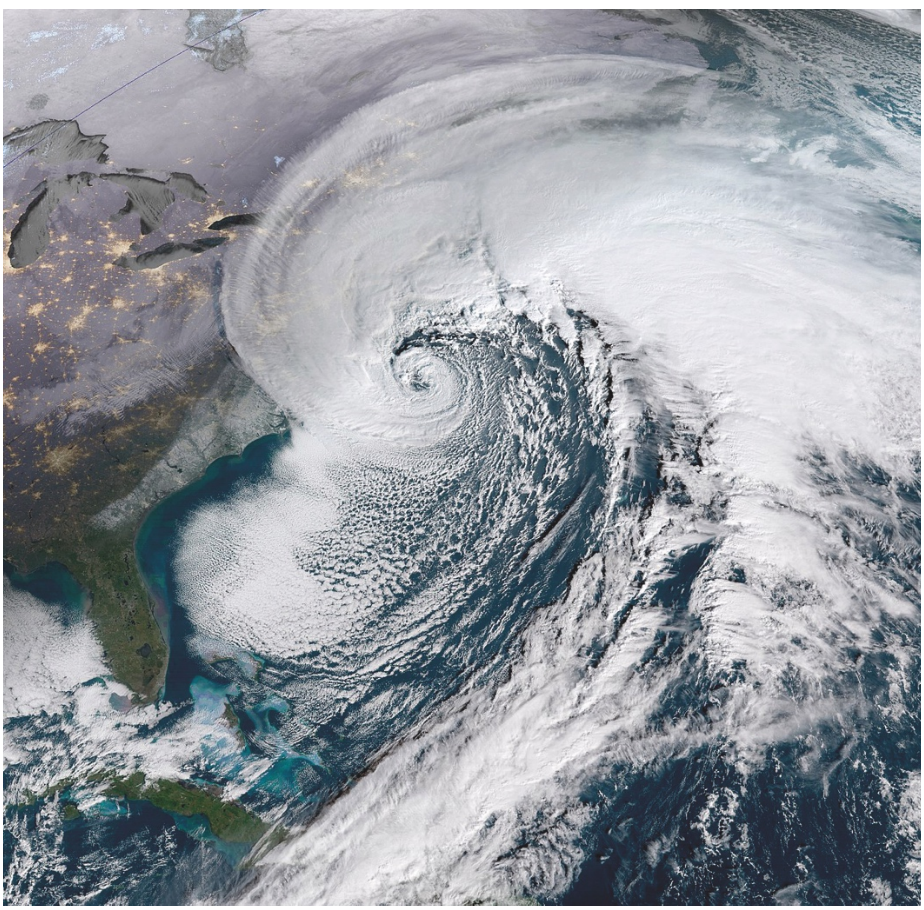


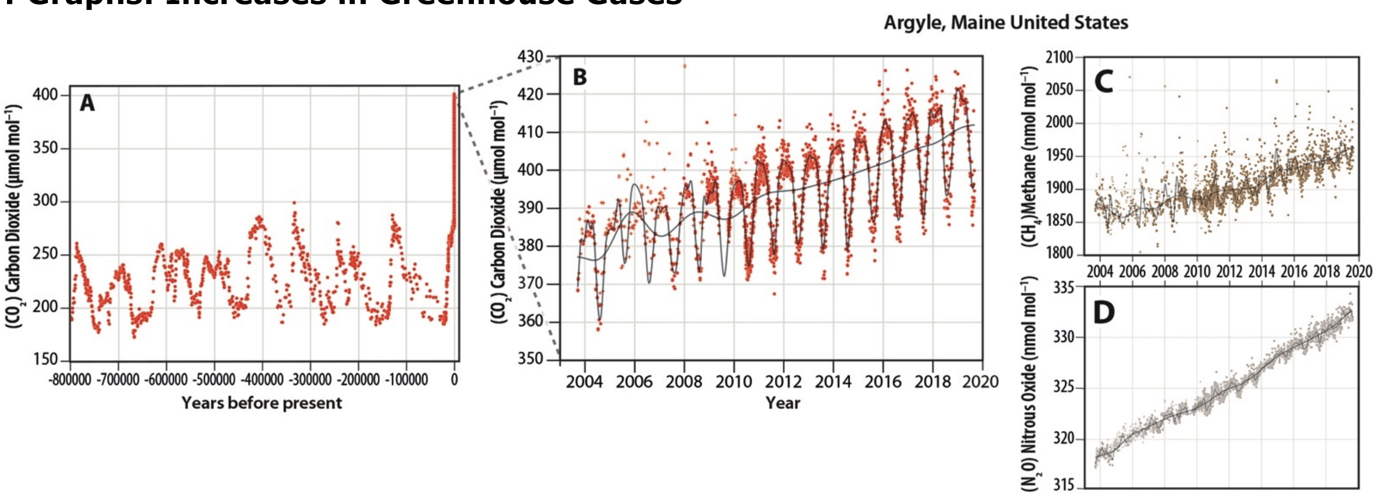
Photo: NOAA

Air pollution is the force behind these changes—and also hurts our health.

Accelerated atmospheric warming is the result of increased concentrations of the greenhouse gas carbon dioxide (CO_2) and other pollutants in the atmosphere. The increase in CO_2 has rapidly accelerated in recent years. Globally and in Maine, atmospheric CO_2 concentrations are now consistently above 400 parts per million (ppm) and vary seasonally because plants take up CO_2 through photosynthesis during the growing season.

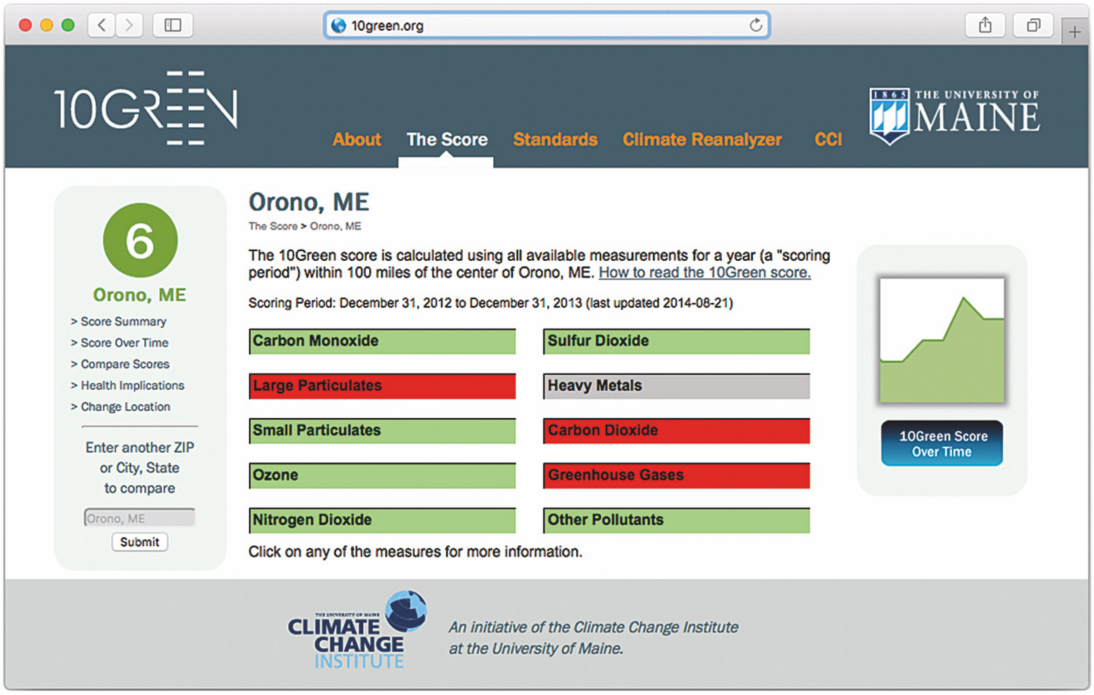
Methane and nitrous oxide, though present at lower concentrations, are many times more potent greenhouse gases than CO_2 (EPA 2019) and their atmospheric concentrations are also increasing in Maine.

4 Graphs: Increases in Greenhouse Gases



Global concentration of atmospheric carbon dioxide, 800,000 years ago to present in parts per million (µmol mol^{-1}) from a variety of data sources (A); EPA-GGE). Atmospheric carbon dioxide (B) in parts per million (µmol mol^{-1}); methane (C), and nitrous oxide (D) in parts per billion (nmol mol^{-1}) measured at Argyle, Maine, 2003-2018 (NOAA-ESRL). This Earth System Research Laboratory (ESRL) site is a collaboration between the University of Maine and the National Oceanic and Atmospheric Administration.

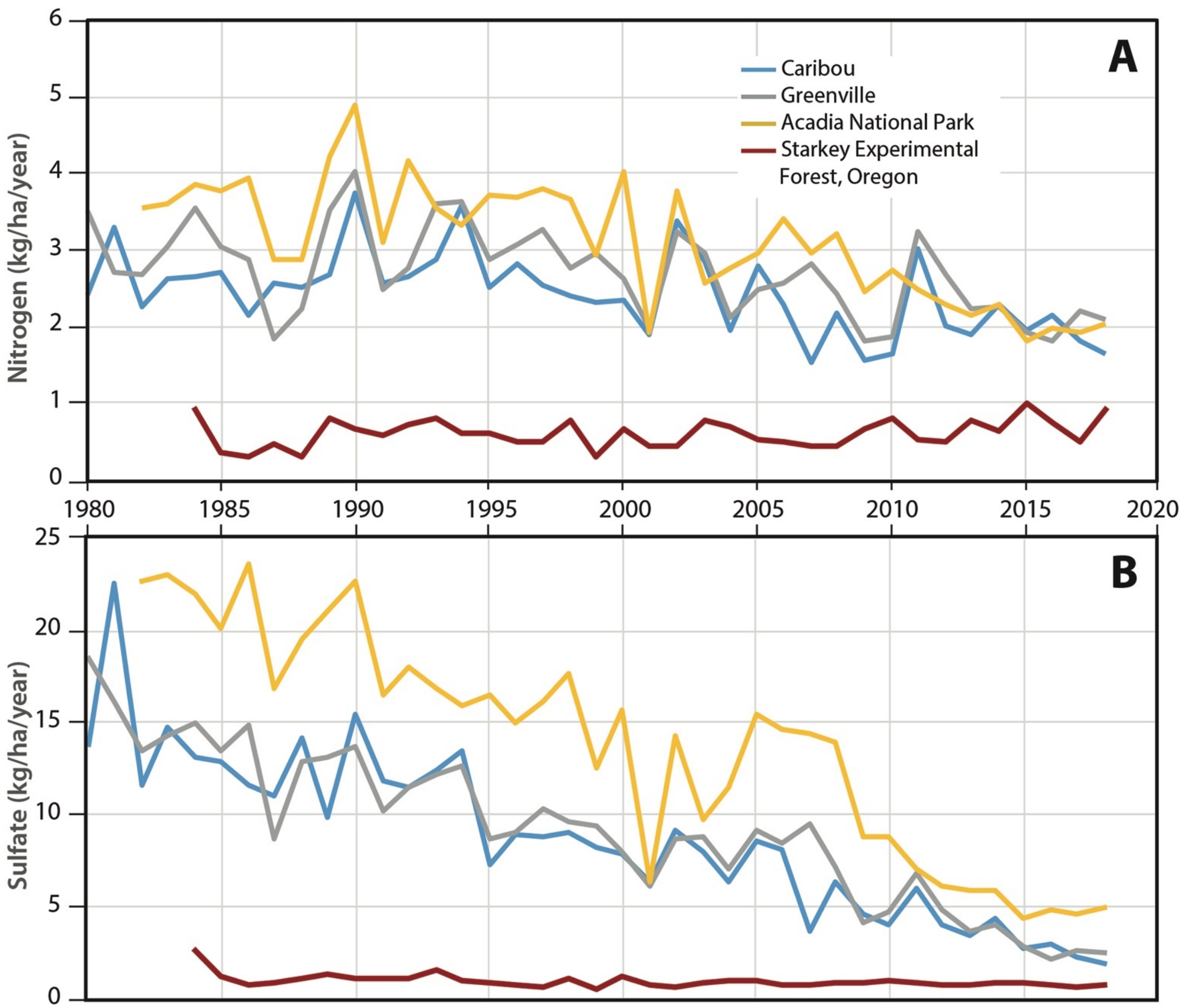
Atmospheric CO_2 acts as a "fertilizer" for essentially all plants, enhancing growth of pasture grasses (Hristov et al. 2018) and forests (Norby et al. 2010, Loehle et al. 2016), although over the long-term these effects could disappear when conditions get hotter, wetter, or drier (Nowak 2017) or are limited by available nutrients (e.g., nitrogen) and damaging effects of tropospheric ozone (Norby et al. 2010, Talhelm et al. 2014) and thawing permafrost (Natali et al. 2019, Turetsky et al. 2019). Rising atmospheric CO_2 is also contributing to longer and more potent pollen seasons that have growing negative impacts on human health (Manangan et al. 2015, Zhang et al. 2015, Watts et al. 2018, Climate Central 2019).



The Maine Department of Environmental Protection and Maine Center for Disease Control & Prevention (MCDCP 2019b) provide information on air quality in Maine, and current local air quality conditions can be tracked using the Climate Change Institute's 10Green tool as noted in MCF 2015 (CCI 2019). 10Green includes current and historical data for carbon monoxide (CO), large particulates (PM10), small particulates (PM2.5), ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), heavy metals (As, Cd, Pb, Ni), greenhouse gases, and other pollutants such as benzene and polycyclic aromatic hydrocarbons.

Burning fossil fuels releases additional air pollutants—ozone, lead, mercury, acid rain, soot—that can cause health problems including asthma, kidney disease, diabetes, and bone weakening. Air pollution disproportionately affects children and teenagers, older adults, people who have low incomes, people who work or exercise outdoors, and people who live or work near highways (Kotcher et al. 2019). Damages from lost labor hours and deaths associated with worsened air quality and increases in extreme temperature are on the order of billions of dollars in damage each year from climate change (EPA 2017). Hundreds of public health organizations have issued an urgent call to action (Climate Health Action 2019) to address greenhouse gas emissions, calling climate change one of the greatest threats to health America has ever faced and a true public health emergency (Harrington 2019; see also USGCRP 2016 and Watts et al. 2018).

2 Graphs: Acid Rain Trends



Total annual wet-only inorganic nitrogen (A) and sulfate (B) deposition, from three Maine monitoring stations in the National Atmospheric Deposition Program (NADP). Data from an Oregon monitoring station (without upwind pollution sources) shown for contrast

Reducing the burning of fossil fuels will reduce greenhouse gas emissions and improve air quality overall. This is an attainable goal. Federal policies such as the 1990 Clean Air Act Amendments resulted in dramatic declines in sulfur and nitrogen deposition in Maine demonstrating how science-informed environmental policy can result in cost-effective improvements in the environment. Indeed, Goyal et al. (2019) recently demonstrated that the international cooperation that resulted in the 1987 Montreal Protocol allowed the world to reduce chlorofluorocarbon (CFC) emissions resulting in recovery of the stratospheric ozone hole. This dramatically reduced human exposure to cancer-causing UV radiation, *and* because CFCs are also greenhouse gases, this international treaty avoided significant additional global warming we would have otherwise experienced, particularly in the Arctic. There remains concern for the improved yet still elevated levels of air pollutants in Maine, because we are downwind from major pollution sources in the Midwest and Northeast. This concern is further heightened by recent trends (Popovich 2019) for weakening the existing environmental regulations that allowed us to achieve air quality progress to date. The possibility of beginning to reverse the progress in air quality is alarming, as recently noted (PPH 2019). Even in a year like 2015, when every county in the U.S. met federal air quality standards, we still experienced more than 30,000 premature deaths from air pollution (Bennett et al. 2019).

Despite predictions for future declines due to warming temperatures, red spruce have shown evidence of improved growth, attributed to decreases in acid deposition and more favorable climatic conditions that could persist in the short-term, particularly for red spruce at high elevations (Kosiba et al. 2018). Forests also may have benefited from nitrogen deposition that was part of acid rain, but this could have been more important for hardwoods than spruce (Patel et al. 2019). *Photo: USDA*

Declines in acid deposition have improved water quality in a majority of lakes and streams throughout Maine and the Northeast (Rosfjord et al. 2017). However, changing water chemistry also has resulted in increased dissolved organic carbon, thought to be attributable to decreased soil acidity and adsorption of dissolved organic carbon, and rising temperatures increasing the rate of organic matter decomposition which has implications for water quality and habitat in Maine (Gavin et al. 2018). *Photo: C Schmitt*

The Great Acceleration

Almost every metric or indicator of climate presented in this report is changing faster in recent years than in the past. The "great acceleration" we are experiencing in Maine is a global phenomenon, as each year smashes records set the year before (Steffen et al. 2015, Xu et al. 2018).

The National Oceanic and Atmospheric Administration reported that July 2019 was the hottest month on record for the planet and polar sea ice melted to record lows. Arctic permafrost is rapidly melting, releasing greenhouse gases as it thaws (Box et al. 2018, Farquharson et al. 2019, Natali et al. 2019). From Antarctica to the Himalayas to Greenland, ice is disappearing into the ocean (Bevis et al. 2019, Maurer et al. 2019, Rignot et al. 2019), contributing to accelerated rates of sea level rise (Dangendorf et al. 2019). Mouginot et al. (2019) found a sixfold increase in the rate of Greenland ice melting since the 1980s, with half of the Greenland glacial melting contribution to sea level rise in just the last eight years. On August 1, 2019 Greenland beat the all-time single- day melt record (Duncombe 2019). A 40-year record of satellite observations of sea ice in Antarctica found that a decades-long increase in sea ice cover reversed in 2014, with Antarctic sea ice decreasing between 2014 and 2017 more rapidly than the more widely reported Arctic sea ice declines (Parkinson 2019). The year 2018 was the hottest on record for ocean temperatures, surpassing the previous hottest year for the world oceans, which was 2017 (Cheng et al. 2019a), and the rate of ocean warming continues to accelerate (Cheng et al. 2019b). The Gulf of Maine has been warming faster than 99 percent of the world oceans (Pershing et al. 2015, 2018).

The big warm-up in the Gulf of Maine was from the mid-2000s to 2012. Since 2012 the trend is relatively flat, at least for surface data on a basin-wide average; 2019 was the coolest year of the last 10 years, yet still had heat wave conditions for brief periods during the summer and fall. When will the trend head back up, and what trajectory will it follow? These uncertainties were described in background papers for the Gulf of Maine 2050 conference in November 2019 and remain a priority uncertainty as we prepare for the future (Gulf of Maine 2050).

There is also evidence that the changing climate, along with other human influences, is having profound impacts on other characteristics of our planet. Climate was noted as one of the key stressors by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services that reported the accelerating loss of ecosystem health across the planet with approximately one million species threatened with extinction (Diaz et al. 2019). Evidence suggests that Maine is experiencing similar losses in biodiversity (MacKenzie et al. 2019).

Improved climate models appear to be projecting a warmer future earth than previously anticipated, suggesting many of the current projections may be underestimating the rate of climate change. Xu et al. (2018) argue that we are underestimating the rates of future warming because

1) we are still increasing the emissions of greenhouse gases to the atmosphere;
2) governments are cleaning up other air pollutants faster than are being accounted for in the climate models; and
3) the planet may be entering a natural warm phase, and these three forces reinforce each other.

The implications of "acceleration" in this context are profound for Maine. Acceleration is not just an increase, but an increase in the rate of change, meaning that we will be increasingly challenged to keep up.

Photo: Jeremy Potter–NOAA licensed under CC BY 2.0

Climate change and working Maine.

The reality of a changing climate influences all aspects of Maine life. Given the natural resource-based economy of Maine, these are readily evident in farms, forests, fisheries, tourism, and recreation. The following additional insights are recent evidence of this emerging reality.

Fields and farms

There have been a number of efforts in recent years to conduct climate change assessments in agriculture in our region through more direct engagement with the experts: farmers, growers, and other practitioners such as technical advisors with a wealth of experience and expertise. These are the people increasingly talking about the novel characteristics and increasing uncertainty in the weather. The USDA Climate Hub conducted a national survey (Schattman et al. 2018, Wiener et al. 2018) of field staff in the Farm Service Agency and the Natural Resources Conservation Service detailing resources used by farmers and their concerns for specific climate and weather effects. Targeted weather products critical for managing crops and their pests, such as Ag Radar for apple growers (Cooperative Extension 2019b), are becoming increasingly important for agricultural operations. Indeed, improved weather forecasts are needed for everyone as variable "whiplash" conditions continue. Reduced snow cover could result in greater winterkill of crops even when average winter temperatures are increasing, especially in northern Maine. Changes in freeze/thaw patterns are likely to impact plant growth throughout the region, while warmer and wetter conditions increase problems associated with heat stress in dairy cattle and poultry (Walthall et al. 2012, Hristov et al. 2018). New England farmers have responded to impacts from wet and dry conditions in a variety of ways, including establishing raised bed systems, dividing fields into smaller parcels, adding berms, and planting fast-growing turf grass species to protect against erosion. They are selecting drought-resistant pasture grasses and eliminating vegetable crops that under-perform on heavy soils during cool, wet springs. Farmers are making investments and altering production practices, from purchasing four-wheel drive turf harvesters for driving on wet fields, to installing irrigation systems and using cover crops and other strategies to enhance "soil health" (Leslie 2017, White et al. 2018).

Forests

Changing temperature, precipitation, and CO_2 levels have direct effects on forests (Janowiak et al. 2018). The long-lived nature of trees makes forest composition change difficult to detect. However, there is evidence that the occurrence and abundance of sugar maple, red maple, and birch all declined in recent decades, and American beech appears to be gaining prominence in Maine forests, partly attributed to a changing climate (Bose et al. 2017). Increasing American beech composition is generally viewed as an unwelcome trend, given its susceptibility to beech-bark disease, its relatively low commercial value, and its capacity to limit the regeneration of other more desirable forest species. Forest land managers report observing increased insect pests and diseases, as well as warmer winters and less snow cover (Reilly et al. 2020). Snow cover is important to the growth of Maine trees like sugar maple (Reinmann et al. 2019) while cold minimum temperatures historically prevented the spread of pests like Southern pine beetle, which has expanded into New England as winters have warmed (Lesk et al. 2017, Dodds et al. 2018).

White pine needle disease is caused by a fungus that thrives in higher temperatures and humidity. Wyka et al. (2017) reported that the best predictor of defoliation of white pine from this disease was the previous year May, June, and July rainfall amount. *Photo courtesy University of Maine*

Climate also affects forests indirectly through altered, new, and interacting stressors. For example, warming temperatures appear to contribute to the presence and magnitude of stress from earthworms, deer herbivory, and invasive plants, all of which are encouraged by increased forest fragmentation and conversion to other land uses (Fisichelli and Miller 2018).

Most forest managers in New England, while they have yet to integrate climate adaptation into their strategic and operational planning, are increasingly interested in considering climate change in their decisions such as managing for natural regeneration, restoring river and riparian health, planting climate-adapted trees, and controlling invasive species. Uncertainty about possible climate change effects is the major barrier preventing forest stewards from doing more (Scheller and Parajuli 2018, Janowiak et al. 2020). There are examples of action, such as leadership by Wabanaki Tribes to address emerald ash borer infestation and ensure ecological and cultural persistence of the brown ash tree (Blackmore 2019), and experiments in tree migration (Rankin 2019).

The potential for Maine forests to contribute to climate solutions by increasing carbon sequestration and storage is of high interest to land managers in the region. This is driving the development of resources about forest carbon management (Ontl et al. 2019) and the carbon potential of forests in New England (Catanzaro and D'Amato 2019).

Resources for Forestry and Agriculture

The USDA Northeast Climate Hub and the USDA Northern Forests Climate Hub offer a growing set of resources and assessment tools, including a recent comprehensive condition assessment of New England forests (Janowiak et al. 2018); reports on adaptation in agriculture (Janowiak et al. 2016) and forests (Tobin et al. 2015, Shannon et al. 2019); the Climate Change Tree Atlas, which can be used to understand and assist tree migration (e.g., Iverson et al. 2019a); the national Adaptive Silviculture for Climate Change project (Nagel et al. 2017); and a Climate Adaptation Workbook for land managers. In 2019, a Climate Adaptation Curriculum was released providing farmers, foresters, and their technical advisors with a package of information about climate-smart options.

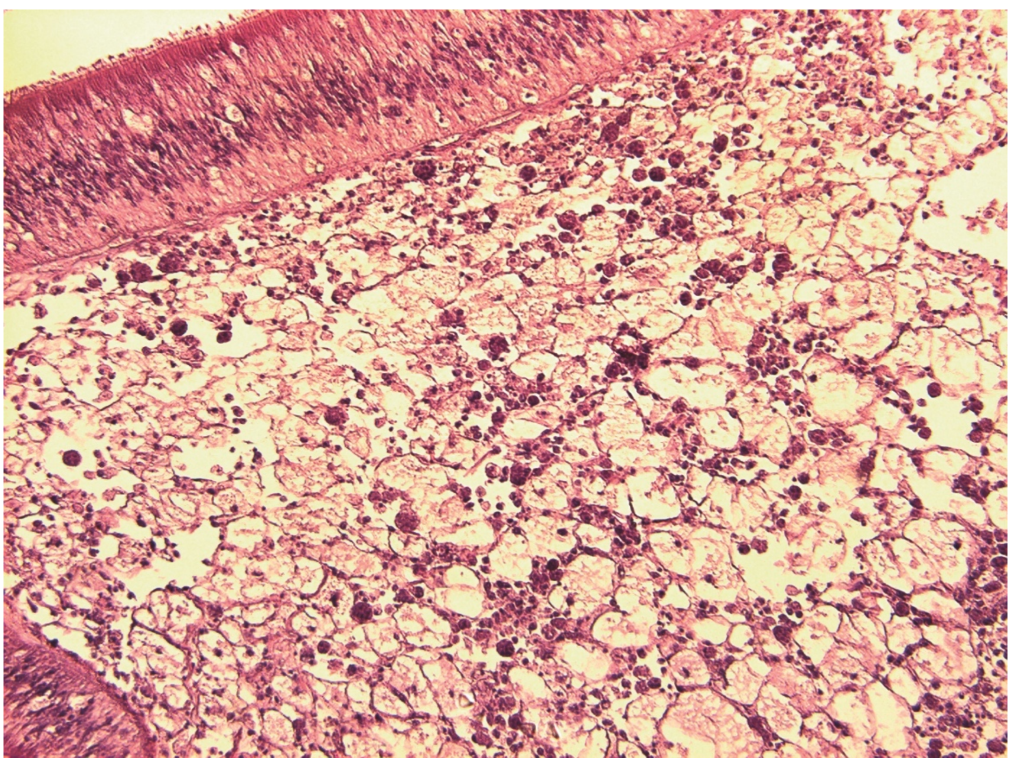
USDA also has other assistance for land managers dealing with weather-related crop losses like prevented planting, the Disaster Resource Center (USDA DRC), and other assistance programs. Resources outside of federal agencies also exist for land managers like the Climate Smart Land Network (Manomet 2019). In addition, the University of Maine's Maine Climate and Ag Network (MECAN) and the Forest Climate Change Initiative (FCCI 2019) were developed to coordinate information and resources on climate for those managing Maine's farms and forests.

Marine fisheries

The ranges of many cold-water species in the Gulf of Maine are shrinking northward, while warm-water species are expanding. Lobsters are the most valuable fishery in the nation, and a centerpiece of the Maine economy (Trotter 2018). The northward shift in the center of New England lobster harvesting is at least partially related to warming temperatures (Pinsky et al. 2013). Die-offs and disease induced by excessive summer temperatures caused lobster to recede from the south (Wahle et al. 2009, 2015) just as the fishery expanded north and east. Settlement of juvenile lobsters also appears to have shifted northeastward in the Gulf of Maine as ocean temperatures warmed, with subsequent record-high lobster landings along Maine's Downeast coast six to eight years later (Le Bris et al. 2018, Oppenheim et al. 2019). The landings boom may have even been amplified by the expansion of suitable habitat in deep water, especially in the east where strong tides mix warmed surface waters to greater depths (Goode et al. 2019). In recent years, however, despite continued historic highs in breeding females the Gulf of Maine has seen a widespread decline in larval settlement, possibly due to reduced egg production (Koopman et al. 2015) or changes in the food web (Carloni et al. 2018, Morse et al. 2017, Perretti et al. 2017). The decline in settlement is projected to lead to a decline in landings in the next few years (Oppenheim et al. 2019). Continued warming over the next 30 years is expected to lead to a decline in lobster abundance to levels similar to those in the early 2000s (Le Bris et al. 2018).

The potential impacts on shellfish are worrisome given that crustaceans and mollusks have increased as a proportion of Maine's commercial seafood over the last 50 years (Gledhill et al. 2015). Since 2015, research has provided evidence that decreased pH negatively affects lobster molting (McLean et al. 2018), contributes to impaired lobster growth and behavior and increased shell disease (Waller et al. 2017, McLean et al. 2018, Menu-Courey et al. 2019, Harrington and Hamlin 2019, Harrington et al. 2019), and contributes to decreased biomass of sea scallops (Rheuban et al. 2018). *Photo: Jesica Waller, University of Maine*

Fish in the semi-enclosed Gulf of Maine are shifting to cooler, deeper waters in the southwestern Gulf as they lose habitat with suitable temperature, while fish that migrate along the continental shelf are shifting northeast—this is especially true for shallow-water fish like Atlantic herring, winter flounder, haddock, and alewife. Deep-water species are able to go deeper to find cool water (Kleisner et al. 2016). Since 2014, the Northern shrimp fishery has been closed due to warming temperatures that have created "an increasingly inhospitable environment" (Richards 2016, ASMFC 2019). The decline of Gulf of Maine cod and lack of rebuilding in recent years also has been linked to warming (Pershing et al. 2015). These changes call for more nimble and cooperative policies and regulations and for including climate information into fisheries management. For example, management frameworks that facilitate new opportunities can support the incredible adaptive capacity of Maine fishing families, only 12 percent of whom currently hold licenses that would allow access to new species like black sea bass (Stoll et al. 2017). In contrast to the changes made by individuals and businesses, fisheries in the Gulf of Maine are still managed without accounting for current or projected ocean conditions (Pershing et al. 2018).



Warm-water oyster diseases MSX and Dermo have become more prevalent in the Gulf of Maine in recent years (Marquis et al. 2015, Robledo et al. 2018). *Photo courtesy Kennebec River Biosciences*

Resources for Fisheries and Aquaculture

The National Oceanic and Atmospheric Administration (NOAA), Sea Grant, the Gulf of Maine Research Institute, and the Island Institute among others provide information and assistance for Maine coastal communities, fisheries, and other resource managers. Residents of coastal communities can access resources at the state or county level (e.g., LCRPC 2019), and participate in citizen science monitoring such as photographing King Tides (Gulf of Maine Council 2019) or monitoring for acidification on Shell Day (NECAN 2019), or making phenology observations on plant and animal species with Signs of the Seasons (2019). Resources are also available for evaluating flood risk (Sherwin 2017) and other municipal planning subjects (MDACF 2019).

Working, playing, living

Rising temperatures increase the risk of heat stress, especially during summer nights, which are warming faster than daytime temperatures (Bangor Daily News 2018, Pierre-Louis and Popovich 2018). Increasingly, cities and towns are having to manage risks to sensitive populations during heat waves (e.g., Singh et al. 2019). Meanwhile, we are losing the cold, snowy conditions that are important to Maine's natural environment, and the lives of Maine people. Cold temperatures kill many insect pests, and inhibit the spread of vector-borne diseases such as Lyme disease and West Nile virus (Ogden et al. 2014, Beard et al. 2016), while snow and ice support recreation, tourism, forestry, and other economic sectors in addition to our cultural heritage. Together, the changes to winter means fewer days for ice fishing, making snow, and harvesting timber, and more days when insect pests like ticks, mosquitoes, pine beetle, and hemlock woolly adelgid can survive—along with their potential for damage to landscapes, wildlife, and people. Wild swings in weather can have outsized impacts on communities, through ice and flooding damage to pipes, roads, and buildings, and effects on recreation and nature-based industries (e.g., Associated Press 2018, Brogan 2018b). Lengthening summers may increase recreation pressure, testing the capacity of public lands to accommodate demand and requiring adaptation by landowners and the outdoor recreation and tourism industry (O'Toole et al. 2019).

Climate Future

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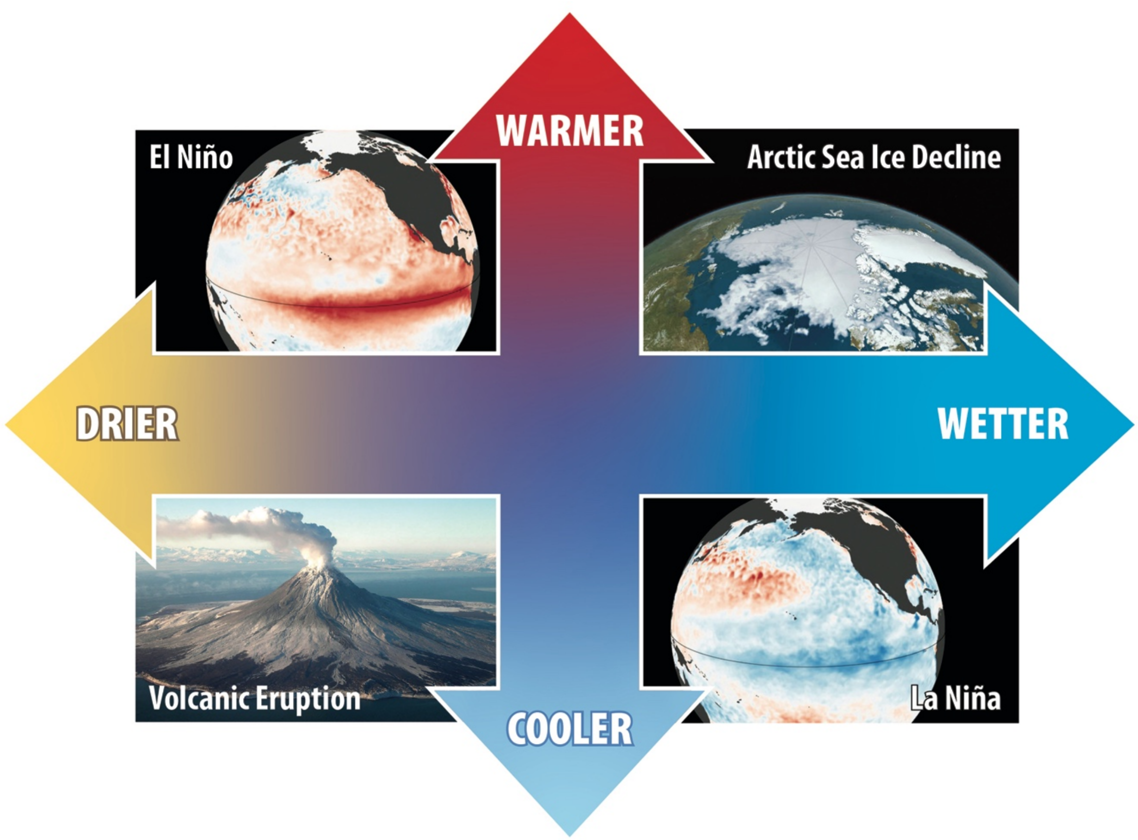
In December 2015, Parties to the United Nations Framework Convention on Climate Change reached an historic agreement better known as “The Paris Agreement” where the international community agreed to limit global warming to below 2 °C (3.6 °F), and to attempt to reduce greenhouse gas emissions even further to limit warming to 1.5 °C (2.7 °F) (UNFCCC 2016). They also charged the IPCC with developing a report on the consequences of warming to 1.5 °C compared to 2 °C. That report, Global Warming of 1.5 °C, outlined dire consequences for the planet, with 1.5 °C of warming possible as early as 2040, bringing us worsening food shortages, wildfires, droughts, and the die-off of coral reefs with expanding human and economic consequences (IPCC 2018). The report went on to describe devastating consequences of an additional 0.5 °C warming to 2 °C. Greenhouse gases already loaded into the atmosphere were likely to achieve a global warming of 1.5 °C, but not much beyond. *However, the continued rapid rise in greenhouse gas concentrations beyond the present all but assures we will exceed 1.5 °C warming,* which is why the IPCC called for global anthropogenic greenhouse gas emissions to be cut in half in 12 years (by 2030) and reach zero by 2075 to avoid the most dire consequences to humans and the environment. To date, significant planetary greenhouse gas emission reductions are not yet evident. Data from 2018 shows *the rate of global* *greenhouse gas emissions is still increasing, and accelerating* (Le Quéré et al. 2018). Lenton et al. (2019) recently warned that we are in a state of planetary emergency because the time left to avoid critical tipping points in the climate system may be zero or close to it. In November 2019, the United Nations Environment Programme published an Emissions Gap Report stating that to date, countries have failed to stop the rise of greenhouse gas concentrations and an aggressive reduction of 7.6 percent per year on average is now needed to limit planetary warming to the 1.5 ^{o}C goal (UNEP 2019). Greater cuts are required the longer policy implementation is delayed.

The preceding pages make it clear that Maine and the planet are on a trajectory of change reflecting natural processes and escalating forcing from greenhouse gas emissions. These realities will persist throughout this century and beyond, with the trajectory of change influenced by actions we take to curb the sources of human impact on the climate system both now and in the future. However, as discussed in Maine's Climate Future 2015, it is important to recognize that there is uncertainty in predictions about our future climate and an awareness of that uncertainty should to be incorporated into our responses to the climate challenge, both in the next decade or two, and over the rest of this century.

Plausible Future Scenarios

In the near-term (between now and 2050), the recent Coastal Maine Climate Futures report (Birkel and Mayewski 2018) outlined five "Plausible Future Climate Scenarios" that could play an important role in the weather and climate we experience over the next decade or more. They range from the mundane to significant "climate surprises" and include:

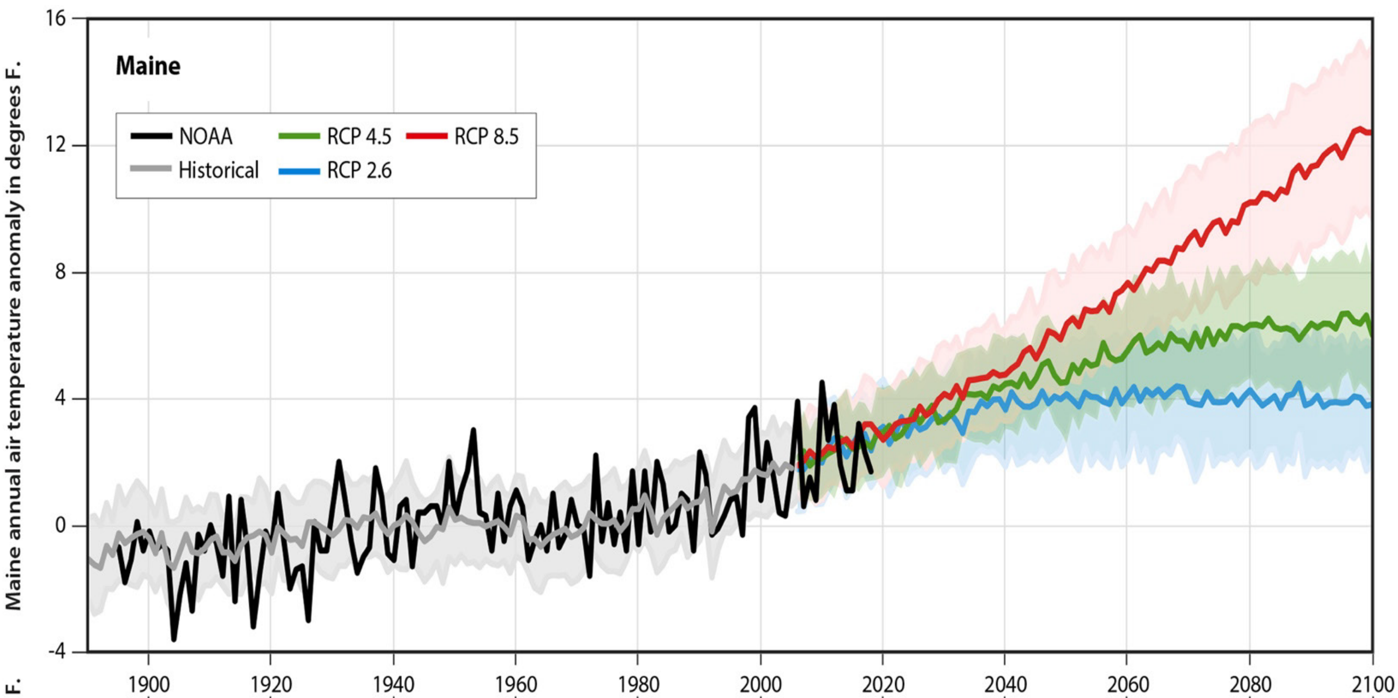
1) the "New Normal" with recent patterns persisting without additional change for the next decade;
2) "Moderate Warming" which, in the near-term, reflects the trends we have seen in the 2000s with significant consequences even despite modest rates of warming of about 1 oF over the next decade;
3) "Abrupt Arctic Warming," as we experienced in 2012, causing abrupt warming in Maine but also a potential chronic change driven by the loss of Arctic sea ice;
4) temporary "Volcanic Cooling" due to the chance of a major volcanic eruption someplace on the planet; or
5) "El Niño Warming." These four large-scale climate teleconnections could influence Maine's weather over the near-term, with particular uncertainty associated with precipitation impacts from El Niño.



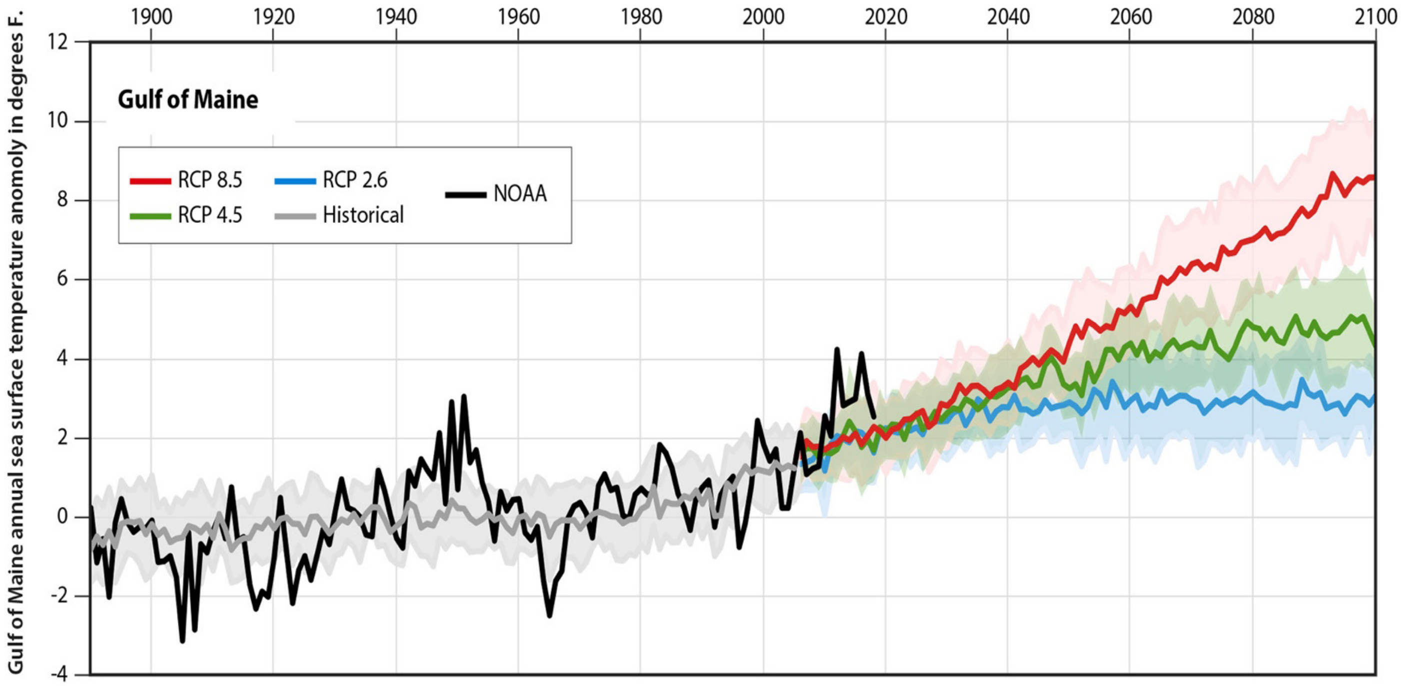
Factors Influencing Future Scenarios

The future is difficult to predict and much uncertainty remains. Yet, every day, we make decisions using the best available information. These figures represent measured and modeled data across several scenarios of potential future warming. Here, we describe likely conditions in Maine's future for these paths, based on the best available information. Humans have control over which path we follow.

2 Graphs: Maine's Temperature Future(s)



Statewide annual temperature anomalies (departure from average), 1895-2018 observed (black line) and 2019-2100 model-projected (gray and colored lines) under different /emissions scenarios or Representative Concentration Pathways (RCPs) from the Coupled Model Intercomparison Project Version 5 (CMIP5) (Taylor et al. 2012). RCP numbers indicate the projected radiative forcing (W/m^2) on the climate system from greenhouse gas emissions by the year 2100. Colored lines represent multi-model means (one ensemble member per model) for each RCP, whereas the corresponding spread denotes the standard deviation from the mean as calculated from all utilized model outputs. The number of available models is different for each RCP: 32 (RCP 2.6), 42 (RCP 4.5), and 39 (RCP 8.5). The gray line and shaded area represent the multi-model CMIP5 historical simulation (38 models). Observational values shown in black are from the NOAA U.S. Climate Divisional Database (NOAA CAAG). FutureCMIP5 multi-model temperature time series were obtained using the KNMI Climate Explorer for land-only grid cells spanning Maine.



Annual Gulf of Maine sea surface temperature anomalies (departure from average), 1895-2018 observed (black line) and 2019-2100 model-projected (gray and colored lines). As with the temperature models, the number of available models is different for each RCP: 14 (RCP 2.6), 20 (RCP 4.5), and 18 (RCP 8.5). The gray line and shaded area represent the multi-model CMIP5 historical simulation (17 models). Observational values shown in black are from the NOAA Extended Reconstructed Sea-Surface Temperature version 5 (NOAA ERSST5) gridded dataset. CMIP5 multi-model SST time series were obtained using the KNMI Climate Explorer for ocean-only grid cells spanning the Gulf of Maine

Maine at 8.5: A different place

Maine's average air temperature is 6 °F warmer in 2050, and more than 12 degrees warmer by century's end. Maine cities experience 20–30 more high heat index days, when it feels like 90 °F or hotter; by the end of the century, there are 48–57 more days of such heat (Dahl et al 2019). More than 500 cases of West Nile Virus occur each year (EPA 2017). Precipitation is frequent, intense, and highly variable—droughts still occur. Snow days decline by 38 percent in southern Maine and 24 percent in northern Maine.

The Gulf of Maine is 2 to 4 °F warmer by 2050, and could be more than 7 °F warmer in 2100. Chemical conditions in seawater become corrosive by the second half of the century. The 2012 heat wave in the Gulf of Maine would be a "normal" year; the coast would experience a sea level rise of 2–3 feet by 2050 and 8–11 feet by 2100.

Maine at 4.5: Moderate change is still major change

With moderate controls on greenhouse gas emissions, warming in Maine still results in a 5

°F increase by 2050, and 6.5 °F by 2100. Maine cities experience 14–23 more high heat index days, when it feels like 90 °F or hotter (Dahl et al. 2019). Warm-climate insects and pathogens spread, with hundreds of more cases of West Nile Virus each year (EPA 2017). Precipitation continues to increase in frequency and intensity, and to shift from snow to more rain. The snowpack will likely be reduced by 50 percent by 2100 for the southern half of the state, or one-third fewer snow days; northern Maine experiences 12 percent fewer snow days. The majority of the losses in the snowpack will occur at the beginning of the spring season, which might have direct impacts on spring streamflow peaks (Demaria et al. 2016).

The Gulf of Maine in 2050 is 1.5 °F warmer, which is similar to conditions in 2010. In this climate, 2008 would be a cool year, and 2012 would be warm, but not extreme (Gulf of Maine 2050). Sea level rises at least 1 foot by 2050, leading to a tenfold increase in flooding to 98 events per year in Portland; by 2100, sea level could rise between 3.6 and 6.5 feet (Slovinsky 2019; Sweet 2017), the latter being the recommended scenario for planning purposes, given uncertainty in the contributions of melting ice sheets to global sea levels (Bamber et al. 2019).

Maine at 2.6: Improbable accelerated societal transformation

Unprecedented transformation of our carbon-intense economies would need to commence almost immediately to achieve this scenario of warming. The greenhouse gases already loaded into the atmosphere as of today will support continued warming until mid-century where temperatures stabilize near 4 °F warmer than average by 2050 with little further warming to 2100. Negative emissions technologies could make this future more plausible, but the speed of implementation to achieve this outcome has no early evidence of occurring. This suggests continued climate change, but with less extreme warming and earlier stabilization of the climate system. This scenario also offers the highest probability of blunting the accumulating evidence of climate acceleration and irreversible tipping points.

Future scenarios depend on us.

The future is difficult to predict and much uncertainty remains. Yet, every day, we make decisions using the best available information. These figures represent measured and modeled data across several scenarios of potential future warming. Here, we describe likely conditions in Maine's future for these paths, based on the best available information. Humans have control over which path we follow…

Given our emerging understanding of future conditions, and the paths we choose to follow, what are the expectations for Maine's natural resources in the future? There is considerable uncertainty in the future responses of these complex systems. While Maine is becoming warmer and wetter overall, we should also be prepared for more variability that could bring isolated years that defy the trends.

Climate can also have indirect effects on communities and natural resources. For example, altered patterns of human migration within the U.S. in the coming decades as a result of climate change and predicted increases in Maine's population may place additional stress on natural resources (EPA 2017).

Fields and farms future

American agriculture has exhibited a remarkable capacity to adapt to a wide diversity of growing conditions amid dynamic social and economic changes (Walthall et al. 2012). Maine's food producers will continue to deal with the challenges of prolonged spring rains, extended spring frost risk, and summer water deficits, despite longer growing seasons and new crop options (Wolfe et al. 2018). The IPCC Special Report on Climate Change and Land (IPCC 2019a) highlights the alarming rate of land degradation around the globe, and the feedbacks between land use and the climate system. Growing negative impacts and future risks of climate and land use affect food security, nutrition, migration, security, water supplies, and other ecosystem services across the planet, with undeniable implications for Maine as a component of the global system. Among Maine farms and food producers, there is growing interest in regenerative agriculture, aquaculture, conservation tillage, improving "soil health," and other practices as an important part of climate response, including plans to pay farmers and others to do so (Leslie 2017, Reiley 2019). As a food-producing state, Maine has a role in advancing current efforts such as wasting less food (Russell 2019) and recognizing the contribution from moderating human diets (Moskin et al. 2019) in ways that can preserve land resources and reduce the drivers of a changing climate.

Forests future

Studies and models of Maine's changing forests suggest there will be short-term increases in growth and productivity, but declining stand density (or carrying capacity) for a majority of tree species (Andrews et al. 2018), with high potential for a "reshuffling" of tree habitats (Iverson et al. 2019b). Spruce and fir are predicted to decline under all scenarios, but the difference between the moderate and extreme scenario could determine whether iconic trees like sugar maple and paper birch persist in Maine or disappear (Janowiak et al. 2018, Iverson et al. 2019b). Uncertainty about outbreaks and the spread of insect pests and fungal pathogens complicate predictions. For example, models show hemlock gaining habitat to the north and west of its current distribution (Dunckel et al. 2017) but do not account for potential damage from the hemlock woolly adelgid.

Trees affected by hemlock woolly adelgid, emerald ash borer, spruce budworm, and butternut canker are expected to have reduced capacity to adapt to climate change (Janowiak et al. 2018). Southern pine beetle is projected to reach the pitch pine forests of southern Maine by 2050, and the red and jack pines of northern Maine by 2100 (Lesk et al. 2017).

The longer-term effects of climate change on forests in Maine to the end of the century and beyond are logically more uncertain (Scheller 2018). As research and monitoring continue, we will both better understand some of the processes of change, as well as discover new factors not previously considered that will influence future forests. For example, Miller and McGill (2019) recently introduced the concept of a regeneration deficit, or the potential loss of the ability of forests to sustain themselves through new growth in the understory. While Maine forests are among the healthiest in the Northeast region they studied, a high regeneration debt in the middle Atlantic region has implications for the ability of tree species to migrate in response to a warming climate. As with most climate change effects, other factors such as deer browsing pressures and invasive species were also important in explaining their results, sometimes more so than climate. Changes in temperature and precipitation are expected to increase stress and disturbances in forests. Disturbances such as flooding, ice storms, and wildfire can open forest canopies, expose mineral soil, and reduce tree cover, providing greater opportunities for invasion (Ryan and Vose 2012). The New England region and Maine have been losing forest in recent decades, with continued forest loss and fragmentation predicted if current development trends continue or accelerate (Thompson et al. 2017, Adams et al. 2019). Maine's forest-dwelling birds are especially vulnerable to projected changes (Wilsey et al. 2019). On the other hand, future carbon policies have the potential to incentivize forest growth. A recent regional analysis by Vickers et al. (2019) demonstrated the important influence of forest management practices in both maintaining current forest composition while at the same time ensuring the viability of future forests.

Marine fisheries future

As with research on climate and forests, fisheries climate studies mostly model future habitat conditions based on temperature, but don't always account for uncertainties like ecological interactions, pathogens and diseases, and the effects of ocean acidification. Pershing et al. (2019) found that warming at the level experienced and projected for the Gulf of Maine will increasingly challenge human adaptation capacity as the frequency of unexpected climate conditions, or "surprises," increases. Several recent studies (Hare et al.

2016, Kleisner et al. 2016, Rogers et al. 2019) agree that some species will likely lose habitat (redfish, cod, cusk, plaice, haddock, halibut, herring, pollock, white hake, and witch flounder) while others may find new habitat

in the Gulf of Maine (Atlantic croaker, black sea bass, bluefish, butterfish, longfin squid, scup, and windowpane flounder). Other highly vulnerable species include Atlantic salmon, alewife, blueback herring, Eastern oyster, rainbow smelt, shortnose sturgeon, Atlantic sturgeon, and winter flounder (Hare et al. 2016). Current record- high harvests of American lobster could continue or even increase in the near term as lobster habitat continues to shift Downeast (Goode et al. 2019), but other modeling efforts predict declines in both the near-term (7 years, Oppenheim et al. 2019) and long-term (30 years, Le Bris et al. 2018).

Recreation future

As highlighted earlier, winter is Maine's fastest changing season, and this has a clear impact on Maine's important winter recreation season and associated economic benefits. Controlling greenhouse gas emissions today determines the extent to which people can still be skiing in Maine tomorrow. A recent study estimated decreases in downhill ski seasons under different climate models (Wobus et al. 2017). When averaged across models, their data show that downhill ski season shrinks from 21 days at Shawnee Peak to 109 days at Sugarloaf by 2050 and cross-country ski season shrinks to 7–44 days by

2050 and 5–34 days by 2100 in the moderate emissions scenario. With higher emissions, downhill ski season shrinks to just two weeks at Shawnee Peak to 38 days at Sugarloaf by 2100. Cross-country ski season shrinks to 6–35 days by 2050 and 1–10 days by 2100. In rivers, changes in stream flows and temperature will affect habitat and fishing opportunities for cold-water species like trout and salmon. With emission controls, much of the western half of the state could retain cold-water fish habitat, otherwise salmon and trout are likely to disappear from all but a few streams in the White Mountains in western Maine (EPA 2016). In contrast, delays in winter onset has lengthened the fall tourist season. In Acadia National Park, September and October have experienced the greatest increases in visitation in the last two decades (NPS-IRMA).

Resources

Numerous tools and strategies are increasingly available for use by individuals, companies, governments, and other entities to inform actions to address climate change and related impacts, including the IPCC Working Group II report on climate change Impacts, Adaptation, and Vulnerability (IPCC 2014b), the U.S. Global Change Research Program's U.S. Climate Resilience Toolkit (NOAA-CRT) the Climate Adaptation Knowledge Exchange (EcoAdapt 2019) and U.S. Environmental Protection Agency's Resilience and Adaptation in New England (EPA- RAINE). State government resources include the Maine Department of Environmental Protection's Maine Adaptation Toolkit (MDEP-MAT) and Climate Trends and Data (MDEP-CTD), and information from the Maine Interagency Climate Adaptation (MDEP-MICA) Work Group reports. The Maine Adaptation Toolkit is perhaps the single most comprehensive portal to climate change adaptation and mitigation information specifically targeting Maine. At the University of Maine, the Climate Change Institute's Climate Reanalyzer is an internationally recognized resource for access to climate and weather data (CCI 2019), and the Maine Climate News and Maine Climate Office websites provide extensive information relevant to climate and weather for Maine.

Maine Leads

In Maine, our deep cultural connections to, and reliance on, natural land- and sea-scapes have made a difference in making climate change local, visible, knowable. We all have a story to tell.

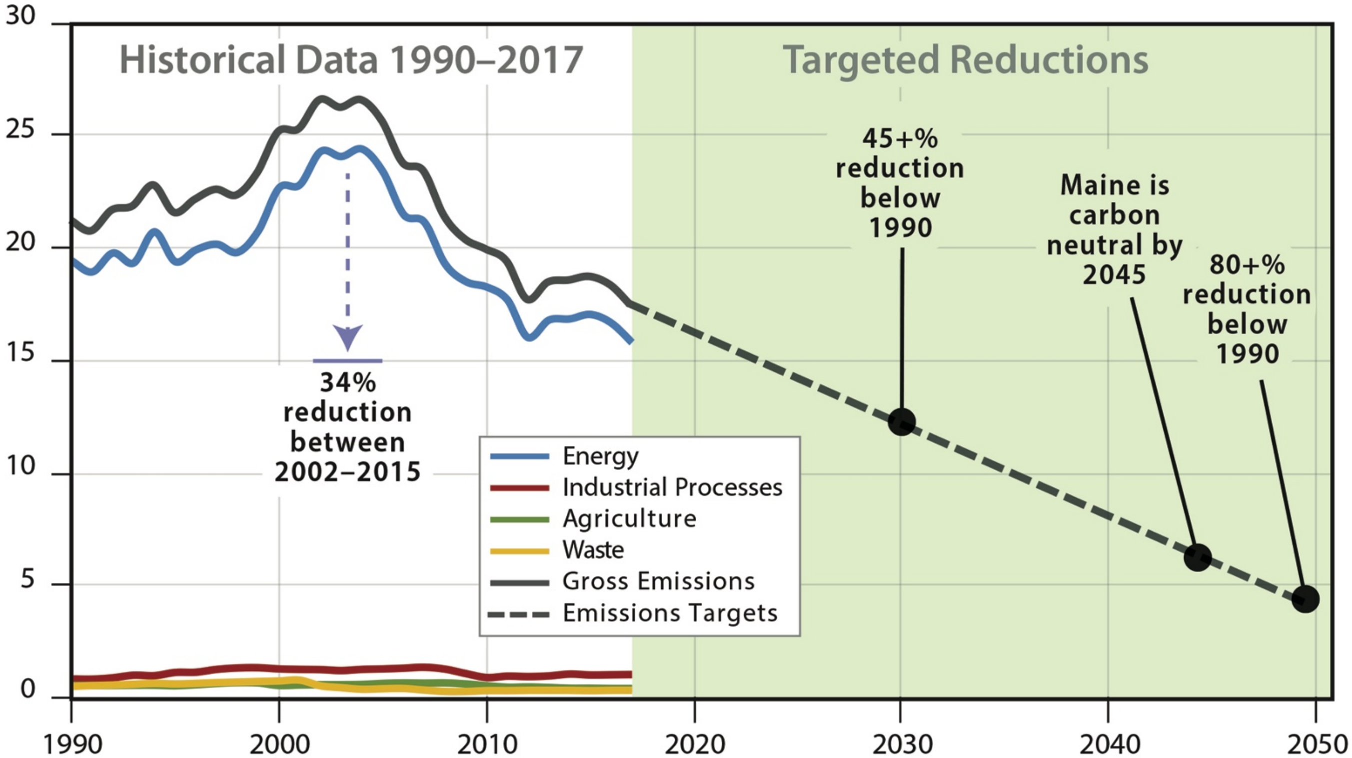
In previous Maine's Climate Future reports, we concluded by highlighting the long history of leadership in Maine on climate change starting in the 1990s. Maine's Department of Environmental Protection has published short listings of milestones in climate change mitigation and adaptation for the state (MDEP 2019). In addition to updating data on trends in weather and air quality that define a changing physical and chemical climate, this report contains more evidence of both the consequences of the changing climate for Maine and how Maine people are responding.

In 2020, there is no question that climate change in Maine:

- is accelerating,
- impacts all aspects of Maine life,
- has growing costs to society, and
- does not leave us helpless, but
- business as usual is not an option.

Modern society has demonstrated a capacity to change…and change fast. Transformational change can occur in remarkably short periods of time, and we have witnessed this from the inventions of cars and telephones and the internet to the discovery of how to capture nitrogen from the air and make fertilizers, giving us the agricultural revolution of the last century. With the right policies and economic incentives, we can reverse the trend of society's increasing carbon intensity and avoid the looming tipping points and worst-case scenarios that await us if we continue on our current path. Because we have waited so long to act, we are challenged to address both mitigation and adaptation at the same time. Doing nothing will make everything increasingly more expensive as we are forced to react, rather than investing in greenhouse gas mitigation and science-informed adaptation now. Business as usual is having negative consequences for the state's economy, individual incomes, labor productivity, and employment, as well as agriculture, forestry, manufacturing, services, retail sales and wholesale trade (Kahn et al. 2019). Despite the uncertainty around the timing and scale of impacts, financial advisors are recommending that communities can and should invest in adaptation now, in ways that allow for maximum flexibility in the future, without committing to any one specific climate projection (Hindlian et al. 2019).

Graph: Maine Greenhouse Gas Emissions



1Historical greenhouse gas emissions in million metric tons of carbon dioxide equivalents (MMTCO2e) from the Maine DEP report on progress towards greenhouse gas reduction goals (MDEP 2020), along with future reduction targets based on the 2019 legislation signed by Governor Mills.

The 2018 National Climate Assessment states, *Proactive adaptation initiatives—including changes to policies, business operations, capital investments, and other steps—yield benefits in excess of their costs in the near term, as well as over the long term. Evaluating adaptation strategies involves consideration of equity, justice, cultural heritage, the environment, health, and national security* (USGCRP 2018). For example, the Clean Air Act and other laws have continually resulted in human health improvements and cost-effective benefits for the U.S., as have the development of wind and solar power (Millstein et al. 2017, Sullivan et al. 2018). According to the Global Commission on Adaptation (GCA 2019), investing in adaptation, and in the innovation that comes with it, can unlock new opportunities and spur change across the globe. Just exceeding or meeting current international building codes can prevent death, injury, and mental health problems from extreme weather events, while providing employment and other forms of economic development (Multihazard Mitigation Council 2019).

Despite the historical leadership from Maine government on climate change, up until recently, there were no clear plans for future greenhouse gas emissions reductions beyond 2020 (Fernandez 2018). During the recent past, much of the climate change work in Maine to adapt to the reality of a changing climate and reduce greenhouse gas emissions has been led by numerous entities in Maine from communities and non-governmental organizations to private citizens. The Maine Department of Environmental Protection's website lists many of those organizations. Maine coastal municipalities have progressed in their understanding of and taking action in both mitigation and adaptation, as recently documented by Johnson et al. (2019).

Leadership from state government changed dramatically in 2019, when Governor Janet Mills made Maine the 22nd state to join the U.S. Climate Alliance (USCA 2019). By the end of 2019, the U.S. Climate Alliance had grown to encompass 25 states, representing 55 percent of the U.S. population, and 40 percent of U.S. greenhouse gas emissions, all committed to at least a 26–28 percent reduction in emissions below 2005 levels by 2025. In June 2019, Governor Janet Mills signed into law bills (Office of the Governor 2019a) that focused on reducing greenhouse gas emissions in Maine by enhancing renewable energy like solar and wind, and establishing the Maine Climate Council (MCC 2019) to provide an integrated and updated Maine Climate Action Plan in 2020 that will be updated every four years thereafter. The law sets out critical goals for reducing gross annual greenhouse gas emissions in Maine by at least 45 percent below 1990 levels by 2030 and at least 80 percent below 1990 levels by 2050. In addition, in an address before the United Nations in September of 2019, Governor Mills announced that Maine would be carbon neutral by 2045 (Office of the Governor 2019b).

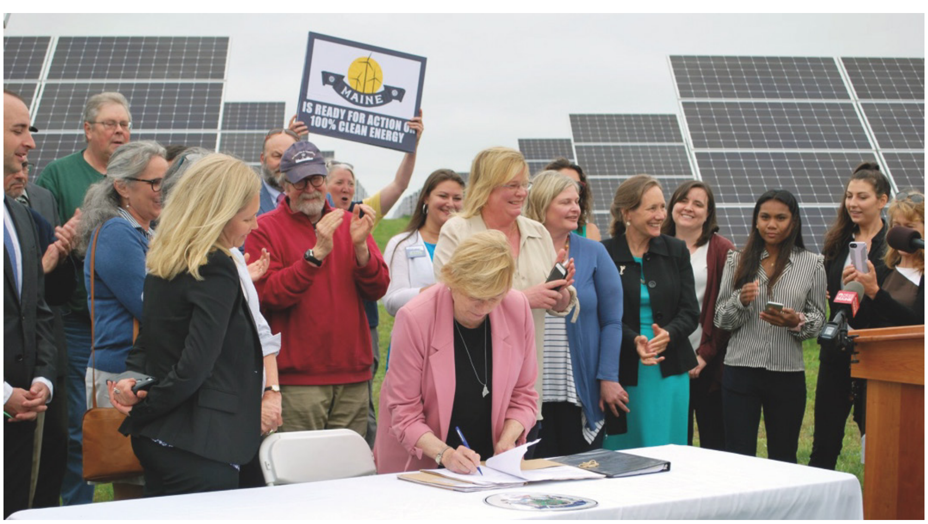
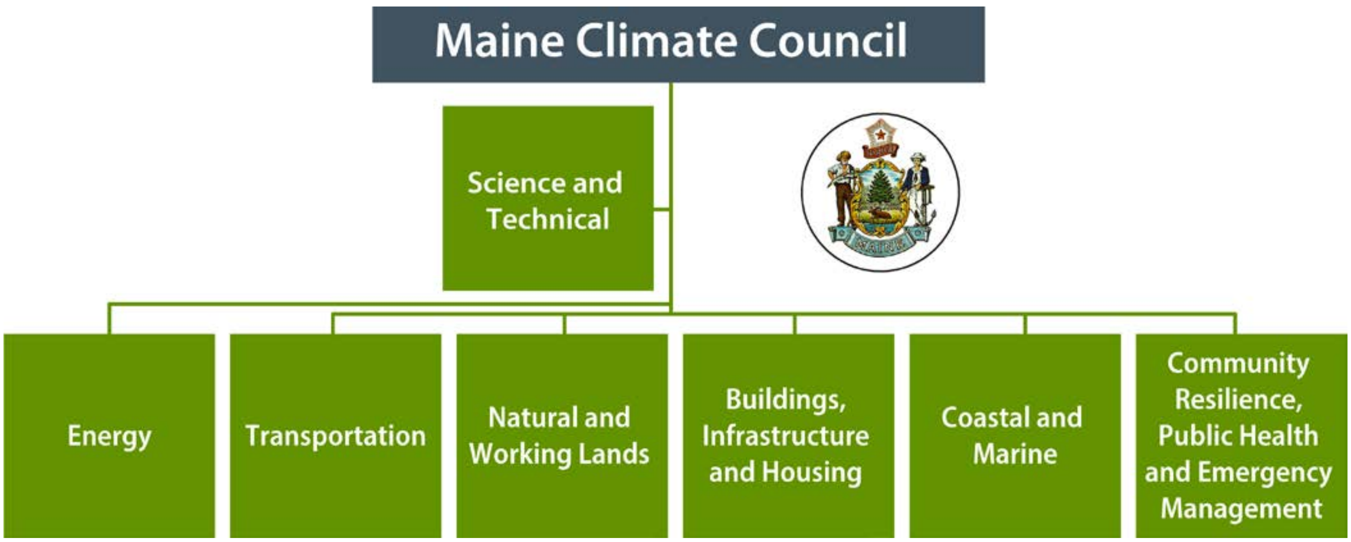


Photo Courtesy Office of Governor Janet T. Mills.

Any realistic assessment of the social and technical challenges that lie ahead must recognize the enormity of what needs to be done to assure a livable Maine for future generations. What happens elsewhere affects us in Maine, and we are also part of the collective solution to a truly global problem. Yet we are fortunate in Maine for our exceptional natural resources and the character of our people. Maine's motto is "Dirigo," which invites us to lead—*today*—on just and equitable climate change solutions.

Flowchart: The Maine Climate Council



The organization of the Maine Climate Council, including its Scientific and Technical Subcommittee and Working Groups.

Photo: K Tenga-González

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Credits

Written by Ivan Fernandez, Sean Birkel, Catherine Schmitt, Julia Simonson, Brad Lyon, Andrew Pershing, Esperanza Stancioff, George Jacobson, and Paul Mayewski.

Design and production by Kathlyn Tenga-González

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