



# MAINE CLIMATE SCIENCE UPDATE 2021

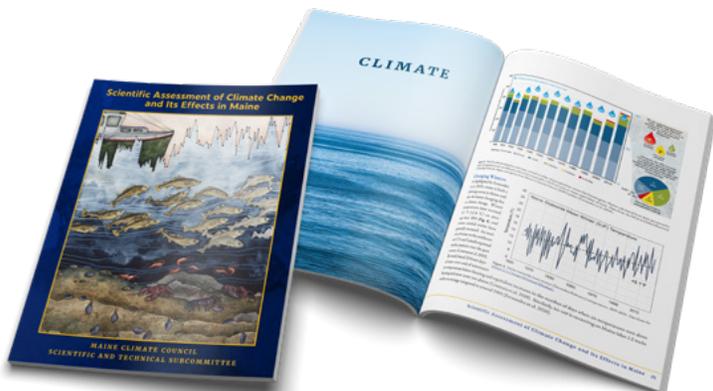
An Interim Communication of the Maine Climate Council's  
Scientific and Technical Subcommittee

December 2021

## Key Messages

1. Frequent reports of wildfires, hurricanes, droughts, intense downpours, warming winters, heat waves, flooding and more have again filled the news in Maine and around the world during the past year. Extreme weather events are increasingly being associated with climate change as a contributing factor.
2. The UN Intergovernmental Panel on Climate Change report (AR6) published in August 2021 found that rapid and large reductions in global greenhouse gas emission by 2030 are required to avoid severe disruption and negative consequences from continued warming and other impacts of climate change.
3. Recently published research about the impacts of climate change in Maine continues to provide a foundation for policy and management decisions at the state and municipal level.

In 2020, the [Scientific and Technical Subcommittee](#) (STS) of the [Maine Climate Council](#) completed an extensive scientific climate change assessment for Maine. The 370-page report, a [Scientific Assessment of Climate Change and its Effects in Maine](#), provided



the scientific basis for the development of Maine's first state climate action plan, [Maine Won't Wait](#), which integrated greenhouse gas emissions reductions and adaptation recommendations. [Maine Won't Wait](#) was released by the [Maine Climate Council](#) on December 1, 2020. We continue to look to science to guide both daily and long-term decision-making. [Maine Won't Wait](#) will be updated every four years and prior to the next update, the [Scientific and Technical Subcommittee](#) will again provide an extensive assessment of the new science, building on our 2020 report.

This document, an "[Maine Climate Science Update 2021](#)", is an interim communication to the [Maine Climate Council](#) and the public about the ongoing work of the scientific community and recent events associated with climate change. It is divided into three sections: (1) current events that reflect the acceleration of extreme weather events in Maine and elsewhere with possible connections to climate change; (2) noteworthy scientific reports with national and international scope released in 2021; and (3) examples of recent peer-reviewed publications from the ongoing work of the scientific community to understand climate change in Maine.

## Climate in The News in 2021

Media reports about extreme weather and negative impacts attributed to climate change appeared regularly in the news in 2021. Scientific studies about each of these phenomena typically take months or years to appear in the scientific literature after careful analysis, yet our first knowledge of these events comes from the news. [Nearly 1 in 3 Americans live in a county](#) that experienced a federally declared disaster related to extreme weather during summer 2021, and more than 18 weather and climate disasters [exceeded \\$1B in losses so far in 2021](#). While these events have the



Figure 1. Photographs of fire crews monitoring the Dixie Fire, California, which burned 963,309 Acres from July to October 2021. Image credits: Bureau of Land Management.

greatest impact on the people directly involved, they also impose costs, disruption and other damage on society at large. Even if an individual is not directly affected, public resources are diverted for fighting wildfires, disaster relief for floods and hurricanes, public health impacts and medical costs, and damage to public infrastructure.

Weather extremes in the US and worldwide appeared regularly in the [news](#) in 2021. A rare [winter storm in Texas](#) in February resulted in massive power outages and over 210 deaths. Early in 2021, rapid warming in the Indian Himalayas caused a glacier to burst apart, destroying a hydroelectric dam and killing at least 32 people [reported at the time](#). At the beginning of October, more than [29 inches of rain fell within 12 hours in Italy](#), breaking a European record. Closer to home, on June 9 an intense downpour brought over 5 inches of rain to Downeast Maine in a matter of hours, causing extensive damage to communities and [washing out 10 miles](#) worth of the carriage road system in Acadia National Park. A New York Times article from May 2021 titled [“What to Save? Climate Change Forces Brutal Choices at National Parks”](#) featured Acadia. [Another downpour](#) in late October washed out roads in Midcoast Maine and caused power outages and flash flooding.

The most recent [national wildfire summary](#) found that over 10 million acres burned in 2020, with large fire activity well above average. Over the last half-century (the era for which reasonably reliable and comprehensive national wildfire statistics have been tallied) only two other years (2015, 2017) saw in excess of 10 million acres burned. The [National Interagency Fire Center](#) listed over 48,000 wildfire incidents in the US for 2021 as of early November, with over 6.5 million acres burned. The [Dixie fire](#) in California alone (Fig. 1) burned nearly a million acres, taking more than 6,500 people, three months, and \$610 million to bring under control, and even [creating its own weather system](#) because of the intensity of the wildfire. As these wildfires burned in the western US, the smoke and degraded air quality traversed the continent on the prevailing westerlies, [reaching into Maine](#) and degrading air quality far from the source of the flames. In addition to the western US, the news carried reports of wildfires in 2021 that were burning [around the world](#).

After an active start, the [2021 hurricane season slowed](#) and will end up with less total storm energy than 2020. However, that is little comfort to those subject to the impacts of the storms we experienced that often brought widespread devastation. Claudette, Elsa, Grace, Ida, and Nicholas are [names](#) that became part



Figure 2. Cars in a flooded parking lot in Pennsylvania after Post-Tropical Storm Ida passes through, Sept. 2, 2021. Image credit: Michael M. Stokes, CC BY 2.0

of the news cycle. [Hurricane Ida](#) was noteworthy as it made landfall on August 29 as a Category 4 hurricane and left Louisiana and Mississippi with a death toll over 30, power outages, and flooding. As the storm continued up the East coast, at least 55 people died across New York, New Jersey, and surrounding states with intense rainfall and flooding (Fig. 2).

At the same time that Ida left southern and Northeastern states in crisis, wildfires were raging in the western US, resulting in discussions in the press about the implications of multiple [overlapping climate disasters](#) on US readiness.

In June, Oregon, Washington, British Columbia and other areas of the Pacific Northwest [experienced a “heat dome”](#) resulting in record breaking extreme high temperatures. [July 2021 was the hottest month](#) the world has ever recorded. On August 12 a [newspaper reported](#) that it would feel like 100°F across much of Maine with warnings about the risks to human health. In another troubling sign of a rapidly warming planet, it [rained at the summit of the Greenland glacier](#) for the first time in recorded history.

Warming in the Gulf of Maine also continues with [impacts on marine species from lobsters to right whales](#). [Puffin chick survival](#) this past year was 65% below the previous 17 years because of climate-related stressors. While this [Maine Climate Science Update 2021](#) emphasizes the climate crisis, it is important to recognize the

simultaneous global loss of biodiversity and the [global biodiversity crisis](#). Noteworthy in 2021 are the deliberations of the [UN Biodiversity Conference](#) towards a global biodiversity framework.

Drought exacerbated by above normal temperatures was a dominant feature of extreme weather in the [US in 2021](#). [As of June 29](#), 47% of the continental US (i.e. lower 48 states) was classified as experiencing moderate to exceptional drought. For the first time ever, the US federal government [declared a water shortage](#) in the Colorado River basin triggering water allowance reductions affecting seven states, with more reductions anticipated in coming years if predicted drought continues into 2022. The Maine Drought Task Force tracked [drought status in Maine](#) (Fig. 3) that was most pronounced in May and June followed by above average rain in July.

### U.S. Drought Monitor Maine

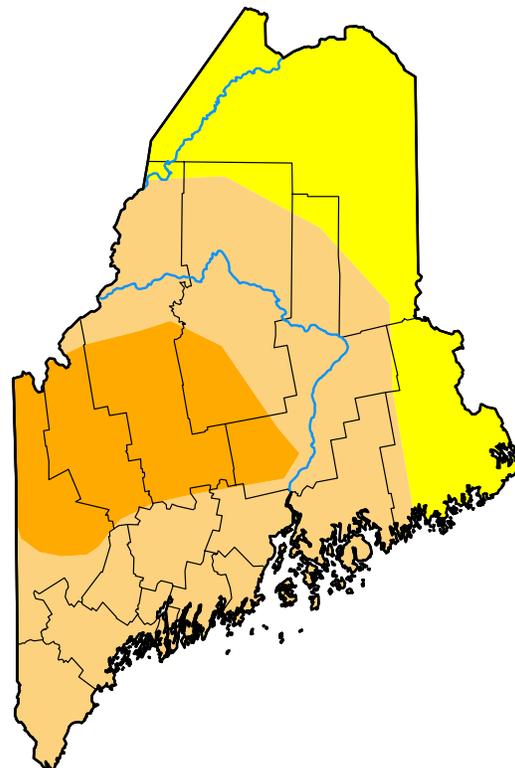
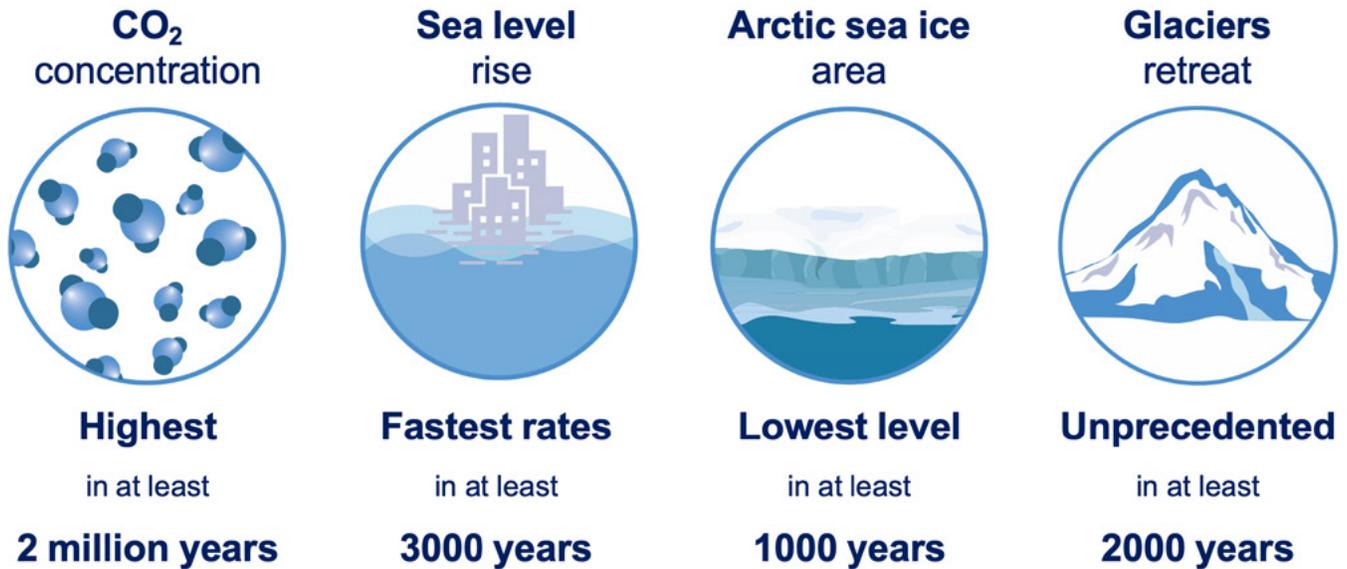


Figure 3. Drought conditions across a map of Maine on July 6, 2021. Image credit: US Drought Monitor.

# How Global Climate is Changing



**Extreme heat**  
More frequent  
More intense



**Heavy rainfall**  
More frequent  
More intense



**Drought**  
Increase in some  
regions



**Fire weather**  
More frequent



**Ocean**  
Warming  
Acidifying  
Losing oxygen

Figure 4. Key observations about how Earth's climate is changing globally and major "milestones" being reached. The climate is changing at rates that are unprecedented in at least thousands of years, and carbon dioxide concentrations have reached their highest levels in at least 2 million years (images above), with several kinds of impacts affecting people and ecosystems (images below). Image credit: IPCC.

## Climate Science from the International Scientific Community

The scientific consensus on the human causes of climate change is stronger than ever, with more than [99% of recent peer-reviewed research](#) (the gold-standard of science) in agreement, just as strong as the [consensus between smoking and lung cancer](#).

The most noteworthy report in 2021 was the [Intergovernmental Panel on Climate Change's \(IPCC\) Sixth Assessment Report "AR6 Climate Change 2021: The Physical Science Basis" from Working Group I](#). The IPCC has brought the world [periodic assessments](#) of the evidence of escalating climate change since 1990, with AR6 being unique in its message of urgency for action. UN Secretary-General António Guterres referred to this report as "[code red for humanity](#)". While the full report contains detailed scientific data, there are several key takeaways for Maine and the world (Fig. 4).

**Humans have unequivocally warmed the atmosphere, oceans, and land**, with approximately 1.1°C (~2°F) of global atmospheric warming evident since the 19th century (Fig. 5). Each of the last four decades has been warmer than the previous decade.

**Climate science is getting better and more precise**, providing a stronger scientific basis for policy decisions with greater confidence in the dangers of future climate change and more rapid [attribution](#) of climate change contributions to extreme weather events.

**Escalating temperatures and extreme events will continue for at least the next 2-3 decades** because of the accumulation of greenhouse gases already in the atmosphere.

**Most rates of change in climate indicators are accelerating** (e.g., atmospheric warming, extreme weather events, sea level rise, ocean acidification and warming, declining Arctic sea ice and melting glaciers, increased precipitation intensity *and* drought, intensifying wildfires).

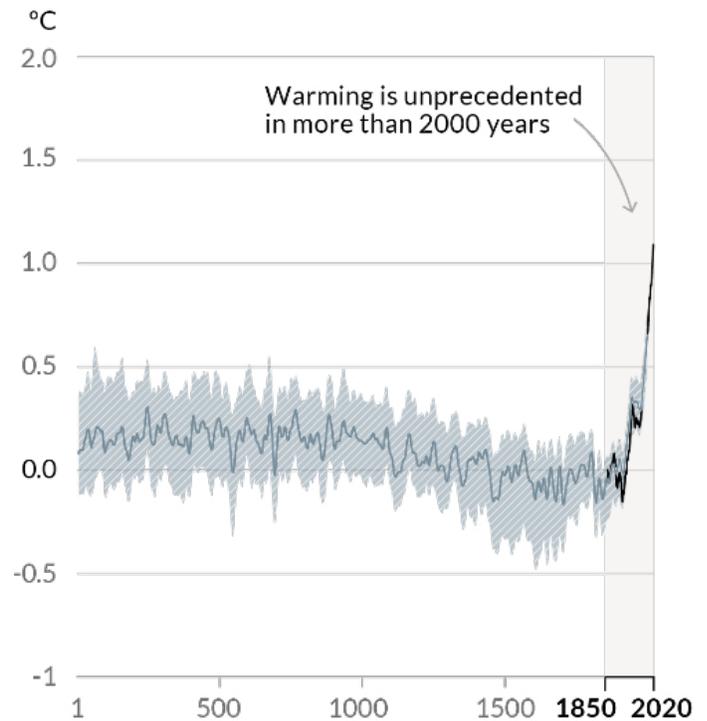


Figure 5. Changes in global surface temperatures show that human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years. Data shown are decadal averages as reconstructed (years 1-2000 current era) and observed (1850-2020 current era). Image credit: IPCC.

**Some of the changes are now irreversible for centuries to millennia** (e.g., sea level rise, ocean warming and acidification, melting ice) but *rates* of continued change can be decreased or reversed for *all* indicators of climate change with deep reductions in greenhouse gas emissions.

**Additional warming is directly proportional to how much additional greenhouse gas we emit.** Reductions in greenhouse gas emissions also result in improved air quality.

**This is the last IPCC report that will be released while the world still has time to avoid the worst of our possible climate futures beyond 1.5°C (2.7°F) global warming after 2050. However, that requires society to immediately cut greenhouse gas emissions to be able to achieve carbon neutrality by around 2050.**

The [American Meteorological Society's State of the Climate in 2020](#) describes a changing climate that parallels the evidence from IPCC. The report notes that the US experienced 22 weather and climate events in 2020 of \$1 billion losses or greater, shattering previous records of 16 events that occurred in both 2011 and 2017. Scientists expect this pattern of record-breaking climate extremes to continue and accelerate, proportional to the pathway of greenhouse gas emissions that we follow in the future ([Fischer et al. 2021](#)). [Dietz et al. \(2021\)](#) recently reported on the economic impacts of eight “tipping points” in the climate system such as melting permafrost, Arctic sea ice decline, Amazon forest dieback or changing ocean circulation patterns. They modeled the impacts of these abrupt climate change drivers and their impacts on increasing the social cost of carbon that is critical in policy decision-making. One of those tipping points, the possible weakening of the Atlantic Meridional Overturning Circulation (AMOC), was reported to show signs of weakening in recent decades and has evolved from stable to close to a critical transition status ([Boers 2021](#)).

In an unusual joint statement by the editors of multiple internationally recognized medical journals, and published in over 200 journals worldwide including the [New England Journal of Medicine](#), the medical community called for “urgent action to keep average global temperature increases below 1.5°C, halt the destruction of nature, and protect health”. They go on to state that no temperature rise is “safe”, noting that in the past 20 years heat-related mortality among people over 65 years of age has increased by more than 50%. They also point to the loss of biodiversity as a human health risk, and the consequences for the health of ecosystems everywhere on the planet.

The human consequences of climate change around the globe were detailed this past year in the [WMO Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes \(1970-2019\)](#). They reported that from 1970 to 2019 there were a total of 22,326 disasters

worldwide, of which approximately 50% were due to weather, climate, and water hazards resulting in 45% of the related deaths (2.06 million) and 74% of the related economic losses (US\$ 3.64 trillion). In support of the IPCC meetings in late 2021, the World Health Organization also released their [COP26 Special Report on Climate Change and Health – The Health Argument for Climate Action](#), where they state that “**Climate change is the single biggest health threat facing humanity...**”. This was followed in 2021 by the annual [Countdown on Health and Climate Change: Code Red for a Healthy Future](#) published in the medical journal *The Lancet*, reporting “**The 44 indicators of this report expose an unabated rise in the health impacts of climate change and the current health consequences of the delayed and inconsistent response...**”.

Swiss Re, one of the world’s leading reinsurance and insurance companies, published [The economics of climate change: no action not an option](#) in 2021, warning that the world economy could be 10% smaller if the Paris agreement greenhouse gas targets are not met by 2050. These climate disruptions also impact human migration as evident in the most recent report from The World Bank [Groundswell Part 2: Acting on Internal Climate Migration](#), and impacts the security among nations as described by the National Intelligence Council’s [Global Trends 2040 – A More Contested World](#). In their analysis of security risk, the National Intelligence Council states “**During the past year, the COVID-19 pandemic has reminded the world of its fragility and demonstrated the inherent risks of high levels of interdependence. In coming years and decades, the world will face more intense and cascading global challenges ranging from disease to climate change to the disruptions from new technologies and financial crises.**”

The recently released International Energy Agency’s (IEA) [World Energy Outlook 2021](#) details the progress in renewable energy critical to limit global warming to 1.5°C (2.7°F) but warns that progress on clean energy

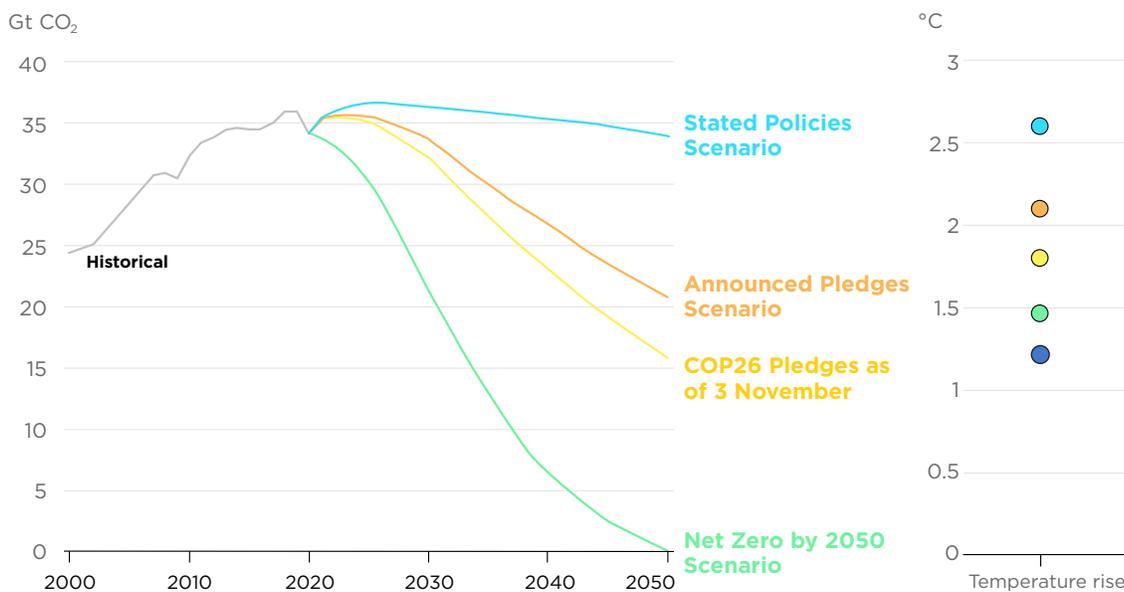


Figure 6. Carbon dioxide emissions in World Energy Outlook scenarios over time (left side), 2000-2050, and the corresponding rise in global temperature in 2100 (right side). Image credit: IEA

remains **“far too slow to put global emission into sustained decline towards net zero.”** This shortfall was echoed by the [2021 UN Emission Gap Report](#) that states **“The emissions gap remains large...the new pledges for 2030 reduce projected 2030 emissions by only 7.5%, whereas 30% is needed for 2°C and 55% is needed for 1.5°C.”** (Fig. 6)

Indeed, the [2021 Global Carbon Project](#) reports that global fossil carbon dioxide emissions in 2021 are set to rebound to close to pre-pandemic levels and emissions from coal and gas are set to grow more in 2021 than they fell in 2020.

The reality of the climate crisis leads to instability around the world as well as risks to our military infrastructure that influences national security. In late 2021 the publication of the [US Department of Defense Climate Risk Analysis](#) and the [National Intelligence Estimate - Climate Change and International Responses Increasing Challenges to US National Security Through 2040](#), both called for consideration of worsening climate realities at all levels of their work.

A *Science* paper published in the fall of 2021 underscores the consequences of our actions today for generations to come. [Thiery et al. \(2021\)](#) estimated that children born in 2020 will experience a two- to seven-

fold increase in exposure to extreme events and heat waves in the world they will live in compared to people born in 1960, even accounting for current climate pledges for reductions in greenhouse gas emissions. They conclude that their findings **“have implications for climate litigation and call for ambitious mitigation to improve intergenerational and international justice.”**

## Climate Science in and for Maine

Scientific research useful for directing climate policy in Maine continued in 2021. Here we describe examples of that work focusing on climate science and our natural resources. This is not intended as a comprehensive literature review. A full assessment of the science, building on our 2020 report, will be developed in support of the quadrennial update of [Maine Won't Wait](#) in 2024.

Since 1895, Maine's annual average air temperature has increased by about 3°F, and precipitation has increased by about 6 inches (15%) in Maine, similar to the broader Northeast region ([Horton et al., 2014](#); [Fernandez et al., 2020](#)). The changing climate also brings a longer growing season, shorter winters, more heavy precipitation events and other extremes, accelerating sea level rise, and subsequent impacts to terrestrial and marine environments. Several studies have been conducted in the

past year that advance our understanding of present and future climate change both globally and in Maine.

### Large-Scale Ocean/Atmosphere Warming

One such study by [Karmalkar and Horton \(2021\)](#) looked at a century of surface observations to understand how changes in ocean-atmosphere circulation have together led to warming on a large scale across the Northeastern US and adjacent Northwest Atlantic Shelf (Fig. 7). The results suggest that ocean warming in the Northwest Atlantic Ocean, including the Gulf of Maine, is associated with weakening of ocean overturning circulation and more persistent atmospheric patterns favoring a northward-shifted North Atlantic jet stream. The study reaffirms similar findings for how ocean circulation changes have produced exceptional warming in the Gulf of Maine in recent decades ([Pershing et al., 2015, 2021](#); [Neto et al., 2021](#); [Record et al., 2019](#)), while also identifying an important role of the atmosphere. [Karmalkar and Horton \(2021\)](#) also highlight that existing coupled ocean-atmosphere models do not realistically reproduce observed warming patterns across the region, and therefore suggest that future projections could benefit from increased spatial resolution and other model improvements.

### Jetstream Changes and Implications for Weather Patterns

The average position of the North Atlantic jet stream (NAJ) is an indicator of large-scale atmospheric patterns that affect weather in the middle latitudes – and, thus, important to us here in Maine. [Osman et al. \(2021\)](#) looked at long-term historical evidence to determine if recent changes in the jet stream are outside of normal range. To do this, the researchers used a climate model run in conjunction with glacial ice core records from Greenland to reconstruct the jet stream winds back to the 8<sup>th</sup> century. The results indicated that recent variations in the jet stream position and intensity were likely within the range of long-term natural variability. However, future projections suggested that changes in the jet stream distinct from natural variability could emerge around 2060.

## Recent Notable Climate Records For Maine

### DROUGHT 2020

Driest May to September period since 1895.

### SEPTEMBER 2020

Driest month since 1895.

### OCT - SEPT 2021 (WATER YEAR)

2nd warmest since 1895 (2010 and 2012 are tied for 1st).

### JANUARY 2021

Tied with 1956 for warmest monthly minimum temperature since 1895.

### JUNE 2021

2nd hottest maximum monthly temperature since 1895 (1999 is 1st).

### AUGUST 2021

Warmest minimum temperature since 1895 (associated with humid conditions and unusually warm overnight lows). [ERA5](#) reanalysis indicates Aug. 2021 as the most humid of all months since 1950.

### WINTER 2021

3rd warmest winter [December + January + February] temperature since 1895 (2016 and 2002 are 1st and 2nd).

### SUMMER 2021

2nd warmest minimum summer [June + July + August] temperature since 1895 (1973 is 1st).

### SUMMER 2021

Warmest minimum [June + July + August] coastal temperature since 1895.

The North Atlantic Ocean has had record high daily [average surface temperatures](#) since early September 2021.

**Sea Surface Temperature Anomaly (°C)**

ECMWF ERA5 (0.5x0.5 deg)

Annual 2011-2020 - 1951-2000

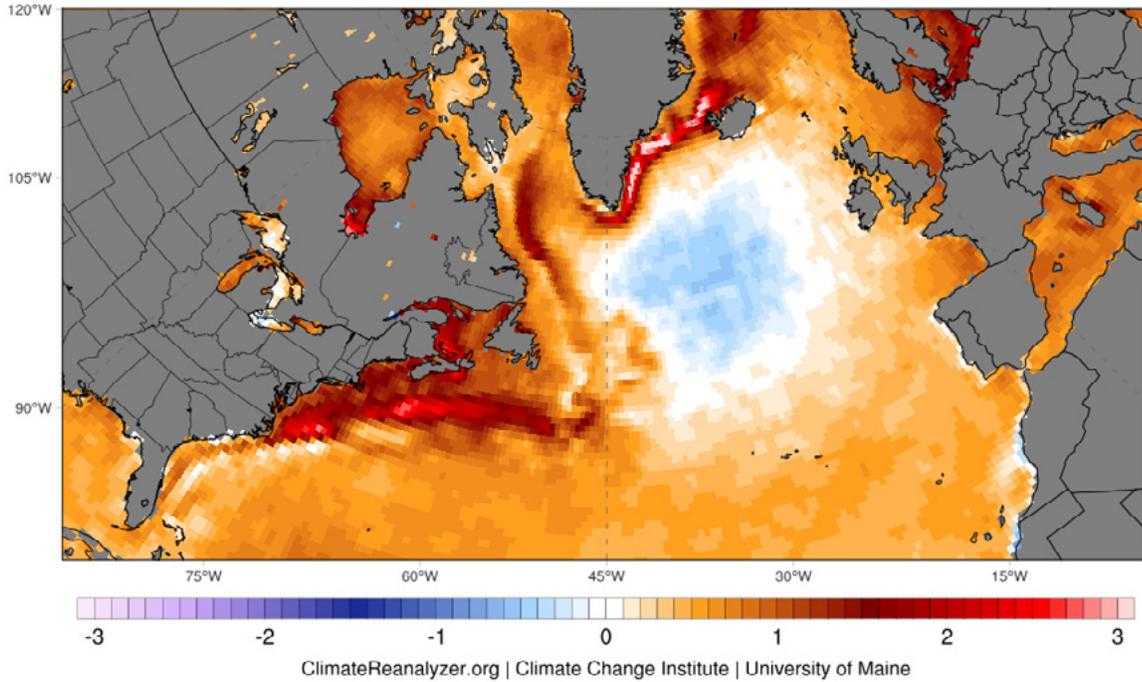


Figure 7. Sea surface temperature difference map for annual means 2011–2020 minus 1951–2000. Changes in atmospheric and oceanic circulation have brought unprecedented warming to the Northwest Atlantic Shelf, and modest cooling to the subpolar gyre southeast of Greenland.

**URMA 2.5km 2m Temperature (°F)**

Analysis 2021/02/16 10Z | Valid Tue 05EST, Feb 16, 2021

ClimateReanalyzer.org  
Climate Change Institute | University of Maine

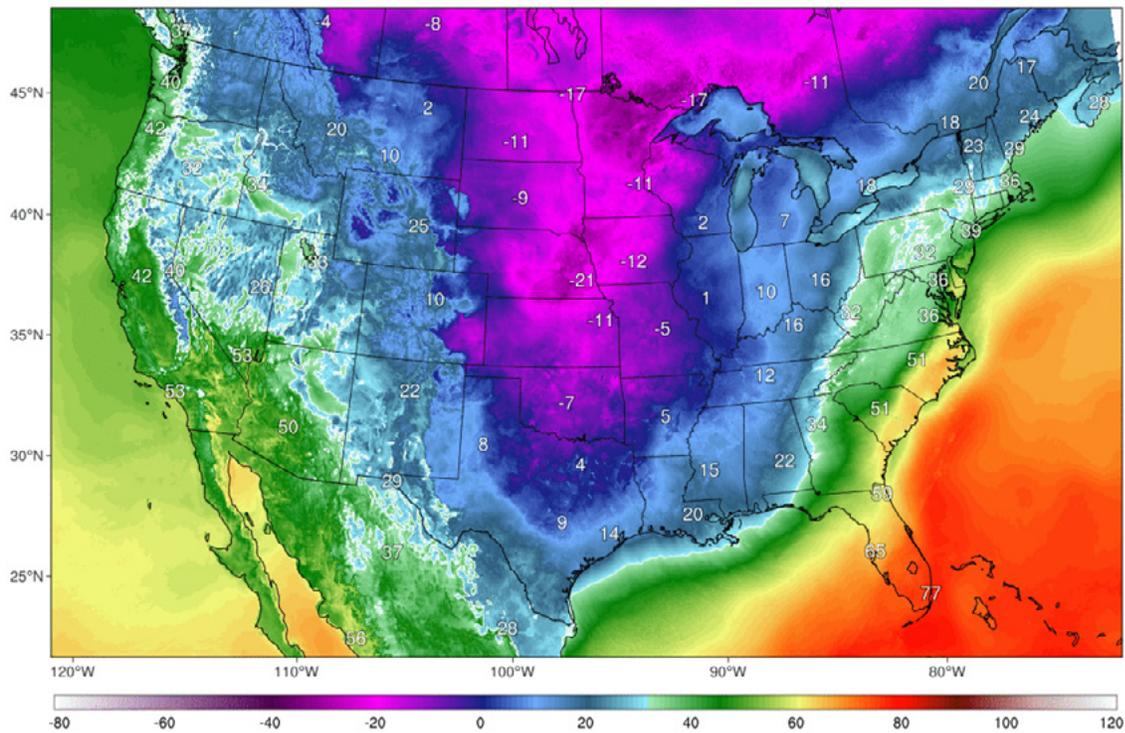


Figure 8. February 16, 2021 near-surface air temperature estimates from the NOAA Unrestricted Mesoscale Analysis (URMA) depicting a deep-plunging cold trough that brought extreme cold temperatures to Texas. This weather pattern also produced severe storms from Texas to the Northeast.

Through a climatic phenomenon called *Arctic Amplification*, the high latitudes have warmed much faster than the rest of the world. The reduced temperature difference between the equator and pole could also affect the jet stream and weather (e.g., [Francis and Vavrus, 2012](#); [Screen et al., 2016](#)), but specific mechanisms remain uncertain ([Taylor et al., 2017](#)). [Cohen et al. \(2021\)](#) showed that a disruption in the stratospheric polar vortex (winds circulating high above the pole) has been increasing in frequency during fall and winter. The phenomenon amplifies wave patterns in the jet stream over Asia and North America, leading to extreme cold air outbreaks plunging deep into the middle latitudes. One notable example is the February 2021 Texas cold wave, an event that also brought severe winter weather to the Northeastern US and Maine (Fig. 8). Modeling experiments suggest these stratospheric disruptions are affected by snow and sea-ice cover, offering evidence that Arctic warming and the loss of Arctic sea ice is accelerating the frequency of these extreme winter weather events.

### Hydrology and Drought

The warming climate brings changes in precipitation and duration of winter snow cover with the potential to affect water resources and streamflows, or the amount of water flowing in rivers and streams. [Lombard and Hodgkins \(2020\)](#) looked at flood frequency data from stream gages across Maine and nearby areas to estimate the size and frequency of streamflows (Fig. 9). The study showed some evidence of increasing peak streamflows over time, but no evidence for decreasing annual peak flows. Peak flow trends depend on the time period analyzed and vary substantially from site to site. This work contributes to the development of effective flood risk management, mitigation, and recovery programs in Maine.

In May 2020, dry conditions emerged across Maine and much of New England, and scarcity of rainfall over the summer led to extreme hydrologic drought, rivaling historic droughts such as those in 1995 and 1998–2002 ([Lombard et al., 2021](#)). Agriculture faced devastating impacts, and in September 2020 the US Department of Agriculture declared crop disaster areas in Aroostook County in Maine and elsewhere in New Hampshire. Also in September 2020, the lowest 7-day average streamflows were measured at 14 USGS streamgages throughout New England for a 30-year record. Similarly, 24 USGS monitoring wells throughout New England recorded record low levels for the past 25 years. Streamflow and groundwater indicators began to recover after widespread rainfall in October and November 2020.

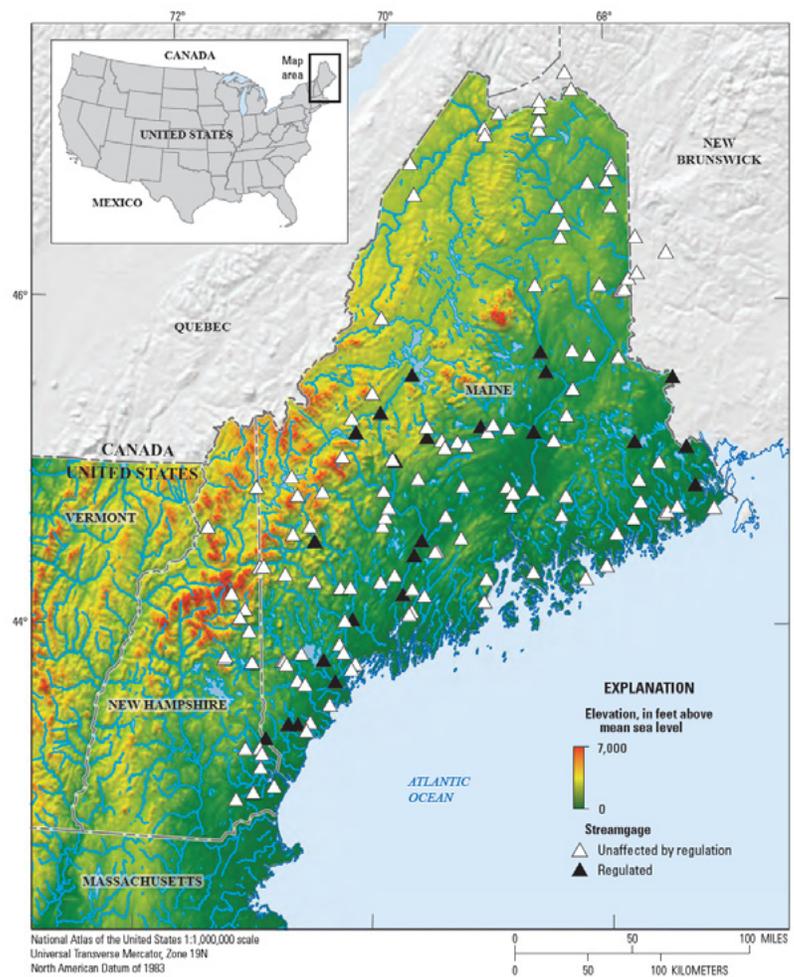


Figure 9. Locations of USGS and Environment Climate Change Canada streamgages. From Lombard and Hodgkins, 2020.

A recent study looked at how droughts in the Northeastern US might behave in the context of warmer climate conditions in the future. [Xue and Ullrich \(2021\)](#) conducted a climate modeling study of the 1960s Northeastern US drought, the most severe in the last century, under conditions from a high-emissions (SSP585) projected warming scenario for future periods 2021–2027, 2041–2047, and 2091–2097. The results indicated that several years with meteorological conditions similar to the 1960s but with higher future temperatures will produce more precipitation, increased soil moisture and evapotranspiration, and reduced snowpack. The simulations also showed an increase in extremes: wet months become wetter and dry months become drier, with increasingly rapid transitions from wet to dry conditions posing water management challenges. The trend towards wetter conditions was expected to provide little relief from the effects of extremely dry months. Additional impacts

in the future simulations included more extreme hot days, reduced snowpack, diminished frozen ground, and less surface runoff.

### Heat Waves

New research by [Agel et al. \(2021\)](#) has found four unique kinds of heat wave patterns in the Northeastern US. Each of the four heat wave patterns had an associated seasonality, mechanism for producing heat, and resulting consumer demand for electricity. Previous studies for the region have focused primarily on a mid-level high pressure pattern associated with air masses sourced from the Gulf of Mexico or tropical Atlantic. However, these newly identified patterns have additional characteristics of such events, including soil moisture changes and the influence of humidity on a heat index. All regional heat-wave days in the analysis occurred April–September. Future studies can use this work in the context of heat wave predictability and climate projections for the region.

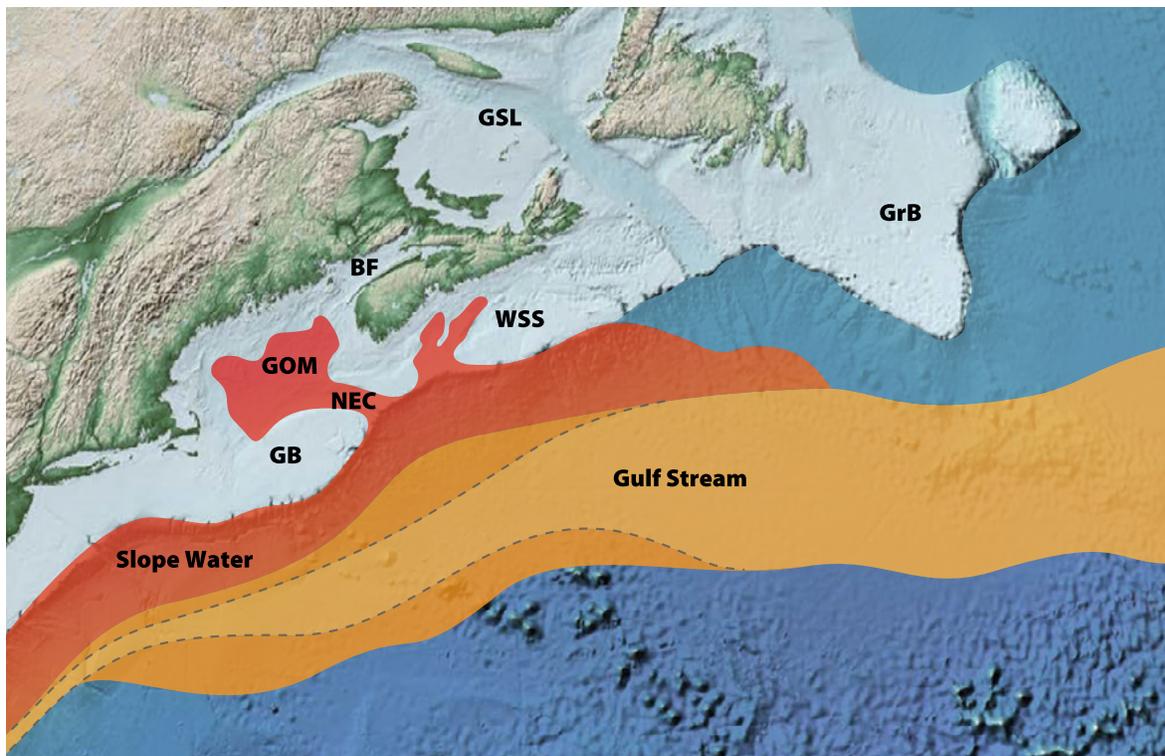


Figure 10. Changes in Northwest Atlantic circulation. The lighter orange within the dashed lines corresponds to the trajectory during 2000–2009 and the darker orange contains its meanders during 2010–2019. The red shows the subsurface movement of warm slope water into the Gulf of Maine and Western Scotian Shelf. BF = Bay of Fundy. GB = Georges Bank. GrB = Grand Banks. GOM = Gulf of Maine. GSL = Gulf of St. Lawrence. NEC = Northeast Channel. WSS = Western Scotian Shelf (modified from Meyer Gutbrod et al., 2021)

## Ocean Climate Change Science

### Circulation Changes Driving Warming

The Gulf of Maine has one of the fastest rates of warming of any ocean ecosystem in the world ([Pershing et al., 2015](#)). This trend continues, with the last 5-year period, 2015-2020, being the warmest recorded by instruments in the region ([Pershing et al., 2021](#)). The Gulf of Maine is part of an interconnected continental shelf sea along the Northeastern coast of the United States and the east coast of Canada. The region off of the shelf is where the warm Northeastward flowing Gulf Stream and the cold southwestward flowing Labrador Current converge, and the temperature in the Gulf of Maine depends in part on the broader circulation of this region ([Loder et al., 1998](#)).

A growing body of research is showing important links between the rapidly warming Arctic and changes in marine ecosystems at lower latitudes, especially in the Northwest Atlantic Ocean and the Gulf of Maine. Arctic warming and accelerating ice melt from Greenland have impacts of concern for ocean circulation (namely the Atlantic Meridional Overturning Circulation or AMOC) that can influence marine food webs at lower latitudes like Maine ([Boers 2021](#)). Continued monitoring and research to improve our understanding of these connections between ocean circulation and key fisheries and coastal communities is critical.

Numerous studies have linked a 20th century slowdown of the AMOC with a northward shift of the Gulf Stream and retreat of the Labrador Current (Fig. 10), resulting in warmer water entering the Gulf of Maine through the Northeast Channel ([Saba et al., 2016](#); [Caesar et al., 2018](#); [Record et al., 2019](#)). A new analysis of nearly a century of hydrographic data supports this hypothesis. Through satellite altimetry and field measurements, [Gonçalves Neto et al. \(2021\)](#) showed that beginning in 2008, the Gulf Stream migrated closer to the tail of The Grand Banks (TGB). This shift reduced the input of the colder, fresher, oxygen-rich Labrador Current, and within one year after the appearance of the unusually warm and salty water at



Figure 11. Coastal erosion at the foot of several houses, Popham Beach, Phippsburg. Image credit: Maine Geological Survey.

the TGB, subsurface warming progressed into the Gulf of Maine. The ability to monitor and understand the Gulf Stream-Labrador Current interactions and their impacts on the region may help predict future conditions in the Gulf of Maine and shifts in species distribution and abundance.

### Sea Level Rise

Circulation changes in the Atlantic Ocean related to the combination of storm tracks, the Gulf Stream, and deep convection currents (Atlantic Meridional Overturning Circulation or AMOC) affect water levels in the Gulf of Maine. Recent studies of ocean circulation indicate the AMOC may slow down ([Boers 2021](#)) which can lead to higher sea levels in the Gulf of Maine as was reported in the [Maine Climate Science Update 2021](#). In addition, a westward and northward shift in storm tracks ([Wang and Toumi, 2021](#)) can increase storm surge and the frequency of coastal flooding (Fig. 11). Atmospheric and oceanic shifts may increase both sea level and storm surges in addition to glacial melting and thermal expansion, the main drivers of sea level rise.

In the next five years, the rate of sea level rise may slow due to the orbital path of the moon ([Baart et al., 2012](#)) but by 2030 or sooner, the rate of sea level rise will likely rise significantly for over a decade and lead to a rapid increase in high-tide flooding ([Thompson et al., 2021](#)).

## RECORD HIGH MAINE SEA LEVELS IN 2021

Since the *STS Scientific Assessment*, sea level has continued to be above average along the Maine coast. Analysis by the Maine Geological Survey (MGS) found that tide levels were running high and in the top 10th percentile from January through September 2021 in Wells, Portland, Bar Harbor, and Eastport.

### SEA LEVEL RECORDS SET IN 2021:

- Record-highest September: Wells, Bar Harbor, Cutler
- 2<sup>nd</sup> highest September: Eastport; 3<sup>rd</sup> highest September: Portland
- Record-highest October in Wells, Portland, Bar Harbor, Cutler, Eastport.

Top monthly ocean levels are shown in the table below. Trends and records can be followed online via monthly updates at the MGS sea level rise [ticker](#) and [dashboard](#). Recent tracking of tide gauges confirms that since 1993 the rate of sea level rise on the Maine coast is more than a foot per century, a rate that is about 50% higher than in the 20th century.

Month	Highest Average Monthly Sea Level (through Oct 2021)				
	Wells	Portland	Bar Harbor	Cutler	Eastport
	(2005-2021)	(1912-2021)	(1947-2021)	(2011-2021)	(1929-2021)
January	2021	2010	2010	2021	2019
February	2010	2010	2010	2020	2010
March	2018	2010	2018	2018	2018
April	2020	2020	2020	2020	2020
May	2017	2017	2017	2017	2017
June	2012	2012	2012	2018	2011
July	2019	2009	2019	2019	2011
August	2021	2011	2011	2011	2011
September	2021	1996	2021	2021	2010
October	2021	2021	2021	2021	2021
November	2019	1970	2019	2019	2019
December	2012	2010	2019	2019	2010

**Table 1:** Five tide gauges along the coast show record highest water levels in 2021 in white. Most of the other monthly records fall in the 21<sup>st</sup> century. Years of available records are shown under each station name. Table by P. A. Slovinsky, Maine Geological Survey with data through October 2021.

Importantly, this possible temporary reprieve in the rate of sea level rise over the next few years should not mask the fact that it will be replaced by even faster rates of sea level rise in about a decade.

### Shifts in Food Webs and Predator Prey Dynamics

The abrupt warming that occurred in 2009-2010 prompted an ecosystem shift with consequences for newsworthy species, like endangered marine mammals and commercially important fisheries. More troubling, perhaps, is that warming and reduced salinities have altered the composition of the phytoplankton community at the base of the marine food web (Balch et al. 2012; Friedland et al. 2021). In turn, these changes have resulted in some significant declines and shifts in distributions of the cold water copepod, *Calanus finmarchicus* (Beaugard, 2012; Record et al., 2019; Ji et al. 2017), hereafter referred to as *Calanus*. This species of zooplankton is a critical part of the food web, and is an energy-rich food source for many marine animals including fish, lobster, shrimp, and whales (Pershing & Stamieszkin, 2020).

The population of the endangered North Atlantic right whale has declined by an estimated 26% in the last decade (Pettis et al., 2021). Since that estimate (although yet to be published) the numbers are thought to have declined further to 336 individuals, the lowest number in 20 years. Metyer-Gutbrod et al. (2021) discuss how the climate-driven changes in ocean circulation, including the 2010 Gulf of Maine and Scotian Shelf regime shift due to the changes in the Gulf Stream, led to less favorable foraging for right whales, reducing the calving rate, and exposing them to greater mortality risks from ship strikes and entanglements. With the warming of the Gulf of Maine, the right whales began abandoning traditional foraging grounds, like the Bay of Fundy (Pettis et al., 2020). Since 2015, more right whales are foraging in the Gulf of St. Lawrence, and coinciding with this change, is an unusually high mortality rate since 2017 (Pettis et al., 2021).

The *STS Scientific Assessment* report in 2020 discussed connections between lobster recruitment and changes in the abundance of planktonic foods, specifically the zooplankton *Calanus*. A study this past year showed how changing predator-prey dynamics have impacted northern shrimp. Maine's formerly robust commercial northern shrimp fishery was closed in December 2013, after the collapse of the fishery following an intense 2012 Gulf of Maine marine heatwave, and has remained closed ever since (Hunter et al. 2019). New evidence suggests that longfin squid migrated into the Gulf of Maine much earlier than normal during early onset of spring conditions in 2012, coinciding with the presence of female shrimp in the Gulf of Maine. These shifts in migration phenology (the timing of when organisms migrate), along with an expanded presence of squid in offshore waters in 2012 and 2013, likely led to unrecoverable levels of predation on the shrimp population (Richards & Hunter, 2021). This is yet another example of how climate change is having major impacts on marine ecosystems, species interactions, and important commercial fisheries in Maine.

### Realities and Technological Advances in Blue Carbon Quantification

Momentum is building around the possibility of earning carbon offset credits or selling credits in a voluntary carbon market for seaweed farming (Froehlich et al. 2020). There are companies in Maine already optimistically advertising imminent carbon credit offerings. However, standardized and universally accepted



Figure 12. Harvesting farmed kelp. Photos courtesy of Matt Wade, Bigelow Laboratory for Ocean Sciences, Boothbay, Maine.

verification processes by carbon market brokers have yet to be developed for seaweeds. Further, the expense of traditional measurement methods far outweigh the market value of carbon credits. Seaweed aquaculturists in Maine will not realize the potential added-value of their farms until novel cost-effective metrics or proxies and verification processes are identified and approved.

How seaweeds absorb carbon dioxide to grow new tissue is easier to measure and estimate than understanding where the resulting seaweed tissue ends up after it fragments and falls off the “plant” (thallus). Scientists in the US and abroad are actively researching and debating methods to better understand how quickly different species of seaweeds take up carbon dioxide (Fig. 12), where the shed tissue fragments are distributed, and how long the carbon remains buried or stored in deep waters or in the seafloor ([Veraart et al. 2020](#), [Bach et al. 2021](#), [Gallagher et al. 2021](#)).

Environmental (e)DNA ‘fingerprinting’ of marine sediments may hold the key to approximating species-specific carbon storage rates for seaweeds, alongside traditional radioisotope dating (e.g., [Arias-Ortiz et al. 2018](#)). In fact, eDNA has already indicated that seaweeds represent up to 33% of the DNA found in traditional tropical blue carbon habitats (i.e., seagrass beds and mangrove forests) and thus likely represent a larger fraction of the sedimentary carbon pool than previously appreciated ([Ortega et al. 2020](#)).

Additional opportunities for generating revenue while avoiding CO<sub>2</sub>-equivalent emissions may lie in the use of harvested seaweed as a biogas feedstock ([Seghetta et al. 2017](#)), as a precursor to bio-based plastics *and* biodegrader of plastic waste ([Chia et al. 2020](#)), or as sustainably produced feeds that replace those with a larger carbon footprint and possibly reduce enteric methane emissions ([Seghetta et al. 2017](#), [Vijn et al. 2021](#)). Despite the remaining challenges and costs in quantifying the rate of carbon sequestration from farmed seaweeds, conserving and expanding (where possible) blue carbon habitats is important for sequestration and numerous other co-benefits ([Duarte et al. 2021](#)).

## Farms, Forests, and Biodiversity Agriculture

In a global analysis, [Caparas et al. \(2021\)](#) found that by 2030, the probability of crop failures in the world’s breadbasket regions is projected to be as much as 4.5 times higher than today. In tightly bound food markets, crop yield reduction on that scale can affect market prices and availability. Water scarcity is the primary risk factor driving risk of crop failures. By 2050 the risk of yield failures for individual production areas (US, China, India) increases up to 25X, with a 50% chance of a failure per year.

The calculated yield failure risks account for expected changes in climate, water availability, and continuation of current irrigation patterns. They do not account for technology, cultivar development, other adaptation strategies, and assume no benefit from a hypothesized “carbon dioxide fertilization effect” by which elevated future levels enhance plant growth. The hypothetical carbon fertilization effect was recently documented as possible for trees in the absence of nutrient or water limitation ([Wang and Wang 2021](#)). However, observations of global vegetation found a weakening of carbon fertilization from 1982 to 2015, possibly due plant nutrient limitations ([Wang et al. 2020](#)).

The [Caparas et al. \(2021\)](#) study estimated that staple crop production areas in North America could shift northward in response to warming temperatures, but that this was not possible for the other two areas studied (India and China) due to soil limitations. The climate in Maine was projected to become more suitable for corn and soybean production by 2030, but less suitable for wheat production by 2050. To meet global food demand without expanding cultivated areas will require expansion of irrigated croplands where water resources are available.

Relative to most of the US and world, climate projections show Maine with favorable annual net soil moisture balance from increases in both annual precipitation and evapotranspiration ([Cook et al. 2015](#), [IPCC 2021](#)). In the coming decades, water access and regulation may

bring changes to agriculture in the Northeastern US with changes in enforcement and increased competition between agriculture and other users ([Schattman et al. 2020](#)). In 2020, Maine experienced a widespread and severe drought with negative impacts on agriculture ([Schattman et al. \(2021\)](#)).

[Tasnim et al. \(2021\)](#) found that wild blueberry fields (Fig. 13) in Downeast Maine warmed faster and become wetter faster than other parts of Maine, and that continued warming and increasing precipitation could have negative effects on crop health and productivity.

[Tooley et al. \(2021\)](#) modeled the responses of potato and barley to future climate change in Maine. Their results suggested that climate change may favor longer-season varieties, as the yield of all potato and barley varieties increased or were unchanged when accounting for increased concentrations of atmospheric carbon dioxide that can stimulate plant growth. The modeling results demonstrated the complex relationships between climate change impacts and land-use and suggest that climate change will create both winners and losers for crop species and variety selection.

Agriculture, including the wider food system (e.g., transport, packaging, refrigeration, waste management) is an important contributor to greenhouse gas emissions, accounting for about 20% of US anthropogenic emissions ([Crippa et al. 2021](#), [Tubiello et al., 2021](#)). The agricultural sector can play a critical role in reducing greenhouse gas emissions via soil



Figure 13. Maine wild blueberries in Downeast Maine.

carbon sequestration ([Rodrigues et al., 2021](#)). Methane from livestock digestion and manure is a major component of on-farm emissions nationally ([Crippa et al. 2021](#)) and is the largest source of greenhouse emissions from Maine farms ([MCC STS 2020](#)). Interest in emissions reduction could bring pressure on agriculture to reduce methane emissions ([Costa et al. 2021](#)), especially as agricultural methane reductions provide quick returns in terms of greenhouse gas equivalents ([IPCC 2021](#)). Tactics such as feed supplementation with seaweed to reduce enteric digestion methane from cows are being investigated (e.g., [Vijn et al. 2020](#)).

### Changing Forests

[Woodall & Weiskittel \(2021\)](#) modeled the relative densities of forests over the last 20 years in the US, including Maine. Maine has experienced one of the largest increases in relative forest density, suggesting higher risk of tree mortality and disturbance with implications for decisions around carbon sequestration and management strategies. [Simons-Legaard et al. \(2021\)](#) simulated future tree species distributions and abundance based on timber harvesting patterns. Their results suggested that with continued harvesting, species co-occurrence may shift, such that forests may transition to dominance by balsam fir or paper birch, and the combined effects of timber harvesting and forest succession may include a loss of northern hardwood forests (i.e., sugar maple, yellow birch, and American beech).

### Adaptation and Mitigation Solutions from Land Management

Modeling historical changes and potential future scenarios provides insight into the capacity of forests in Maine to store carbon ([Puhlick & Weiskittel, 2021](#)). [Hollinger et al., \(2021\)](#) found surprising stability in annual carbon sequestration in an unmanaged central Maine coniferous forest despite extreme climate events over the past 25 years. [Quirion et al. \(2021\)](#) found that insect and disease disturbance can greatly reduce forest carbon sequestration capacity. [MacLean et al. \(2021\)](#) found that changes in harvesting will have the most profound impacts on projected carbon stocks

and fluxes of Northeastern forests over the next 50 years. These studies indicate that forest management decisions can have major impacts on efforts to reduce Maine greenhouse gas emissions. [Smith et al. \(2021\)](#) recently reported little evidence of negative effects after 35 years on productivity measures from whole-tree and stem-only harvesting in a north-central Maine spruce-fir forest.

The University of Maine released a report in 2021 describing alternative “Natural Climate Solutions,” where natural resources are managed to meet some of Maine’s climate response goals. [Daigneault et al. \(2021\)](#) modeled alternative management scenarios in both forests and on farms based on input that included a mix of biological and economic data as well as stakeholder input. Their results suggested that a mix of strategies in both forests and farms (e.g., improved cropland nutrient management, reduction of tillage intensity, planting trees, conservation) could help the state meet its goals for carbon neutrality at a cost of \$21-33 million per year for forestry and \$25-29 million per year for agriculture. These findings also have implications for conservation actions. [Anderson et al. \(2021\)](#) identified important plant communities across the Northeastern US and called for continued efforts to protect under-represented communities that are climate resilient and serve as climate refugia.

Several recent studies in Maine investigated perceptions of climate change risk and adaptation among forest and farm stakeholders. [Soucy et al. \(2021\)](#) found that landowners and managers acknowledge the threat of climate change to the forest sector but are uncertain about the magnitude and timing of future impacts and relevant adaptation strategies. Based on interviews with farmers in Maine, [Clements et al. \(2021\)](#) found that beginning and small to medium-sized farm owners did not perceive climate change to have a large impact on their farming systems. Results of both studies suggested that framing climate change outreach in ways that resonate with audience priorities and perspective will be critical for success. Addressing key barriers to farmer adoption of new management strategies, such as cost,

lack of labor, and administrative burden will also need to be a part of outreach efforts to convey climate smart strategies ([Daigneault et al., 2021](#))

### **Ecology, Health, and Biodiversity**

Over the period of 1952–2011, the average length of Northern Hemisphere midlatitude summer increased by 17 days (from 78 to 95) ([Wang et al. 2021](#)). The length of autumn, winter, and spring decreased by -5, -3, and -9 days, respectively. Looking forward, even assuming greenhouse gas emission reductions similar to universal compliance with the 2015 Paris Climate Accord commitments, season length changes would continue such that by 2050 summer would increase by another +28 days, with decreases of autumn, winter, and spring by -11, -17, and 0 days, respectively. Ongoing changes in seasonality will affect public health, forestry, agriculture, disaster prevention, natural resources and many other policy arenas. For example, changing winters are contributing to shifting chemistry of Northeastern US mountain ponds ([Nelson et al., 2021](#)).

A field trial found that snow cover allowed blacklegged ticks (the vector for Lyme disease, anaplasmosis, babesiosis and other diseases) to survive in northern Maine even though their population levels are much lower there than in southern Maine ([Volk, 2020](#)) While over half of the moose in Maine and New Hampshire were infected with *Anaplasma* bacteria, differences with the *Anaplasma* species found in their winter tick parasites indicated that the ticks were unlikely to play a significant role in *Anaplasma* transmission to moose ([Elliot et al., 2021](#)).

Modeling of biodiversity loss indicates that under a high emissions scenario, Northern Hemisphere midlatitude marine and terrestrial species will experience abrupt disruptions due to climate change by 2050 ([Trisos & Pigot, 2020](#)).

*Information about the meetings of the Scientific and Technical Subcommittee and all Maine Climate Council activities can be found [here](#).*

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