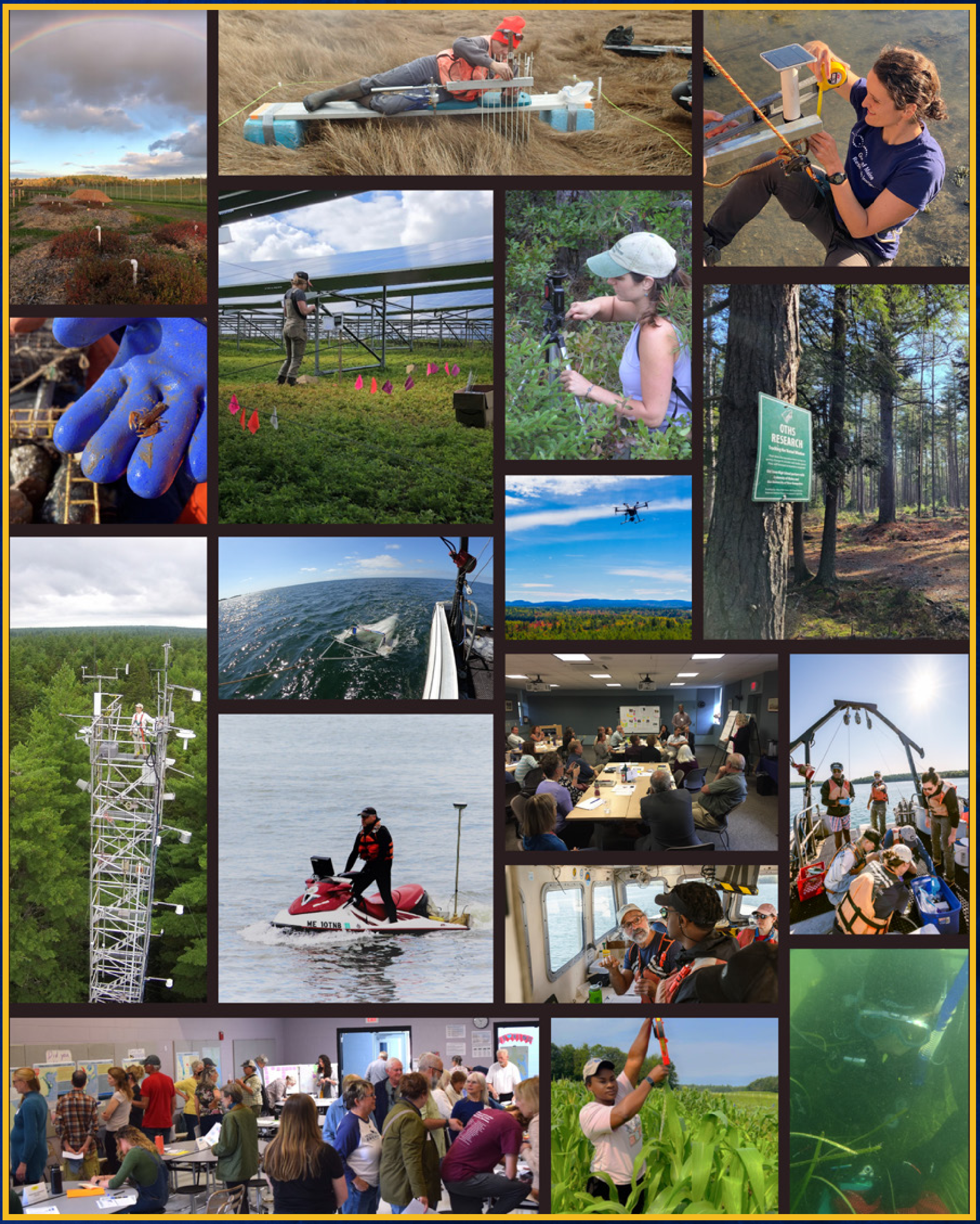
Scientific Assessment of Climate Change and Its Effects in Maine



MAINE CLIMATE COUNCIL

SCIENTIFIC AND TECHNICAL SUBCOMMITTEE

Scientific Assessment of Climate Change and Its Effects in Maine
2024 Update

A REPORT BY
THE SCIENTIFIC AND TECHNICAL SUBCOMMITTEE
OF THE MAINE CLIMATE COUNCIL

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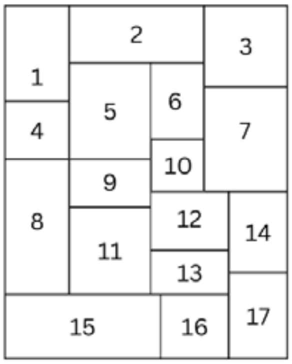

1. A rainbow over the Wyman's Center for Wild Blueberry Research and Innovation. Experimental wild blueberry plots will receive simulated temperature and precipitation treatments in 2024-2028, allowing a team of researchers to explore how this unique crop is likely to be affected by climate change. The project lead PI is Rachel Schattman.

   Photo credit: Kylie Holt, UMaine Agroecology Lab

2. Maine Natural Areas Program (MNAP) Ecologist Kristen Puryear takes readings from a Rod-Surface Elevation Table (RSET) at a State of Maine tidal marsh sentinel site. RSET readings track high resolution (millimeters) changes in the soil surface. Coupled with marker horizon readings and vegetation transects, these data are collected every year to monitor how the marsh platform and plant communities are responding to sea level rise and can indicate whether and at what rate the marsh is "keeping up" with higher water levels. MNAP and the Maine Coastal Program have partnered to establish and monitor 33 of these sentinel sites from York to Lubec.

   Photo credit: Emily Carty, Maine Natural Areas Program

   Courtesy: Kristen Puryear, Maine Natural Areas Program, Maine Department of Agriculture, Conservation and Forestry

3. Dr. Hannah Baranes, coastal scientist at the Gulf of Maine Research Institute, installing a Hohonu tide gauge on the Fore River pedestrian bridge in Portland. The team is improving flood forecasting for Maine's coastal communities by installing low-cost tide gauges and organizing community (citizen) science programs.

   Photo credit: Gulf of Maine Research Institute

4. Benthic young-of-year lobster retrieved from a vessel deployed bio-collector. Annual monitoring of newly settled lobsters provides an early warning of lobster year class strength. Monitoring is conducted through the American Lobster Settlement Index collaborative, a partnership of lobster producing states and provinces in New England states and Atlantic Canada.

   Photo credit: Richard Wahle

5. Dr. Lily Calderwood's Extension and Research team studying the impact of solar array installation on an existing wild blueberry field in Rockport. The project team works closely with the farmer to understand field management costs and adjustments required to farm under panels in addition to the impact of shading on the wild blueberry crop and changes to pest populations.

   Photo credit: UMaine Extension

6. Laura Lalemand, research assistant and student from University of Maine at Farmington, measuring understory light with a digital camera equipped with a fish-eye lens. These measurements were part of a project (PI, Andrew Barton, University of Maine at Farmington) to assess the dynamics and role of fire in ridgetop pitch pine woodland in The Nature Conservancy's Basin Preserve, Phippsburg peninsula.

   Photo credit: Andrew Barton, University of Maine at Farmington

7. Site of climate change research by Old Town High School students with their teacher, Ed Lindsey, in collaboration with Alix Contosta from the University of New Hampshire and the University of Maine. Students are measuring air temperature, relative humidity, snow depth, soil temperature, and soil moisture, plus a camera for tracking vegetation phenology in the forest shown in this photo.

   Photo credit: Ivan Fernandez

8. Research Associate Holly Hughes from the University of Maine checking environmental monitoring instruments at the top of a 27-m tower at Howland Research Forest, a core site of the AmeriFlux monitoring network. The primary measurements on the tower include meteorology and carbon dioxide (CO_2). These systems allow for the rare opportunity of direct measurements of carbon exchange between the atmosphere and the ecosystem, often only able to be estimated by measuring carbon stock changes over time.

   Photo credit: David Hollinger, USDA Forest Service

   Courtesy: Shawn Fraver, University of Maine

Contributor Contact: Ivan Fernandez, ivanjf@maine.edu

9. Neuston net under tow to collect lobster larvae off Boothbay Harbor for research supported by NSF and NOAA Sea Grant to evaluate climate effects on larval lobster trophic interactions in the pelagic foodweb.

   Photo credit: Richard Wahle

10. An unoccupied aerial vehicle (UAV) carrying a thermal camera flies over the University Forest in Old Town, Maine, capturing imagery of the tree canopy. The UAV image acquisitions were flown as part of a class demonstration in remote sensing at the University of Maine's School of Forest Resources.

    Photo credit: Adam Küykendall, University of Maine Division of Marketing and Communications

    Contributor: Daniel Hayes

11. Maine Geological Survey (MGS) Marine Geologist Peter Slovinsky on the MGS Nearshore Survey System (NSS) collecting nearshore bathymetric data near Camp Ellis Beach in Saco. The RTK-GPS antenna and narrow-beam depth sounder work at 10 Hz to map the underwater beach. A waterproof screen displays tracklines and collected data in real time between the handlebars while a navigation computer is stowed in the watertight bow compartment. MGS has been collecting nearshore bathymetric data in the vicinity of federal beach nourishment projects for two decades to keep track of the beneficial reuse of dredged sediment.

    Photo credit: Stephen Dickson, Maine Geological Survey.

12. Photo taken during a stakeholder engagement workshop focused on food waste (including policy to prevent food waste and the associated emissions). The workshop was led by the Materials Management Research Group at the Senator George J. Mitchell Center for Sustainability solutions and included participants from food producers (farmers); waste generating organizations (grocers, hospitals, schools); food waste managers (haulers, composters, landfillers, digesters); food recovery and hunger relief organizations (food banks, gleaning operations).

    Contributor: Cindy Isenhour

13. Senior Research Scientist David Fields of Bigelow Laboratory for Ocean Sciences talks with a Sea Change Semester student while on a research cruise along the Damariscotta River estuary. Bigelow Laboratory's Sea Change Semester gives students the chance to live at the nonprofit institute's coastal Maine campus and get hands-on research experience while working alongside leading researchers that study the foundation of global ocean health.

    Photo credit: Bigelow Laboratory

    Contributor: Nicholas Record

14. Bigelow Laboratory scientists and Sea Change Semester students take oceanographic samples along the Damariscotta River estuary. Over the course of the semester-in-residence program at Bigelow Laboratory, Sea Change students get access to emerging technologies at the frontiers of ocean science (from AI to environmental DNA), as well as the tried-and-true techniques that are used in professional labs and on research vessels worldwide.

    Photo credit: Bigelow Laboratory

    Contributor: Nicholas Record

15. A Gouldsboro community resilience workshop, May 2023, at the Gouldsboro School. With a grant from the Maine Coastal Program, Gouldsboro map to identified important shellfishing access points and identified roads and infrastructure that are climate vulnerable, helping the town prioritize where to focus their resilience efforts moving forward. As a result of the workshop, the project team heard how interconnected resilience efforts need to be and expanded their focus to include resiliency needs such as broadband connectivity and food security. The town now has a climate committee and joined the state Community Resilience Partnership.

    P*hoto credit: Bill Zoellick*

    Courtesy: Melissa Britsch, DMR

    Photo contact: Jessica Reilly-Moman, Klima Consulting

16. Gladys Adu Asieduwaa, a PhD Student in the University of Maine Agroecology Lab, measures out a plot of corn in an interseeding trial. Interseeding is the practice of planting cover crops, in this case rye and red clover, in between standing cash crops. Gladys's goal is to better understand the effects of different seeding timings and planting methods on cover crop establishment and corn performance. The experiment took place at Rogers Farm, part of the Maine Agricultural and Forestry Experiment Station (MAFES) in Stillwater, Maine. The project lead PI is Jason Lilley, University of Maine Extension; Co-PI is Rachel Schattman, University of Maine School of Food and Agriculture.

    Photo credit: Charlie Cooper

17. Maine Department of Environmental Protection (MDEP) biologist Emily Zimmermann surveying subtidal eelgrass in Casco Bay. The MDEP team dives during the summer to assess eelgrass health, by measuring density, size and amount of leaves, and light levels. This data allows characterization of conditions experienced by eelgrass, and allows documentation of short- and long-term changes to eelgrass meadows.

    Photo credit: Angela Brewer

    Contributor: Nathan Robbins

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EXECUTIVE SUMMARY

Climate

Maine's climate is getting warmer. The past four years in Maine (2020-2023) have ranked among the ten warmest on record. Across the globe, record high temperatures were set by a large margin in 2023. Even when factoring in El Niño and the effects of increasing greenhouse gas emissions, predictions for global temperature leading into 2023 failed to account for the exceptional warming.

Maine's climate is getting wetter, with more high-intensity precipitation. Maine's climate is getting wetter overall and drought has not increased in the historical record. Precipitation (rain and snow) variability is increasing due to intensification of the hydrologic cycle, meaning that water cycles faster through the atmosphere, land, the oceans, freshwater, and glacial ice in response to warming. Maine now receives 1–2 additional days per year with 2+ inches of precipitation, and 2–3 more days per year with 1 inch of precipitation. Storm events with high one-hour intensities have prompted adaptive actions.

Maine is experiencing more extremes, from hourly and daily weather to monthly and seasonal climate. Dry periods will continue to become drier and wet periods will continue to become wetter. Precipitation variability between years is increasing and has recently produced impactful seasonal extremes; for example, the 2020 growing season was the driest on record, and summer 2023 was the wettest.

As temperatures rise, the warm season is getting longer as the winter season shortens and snow and ice declines. Winter in particular has warmed 5°F compared to a century ago and is the fastest warming season. In projected trends of winter indicators in the Northeast, current snow cover is reduced and there are fewer freezing days in both winter and the shoulder seasons. The average warm season for the recent period 2010–2023 is about two weeks longer, and winters are about two weeks shorter, in comparison to a 1901–2000 historical climate baseline. Similarly, there has been a two-week increase in the average length of the growing season since 1950. Maine's warm season is lengthening more towards late summer and early fall, which may be associated with Arctic summer sea ice decline delaying the arrival of cold air masses to New England.

A series of weather extremes in 2023 worldwide and in Maine were associated with record high global temperatures. In addition to the second warmest calendar year and first wettest summer, Maine experienced a series of weather extremes in 2023 reflective of the anomalous conditions worldwide. An unusually active weather pattern developed in mid-December 2023 against the backdrop of record warm wintertime ocean temperatures in the North Atlantic, and with a strong El Niño event influencing worldwide weather.

Winter storms are projected to become more intense, but their frequency remains uncertain. Recent "southeaster" storms in December 2023 and January 2024, in addition to major wind storms in fall 2017 and 2019, have generated significant concern for future extratropical storm trends. "Extratropical" refers to storms that are usually between 30° and 60° latitude from the equator (Maine sits at 45°North), and they are often associated with cold air. Most climate models project more intense cyclones (lower central pressure and increased heavy precipitation), but with an overall decrease in the number of storms as the climate warms. However, future storm frequencies remain uncertain because of model disagreement on average future positions of North Atlantic storm tracks. These changes reflect high rates of warming in the Arctic that decrease the differences between Arctic and equatorial temperatures, so are important for steering the movement of storms.

Temperature projections for Maine are for 2–4°F increase by 2050 and up to 10°F by 2100. Temperature projections worldwide and for Maine are based on modeled Representative Concentration Pathways, RCPs, which define a range of possible greenhouse emissions based on estimates of future energy use and development worldwide. The different trajectories, written as numbers such as 4.5 (intermediate emissions) and 8.5 (high emissions), reflect societal decisions to control greenhouse gas emissions. Temperature projections reported in the 2020 STS report continue to represent a reasonable spread of potential warming outcomes for Maine through the end of this century.

Human Health

Maine is vulnerable to increasing Illnesses and deaths stemming from extreme weather–especially heat, cold, and storm impacts such as flooding. Maine is projected to experience more periods of extreme heat, and Maine's population is likely to be vulnerable; currently, certain groups (men, middle-aged adults, and those working outdoors) experience higher rates of heat-related illness and may be at higher risk. Even as heat risks increase, Maine experiences more cold-related illnesses. Extreme weather events can cause significant injuries and fatalities, such as four confirmed deaths due to injuries and floodwater-associated drownings in Maine's December 2023 storm.

Adverse mental health impacts of climate change are well-documented and vary significantly depending upon how much a person is exposed to climate impacts, underlying burdens of adverse mental health conditions, quality of and access to emergency response and mental health services, and social and cultural support systems. In Maine and around the world, populations that may be at particular risk for the mental health impacts of climate change are children and adolescents, women, and Indigenous peoples. Like other regions, Maine has a significant gap in available mental health services for those in need.

Deer tick populations have stabilized in southern Maine but are increasing in northern counties, which is reflected in the high and increasing rates of Lyme disease in the state. Climate variations, such as increased precipitation or warmer winters, can cause decreases and increases in deer (blacklegged) tick populations, respectively. Warmer temperatures year round are likely to support increasing deer tick prevalence in northern Maine, and establishment (the consistent presence) of Lone star tick populations in southern and coastal Maine. Lyme disease incidence in Maine is consistently in the top five among U.S. states and has been increasing over time, in part reflecting range expansion of deer ticks in Maine. Deer ticks transmit the agents of multiple diseases such as Lyme disease, anaplasmosis, babesiosis, Powassan encephalitis virus, and relapsing fever.

Incidences of diseases associated with lone star ticks, such as red meat allergy, are increasing. Lone star ticks, which can transmit the agents of diseases such as ehrlichiosis and tularemia, and can cause alpha-gal syndrome (red meat allergy), are not established but increasing.

Mosquito-borne diseases are increasing in Maine, including a second veterinary outbreak of eastern equine encephalitis virus (EEEV) in 2023. Increased precipitation and longer growing seasons may prolong the active biting season of mosquitoes, which increases the potential for more outbreaks of eastern equine encephalitis virus (EEEV) in Maine. West Nile Virus and Jamestown Canyon Virus (JCV) were reported in Maine in 2023, with a JCV human fatality in Maine reported in 2022.

Smoke from wildfires in Canada and the Western U.S. and increased aeroallergens such as pollen are impacting air quality in Maine. Although large-scale wildfires have been more common in the Western U.S. and Canada than in the Northeast in recent decades, wildfire smoke can be transported to the East Coast and cause significant exposures and associated health outcomes. Climate change is making aeroallergens (airborne allergens) like pollen in the air worse, and the trend is for this problem to continue to increase with a changing climate.

Climate change threatens food security. Food insecurity affects ten percent of Maine's population, and is exacerbated by high prices driven in part by climate change. Indigenous food supplies are threatened by climate change in Maine; preserving traditional food systems and food sovereignty can support food security in the face of climate change.

Social and Economic Systems

Maine homeowners will see the second largest home insurance rate increase in the country in 2024. While Maine's homeowners insurance rates remain low compared to the rest of the country, the record increase is driven largely by increased storm severity and associated damages. Changing insurance rates are an example of an economic signal of changing incentives and opportunities for households, businesses, governments, and institutions. Research predicts higher demand on government systems: civic institutions should prepare to see existing programs used more intensively or in new ways as populations cope with climate change.

The social cost of carbon is higher than previously calculated, and federal guidance changed to better account for ecosystems and cultures when providing funds for disaster recovery. Comprehensive evidence implies that the social cost of carbon, which measures the dollar value of the damages to society caused by an incremental metric tonne of carbon dioxide (CO_2) emissions, should be significantly higher than its current value. Updated Federal Guidance on Benefit-Cost Analysis (BCA), which is used to determine whether a disaster recovery project is funded, accounts for ecosystem services and addresses benefits and costs that cannot be monetized. Frequently the value of physical infrastructure has been prioritized in BCA calculations, entrenching existing inequities (such as providing funding to areas with high property values but not to areas with lower property values given the benefit-cost ratios).

Climate change impacts the supply and demand of tourism, affecting how tourists plan their Maine travels. Tourism, an $8.6 billion dollar industry in Maine that supports over 150,000 jobs, depends on the quality and management of natural and cultural resources, particularly the complex relationship between climate hazards, risks, tourism demand, and tourism experience. Research in Maine shows Maine tourists perceive that climate change is impacting the environment they visit and the built infrastructure they use; their decision to travel depends on how they evaluate their potential exposure to climate-related risks at their destination.

Mainers particularly vulnerable to climate change include rural, older and lower-income residents, as well as those people and places with economies tied to climate-sensitive resources. Mainers experience different levels of vulnerability, and climate-vulnerable communities in Maine come from across the state, especially those whose economies are particularly sensitive to climatic change (such as lobstering or timber harvesting). Rural communities can be particularly vulnerable because local governments are challenged by constrained financial and human resources and consequently have lower levels of adaptive capacity to plan for and respond to climate-related natural disasters. Older, isolated, and lower-income residents may experience more harm from climate impacts such as power outages and flooding. Finally, cultural identities, such as the values and activities tied to various regions of Maine, are at risk from climate impacts. Intangible resources that support well-being, such as community cultural practices, can be impossible to replace once lost. For example, a cultural dependence on natural resources and systems makes

Wabanaki citizens particularly vulnerable. However, Wabanaki citizens can be uniquely resilient to climate change, as cultural traditions help to process change.

When municipalities are able to put time and resources into vulnerability assessments and engage meaningfully with the public in that process, this increases municipal climate resilience in Maine. Maine research shows that vulnerability to negative climate change impacts can be reduced through participation and engagement in climate adaptation. This includes building municipal capacity (such as having adequate funding for municipal employees to build relationships, apply for grants, and acquire needed skills to engage meaningfully with the community) to assess community vulnerability. This highlights the importance of creating opportunities for community involvement in local and state vulnerability assessments.

Climate Resilience

In Maine, resilience to climate change depends on relationships: this includes a strong sense of community among residents, solid connections between the economy and healthy natural systems, and maintaining ties to heritage. In Maine, partnerships, collaboration and funding for climate project implementation were identified as key municipal needs for enhancing resilience. In municipalities where coastal community comprehensive plans include social resilience, many 1) emphasize a strong sense of community and a desire to maintain a rural character; 2) focus on shoreline erosion and flooding; and 3) recognize the relationship between healthy natural systems and a healthy economy. Maine can improve climate resilient development by building on important aspects of Maine's culture, such as reuse and thrifting.

Tribal sovereignty enables climate resilience for Native nations. Building research relationships with Wabanaki nations requires slowing down, centering Wabanaki diplomacy and methods, and creating rhythms of collaboration. Both federal and state interference in Tribal sovereignty can limit the ability of Tribes to develop, fund and implement culturally appropriate climate adaptation plans and activities. When conducting sustainability science in Indigenous homelands of Penobscot, Passamaquoddy, Maliseet, and Mi'kmaq, researchers found that 1) centering Wabanaki diplomacy and Indigenous research methods; 2) a multi-perspectives, recurrent engagement; 3) slowing down; and 4) supporting Wabanaki students as leaders and researchers could begin to address tensions between Western and Indigenous ways of knowing. Traditional ecological knowledge is not another form of "data" to be folded into existing Western governance structures; practices around data sovereignty, in which Native nations control and maintain their personal and environmental data, begin to address this.

Housing security for low income and rural Maine residents may be stressed by high fuel and electricity costs, along with climate migration to Maine. Rural residents are not adequately supported by unstable funding for heating oil, such as funding provided in the Low Income Home Energy Assistance Program (LIHEAP). Longer term and more cost effective solutions to high heating costs include improvements in building insulation and energy efficiency.

Individual renewable energy systems can provide reliable power during extended outages. Solar panels with battery storage can meet individual homeowner basic backup power needs during extended power outages, and storage (such as batteries) can meet most of the critical heating and cooling needs during outages. In 2023, Vermont instituted a program now underway to test "solar+storage" to improve grid resiliency.

Resilience metrics should measure baseline conditions, assess both process and outcomes, engage and enable communities early and often, and address equity. When assembling resilience metrics, a critical question to ask is "resilience for whom, at what cost to whom else?" Indicators of resilience can be singular or composite, often mix qualitative and quantitative approaches, and measure an initial baseline. Involving communities in creating and using metrics allows them to steer conversations towards neglected social needs and exert influence and control in the adaptation process, increasing the likelihood of long-term effectiveness of a project to meet its resiliency goals.

Ensuring power, access and standing for public participants in climate decision-making builds trust and leads to better outcomes. When done well, public participation in decision-making improves legitimacy, builds capacity, leads to better environmental and social outcomes, and enhances trust and understanding among parties. Five key principles help to bring together science and the public in decision-making: 1) transparency of information and analysis; 2) giving explicit attention to facts *and* values; 3) addressing assumptions and uncertainties; 4) including independent review; and 5) allowing for iteration with new information. Maine research shows that commitment to community agency (the combination of access, standing, and influence that gives a community real power in a process) helps build trust and has proved locally successful in implementing renewable energy projects.

Sea Level Rise and Coastal Storms

Sea level is 7.5 inches higher than in early 20th century Maine, and the rate of sea level rise has nearly doubled in the past 30 years. Over the past 30 years, the rate of sea level rise was 1.4 inches per decade, while the previous rate was 0.7 inches per decade. Sea level rise rates in Maine remain similar to the global averages for both short- and long-term rates.

Record-high sea levels were measured along the coast in 2023 and 2024. 2023 set a new record-high annual average sea level at all three of Maine's long-term tide gauges, and also set numerous new monthly average sea level records. In 2023, the record for highest monthly average water level was broken at all long-term gauges for at least six months out of the year, with all remaining months except one falling within the top three highest levels for each month.

Rising sea levels have caused recent increases in coastal flooding, such as the record-breaking storm events of January 2024. The combination of high tide and storm surge (called storm tide) on January 10 and 13 were not historically unprecedented, but coming on top of a rising sea level is what caused the events to break records. This increase in sea level on top of high tides and storm surge, contributed to severe coastal flooding during the back-to-back January 10 and January 13, 2024, storms. Sea level rise has caused coastal flooding to occur about three times more often since 2010 in Portland compared to the past century. The frequency of minor high tide flooding will increase over the next decade, driven by sea level rise and an increasing tidal range induced by a lunar cycle.

Maine's "commit to manage" sea level rise targets (1.5 feet by 2050 and 4 feet by 2100) remain unchanged from the 2020 STS report. Maine's "commit to manage" sea level rise scenario (1.5 feet by 2050 and 4 feet by 2100, relative to 2000 average or "mean" sea level) remains within the statistically likely range of the equivalent sea level rise scenario in updated projections.

The timing of the "prepare to manage" targets (3 feet by 2050 and 8.8 feet by 2100) should be shifted to two decades later. Updated projections indicate that the timeframe of Maine's "prepare to manage" sea level rise scenario (3 feet by 2050 and 8.8 feet by 2100, relative to 2000 mean sea level) should be shifted two decades later, to 3 feet by 2070 and 8.8 feet in the 2120s.

Due to a possible large increase in the rate of sea level rise at the end of this century, Maine needs to extend planning horizons beyond 2100. Sea level is currently rising about 1.2 inches per decade in Maine. In 2100, this rate would increase to 8.4 inches per decade under the Intermediate (RCP 4.5) scenario and 1.2 feet per decade under the High (RCP 8.5) scenario. This possible order-of-magnitude increase in the rate of sea level rise by the end of the 21st century may cause physical impacts that outpace planning and adaptation efforts, highlighting the need for planning beyond 2100. Beyond 2050, when the different carbon emissions scenarios begin to diverge, the major driver of uncertainty in sea level rise projections is continental ice sheet melting, which in turn depends on emissions.

Catastrophic tropical storm surges are unlikely for Maine; winter storms will continue to be the main threat for severe flooding. It is unlikely that Maine would experience a tide-and-surge combination that would drive flooding multiple feet above the historical record. Instead, sea level rise and variability (such as astronomical or lunar-driven tides) drive severe flooding, as was the case for the January 2024 storms. In Maine, extratropical (originating between 30-60° latitude, usually cold-season) storms are the primary cause of flooding, and maximum wind speeds for these storms are less than half of hurricane maximum wind speeds. Tropical (originating in the tropics, usually within the warm seasons) cyclone intensity has increased in the North Atlantic, but this increase has not been connected with increasing surge intensity in the Gulf of Maine. There is also evidence for future changes in extratropical cyclone activity globally, but there is no evidence that storm surges will become larger or more frequent with future warming in the Gulf of Maine. However, as sea level rises, the same surges superimposed on higher sea levels will make coastal flooding and inundation more frequent and severe.

Marshes are not building elevation fast enough to keep up with sea level rise and need room to migrate upland, but coastal development restricts their ability to move, especially in southern Maine. Salt marshes in Maine currently store more carbon than salt marshes in all other states except Massachusetts, but are threatened by sea level rise.

Much of Maine's salt marshes are building elevation at a slower rate than sea level is rising: 75% of the Northeast's marsh area could be lost to inundation unless the habitat is able to migrate landward into undeveloped natural areas. There is six times less marsh migration space available south of Penobscot Bay than north of the Bay. Coastal bluff stability and landslide hazard maps, published by the Maine Geological Survey (MGS) in the early 2000's, need to be updated due to changing conditions. New maps from the MGS depict the full extent of coastal sand dune systems that are highly vulnerable to sea level rise.

Marine

The Gulf of Maine is warming faster than 97% of the world's ocean surface and is experiencing near-constant ocean heat waves. In 2022, sea surface temperature met the heatwave criteria for 353 days, or 97% of the year. Research indicates that the northward shift of the Gulf Stream and the deflection of the Labrador Current led to rapid warming and a "regime shift" in the Gulf of Maine beginning around 2008, in which the base of the food web was altered by warm water, sending a cascade of impacts up through iconic species such as Atlantic cod, North Atlantic right whales, and Atlantic puffins, a shift that has persisted.

Increased ocean temperature has decreased the size and quality of the food source that supports the marine food web, causing species to shift, become less abundant, grow faster but mature at smaller sizes, and results in species changes in the Gulf of Maine. Declines in primary production, or the rate at which organisms photosynthesize to build organic matter, have meant a fundamental change in the size and quality of the phytoplankton which supports food webs. The signature subarctic zooplankton species, which is the primary food for young lobster, has declined in the Gulf of Maine. Climate-driven changes in the planktonic community have the potential to influence maritime activities, including fishing, aquaculture, and tourism, as well as ecological communities. The biomass of certain groups of marine organisms has declined, and many fish and invertebrate populations shifted their spatial distributions, such as wild kelp populations that are disappearing from southern Maine, yet were still affected by warming: most species have grown faster at early life stages but plateaued at smaller body sizes. Research has found increased species diversity and "tropicalization" of the fish community. Certain species are being particularly affected by warming ocean temperatures and associated ecosystem changes, such as Atlantic cod, Atlantic herring, northern shrimp, Atlantic puffins, and North Atlantic right whales.

Warming is affecting the timing of food availability and migrations of iconic and endangered species. Significant shifts are occurring in the Gulf of Maine in the timing of ecological processes. The migration of certain diadromous fish, including Atlantic salmon and alewife, have advanced to earlier in the year, while other events are occurring later: these include spring and fall phytoplankton blooms, fledging of Atlantic puffin chicks, and the appearance of certain species of larval fish. These changes include the increasingly mismatched timing between larval lobster and their primary food source.

Maine's lobster harvest in 2022 declined by 26% in volume from its historic highs in 2016. The Maine lobster industry provided 18,000 jobs and $464 million in revenue in 2023. Lobsters are being directly impacted by warming waters as well as climate-driven changes to the zooplankton community, effects that have important implications for the future of Maine's lobster industry. While lobster appear to be relatively resistant to ocean acidification effects compared to other commercially valuable shellfish, climate-related changes in the reproductive performance of lobsters and the supply of planktonic foods have contributed to declines in lobster settlement over the past decade. Additional climate-related issues facing the lobster industry include an over-dependence on the fishery, anticipating sea level rise and storm damage to working waterfronts, minimizing interaction between the North Atlantic right whale and lobster fishing, and offshore wind energy development.

Under the highest emissions scenario (RCP 8.5), the Gulf of Maine will experience ocean acidification conditions that are unfavorable for shell growth for most of the year by 2050. Additional species, including invertebrate pelagic species, have been identified since 2020 as vulnerable to ocean acidification. Rising atmospheric CO_2 will lead to more acidic (lower pH) conditions in the Gulf of Maine.

Increasing hypoxia (low oxygen) events in the Gulf of Maine, which have resulted in lobster die-offs, have attracted research to understand the environmental causes and drivers of these conditions and to predict them in advance. Seaweed aquaculture can remediate localized low dissolved oxygen as well as low seawater pH, particularly with sugar kelp. However, a lack of genetic knowledge around kelp biodiversity limits the expansion of kelp aquaculture. Aquaculture systems in cold water environments face global change challenges, but can be adapted with investment into infrastructure, strain selection, and emergent species.

Accounting for carbon and removing it is a burgeoning area of marine research. Maine is at the forefront of research and policy by attempting to include coastal carbon sequestration in the 2023 Maine Carbon Budget. New guidelines to responsibly conduct marine carbon dioxide removal research stress the need for caution and development of Measurement, Reporting, and Verification Tools (MRV) to ensure claims about carbon burial and sequestration from seaweeds in particular are evidence-based.

Communities that are heavily invested in one fishery (such as lobster) face resilience planning challenges. Different lobster fishing business models, such as the inshore single-operator fishermen versus more capital intensive multi-crew operations, may experience differential impacts from climate change. Socioeconomic indicators of resilience in Maine's lobster fishery include profitability, coastal accessibility, community change, and physical and mental health, but more data are needed to quantify specific impacts. Co-management of fisheries and ecosystems are increasingly important.

In Maine, using nature to protect infrastructure and environments, or "nature-based solutions," can provide climate risk reduction, habitat, and social benefits, but planners need streamlined planning and regulation supported by a network of interagency partnerships to have solutions be effective at scale. Nationally, the effectiveness of nature-based solutions to meet coastal adaptation needs is well-documented but depends on a wide range of conditions, knowledges and capacities, with the bottlenecks for implementation similar to those found in Maine: governance (such as regulatory streamlining), communication (such as social proof from neighbors implementing projects), and equity (such as attention to who sees value from projects).

Agriculture

Weather variability is reducing crop yields, causing economic impacts to farms, and mental and physical health impacts to farmworkers in Maine. Maine has over 7,600 farms, 96% of which are family farms, on 1.3 million acres. The industry generates $3.6 billion and 27,000 jobs. Producers report concern about reduced crop yields and quality, poor crop and cover crop germination, and increased labor needs associated with irrigation. Survey respondents noted that extreme weather, such as an overabundance of rain, makes field access more difficult, increases soil erosion, and has negative effects on farm viability and farmworker health and wellbeing. Crop insurance policies designed for diversified farms have low utilization rates by the Maine farmers, but the industry has new opportunities with climate-related crop insurance policies that are becoming available.

New opportunities and both positive and negative impacts for Maine agriculture are likely with warmer temperatures and longer growing seasons. Longer growing seasons allow new insect pests, diseases, or weeds to become established or allow existing species to have additional generations. Longer and warmer growing seasons can increase the frequency and intensity of stress to crops, livestock farmworkers and water demand. Earlier spring warmup can lead to damage to perennial plants if the date of spring cold temperatures does not shift earlier at the same rate. Higher winter temperatures can also allow agricultural pests that are not currently able to overwinter in Maine to persist year-round. The benefit of longer, warmer growing seasons that permit a wider range of crop options and higher productivity could be curtailed or even eliminated if the increase in growing degree days is not synchronized with a matching shift in the dates of spring and fall frosts, or if heat waves, droughts, or other extreme weather events degrade productivity.

Updated USDA plant hardiness zones show average annual minimum temperatures increasing by about 20°F between 2005 and 2085. By 2085, under the highest emissions scenario (RCP 8.5), average annual minimum temperatures in central Maine will resemble current (2024) conditions in central New Jersey; and northern Maine will be similar to current conditions in Connecticut.

Climate change poses a substantial risk to U.S. agricultural yields. Using corn and soybeans as model crops, climate change is expected to have negative impacts on crop production nationally. Studies are not specific to Maine, but given that Maine imports 90% of its food, the national market directly impacts Maine food pricing and security.

Effective agricultural adaptation requires decades to implement and faces constraints, but can be highly effective if warming remains under 2.7°F (1.5°C). Agricultural and water management adaptation options are on average 90% effective in reducing risks up to 2.7°F of warming, but with increased warming above 2.7°F, effectiveness declines across all options and regions. More broadly, the U.S. and Canada were ranked as having higher constraints to adaptation than countries in western and southern Europe when using indicators such as GDP per capita, governance, education, and gender inequality.

Agriculture accounted for approximately 2% of total Maine statewide emissions in 2019. From 2010-2021, total emissions from Maine agriculture decreased. In 2021, livestock accounted for more than 86% of Maine's agricultural emissions, primarily from methane. Enteric methane emissions (from ruminant digestion) have been on a slow but steady decline since 1996. Conversely, methane emissions from manure have increased over that same period. Globally, livestock methane emissions represent the largest agricultural contribution to climate change. Livestock emissions can be reduced through feed additives, and research suggests that methane emission from beef and dairy cattle can be reduced by 50%. Over half of Maine's organic dairy producers surveyed were familiar with, and a third were using, red seaweed as a feed supplement to reduce enteric methane emissions.

Mitigation in agriculture can come from biochar and adding renewable energy to farms. Evidence suggests that biochar, a form of charcoal, can enhance soil carbon sequestration and improve soil health with appropriate management. Maine farmers are installing renewable energy infrastructure on agricultural land to increase farm economic viability and contribute to greenhouse gas mitigation goals.

There are multiple challenges and constraints for effective soil carbon sequestration, including ecological and socioeconomic factors, lack of standardized soil carbon monitoring and measuring methods, and documentation of sustainability and permanence. While there is a great deal of enthusiasm for the potential of soil carbon sequestration globally, recent studies have pointed to the ecological, biogeochemical, and socioeconomic challenges of achieving enhanced, sustained, and demonstrable carbon sequestration in soils. Research on mechanisms of soil carbon sequestration indicates that crushed rock mineralization, also known as enhanced silicate weathering, could theoretically remove billions of tons of CO_2 per year if implemented on a global scale.

Biodiversity

The globe experienced its first documented climate-driven extinctions of this era, along with widespread localized extirpations: a quarter of all species on earth are at risk of extinction. Climate change has been identified as the cause of at least two species extinctions. An additional 5% of currently living species are at risk for climate-driven extinction with 3.6°F (2°C) warming and 16% at 7.7°F (4.3°C) warming. Research shows that one million species, or 25% of all the world's known species, are threatened with extinction due to other reasons alone or in conjunction with climate change. Climate change is causing local species extinctions, often driven by increases in annual high temperatures.

Eight new wildlife species were added to the Maine State List of Endangered and Threatened Species in 2023, many of which are additions driven in full or part by climate change. New species are the Saltmarsh Sparrow, Bicknell's Thrush, Blackpoll Warbler, Marginated Tiger Beetle, Cliff and Bank Swallows, the Tricolored Bat, and Ashton's Cuckoo Bumblebee. Maine's Beginning with Habitat program identifies areas where a disproportionate concentration of at-risk species and habitats are located. Additional species not listed but vulnerable to climate change include additional bats, amphibians, turtles, salmonid fish and moose. A quarter of Maine's at-risk butterflies are threatened by climate change.

Climate warming is expected to facilitate the establishment and spread of more invasive species in the Northeast, and Maine's biodiverse river shores and floodplains are particularly vulnerable. Many of Maine's species have already been impacted by climate-driven changes to climate niche space and ecosystem structure. This includes the loss of eelgrass and kelp beds, and the loss of forest understory plant diversity due to invasive species. In Maine, the range of invasive Common and Glossy Buckthorn, for example, has expanded due to warming temperatures, contributing to the loss of native species through overcrowding in the forest understory and shading out natural regeneration, decreased carbon sequestration, and increases in invasive earthworms.

Climate change impacts on biodiversity are expected to increase, but are currently less impactful than habitat loss. Species distribution in the Northeast depends more on precipitation than temperature. While temperatures are important limits to species distributions, research identified physical habitat factors, such as soil and geological factors, as well as precipitation to be slightly more important than temperature for defining distributions. Research projects a loss of at least 6% (386 species) of current species by 2100 under the highest emissions (RCP 8.5) scenario.

Almost all birds are declining and shifting their ranges; wetland bird populations have benefited from adaptive management and long-term wetland protection. Maine birds are expanding or shifting their ranges, which can lead to decreased nesting success. While resident bird species in the Northeast are projected to increase as more southern species move northward, about two-thirds of short-distance migrant birds, such as Hermit Thrush, and a third of long distance migrants, such as the Rose-breasted Grosbeak, are projected to decrease. Residents that will decrease are culturally important species such the Black-capped Chickadee (the Maine state bird). Species reliant on high-elevation forests, such as Bicknell's Thrush, are especially vulnerable because such forests are limited in their ability to move upslope with warming.

Due to climate change, insects will alter their flight periods, and amphibians will be impacted by changes in seasonal events and hydrology. Many of Maine's insects, foundational to most ecosystem food webs, will respond to climate change by altering their flight periods. Changes in precipitation and hydrology, especially of ephemeral or vernal pools, are likely impacting the state's amphibians. Along with changes in seasonal emergence, highly variable late winter and spring freeze-thaw events are impacting regional amphibians.

Maine is not on track to add approximately 200,000 acres of conserved land per year to reach the national and state goal of 30% of land conserved by 2030. Though Maine's overall conserved area (22%) is low relative to most states in the Northeast, rates have recently increased. At present, the state is projected to reach 30% land conserved in 2047 and would need to triple the current rate of conservation to meet the 2030 goal. Although state ownership makes up the largest proportion of conservation lands, lands held in conservation easement (primarily as working forest) are the predominant form of conservation (54% of conserved lands), followed by state ownership (23%).

Old growth forests are the best forest type for sequestering carbon, and young forests sequester carbon quickly. Old growth forests (older than 170 years old) support the largest carbon pools of all Northeast forest conditions while concurrently supporting the highest biodiversity. Severe disturbances (such as clearcutting or infestation by invasive insects) have the potential to convert forests from carbon sinks to sources at least temporarily depending on the severity and frequency of the disturbance. Young forest stands (younger than 15 years) sequester carbon quickly and provide important habitat for species that rely on early successional forests.

Freshwater

Maine's wetlands are a bright spot for biodiversity and carbon storage, with some of the highest quality and quantity of these types of ecosystems across New England, but remain at risk from poorly planned development and climate impacts. Maine has lost up to 20% of its wetlands since the 1780s, but has some of the most intact and extensive floodplain forests remaining in the northeastern U.S. Conservation plays a critical role in maintaining these ecosystems. Maine hosts an exceptional number and diversity of peatlands such as bogs and fens, which store the most carbon of all wetland types, but are at risk of switching from a sink to a source with climate warming, because wetlands only store carbon when they are wet. Although wetlands are recognized for their important role in carbon sequestration and storage, accurate assessments of their carbon sequestration ability are limited.

In Maine's streams and rivers, intense flooding and increased temperature will impact fish species. Increased frequency and greater magnitude of floods can erode stream banks, reshape stream channels, accelerate the spread of invasive species, and increase sediment deposition in other parts of a river system. In addition to affecting stream and river geomorphology and habitat quality, intense floods can directly impact aquatic life by killing some organisms and washing others downstream. Significant rain events in late winter and early spring on frozen ground can increase stream scouring when larval Brook Trout and Atlantic Salmon are sac fry in the loose gravels and cannot evade these conditions. A key problem for Brook Trout and Atlantic Salmon is likely to be range expansion of introduced non-native species as waters warm. Maine's Eastern Brook Trout population is especially important for long-term conservation of the entire species because Maine is predicted to be a regional stronghold for suitable habitat.

For coldwater fish species, earlier onset of ice-out conditions means a longer open water season, more opportunity for water temperature increase and a longer duration of stressful or lethal summer temperatures. This is exacerbated in drought years that would already stress coldwater fish species. Lake conditions are changing to the advantage of warmer water species moving northward, often to the detriment of smaller resident and native forage species, such as rare minnows. Overnight recovery of water temperatures in lakes and streams from extreme high temperatures are reduced when overnight temperatures remain at or near the thermal tolerance limits for coldwater species.

Climate change, changes in air quality, and human impacts interact to drive regional changes in lake water quality in Maine. Climate change and land use (particularly road salt), as well as rising concentrations of dissolved organic carbon attributed to climatic warming and recovery from acid rain, are changing lake chemistry and decreasing lake clarity, with demonstrable impacts on lake biology including zooplankton as an indicator of ecological health.

Annual peak streamflows have increased in magnitude in Maine's rivers and streams over the last century, while the length of warm low-flow periods may increase. Future changes in larger, less-frequent peak flows (such as the 100-year peak flow) are uncertain but may increase with increased precipitation or decrease with increased temperatures and decreased snowpacks. In the last 50 to 100 years, snowpack depths have decreased in late winter and snowpack densities have increased. Groundwater levels and low stream flows have increased in recent years or not changed significantly. However, there may be an increase in the length of the warm low-flow season in the future for high-emission scenarios. Competing water demands in some Maine watersheds during low-flow periods have the potential to become more problematic during future droughts. Increased cyanobacteria blooms and cyanotoxin production continue to threaten drinking water and recreational uses.

The potential inland reach of saltwater intrusion has not been systematically studied in Maine. Inundation of the land surface during coastal storm surges or higher tides from sea level rise can contaminate an aquifer with salt from above or laterally through rock fractures. From below, sea level rise can permanently replace freshwater volume in a coastal aquifer with salt water.

Mapping vulnerable waters, determining their hydrological thresholds, and engaging in adaptive management can support watershed resilience. Freshwater resources can be supported with planning that encompasses climate, human activities, uses, economies, and lake characteristics. Building resilience into watersheds can be supported with risk assessments, integrative implementation, and monitoring.

Forests and Forestry

Treelines, the growing season, and foliage timing in Maine's forest are all shifting; peak fall foliage is now occurring almost two weeks later than 1950. Future climate projections predict that the timing of peak fall foliage will occur between October 30 and November 2 by 2060. Treelines are shifting upslope due to climate change, and some treelines are shifting faster. Among the climate impacts to Maine forest management, warming winters and increased frequency of winter freeze-thaw cycles is disrupting forest harvesting.

Elevated atmospheric carbon dioxide (CO2) has had a strong and consistently positive effect on wood volume, growth, and yield. CO2 fertilization is the dominant driver of the observed forest biomass increase over recent decades, increasing forest biomass accretion by over 50% in forests studied. The positive effect of CO2 fertilization may slow down and eventually reach saturation in the future, potentially reducing the forest ecosystem's contributions to achieving carbon neutrality. Future CO2 fertilization could increase total forest carbon by 0.8% to 5.1%, and could increase harvest volumes by up to 20% compared to the no-CO2 fertilization scenarios.

Maine's forestry industry has the highest vulnerability in the rural northern and western parts of the state, where forest industry activities are most prevalent. The Maine forestry sector is a heritage industry worth $8 billion per year and over 17,000 direct jobs. Reduced forest sensitivities and an increased capacity to adapt to a changing climate have the potential to decrease overall vulnerability in many parts of the state. Forest management would benefit from improving communication strategies to get relevant research to land managers and decision makers; providing funding sources for research that better match the needs of forest managers and decision makers; and creating a conservation landscape that embraces the value of both actively managed and unmanaged forests.

Climate change, coupled with increased pressure from non-native pathogens, insect pests and invasive species, will change Maine forests. Some tree species that occur south of Maine today are likely to migrate into the state, creating novel forest types. Certain tree species are also especially vulnerable to pests that target only one or a few tree species (such as the emerald ash borer). Cedar and fir may be particularly sensitive to future temperature and precipitation changes. Modeling found that the most sensitive seasonal climate variables for cold-adapted species included colder temperatures and preferences for wet weather concentrated in the winter months.The arrival and spread of invasive earthworms in Maine forests also poses a risk to forest carbon stocks and forest resilience to climate change.

Nationally, the future of the land carbon balance will be strongly influenced by the geographic extent of drought and heat stress, but projections show that socioeconomic factors are a greater driver of harvest and carbon stocks than climate change. The western U.S. is showing negative productivity trends while the eastern U.S. is showing positive productivity trends, strongly influenced by climate change.

Maine's extensive wildland-urban interface makes Maine vulnerable if a large wildfire were to occur. Projections for the Northeast predict intensification of conditions conducive to wildfire: warmer temperature, more variation in precipitation, more lightning, and longer periods of high-fire risk. Models predict an earlier fire season and more than a doubling of fire probability in the state. Maine has many houses in the wildland-urban interface (WUI), and 19% of the state's more than 17 million forest acres are considered WUI. These patterns make Maine particularly vulnerable if a large, severe wildfire were to occur. While large-scale, catastrophic wildfires are unlikely in Maine for a range of future climatic conditions, some Maine forests have characteristics that are similar to the Canadian Acadian forests that recently burned. The record-breaking 2023 wildfire season in Nova Scotia was driven largely by extreme short-term drought in May and June, and provided a glimpse of future fire risk in Maine. Increased fire risk in Maine's future can potentially be reduced by efforts to minimize human ignitions, employ prescribed fire where appropriate, and increase wildland fire-fighting preparedness.

Maine forests and wood products are a net carbon sink and are the largest contributor to the state's carbon neutrality target. Forests and wood products are estimated to have acted as a net sink between 2017 and 2021, offsetting about 101% of Maine's total gross GHG emissions. Carbon sequestration could be greatly increased by managing forests using a 'triad' approach consisting of harvesting to create uneven age continuous cover, intensive plantations, and permanent set-asides. In addition, optimally implementing forest management practices can increase carbon storage by 20% or more. Achieving forest carbon objectives requires attention to the choice of species cultivated, overall species diversity, and a mix from uneven age continuous cover to intensive plantations.

Hope (the science)

Hope theory can be a framework for action in the face of climate change. Hope theory is made up of three primary components: (1) goal setting (having a personally meaningful goal), (2) agency thinking (having the knowledge and determination to achieve the goal), and (3) pathways thinking (having a plan and a willingness to tweak the plan). Hope theory provides specific and systematic actions that can reduce anxiety and increase well-being.

Hope-based science communications are urgently needed. Maine-based physicians report that climate change is worsening the mental health and well-being of their patients. Climate anxiety, particularly in young people, can be alleviated through the creation of social outlets, agency, and providing avenues for meaningful action. In addition, hope increases the likelihood of individual success.

Having an accessible roadmap, such as Maine Won't Wait, is a key strategy for nurturing hope. Hope helps people cast a vision of what future success will look like. Every success is an opportunity to show that the future we want is possible.

INTRODUCTION

On June 26, 2019, Governor Janet Mills signed into law LD 1679 *An Act To Promote Clean Energy Jobs and To Establish the Maine Climate Council*. The law established ambitious goals for greenhouse gas reductions and cost-effective adaptation and resilience in Maine, and it charged the newly created 39-member Maine Climate Council (MCC) with developing an integrated Maine Climate Action Plan by December 1, 2020. In support of the work of the MCC, the law also established six working groups with various areas of focus that included transportation, coastal and marine systems, infrastructure, housing, natural and working lands, energy, community resilience, public health, and emergency management, all within an overarching framework of equity and economic development. The working groups were charged with developing draft strategy recommendations for the MCC that formed the basis for MCC deliberations in the development of the initial comprehensive Maine Climate Action Plan Maine Won't Wait in 2020, and subsequent quadrennial updates thereafter.

In addition, the 2019 law established the Scientific and Technical Subcommittee (STS) to support the work of the MCC and the working groups. The STS was established to *"identify, monitor, study and report out relevant data related to climate change in the State and its effects on the State's climate, species, marine and coastal environments and natural landscape and on the oceans and other bodies of water."* The STS is primarily composed of scientists with a broad array of expertise on climate change globally and in Maine who are committed to supporting the work of the MCC with the best available science to inform decision-making. In 2020, the STS released its initial comprehensive report Scientific Assessment of Climate Change and Its Effects in Maine to support the deliberations of the working groups and the MCC in the development of *Maine Won't Wait*. The following year, the STS released the short report Maine Climate Science Update 2021. These reports were preceded by Maine's Climate Future assessment reports in 2009, 2015, and 2020, led by the University of Maine.

This report, ***Scientific Assessment of Climate Change and Its Effects in Maine—2024 Update*** builds on the existing body of work by the STS to provide an up-to-date scientific assessment for working groups and the Maine Climate Council in the development of a science-informed quadrennial update of *Maine Won't Wait* by December of 2024. The authorship of this report includes members of the STS and additional contributors noted in the title page, as well as others who were generous with their expertise, some of whom are recognized in the Acknowledgements.

As we have noted in prior reports, but warranting reiteration here, are issues of *extent* and *uncertainty*. The *extent* of the subject matter in this report focused on the priority charge of the STS, and the STS membership does not presume to have fully addressed all possible subject matter. The STS members are highly regarded scientists with an expertise and passion about Maine across many key sectors of our state, and drawn from academic institutions, non-governmental organizations, and state and federal agencies. The STS also includes bipartisan membership of both the Maine House and Senate. In addition, our work in scientific assessment is only meaningful if it provides guidance within the relatively short timeline of the MCC process. Thus, our work has been carried out within the practical constraint of available time but received and included feedback on key issues from the working groups during our process.

The other issue of importance for readers of this document is how science deals with *uncertainty*. To that end, as we did in 2020, we have included here several terms (see insert) to guide the reader on how these concepts are used in the sciences.

Uncertainty, Likelihood, Variability, and Confidence

Scientists describe varying degrees of 'certainty' in our ability to predict climate-related changes. There are common terms used throughout this report that have different connotations of certainty, and we briefly describe them here:

- **Uncertainty:** A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts)[1].
- **Likelihood**, or probability, is a calculable statistic. But the word 'likely' is also used to convey a higher level of certainty. Generally speaking, scientists are more comfortable using this term when at least one well-regarded citation from the primary literature (and often more) can support the statement. Scientists use this term when there is sufficient probability that a change will have a specific directionality and that the mean magnitude of change is measurable and impactful. This is the state of much of our knowledge about select highly studied trends in the face of climate change.
- However, even if a directional, measurable gradual average change is likely to occur, it will almost always follow a fluctuating path. **Variability**, in a statistical sense, doesn't preclude a pattern - it is just the measurable amount of noise around that temporal or spatial pattern. For more easily measured parameters, like temperature and rainfall, we have large data sets from which to calculate annual, seasonal, or geographic variability. But for others, like ocean acidification, we are still hard-pressed to constrain the range of variation in seawater pH along the state's shorelines. Climate change not only can influence general trends, but it can also expand the range of variation. Extreme events outside this range of variation can emerge that further constrain our sense of certainty.
- The range of variation can be very strictly defined using probabilities, or likelihoods, that the mean trend will persist, despite the noise around it. Scientists often define **confidence** in the conclusions they draw as a percentage of certainty (e.g. 95%) that a trend is occurring and will continue in future projections. For rates of temperature increase and sea level rise, we can estimate with higher confidence what those changes will be in the coming decades based on robust and comprehensive historical data sets.

[1] IPCC, 2013: Annex III: Glossary [Planton, S. (ed.)]. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

This ***Scientific Assessment of Climate Change and Its Effects in Maine – 2024 Update*** focuses on Maine, and on the recent and critical areas of climate change effects science within the subject domain of the Scientific and Technical Subcommittee. While we do not attempt to assess all the most recent literature on the broad subject of climate change globally, many readers will also be interested in knowing about access to that body of science. Here we briefly point to some of those relevant resources.

Global Climate Assessments

The most widely recognized assessment of the latest climate-relevant science globally comes from the Intergovernmental Panel on Climate Change (IPCC), created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The IPCC has been conducting comprehensive assessments every six to seven years since 1990, with the most recent assessment being the IPCC 6th Assessment Report (AR6) comprising multiple reports covering the physical science, adaptation, and mitigation. The IPCC AR6 Synthesis Report released on March 20, 2023, provided an integrated summation of key findings. Some of that messaging included:

- Most indicators of a changing climate are accelerating, including the frequency and variability of extreme events.

- The current pace of greenhouse gas reductions needs to accelerate if we are to cut greenhouse gas emissions in half by 2030 to avoid exceeding 1.5°C this century, and carbon removal (e.g., CDR or carbon dioxide removal) will be necessary for those goals.

- Despite the focus on warming 1.5°C, every fraction of each degree of warming avoided matters.

- Taking the right actions now could result in transformational change essential for a sustainable, equitable world.

- There are tipping points in climate and ecological systems that are potentially irreversible with inevitable negative outcomes.

- Equally important to the consequences of a changing climate, IPCC emphasized the wide array of strategies to mitigate, adapt, and build resilience to the changing climate that are at our disposal with some evidence of growing utilization of these tools but much more is needed.

  There were several Special Reports developed by the IPCC since the UN Climate Change Conference (COP21) in Paris in 2015 that produced The Paris Agreement. They include:

  - Global Warming of 1.5°C—An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

  - Climate Change and Land—An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

  - IPCC Special Report on the Ocean and Cryosphere in a Changing Climate – An IPCC Special Report on climate change, the oceans, and the largely frozen parts of the planet from polar regions to high mountain systems.

In addition, an international team of scientists closely following IPCC protocols produce annual open source scientific assessment of indicators of global climate change, the last of which was Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence. These publications provide annual updates of climate change indicators that help bridge the time between full IPCC assessment reports.

Several other reports of global scope offer important insights on the evolving science of climate change. The United Nations Environment Programme annually releases a report on global greenhouse gas emissions and estimates of the "gap" between historical emissions to date, and the targets set for emissions reductions to limit the negative consequences of climate change. The most recent report was the 14th edition, Emissions Gap Report 2023. The most recent report concludes that Nations must go further than the Paris pledges or face global warming of 2.5-2.9 C. *Humanity is breaking all the wrong records on climate change. Greenhouse gas emissions and the global average temperature are hitting new highs, while extreme weather events are occurring more often, developing faster and becoming more intense.* The National Oceanic and Atmospheric Administration's (NOAA) Global Monitoring Laboratory tracks the global trends in major greenhouse gasses and is widely recognized as the source of up-to-date data on current atmospheric greenhouse gas concentrations and trends. One of the most frequently cited time series for atmospheric CO_2 comes from the longest record of direct measurements of atmospheric CO_2 at the Mauna Loa Observatory in Hawaii begun in 1958. The data from Mauna Loa shows atmospheric CO_2 concentrations still rising in 2023, with December 2023 at 421.86 ppm compared to 418.99 ppm in December 2022, significantly higher than pre-industrial concentrations of atmospheric CO_2 of approximately 280 ppm. The World Meteorological Organization (WMO) produces an annual WMO State of the Global Climate report that tracks key indicators of changing atmospheric chemistry, temperatures, sea level rise, ocean heat and acidification, sea ice and glaciers, while also highlighting the impacts of climate change and extreme weather. This is typically one of the key sources that officially declares the ranking of annual global temperatures, and on January 12, 2024 WMO issued a press release confirming that 2023 was the warmest year on record by a huge margin. The WMO reported that 2023 was 1.45±0.12°C above pre-industrial levels (1850-1900) in 2023, just shy of the often discussed long-term (a 30 year mean) of 1.5°C warming as a critical threshold for the planet. The WMO release states *The State of the Global Climate 2023 report shows that records were once again broken, and in some cases smashed, for greenhouse gas levels, surface temperatures, ocean heat and acidification, sea level rise, Antarctic sea ice cover and glacier retreat.*

The National Aeronautics and Space Administration (NASA) GISS Surface Temperature Analysis also produces estimates of planetary temperatures declaring 2023 the warmest year on record. Another source of these data comes from the European Commission's Copernicus project, which is the Earth observation component of the European Union's Space programme. In their recently released 2023 Annual Climate Summary Copernicus also declared that 2023 experienced the warmest global temperatures on record going back to 1850 being close to 1.5°C (1.48°C warmer than 1850-1900 pre-industrial) above pre-industrial levels. They reported that globally each month from June to December in 2023 was the warmest of that corresponding month in any previous year on record.

The Global Carbon Project produces global budgets of the three dominant greenhouse gasses CO_2, methane (CH_4), and nitrous oxide (N_2O), annually releasing an updated budget for carbon. The most recent Global Carbon Budget 2023 migrated to a new web site still linked to the Global Carbon Project. One of the major findings each year is reporting on a high-level global carbon balance, with the 2023 budget for the major sources of anthropogenic CO_2 emissions for the period 2013 to 2022 coming from fossil fuels (88%) and land use change (12%). The sinks for this excess carbon were the ocean (26%), the land sink (31%), with the remaining excess carbon as CO_2 (47%) being emitted to the atmosphere driving the rising atmospheric concentrations of this greenhouse gas.

The International Energy Agency provides detailed data on world energy production in all its forms. The most recent report is World Energy Outlook 2023. This flagship publication of the International Energy Agency is likely the world's most authoritative source of analysis and projections on energy. Published each year since 1998, it provides critical insights into global energy supply and demand under different scenarios and the implications for energy security, climate change goals and economic development.

A common question after weather disasters occur is whether climate change caused the event. In the rapidly evolving world of the science of climate change, significant advances have taken place in an area of science known as *attribution science*. This is a body of literature that addresses questions about whether or not climate change was all or part of the cause of a particular weather event. The World Weather Attribution initiative is a coalition of several climate science institutions who evaluate the role of climate change in weather events, and have become valuable for relatively rapid analyses of major weather events to determine the role that climate change has played. Other organizations apply various approaches to climate attribution such as Climate Central's Climate Shift Index.

National Climate Assessments

To help Americans anticipate how changing climate conditions might affect their homes and businesses, the United States Global Change Research Program conducts a comprehensive review of scientific information on climate trends and impacts in our country every four years. The 5th National Climate Assessment–often referred to as NCA5–was published in 2023. NCA5 also includes the NCA Interactive Atlas providing access to the data, maps, and climate stories that expand the utility of NCA for users.

The NCA5 also includes chapters that focus on U.S. regions, including a chapter for the Northeast region. In the Northeast, extreme weather events and other climate-driven changes are shaping mitigation and adaptation efforts, such as coastal wetland restoration and changes in fishing behavior. Many climate impacts in the region have disproportionate impacts on low-income communities and communities of color. Cities and states are implementing climate action plans with innovative approaches that embrace inclusive and equitable processes.

Also at the national scale, The National Oceanic and Atmospheric Administration (NOAA) tracks Billion-Dollar Weather and Climate Disasters in the U.S. at their National Centers for Environmental Information: in 2023, there were 28 confirmed weather/climate disaster events with losses exceeding $1 billion each to affect the United States. These events included one drought event, four flooding events, 19 severe storm events, two tropical cyclone events, one wildfire event, and one winter storm event. Overall, these events resulted in the deaths of 492 people and had significant economic effects on the areas impacted. The 1980–2023 annual average is 8.5 events (CPI-adjusted); the annual average for the most recent 5 years (2019–2023) is 20.4 events (CPI-adjusted).

Climate Dashboards

Lastly, there are many places to go to find climate science data. Climate "dashboards" of various types are popular for providing access to key climate data. There are a few we mention here that are particularly relevant to Maine, like the Maine Climate Council's Impacts of Climate Change Across Maine website, the Maine Climate Impact Dashboard, the Maine Department of Environmental Protection's Maine Climate Hub, the Maine Geological Survey's Sea Level Rise Ticker, or, the Maine Climate Office and the internationally recognized Climate Reanalyzer. Nationally, useful websites include NOAA's Global Climate Dashboard, NOAA's National Centers for Environmental Information's Climate at a Glance, the NOAA Sea Level Rise Viewer, the National Aeronautics and Space Administration's (NASA) Global Climate Change website, or the U.S. Environmental Protection Agency's Climate Change Indicators in the United States website.

CLIMATE

CLIMATE INSIGHTS SINCE 2020

Maine's climate is getting warmer and wetter and experiencing more extremes. In the four years since the 2020 STS report, researchers have seen further indications of these primary trends in Maine's changing climate. As a statewide mean, each of the calendar years 2020–2023 rank among the top 10 warmest for records beginning in 1895 (**Figure 1**). Calendar year 2023 ranks 2nd warmest and 5th wettest for Maine, with the precipitation surplus being a distinct departure from recent years.

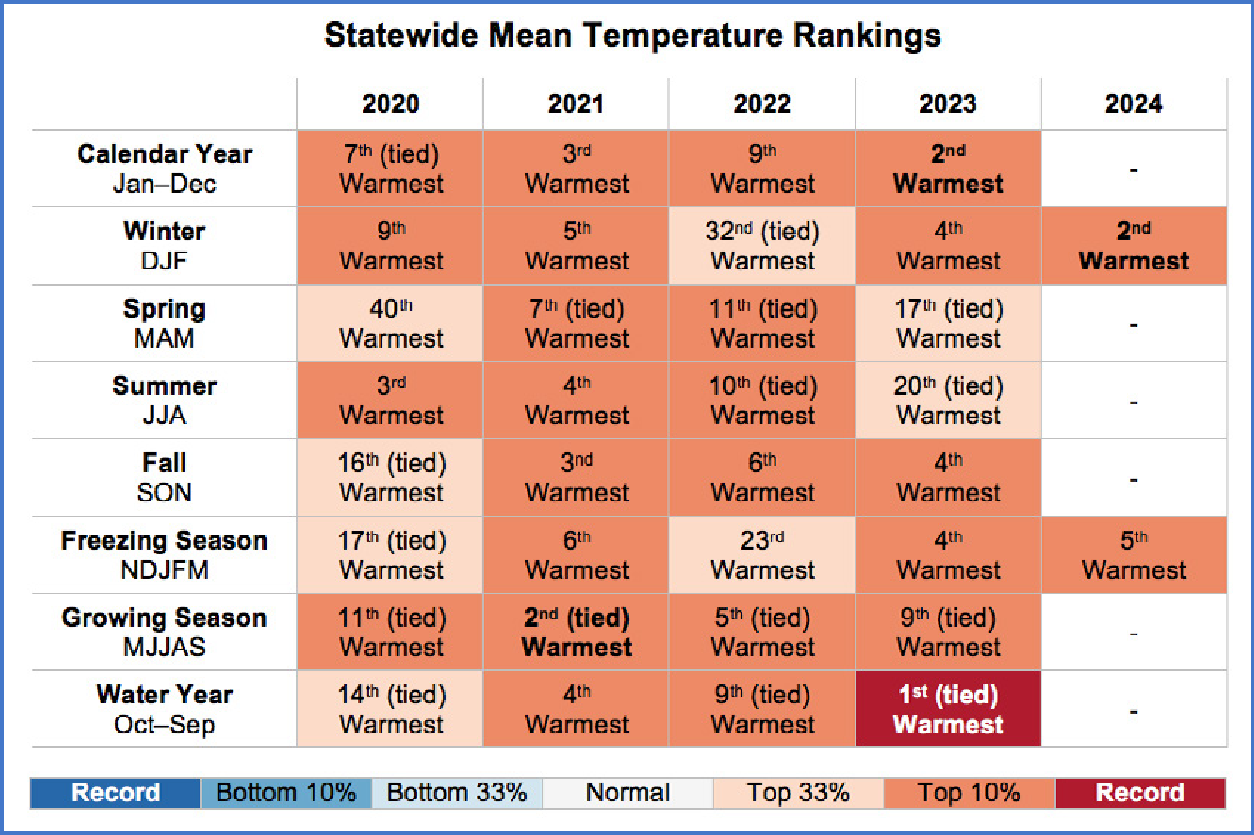
What is "the climate"?

Climate can be defined as the average weather over a period of time. It includes temperature, precipitation, and wind (Jay et al., 2023). More technically, the climate is a statistical description of the average and variability of weather, including meteorological trends from days to millions of years. A second, related definition of "climate" refers to the complex system in which the sun, land, ocean, ice, and living organisms interact with and influence each other and the atmosphere (Jay et al., 2023).

Increasing Extremes

In addition to more days per year with over an inch of precipitation, storm events with one-hour intensities have prompted adaptive actions. Heavy precipitation events continue to impact Maine and the broader Northeast region as warming drives a more intense hydrologic cycle (Whitehead et al., 2023). Based on an analysis of daily surface observations since the 1950s, Maine now receives on average 1–2 more days per year with 2 inches or greater precipitation, and 2–3 days more per year with 1 inch of precipitation (**Figure 2**). Short-duration (minutes to hours), high-intensity precipitation events with several inches of accumulation can occur over limited areas during thunderstorms, tropical or strong extratropical cyclones, and in association with meteorological factors such as topographic enhancement. A previous examination of data across New England and New York found that extreme precipitation days (top 1% of wet days) tended to have 50% of the total accumulation occurring in 3 hours or less (Agel et al., 2015). Historical and future trends for the frequency of these intense sub-daily events are not yet established for the region, but recent storms with record one-hour intensities have spurred adaptive measures nonetheless (Whitehead et al., 2023).

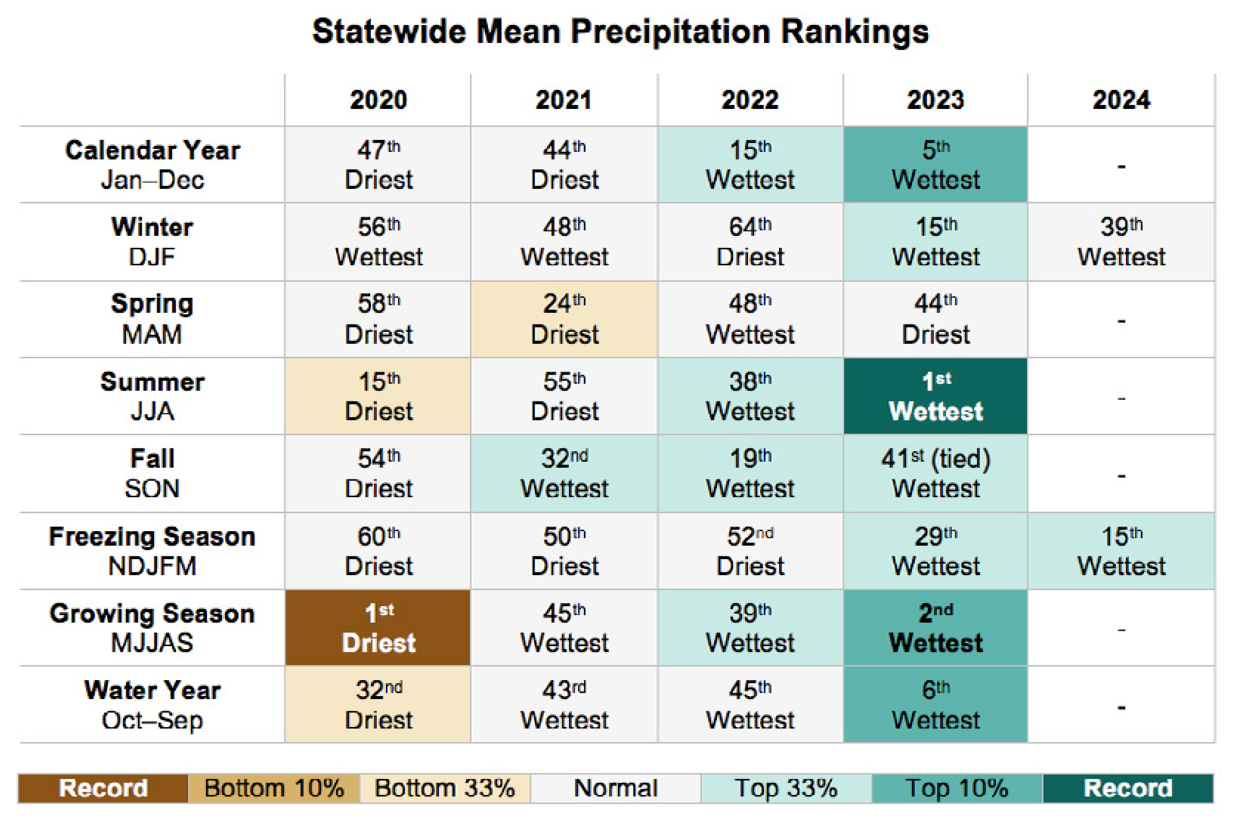
2020–2024 Temperature and Precipitation Rankings



Statewide Mean Temperature Rankings

	2020	2021	2022	2023	2024
Calendar Year Jan–Dec	7th (tied) Warmest	3rd Warmest	9th Warmest	**2nd Warmest**	-
Winter DJF	9th Warmest	5th Warmest	32nd (tied) Warmest	4th Warmest	**2nd Warmest**
Spring MAM	40th Warmest	7th (tied) Warmest	11th (tied) Warmest	17th (tied) Warmest	-
Summer JJA	3rd Warmest	4th Warmest	10th (tied) Warmest	20th (tied) Warmest	-
Fall SON	16th (tied) Warmest	3rd Warmest	6th Warmest	4th Warmest	-
Freezing Season NDJFM	17th (tied) Warmest	6th Warmest	23rd Warmest	4th Warmest	5th Warmest
Growing Season MJJAS	11th (tied) Warmest	**2nd (tied) Warmest**	5th (tied) Warmest	9th (tied) Warmest	-
Water Year Oct–Sep	14th (tied) Warmest	4th Warmest	9th (tied) Warmest	**1st (tied) Warmest**	-

Record	Bottom 10%	Bottom 33%	Normal	Top 33%	Top 10%	Record



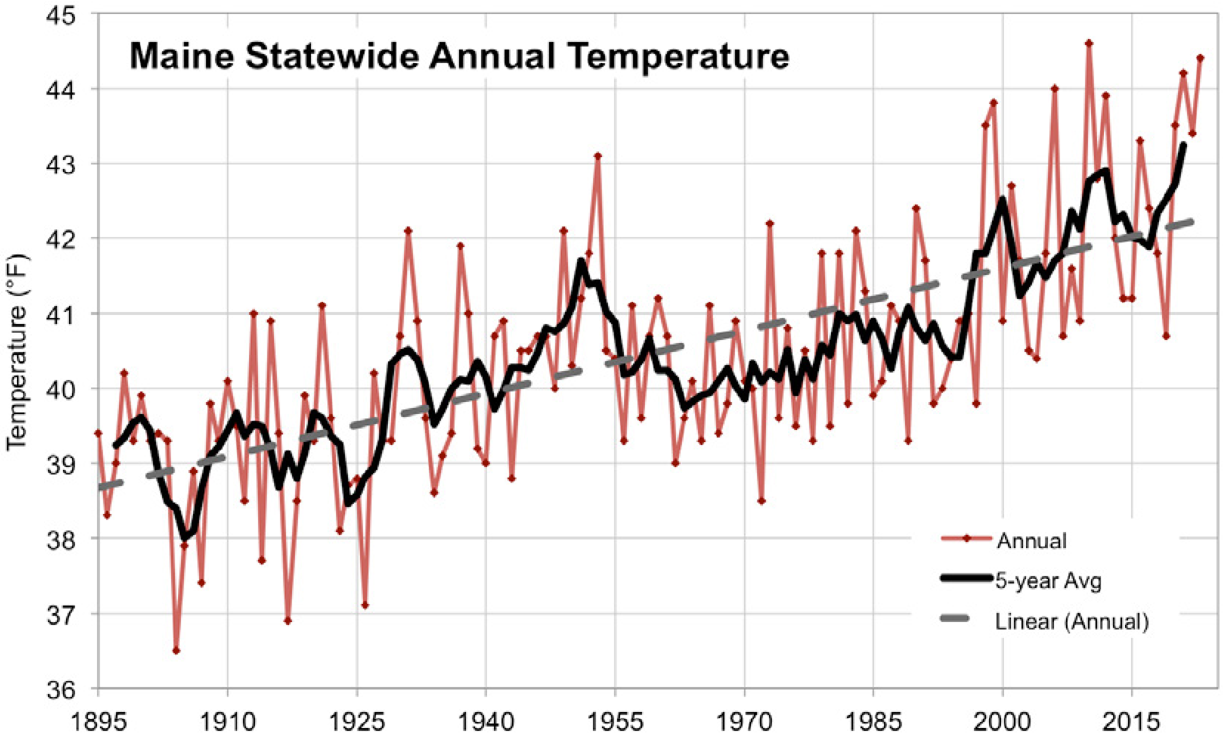
Statewide Mean Precipitation Rankings

	2020	2021	2022	2023	2024
Calendar Year Jan–Dec	47th Driest	44th Driest	15th Wettest	5th Wettest	-
Winter DJF	56th Wettest	48th Wettest	64th Driest	15th Wettest	39th Wettest
Spring MAM	58th Driest	24th Driest	48th Wettest	44th Driest	-
Summer JJA	15th Driest	55th Driest	38th Wettest	**1st Wettest**	-
Fall SON	54th Driest	32nd Wettest	19th Wettest	41st (tied) Wettest	-
Freezing Season NDJFM	60th Driest	50th Driest	52nd Driest	29th Wettest	15th Wettest
Growing Season MJJAS	**1st Driest**	45th Wettest	39th Wettest	**2nd Wettest**	-
Water Year Oct–Sep	32nd Driest	43rd Wettest	45th Wettest	6th Wettest	-

Record	Bottom 10%	Bottom 33%	Normal	Top 33%	Top 10%	Record

Maine statewide annual and seasonal temperature and precipitation rankings based on data beginning 1895. Source from the National Centers for Environmental Information (NCEI, 2024b).

Flood damage on Woodman Hill Road in Jay, Maine, after heavy rainfall in summer 2023. Photo credit: Murray Carpenter, Maine Public Broadcasting Network. (https://www.mainepublic.org/climate/2023-08-07/maine-has-been-hit-by-an-unusually-high-number-of-flash-floods-this-summer-straining-small-towns)



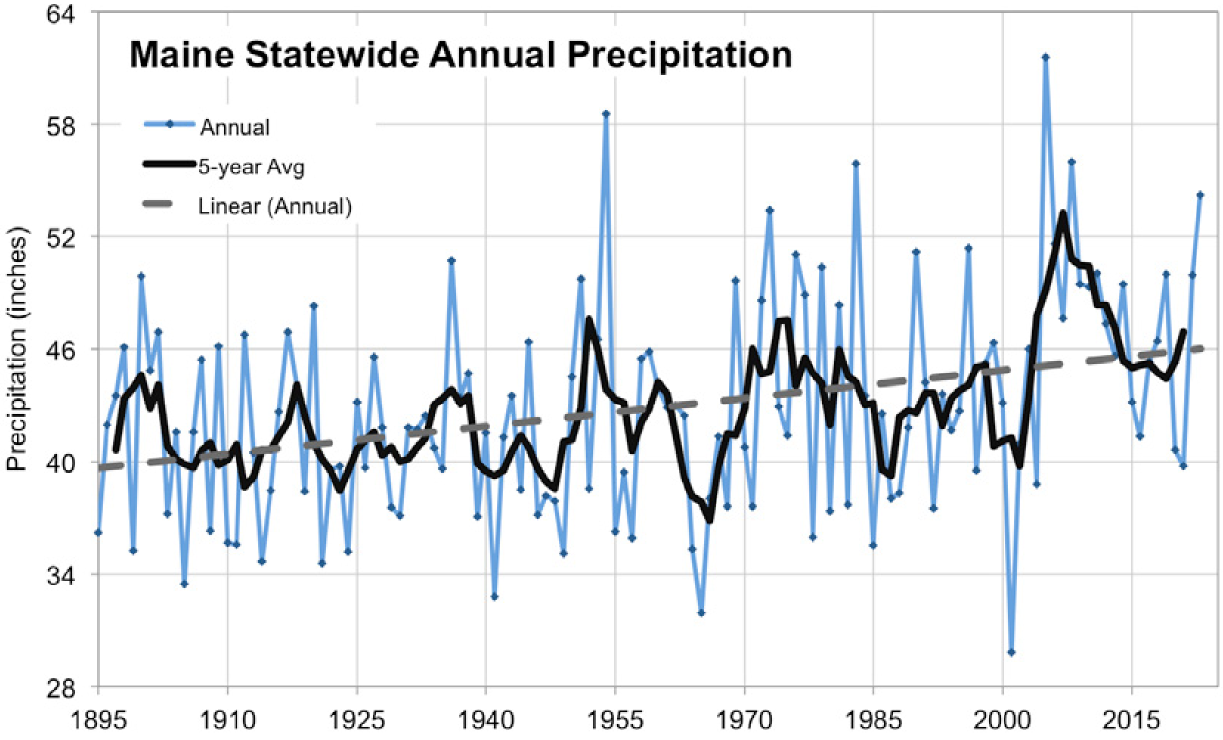
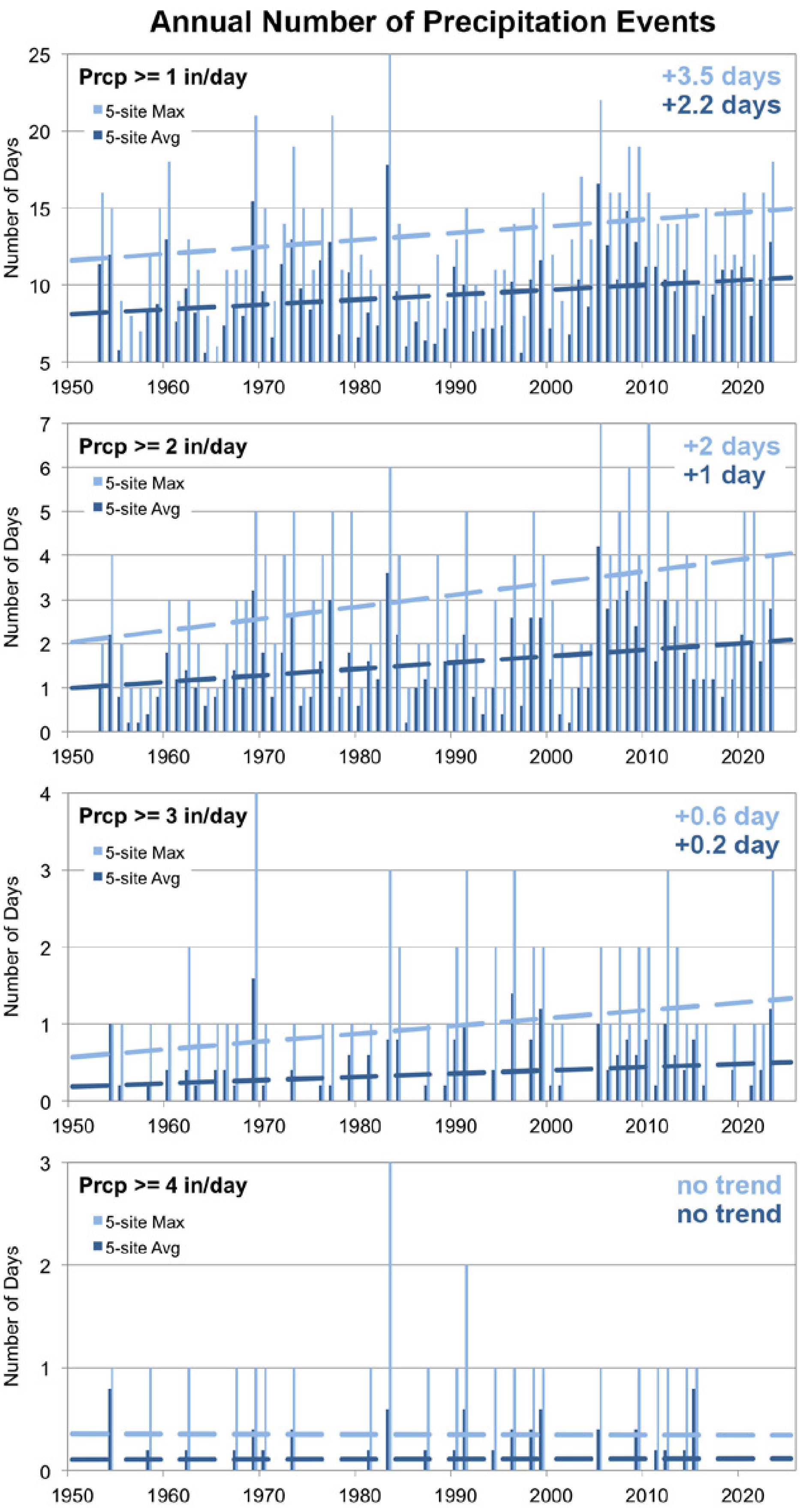


Figure 1. Maine's annual mean temperature (top) and cumulative precipitation (bottom) 1895–2023 based on data from the National Centers for Environmental Information (NCEI, 2024a). The dashed linear trendlines show temperature and precipitation increases of 3.5°F and 6 inches (1.9°C and 15 cm), respectively, across the record period. Bold black lines represent five-year averages.

Figure 2. Annual number of daily precipitation events greater than accumulation thresholds of 1–4 inches based on five observational records, each with data 1953–2023: Augusta, Bangor, Caribou, Farmington, and Portland. These five records were chosen for representing different areas of the state and having more than 60 years of observations for long-term context. Some extreme precipitation events are very localized, especially related to convective thunderstorms, and can produce several inches of accumulation that may go unmeasured. For example, none of these five long-term stations recorded > 6 inch rainfall totals observed in some areas of western Maine during the recent December 18, 2023 storm. Dark blue bars represent the average number of events across all five sites, whereas the light blue bars represent the maximum number of events. Dashed lines are corresponding trendlines; the record period increase in the average number of events per year is labeled above the lines on the right of each chart. Data from NCEI (2024)[1].



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[1] GHCN station IDs USW00014605, USW00014606, USW00014607,

Extremes (e.g., in temperature, precipitation duration and intensity) can occur over a range of time scales, from hourly or daily weather to monthly or seasonal climate. A key example of seasonal extremes is found in the contrast between the growing season (May–September) of 2020 and the same period three years later, in 2023. May–September of 2020 was the *driest* on record with temperature also ranking 11th warmest, while 2023 was the second *wettest* on record and 9th warmest. (see callout box "2020–2024 Temperature and Precipitation Rankings" and Appendix A **Figure A1**).

In 2020, dryness began in May and drought conditions developed through summer. By September, most of the state was in severe drought, with some areas at extreme levels, and a crop disaster area declaration was made by the U.S. Department of Agriculture for Aroostook and adjoining counties (DACF, 2020; Lombard et al., 2020). With drought conditions having also developed variously in parts of Maine in 2021 and 2022 (e.g., MEMA, 2021), many agricultural producers began seeking irrigation systems. These efforts were seemingly upended in 2023 when persistently wet conditions caused growers to suffer crop losses or decreased yield from excess water (e.g., USDA, 2023). This abrupt shift in precipitation regime in 2023 is especially instructive: the summer was among the warmest on record, but rainfall surpluses and cloud cover counterbalanced the drying effects that increased temperature would have otherwise brought. (For impacts from these conditions, see *Agriculture*.)

As discussed in the 2020 STS report, **Maine's climate is getting wetter overall and meteorological drought has not increased in the historical record, but interannual precipitation variability is increasing** due to intensification of the hydrologic cycle. This is exemplified by the season-scale precipitation extremes observed in 2020 and 2023. A recent downscale precipitation modeling study for the Northeast likewise finds that in a warming climate **dry periods become drier and wet periods become wetter** (Xue & Ullrich, 2022). While future drought trends remain uncertain, warmer temperatures and earlier snowmelt can exacerbate dry conditions when they develop. For example, the 2020 drought had hydrologic impacts that carried over into 2021. For additional historical context, a similar figure from the previous STS report has been updated, showing placement of the 2020–2021 event against others for a common drought index in terms of both intensity and duration (**Figure 3**).

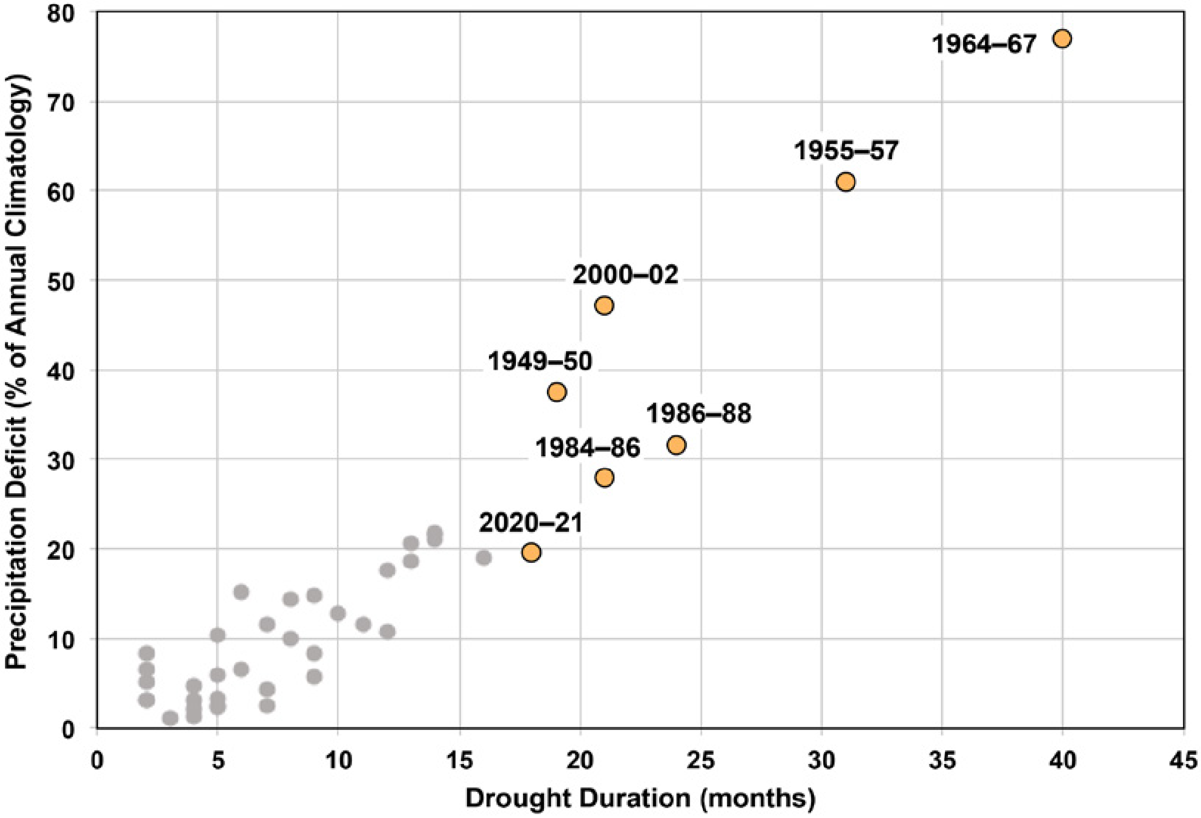


Figure 3. Record of statewide droughts 1948–2022 based on the 6-month Standardized Precipitation Index (SPI6), computed from monthly precipitation values averaged across Maine using the NOAA Unified Gauge-based Precipitation Analysis. Drought severity is measured by both drought duration (number of months SPI6 below 0) and associated cumulative precipitation deficit (sum of monthly precipitation departure from the mean over the course of the drought, displayed here as percentage of annual mean statewide precipitation). The several most significant events are labeled, including the recent 2020–21 drought, which ranks 7th in duration by this measure. Data source: https://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.CPC/.UNIFIED_PRCP/.GAUGE_BASED/.CONUS/.v1p0/#info

Impacts of Rising Temperatures

As temperatures rise, the warm season is getting longer as the winter season of snow and ice declines. The average warm season for the recent period 2010–2023 is about two weeks longer, and winters are about two weeks shorter, in comparison to a 1901–2000 historical climate baseline. Similarly, an analysis of statewide daily minimum temperature data found a 16-day increase in the average length of the growing season since 1950 (Fernandez et al., 2020). It is notable that warm season lengthening is skewed towards late summer and early fall, which may be associated with Arctic amplification and sea-ice decline (Screen & Simmonds, 2010).

The seasonal progression of temperature in Maine resembles a sine wave, where the coldest part of winter occurs in late January on average (about one month after the winter solstice), whereas peak summer temperatures tend to occur in late July (also lagging the solstice). (**Figure 4**). The threshold between melting and freezing – and accumulation of heat or cold – is inextricably linked to snow season duration, lake ice cover, phenology, and natural systems in general. The RCP (Representative Concentration Pathway) 8.5 projection in **Figure 4** shows additional relative change in season lengths of about two weeks by 2050. (RCP 8.5 is a high-end future greenhouse gas emissions scenario in which the climate is affected by an excess of 8.5 W/m^2 radiative forcing by the year 2100.) (See *Agriculture* for impacts linked to changes in the growing season.)

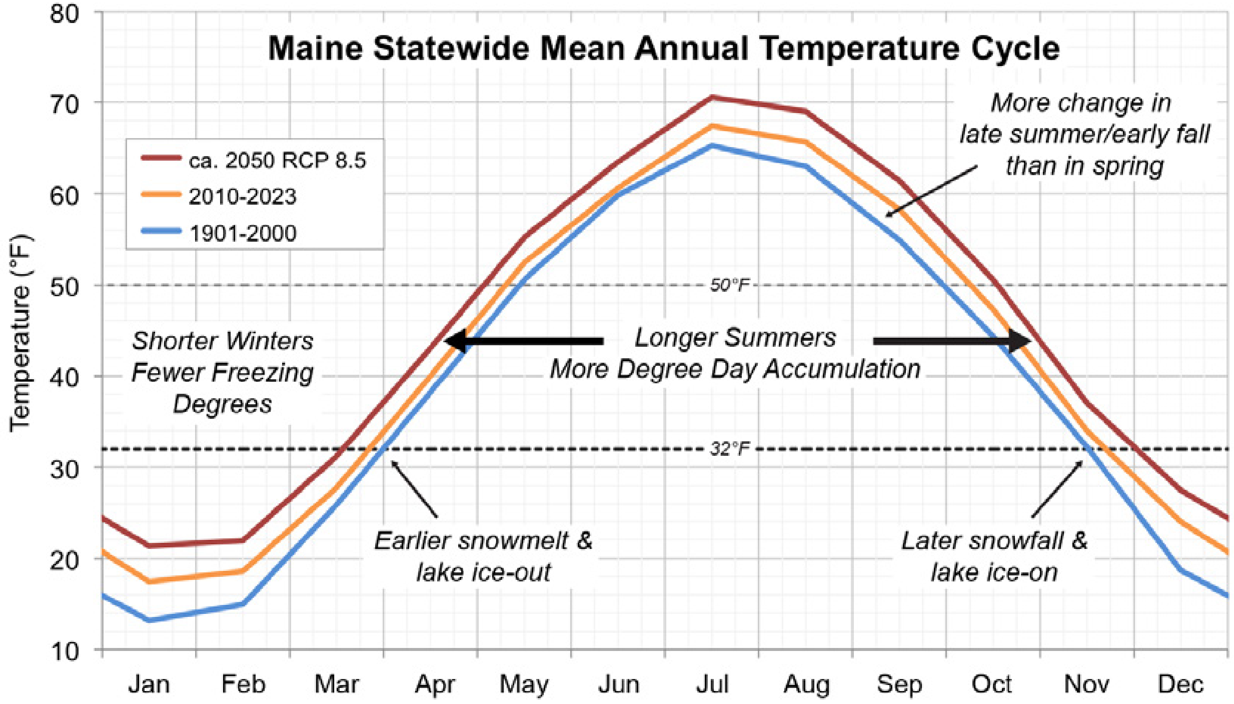


Figure 4. Maine statewide mean annual temperature cycle based on monthly climatologies for 1901–2000, 2010–2023 (from NCEI, 2024a), and 2041–2050 RCP 8.5. The RCP 8.5 projected temperature time series is from a multi-model ensemble mean of the Coupled Model Intercomparison Project version 5 (CMIP5) (Taylor et al. 2012), downloaded from the KNMI Climate Explorer (KNMI, 2024). Horizontal dashed lines marking freezing = 32°F (0°C) and growing season = 50°F (10°C) thresholds are marked for reference. This figure shows how warming drives changes in the relative length of the seasons by plotting monthly temperature means for different climate periods (e.g., 1901-2000) and comparing the resultant sine waves to a 32°F (0°C) datum.

Winter in particular has warmed 5°F (2.8°C) compared to a century ago and is the fastest warming season. Further evidence from Young & Young (2021), using data from the U.S. Historical Climatology Network, confirms that winter has experienced the most rapid rate of warming of all seasons, both in Maine and across New England, for both average and minimum winter temperatures. As highlighted in the Climate section of the 2020 STS report, shorter, warmer winters yield less snow, more rain, and earlier lake ice-out (MCC STS, 2020). These changes in turn impact plants, soils, surface and groundwaters. For example, increased winter rainfall, including rain-on-snow, can result in poorly quantified nutrient export from terrestrial to aquatic systems potentially masking the risk of pollutant runoff (Seybold et al., 2022). Changes in the snowpack can also impact the soil; data from a northern hardwood forest in New Hampshire demonstrated that reduced depth and duration of snow cover can result in lower soil moisture the following growing season (Wilson et al., 2020).

Under the highest warming scenario, only 15% of ski areas in the northeastern U.S. may be viable by the end of the century. A regional analysis by Burakowski et al. (2022) projected future trends of winter indicators across the northeastern US. These include fewer days above freezing: a 50-90% increase in days above freezing during December, January, and February, as well as the shoulder seasons in fall (October and November) and spring (March and April). The study also finds a shortened period of snow cover, where the current snow cover of 3 months will be reduced to 1.5 or 2.5 months under the future warming scenarios RCP 8.5 and 4.5, respectively. Moreover, fewer winter snowmaking days are projected: winter conditions amenable for snowmaking where the minimum temperature is less than 28.4°F (-2°C) are reduced from 2 months to 2-3 weeks by 2100 for winter recreation and tourism. Based on these estimates, the study finds that, even with improvements in snowmaking technology, only 15% of ski areas in the northeastern U.S. and Quebec may remain viable if there is significant warming using the higher warming scenario of RCP 8.5.

Record high global temperatures were set in 2023 by a large margin. Global mean sea surface temperature reached record highs in 2023 associated with the onset of a strong El Niño (Cheng et al., 2024). El Niño is the warm phase of the El Niño Southern Oscillation (ENSO), in which warmer-than-normal surface temperatures emerge across the equatorial Pacific in connection to changes in global weather patterns. (La Niña is the cool phase.) The 2023 El Niño began developing in spring, following a rare prolonged La Niña that persisted through three consecutive winter seasons. During the El Niño buildup in the Pacific, temperatures also increased over the North Atlantic, where record warm ocean waters facilitated an active hurricane season (Cheng et al., 2024). Global mean air temperatures reached record highs (C3S, 2023; NOAA, 2023a) **(Figure 5)**, most notably in July when values exceeded 1.5°C (2.7°F) above pre-industrial climatology, a key threshold identified by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2018). High global mean ocean and air temperatures persisted, and 2023 concluded with the ranking of warmest year for records beginning 1850 (Cheng et al., 2024; NASA, 2024a; NOAA, 2024; UKMet, 2024).

Even when factoring ENSO and the effects of increasing greenhouse gas emissions, global temperature estimates leading into 2023 failed to predict the exceptional observed warming of up to 0.2°C (3.6°F) beyond previous records (Schmidt, 2024). Possible contributing factors underlying this unexpected temperature jump include drastic sulfate aerosol reductions from new shipping regulations, an uptick in solar activity heading into a solar maximum, and possible impact from the January 2022 eruption Hunga Tonga-Hunga Ha'apai, which injected a large amount of water vapor into the stratosphere (Bao et al., 2022; Berkeley Earth, 2023; NASA, 2024b; Schmidt, 2024). However, the warming estimates for these contributors are exceedingly small, and thus this is a crucial knowledge gap that scientists must urgently address (Schmidt, 2024).

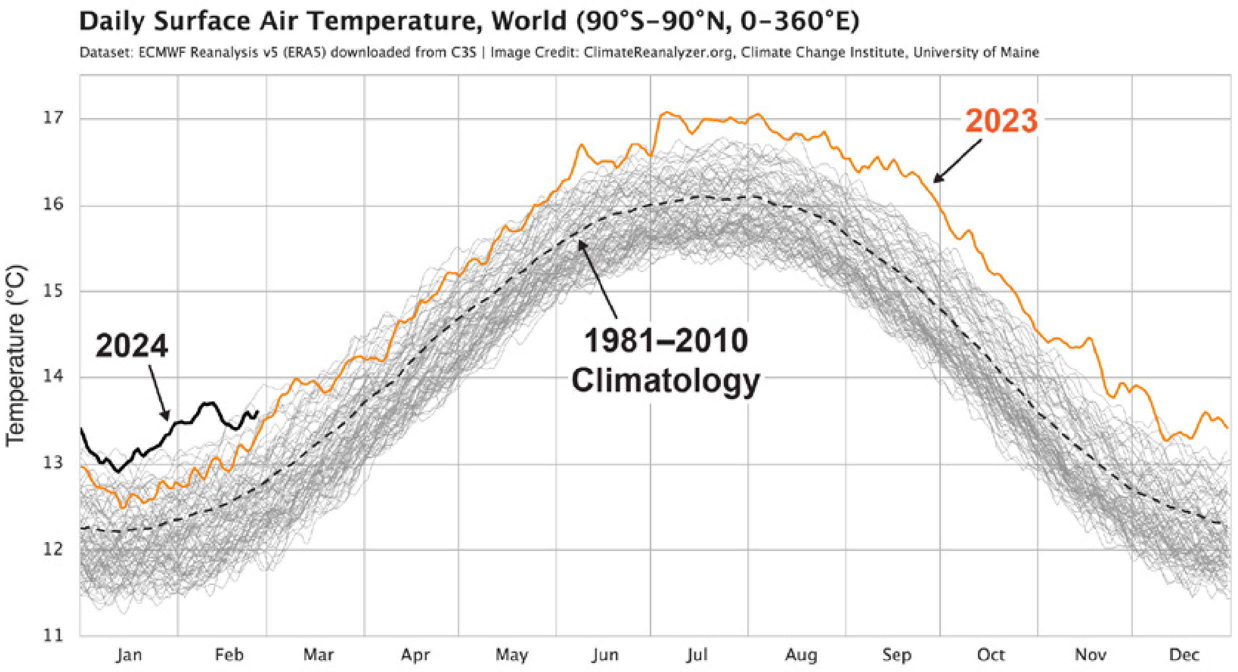


Figure 5. Global mean daily surface air temperature estimates from the ECMWF Reanalysis version 5 (ERA5) for the period January 1940 to late February 2024. Lines representing 2023, 2024, and 1981–2010 climatology are labeled. Chart from Climate Reanalyzer (2024) with data from C3S (2024).

A series of weather extremes in 2023 were documented worldwide and in Maine in association with the record high global temperatures (e.g., Di Capua & Rahmstorf, 2023; NCEI, 2024c; Ripple et al., 2023). Examples of these extremes in the U.S. included the record May heat wave across the Pacific Northwest (and western Canada) associated with an unusually strong warm-air ridge, a blocking pattern (persistent interruption of west-to-east atmospheric flow) (see Appendix B **Figure B1**), that facilitated early season wildfires. This anomalous atmospheric circulation in May also facilitated wildfires in Quebec, and in early June smoke from these fires was carried across Chicago and New York City, causing record low air quality (Thurston et al., 2023)

Heat extremes included the early heatwave and record July heat in Arizona and New Mexico; record high July overnight low temperatures in New England, and a record July marine heatwave off the coast of southern Florida. Precipitation extremes included a storm system that tracked over Vermont on July 10th and dumped a record 5.28 inches of rainfall in Montpelier, causing the worst flooding in the state since Hurricane Irene in 2011, and a historic flash flood July 18–19 in areas of Kentucky and Illinois from a storm that produced up to 12 inches of rainfall (NCEI, 2023a,b; NOAA, 2023b).

In addition to the 2nd warmest calendar year and 1st wettest summer (see *2020–2024 Temperature and Precipitation Rankings* callout box), Maine experienced a series of weather extremes in 2023 reflective of the anomalous conditions worldwide. In mid May, a deep cold trough developed downstream of anomalous ridging over western Canada (see Appendix B **Figure B1**), and on the morning of May 18th, a late-season freeze damaged some crops, including tree fruits, in Maine, New Hampshire, Vermont, and New York (NRCC, 2024a). Then between June 6th and 9th Maine received copious rainfall from a low pressure system stalled over New Brunswick; the counterclockwise circulation of this low pressure system transported smoke from the Quebec wildland fires into the Chicago and New

York City areas as noted above. In mid-September, southeastern Maine received over 3 inches of rain, and locally over 6 inches, associated with Post-Tropical Cyclone Lee, which tracked across the Bay of Fundy and southeastern New Brunswick (NRCC, 2024b).

An unusually active weather pattern developed in mid-December 2023 against the backdrop of record warm wintertime ocean temperatures in the North Atlantic, with the strong El Niño still influencing worldwide weather. On December 18, Maine was impacted by a major storm system that had traveled up the East Coast as a nor'easter, but then veered inland and tracked north across western New York and into Quebec (see *Anatomy of the December 18, 2023 Storm* callout box). This inland track produced strong southeasterly winds in Maine associated with counter-clockwise circulation around low pressure centered to the west. Gusts 50–70 mph were observed across much of the state, with the strongest winds focused across the southeast (**Figure 6**). Analysis from the National Weather Service shows an 81 mph gust recorded from a buoy in Eastport, and a 93 mph gust recorded by a trained spotter in Trescott (NWS, 2023a). These winds combined with heavy rainfall to produce widespread power outages and the worst flooding along the Androsoggin and Kennebec rivers in almost four decades (Lowell, 2023). While storm precipitation totals ranged 1–3 inches across most parts of the state, parts of southeastern and western Maine received 4–5 inches, and with some localized totals exceeding 6 inches.

Two storm systems, also tracking to our west across the Great Lakes region, impacted Maine shortly after the New Year on January 10 and 13 (**Figure 6**). These two storms, which caused compounded damages, hit coastal communities particularly hard as strong winds coincided with astronomical high tide to produce significant to record storm-surge flooding. Portland, for example, saw a high tide of 14.57 ft as a result of the most recent storm, breaking the previous record of 14.17 ft set in 1978. (see *Sea Level Rise, Coastal Storms* section for additional discussion on coastal drivers and impacts).

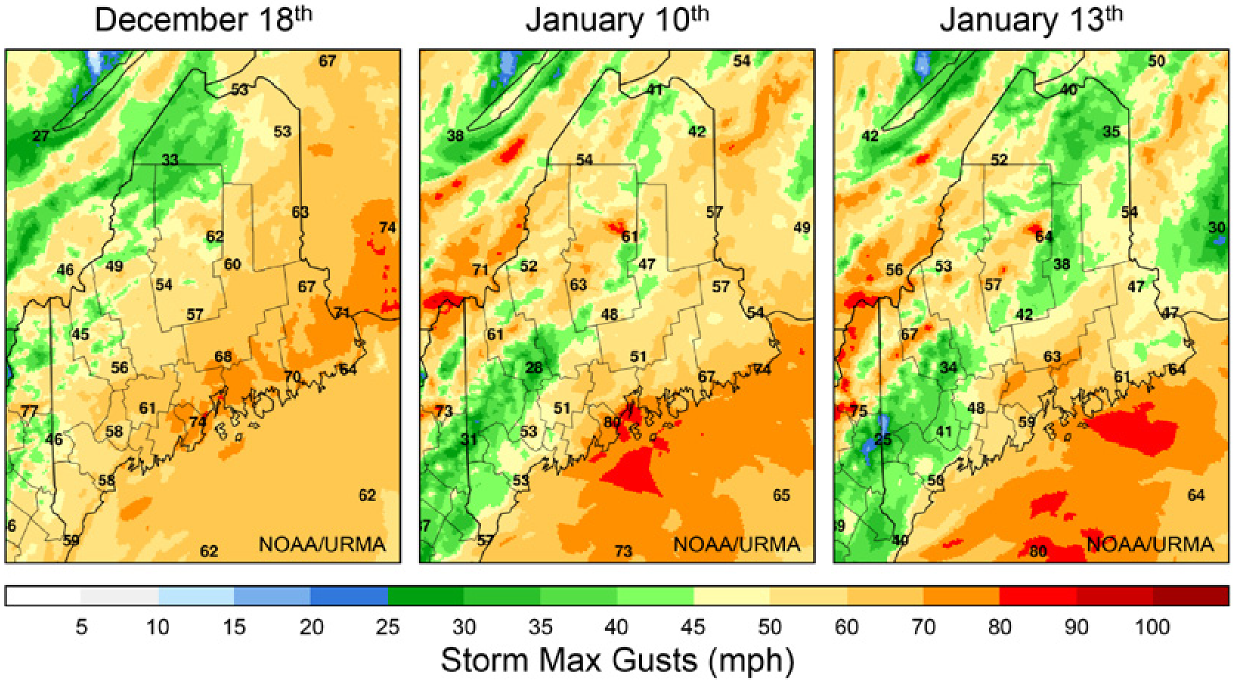
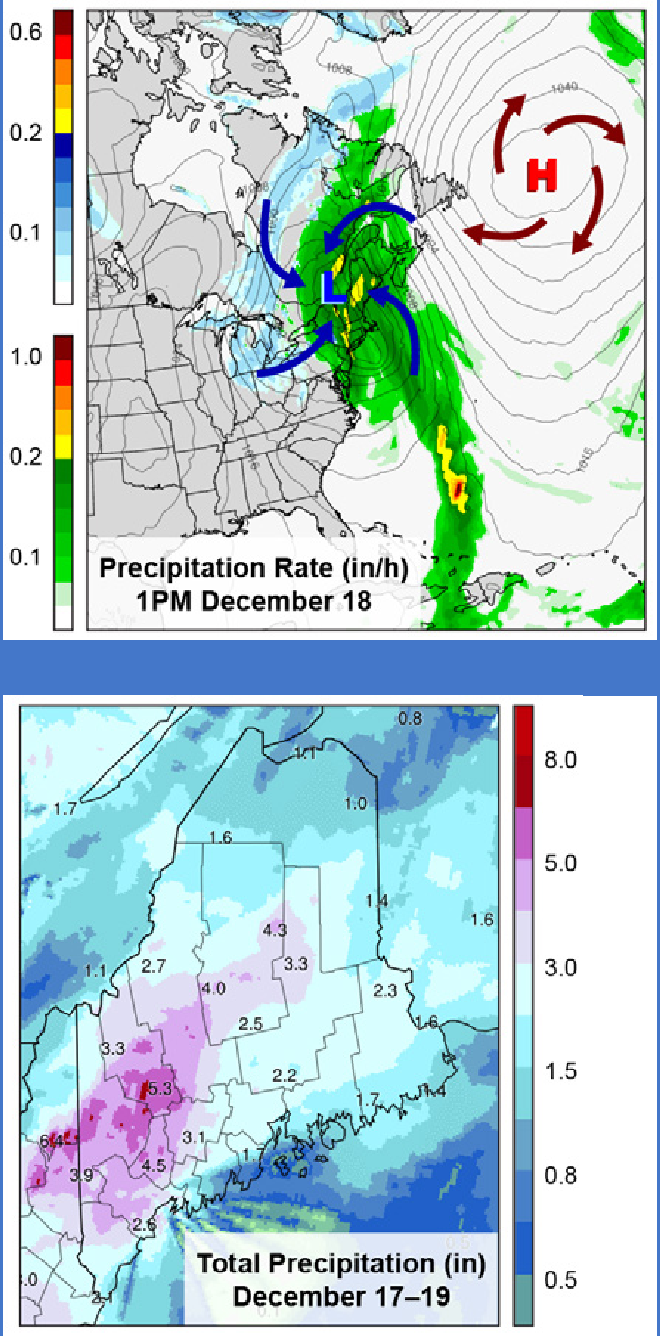


Figure 6. Estimated maximum wind gusts attained for recent major storms in December 2023 and January 2024, shown as color coded base maps with numerical max wind gusts for specific locations throughout Maine. Data source NOAA Un-Restricted Mesoscale Analysis (URMA). Map images from Climate Reanalyzer (2024).

Anatomy of the December 18, 2023 Storm

The December 18, 2023 storm caused significant flooding and wind damage across the state of Maine and triggered a disaster declaration in 10 counties. This weather event occurred in association with record warm ocean temperatures across the North Atlantic and a strong El Niño in the Pacific.

- The storm began as a low-pressure disturbance December 15–16 in the Gulf of Mexico, where it then passed northeast across Florida and began tracking up the East Coast as a strong extratropical cyclone, causing flooding and other damage in several states (NWS, 2023b; NYT, 2023).
- Although the storm first moved up the eastern seaboard as a nor'easter (bringing predominantly strong northeast winds along the coast), on the 18th the system tracked inland and northward across eastern New York and into Quebec, which produced strong southeast winds (blowing southeast to northwest) across Maine. This wind direction resulted from the counterclockwise circulation of low pressure centered west of the state (see figure).
- The northward track of the December 18 storm was influenced by a slow-moving high-pressure system southeast of Newfoundland. The steep gradient between the high- and low-pressure centers produced strong winds, and advected warm moisture-laden air from the subtropics that fueled heavy precipitation across Maine and New England. Some areas of the state experienced winds gusting near or above 50 mph for around 12 hours, with average wind speeds in the 20s and 30s.
- Nor'easters are cold-core extratropical cyclones that develop from instabilities arising between air masses of contrasting temperature and abetted by a strong jet stream (Davis and Dolan, 1993). Unlike tropical storms, which are fueled by warm sea surface temperatures, nor'easters intensify as jet stream winds remove mass from the storm center and cause pressure to drop.
- Strong extratropical cyclones most commonly form during the cold season, between November and April, when the equator-to-pole temperature gradient is steep and jet stream winds are strong. As discussed under *Projections*, most climate models project that warming will drive more intense extratropical cyclones, but there is significant uncertainty whether these storms will become more or less frequent.



Precipitation rate and mean sea level pressure (1PM December 18) from the NOAA Global Forecast System model (top) and total storm precipitation (December 17–19) from the NOAA UnRestricted Mesoscale Analysis (bottom). Low (L) and high (H) pressure centers are labeled in the top panel. The blue and red arrows are schematic depictions of counterclockwise airflow associated with low pressure and clockwise flow associated with high pressure. The northward storm track to the west of Maine produced southeasterly winds across the state. Images adapted from Climate Reanalyzer (2024).

Projections

Storms that originate in the mid latitudes ("extratropical cyclones") are projected to become more intense in a warming climate, but storm frequencies remain uncertain. The recent 'southeaster' storms in December 2023 and January 2024, in addition to major wind storms in fall 2017 and 2019 (Simonson et al., 2020), have generated significant concern for future extratropical storm trends. An unpublished preliminary study utilized wind data from the Portland Jetport and mean sea level pressure composite data to develop a climatology of southeaster storms 1950–early 2024 (personal communication, Derek Schroeter and Justin Arnott, National Weather Service, March 13, 2024). When including only low pressure systems tracking west of Maine, and filtering for sustained winds > 25 kts (29 mph) and directions between 100° and 170°, the analysis identified a total of 92 events without any clear trend in frequency over the study period. A broader reanalysis-based study of cold-season extratropical storm trends across North America found a slight decrease in cyclone formation across the U.S. East Coast for the period 1979–2019 (Fritzen et al., 2021). In a comprehensive review of available studies for the U.S. East Coast and western North Atlantic, Colle et al. (2015) found that most climate models produce more intense cyclones (lower central pressure and increased heavy precipitation), but with an overall decrease in the number of storms as the climate warms. The authors note large timescale variability. Despite most models showing decreased storm counts, there is significant uncertainty in these projections due to competing mechanisms: an expected decrease in low-level poleward temperature gradients (associated with Arctic warming) and steepened temperature gradients aloft (Meehl et al., 2007; Colle et al., 2015). A spread in North Atlantic storm track projections also adds uncertainty (e.g., Harvey et al., 2020). Additional research is needed to better constrain both historical and future projected trends.

RCPs and SSPs

Climate models use physics to simulate the interactions between the atmosphere, ocean, land, and sea ice. These models can be used to forecast, or project, future climate by calculating changes in global thermal balance resulting from human-sourced greenhouse-gas emissions, and natural factors such as large volcanic eruptions and solar variability. The World Climate Research Programme (WCRP) first developed modern climate models in 1990, and the Coupled Model Intercomparison Project (CMIP) sets standards and protocols for which input and output variables must be included (USDA Climate Hubs, n.d.). The CMIP models can run simulations under different input greenhouse gas emissions scenarios. The fifth phase of CMIP utilized Representative Concentration Pathways (RCPs), which define a range of plausible emissions trajectories based on estimates of future energy use and development worldwide. New models are developed as the understanding of climate processes improves. The latest and most widely utilized models are in the fifth and sixth phases of CMIP (CMIP5 and CMIP6).

Where do Shared Socioeconomic Pathways, or SSPs, come in? In CMIP6, SSPs were introduced and represent "changes in population, economic growth, education, urbanization, and the rate of technological development that would affect future greenhouse gas emissions, providing a storyline of how we could reach certain levels of warming" (USDA Climate Hubs, n.d.). While CMIPs outputs are based solely on GHG concentrations, SSPs incorporate anthropogenic drivers that determine the trajectory of GHG emissions in the future. RCPs give us the possible outcomes, and SSPs tell us how we get there (USDA Climate Hubs, n.d.).

The numbers associated with SSPs and RCPs represent the expected change in radiative forcing, or the net amount of energy that enters Earth from the sun minus energy that the Earth reflects, measured in watts per meter squared (W/m2), from the years 1750-2100: "8.5" would be an increase of 8.5 watts per square meter for that time period (USDA Climate Hubs, n.d.). CMIP5 used the scenarios of RCP2.6, RCP4.5, RCP6.0, and RCP8.5. CMIP6 developed five narratives known as SSP1 through SSP5. Further details of how these scenarios compare can be found here.

Future RCP temperature projections for Maine reported in the 2020 STS report remain valid. In the previous STS report, temperature projections from CMIP5 multi-model means based on RCPs 2.6, 4.5, and 8.5, representing best to worst case future greenhouse-gas emissions scenarios, were used to show the plausible range of future mean annual temperature (MCC STS, 2020, **Figure 9,** p. 30). CMIP6 model outputs are now available with simulations based on Shared Socioeconomic Pathways (SSPs), but it has been found that a subset of the models produce temperatures warmer than observations for the recent historical period (Hausfather et al., 2023), and thus unfiltered CMIP6 multi-model means also show more warming than CMIP5 for equivalent SSP/RCP scenarios (**Figure** 7). Many widely-used climate applications continue to use RCP-based future projections (e.g., the NOAA/USDA-funded Climate Toolbox, 2024). In all, the CMIP5 RCP-based mean annual temperature projections reported in the 2020 STS report, **2 to 4°F (1.1 to 2.2°C) by 2050 and up to 10°F (5.6°C) by 2100**, continue to represent a reasonable spread of physically plausible warming outcomes for Maine from the mean of the last 20 years to the end of this century.

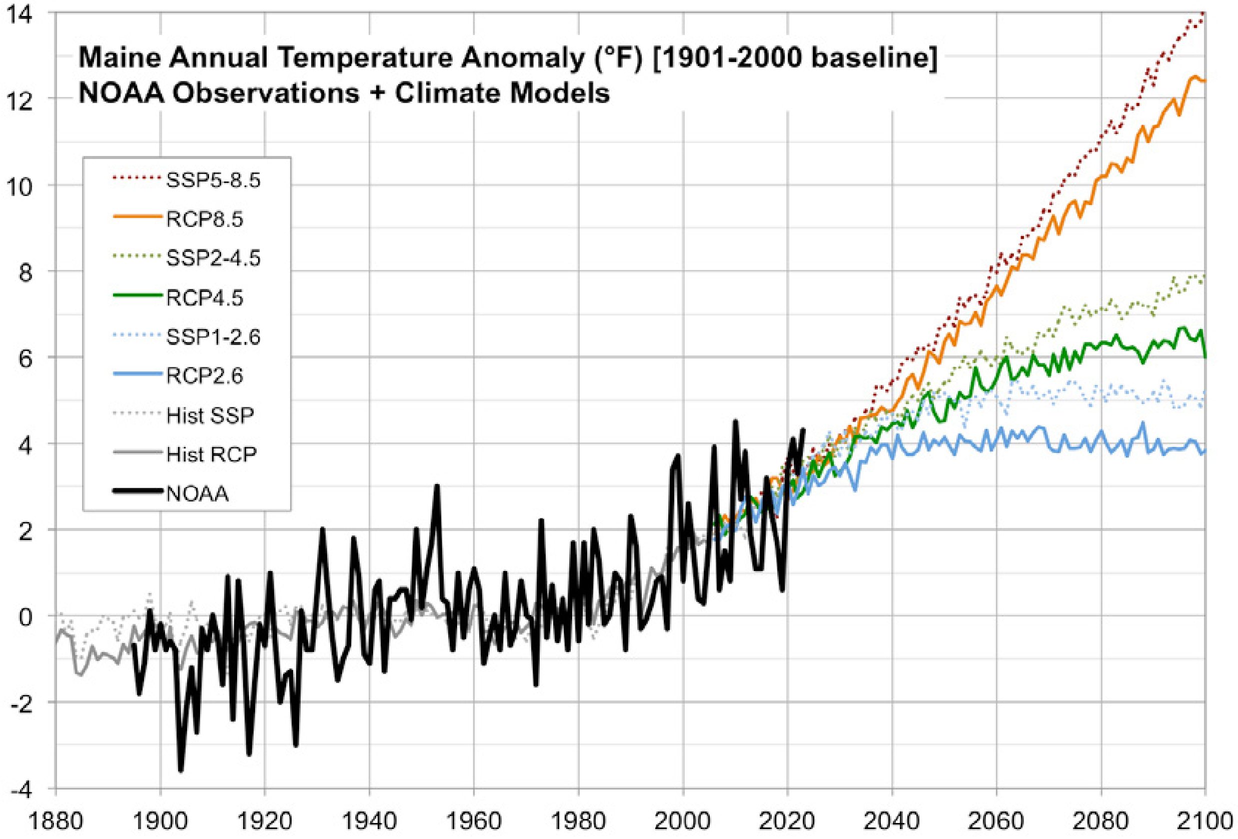


Figure 7. Maine annual temperature departure (anomaly) from 1901–2000 mean climatology observed 1895–2023 (black line) and projected to 2100 (colored lines; gray lines are historical runs) for a spread of future greenhouse gas emission scenarios. The projections include multi-model ensemble means derived from comparable CMIP5-based Representative Concentration Pathways (RCP) and CMIP6-based Shared Socioeconomic Pathways (SSP) future scenarios. Observations from NCEI (2024a). Model outputs for CMIP5 and CMIP6 from KNMI (2024).

Air Quality

While the focus in assessing the effects of climate change are on greenhouse gas concentrations in the atmosphere, the processes that increase greenhouse gas emissions often also increase other chemical pollutants that can have negative direct and interactive effects on humans and ecosystems. Appendix C provides a dashboard of patterns of air pollutant concentrations over time in Maine.

Climate change is making allergens like pollen in the air worse, and the trend is for this problem to continue to increase with a changing climate. "Aeroallergens" are small particles in the air that humans often have an allergic reaction to, with plant pollen being one of the most widely recognized and problematic allergens. Because they travel easily in the air, they are referred to as aeroallergens. A recent publication in the Proceedings of the National Academy of Sciences (Anderegg et al., 2021) highlighted that climate change is making the pollen season worse for humans and will likely get worse with time, further exacerbating respiratory health impacts.

Measuring aeroallergens in Maine

In response to the recommendations made in the 2020 STS report, Maine Center for Disease Control and Prevention (ME CDC) and Maine Department of Environmental Protection (ME DEP) have collaborated to significantly advance the State's ability to measure and report aeroallergens (fine particles in air that cause human allergic reactions) present in the ambient air. Five state-of-the-art technology continuous real-time pollen/aeroallergen samplers and two traditional manual samplers will be deployed early spring 2024 at four locations across the state. A website to support publicly reporting pollen count information from the network sites will be under development in spring 2024.

A manual Rotorod Sampler that samples for 24 hours with samples analyzed by microscopy and results available in days to weeks. An automated Pollen Sense Sampler runs continuously with data sent to the 'cloud' and analyzed by artificial intelligence producing data in minutes to hours. Photo credit: A. Johnson, Maine Department of Environmental Protection

Priority Information Needs

The top three information needs for climate that arose during this science assessment process were all projects with crosscutting support for the agricultural and forestry sectors. These top priority information needs include:

1. **Better understanding of the frequencies and trends of high-impact storm events in the historical record and improved future projections.** This would include historical analyses using weather station observations, gridded data, and reanalysis products, and including future projections based on historical trends, climate models, and plausible scenarios. Of particular use would be the events with high winds (e.g., > 50 mph) and heavy precipitation (e.g., > 3 inches per day or number of hours). This information has applications and uses across all sectors.

2. **Improved real time drought information.** This includes gathering existing data and conducting new monitoring for precipitation, streamflow, groundwater, soil moisture, snowpack/snow water equivalent and temperature. This monitoring project could run long term.

3. **Cloud cover and sunshine monitoring.** This would establish new observation stations or utilize existing observation stations for understanding changes in cloud cover and solar radiation in support of solar projects. This long-term project involving data analysis and monitoring would support agriculture and forestry, along with renewable energy electrification for the state.

A list of all of the priority information needs beyond those addressed here can be found in Report Appendix I.

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HUMAN DIMENSIONS

INTRODUCTION

The human dimensions of global change include human activities that alter our environment; the driving forces of those activities; the consequences of environmental change for economies; societies; livelihoods, and well being;, and human responses to global and local change (National Research Council, 1999). At the recommendation of the MCC Equity Subcommittee (2023), additional elements of human dimensions have been included in this 2024 STS update.

Given the enormity of the scope of human dimensions, the timeline of the STS report, and the expertise of the STS subcommittee, this section focuses on 1) the impacts of climate change on Maine's human systems (social, economic and health), and 2) specific areas of human adaptation, including resilience, knowledge, governance, engagement, and communication. The science in this section focuses on the human dimensions of climate change in Maine and New England, but some findings from additional locales are included given their relevance to human health and socio-economic systems in Maine. For a national perspective on the human dimensions of climate change, the 5th National Climate Assessment includes chapters on Human Health (Chapter 15), Indigenous Peoples (16), Complex Systems (18), Economics (19), Social Systems and Justice (20), Adaptation (31), and Mitigation (32) responses.

While the scope of this section was necessarily narrowed, delineating the differences between human drivers of climate change, impacts on human systems, and human responses (adaptation and mitigation) ignores important connections and synergies that inform how these topics integrate and depend on each other. Understanding all the human dimensions of climate change and how they interact is a monumental task that requires significant investment and transdisciplinary engagement that goes beyond the confines of science and academia. Including the knowledge, perspectives, and needs of local communities, Maine residents, and members of the Wabanaki Nations is important to ensure a representative account of the human dimensions of climate change in Maine.

Impacts on Human Systems

Human Health

Climate change currently affects human health and well-being across the globe, including in Maine, and is projected to have significant impacts in the future (e.g., Carlson 2023; Mbok et al., 2019). In addition, climate change is considered a threat magnifier that exacerbates the burdens of a broad range of diseases and other physical and mental health conditions. While some of these impacts have been documented in the scientific literature in Maine (e.g., Bonthius et al., in preparation; Wellenius et al., 2017), others have not, due to a variety of factors such as the translation of practitioner knowledge and data into publications. However, because the human health impacts of climate change-driven hazards can be similar across locations, studies done in populations elsewhere can help identify health risks in Maine. Ongoing epidemiological studies in Maine (e.g., Bonthius et al., in preparation), will better characterize Maine-specific risks and identify subpopulations that may face disproportionate health burdens.

Extreme Temperature and Weather

Maine is projected to experience more periods of extreme heat and Maine's population is likely to be vulnerable. Maine's climate is getting warmer and wetter and exhibiting more extremes. Given Maine's relatively cool climate and low rates of air conditioning in homes, schools, workplaces and residential facilities, Mainers are likely to be unacclimatized to extreme hot weather, and strategies for preventing heat-related illnesses will need to be developed or expanded (Ebi et al., 2021).

In Maine, certain groups experience higher rates of heat-related illness and may be at higher risk. Analyses of Maine emergency department visit data for heat-related illnesses suggest that men, middle-aged adults, and those who work outdoors or in hot environments experience higher rates of heat-related illness than other groups (Bonthius et al., in preparation; Maine CDC, n.d.a.). Maine CDC is also conducting research to better understand risk factors for heat-related illness among Mainers, and has identified several activities or situations that are associated with higher risk. In a study of emergency department visits to Maine hospitals from 2017 to 2021, visits due to a heat-related illness were almost eight times more likely to be work-related than were all-cause emergency department visits (Bonthius et al., in preparation). Other risk factors that were significantly associated with heat-related illness included outdoor home maintenance tasks like yard work and mowing; participation in outdoor exercise or sports; and homelessness or other housing insecurity (Bonthius et al., in preparation).

Evidence of the health consequences of exposure to extreme heat continues to expand, and periods of extreme hot weather have affected more areas of the U.S. in recent years with significant morbidity and mortality impacts. The physiological impacts of extreme heat, and in particular the physiological limits of heat tolerance, are becoming better documented through research conducted both nationally and globally (e.g., Vanos et al., 2023). Recent research has found that previous estimates of the maximum environmental heat that humans can tolerate, known as uncompensable heat stress and commonly estimated at a wet bulb temperature of 95°F (35°C) under standard hot and dry conditions, may be too high (Vanos et al., 2023). More complete modeling of heat stress in older and younger adults under a wider variety of environmental conditions suggests that exposure in direct sun or more humid conditions is more dangerous, and that for adults over 65, survivability thresholds in all conditions are significantly lower than for younger adults (Vanos et al., 2023). In addition, recent research in South Asia has also found that periods of uncompensable heat can occur later in the day, and under a wider variety of conditions, suggesting that populations in these areas are more exposed to dangerous heat than was previously thought (Justine et al., 2023).

Recent research provides additional evidence from international, national, and regional cohorts for the overall burden of heat-related morbidity and mortality (e.g.., Burkart et al., 2021), and for impacts of extreme heat of a variety of health outcomes such as adverse pregnancy, birth, and pediatric outcomes (e.g. Ebi et al., 2021; Qu et al., 2021; Syed et al., 2022; Uibel et al., 2022); kidney disease (e.g., Qu et al., 2023); diabetes (e.g., Tuholske et al., 2021); cardiovascular disease (e.g., Khatana et al., 2022); and adverse mental and behavioral health outcomes (e.g., Cloud et al., 2023; Ebi et al., 2021; Yoo et al., 2021). High heat stress can also reduce physical work capacity and motor-cognitive performances; almost half of the global population and more than one billion workers are exposed to high heat episodes and about a third of all exposed workers experience negative health effects (Ebi et al., 2021).

Record-setting heat and the human health toll

In 2021, much of the Pacific Northwest region of the U.S. and Canada experienced a record-setting heat event in early summer. The impact of extreme heat in these generally temperate areas was significant. For example, most households in greater Vancouver, B.C., do not have air conditioning, and the city saw a 440% increase in community deaths during the event (Henderson et al., 2022). The midwest, south, and southwest regions of the U.S. experienced similar extreme heat conditions in late August 2023, coinciding with the start of school in many regions and exposing hundreds of millions of residents to unsafe conditions (Knutson et al., 2023; NWS, 2023).

Even as heat risks increase, Maine experiences more cold-related illnesses, which may also be driven by climate change through extreme cold. Despite an overall warming climate and the increasing risks to health presented by more frequent and severe heat events, Mainers currently experience more cold-related illnesses than heat-related illnesses every year (Maine CDC, 2024b). In addition, although winters in Maine are likely to grow warmer on average (see Climate chapter), recent research shows that warming in arctic regions has contributed to episodes of stratospheric polar vortex disruption, and these episodes in turn can trigger periods of extreme cold weather in temperate latitudes (Cohen et al., 2021). This suggests that climate change has the potential to contribute to an increase in extreme cold weather events. However, given Mainers' relative adaptation to cold weather, and lack of adaptation to hot weather, health impacts of an increase in extreme heat may outpace health impacts of any increase in extreme cold. Research has consistently shown that impacts of heat in relatively cool climates are more significant than impacts of cold in those climates and vice versa (Anderson & Bell, 2009; Heutel et al., 2021).

Extreme weather events can have significant impacts on morbidity and mortality. Storm hazards can directly and indirectly impact human health. In Maine, the December 2023 storm resulted in severe flooding and widespread power outages and was associated with at least four confirmed deaths due to injuries and floodwater-associated drownings. A review of hospital discharge data for the week including and following the event showed multiple emergency department visits for storm-related health impacts such as injuries from the storm and associated clean-up; hypothermia; carbon monoxide poisoning following improper generator use; interrupted access to medication, medical devices, or medical care; and mental and behavioral health outcomes (Maine CDC, 2023, unpublished data). As the frequency and severity of such extreme weather events increase, associated morbidity and mortality are also likely to increase (USGCRP, 2016).

Mental Health

Adverse mental health impacts of climate change are well-documented and vary significantly depending upon exposure to climate stressors, underlying mental health conditions, access to emergency response and mental health services, and social support systems. Climate change affects mental health and well-being in two major ways: as a result of direct exposure to a climate hazard, often through the exacerbation of depressive or anxiety disorders or by inducing or worsening post-traumatic stress disorder (PTSD); and as an emotional reaction to the current and future threats posed by climate change. These emotional responses, including climate anxiety, may result in significant episodes of worry, anger, fear or grief, and they may also motivate people to take climate action (Hrabok et al., 2020).

Adverse mental health impacts of climate change can vary significantly depending upon severity of exposure to climate stressors, underlying burdens of adverse mental health conditions, quality of and access to emergency response and mental health services, and social and cultural support systems. In particular, exposure to extreme weather events, including severe storms, flooding events, and wildfires, is associated with an increase in anxiety, depression and PTSD (Hrabok et al., 2020).

Many people around the world, particularly young people, are significantly affected by climate anxiety and other adverse emotional responses to climate change (Hickman et al., 2021). A recent survey of Maine physicians revealed that many believe that climate change is worsening mental health and well-being among their patients (Carlson, 2023).

In Maine and around the world, populations that may be at particular risk for the mental health impacts of climate change are children and adolescents, women, and Indigenous peoples (e.g., White et al., 2023). Like other regions, Maine has a significant gap in available mental health services for those in need (Maine Shared CHNA, 2022). According to the World Health Organization (WHO), only 40% of people with depression are receiving mental health services, and on average, less than 2% of government spending on health targets mental health (WHO, 2021).

Diagnosable mental disorders, including anxiety and depression, are prevalent Maine, the U.S., and countries around the world (CDC, 2023). In 2020, the American Academy of Nursing issued a policy brief recommending specific actions "to reduce the psychiatric suffering exacerbated by climate change" (Liu et al., 2020, p. 519). These recommendations are relevant for Maine and include increasing funding for mental health research, prevention and care; increasing access to mental health services globally; promoting community-level mental health initiatives; and educating patients about the mental health risks of climate change and how they might prepare and protect themselves (Liu et al., 2020).

Vector-borne diseases and climate

Ticks

Shorter, milder winters and longer, warmer growing seasons are likely to support increasing abundance of blacklegged or deer ticks in northern Maine, and the establishment of lone star tick populations in southern and coastal Maine. Blacklegged or deer ticks (*Ixodes scapularis)* transmit the agents of Lyme disease, anaplasmosis, babesiosis, Powassan encephalitis virus, and relapsing fever. **Lyme disease incidence in Maine is consistently in the top five among U.S. states and has been increasing over time, in part reflecting range expansion of blacklegged ticks in Maine** (CDC, 2023a; Elias et al., 2020a; ME DHHS, n.d.). In all counties of Maine, including

Aroostook County, the blacklegged or deer tick is established (defined as six or more ticks of a single life stage or more than one life stage of the tick collected in the county within a 12-month period [CDC, 2023b]). However, the blacklegged tick is not yet abundant in northern Piscataquis and Penobscot Counties or in Aroostook County. Evidence shows that blacklegged tick populations have stabilized in the southern tier of Maine but have been increasing in the northern tier (Elias et al., 2021a).

A warming climate will support tick survival, but only where there is suitable habitat for ticks and hosts, such as deciduous/mixed forest juxtaposed with residential development, and abundant tick hosts such as white-tailed deer. In a spatiotemporal model of tick abundance versus deer and temperature and humidity in Maine, Elias et al. (2021b) found that 41% of the variance in tick abundance was attributable to white-tailed deer density and 33% to several climatological variables: summer relative humidity (18%), winter minimum temperature (12%), and degree-day accumulation (3%). The model predicted increased tick abundance with increasing temperature, but only where there were at least six white-tailed deer per square mile.

Interactions among climatological factors associated with climate change may offset one another with respect to their influences on tick behavior and survival. Overwintering ticks readily survive cold and varying winter temperatures in southern and northern Maine as long as there is adequate insulation in the form of snow and leaf litter (Linske et al., 2019; Volk et al.,2022). Where there is less ground insulation, temperature swings could cause decreased overwinter survival of blacklegged ticks (Schappach, 2022).

Lone star ticks are not established in Maine, but reports are increasing. The lone star tick (*Amblyomma americanum*) has "reported" status, in which fewer than six ticks of a single life stage are collected in a county within a 12-month period (CDC, 2023). Public submissions of specimens to the University of Maine Cooperative Extension Service Tick Lab appear to be increasing (five of ten specimens from five counties in 2019 versus 11 of 28 specimens from eight counties in 2022) (Dill et al., 2022). Lone star ticks can transmit the agents of diseases such as ehrlichiosis and tularemia, and can cause alpha-gal syndrome (red meat allergy), of which eight cases were reported in Maine in 2023.

Mosquitoes

Increased precipitation and longer growing seasons may prolong the active biting season of treehole mosquitoes (*Culiseta melanura*) that live in forested wetlands, which increases the potential for more outbreaks of eastern equine encephalitis virus (EEEV) in Maine. Mosquito-borne disease is still rare in Maine, with nine documented cases since 2014**.** However, in 2023 Maine underwent its second EEEV veterinary outbreak (horses and emus affected), which extended farther north (Penobscot and Piscataquis Counties) than did the first veterinary outbreak in 2009 (Waldo County). Maine has not yet experienced a human outbreak of EEEV, but there is concern that veterinary EEEV outbreaks could portend human outbreaks. A 2023 West Nile Virus (WNV) detection in a collection of another species of tree hole mosquito (*Culiseta morsitans)* in Penobscot County (Greenbush) was the northernmost detection of WNV in Maine to date. Additionally, 2023 was the first year in which EEEV, WNV, and Jamestown Canyon Virus (JCV) were reported in Maine mosquitoes within the same year. Schneider et al. (2022) described three human cases of JCV in Maine, one of which was fatal, and JCV detections in four mosquito species in Maine.

Climate and increasing EEEV risk

Maine's first documented veterinary outbreak of EEEV (eastern equine encephalitis virus) was in 2009; a record spike in the primary EEEV vector *Cs. melanura* (tree hole mosquito) followed record summer precipitation in 2009 (Lubelczyk et al., 2013). The northern extent of the 2009 EEEV outbreak was Waldo County. Maine underwent its second veterinary EEEV outbreak in 2023 with 12 emus and four horses testing positive, following another summer of record precipitation, surpassing 2009's record. Data from 2023 statewide mosquito surveillance indicate record high mosquito counts across multiple species including the primary EEEV vector *Cs. melanura*. Compared to 2009, the 2023 outbreak extended farther north to towns in Penobscot and Piscataquis Counties. Nine mosquito pools tested positive for EEEV, including pools from towns in Penobscot County for the first time. Mutebi et al. (2021) confirmed statewide (and New England-wide) distribution of EEEV antibody detection in deer and moose.

Maine has relied on hard frosts in October to end the mosquito season, but climate change in Maine has manifested as earlier degree-day accumulation, more extreme rain events in spring and summer, and extended frost-free falls (Birkel & Mayewski, 2018; Elias et al., 2021a; Fernandez et al., 2020; Simonson et al., 2022). In 2009, the first hard fall frost in Portland was October 17th; in 2023 it was November 2nd (see also Climate chapter **Figure 4**). Taken together, these climatic conditions may promote EEEV amplification within mosquitoes and increase transmission from mosquitoes across the summer, leading to late season outbreaks. EEEV is present in Maine, but the exact conditions that lead to viral amplification and outbreaks in specific locations are not well understood. In the event that Maine experiences its first human arboviral outbreak, Maine statutes §171 and §1447 provide Maine DHHS authority to declare a public health threat.

Air Quality and Wildfire Smoke

Although large-scale wildfires have been more common in the Western U.S. and Canada than in the Northeast in recent decades, wildfire smoke can be transported to the East Coast and cause significant exposures and associated health outcomes. Extreme wildfire smoke exposures in the eastern U.S. in summer 2023, due primarily to Canadian wildfires, revealed the importance of monitoring wildfire smoke pollutants in Maine, predicting and measuring for human health impacts of short-term (and possibly long-term) exposures, and developing programs to communicate these risks and mitigate harmful exposures. A 2021 study reported that although the majority of large landscape fires occur in the western U.S., the majority of mortality (74%) and asthma morbidity (on average 75% between 2006–2018) attributable to particulate matter (PM2.5) from wildfire smoke occurred in the Eastern U.S., due to higher population density in that region (O'Dell et al., 2021). Maine CDC is working with the Maine Department of Environmental Protection (ME DEP) to develop a data dashboard to display near real-time air quality data, wildfire smoke plume maps, and real-time emergency department visits for respiratory conditions, expected to be available in summer 2024.

Food Security and Water Supply

Globally, the climate crisis is one of the leading causes of hunger. Hunger and food insecurity are rising globally, and increases have been attributed primarily to climate change, conflict, rising food costs, and the Covid-19 pandemic (WFP, 2023). According to the World Food Programme (WFP) in 2023, "the climate crisis is one of the leading causes of the steep rise in global hunger. Climate shocks destroy lives, crops and livelihoods, and undermine people's ability to feed themselves. Hunger will spiral out of control if the world fails to take immediate climate action" (WFP, 2023).

Food insecurity affects ten percent of Maine's population, and is exacerbated by high prices driven in part by climate change. Food security is the access to safe, sufficient, and nutritious food to meet the dietary needs and preferences for a healthy and active life for all people (FAO, 2001). Access includes social, physical, economic aspects of obtaining food, and is increasingly acknowledged to include multi-generational sustainability (Mbow et al., 2019). Food insecurity in the U.S. and in Maine increased during the Covid-19 pandemic, and remains elevated relative to prior years (USDA ERS, 2024). According to the USDA Economic Research Service (ERS), the average level of food insecurity in Maine from 2020-22 was 10.1% of the population (approximately 144,000 people) (USDA ERS, 2024). Maine food insecurity varies from a low of 8.2% of the population in Cumberland County to a high of 15.1% in Washington County (Hake et al., 2023). In the U.S. and in Maine, food insecurity varies by household income level, race/ethnicity, household composition, education level, and urban/suburban/rural areas (USDA ERS, 2024). Food insecurity can be exacerbated by weather-related price shocks that can lead to rapid food price inflation, which affects the most economically disadvantaged, who then choose lower quality foods and lesser quantities (Bailey et al., 2015).

Indigenous food supplies are threatened by climate change in Maine and can be addressed through preserving food systems and food sovereignty. "There's no universal definition for food sovereignty, but it can be described as the ability of communities to determine the quantity and quality of the food that they consume by controlling how their food is produced and distributed. Food sovereignty initiatives like farm-to-table and farm-to-school programs are important for the long-term health, economic stability, and cultural preservation of American Indian and Alaska Native (AI/AN) communities" (BIA, n.d., paragraph 1.) Many factors, including climate change, threaten Indigenous food supplies, including traditional foods, hunting and fishing, which often have significant physical and mental health impacts on tribal members. Combined with an inability to self-determine traditional food systems, tribes have been prevented from building mechanisms for social-ecological resiliency amid environmental challenges (Michelle, 2021).

Climate linkages with Maine's Roadmap to End Hunger

Maine's Roadmap to End Hunger by 2030 highlights the linkages between resource inequality and hunger, and addresses the cultural and economic forces that entrench and stigmatize hunger (ME DACF, 2019). These cultural and economic forces, such as low wages and high cost of living, influence climate vulnerability and resilience in Maine and globally (Maine Equity Subcommittee, 2023; Mbow et al., 2019). Maine's Roadmap to End Hunger by 2030 notes that there is a spending gap for food budgets for food-insecure households of over $100 million, and if this gap is not filled, the state will face over $700 million in human costs, including those associated with preventable health conditions, special education services, and lost productivity (Mbow et al., 2019). The Roadmap report cites goals to "ensure consistent, easy, and equitable access to healthy and culturally appropriate food" (p. 15), and "promote, bolster, and enable economic security and opportunity for all Maine households" (p. 18), among other goals, which would simultaneously support climate resilience (Mbow et al., 2019).

Drinking Water and Water-related Illnesses

Drinking water quality is vulnerable to the impacts of climate change, especially from flooding or periods of drought. Recent national and international research has shown that extreme precipitation events are associated with outbreaks of gastrointestinal disease due to bacteria washed into drinking water source bodies (DeRoos et al., 2020; Ethan et al., 2024); and has shown that increasing heat and atmospheric carbon dioxide are associated with more frequent and intense harmful algal blooms (HABs) and generally decreased surface water quality (Li et al., 2023; Visser et al., 2016; Wang et al., 2020). Recent news coverage in Maine confirms the local relevance of these issues, as outlets reported how heavy precipitation from recent storms has caused concern around wastewater discharges and drinking water quality (Overton, 2024), and how climate change is negatively impacting water quality in Lake Auburn, which provides drinking water to Lewiston and Auburn (Wight, 2023).

In addition, to the extent that Maine experiences future periods of drought, the approximately 50% of Mainers who get their drinking water from private wells (Gordon et al., 2021) may experience negative impacts, including dry wells and changes to water quality. A 2021 USGS study modeled drought conditions across the U.S. and in Maine, and found that increasing drought severity and duration was associated with a higher proportion of the population exposed to levels of arsenic in groundwater that exceed health guidelines (Lombard et al., 2021). In addition, a recent study of drinking water quality in Barcelona, Spain, showed that drought conditions and extreme precipitation conditions can both impact source water quality, concentrating heavy metals in water during periods of drought, and increasing turbidity and other markers of poor water quality during periods of heavy rainfall (Benitez-Cano et al., 2024). Drought conditions combined with ongoing sea level rise can also cause saltwater to move into coastal freshwater aquifers, a process known as saltwater intrusion, which can significantly impact the quality and quantity of available drinking water in coastal areas (USGCRP, 2016).

In addition to impacts on freshwater resources, climate change can modify saltwater quality through warming temperatures and decreased salinity due to increased infusion of freshwater from extreme precipitation. These conditions can trigger the growth of harmful pathogens in ocean waters, such as *Vibrio* bacteria that can contaminate shellfish and lead to foodborne illnesses or cause a direct infection through contact with an open wound (USGCRP, 2016). Recent research in Maryland found an almost 40% increase in incidence of *Vibrio* infections between 2006 and 2019 (Morgado et al., 2024), and a predictive modeling study found that under medium-to-high future emissions scenarios, *Vibrio* wound infections may almost double by the end of the century, impacting the East Coast and putting an additional 15 million people at risk of infection (Archer et al., 2023).

Health Sector Communication Systems: Learning from Covid-19

The Covid-19 pandemic highlighted ways in which Maine municipalities can augment resilience through communication systems. Different digital platforms used to communicate with residents through the early stages of the pandemic highlight opportunities for expanding information and communication systems (Levesque et al., 2021). Expanding community digital information and communication systems may require continued investments to address issues of equity through the expansion of broadband access as well as building the human and digital capacity of smaller communities to support platforms and technologies that engage and inform citizens. These systems can be leveraged for use during climate and weather emergencies as a means to build community resilience (Levesque et al., 2021; Levesque et al., 2023).

IMPACTS ON ECONOMIC SYSTEMS

In 2024, Maine will see the second largest home insurance rate increase in the country. Despite annual average rates that are lower than the national average, Maine will see one of the largest jumps following impacts of 2023 weather, sea level rise, and severe storms: over a quarter of homeowners will see increased rates for 2024 (Insurify, 2023). Rates are additionally influenced by the rising cost of building repair (Insurify, 2023). The Climate Check website offers a snapshot of individual and combined risk to properties from storms, heat, fire, drought and flood.

Climate change is affecting the economy directly. Climate change directly impacts the economy, from finance to real estate, through increases in temperature, rising sea levels, and more frequent/intense weather-related extreme events (e.g., wildfires, floods, hurricanes and drought), which generate substantial economic costs in many sectors (Hsiang et al., 2023; Weinstock 2022). Research finds that "summer temperatures have significant and systematic effects on the U.S. economy, both at the aggregate level and across a wide cross section of economic sectors. A 1°F (0.56°C) increase in the average summer temperature is associated with a reduction in the annual economic growth rate of state-level output of 0.15–0.25 percentage points" (Colacito et al., 2019).

Markets are beginning to respond to climate change. Markets, including insurance and stock markets, are beginning to respond to current and anticipated climate changes, and stronger market responses are expected as climate change progresses (Brunetti et al., 2021;, Hsiang et al., 2023). While the U.S. (re)insurance market has used catastrophe "cat" modeling to avoid underestimating risk, their use in standard economic processes has instigated larger political debates about how risks should be allocated across stakeholders (Gray, 2021).

Climate change has increased global economic inequity. Research that quantifies the influence of climate on economic trends finds that, even as economic disparity between countries has decreased in the last half century, climate change has likely increased the inequality between the lowest and highest GDP countries by 25% (Diffenbaugh & Burke, 2019). The research suggests that climate change will "generally increase economic growth in cool countries [high latitudes] and decrease economic growth in warm countries [low latitudes]" with within-country impacts presenting a continued challenge to researchers, largely from lack of available socioeconomic data (Diffenbaugh & Burke, 2019, p. 9809).

Economic opportunities for households, businesses, governments and institutions will change. Climate change is projected to impose a variety of new or higher costs on firms and households and to impact employment, income, and quality of life, while at the same time providing new opportunities (Hsiang et al., 2023). Civic institutions and governments are expected to see existing programs used more intensively or in new ways as populations cope with climate change. Design, evaluation, and deployment of adaptation technologies and policies could strengthen Maine's ability to adapt to climate change (Hsiang et al., 2023; Martinich et al., 2019).

Comprehensive evidence implies the social cost of carbon (CO_2) should be higher. The social cost of CO_2 measures the monetized value of the damages to society caused by an incremental metric tonne of CO_2 emissions, balancing the cost of reducing emissions with the benefits of reducing damages (Nordhaus, 2007), and is a key metric informing climate policy. New estimates of the social cost of carbon are substantially higher than previously estimated at $185 per tonne of CO_2 ($44–$413 per tCO_2: 5%–95% range, 2020 US dollars) at a near-term risk-free discount rate of 2% (Rennert et al., 2022).

Updated Federal Guidance on Benefit-Cost Analysis accounts for ecosystem services and addresses benefits and costs that cannot be monetized. Benefit-cost analyses (BCAs) are the standard economic analysis used for comparing investments in infrastructure across U.S. federal agencies and awarding funding, from the Department of Transportation (DOT) to the Federal Emergency Management Agency (FEMA). Using consistent rules across different sectors (housing, transportation, energy, marine, and so forth) is essential to accurately compare quantified and non-quantified impacts from GHG mitigation and climate adaptation. The White House has issued updated guidance (Circular A-4 and A-94) on how to conduct benefit-cost analysis for analyses of regulations and projects (Office of Management and Budget [OMB] 2023a; OMB 2023b). They include specifics about the environment, new guidance on distributional analyses, and a 2% discount rate. There is guidance on accounting for ecosystem services in benefit-cost analysis and how to account for benefits and costs that cannot be quantified.

Tourism

Climate change impacts tourism, since both the supply and demand of tourism services depend on the quality and management of the given resources, particularly the complex relationship between climate hazards, risks, tourism demand and tourism experience (Arabadzhyan et al., 2020). How climate change interacts with Maine's tourism sectors is not currently well understood. In 2022, tourists spent more than $8.6 billion in Maine. As one of the state's largest industries, tourism supported 151,000 jobs and contributed nearly $5.6 billion in earnings to Maine's households (Maine Office of Tourism, 2022). In the Maine's Climate Future Report (Jacobson et al., 2009), researchers recognized that "Maine's growing tourism economy, which relies heavily on outdoor activities, must prepare for shorter ice-fishing, skating, skiing, and snowmobiling seasons, while simultaneously anticipating more visitors during longer "shoulder" seasons in spring and fall. Tourism attractions and activities associated with our cultural and natural heritage may be diminished by the potential loss of moose, trout, and brown ash trees from certain areas of the state" (p. 50).

A global review of peer-reviewed literature on coastal and marine tourism found the impacts of climate change focused on the diminished tourist experience based on environmental change, shrinking beaches, increased danger from forest fires, species loss and invasives; loss of comfort from increased heat and pests; increased damage to infrastructure and facilities; and tourism's contribution to the loss of cultural heritage (Arabadzhyan et al., 2020). Most research on tourism and climate focused on the demand side experience, and minimal research focused on the interplay of tourism, infectious disease and climate, or on the loss of cultural heritage on the destination's image (Arabadzhyan et al., 2020).

In tourism, risk perceptions do not necessarily translate into behavioral outcomes. Research in Maine has begun to look at what factors may shape visitor perceptions of risk. In particular, Acadia National Park has been a site for gathering and evaluating visitor perceptions. De Urioste-Stone et al. (2016) found that visitors to Acadia National Park perceived the area to be vulnerable to climate change effects that are likely to impact the natural environment and infrastructure. Whether or not a person would be influenced to alter their travel decisions was based on their evaluation of risk around potential impacts. Horne et al. (2021) found that understanding how visitors process climate change risks can help managers understand how to effectively communicate changes that might impact visitor experiences.

IMPACTS ON SOCIAL SYSTEMS

Social, natural and climate systems are interconnected. Increasingly science recognizes strong interactions and interdependencies between social, natural, and climate systems. The vulnerability of human and ecological systems are interdependent. These connections necessitate that we improve understanding of climate impacts and solutions that engage across socio-natural systems (Pörtner et al., 2022).

Cultural identities are at risk, and intangible resources that are connected to well-being can be impossible to replace once lost. Projections of climate impacts often focus on ecosystems, physical infrastructure or economic prosperity; less often considered is loss of cultural identity, belonging and heritage (Adger et al., 2013). These intangible resources, often linked to community belonging and place attachment, can be taken for granted but are deeply connected to well-being (Comtesse et al., 2021; Peterson & Maldonado, 2016; Sesana et al., 2021) and are difficult or impossible to replace once lost, as their value is incommensurable (Barnett et al., 2016).

Mainers experience differential levels of vulnerability. Climate vulnerabilities are a function of exposure to climate risks, sensitivity to that risk, social vulnerabilities and adaptive capacity. The Maine Climate Council (MCC) Equity Subcommittee report (2023) describes vulnerable populations as "those counties and communities in the State containing populations that are disproportionately burdened by existing social inequities or lack the capacity to withstand new or worsening burdens" (p.41). Vulnerabilities may be experienced at an individual or household level and associated with sociodemographics (age, health, race, employment status, proficiency with English), community composition, governance systems, or economic sensitivity to climate change (low-income and rural communities, communities with low levels of governance capacity, tribal and indigenous communities, communities with economic sectors sensitive to climate change) (Adger, 2006; Maine Equity Subcommittee, 2023; Pörtner et al., 2022). In Maine, the Equity Subcommittee observed vulnerable communities that, "due to systemic and structural disadvantages, have limited resources and capacity [to] respond to these natural hazards" (Maine Equity Subcommittee, 2023, p.67).

Inquiry Paradigms: How Worldviews Interact with Climate Research

Researchers from different fields of inquiry approach the study of impacts, adaptation and resilience with separate worldviews and different practices. For example, how an anthropologist perceives and studies the world is different from how an economist or a biologist thinks about and knows the world, although all are included under scientific inquiry. Given historical debate around which paradigms hold power and legitimacy in academic and policy spaces, attention to paradigmatic differences can support transparency and space for equity (Lincoln et al., 2018). "In practice, this means that some perspectives and worldviews, such as those associated with "objective science," have been privileged over others perspectives, such as viewpoints that recognize the inherent biases in all research, or those associated with Indigenous Research Methods." Attention to underlying difference in perspective can illuminate potential barriers in climate adaptation processes, including (lack of) detection that a problem exists; examining who has the control of a climate response process; and varying intent, resistance, (mis)aligned knowledge, lack of or unaccessed skill, and access to resources during implementation of a planning process (Moser & Ekstom, 2010; Reilly-Moman, 2021).

Climate-vulnerable communities in Maine come from across the state, including economies tied to climate-sensitive resources. Examples include communities whose economies are particularly sensitive to climatic change; for example, those with a large, independently owned and operated lobster fishing fleet (Le Bris et al., 2018). These communities are closely linked to their local and regional social-ecological systems, which includes a working waterfront culture and supports multiple generations of owner-operator fisheries entrepreneurs, their families and communities (Coombs, 2020). At the same time, their economic sensitivity to a rapidly warming and increasingly acidic gulf of Maine has made them uniquely vulnerable (see Marine Ecosystems chapter). Other examples of vulnerability linked to economic sensitivity include independent farms and dairies that provide the foundation of community engagement in food production and community events such as farmers' markets and fairs.

Rural communities are often particularly vulnerable. Many Maine communities are small and rural, with a strong dependence on natural resources sensitive to climatic change. In these small communities, local governments are challenged by constrained financial and human resources (Cucuzza et al., 2019). As such, rural communities may have lower levels of adaptive capacity to plan for and respond to climate-related natural disasters (Levesque et al., 2021).

A cultural dependence on natural resources and systems, from strawberries to fishing, makes Wabanaki citizens particularly vulnerable and uniquely resilient to climate change, as cultural traditions help to process change (Daigle et al., 2019). In addition to research showing the effectiveness of storytelling to understand the culturally-inseparable social and ecological impacts of climate change, Wabanaki Tribal Nations, who will face disproportionate impacts, are building a regional tribal network and workbook for climate change adaptation and adaptive management (Ranco, personal correspondence, October 2023).

Older, isolated and lower-income residents may experience more harm from climate impacts such as power outages and flooding. Maine's experience of certain impacts, such as extended power outages as occurred following the December 18, 2023 storm, may result in enhanced risk or harm to isolated, older residents and residents dependent upon medical equipment (Ganz et al., 2023). Research on manufactured housing communities shows that while these communities provide important housing affordability options they may pose challenges due to the heightened social vulnerability of residents and ownership structures which might impact residents' ability to address and manage the impacts of extreme storm events (Lamb et al., 2023). Research on the impact of flood events

Shell Middens and Climate Change

Shell middens, composed of shells, faunal, and botanical remains on the coast, provide a historical and cultural archive of Indigenous people in Maine over thousands of years of coastal occupation, and are threatened by erosion from sea level rise and increased freeze/thaw activity (Maine Midden Minders, n.d.). Oyster middens in Maine record harvests back at least 2,200 years during a period of relatively slow sea level rise (Reeder-Myers et al., 2022).Virtually all of Maine's 2,000 documented middens are eroding (Maine Midden Minders, n.d.). Thus in addition to threats Indigenous communities face from economic and political inequalities and the residual impacts of colonization, climate change alters familiar landscapes and impacts heritage spaces such as shell middens (Newsom et al., 2023). In a larger context, climate change threatens widespread loss of cultural resources and scientific knowledge (Society for American Archaeology, 2022). In Maine, service-based approaches to research demonstrate how archaeology can support descendant communities to address present day challenges, drawing together language preservation and addressing and mitigating the cultural loss from eroding shell middens (Maine Midden Minders, n.d.).

in other states highlights the potential risks that exist for mobile home park residents (Baker et al. 2024; Rumbach et al., 2020). Although rural communities are heterogeneous, research indicates that, on average, rural communities face risks from flood events to a greater extent than urban communities (Rhubart & Sun, 2021).

Vulnerability can be reduced through the participation and engagement of potentially impacted people. Research suggests that climate vulnerability and risk can be reduced through interventions that carefully target inequities through collaboration, stakeholder engagement, co-learning, and participatory processes that incorporate the perspectives and needs of the most vulnerable communities (Pörtner et al., 2022). Research in Maine suggests that governmental representatives do not share common understandings of social impacts and climate vulnerabilities (Cucuzza et al., 2019; Johnson et al., 2019.) As such, many communities could benefit from capacity building in assessing community vulnerability and in the importance of creating opportunities for community involvement in these assessments (Johnson et al., 2019).

Climate Adaptation and Resilience

Scientists and practitioners have identified conditions that enable successful adaptation to climate change. The Intergovernmental Panel on Climate Change's sixth assessment report synthesizes valuable scientific insights in adaptation science, generated around the world, including here in Maine (see Pörtner et al., 2022). Enablers of successful adaptation include information about climate impacts and potential solutions, political commitments and follow through, the institutionalization of frameworks for climate planning, policies with clear goals, adequate financial resources and processes for inclusive governance (Peterson & Maldonado, 2016; Pörtner et al., 2022; Reilly-Moman et al., 2023).

Resilience

Resilience encompasses multiple simultaneous meanings in climate impacts and responses, often drawing from narratives that are value- and place-based (Soden et al., 2015). Resilience can be defined as the ability of a system to cope, adapt, and possibly transform (Walker & Salt, 2012; Folke, 2016; Galappaththi et al., 2019), but the theory and practice of resilience has its own discourse that shapes and constrains itself: common definitions may obscure complex social issues, especially those rooted in ecological processes (Glandon, 2015; McGreavy, 2016; Russill, 2008). Consequently, defining resilience has moved towards addressing systemic and root causes of vulnerability to climate stressors (Center for Resilient Cities and Landscapes, 2020). While resilience has often been described as the ability to "bounce back," critiques of this framing point to important questions of 'for whom, and at what cost to whom else?' (Cote & Nightingale, 2012; Maine Equity Subcommittee, 2023). The many meanings of resilience may create contradictory framings, but this discourages oversimplification and presents opportunities for co-producing the multiple processes and metrics of measurement (i.e., Norström et al., 2020; Soden et al., 2015).

Community and social capital is particularly important for building resilience in rural communities. Social capital, or the network of a community's relationships, is critical for providing the foundation for rural communities to adapt to challenges (Cutter et al., 2016, Isenhour & Berry, 2020). Building social capital requires focusing on how organizations are set up, how they connect with each other and with people, and how much people trust each other and follow community rules (Isenhour & Berry, 2020). In practice, this can be supported by community events such as group discussions or planning meetings prior to possible impacts, and creating places where people in the community can meet and build trust that can support the growth and maintenance of social capital (Aldrich & Meyer, 2015).

Particularly for rural areas, the existence of strong social networks can be key for building resilient economies, such as rural tourism economies (Aldrich, 2012; Cucuzza et al., 2019; Horne et al., 2022). Strengthening social infrastructure, or the connections between individuals and between organizations that build upon the strengths of the individual or organization and include both formal and informal collaborations, is key for disaster preparedness (O'Sullivan et al., 2013). Strategies for enhancing social infrastructure include the use of scenario planning exercises that serve to convene organizations across sectors to identify community vulnerabilities (The Southern Midcoast Maine Social Resilience Project, 2022).

In Maine, partnerships, collaboration and funding for implementation were identified as key municipal needs for enhancing resilience (Cucuzza et al., 2019). Research shows that some of Maine's towns have identified physical vulnerabilities as part of adaptation planning processes, but very few have identified social ones, representing a disconnect with comprehensive plans (Cucuzza et al., 2019; Johnson et al., 2019). Municipal leaders can struggle to find funding for capital project implementation, such as shoreline stabilization or larger culverts, as opposed to funding for planning (Genoter et al., 2022; Reilly-Moman et al., 2023). Partnerships were seen as critical for increasing the likelihood of receiving grants (Cucuzza et al., 2019). Many communities specifically identified the need for spatial planning tools such as interactive maps to inform decision making (Cucuzza et al., 2019). Effective use of spatial planning tools may require additional support for communities in the form of expertise to assist with interpreting spatial data at a community scale and support for use of spatial data to engage the public in planning processes (Cucuzza et al., 2019; Johnson et al., 2019). However, a growing body of research indicates that spatial data have limitations in supporting equitable climate adaptation; stories and storytelling, both solicited and unsolicited, can provide critical knowledge and methods of engagement (Klenk, 2018; Voinov et al., 2018).

In Maine, where coastal community comprehensive plans include social resilience, many 1) emphasize a strong sense of community and a desire to maintain a rural character; 2) focus on shoreline erosion and flooding; and 3) recognize the relationship between healthy natural systems and a healthy economy. Comprehensive plans in Maine vary widely in their inclusion of indicators of resilience: plans focus more on social than ecological or economic resilience, have generally increased their focus on resilience over time, and allusions to specific climate change impacts were absent from the majority of plans (Cucuzza et al., 2019). Climate impacts and drivers of change, such as flooding and demographic change, are experienced at the local scale. In Maine and elsewhere, research has shown municipal capacity and local planning tools, such as comprehensive planning and zoning ordinances, support the inclusion of climate resilience in planning (Cucuzza et al., 2019).

Climate resilient development can integrate adaptation and mitigation, resulting in co-benefits. Across adaptation and comprehensive plans for eight cities across the globe, actions to mitigate climate change could create "political buy-in for the climate change agenda and commitment from stakeholders;" it could spur and enhance informal knowledge sharing networks; and planning processes more broadly could benefit from tools created to enhance the co-benefits of adaptation and mitigation and reduce tradeoffs (Boyd et al., 2022, p. 9).

Maine can improve climate resilient development by building on important aspects of Maine's culture, such as thrift and reuse. These include: 1) building on Maine's culture of thrift to reduce food waste, which can mitigate emissions, reduce economic costs and improve food access for Maine citizens; 2) nature-based solutions, such as forms of aquaculture and forestry that can provide economic diversification, carbon sequestration and economic development (Daignault et al., 2022); and 3) circular economic strategies such as repair and reuse that can leverage Maine's culture in ways that reduce waste and emissions, increase adaptive capacity with alternative procurement networks, and provide jobs and economic development for small businesses (Isenhour et al., 2022).

Housing Resilience

Housing security for low-income and rural Maine residents may be stressed by high fuel and electricity costs, along with climate migration to Maine. Beyond the climate impacts, the energy intensive nature of heating homes has a human dimensions impact. The cost of heating can represent a significant component of residents' utility costs, which can be a particular challenge for low-income residents (Gleason et al., 2023). Energy insecurity and climate hazards have been shown to increase the risk of homelessness for those with housing insecurity (Bezgrebelna et al., 2021).

Research on the drivers of climate migration, which could impact the movement of people to and from Maine as well as within Maine, identifies thresholds that impact movement instead,". These thresholds include the need for adaptation; adaption becoming ineffective; changes to land and livelihoods; failures of place-based adaptation; and ensuing migration in incremental then linear patterns (McLeman, 2018). The impacts of climate migration may exacerbate existing pressures on housing stock and warrant additional planning and coordination to better understand and anticipate these impacts (Shi et al., 2023). At the same time, increased migration into Maine from elsewhere will likely raise housing prices and municipal and state tax revenues that can be used to offset impacts and have important implications for economic and workforce development (Shi et al., 2023). Flooding represents an increased threat to homes and businesses throughout Maine (see Climate and Sea Level Rise chapters). In Maine, the percentage of affordable housing units at risk from the impacts of sea level rise is significantly greater than risks to Maine's overall housing stock (Buchanan et al. 2020).

Energy poverty is poorly measured and understood in the U.S. Current measurement and evaluative metrics focus on the distribution of government resources and the number of vulnerable households assisted. Research has found that rural residents are not adequately supported by unstable funding for heating oil, such as funding provided in the Low Income Home Energy Assistance Program (LIHEAP). Longer term and more cost effective solutions to high heating costs include improvements in building insulation and energy efficiency (Bednar et al., 2020).

Solar with battery storage can meet individual homeowner basic backup power needs during extended power outages, and storage can meet most of critical load, including heating and cooling, with efficiency upgrades (Gorman et al., 2023a, 2023b). Power system resilience research for natural disasters has increased as large outages have frequently impacted the electrical grid. While low-income communities experience more frequent blackouts and less reliable electricity, determining who pays for reliability and resilience improvements presents challenges (Macmillan et al., 2023). Research that included data from all Maine counties found that electric power and grid resilience is best addressed with updates to hard infrastructure (e.g.., updates to the transmission and distribution system). However, given the high cost of updating hard infrastructure in "front of the meter," behind the meter storage (e.g., solar paired with batteries, known as solar-plus-storage, for individual homes and businesses) interventions showed the most resilience in a recent study, particularly for rural areas (Carvallo et al., 2021). Vermont's utility, Green Mountain Power, plans to install battery storage for all of its 270,000 customers by 2030 as part of its Zero Outages Initiative, with the most rural residents receiving batteries first (Lewis, 2023).

Resilience Metrics

The term resilience has gained popularity in both popular and policymaking discourses as a means to understand and address climate impacts, offering a possible pathway for practitioners to assess and monitor the social, economic, and ecological impacts of climate change (Quinlan et al., 2016).

Measuring resilience has evolved from a physical-based risk analysis to metrics that integrate social impacts and attend to social and political power dynamics. Disaster resilience has evolved from an "objective" analysis of risk, hazards, and natural disasters to more integrative, subjective, socially differentiated experiences of disaster (Brown & Westaway, 2011; Center for Resilient Cities and Landscapes, 2020). In monitoring and evaluating resilience, Cutter et al.'s (2008) Disaster Resilience of Place (DROP) model exemplifies this shift while maintaining a focus on disaster response. Moser et al. also provide leadership on integrating physical and social hazards (Moser et al., 2008; Moser et al., 2014). Scholars further recognize the role of context, including political and social power and politics, in the development and implementation of metrics (Cutter et al., 2003; Cutter 2016a, 2016b; Moser & Ekstrom, 2010). Galappaththi et al. (2019) highlight that adaptation and resilience are both a response and a process. They note the three characteristics of people to cope, adapt, and transform, along with the "3R's" of resilience: resistance, rootedness, and resourcefulness (Brown, 2016). They identify characteristics of place, human agency, collective action, institutions, and knowledges that lead to measures and indicators (Brown, 2016).

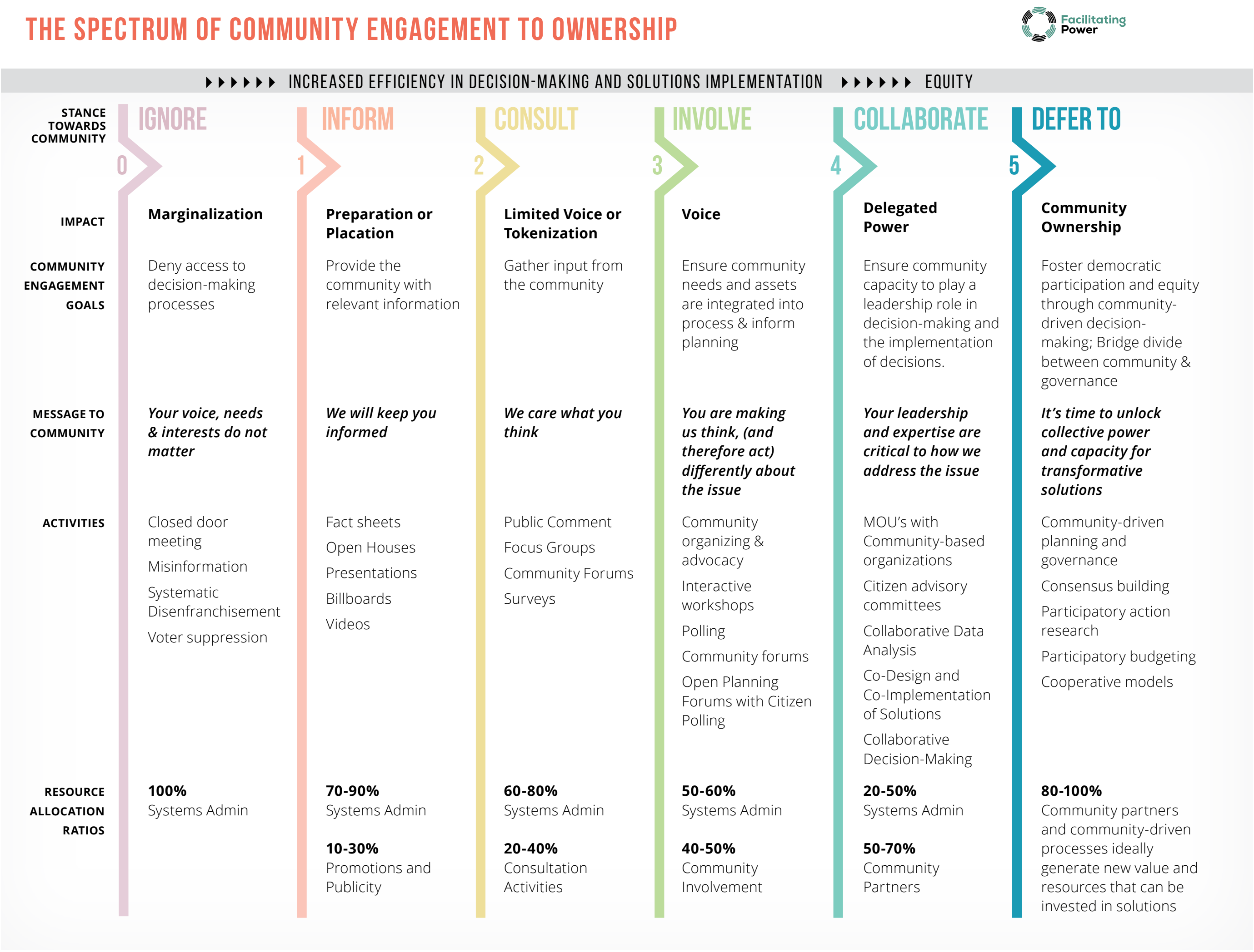
When assembling resilience metrics, a critical question to ask is resilience for whom, at what cost to whom else? (Brown, 2014; Cote & Nightingale, 2012; Haverkamp, 2017). As Schipper and Langston (2015, p. 12) note, "the key to good indicators is credibility rather than volume of data or precision of measurement." They further note that it can be difficult to compare metrics, given that "each framework is strongly influenced by its conceptual entry point" (p. 8). Additional key considerations when developing metrics come from the Food Security Information Network's Resilience Measurement Technical Working Group that build on priorities expressed by leaders from United Nations agencies, policy makers from national governments, and resilience measurement experts at a meeting held in Dakar, Senegal in December 2018, that include 1) a better understanding of the varied impacts of shock events; 2) placing well-being as a core measurement outcome; 3) identifying capacities that maintain well-being in the face of shocks; and 4) drawing on contextual factors to explain regional variation in resilience (Jones et al., 2021).

Resilience indicators often mix qualitative and quantitative approaches. For example, the International Union for the Conservation of Nature (IUCN) (2014), in a place-based and locally-driven process, developed a toolkit for a circular participatory planning cycle. They utilized a sequence of simple steps to define a problem and its causes, identify actors, articulate responses and key barriers, detail activities to overcome these barriers, and created a review process to ensure that results were met. Their metrics were process-based and determined by impacted communities, following "flows of activities" with inputs, outputs, capacities, and an attention to the gradual time scale of changes in resilience. As a resilience planning effort, a "resilience vision" was followed by resilience assessment, resilience strategies, planning, implementing, reflection, then repeating the sequence (IUCN, 2014).

The National Oceanic and Atmospheric Administration (NOAA) utilized existing county-level census data to create quantitative composite indicators to measure well-being (Dillard et al., 2013). The approach utilized expert input from convened conferences to develop and hone nine composite indicators by putting them "on trial" amid the judging of experts (Dillard et al., 2013). However, this process did not include co-creation with local partners. More recently, NOAA's Climate Resilience Toolkit provides a step-by-step guide for building climate resilience, which includes assembling a planning team, community participation, understanding community history, consulting pre-existing plans and resilience efforts and defining equity-centered goals (Gardner et al., 2022).

Quinlan et al. (2016) take a systematic approach to measuring resilience, and their examination developed six recommendations: 1) ground the metrics in theory; 2) take the opportunity to deepen understanding of systems dynamics; 3) note the tension between “expert” and “participatory” strategies, thus urging metrics developers to seek and identify self-organization and agency in their processes; 4) pay attention to context, asking questions such as resilience of what? to what? for whom? for what purpose?; 5) define resilience for the given approach, and; 6) the scales (time and space) at which metrics are measuring.

In a working report for the Maine Department of Environmental Protection (ME DEP) and the Maine Interagency Climate Adaptation Workgroup, Haverkamp (2017) provides frameworks and potential indicators for measuring climate resilience in Maine.


THE SPECTRUM OF COMMUNITY ENGAGEMENT TO OWNERSHIP

▸▸▸▸▸▸ INCREASED EFFICIENCY IN DECISION-MAKING AND SOLUTIONS IMPLEMENTATION ▸▸▸▸▸▸ EQUITY

STANCE TOWARDS COMMUNITY	0 IGNORE	1 INFORM	2 CONSULT	3 INVOLVE	4 COLLABORATE	5 DEFER TO
IMPACT	**Marginalization**	**Preparation or Placation**	**Limited Voice or Tokenization**	**Voice**	**Delegated Power**	**Community Ownership**
COMMUNITY ENGAGEMENT GOALS	Deny access to decision-making processes	Provide the community with relevant information	Gather input from the community	Ensure community needs and assets are integrated into process & inform planning	Ensure community capacity to play a leadership role in decision-making and the implementation of decisions.	Foster democratic participation and equity through community-driven decision-making; Bridge divide between community & governance
MESSAGE TO COMMUNITY	***Your voice, needs & interests do not matter***	***We will keep you informed***	***We care what you think***	***You are making us think, (and therefore act) differently about the issue***	***Your leadership and expertise are critical to how we address the issue***	***It’s time to unlock collective power and capacity for transformative solutions***
ACTIVITIES	Closed door meeting Misinformation Systematic Disenfranchisement Voter suppression	Fact sheets Open Houses Presentations Billboards Videos	Public Comment Focus Groups Community Forums Surveys	Community organizing & advocacy Interactive workshops Polling Community forums Open Planning Forums with Citizen Polling	MOU’s with Community-based organizations Citizen advisory committees Collaborative Data Analysis Co-Design and Co-Implementation of Solutions Collaborative Decision-Making	Community-driven planning and governance Consensus building Participatory action research Participatory budgeting Cooperative models
RESOURCE ALLOCATION RATIOS	**100%** Systems Admin	**70-90%** Systems Admin **10-30%** Promotions and Publicity	**60-80%** Systems Admin **20-40%** Consultation Activities	**50-60%** Systems Admin **40-50%** Community Involvement	**20-50%** Systems Admin **50-70%** Community Partners	**80-100%** Community partners and community-driven processes ideally generate new value and resources that can be invested in solutions

Figure 1: The spectrum of community engagement to ownership, from Gardner et al. (2022). The stance toward community ranges from “ignoring” to “deferring to.” The impacts from ignoring are marginalization, while deferring creates community ownership. Importantly, even when communities are “consulted,” the impact is “limited voice or tokenization.”

THE CITY RESILIENCE INDEX (modified from Arup Foundation [2016])

DIMENSIONS	GOALS	INDICATORS
Health & Well-being (PEOPLE)	Minimum Human Vulnerability	Safe and affordable housing
		Adequate affordable energy supply
		Inclusive access to safe drinking water
		Effective sanitiation
		Sufficient affordable food supply
	Diverse Livelihood & Employment	Inclusive labor policies
		Relevant skills and training
		Local business development and innovation
		Supportive financing mechanisms
		Diverse protection of livelihoods following a shock
	Effective Safeguards to Human Health & Life	Robust public health systems
		Adequate access to quality healthcare
		Emergency medical care
		Effective emergency response services
Economy & Society (ORGANIZATION)	Collective Identity & Mutual Support	Local community support
		Cohesive communities
		Strong city-wide identity and culture
		Actively engaged citizens
	Comprehensive Security & Rule of Law	Effective systems to deter crime
		Proactive corruption prevention
		Competent policing
		Accessible criminal and civil justice
	Sustainable Economy	Well-managed public finances
		Comprehensive business continuity planning
		Diverse economic base
		Attractive business environment
		Strong integration with regional and global economies
Infrastructure & Ecosystems (PLACE)	Reduced Exposure & Fragility	Comprehensive hazard and exposure mapping
		Appropriate codes, standards and enforcement
		Effectively managed protective ecosystems
		Robust protective infrastructure
	Effective Provision of Critical Services	Effective stewardship of ecosystems
		Flexible infrastructure
		Retained spare capacity
		Dilligent maintenance and continuity
		Adequate continuity for critical assets and services
	Reliable Mobility & Communications	Diverse and affordable transport networks
		Effective transport operation and maintenance
		Reilable communications technology
		Secure technology networks
Leadership & Strategy (KNOWLEDGE)	Effective Leadership & Management	Appropriate government decision-making
		Effective coordination with other government bodies
		Proactive multi-stakeholder collaboration
		Comprehensive hazard monitoring and risk assessment
		Comprehensive government emergency management
	Empowered Stakeholders	Adequate education for all
		Widespread community awareness and preparedness
		Effective mechanisms for communities to engage with government
	Integrated Development Planning	Comprehensive city monitoring and data management
		Consultative planning process
		Appropriate land use and zoning
		Robust planning approval process

Table 1: The City Resilience Framework (CRF), developed by the Arup International and the Rockefeller Foundation (2016), outlined 12 research-based indicators, adapted and summarized in the table above.

Methods such as interviews and ethnography allowed coastal community residents to steer conversations towards neglected social needs and exert influence and control in the scientific process (Reilly-Moman, 2021). Climate impacts and adaptations have largely been approached as biophysical and technical problems, but the inclusion of social science methods, such as interviews, allows participants to push back on this framing, particularly when it does not represent their lived experience of climate change (Reilly-Moman, 2021). To reflect this, Reilly-Moman (2021) framed social indicators of resilience around the concept of "care," with four mixed quantitative and qualitative measures of care: relational, network, place-based and inclusive. Using a framework built around the parameters of "care" above, quantitative indicators of social connectedness (e.g., Bailey et al., 2018) can complement qualitative documentation of knowledge exchange (Reilly-Moman, 2021). Metrics for equity abound (e.g., Finucane et al., 2021; VEIC, 2019), and context plays an important role for the community or system. When considering equity, nonhuman agency and interests can be included in the framing to support transformative change (Reilly-Moman, 2021).

Measuring climate resilience presents unique challenges; measuring an initial baseline is key. Climate-specific challenges to developing metrics include climate's long time horizons, where project impacts may not be seen for decades; cross-scale changes and impacts with uncertain local impacts; shifting baselines and contexts mean that a typical before and after comparison loses validity; and divergent values, perceptions, and goals among community members, technical experts, and policymakers can create conflict or lead to the undermining of key perspectives. In addition, the fundamental inequity of climate impacts need to be included in metrics. Finally, to support addressing many of these challenges, the use of baseline comparisons is an essential strategy in evaluating the outcomes and impacts from resilience initiatives (Cutter et al., 2010).

Qualitative data play an important role in resilience metrics (Brown 2016). Some qualitative indicators employ a 1–5 rank scoring system; some use "positive, negative or neutral" or "improve, worsen, or stayed the same" ranking systems, as well as non-ranking, open-ended qualitative formats (Haverkamp, 2017). Qualitative values can be used to create baselines and/or assess program outcomes and process. They can also address difficult to quantify but critically important entities such as values, beliefs, place attachment or cultural identity (Cutter, 2016; Devine-Wright & Wiersma, 2020).

Research from Leslie et al. (2015) and Klenk (2018) point to the beneficial aspects of qualitative stories. Stories can influence policy and serve as communication, data and translation (Leslie et al., 2015). Stories also challenge the single, unified voice that the maps and scenarios present in climate adaptation planning. They can be used to highlight key political and social power struggles over regional decision-making, as well as the perception of adaptation as a personal story of empowerment or victimization (Klenk, 2018). Finally, storytelling can disrupt authoritative accounts of local vulnerabilities that gave impunity to critical actors outside the community (Klenk, 2018).

Critically, assessments conducted to understand community climate-related needs, and their metrics, are "world-making" practices: they shape climate responses by embedding global narratives of climate change within local narratives about the past such as shared stories around extreme weather events and disasters, present (such as the ongoing successes and challenges of addressing environmental change), and imaginaries of the future (Klenk, 2018). Science—its discourse, methods, and power politic—can exacerbate community vulnerability and inequities in these planning and implementation processes (Klenk, 2018). Stories and storytelling practices, part of metrics and otherwise, can help address this (Klenk, 2018, Leslie et al., 2015, Wake et al., 2020).

Climate Knowledge

Climate impacts and responses are socially mediated. Ideas about climate risk and how to adapt to change are shaped by culture, which is connected to place (Adger et al., 2013). Culture includes values, beliefs, practices and stories that create collective understanding and behaviors from which a group then bases their response strategies as well as the physical and social infrastructures that support that way of life (Adger et al., 2013; Hays, 1994). While many theories suggest a direct link between the risk posed by climate change and how society responds, the reality is more complex. Perceptions of risk and responses are influenced by cultural background and can vary greatly. Local institutions, social structures, and survival strategies play a big role in how people in Maine interact with climate change. It is important to understand these factors for effective and fair planning for climate change (Adger et al., 2013).

Although the majority of Mainers are concerned about the impacts of climate change, there are differences in how residents understand the causes, risks and impacts of climate change. Mainers' understandings of climate change are shaped by several factors including geography, employment, political affiliation and experiences of direct impacts (Horne et al., 2022; Johnson et al., 2019; Runnenbaum et al., 2023). Understanding these differences is key to developing policies to communicate about and address climate impacts (Runnenbaum et al., 2023).

Data Sovereignty and the Challenges of "Integrating" Knowledge Systems

Social research on the uses of environmental DNA (eDNA) in Maine illuminates ways to begin to address ongoing issues with Indigenous sovereignty and Western science. Collecting eDNA, which involves taking water and soil samples from specific locations, relies on a "technical definition of eDNA emphasiz[ing] individual agency to collect eDNA as a material entity in ways that can reinforce anthropocentric, neoliberal, and colonial assumptions about who has the ability and the right to collect data and for what purposes, in this case the purpose of producing scientific knowledge to guide management" (McGreavy et al., 2022, p.11). The Local Contexts initiative shifts management of biocultural data from individual to a collaborative approach through Biocultural (BC) Labels and Notices on data. The BC Labels signal "the right of Indigenous communities to define the use of information, collections, and data generated from biodiversity and genetic resources associated with their traditional lands or water" (Liggins et al., 2021, p. 2478). This represents a collaborative approach to define how data and related knowledge should be described, shared and archived (McGreavy et al., 2022).

The ways in which knowledge is produced forms the orders of society, including identities, organizations, and discourses (Jasanoff, 2004; McGreavy et al., 2022; TallBear, 2013). Traditional ecological knowledge (TEK) is often referred to as the human knowledges, practices, and beliefs in Indigenous societies that are passed along culturally and through generations; TEK draws on cultural memories and relates to the relationships of living beings with each other and their environment (see Berkes, 1993; 2009; Gann et al., 2019). Integrating TEK into Western scientific processes and assessment implies that "traditional knowledge" conforms to Western conceptions of "knowledge": TEK becomes another form of "data" that can be folded into existing governance and management processes that maintain disempowered Native nations (Nadasdy, 1999). Consequently, to participate in decision making, Indigenous people must subsume the knowledge and beliefs in their own management practices in institutionalized power structures (Nadasdy, 1999). In Maine, the 1980 Maine Indian Claims Settlement Act demonstrates these institutionalized relationships: to participate in state climate decision making, Indigenous partners must conform to state processes without state recognition of Tribal governance and sovereignty.

Residents vary on the role of natural resource industries as a dimension of resilience, such as contributing to communities' economies. Views on the role of conservation programs in contributing to natural resource economies and livelihoods also varied by geography and demographics such as political affiliation, gender, age and level of educational attainment (Sherman & Daigneault, 2022).

Understanding the unique perceptions and understandings of the impact of climate change on specific groups can enable policies that promote better participation in climate decision-making. In Runnebaum et al.'s (2023) examination of fisheries and associated livelihoods, individuals with a shared understanding of climate change, did not rank it among their top three concerns (which were fisheries regulations, market access and access to working waterfronts). The research notes that policies, including various forms of cooperative management, can increase harvesters' resilience and adaptive capacity to climate change (Runnebaum et al., 2023).

Developing a universal shared understanding of climate resilience may be challenged by the fact that not all rural residents think about climate risks and appropriate responses in the same way. These understandings may be shaped by where residents live and demographic characteristics such as political affiliation and educational attainment. As a dimension of resilience, the role of culture and the development of political and social capital is felt to be particularly important by residents of Maine's more rural communities (Sherman & Daigneault, 2022).

Public Participation in Climate Decision Making

Extensive research shows that effective public involvement in environmental decisions, specifically in building trust between decision makers and stakeholders, relies on the "trinity of voice": the power, access, and standing of participants (Senecah, 2023). In practice, access to climate decision making processes includes attitudes of collaboration, convenient meeting times and places, readily available and relevant information, diverse opportunities to access information and education, technical assistance and early and ongoing public involvement opportunities. Standing is the respect and esteem given to all stakeholders. Influence, the outgrowth of access and standing, lets participants feel that their ideas have been respectfully considered along with those of other stakeholders (Senecah, 2023). This translates to transparent processes that consider alternatives, opportunities to meaningfully scope alternatives, and opportunities to inform the decision criteria and thoughtful responses to stakeholder concerns and ideas (Senecah 2023).

The trinity of voice relates to concepts of community agency, defined as the capability of a group to achieve change when needed. Agency relates to empowerment and depends on internal and external community structures, specifically local culture and tradition, ruling or dominant belief systems, political systems, and socioeconomic conditions (Målqvist, 2023).

In their book, *Public Participation in Environmental Assessment and Decision Making,* Dietz & Stern (2008) reviewed decades of peer-reviewed literature, reports, and case studies to provide a seminal text in environmental communication. The following section summarizes some of their key findings.

When done well, public participation in decision making improves legitimacy, builds capacity, leads to better environmental and social outcomes and enhances trust and understanding among parties. Innumerable studies demonstrate positive results from public participation. When not done well, participation has been shown to do more harm than good. A poorly designed process without adequate support and engagement from the implementers can decrease legitimacy and trust (Dietz & Stern, 2008).

Government agencies can meet decision making goals with public input by having clarity of purpose; a commitment to use the process to inform actions; adequate funding and staff; appropriate timing in relation to decisions; a focus on implementation; and a commitment to self-assessment and learning. Available evidence also shows that, without these factors, public participation processes can be counterproductive and worse than not including the public. For example, selection of participants can present tensions and conflict if those individuals or organizations selected share the same interests and perspectives as the selecting government agencies, or are perceived as such (Dietz & Stern, 2008).

Five key principles emerge for bringing together science and the public in decision making: 1) transparent information and analysis; 2) explicit attention to facts *and* values; 3) addressing assumptions and uncertainties; 4) including independent review; and 5) allowing for iteration with new information. An effective process must deal with both facts and values, given that decisions and resulting changes will affect the things that people value. A variety of processes can help to characterize the uncertainty of facts, examine the implications of decisions, address diverse values and help individuals examine trade-offs. Trust and understanding can emerge only if uncertainties and assumptions around facts and values are addressed. Peer review should be credible to all parties engaged (Dietz & Stern, 2008).

Justice in Climate Projects

Procedural justice plays a significant role in project support for land-based and offshore renewable energy siting; Maine research shows that commitment to giving communities real power in siting processes helps to build trust. Procedural justice, or the fair processes for participation and access to information that inform decision-making with a recognition of the importance of place, local history, and connection to meaning enmeshed in landscapes, is increasingly studied in the context of social acceptance of renewable energy siting (Elmallah & Rand, 2022). Research finds that if communities feel excluded from a planning process which will alter the place where they have built families and livelihoods, they can turn against a development that would otherwise offer some benefits to their community. Place attachment and identity are also critical to understand when addressing community concerns (Elmallah & Rand, 2022).

When conducting sustainability science in Indigenous homelands of Penobscot, Passamaquoddy, Maliseet, and Micmac, researchers found that 1) centering Wabanaki diplomacy and Indigenous research methods (IRMs); 2) a multi-perspectives approach that included pilot work and iterative engagement; 3) slowing down to create rhythms of collaboration; and 4) supporting Wabanaki students as leaders and researchers could begin to address tensions between Western science and Indigenous discourses (McGreavy & Ranco et al., 2021). Having time to co-define the problems is critical, but often hamstrung by funding requirements (McGreavy & Ranco et al., 2021). Naming was found to be a critical tension: examples include names that reinforce colonial cartographic violence, such as using the "State of Maine" and the term "decision maker," which excludes both other people and possibilities for transformations. Researchers used a "dialogic" approach, building capacities for knowledge production that do not conform to western colonial conceptions, with early and iterative collaborations on research directions (McGreavy & Ranco et al., 2021). Finally, in addition to the multiple perceptions of time, practical time is valued differently if some are paid to be there while others are not; this differential value of time reinforces hierarchies of expertise and knowledge. Centering Indigenous student leadership with a network of support was critical for addressing tensions and conducting sustainability research (McGreavy & Ranco et al., 2021).

The Wabanaki Cultural Lifeways Exposure Scenario, a numerical representation of the environmental contact, diet, and exposure pathways present in traditional cultural lifeways in Maine, documented subsistence and traditional lifeways for the Wabanaki nations, providing a baseline for assessing risks to social-ecological lifeways. This EPA report, produced in 2010, provided "scientifically sound data that describes traditional uses, not contemporary uses that are suppressed or distorted for many individuals by lack of access, resource degradation, or knowledge of contamination" (Harper & Ranco, 2010). The Scenario, in combination with exposure factors, examined the multiple contexts, settings, natural resource uses and diet that would lead to exposure to degraded or contaminated resources through activities such as gathering, hunting, water ingestion and air inhalation, and quantified the subsequent risks. While this project did not single out climate change as a stressor, the delineation of lifeways provided initial parameters for understanding and measuring impacts.

Multiple studies in Maine have researched the interaction of Indigenous lifeways with natural resources (i.e., Bassett, 2015; Baumflek et al., 2010). Based on an examination of history and policy in sustenance fishing, the Maine Indian Tribal-State Commission (2022) addressed the potential impact on anadromous fish and Wabanaki fishing and made nine recommendations relevant to tribal-state climate policy, including discussions between the State of Maine and the Wabanaki Nations to reach a mutual understanding of sustenance practices that take into account the way Wabanaki people understand that phrase; coordination between Maine Department of Marine Resources and the Maine Department of Inland Fisheries and Wildlife that include Wabanaki Nations and the Maine Indian Tribal-State Commission (MITSC); and requiring Traditional Ecological Knowledge in the same ways that environmental impact statements are required (MITSC, 2022).

Research in Maine shows that climate project developers that moved beyond information sharing to a relationship committed to community agency in decision-making proved locally successful in implementing renewable power (Johnson et al., 2013). When communities are inclusively engaged early through a neutral (or local) agent, place attachment and meaning is integrated into the process. Specifically among ocean renewable energy projects, in Maine and nationally, research shows that a locally-based and full time community liaison between developers and the community, often a person from the community, built trust and support for the project (Bingaman et al., 2022; Elmallah & Rand, 2022; Johnson et al., 2013).

Communities benefit from "packages" of financial support, but community engagement in the siting process also benefits communities and renewable energy developers (Bingaman et al., 2022; Elmallah & Rand, 2022; Johnson et al., 2013). Community benefits are often "packages," with agreements and payments to meet specific community needs, such as a power purchase agreement or internet access. But communities and renewable energy project developers also benefited when they were genuinely engaged in the siting process (Johnson et al., 2013). How a community perceives and acts on its social and political power can depend, in part, on the agency given to local stakeholders in planning. Specific methods for engagement have included "landscape fora," where a representative sample of local citizens and local leadership are convened to discuss landscape values and define preservation and development priorities (Phadke, 2013).

Climate Governance and Planning

Tribal sovereignty enables climate resilience for Native nations. In the U.S., political obstructions often constrain climate adaptation for Native nations. According to the 5th National Climate Assessment (NCA) (USGCRP, 2023), both federal and state interference in Tribal sovereignty can limit the ability of Tribes to develop and implement culturally appropriate climate adaptation plans and activities. The NCA also points out that climate change is already negatively impacting Tribal food sovereignty, as traditional gathering, planting, harvesting and hunting areas are transformed, destroyed and moved by climate change. Implementation of climate adaptation plans often requires significant funds, often sourced through multiple agencies. In Maine, accessing these funds is particularly challenging to the Wabanaki Tribal Nations because the 1980 Maine Indian Claims Settlement Act prevents them from obtaining the emergency funds made available to other Tribes via the Federal Emergency Management Agency through the 1988 Stafford Act (FEMA).

In adaptation planning, trust and technical assistance can be more important than co-production. Research from coastal New Hampshire engaged with multiple communities in riverine flood mapping and found that mapping products that were not co-produced still had credibility, but that the saliency of the project depended on engaging the right group of municipal decision makers (such as public works, conservation commissions, emergency management and planners) in a cross-sectoral team that regularly communicated (Levesque et al., 2021). In particular, technical assistance throughout the process of planning and implementation was critical; otherwise, small municipalities did not have the technical expertise or funding resources to take action with the generated flood maps (Levesque et al., 2021). Enhancing the capabilities of communities to provide a wider range of ways to communicate information to residents is also a key factor of resilience (Levesque et al., 2021).

Arts and humanities provide an opportunity to engage in critical and difficult conversations around climate change, such as relocation due to sea level rise. On the New Hampshire coast, interactive theater was used as a tool at the intersection of science and effective communication (Wake et al., 2020). Multiple workshops produced survey results in which approximately two-thirds of respondents noted that the interactive theater increased their capacity to engage in community conversations about retreat, and that the workshop affected the way participants think about designing and conducting climate adaptation work (Wake et al., 2020).

PRIORITY INFORMATION NEEDS

The top information needs for human dimensions that arose during this climate science assessment process represent projects that support better statewide knowledge of the impacts of and responses to climate change. The top priority information needs include:

1. **Better information on regional differences in vulnerability and readiness.** This includes building on existing analyses of differential vulnerability with more information about the relationship between: 1) the types of climate risks communities face (coastal flooding, inland flooding, sea level rise, drought); 2) sensitivity to those risks, including economic and infrastructural dependencies; 3) community demographics; and 4) levels of readiness. Mixed social science methods (e.g. surveys, interviews, and spatial analysis) could be deployed across the state to map differences and inform state investments, community readiness efforts and strategies to communicate with those most vulnerable.

2. **Improved understanding of mental health impacts, prevention, and treatment**. This effort would build on recent insights into the mental health impacts of extreme climatic events and disasters to include the impact of loss of culture and heritage as well as the potential impacts of the inability to adapt in place. Analysis from mixed methods, including case studies, experimental design, interviews and clinical trials, would inform effective public health interventions/healthcare responses to address the mental health impacts of climate change in Maine. This research would overlap with multiple climate-impacted communities, especially agriculture.

3. **Develop a stronger understanding of potential migration patterns and population shifts.** More information is needed to enable projections of climatic impacts on population, including settlement patterns and migration to and within the state. This information—gathered using demographic projections, build-out scenarios, and real estate data—would provide a better understanding of the impacts of shifting populations and settlement patterns on a wide range of human systems including housing, transport, electrical grids, healthcare systems, tourism and tax revenues.

4. **Develop a stronger understanding of insurance markets**. The state would benefit from a stronger understanding of insurance markets in a wide range of sectors (crop, home, business, municipality, etc.) and the relationship between these markets and risk assessments under a changing climate. A synthetic and systematic analysis of economic models and qualitative collection with insurance specialists could inform a wide range of adaptation policies, such as state and municipal development and zoning, and support effective decision making around, for example, coastal engineering and nature-based solutions (see Marine Ecosystems chapter) or managed retreat.

A list of all of the priority information needs beyond those addressed here can be found in Report Appendix I.

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SEA LEVEL RISE AND COASTAL HAZARDS

SEA LEVEL RISE

The rate of sea level rise continues to accelerate in Maine, and record-high sea levels were measured along the coast in 2023. Sea level has been rising at a rate of 0.117±0.025 feet/decade (3.57 ± 0.75 millimeters (mm)/year) over the past 30 years (1993-2023) in Portland. This demonstrates a recent acceleration when compared to the long-term (1912-2023) rate of 0.064 ±0.003 feet/decade (1.94 ± 0.09 mm/year). Sea level rise rates in Maine remain similar to the global averages for both short-and long-term rates. Record-high monthly mean sea levels were recorded for six to seven months in 2023 at Maine's long-term tide gauges (Eastport, Bar Harbor, and Portland).

Mean sea level over the most recent 19-year period (2005-2023) is 7.5 inches higher than it was in the early-1900s (specifically measured against the time period 1912-1930, or the earliest complete 19-year period of sea level measurements in Maine, measured at the Portland NOAA tide gauge). Mean sea level must be calculated over a 19-year period to average out seasonal-to-decadal variability that can bias the trend. Although Maine does not have sea level records dating to before the early 1900s, archival water level measurements from Boston indicate that relative sea level changed little during the 1800s, with decadal variability outweighing any long-term trends (Talke et al., 2018).

2023 set a new record-high annual mean sea level at all three of Maine's long-term tide gauges (**Figure 1**), and also set numerous new monthly mean sea level records. This increase in sea level, in addition to the long-term increase in sea level, contributed to severe coastal flooding during the back-to-back January 10 and January 13, 2024 storms (see callout box "Recent extreme high water events"). Between January and December 2023, the record for highest monthly mean water level was broken at all long-term gauges (from northeast to southwest, Eastport, Bar Harbor, Portland) for 6-7 months out of the year, with all remaining months except one falling within the top 3 highest levels for each month (**Table 1**). Over the course of 2023 in Portland, monthly mean sea levels were between 4.8 to 8.4 inches (0.4 and 0.7 feet) higher than 1991-2009 mean sea level (the 19-year period centered on 2000 used as the baseline for sea level projections; see callout box "Water level datums and baselines") (**Figure 2**). Compared to 2022 mean sea level, 2023 mean sea level was approximately three inches higher: approximately 3 inches (0.26 feet) higher in Portland, 2.5 inches (0.21 feet) higher in Bar Harbor, and 2.1 inches (0.18 feet) higher in Eastport. Examples in **Figures 1 and 2** are provided from the Portland tide gauge; data from the other long-term gauges are provided in **Figures D1 and D2** of Appendix D.

The cause of high sea level in 2023 and the first two months of 2024 remains unknown. There was a high sea level anomaly in the Gulf of Maine in 2010 (**Figure 1**) that has been attributed to wind patterns associated with a strongly negative North Atlantic Oscillation and a reduction in Atlantic Meridional Overturning Circulation slowing the Gulf Stream (Goddard et al., 2015; Rossby et al., 2014; see also callout box "Potential decline of the AMOC" and the 2020 STS report). The 2010 high sea level anomaly lasted one year, and it is unknown whether the current high sea level will lower again.

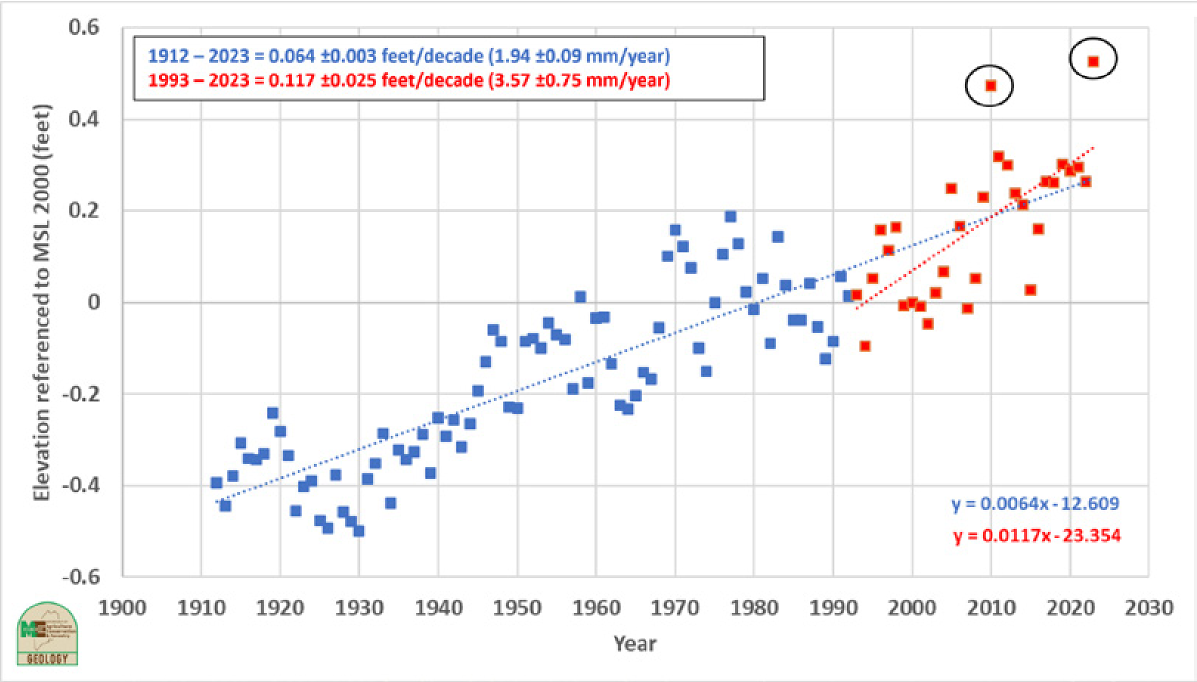
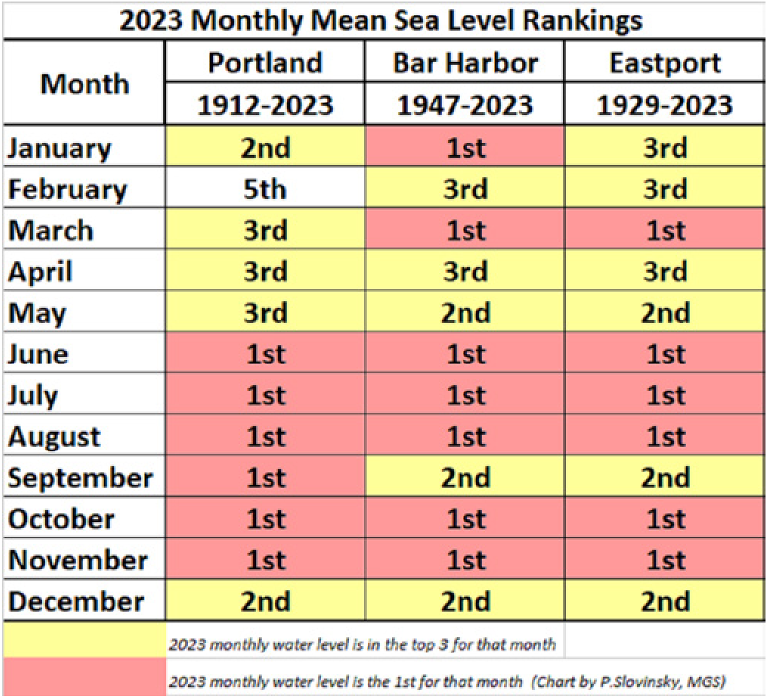


Figure 1. Observed annual mean sea level (blue and red dots), with long-term (1912-2023; blue line) and short-term (1993-2023; red line) sea level rise trends at the Portland, Maine, NOAA tide gauge. Measurements are relative to 2000 mean sea level, and anomalous high sea level years of 2010 and 2023 are circled (see **Figure D1** in Appendix D for Bar Harbor and Eastport). For more information on 2000 mean sea level and other vertical datums used in this text, see callout box "Water level datums and baselines."



2023 Monthly Mean Sea Level Rankings

Month	Portland	Bar Harbor	Eastport
	1912-2023	1947-2023	1929-2023
January	2nd	1st	3rd
February	5th	3rd	3rd
March	3rd	1st	1st
April	3rd	3rd	3rd
May	3rd	2nd	2nd
June	1st	1st	1st
July	1st	1st	1st
August	1st	1st	1st
September	1st	2nd	2nd
October	1st	1st	1st
November	1st	1st	1st
December	2nd	2nd	2nd
🟨	*2023 monthly water level is in the top 3 for that month*		
🟥	*2023 monthly water level is the 1st for that month (Chart by P.Slovinsky, MGS)*		

Table 1. Monthly mean sea level rankings from 2023 for Portland, Bar Harbor, and Eastport, Maine. New records were set for six to seven months out of the year at each of Maine's long-term continuous tide gauges, with the remaining months (except for February 2023) within the top three three since data collection was initiated in 1912, 1947, and 1929 for Portland, Bar Harbor, and Eastport, respectively.

Potential Decline of the Atlantic Meridional Overturning Circulation (AMOC) and its Implications for Sea Level Rise

The weakening and changes in major North Atlantic circulation patterns like the Gulf Stream, one of the major components of the Atlantic Meridional Overturning Circulation (AMOC) and the primary pathway of warm and saline waters towards higher latitudes along the U.S. eastern seaboard, are also drivers of relative sea level rise in the Gulf of Maine. Although there is a tremendous amount of evidence suggesting that weakening of the Gulf Stream and AMOC is "very likely" in the 21st century (Fox-Kemper et al., 2021), there is disagreement about the extent and timing of such a decline (Lenton et al., 2023) or even the likelihood of a potential future AMOC collapse (Chen & Tung, 2024). Projected AMOC weakening is mainly associated with climate-driven changes in ocean stratification in high latitudes, whereas, the Gulf Stream is primarily driven by the prevailing large-scale wind patterns blowing over the subtropical North Atlantic (e.g., Roquet & Wunsch, 2022). In addition to the projected weakening, changes in the wind patterns (Yang et al., 2020) have also been contributing to the Gulf Stream migration closer to the coast and, hence, to coastal sea level rise (Todd & Ren, 2023).

A weakened AMOC alone can potentially increase sea level along the northeastern and southeastern coastlines of the U.S. by tens of centimeters (Krasting et al., 2016; Yin et al., 2020; Yin et al., 2009, 2012). Sweet et al. (2022) isolates sterodynamic contributions to SLR, or the portion of sea level change caused by variability in the ocean's circulation, temperature, and salinity. Median estimates of sterodynamic contributions to Portland SLR for the Intermediate scenario are 7.8 inches / 0.65 ft (20 cm) by 2050, 1.61 ft (49 cm) by 2100, and 2.76 ft (84 cm) by 2150, or approximately 62%, 47%, and 43% of total relative project sea level rise for 2050, 2100, and 2150, respectively. Variability in the AMOC also directly impacts nutrient concentrations in the Gulf of Maine, which has implications for primary and secondary productivity.

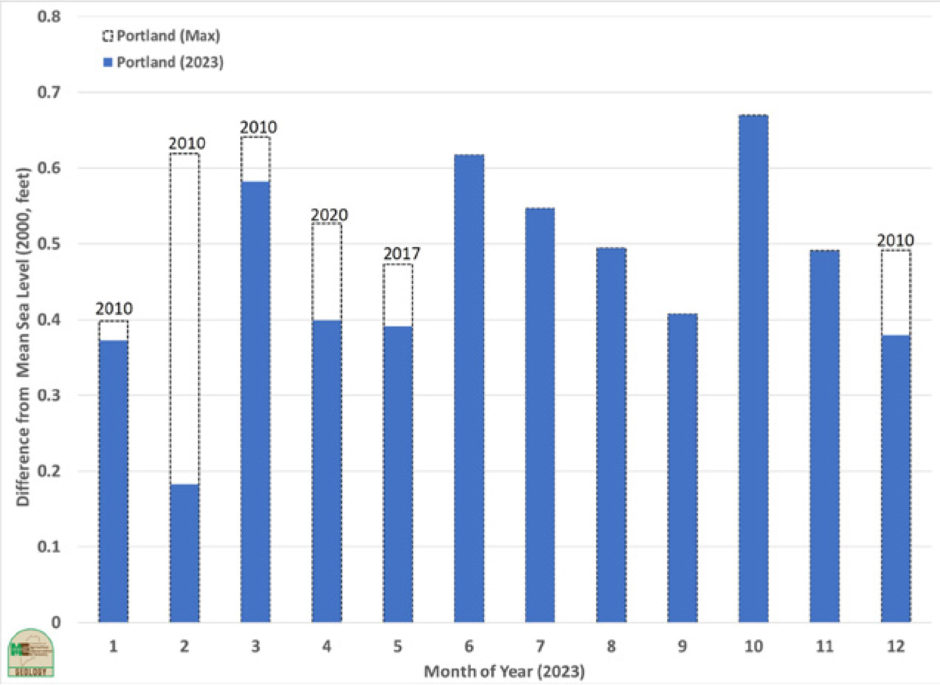


Figure 2. Monthly mean sea levels in 2023 for Portland referenced to 2000 mean sea level (MSL). 2023 set records from June through November, and aside from one month (February) was within the top three highest recorded monthly water levels for the remaining months since data collection initiated (1912). Months where 2023 did not set records are labeled with the maximum year. See **Figure D2** in Appendix D for Bar Harbor and Eastport, and the callout box "Water level datums and baselines for additional context."

Water Level Datums and Baselines

For any measurement, there has to be a reference point that is assigned a value of zero. For example, when measuring a person's height, that zero reference point is the bottom of their feet. For elevation measurements, zero reference points are called *vertical datums*.

Water surface elevations are commonly measured relative to a *tidal datum*, which is the average elevation over time of a certain phase of the tide. Common tidal datums include mean sea level (MSL), mean lower low water (MLLW), mean higher high water (MHHW), and highest astronomical tide (HAT). Tide predictions and National Weather Service flood forecasts are reported relative to the MLLW datum, and colloquial references to water level are generally in feet above MLLW. NOAA CO-OPS provides detailed explanations of each datum (https://tidesandcurrents.noaa.gov/datum_options.html), and note that tidal datums are local and cannot be applied to areas with different oceanographic characteristics. In other words, MLLW and MSL are different in Portland than they are in Eastport.

The National Oceanic and Atmospheric Administration (NOAA) computes tidal datums over a standard 19-year period called the *National Tidal Datum Epoch (NTDE)*. Averaging over 19 years accounts for variability in tidal range and sea level caused by planetary cycles and seasonal-to-decadal weather patterns. The current NTDE is 1983-2001, or the 19-year period centered on 1991. NOAA will update the NTDE to 2002-2020 in 2026. This update will raise all tidal datums (MSL, MLLW, MHHW) due to sea level rise since 1983-2001.

Additional datums in this report include 2000 MSL, NAVD88, and annual MSL. 2000 MSL is the baseline used for U.S. sea level rise projections and is calculated as mean sea level over the 19-year period centered on 2000 (1991-2000). NAVD88, or the North American Vertical Datum of 1988, is a land-based "zero" commonly used for measuring elevations of features on land. Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps define flood zones using a *base flood elevation* measured relative to NAVD88. Base flood elevation is the water surface elevation resulting from tides, surge, and waves that has a 1% chance of occurring in a given year, generally assuming that sea level is NTDE MSL (i.e., 1983-2001 MSL). NAVD88 is close to NTDE MSL, but the offset varies spatially. In 2025, NAVD88 will be replaced with a new datum, NAPGD2022. This report provides extreme water level statistics (i.e., water surface elevations of the 1%, 10%, etc. annual chance events) relative to annual MSL. Using the 1% annual chance event as an example, these statistics provide the water level that has a 1% chance of being reached by the combination of high tide and surge, and that value can be added to MSL in any year of interest to estimate the 1% flood height for that year.

Appendix D, **Table D1** provides datum conversions at the Portland, Bar Harbor, and Eastport tide gauges. At locations without tide gauges, NOAA's VDatum tool (https://vdatum.noaa.gov/) can be used to convert among NAVD88 and most NTDE tidal datums. Maine Geological Survey's Highest Astronomical Tide Line tool (https://www.maine.gov/dacf/mgs/hazards/highest_tide_line/index.shtml) provides conversions between NAVD88 and NTDE HAT along Maine's entire coastline.

Maine's "commit to manage" and "prepare to manage" sea level rise scenarios

The 2020 STS report recommended that Maine "commit to manage" 1.5 ft of sea level rise by 2050 and 4 ft by 2100, and that Maine "prepare to manage" 3 ft by 2050 and 8.8 ft by 2100 (relative to 2000 mean sea level). These values were based on the Intermediate and High sea level rise scenarios in a 2017 NOAA Technical Report (Sweet et al., 2017). Since then, a newly formed U.S. Interagency Sea Level Rise Task Force has updated these sea level rise scenarios (Sweet et al., 2022) for the Fifth National Climate Assessment (May et al., 2023), drawing on new science in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (Fox-Kemper et al., 2021). These updated scenarios are provided in **Table 3** and Appendix E **Table E1**, and the callout box "Applying sea level rise scenarios" provides application guidance. The following section summarizes the new science and discusses Maine's adopted sea level rise targets relative to the updated scenarios in Sweet et al. (2022). ***In summary, the "commit to manage" targets remain unchanged, while the timing of the "prepare to manage" targets should be shifted two decades later.***

Maine's "commit to manage" sea level rise scenario (1.5 feet by 2050 and 4 feet by 2100, relative to 2000 mean sea level) remains within the statistically likely range of the equivalent sea level rise scenario in updated projections. Maine's "commit to manage" sea level rise targets are based on the Intermediate scenario from Sweet et al. (2017). These targets still fall within the statistically likely range of the updated Intermediate scenario (Sweet et al., 2022) averaged across Maine's tide gauges (0.9 to 1.5 feet by 2050 and 2.6 to 4.3 feet by 2100, relative to 2000 mean sea level). **Figure 3** shows historical measured sea level, along with three future sea level rise scenarios from the U.S. Interagency Task Force Report (Sweet et al., 2022) and Maine's "commit to manage" sea level rise values for 2050 and 2100 for Eastport, Bar Harbor, and Portland.

Updated projections indicate that the timeframe of Maine's "prepare to manage" sea level rise scenario (3 feet by 2050 and 8.8 feet by 2100, relative to 2000 mean sea level) should be shifted two decades later, to 3 feet by 2070 and 8.8 feet in the 2120s. Maine's "prepare to manage" scenario, based on the Sweet et al. (2017) High scenario (3 and 8.8 feet for 2050 and 2100, respectively) now falls outside of the statistically likely range of the updated Sweet et al. (2022) High scenario averaged across Maine's three tide gauges (1.0 to 2.0 feet for 2050 and 4.3 to 7.5 feet for 2100). This is largely due to updated science indicating that ice sheet contributions to sea level rise, which remain highly uncertain, are likely to occur later than previously thought. Maine's "prepare to manage" values of 3 and 8.8 feet for 2050 and 2100, respectively fall within the statistically likely range of the updated High scenario two decades later, such that 3 feet of rise by 2050 shifts to 3 feet of rise by 2070, and 8.8 feet shifts from 2100 to 2120 (**Figure 3**).

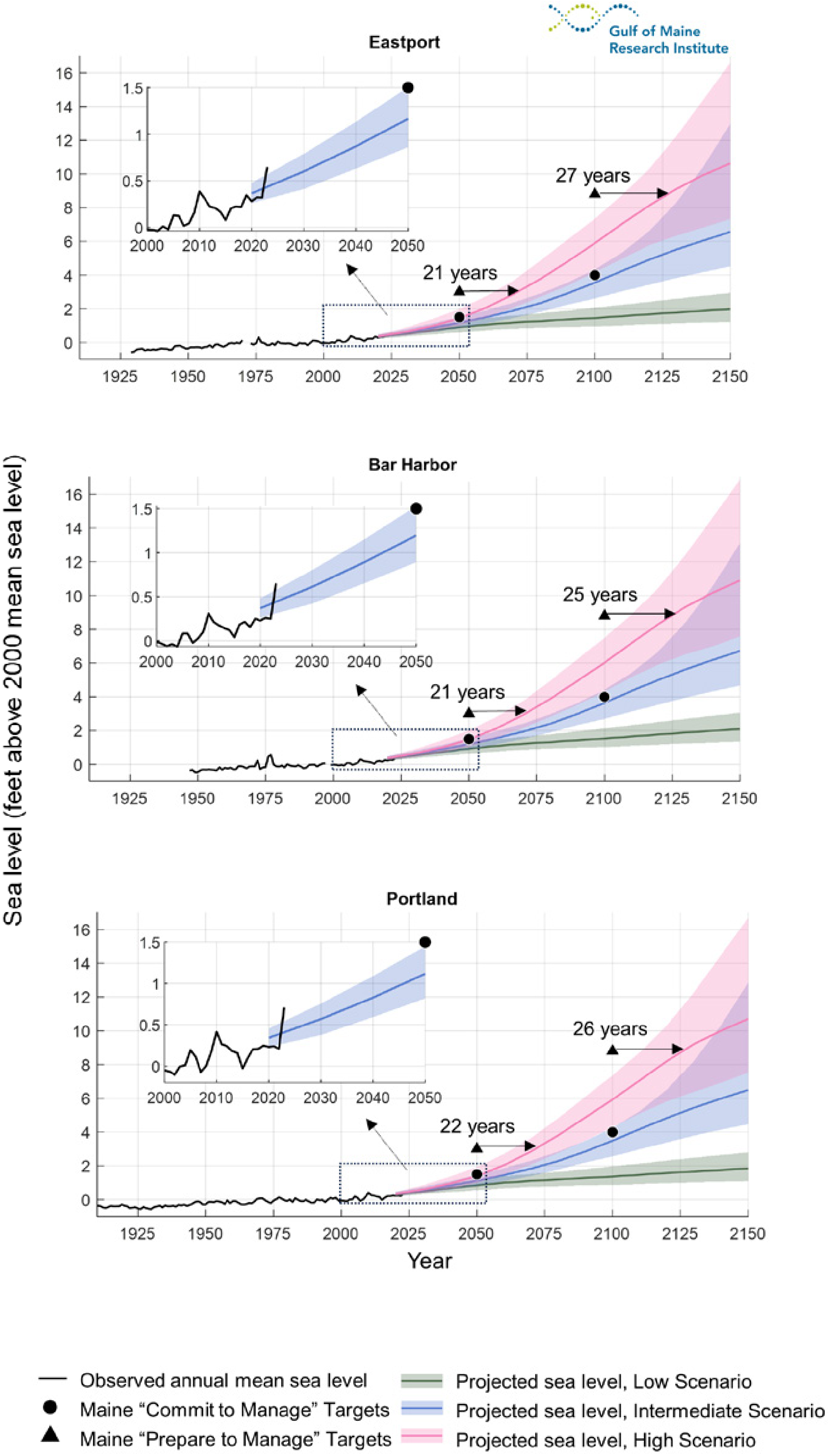
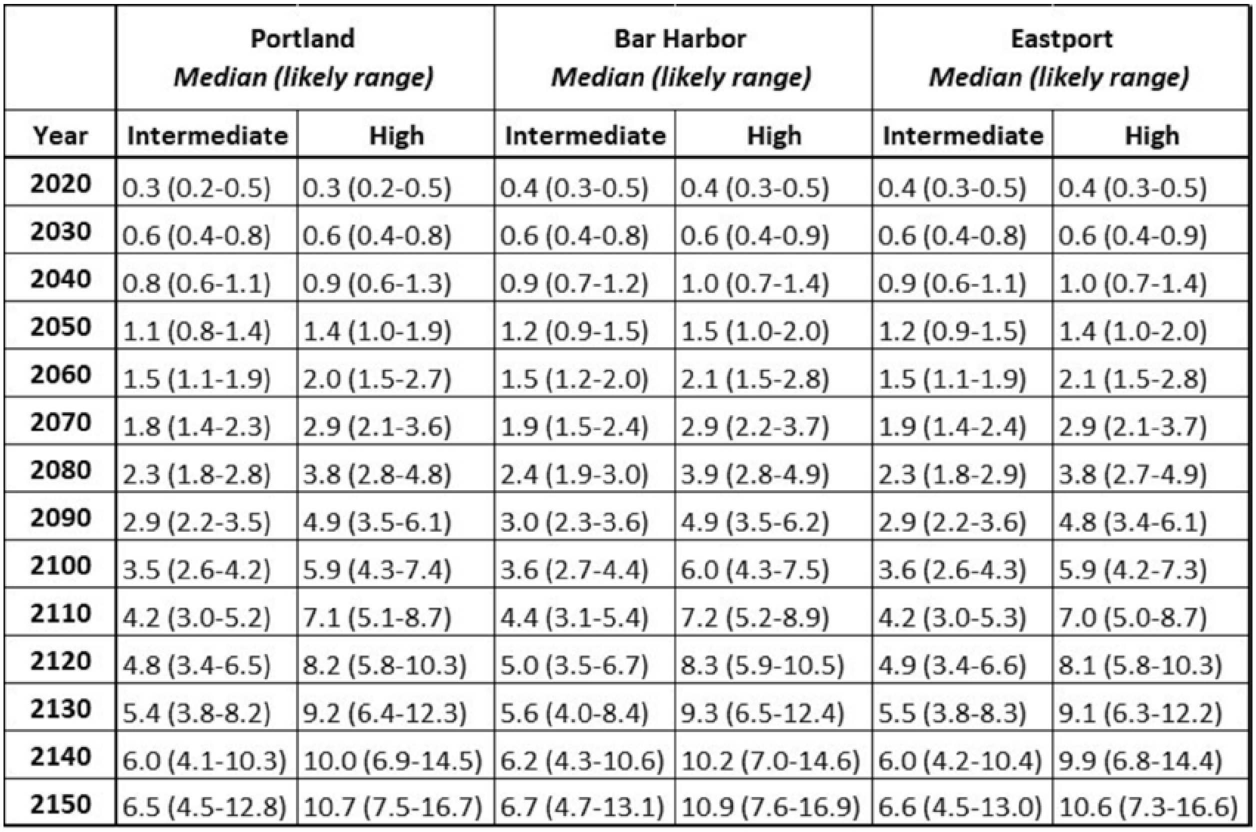


Figure 3. Observed and projected sea level rise in Portland, Bar Harbor, and Eastport. The black line shows measured annual mean sea level from the beginning of each tide gauge record (1912 for Portland, 1947 for Bar Harbor, and 1929 for Eastport) through 2023. Green, blue, and pink lines and shading show projected future sea level rise 2020 through 2150 for the Low, Intermediate, and High scenarios, respectively, from the 2022 U.S. Interagency Task Force report (Sweet et al., 2022; see **Table 3** for tabulated values by decade). Lines show median estimates, and the shaded regions show the statistically likely range (17th to 83rd percentile) for each scenario. Black circles on each panel mark Maine's "Commit to Manage" targets of 1.5 ft of sea level rise in 2050 and 4 ft in 2100. Black triangles show the high-end "Prepare to manage" targets of 3 ft and 8.8 ft. These values were consistent with the High scenario from the 2017 sea level technical report (Sweet et al., 2017) used by the 2020 STS report, and the horizontal arrows indicate that under the updated High scenario, these amounts of sea level rise are expected to occur 21 to 27 years later. Insets in the upper-left corner of each panel show a close-up view of measured and Intermediate scenario projected sea level rise between 2000 and 2050.



	Portland *Median (likely range)*		Bar Harbor *Median (likely range)*		Eastport *Median (likely range)*	
Year	**Intermediate**	**High**	**Intermediate**	**High**	**Intermediate**	**High**
2020	0.3 (0.2-0.5)	0.3 (0.2-0.5)	0.4 (0.3-0.5)	0.4 (0.3-0.5)	0.4 (0.3-0.5)	0.4 (0.3-0.5)
2030	0.6 (0.4-0.8)	0.6 (0.4-0.8)	0.6 (0.4-0.8)	0.6 (0.4-0.9)	0.6 (0.4-0.8)	0.6 (0.4-0.9)
2040	0.8 (0.6-1.1)	0.9 (0.6-1.3)	0.9 (0.7-1.2)	1.0 (0.7-1.4)	0.9 (0.6-1.1)	1.0 (0.7-1.4)
2050	1.1 (0.8-1.4)	1.4 (1.0-1.9)	1.2 (0.9-1.5)	1.5 (1.0-2.0)	1.2 (0.9-1.5)	1.4 (1.0-2.0)
2060	1.5 (1.1-1.9)	2.0 (1.5-2.7)	1.5 (1.2-2.0)	2.1 (1.5-2.8)	1.5 (1.1-1.9)	2.1 (1.5-2.8)
2070	1.8 (1.4-2.3)	2.9 (2.1-3.6)	1.9 (1.5-2.4)	2.9 (2.2-3.7)	1.9 (1.4-2.4)	2.9 (2.1-3.7)
2080	2.3 (1.8-2.8)	3.8 (2.8-4.8)	2.4 (1.9-3.0)	3.9 (2.8-4.9)	2.3 (1.8-2.9)	3.8 (2.7-4.9)
2090	2.9 (2.2-3.5)	4.9 (3.5-6.1)	3.0 (2.3-3.6)	4.9 (3.5-6.2)	2.9 (2.2-3.6)	4.8 (3.4-6.1)
2100	3.5 (2.6-4.2)	5.9 (4.3-7.4)	3.6 (2.7-4.4)	6.0 (4.3-7.5)	3.6 (2.6-4.3)	5.9 (4.2-7.3)
2110	4.2 (3.0-5.2)	7.1 (5.1-8.7)	4.4 (3.1-5.4)	7.2 (5.2-8.9)	4.2 (3.0-5.3)	7.0 (5.0-8.7)
2120	4.8 (3.4-6.5)	8.2 (5.8-10.3)	5.0 (3.5-6.7)	8.3 (5.9-10.5)	4.9 (3.4-6.6)	8.1 (5.8-10.3)
2130	5.4 (3.8-8.2)	9.2 (6.4-12.3)	5.6 (4.0-8.4)	9.3 (6.5-12.4)	5.5 (3.8-8.3)	9.1 (6.3-12.2)
2140	6.0 (4.1-10.3)	10.0 (6.9-14.5)	6.2 (4.3-10.6)	10.2 (7.0-14.6)	6.0 (4.2-10.4)	9.9 (6.8-14.4)
2150	6.5 (4.5-12.8)	10.7 (7.5-16.7)	6.7 (4.7-13.1)	10.9 (7.6-16.9)	6.6 (4.5-13.0)	10.6 (7.3-16.6)

Table 3. Updated U.S. Interagency Task Force sea level rise scenarios at Maine's three long-term tide gauge (Sweet et al., 2022) for each decade from 2020 through 2150. The table lists median estimates, followed by the statistically likely range in parentheses (17th to 83rd percentile range). Values are in feet above 2000 mean sea level, which is roughly 4 inches (0.3 feet lower than present-day (early-2020s) mean sea level in Maine.

Applying Sea Level Rise Scenarios

The recommended "commit to manage" and "prepare to manage" sea level rise values provide general statewide guidance for the years 2050 and 2100. For planning applications at specific locations and over specific time periods, Sweet et al. (2022) provides more locally accurate projections (i.e., smaller-scale than the state level) at a decadal time resolution (every 10 years). The state's "commit to manage" targets are consistent with the Sweet et al. (2022) Intermediate scenario, and "prepare to manage" targets are consistent with the High scenario. The choice of which scenario to use depends on the risk associated with flooding of the asset under consideration.

In the vicinity of a long-term tide gauge (Portland, Bar Harbor, or Eastport), sea level rise projections at the location of that gauge should be used (**Table 3** and **Tables E2–4** in Appendix E). For locations between tide gauges, Sweet et al. (2022) provides gridded projections for every one degree latitude by one degree longitude area. This divides Maine's coastline into 5 regions and provides more locally accurate projections for communities that are far from Portland, Bar Harbor, or Eastport. **Table E1** in Appendix E includes these gridded projections and discusses spatial variability in sea level rise along Maine's coast. Maine Projections have been synthesized into the tables in this report, and they can be directly accessed through NASA's Interagency Sea Level Rise Scenario Tool: https://sealevel.nasa.gov/task-force-scenario-tool by simply clicking on a location along the Maine coastline.

The Possibility of Rapid Acceleration in Sea Level Rise

A possible order-of-magnitude increase in the rate of sea level rise at the end of the 21st century may cause physical impacts that outpace planning and adaptation efforts, highlighting the need for planning beyond 2100. Sea level is currently rising about 1.2 inches (0.1 feet) per decade in Maine. In 2100, this rate would increase to 8.4 inches (0.7 feet) per decade under the Intermediate scenario and 14.4 inches (1.2 feet) per decade under the High scenario (**Figure 4**; Sweet et al., 2022). The acceleration is driven by the possibility of ice sheets (Greenland, West Antarctica, East Antarctica) reaching critical thresholds where ice loss would continue regardless of emissions reductions (e.g. Fox-Kemper et al., 2021; Lenton et al., 2023; Sweet et al., 2022). It is also critical to plan beyond 2100 because it is highly likely that sea level will continue to rise beyond 2100. Sea level rise scenarios are provided out to 2150, consistent with the Intergovernmental Panel on Climate Change (IPCC) (Fox-Kemper et al., 2021) and the U.S. Government's Fifth National Climate Assessment (May et al., 2023), even though there is uncertainty in the amount and rate of sea level rise, especially beyond 2050.

The major driver of uncertainty in sea level rise projections, especially beyond 2050, is the highly emissions-dependent response of ice sheets to warming. Research around the response of ice sheets to warming climate is rapidly advancing. Several new studies point to ice sheet instability thresholds either already being exceeded, or being exceeded with sustained warming above 2°C (e.g., DeConto et al., 2021; Stokes et al., 2022). These processes include

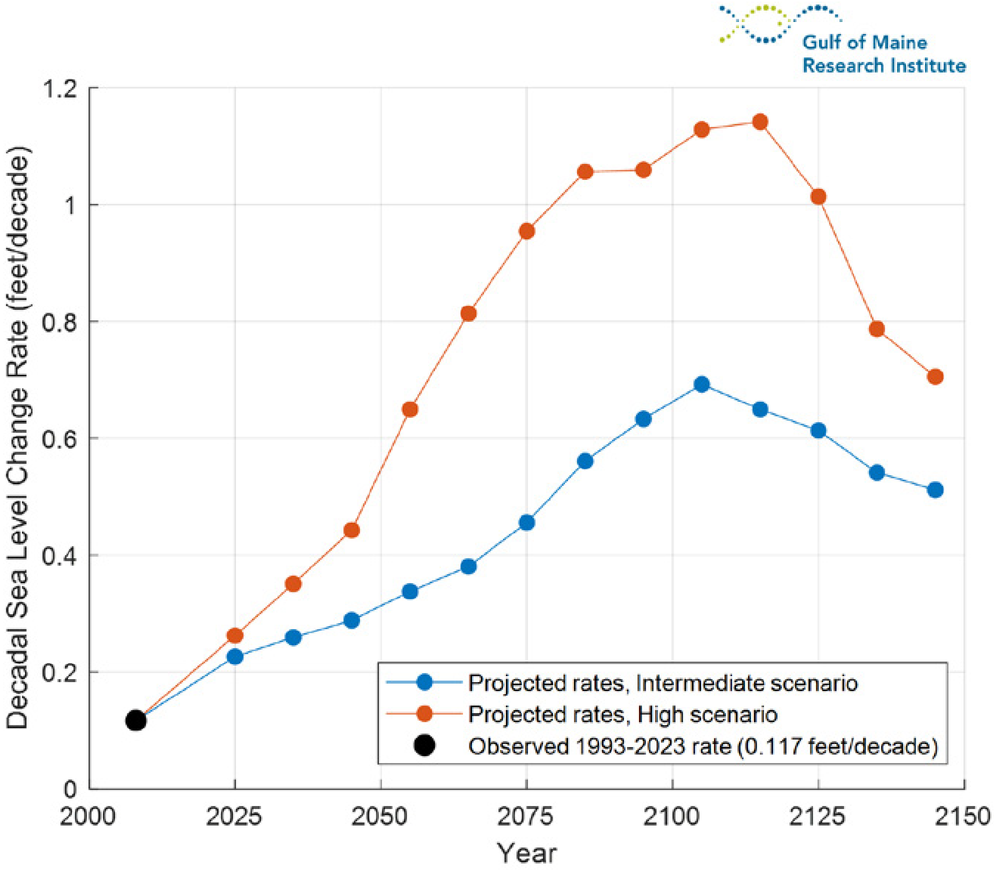


Figure 4. Projected future rates of relative sea level rise in Portland under the Intermediate and High scenarios (Sweet et al., 2022), relative to the observed rate over the past 30 years at the Portland tide gauge (NOAA Station 8418150).

early disintegration of ice sheets in Antarctica; abrupt onset of marine ice-sheet instability and/or marine ice-cliff instability in Antarctica; and ice loss on Greenland due to changes in atmospheric circulation, cloud processes, and albedo changes (Sweet et al., 2022). Appendix F summarizes significant new literature on ice sheet instabilities. Temperature thresholds and the physical drivers of instability are different across the Greenland Ice Sheet, West Antarctic Ice Sheet, marine basins of the East Antarctic Ice Sheet, and non-marine parts of East Antarctica (see Lenton et al., 2023). It is highly uncertain whether temperature stability thresholds for ice sheets can be temporarily overshot without the ice sheets collapsing, and policy decisions should not rely on this possibility (Lenton et al., 2023). However, a handful of recent studies indicate that temperature overshoot may not lead to ice sheet collapse if the overshoot time is short relative to the timescales of ice sheet response to warming (Bochow et al., 2023; Ritchie et al., 2021).

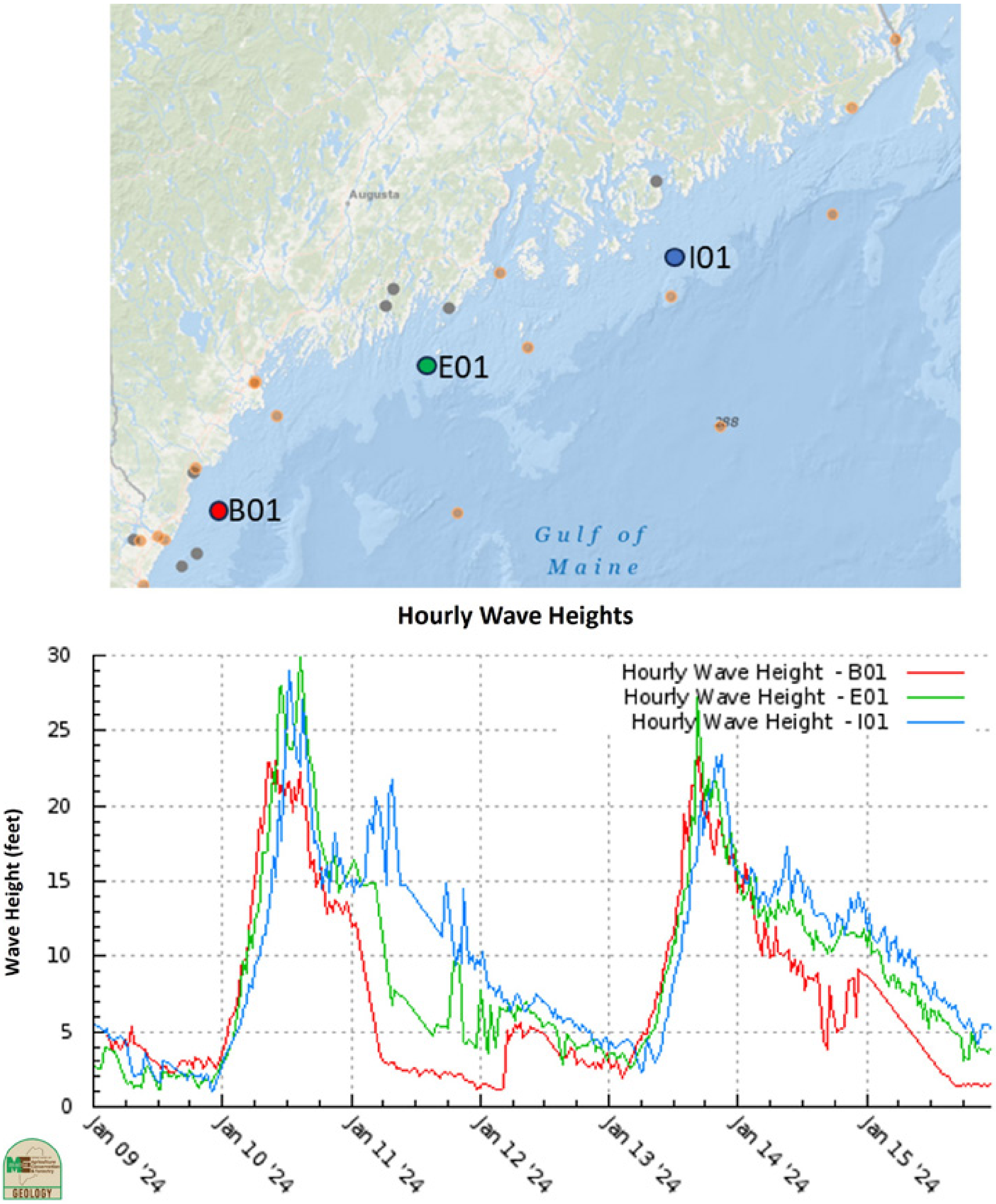
The Sweet et al. (2022) Intermediate, Intermediate-High, and High sea level rise scenarios are all more likely to be associated with these uncertain ice sheet processes. Even under the IPCC's highest emissions scenario (5.0°C of warming at the end of the century), without sea level contributions from ice sheet instabilities, there is a less than 23% chance of exceeding the Intermediate sea level rise scenario and a less than 1% chance of exceeding the High scenario. If ice sheet instabilities are triggered, there is an estimated 7% chance of exceeding the Intermediate scenario in 2100 with 1.5°C of warming and a 49% chance of exceeding it with 5.0°C of warming (Fox-Kemper et al., 2021; Sweet et al., 2022).

Coastal Storms

Historically, extratropical storms, which are storms that occur late-fall through early-spring, have been the primary driver of flooding in the Gulf of Maine. In contrast with tropical storms, extratropical storms are more frequent, following tracks that generate sustained onshore winds, and have longer durations that make them more likely to overlap with high tides (Baranes et al., 2020; Douglas & Kirshen, 2022; Kirshen et al., 2008; Talke et al., 2018). Tropical cyclone (hurricane) intensity has increased in the North Atlantic, but this increase has not been connected with increasing surge intensity in the Gulf of Maine (Garner, 2023; Kossin et al., 2020; Majumdar et al., 2023; Marsooli et al., 2019). There is also evidence for future changes in extratropical cyclone activity globally, but there is not evidence that storm surges will become larger or more frequent with future warming in the Gulf of Maine (Lin et al., 2019). However, as sea level rises, the same surges superimposed on higher sea levels will make coastal flooding and inundation more frequent and severe.

It is uncertain whether climate change is driving changes in wave characteristics for average or extreme conditions. Waves drive additional increases in water levels above high tides and surge during coastal storms, and they can be a dominant cause of erosion and damage. Waves can make up 20-39% percent of total extreme coastal water levels in the Gulf of Maine (Sweet et al., 2022; Vitousek et al., 2017; however there has not been a detailed study on whether climate change is changing the wind-wave climate in the Gulf of Maine and how that might contribute to extreme water levels. The IPCC indicates medium confidence in projected changes in mean wave climatology but low confidence in projections of extreme wave conditions (Fox-Kemper et al., 2021). A recent study found that coastal wave energy has been increasing in most of the world since the 1980s, including the North Atlantic Ocean (Aster et al., 2023), yet another study projected a decrease in mean significant wave heights by as much as 10% in the North Atlantic for a high-end emissions scenario (RCP8.5) due to a lesser meridional temperature gradient (warming poles), therefore weakening winds (Morim et al., 2019). Despite uncertainty in future wind-wave conditions (Ardhuin et al., 2019), relative sea level change is expected to be the main driver of increased future flood hazard (Fox-Kemper et al., 2021).

Impacts of the two January 2024 storms were also compounded by rain and snowmelt associated with warm temperatures. Rain falling on snow on January 10 elevated river flow, leading to joint coastal-riverine flooding in communities along tidal rivers, such as Machias and Bath. On January 13, two inches of rain fell in Portland while storm drain outfalls were blocked by high coastal water levels, leading to widespread rain-driven flooding of major roadways.



Buoy data rom NERACOOS.org

Figure 5. Upper image: Locations of wave buoys B01, E01, and I01 along the Maine coastline. Lower image: Plot of hourly significant offshore wave heights (the average height of the largest one-third of recorded waves) from buoys located offshore of the southern (B01, red line), midcoast (E01, green line) and downeast (I01, blue line) coastlines. Significant wave heights along the midcoast and downeast coastlines during the January 10, 2024 storm reached almost 30 feet, and exceeded 20 feet along the southern coastline. On January 13, 2024, wave heights exceeded 20 feet along the entire coast.

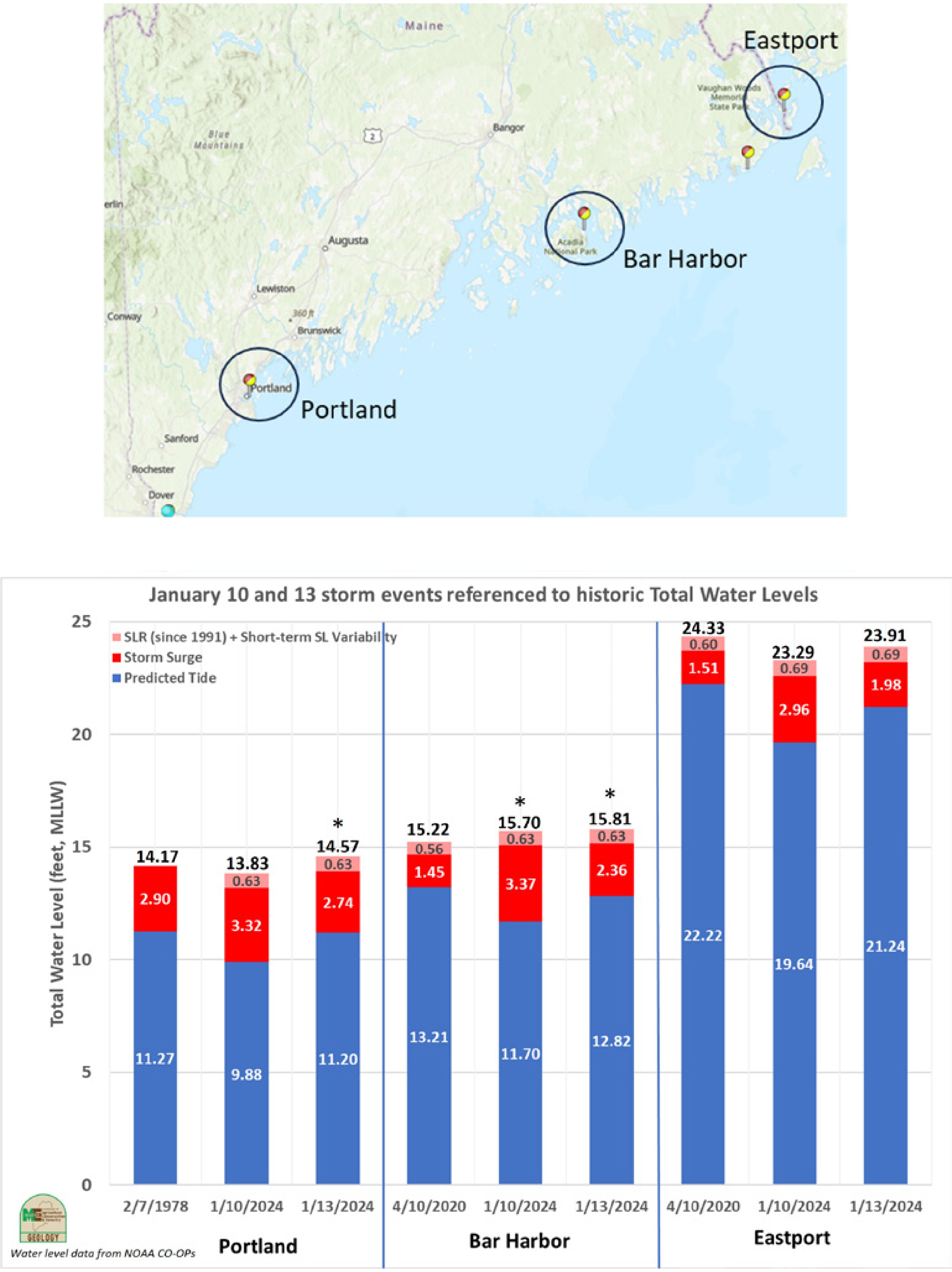


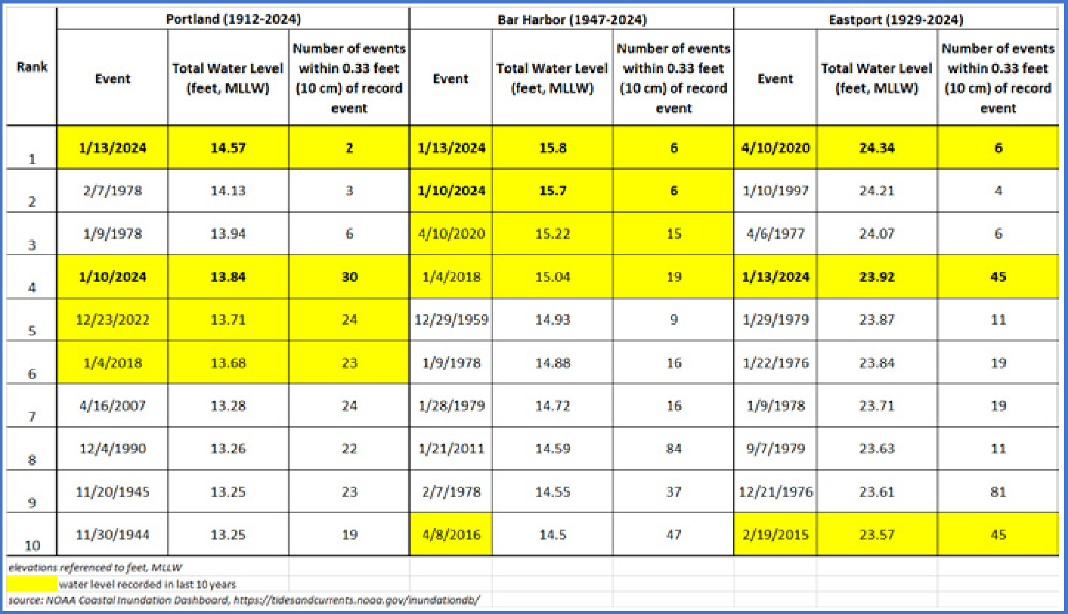
Figure 6. Upper image: Locations of long-term tide gauges at Portland, Bar Harbor, and Eastport. Lower image: Graph showing total water level components (predicted tide, storm surge, and difference in mean sea level) recorded at Portland, Bar Harbor, and Eastport for the January 10 and 13, 2024 storm events in reference to the historic high total water level at each gauge. The predicted tide (based on NTDE mean sea level 1983-2001, which has a midpoint of 1991; see callout box "Water level datums and baselines") is shown in blue. The dark red represents storm surge, and light red represents the difference between January 2024 mean sea level and 1983-2001 mean sea level. Asterisks denote where the January 10 or January 13, 2024 events set new water level record event or greater. For example, although the January 10, 2024 storm led to the 4th highest total water level in Portland, there have been 30 similar storm tides. This indicates that a relatively moderate combination of tide and surge led to extreme flooding because sea level was high.

Recent Extreme High Water Events and Storms with Southeasterly Winds

The majority of Maine's most extreme coastal flooding events over the past century have occurred in recent decades due to the long-term increase in sea level. These events include the January 2018 and April 2020 nor'easters, and three recent southeasters on December 23, 2022 (Winter Storm Elliott) and back-to-back southeasters on January 10 and 13, 2024. Winter Storm Elliott resulted in damages to coastal public infrastructure totaling $3.3 million across six different counties (including roads, culverts, and piers, and excluding private homes, commercial infrastructure, etc.) (S. Roy, personal communication, October 2023). The January 2024 storms inundated low-lying roads and buildings; destroyed piers, wharves, and seawalls; and eroded coastal sand dunes and bluffs. According to the State's filing with FEMA for federally-declared disaster aid for Washington, Hancock, Waldo, Knox, Lincoln, Sagadahoc, Cumberland and York counties, a total of 2,007 Individuals and Households Damage Assessments and 1,181 Business and Agriculture Damage Assessments were received; $70.3 million in public infrastructure damages were reported from the two storms.

Extreme coastal flooding is caused by the combined impacts of high sea level, high tides, storm surge, waves, and, in some areas, precipitation and river flow (Appendix G **Figure G1**). The two January 2024 events were concurrent with the significant increase in sea level that began in early 2023. On January 10, 2024, strong winds out of the southeast raised offshore waves heights to nearly 30 feet, while the January 13, 2024 event resulted in waves between 20 and 25 feet, bringing particularly devastating impacts to Maine's southeast-facing open ocean coastal areas (**Figure 5**). The January 13, 2024 event was an example of moderate storm surge combining with a high astronomical tide, whereas the January 10, 2024 storm drove extreme storm surge and waves on top of a near-average high tide (**Figure 6**). New total water level records were set at Portland and Bar Harbor on January 13, 2024. It is currently unknown whether climate change is affecting the timing of or wind direction associated with coastal storms in the Gulf of Maine.

The January events set total water level records at Portland and Bar Harbor, and came in within the top 5 at Eastport (**Table 4**). Removing sea level rise and variability from the three tide gauge records shows that the combination of high tide and surge (called storm tide) on January 10 and 13 are not historically unprecedented, and high sea level is what caused the events to break records (see the "Number of events within 0.33 feet (10 cm) of record event" column in **Table 4**). For example, in Portland, the Blizzard of '78 storm tide was similar to the January 13, 2024 storm tide, and there have been 30 storm tides equivalent to or greater than the January 10, 2024 storm tide since 1912. record event or greater. For example, although the January 10, 2024 storm led to the 4th highest total water level in Portland, there have been 30 similar storm tides. This indicates that a relatively moderate combination of tide and surge led to extreme flooding because sea level was high.



Rank	Portland (1912-2024)			Bar Harbor (1947-2024)			Eastport (1929-2024)		
	Event	Total Water Level (feet, MLLW)	Number of events within 0.33 feet (10 cm) of record event	Event	Total Water Level (feet, MLLW)	Number of events within 0.33 feet (10 cm) of record event	Event	Total Water Level (feet, MLLW)	Number of events within 0.33 feet (10 cm) of record event
1	**1/13/2024**	**14.57**	**2**	**1/13/2024**	**15.8**	**6**	**4/10/2020**	**24.34**	**6**
2	2/7/1978	14.13	3	**1/10/2024**	**15.7**	**6**	1/10/1997	24.21	4
3	1/9/1978	13.94	6	4/10/2020	15.22	15	4/6/1977	24.07	6
4	**1/10/2024**	**13.84**	**30**	1/4/2018	15.04	19	**1/13/2024**	**23.92**	**45**
5	12/23/2022	13.71	24	12/29/1959	14.93	9	1/29/1979	23.87	11
6	1/4/2018	13.68	23	1/9/1978	14.88	16	1/22/1976	23.84	19
7	4/16/2007	13.28	24	1/28/1979	14.72	16	1/9/1978	23.71	19
8	12/4/1990	13.26	22	1/21/2011	14.59	84	9/7/1979	23.63	11
9	11/20/1945	13.25	23	2/7/1978	14.55	37	12/21/1976	23.61	81
10	11/30/1944	13.25	19	4/8/2016	14.5	47	2/19/2015	23.57	45

elevations referenced to feet, MLLW

🟨 water level recorded in last 10 years

source: NOAA Coastal Inundation Dashboard, https://tidesandcurrents.noaa.gov/inundationdb/

Table 4. Top 10 water levels, referenced to feet. MLLW, for Portland, Bar Harbor, and Eastport. The January 2024 events (bolded) set records at Portland and Bar Harbor and recorded a total water level within the top 4 at Eastport. Events that occurred within the last 10 years are highlighted in yellow. The "Number of events within 0.33 feet (4 inches/10 cm) of record event" column shows the number of historical events where, if sea level rise and variability is removed from the tide gauge record, the combination of high tide and surge was within 4 inches (10 cm) of the record event or greater. For example, although the January 10, 2024, storm led to the 4th highest total water level in Portland, there have been 30 similar storm tides. This indicates that a relatively moderate combination of tide and surge led to extreme flooding because sea level was high.

COASTAL FLOODING

In Portland, sea level rise has caused coastal flooding to occur about three times more often since 2010, compared to the average frequency of flooding over the past century. Flood stage (the water level at which flooding begins to occur) in Portland is 12 ft above mean lower low water (MLLW). This relationship between water level and flood impact was established by the National Weather Service's (NWS) Advanced Hydrologic Prediction Service (AHPS) based on observations. From 1912 through 2023, flood stage has been reached or exceeded four days per year on average (**Figure 7**). Since the year 2000, flood frequency has increased to an average of 10 days per year, and since 2010, an average of 12 days per year, roughly three times the historic rate. Specific information about evolving flood frequency is only available where there are long-term, co-located water level and flood impact observations (e.g. tide gauges and NWS AHPS-established flood impact thresholds).

The frequency of minor high tide flooding will increase over the next decade, driven by sea level rise and an increasing tidal range induced by a lunar cycle. High tide flooding, also called "nuisance flooding," is routine flooding that is not a serious threat to public safety but can overwhelm stormwater systems, close roads, and deteriorate infrastructure by repeated salt exposure (e.g. Sweet et al., 2020). Even under a regime of slow and steady sea level rise, projections show that the frequency of flooding increases dramatically. This is because more frequently-occuring "routine" high tides, rather than just the few highest tides of the year, can cross flood thresholds on top of a higher baseline sea level.

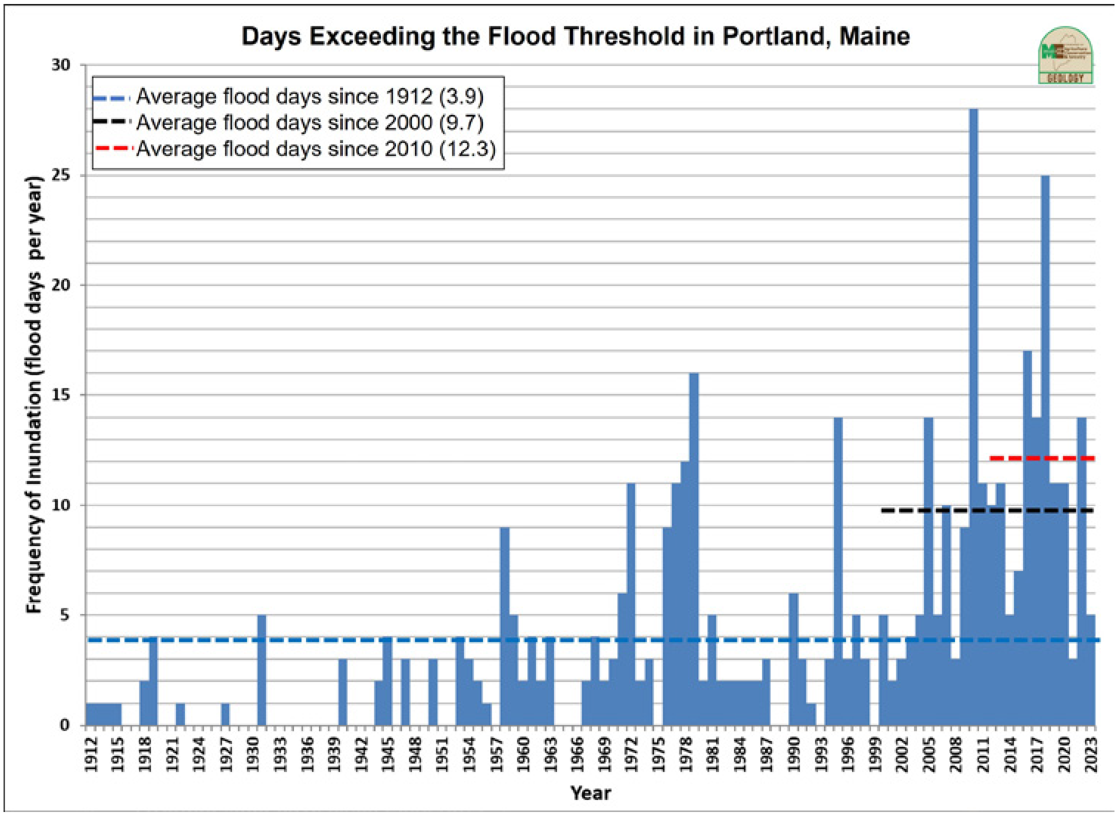


Figure 7. Days per year that exceeded flood stage in Portland, Maine since 1912. Per NOAA Center for Operational Oceanographic Products and Services (CO-OPS), a flood day occurs when verified hourly water levels exceed a flood threshold for at least one hour. In Portland, the NWS AHPS minor flood threshold is defined as 12 feet MLLW.

There is also significant monthly to decadal timescale variability in flood frequency that will lead to periods of enhanced flooding. The 18.6-year lunar nodal cycle, or the precession of the moon's elliptical orbit, causes tidal range to vary on an 18.6-year cycle and has significant implications for flooding in the Gulf of Maine over the next decade. The nodal cycle causes the annual 90th percentile higher high water to vary by about 1.2 inches (0.1 feet) in Portland, 2 inches (0.2 feet) in Bar Harbor, and 4.8 inches (0.4 feet) in Eastport (**Figure G2** in Appendix G; note that the effect of the nodal cycle is largest Downeast because of the larger tidal range). In other words, the highest high tides of the year decrease

The NASA Flooding Analysis Tool

Projections of high tide flooding days that account for sea level rise and tidal and climatic variability are provided by NASA. The NASA Flooding Analysis Tool provides projections of high tide flooding frequency at Portland, Bar Harbor, and Eastport. These projections incorporate the localized sea level rise scenarios used in this report (Sweet et al., 2022), future tides, and ensemble projections of monthly mean sea level that vary due to fluctuations in temperature, salinity, wind, atmospheric pressure, and ocean currents (Thompson et al., 2021). Users can input a flood threshold and view how frequently it will be exceeded in the future under various sea level rise scenarios, for both the average future month, and the most extreme month where variability in tides and monthly mean sea level combine to worsen flooding. **Figure 8** is a screen capture from the NASA Flooding Analysis Tool, showing projected flooding days per month in Portland for a flood threshold of 12 ft MLLW (Portland's observation-based flood stage) and the Intermediate sea level rise scenario (Maine's adopted scenario). Since 2010, flood stage has been exceeded an average of 12 days per year in Portland (**Figure 7**), and under the Intermediate sea level rise scenario, there will be a significant increase by the early 2030s, in part due to sea level rise, and in part due to the 18.6-year nodal cycle peaking and causing higher high tides in the mid-2030s. In the 5-year period from 2030 through 2034, Portland is likely to experience an average of two to three flooding days per month (24 to 36 flooding days per year) and nine to 14 flooding days per month in the most extreme month. In the early 2050s under the Intermediate scenario, flooding frequency further increases to an average of seven to nine flooding days per month (84 to 108 flooding days per year), and 17 to 21 flooding days per month in the most extreme month. **By 2100, Portland will experience minor flooding nearly every day.** The NASA Flooding Analysis tool also provides flooding day projections for Bar Harbor and Eastport, but there are no established observation-based flood thresholds at those locations.

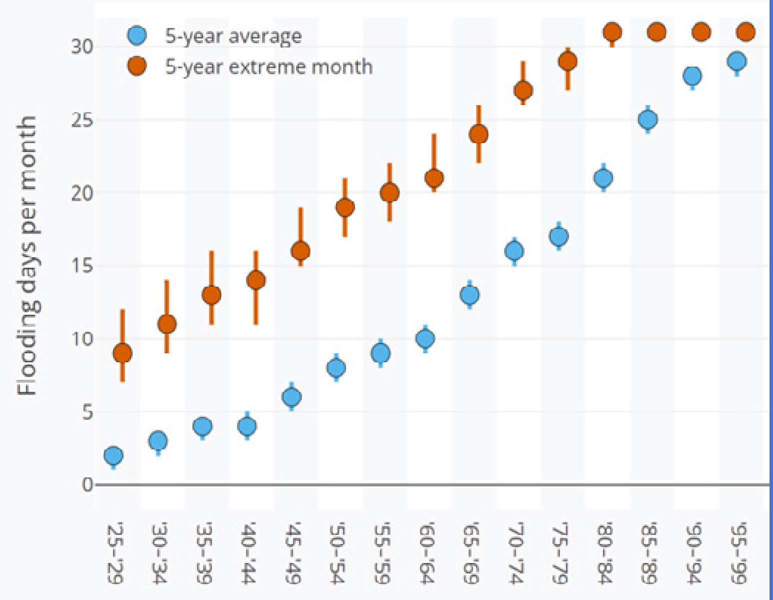


Figure 8. Projected flooding days per month (days where water level exceeds 12 ft MLLW) for 5-year periods from 2025 through 2099 at the Portland tide gauge under the Intermediate sea level rise scenario. Blue circles show the average number of flooding days per month over each five-year period, whereas the red circles show the number of flooding days for the most severe month of each five-year period. Vertical lines show the statistically likely range for each value (17th to 83rd percentile). By the early 2050s under the Intermediate sea level rise scenario, Portland is expected to experience an average of seven to nine flooding days per month, but up to 17 to 21 flooding days per month in the most extreme month. By 2100, Portland is expected to flood nearly every day. Data and figure courtesy of the NASA Flood Analysis Tool.

by 1.2 to 4.8 inches (0.1 to 0.4 feet) over a decade, then increase by 1.2 to 4.8 inches (0.1 to 0.4 feet) over the following decade. By comparison, the rate of sea level rise over the past 30 years is 1.4 inches (0.12 feet) per decade.

The nodal cycle caused astronomical high tides to peak around 2015; thus, over the past decade, tidal range has generally been decreasing, counteracting sea level rise to slow the increase in frequency of flooding. This does not mean the frequency of flooding has been decreasing overall. The nodal cycle affects the vertical distance between high and low tide but not mean sea level; in fact, Maine has still had record-high mean sea levels during the 2023 calendar year that have driven frequent flooding despite tidal range being below average. Between 2024 and 2025, the nodal cycle will reach a minimum and begin increasing tidal range through the mid-2030s, such that increasing high tide heights will combine with sea-level rise to accelerate the increase in flood frequency (Baranes et al., 2020; Peng et al., 2019).

We provide updated present-day and future extreme water level probabilities at Maine's three long-term tide gauges that can be applied in the vicinity of Portland, Bar Harbor, and Eastport and do not include waves. Figure 9, **Table 5**, and **Table E2** in Appendix E provide updated present-day and future extreme water level probabilities at Maine's three long-term tide gauges. We calculate joint tide-surge statistics using a robust joint probability model (see Baranes et al., 2020) and combine them with Maine's adopted Intermediate and High sea level rise scenarios. **Table 5** and the right-hand panels in **Figure 9** show the relationship between storm tide (tide plus surge, relative to annual mean sea level) and recurrence interval (the average number of years between flood events where a storm tide is reached or exceeded). These extreme storm tides can be added to sea level in any year to estimate flood recurrence intervals for that year. **Table E1** in AppendixE provides the one through 200-year recurrence interval water levels for the years 2020 through 2150 under the Intermediate and High sea level rise scenarios. As an example, the left-hand panels of **Figure 9** show the sea level rise-driven increase in the 100-year recurrence interval water level under the two scenarios.

There are several important considerations for applying tide gauge-based extreme water level statistics. First, they should only be applied in the vicinity of the Portland, Bar Harbor, and Eastport gauges because characteristics of flooding vary spatially depending on the geometry of the coastline, local oceanographic characteristics, the coastal environment, and other factors. Second, these statistics incorporate the flood hazard from sea level, tides, and storm surge, but not from waves. Maine's tide gauges are located in wave-sheltered harbors, so tide gauge-based extreme water level statistics cannot be used to characterize flood hazard in wave-exposed coastal areas. Finally, these statistics assume mean tidal and sea level conditions. Therefore, in storm seasons when mean sea level is high (as was the case in 2010 and 2023), the flood hazard would be higher. Astronomical cycles that cause tidal range to vary (such as the 18.6-year nodal cycle) also cause the height of extreme water levels to vary by roughly 1.2 inches (0.1 ft) in southern Maine and 4.8 inches (0.4 feet) Downeast. Practically, these sources of uncertainty are significantly smaller than uncertainty in sea level projections and similar in magnitude to statistical uncertainty. Maine's floodplain management standard of adding 1 foot of freeboard, or additional elevation, to design flood elevations for structures in flood zones helps account for this tidal and sea level variability.

It is unlikely that Maine would experience a tide-surge combination driving flooding multiple feet above the historical record; instead, sea level rise and variability drive severe flooding, as was the case for the January 2024 storms. An important feature to note about flood hazards in the Gulf of Maine is that extreme water levels do not rise significantly with increasing recurrence interval. For example, in Portland, the 10-year event is 1.1 feet higher than the highest astronomical tide, the 100-year event is 9.6 inches (0.8 feet) higher than the 10-year event, and the 200-year event is only 2.4 inches (0.2 feet) higher than the 100-year event (**Table 5**). This is because winter-season

Gulf of Maine
Research Institute

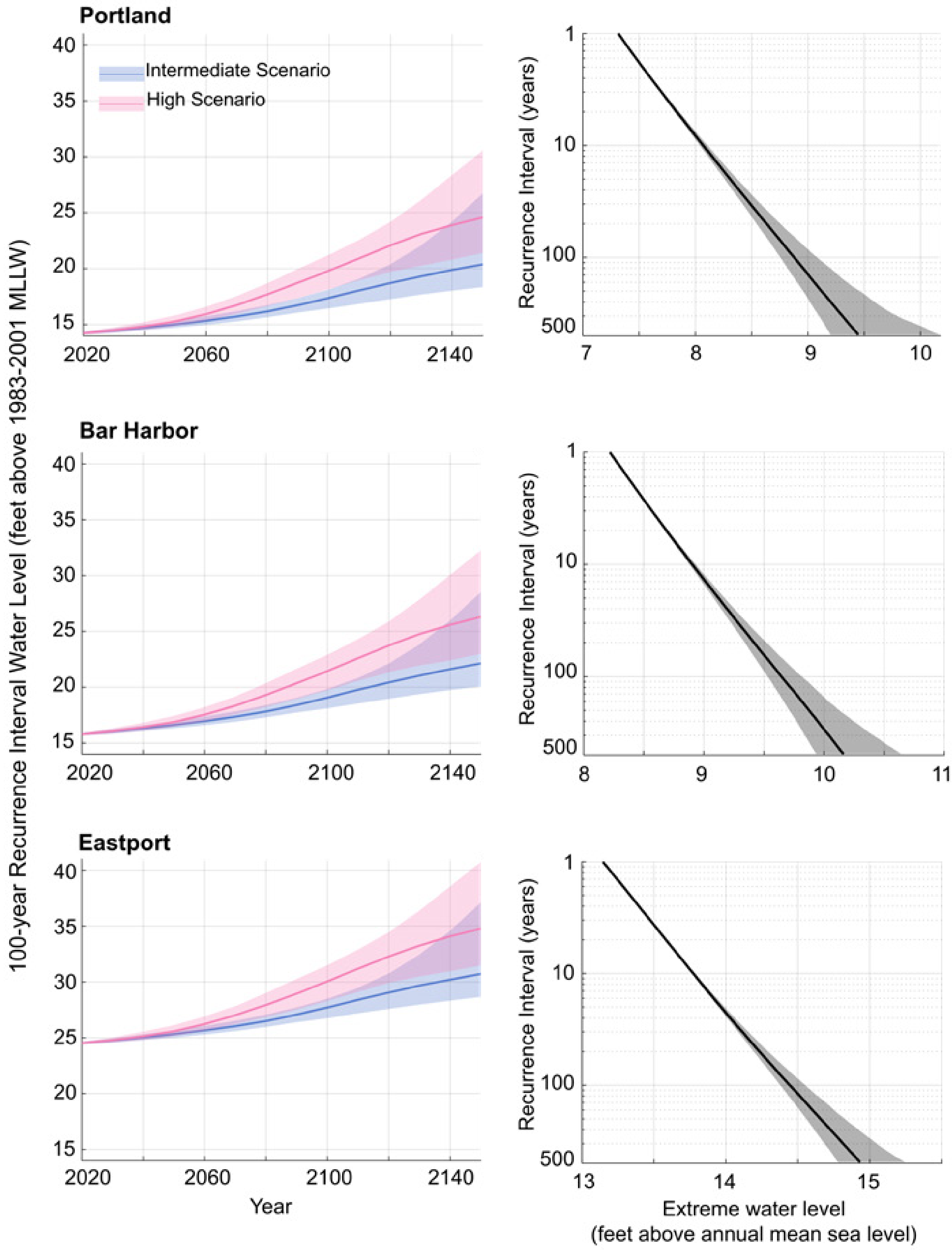


Figure 9. Left panels: Sea level rise-driven increase in the 100-year recurrence interval extreme water level (the water level with a 1% chance of occurring each year) under the Intermediate (blue) and High (pink) scenarios. Shaded areas show the 17th to 83rd percentile uncertainty range of sea level rise projections. Uncertainty due to interannual sea level variability and statistical uncertainty (shown in the right-hand panels) are not included. Water levels are shown relative to 1983-2001 (NTDE) MLLW because that is the datum used by the National Weather Service and most commonly used for tide predictions (see callout box "Water level datums and baselines" and Appendix D **Table D1** for conversions to other datums). Stations with larger tide ranges have higher values. **Table E1** in Appendix E provides extreme water level statistics for the years 2020-2150 and recurrence intervals ranging from 1 to 200 years under the Intermediate and High sea level rise scenarios. **Right panels:** The relationship between storm tide (tide plus surge) and recurrence interval relative to annual mean sea level (also provided in **Table 5**) for the 1-year recurrence interval storm tide (the storm tide that is, on average, met or exceeded annually) through the 500-year recurrence interval storm tide (the storm tide that has a 0.2% chance of being exceeded annually). These storm tides can be added to sea level in any year to estimate total extreme water level recurrence intervals for that year (shown in the left-hand panels for the 100-year recurrence interval water level). Black lines show the median estimate, and the shaded area shows the 17th to 83rd percentile statistical uncertainty. Note that x-axis scales do not match. Figures by Hannah Baranes, GMRI, following methods from Baranes et al. (2020).

		Storm tide (feet above annual MSL)		
Recurrence Interval (years)	Annual % chance of occurrence	Portland (HAT = 7.0)	Bar Harbor (HAT = 8.0)	Eastport (HAT = 13.1)
1	Annual	7.3	8.2	13.1
5	20%	7.8 (7.8-7.9)	8.7	13.6
10	10%	8.1 (8.0-8.1)	8.9	13.8
25	4%	8.4 (8.3-8.5)	9.2 (9.1-9.3)	14.0 (14.0-14.1)
50	2%	8.6 (8.5-8.8)	9.3 (9.3-9.5)	14.2 (14.2-14.3)
100	1%	8.9 (8.8-9.1)	9.6 (9.5-9.8)	14.4 (14.4-14.6)
200	0.5%	9.1 (9.0-9.4)	9.9 (9.7-10.1)	14.7 (14.6-14.8)

Table 5. Extreme storm tide probabilities, in feet above annual mean sea level (see callout box "Water level datums and baselines"). These values can be added to observed or projected sea level in any year to calculate extreme water levels for that year. Values in parentheses are the 17th to 83rd percentile uncertainty range (if an uncertainty range is not provided, it is because the range is less than 0.2 feet). Highest astronomical tide (HAT; see Appendix D, **Table D1**), which is exceeded 2-10 times per year on average, is provided for reference in the second row (determined from the NOAA CO-OPS Datums page for each tide gauge).

extratropical cyclones are the primary cause of flooding, and extratropical cyclone maximum wind speeds are less than half of tropical cyclone (hurricane) maximum wind speeds. The practical implication is that, if sea level were to remain constant, Maine would be highly unlikely to experience a tide-surge combination that drove flooding several feet higher than any event observed in the instrumental record. Rather, record-breaking severe flooding will be driven by sea level rise and variability, as was the case with the January 2024 storms. Conversely, in regions where tropical cyclones (hurricanes) drive flood hazard (i.e., the Atlantic eastern seaboard south of Cape Cod and in the Gulf of Mexico), extreme storms such as Hurricane Sandy and Hurricane Katrina drive flooding significantly higher than instrumental-era historical events.

FEMA provides maps that show the impact of tides, surge, and waves from 1% annual chance event for 1983-2001 sea level conditions. FEMA Digital Flood Insurance Rate Maps (DFIRMs) provide water surface elevations and flood maps for the "present-day" 1% annual chance event (called *base flood elevation*). The most recent FIRMs in Maine's coastal counties assume sea level is equivalent to NTDE mean sea level (mean sea level over the time period 1983-2001; see callout box "Water level datums and baselines"), which is roughly 4.8 inches (0.4 feet) lower than present-day sea level. Although these maps do not account for sea level rise, and therefore cannot be used to view future flood risk, they provide existing flood risk information at all locations along the coast (not just in the vicinity of tide gauges), and the base flood elevations include wave impacts. FEMA maps also designate whether areas are affected by waves with heights less than 1.5 feet (AE zones), 1.5 to 3 feet (Coastal A zones), or greater than 3 feet (VE zones). The Maine Floodplain Management Office maintains a Flood Hazard Map Application that shows the spatial extent of the FEMA flood hazard boundaries and the associated base flood elevations for different flood zones (in feet, referenced to NAVD88; see callout box "Water level datums and baselines"). Updated Digital Flood Insurance Rate Maps (DFIRMs) are being adopted in York and Cumberland Counties in summer 2024.

Hydrodynamic models that simulate storm events combined with various tides and sea level scenarios can provide spatially continuous present and future flood risk information that includes wave and riverine flooding impacts. Hydrodynamic flood models have several advantages over the simpler "bathtub modeling" approach, where design water elevations (often determine by linear addition of a design flood level and sea level rise) are translated to flooding depths and extents by simply mapping water levels onto topography, assuming that the landscape fills up like a bathtub with a consistently level water surface (this is the approach used by the Maine Geological Survey Sea Level Rise/Storm Surge viewer). Dynamic models simulate the flow of water in the ocean and over land, accounting for the fact that water surface does not stay level as it is moved by waves, winds, and currents during storms. Dynamic models also account for the fact that tides and surge may behave differently in deeper water as sea level rises. For example, tidal range and the height of storm surge may change with higher sea level. Appendix G describes a dynamic flood model that was developed for Portland, South Portland and Damariscotta (led by the Maine Silver Jackets), as well as a statewide coastal flood risk model that is under development and will likely be released in 2025 (led by Maine Department of Transportation). The updated DFIRMS for York and Cumberland Counties are also based on dynamic modeling.

Marshes, Mudflats, and Dunes

Some of Maine's salt marshes are building elevation at a slower rate than sea level is rising. A study of National Estuarine Research Reserves (NERRs) throughout New England, including Maine's Wells National Estuarine Research Reserve, documented existing high marsh plant communities transitioning to low marsh vegetation (Burdick et al., 2020). Low marsh areas are lower in elevation, more frequently inundated by high tide, and contain more salt and flood-tolerant vegetation. The regional NERRs study found that although monitored marshes are building elevation, accretion rates vary by marsh, and many marshes are not building elevation fast enough to keep pace with sea level rise (Burdick et al., 2020). For example, accumulation rates in a salt marsh at the mouth of the Kennebec River have accelerated since the 1960s, roughly matching the acceleration in the rate of relative sea level rise since 1900; however, measured accumulation rates do not account for the natural compaction of marsh sediment, and rates of sea level rise in the future may challenge current biological and geological feedbacks (Weston et al., 2023).

Some Maine marshes have available area to migrate inland, but a limited amount of that area is conserved, and there is more space available for marshes to migrate Downeast compared to southern Maine. A new analysis by the Maine Natural Areas Program (Puryear, 2023) quantifies the upland space available for marshes to migrate into in response to 1.6 and 3.9 feet of sea level rise (close to Maine's adopted scenarios of 1.5 feet by 2050 and 4.0 feet by 2100). With 1.6 feet of sea level rise, 11,539 acres of upland space are available for marsh migration, which is 64% of the current tidal marsh area (excluding Merrymeeting Bay). With 3.9 feet of sea level rise, 16,855 acres of upland space are available, or 93% of the current marsh area. These analyses use existing topography of the landscape, do not account for erosion or accretion of the marsh or adjacent landscapes, and do not consider that the rate of sea level rise may increase and outpace the ability of marshes to migrate landward. Therefore, it is unlikely that all viable migration space will be replaced by salt marsh (Puryear, 2023). Additionally, only 30% of the land area identified as potential marsh migration space is currently conserved (Ibid). **There is also six times less marsh migration space available south of Penobscot Bay than north of the bay.** This difference is due to more of the marsh migration space in southern Maine being developed or fragmented, such that marshes would migrate into small and often non-viable units that would inadequately replace lost marsh function. Consequently, marshes south of Penobscot Bay stand to be more adversely affected than those Downeast.

The potential impacts of sea level rise on mudflats and implications for intertidal habitat and the shellfish industry in Maine have not been well studied. Manomet, Inc., began a project in 2023 titled *Understanding sea level rise and coastal flooding impacts on mudflat habitat, shellfish resources, and harvester livelihood* in three Maine coastal communities (Scarborough, Penobscot, and Sipayik). The project is: 1) convening subject matter experts, shellfish harvesters, and managers to discuss what is known about sea level rise impacts to mudflats, identify knowledge gaps, and build partnerships for addressing those gaps; and 2) mapping the existing intertidal area with drones (determining extent and sediment characteristics) as a baseline for measuring and modeling change over time.

New maps from the Maine Geological Survey (MGS) depict the entire extent of regulated coastal sand dune systems for the state. Coastal sand dune systems are regulated resources per Chapter 355 of the Natural Resources Protection Act. MGS released a new map series for the entire state in 2023 (Slovinsky & Dickson, 2023), expanding Maine's currently mapped sand dune system by about 1,500 acres and superseding previously issued 2001 and 2011 MGS maps. These maps serve as the best-available information regarding the locations and extents of coastal sand dunes in Maine. Sea level rise ("a two foot rise of sea level over 100 years" [355, § 5.C.]) is specifically referenced in Chapter 355 in the context of determining site stability and whether or not infrastructure should be elevated. Chapter 355 has not been updated to reference the Maine Climate Council's adopted sea level rise scenarios; consequently, coastal sand dune mapping currently does not account for potential dynamic changes to sand dunes in the future. Dynamic erosion modeling techniques implemented as part of pilot work to support FEMA mapping in Nantucket could be implemented for coastal sand dunes in Maine (Compass, 2019).

Coastal bluff stability and landslide hazard maps, published by MGS in the early 2000's, need to be updated due to changing conditions. Erodible coastal bluffs account for approximately 40% of the Maine coastline and coastal bluff conditions have changed significantly over the last twenty years in response to sea level rise and an increase in impactful coastal storms, especially southeast storms. Analysis by MGS for two communities who had their bluff stability remapped in 2020 indicated that bluff instability increased on average by about 15% (range of 1.9% to 26.6%). Like coastal sand dunes, newly developed erosion modeling techniques that account for coastal bluff changes due to future sea level rise (Compass, 2019) could be implemented in policy.

Priority Information Needs

The top three information needs for sea level rise, storm surge, and coastal flooding that arose during this climate science assessment process, in order of highest urgency, include:

1. **Develop technical guidance that supports waterfront decision-makers and property owners in using tide predictions, coastal flood forecasts, extreme water scenarios, and sea level rise projections to inform adaptive short and long-term management.** These could be guidance documents, checklists, etc., and are needed specifically for post-storm recovery for working waterfronts and would be useful for the entire coast.

2. **Continue to expand Maine's network of water level sensors to support forecasting of local flood thresholds and establishment of local tidal datums that inform coastal planning and ecological restoration.** This monitoring and analysis would require the installation of local monitoring gauges and determination of local flood thresholds. This network will provide data for new flood hazard assessments over time as sea level rises.

3. **Complete erosion hazard modeling that accounts for future SLR along Maine's varied coastline (e.g., bluff, dune, wetland).** Research and data analysis would include modeling that follows protocols established by FEMA contractors in Region 1 and guides development toward safe locations while preserving sediment supplies for coastal wetlands to keep up with sea level rise.

A list of all of the priority information needs beyond those addressed here can be found in Report Appendix I.

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MARINE

OCEAN TEMPERATURE

The Gulf of Maine is warming faster than 97% of the world's ocean surface. Recent sea surface temperatures (SST) in the Gulf of Maine maintain the region's distinction as being one of the fastest-warming ocean regions on the planet. In 2021 and 2022, SSTs were the warmest and second warmest, respectively, recorded since the satellite SST data record began in 1982 (**Figure 1**; GMRI, 2022; 2023). Over the 1982-2023 period, the Gulf of Maine has warmed approximately three times faster (0.48°C / decade) than the global average SST warming rate of 0.16°C / decade (GMRI, 2024). SST in the region shifted into a warm regime during the 2010s (Mills et al., 2024), with temperatures for 2010-2023 averaging 1.38°C above the average for 1982–2009 (**Figure 1**).

Ocean heatwaves continue to increase. Marine heatwaves, a period when the daily average SST is greater than the 90th percentile of the long-term (1991-2020) average for five or more consecutive days, have increased in frequency, duration, and intensity in the Gulf of Maine over the past decade (**Figure 2**). In 2022, SSTs met the heatwave criteria for 353 days, or 97% of the year (GMRI, 2023).

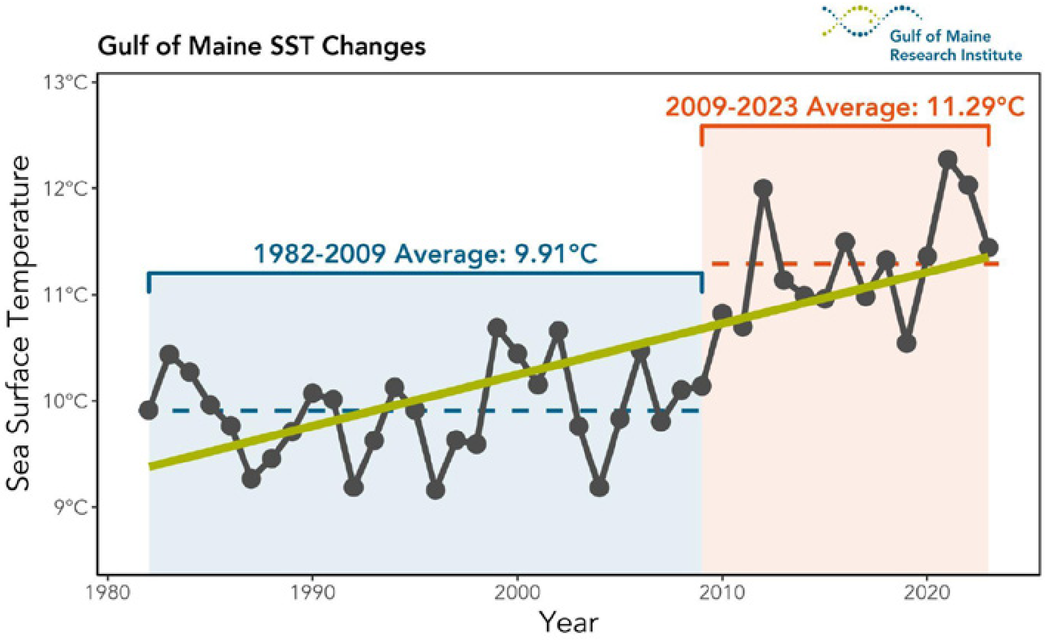


Figure 1. A time series of annual average sea surface temperature (SST) anomalies (i.e., deviations from the long-term average) for the Gulf of Maine (black dots and line) from 1982 through 2023, illustrating that 2021 was the warmest year on record, and 2022 the second warmest. The warming trend in the Gulf of Maine (green line) is three times faster than the global SST warming trend. Between 1982 and 2009, SST averaged 9.91°C (blue line), and the 2009-2023 average jumped to 11.29°C (orange line; GMRI, 2024).

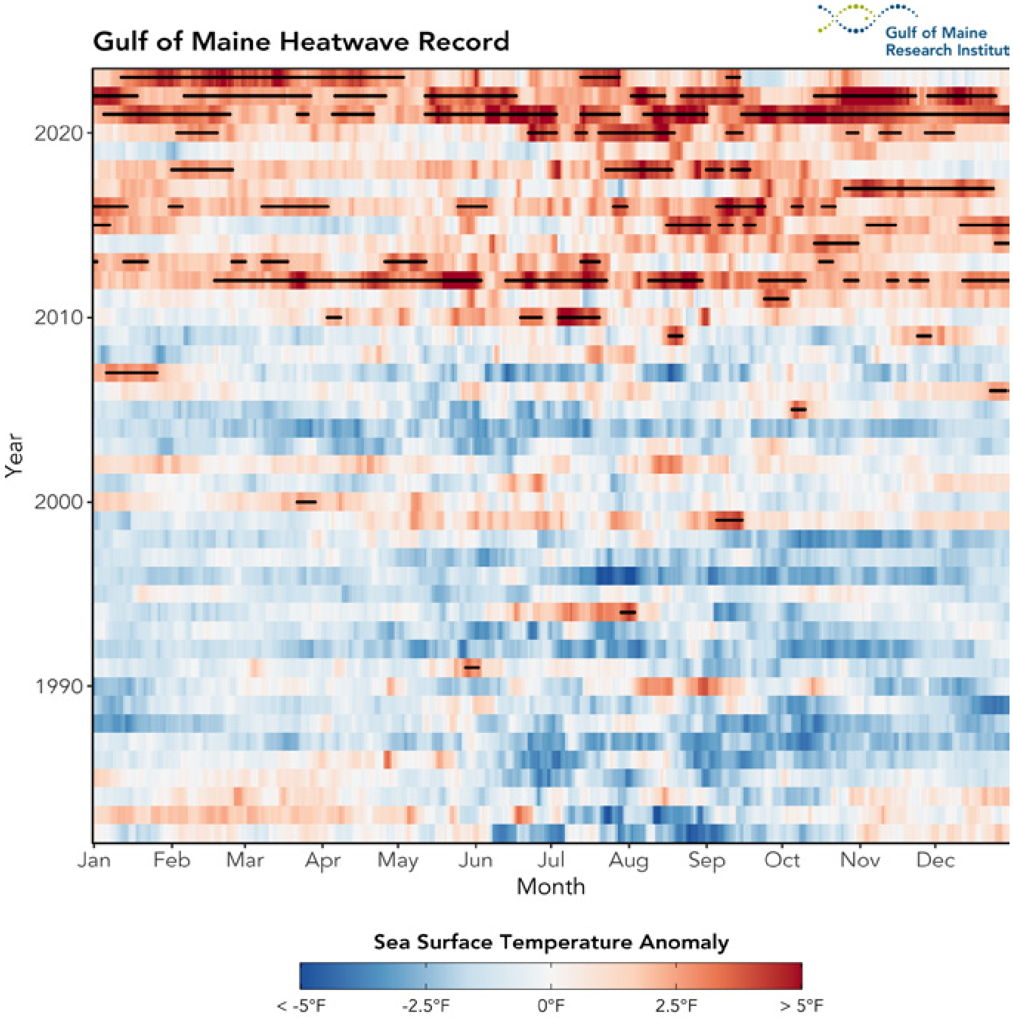


Figure 2. Heat map of daily SST anomalies from the beginning of 1982 through the end of 2023, defined relative to a 1991-2020 climatology (averaging weather statistics over many years) (GMRI, 2024). Red and blue colors indicate the strength of the temperature anomaly and black bars mark days that would be considered part of a heatwave. The frequency and duration of marine heatwaves (black lines) in the Gulf of Maine has become more pronounced in the past decade, especially between 2021 and early 2023.

Research indicates that the northward shift of the Gulf Stream and the deflection of the Labrador Current led to rapid warming and a "regime shift" in the Gulf of Maine (Friedland et al., 2024; Pershing et al., 2018; Saba et al., 2016)). Research continues to enforce Arctic links to changes in Labrador Shelf Water as well as observed regime shifts in the Gulf of Maine ecosystem. Research by Gonçalves Neto et al. (2021) showed that, in 2008, the Gulf Stream migrated closer to the Tail of the Grand Banks, a shift that has persisted into the present (**Figure 3**). This change reduced the westward connectivity of the Labrador Current that supplies cold, fresh, oxygen-rich waters to the shelf. Within one year of the presence of warmer and more saline water at the Tail of Grand Banks, subsurface warming progressed south-westwards.

Ocean temperatures and salinity at Jordan Basin in the central Gulf of Maine show net warming and increasing salinity since 2003 (Townsend et al., 2023). Moored sensors from the surface down to 250 meter (m) depth show warming at all depths over 19 years. Considerable annual and interannual variability is attributed to interactions of the Gulf Stream, related warm-core rings, Scotian Shelf Water, and Warm Slope Water just outside the Gulf of Maine that move into the gulf through the Northeast Channel. From about 2010 through 2022, data show variability on a four to seven year period that is superimposed on a warmer baseline temperature.

A 20-year Gulf of Maine time series shows surface cooling in spring months but warming in all other seasons (Balch et al., 2022). Primary production declined over that time, mostly associated with changes in chlorophyll, particulate organic carbon, temperature, and residual nitrate (nitrate-silicate) (Balch et al., 2022). In addition, changes were observed at higher trophic levels, affecting zooplankton community composition, fish and invertebrate populations, and right whales (ASMFC, 2020; Meyer-Gutbrod et al. 2018; Mills et al., 2024; Pershing & Kemberling 2023).

The Atlantic States Marine Fisheries Commission (ASMFC) (2020) references this shift in their stock assessment for American lobster. They identified a shift in ocean bottom temperature in 2010, which aligned with a reduction in Labrador Slope Water entering the Gulf of Maine and steep declines in *Calanus finmarchicus* (ASMFC 2020; **Figure 4**), a planktonic copepod near the base of the food web thought to explain recent declines in the survival and settlement of larval lobsters in coastal nurseries (MCC STS, 2020).

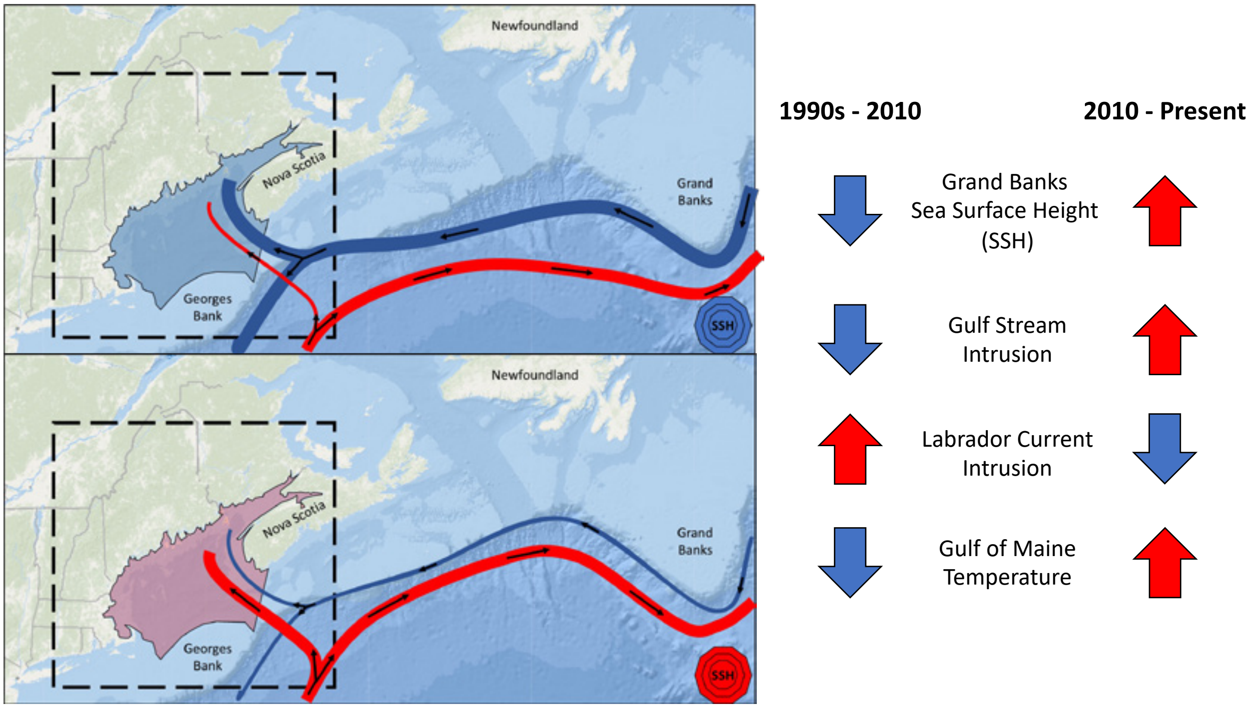


Figure 3. Changes in North Atlantic circulation and the cascading impacts on the Gulf of Maine. Northward migration of the Gulf Stream (red current) has dramatically reduced the westward flow of the Labrador Current (blue), causing a thermal regime shift in the Gulf of Maine that has persisted since 2010 (lower panel).

Ecosystem Change

Right whales (*Eubalaena glacialis*) are changing where they forage and live due to climate-driven changes in ocean circulation (Meyer-Gutbrod et al., 2021). As described above, *Calanus finmarchicus* has declined in the Gulf of Maine, and this zooplankton species is the key prey for right whales. North Atlantic right whales have moved their feeding range to the western Scotian Shelf and the Gulf of St. Lawrence. These changes have reduced calving rates and are exposing the population to greater risks of entanglement with fishing gear and ship strikes (Meyer-Gutbrod et al., 2021).

Research from Richards and Hunter (2021) hypothesized that the warmer temperatures of 2012 led to expansion of longfin squid (*Doryteuthis pealeii*) distribution in the Gulf of Maine, and changes to migration phenology that increased interactions with northern shrimp (*Pandalus borealis*), which suggests that predation by longfin squid was likely a significant influence in the northern shrimp collapse in the Gulf of Maine.

Changes to the Northeast Shelf indicate increased species diversity and "tropicalization" of the fish community. There has been no significant decline in fishing pressure for fish and macroinvertebrate communities of the Northeast Shelf (NES), however, on the continental shelf running from North Carolina to Nova Scotia, species diversity and overall productivity has increased in recent decades (Friedland et al., 2020). Overall, research suggests more intense species interactions, including between predators and prey, as well as for the NES, indicate a potential tropicalization of the fish community. These changes indicate that the cold temperate or boreal NES may be transitioning to warm temperate or Carolinian systems (Friedland et al., 2020).

Significant phenological shifts are occurring in the Gulf of Maine throughout the trophic web. Many groups of organisms in the ecosystem are responding to shifts in the seasonal cycle of warming and cooling (Staudinger et al., 2019; Thomas et al., 2017). Shifts towards earlier timing of environmental events, species appearances, and life history events are being observed across the Gulf of Maine ecosystem (Staudinger et al., 2019). As examples, some zooplankton species, such as *Calanus finmarchicus*, as well as certain larval fish are appearing at higher abundances earlier in the spring (Staudinger et al., 2019; Walsh et al., 2015). In addition, the migration timing of certain diadromous fish, including Atlantic salmon and alewife, have advanced to earlier in the year (Staudinger et al., 2019). Other events are occurring later: these include spring and fall phytoplankton blooms, fledging of Atlantic puffin chicks, and the appearance of certain species of larval fish (Staudinger et al., 2019; Walsh et al., 2015; Whidden, 2016). The combination of seasonal change is also causing

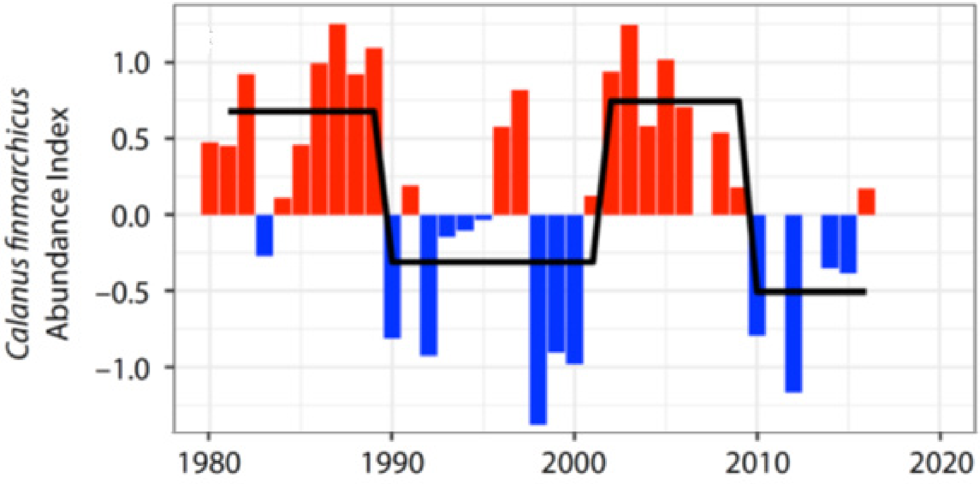


Figure 4. Time series of the Eastern Gulf of Maine *Calanus finmarchicus* abundance index from the Continuous Plankton Recorder survey. Annual values are computed as mean anomalies of late-stage *C. finmarchicus* based on a climatological averaging period of 1991–2010. Figure is taken from Meyer-Gutbrod et al. 2021.

some events to occur over a shorter period of time (i.e., ice-affected stream flows) and others to last longer (e.g., peak abundance periods of zooplankton, lobster fishery landings) (Staudinger et al., 2019).

Phenology shifts are having a significant impact on the Gulf of Maine's lobster population. Carloni et al. (2024) found significant correlation between warming ocean temperature and the earlier onset of the lobster egg hatch and the first appearance of Stage I larvae. Consequently, Stage I larvae have appeared about two weeks earlier than they did in the 1980s, even as their last appearance has been delayed by more than two weeks. Yet the onset, end, and length of the postlarval season has varied without trend. Since 2010, the *C. finmarchicus* season, has more frequently been ending before the peak abundance of Stage I lobster larvae, with the net effect being an **increasingly mismatched phenology between larval lobster and their primary food source.** In this study, the beginning and end of the larval lobster season was based on first and last appearance, respectively, in weekly neuston net tows from May through October. The *C. finmarchicus* season was bounded by the 25th and 75th percentile of the cumulative annual abundance index from monthly plankton tows made throughout the year. See also Appendix H.

Impacts of altered trophic dynamics

Climate-driven changes in the planktonic community have the potential to influence maritime activities, including fishing, aquaculture, and tourism, as well as ecological communities. New potentially harmful, toxic, or nuisance algal species such as *Pseudo-nitzschia australis* in 2016 (Clark et al., 2021), *Karenia mikimotoi* in 2020 (Record et al., 2021), an unidentified Chrysophyte in 2022 and *Tripos muelleri* in 2023 are recent arrivals to the Gulf of Maine. The socioeconomic impacts in Maine are not yet known, but harmful algal blooms are known to have major impacts globally (Hallegraeff et al., 2021). The keystone copepod *C. finmarchicus* has declined in parts of the GOM, and climate projections tend to shift this species out of the region, with impacts on whale feeding migrations, lobster recruitment, and other species (Carloni et al., 2018; Grieve et al., 2017; Record et al., 2019). Open questions concerning plankton include the potential rise of Vibrio species (Archer et al., 2023), epizootic shell disease pathogens in lobsters (Reardon et al., 2018), changes in jellyfish populations (Mills et al., 2001), and changes in the stability of planktonic larvae populations such as mussel spat and lobster larvae.

Maine's lobster fishery has been slipping from its historic highs over the past few years in a manner consistent with climate-informed predictions made just prior to the 2020 STS assessment. See also Appendix H. Direct effects of warming include the lobster population's continuing northward range shift, expansion to deeper water, and decline in size at maturity (Goode et al., 2019; Le Bris et al., 2017; 2018; Miller et al., 2024; Waller et al., 2019; 2021). The earlier onset of the egg hatch and appearance of larvae are also consistent with the lengthening growing season (Carloni et al., 2024; Goode et al., in review). An increasing body of evidence (Ascher, 2023; Layland, 2023; Wahle et al., 2021) suggests larval survival has been adversely affected since the 2008–2010 thermal regime shift by declines in the productivity and composition of the zooplankton prey assemblage widely attributed to the weakening influence of the cold, nutrient-rich Labrador Current on the Gulf of Maine ecosystem (see Ocean Temperature above).

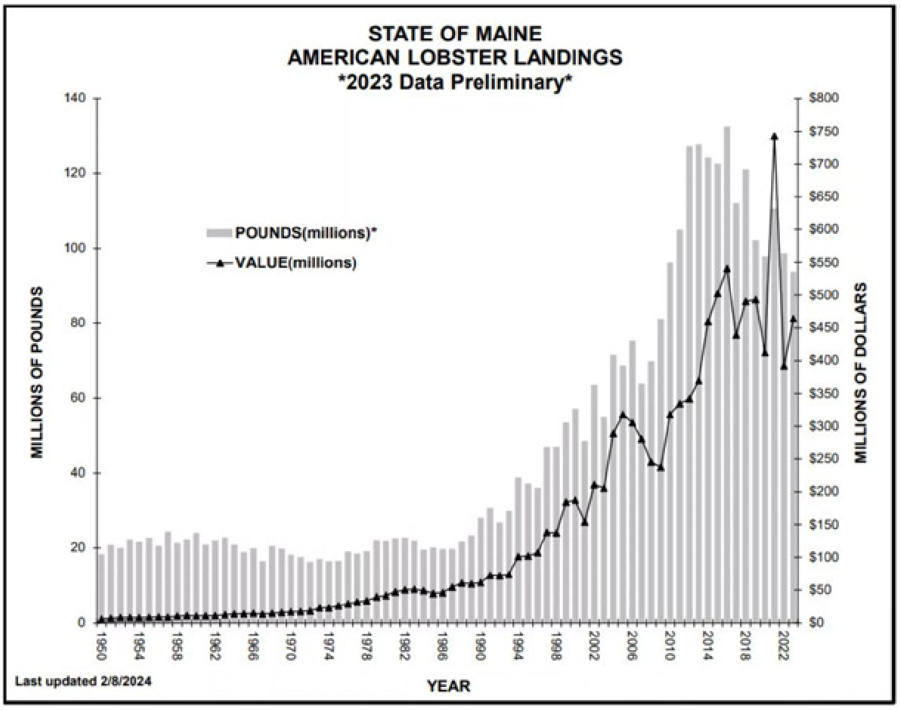


Figure 5. Maine lobster landings 1950–2023 by volume and value (ME DMR, 2024).

Aquaculture

Aquaculture systems in cold water environments face challenges, but can be adapted with investment into infrastructure, strain selection, and emergent species. Gulf of Maine research indicates that new species will be needed for aquaculture, but immediate attention to adapt existing species through measures such as defining and preserving wild biodiversity, breeding for temperature tolerance, and incorporating greater husbandry, along with adapting infrastructure, will support resilience in the aquaculture industry (Bricknell et al., 2021). Additional recent research examines the vulnerability of the aquaculture industry to ocean and coastal acidification (Neumann, 2022), strategies for breeding for heat resilience in kelp (*Laminaria digitata*) (Liesner et al., 2022), and further research on population genetics for breeding thermally resilient kelp (*Saccharina spp.*) in New England (Augyte et al., 2021).

A lack of genetic knowledge around kelp biodiversity limits the expansion of kelp aquaculture. Wild kelp populations in the southern portion of Maine are disappearing, a shifting range correlated with warmer sea surface temperatures (Suskiewicz et al., 2024). There is not any evidence that this shift is impacting farmed seaweeds, which are harvested before summer marine heat waves. However, the losses may start to impact broodstock availability for seaweed nurseries (Suskiewicz et al., 2024). The lack of knowledge around intraspecific connection between native populations inhibits the development of sector management of farmed seaweeds and the possibility for exploring thermally resistant strain selection.

Ocean Acidification and Deoxygenation

Under representative concentration pathway (RCP) 8.5, the highest baseline emissions scenario, the Gulf of Maine will experience ocean acidification conditions below the critical threshold for shellfish health for most of the year by 2050 (Balch et al., 2022; Siedlecki et al., 2021). Projections for the Gulf of Maine indicate aragonite saturation state (Ωa), a proxy for calcification potential, show declines everywhere in the Gulf of Maine, with most pronounced impacts near the coast, in subsurface waters, and associated with more frequent and extreme freshening events (dilution of saltwater by freshwater inputs, such as from riverine flooding). Research from the Gulf of Maine also showed that ocean acidification could be even worse, except that the rate of warming in the Gulf of Maine is partially counteracting the acidification (Siedlecki et al., 2021). The projected warming in the Gulf of Maine imparts a partial compensatory effect to Ωa by elevating saturation states. This preserves some important fisheries locations, including much of Georges Bank, above the critical threshold (Siedlecki et al., 2021).

Additional species, including invertebrate pelagic species such as American lobster, have been identified since 2020 as vulnerable to ocean acidification. American lobsters (*Homarus americanus*) in Maine have been shown to be more susceptible to pathogens in conditions with higher ocean acidification, especially in lower water temperatures (Harrington et al., 2020). Furthermore, Maine research evaluated the interactive effects of increased acidity and temperature on the acute response of gene expression of postlarval American lobster: gene regulation is considerably more responsive to elevated acidity (Niemisto et al., 2020). The combined effect of both acidity and temperature on gene regulation was significantly greater than either stressor alone (Niemisto et al., 2020).

Increasing hypoxia events in the Gulf of Maine, which have resulted in lobster die-offs, have attracted research to understand the environmental causes of these conditions and to predict them in advance. Hypoxia, or low oxygen in seawater, is affiliated with ocean acidification (OA), warming, and nutrient loading. Climate driven changes, such as rapidly warming water and shifts in summer wind direction, led to physical conditions in Cape Cod Bay during late summer that favored the increase in sub-surface phytoplankton production (Scully et al., 2022). Bottom waters in southern Cape Cod Bay in 2019 and 2020 became depleted of dissolved oxygen (DO), with documented benthic mortality each year (Scully et al., 2020; **Figure 6**). In both years, anomalously high sub-surface phytoplankton blooms were observed, and the biomass from these blooms provided the fuel to deplete sub-pycnocline waters of DO.

Temperature and wind shifts both impact the intensity and vertical distribution of thermal stratification and vertical mixing within the water column (Scully et al., 2022). Like the rest of the Gulf of Maine, water temperatures in Cape Cod Bay are increasing rapidly, but bottom temperatures are not warming as quickly as the surface. Consequently, in late summer the vertical temperature gradient increases. This gradient isolates the cold bottom waters from the warmer oxygenated surface waters, cutting off the supply of dissolved oxygen and contributing to hypoxia. These changes may be leading to significant changes in algal species blooming during late summer (Pugh & Scully, 2022; Scully et al., 2022).

Seaweed aquaculture can remediate localized low dissolved oxygen as well as low seawater pH, particularly with sugar kelp (*Saccharina lastissima*) (Ricart et al., 2023). Research suggests that sugar kelp is the most promising macrophyte species in terms of altering seawater chemistry and remediating acidification, but the degree to which this is effective depends on flow rates and CO_2 concentration. Studies outside of Maine using conspecifics include Hamilton et al. (2022), Xiao et al. (2021), and Young et al. (2022). Hamilton et al. (2022) found that integrated multi-trophic aquaculture mitigates the effects of ocean acidification: seaweeds raised system pH and improved growth of juvenile abalone. Seaweed aquaculture has not been specifically tested during a hypoxia event.

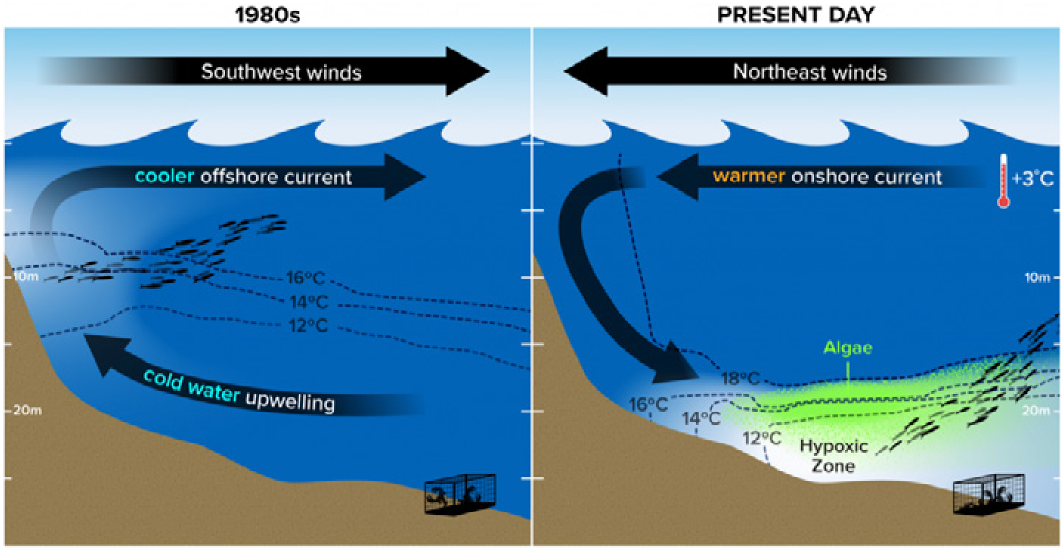


Figure 6. A climate change-related shift in the direction of prevailing summer winds led to low oxygen conditions affecting marine life by stanching cold water upwelling and promoting thermal stratification. This ocean circulation change led to hypoxia in southern Cape Cod Bay. (Illustration by WHOI Sea Grant and WHOI Creative, Natalie Renier, with data from Malcolm Scully © Woods Hole Oceanographic Institution.

https://seagrant.whoi.edu/cape-cod-bay-hypoxia/)

Blue Carbon

Maine is at the forefront of research and policy by attempting to include coastal carbon sequestration in the 2023 Maine Carbon Budget. Data exists for certain submerged aquatic vegetation (salt marshes and seagrasses) in Maine, and "blue carbon" opportunities continue to evolve, particularly for seaweeds, with an emphasis on carefully generated scientific evidence. Integrating coastal carbon into Maine's budget will require timely collaboration to share standing stock biomass data for all submerged aquatic vegetation, along with spatial data for areas actively used for farming seaweed. Recent research indicated that coastal carbon sequestration can be accurately measured using existing methods, but new DNA-based methods are faster and less expensive proxies (N. Price, personal communication, February 2024).

New guidelines exist to responsibly conduct marine carbon dioxide removal research. The Aspen Institute Code of Conduct report (Boettcher et al., 2023) applies to all marine carbon dioxide removal (mCDR) research techniques rather than a "best practices" subset and lays out general principles that are intended to guide planning, scoping, execution, and conclusion of research activities. A plethora of publications promoting caution and need for development of Measurement, Reporting, and Verification Tools (MRV) to ensure claims about carbon burial and sequestration from seaweeds (in particular) are evidence based (N. Price, personal communication, February 2024).

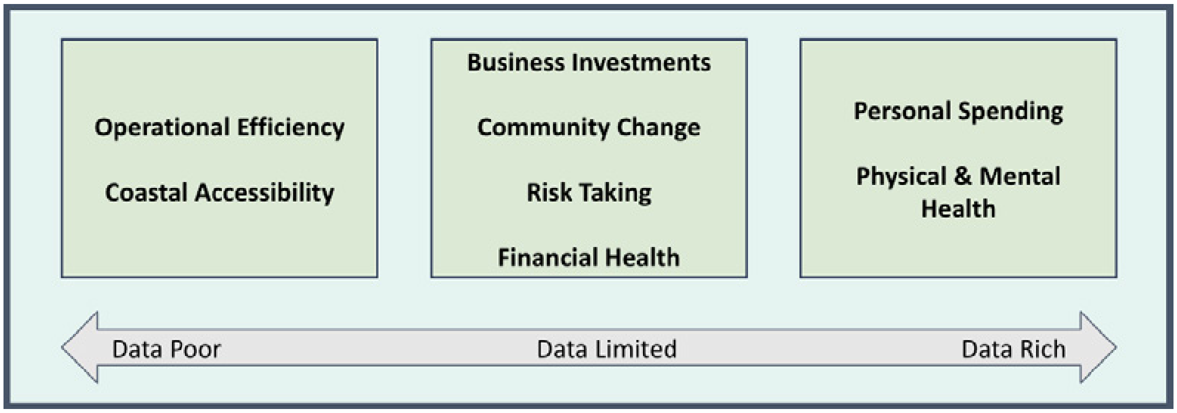
A Nature Climate Change manuscript is currently in review for farmed seaweed carbon deposition rates, which includes Maine data and estimates to be used for the 2023 Maine State Carbon Budget. Additional publications have been released for eelgrasses in Maine that contribute to the understanding of marine carbon storage rates in Maine coastal environments (see Colarusso et al., 2023).

Vulnerability and Resilience

Socioeconomic indicators of resilience in Maine's lobster fishery include profitability, coastal accessibility, community change, and physical and mental health, but more data is needed to quantify specific impacts. Maine's coastal communities, which depend socially and economically on the lobster fishery, are vulnerable to changing resources in measurable ways. Research by Burnham et al. (in preparation), which builds on Greenan et al., (2019), and Jacob et al., (2013), developed as assessment using information such as economic dependence on the fishery, population size, diversity of the fishery revenue, status of harbor infrastructure, total replacement cost of each harbor, increased relative sea level and flooding, and the vulnerability of offshore lobster to ocean warming and changes in zooplankton composition and anticipatory changes in fishery productivity across management borders. The eight social indicators in Maine, developed from extensive stakeholder interaction and derived entirely from publicly available data, included profitability, coastal accessibility, business investments, community change, risk taking, financial health, personal spending, and physical and mental health (**Figure 7**; Burnham et al., 2024; Burnham et al., in preparation). See also Appendix H.

Communities that are heavily invested in one fishery (such as lobster) face resilience planning challenges. Literature on climate resilient fisheries highlights the importance of flexibility and learning as key attributes of resilience (Mason et al., 2022). Studies indicate that Maine's fishermen are constrained by existing licensing and fishery management structure both at state and federal-levels to access new fishing opportunities or flexibly shift their fishing activities under a changing ecosystem (Stoll et al., 2016.; 2017). Over the years, as the lobster stock became more abundant and other fisheries (such as groundfish fishery) have declined, fishermen and fishing communities in Maine have become heavily reliant, invested, and specialized in the lobster fishery (Maltby et al., 2023). This phenomenon has previously been characterized as a "gilded trap" (Steneck et al., 2011), a synonymous concept to a rigidity trap, which limits adaptive capacity. These characteristics, combined with strong ties to local communities and limited economic opportunities in lobster fishing communities, can hinder long-term climate resilience planning (Eurich et al., 2024).

Different lobster fishing business models, such as the inshore single-operator fishermen versus more capital intensive multi-crew operations, may experience differential impacts from climate change. At an individual-level, harvesters perceive climate change impacts on the lobster fishery to be higher than the scientists (Runnebaum et al., 2023). McClenahan et al. (2019) notes that this dominant perception of negative impacts can prevent them from finding the prospect of adaptation. Further, climate resilient fisheries literature cautions that individual-level adaptive capacities are limited by their resources (e.g., financial, knowledge, experiential, socio-cultural norm) and that not everyone can take advantage of emerging opportunities. For example, Stoll et al. (2019) cautioned that the capacity and willingness to take part in aquaculture as an income diversification strategy is limited by access to finance and the ability to withstand years to see returns on investment as well as a negative view towards aquaculture. Dayton and Tokunaga (2023) quantitatively assessed the differences in lobster fishing business models using technical and operational characteristics of the harvester and measured by profit efficiency compared to a 2010 benchmark of the pre-warming economic performance of the fleet. Climate change induced decline in resource availability may crowd out the least economically efficient business model that resembles the "traditional lobsterman" described by Acheson (1975), while the most economically efficient business model that has more intensive fishing strategy may become less efficient due to overcapacity (Dayton & Tokunaga, 2023). The study highlighted the importance of gaining a better understanding of operational adaptation, suggesting that fishermen can change their operations to stay economically productive by increasing soak time (trap time in the water) and reducing trip frequency.



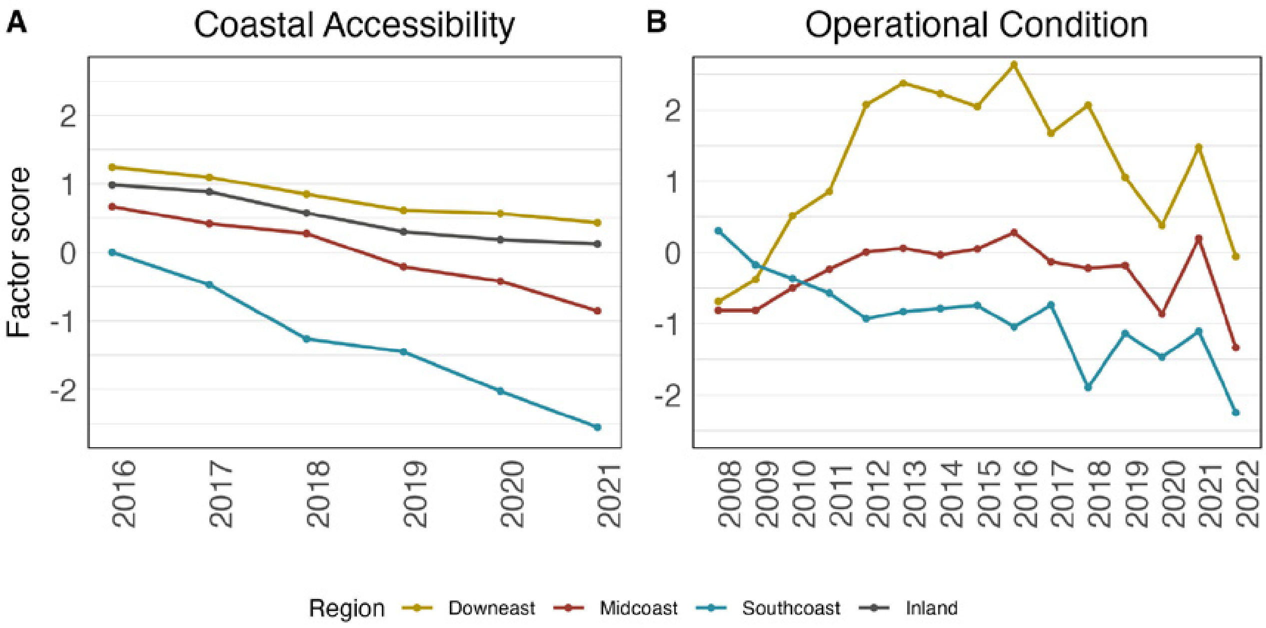


Figure 7. Annual regional trends for socioeconomic indicators of resilience, specifically the indicators of operational condition and coastal accessibility, in the Maine lobster fishery (Burnham et al., in preparation). The X-axis is the year, and the y-axis is the factor score, or the output of the study's factor analysis, which provides a relative comparison of the indicator across time. Since 2010, Eastern Maine has had the highest relative values for operational efficiency, with large regional variation from 2008-2021. Coastal accessibility, here a measure of the availability and affordability of housing, shows declines across the state, including inland, with the most dramatic decline in southern Maine.

Nationally, the effectiveness of nature-based solutions (NbS) to meet coastal adaptation needs is well-documented but depends on a wide range of conditions, knowledges and capacities. Research by Reilly-Moman et al. (2023) found that physical, ecological, economic, and social factors are the key pillars for analyzing the effectiveness of NbS. Within these, key capacities are needed.

First, governance is central to planning, implementation, and maintenance. This includes addressing regulatory challenges, especially at the state level, empowering Native nations leadership, and taking a systems-based approach (Reilly-Moman et al., 2023). Next, how NbS projects are valued and how they create value is a key point for transition. This includes changes to federal benefit cost analyses (BCAs) to value beyond physical property, including ecosystem services and unquantifiable factors. Outcome-based standards also better integrate the value in NbS and have proven helpful to practitioners. Third, how NbS are communicated to stakeholders can build (or damage, if the NbS is portrayed as having attributes such as overestimated protective value for homes) credibility, and adoption is most often influenced by hyper-local social proof (i.e., a neighboring person or town implements a NbS). In addition, planning processes that do not pit green and gray infrastructure as opposed to working along a green-gray spectrum lead to more effective outcomes. Planning should also engage early and often in human and ecosystem relocation conversations. Finally, across all levels of governance and especially at the municipal level, NbS is supported by meeting deep capacity needs, including the need for monitoring and maintenance. Central to meeting needs is addressing existing political and social power structures, and integrating equity considerations into all aspects of planning and implementation (Reilly-Moman et al., 2023).

In Maine, NbS planners and implementers seek streamlined planning and regulation supported by a network of interagency partnerships. In Maine, research found that NbS planners and implementers want a centralized forum for guidance and technical assistance; streamlined permitting; funding to adequately monitor living shorelines; regulatory definitions for nature-based engineering approaches; and interagency partnerships in the state (Genoter et al., 2023). This research aligns with Reilly-Moman et al., (2023) in which researchers found that in the Northeast, where significant areas of the coast are private property, state regulations, locally implemented examples, and informed coastal engineers all play a critical role in successful implementation. Significant areas along the coast are already “gray” or have hard infrastructure such as riprap, and many areas face further coastal “squeeze,”-from sea level rise, forcing conversations around human retreat that need to integrate with ecosystem retreat. In the Northeast, rural areas, often in contrast to urban zones, struggle with capacity to support NbS, even with growing interest. Finally, living shorelines are increasingly implemented in pilot projects for the region, but can suffer damage in the Northeast’s high energy (ice and winter storm) conditions.

Co-management of fisheries and ecosystems are increasingly important. Research shows that elements of co-management regularly appear in conventional management regimes in the state, and elements of ecosystem-based fisheries management appear in co-management initiatives (Cucuzza et al., 2021). This underscores the importance of co-management for Maine fisheries and ecosystem-based fisheries management both at the state and federal levels in creating a framework in concert with existing regional frameworks. This could support Maine’s fisheries and fishing communities as they adapt to impacts and seek new opportunities, including reallocation of quota for species that are becoming more prevalent in Maine (Ibid). Existing regional frameworks include the Atlantic States Marine Fisheries Commission and the Mid-Atlantic Fishery Management Councils.

Priority Information Needs

The top information needs for marine ecosystems that arose during this climate science assessment process were both connected to ongoing and community initiatives. These priority information needs include:

1. **Continue to expand on community initiatives to monitor Maine's complex coastline, with special emphasis on bottom waters that are difficult to monitor with remote sensing products.** For example, this could include expanded collaboration between the lobster industry and oceanographers through the electronic Monitoring of Lobster Traps (eMOLT) program. Specific areas of need include bottom waters, lobstering, expansion into undersampled areas in the Eastern Gulf of Maine and deep water. Monitoring could include temperature, conductivity and dissolved oxygen, with potential cross-cutting applications with sea level rise monitoring and analysis.

2. **Expand initiatives to measure water quality.** Community initiatives such as the Maine Coastal Observing Alliance and existing governmental and municipal water quality monitoring programs can be better supported to determine if warming coastal waters are more susceptible to nutrient loading, eutrophication, harmful algal blooms, bacteria runoff, and other water quality perturbations. This information is of particular need in shellfish harvesting and aquaculture locations.

A list of all of the priority information needs beyond those addressed here can be found in Report Appendix I.

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AGRICULTURE

WEATHER VARIABILITY IMPACTS

Weather variability is reducing crop yields and causing economic and health impacts in Maine and the Northeast. A survey conducted in 2020 with 253 responses from Maine farmers found that changing weather patterns associated with climate change are having negative effects on Maine agriculture (Schattman et al., 2021). Producers report concern about reduced crop yields and quality, poor crop and cover crop germination, and increased labor needs associated with irrigation. Respondents also noted that extreme weather events make field access more difficult, increase erosion and soil loss, and have negative effects on farm viability and farmworker health and wellbeing (Schattman et al., 2021). In addition to runoff and leaching, loss of fertilizer that can occur on flooded fields, which can require expensive re-application, denitrification converts nitrogen fertilizers into gaseous forms such as nitrous oxide (N_2O) and nitrogen gas (N_2), which are lost to the atmosphere leading to reduced nitrogen availability for crops and decreased crop yield (UNH Extension, 2024). The increased solubility and availability of iron (Fe), manganese (Mn), and sulfur (S) in saturated soils can potentially become toxic to plants. Nearly all farmer respondents reported concern about climate change in general (96%) and changing weather patterns (97%) (Schattman et al., 2021).

Multiple rainy weekends in September and October 2023 reduced customer turnout for pick-your-own orchards (R. Moran, personal communication, November 2023). Short-term weather events are not fully represented in yearly and seasonal averages reported in climate change projections but can have strong negative impacts on the profitability of Maine farms.

Several Maine vegetable and small fruit growers have stated that another growing season with similar weather damage as in 2023 (**Figure 1**) could force them to go out of business (J. Lilley, personal communication, November 2023) and has increased farmers' emotional stress (L. Forstadt, personal communication, November 2023).

Figure 1. Apples damaged by the May 18, 2023 freeze. (Photo credit: Glen Koehler.)

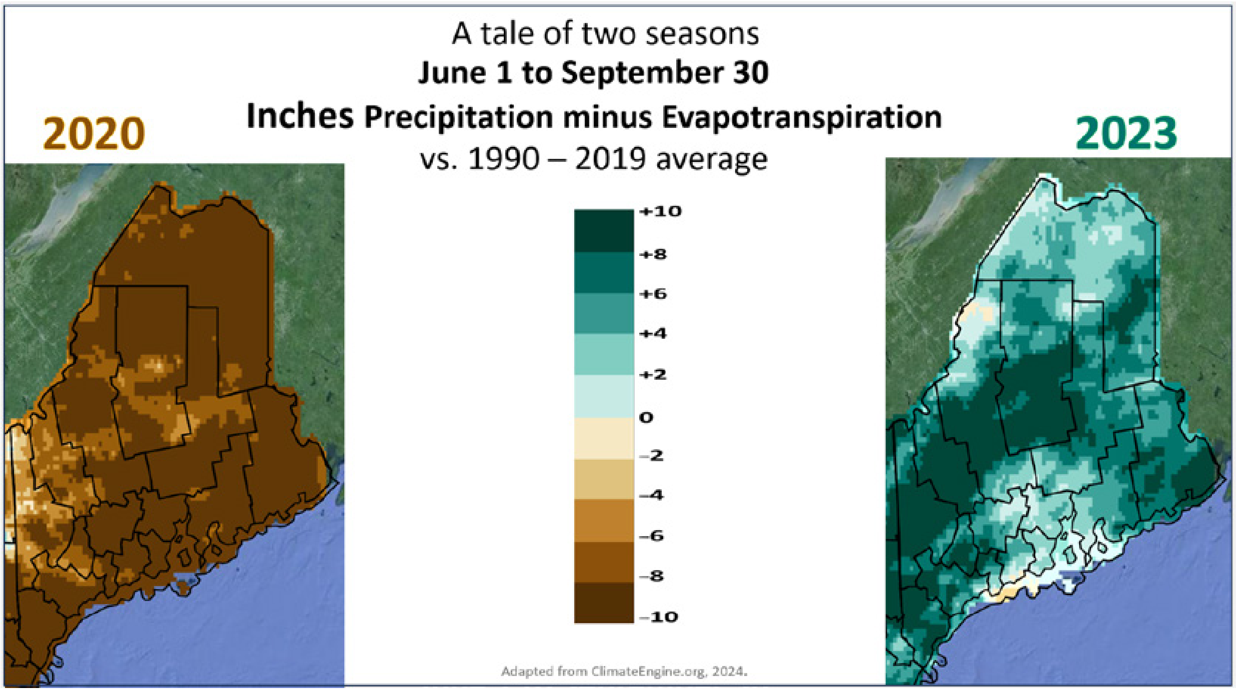


Figure 2. Examples of recent precipitation and temperature variability. Potential Water Deficit (PWD = Precipitation water gains minus water loss through evapotranspiration) for June 1 through September 30 in 2020 and 2023 relative to the 1990-2019 30-year average PWD for June - September Data and maps, Climate Engine, 2024.

New Hampshire Tree Fruit Grower Losses in 2023

Survey responses from 55 New Hampshire tree fruit growers on 2023 revenue losses due to low temperatures amounted to $1.7 million for stone fruit due to the February deep freeze. The May 17-18 bud freeze was cited for losses of $7.9 million from apples (UNH Extension, 2023). The May 2023 freeze resulted in a USDA disaster designation for Maine (USDA, 2023a).

While the overall damage to the Maine apple crop was not as severe as in New Hampshire and Vermont, many Maine growers did lose a large percentage of their crop and most suffered at least some crop loss due to the freeze either through total yield or quality reduction due to freeze-induced skin deformation (**Figure 1**). The direct damage by yield loss is exacerbated by secondary effects such as increased pruning cost in the following year due to the effect of a lower crop creating more vigorous vegetative growth (Harkawik, 2023).

Climate change is impacting the mental and physical health of farmers and farmworkers. In a survey that specifically targeted the effects of water-related extremes (i.e., severe drought and persistent or extreme rainfall), farmer respondents noted that extreme weather events had negative effects on crew health and wellbeing (Schattman et al., 2021). Prior studies conducted with growers in the Northeast show climate change's multifaceted effects on farmer and farmworker well-being (Schattman et al., 2016). Research with a broader geographic scope finds that climate change and weather extremes are one of the leading factors affecting farmer mental health (Daghagh Yazd et al., 2019). While similar research has not yet been conducted in Maine, there is evidence that climate change drives unpredictable weather (see Climate chapter); unpredictable weather combined with unfavorable market conditions can challenge the economic viability of farm businesses (Lengnick, 2015); and financial precarity has a negative effect on farmer mental health and wellbeing (Batterham et al., 2022). The difficulty in predicting planting windows, high and low precipitation and temperature variation, increased disease pressure, soil loss, and other environmental factors is negatively affecting profitability for many forage, vegetable and fruit farmers. Some farm operators have shared their considerations of going out of business if the weather patterns experienced in 2023 continue in subsequent years (J. Lilley, personal communication, September and October 2023). Further research into the effects of climate change on farmer and farmworker mental health and well-being is needed.

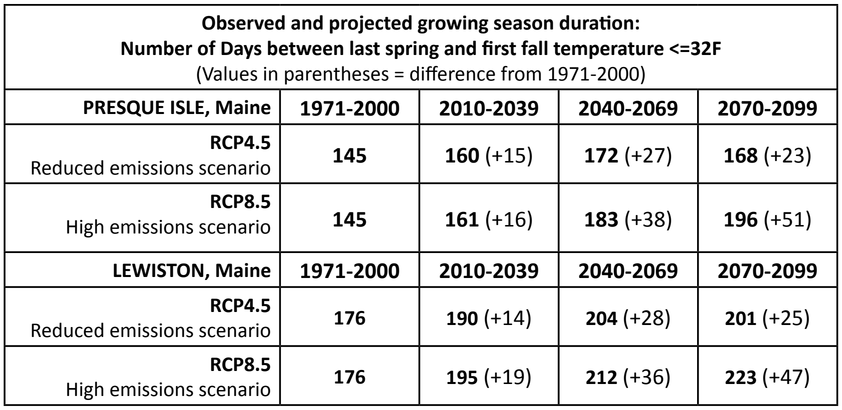
Wild Blueberries

Maine's wild blueberry industry is increasingly threatened by climate change. Wild (lowbush) blueberries in Maine and Atlantic Canada rely upon continued favorable environmental conditions rather than plant breeding or a shift to indoor production. The climate envelope projection in the 2020 STS report showing the geographic region of optimum growing conditions for lowbush blueberry moving north out of Maine and into Canada remains a plausible best estimate for the coming decades (MCC STS, 2020).

Wild blueberry plants live in sandy, well-drained soils, yet these soil characteristics pose challenges to plant growth during times of drought due to their low water-holding capacity. Of note, wild blueberry fields in Washington County, Maine, have warmed faster than the rest of Maine (Tasnim et al., 2021; 2022). The 2020 growing season saw an average of 44% yield loss due to the combination of drought and high temperatures, with individual growers losing anywhere from 0.5% to 97% of their typical yield (Schattman et al. 2021). Precise irrigation timing and volume as well as mulch applications are two management practices that farmers are adopting to reduce plant stress and improve yields in times of extreme weather (Gumbrewicz & Calderwood, 2022). Drought in the wild blueberry growing regions of the state occurred in five of the past eight years. Observationally, drought in May, June and July has impacted the wild blueberry crop most severely. Data collection on critical windows of water availability for this crop are ongoing. Years 2016, 2017, 2018, 2020, and 2022 were seasons where drought conditions occurred for at least part of the growing season while in 2019, 2021, and 2023 the crop received adequate rainfall (one inch per week for at least part of the season) (Birkel, 2016; 2019; NOAA/NIDIS 2017; 2018; 2019;, 2020; 2021; 2022; L. Calderwood, personal communication, March 2024.)

Future opportunities and risks

New opportunities and both positive and negative impacts for Maine agriculture are likely with warmer temperatures and longer growing seasons. Observed and projected increases in the length of the Maine growing season are likely to increase potential agricultural production and crop options for Maine farmers (Climate Reanalyzer, 2024; Hegewisch & Abatzoglou, 2024; Tooley et al., 2021; USGCRP, 2023; Wolfe et al., 2018). Research on hardwood tree species in Ohio found that growing season elongation was not symmetrical: earlier growth in the spring was exceeded by later cessation of growth in the fall (Calinger & Curtis, 2023).

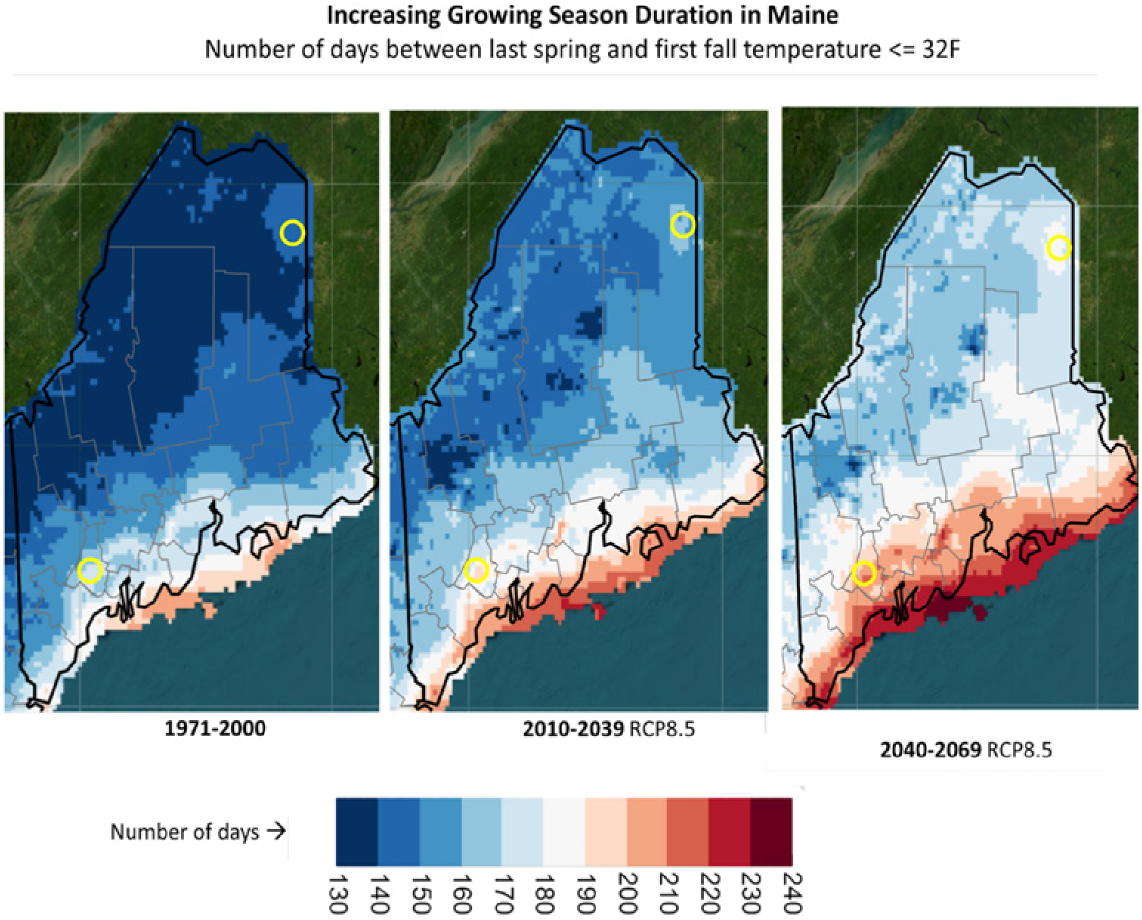


Observed and projected growing season duration:
Number of Days between last spring and first fall temperature <=32F
(Values in parentheses = difference from 1971-2000)

PRESQUE ISLE, Maine	**1971-2000**	**2010-2039**	**2040-2069**	**2070-2099**
RCP4.5 Reduced emissions scenario	**145**	**160** (+15)	**172** (+27)	**168** (+23)
RCP8.5 High emissions scenario	**145**	**161** (+16)	**183** (+38)	**196** (+51)
LEWISTON, Maine	**1971-2000**	**2010-2039**	**2040-2069**	**2070-2099**
RCP4.5 Reduced emissions scenario	**176**	**190** (+14)	**204** (+28)	**201** (+25)
RCP8.5 High emissions scenario	**176**	**195** (+19)	**212** (+36)	**223** (+47)

Data from Climate Toolbox (Hegewisch & Abatzoglou, 2024).

Table 1. Observed and projected growing season days across emissions scenarios, from Climate Toolbox (Hegewisch & Abatzoglou, 2024).



1971-2000

2010-2039 RCP8.5

2040-2069 RCP8.5

Figure 3. Increase in duration of Maine growing season from 1971–2000 (historic) to 2010-2039 and 2040–2069 using the high emission scenario (RCP8.5). Yellow circles mark the location of Lewiston in southern Maine and Presque Isle in northern Maine. Modified from Climate Toolbox (Hegewisch & Abatzoglou, 2024).

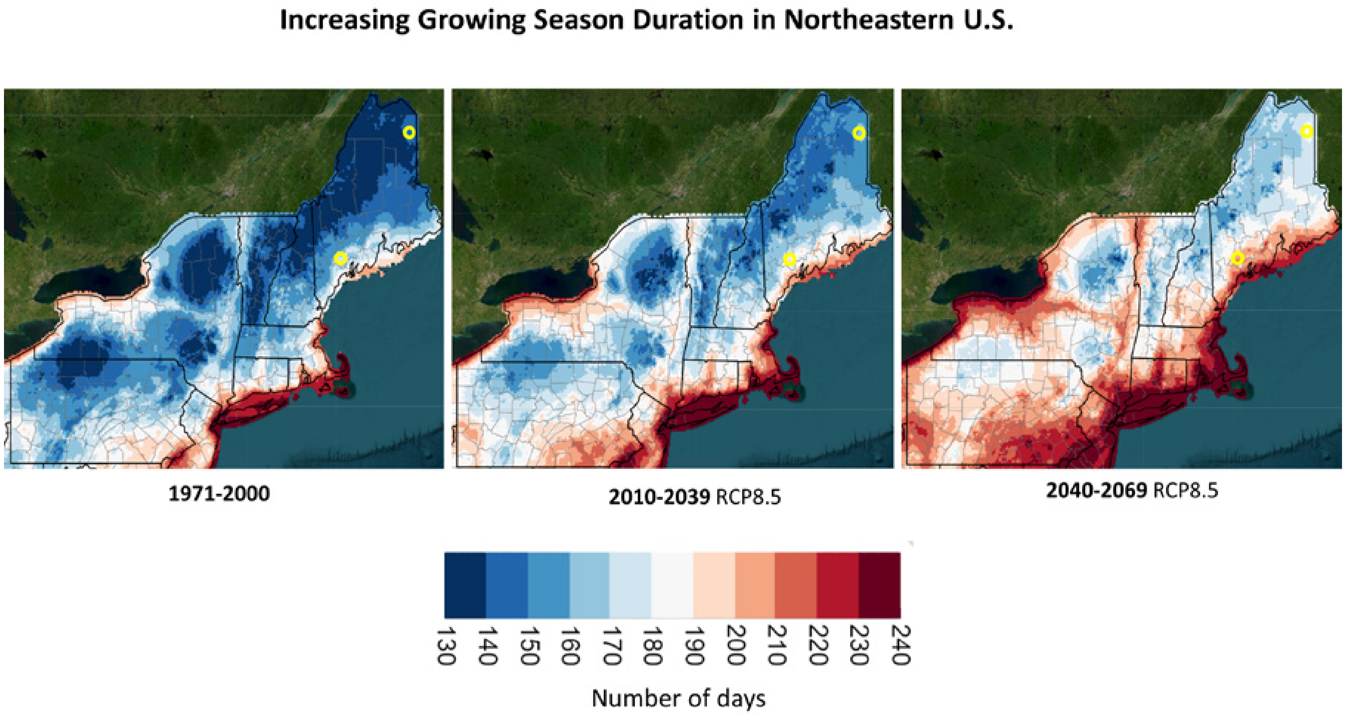


Figure 4. Regional context for past and future growing season duration in Maine. Modified from Climate Toolbox (Hegewisch & Abatzoglou, 2024).

Longer growing seasons can also increase heat stress and increase crop water demand, or lead to frost damage to perennial plants when earlier bud development is followed by cold temperatures in late spring. Higher winter temperatures may also allow agricultural pests to persist year-round or have additional generations, or may allow new insect pests, diseases, or weeds to become established (USGCRP, 2023). The benefits from longer, warmer growing seasons could be curtailed or even eliminated if the increase in growing degree days is not synchronized with a matching shift in the dates of spring and fall frosts, or if heat waves, droughts, or other extreme weather events degrade productivity (Wolfe et al., 2018).

Plant Hardiness Zone maps (**Figures 5, 6,** and 7; USDA 2023c,d) show observed increases in the annual minimum temperatures across Maine locations between 1991 and 2005; increasing shifts for the coming decades; and regional context for shifting plant hardiness zones.

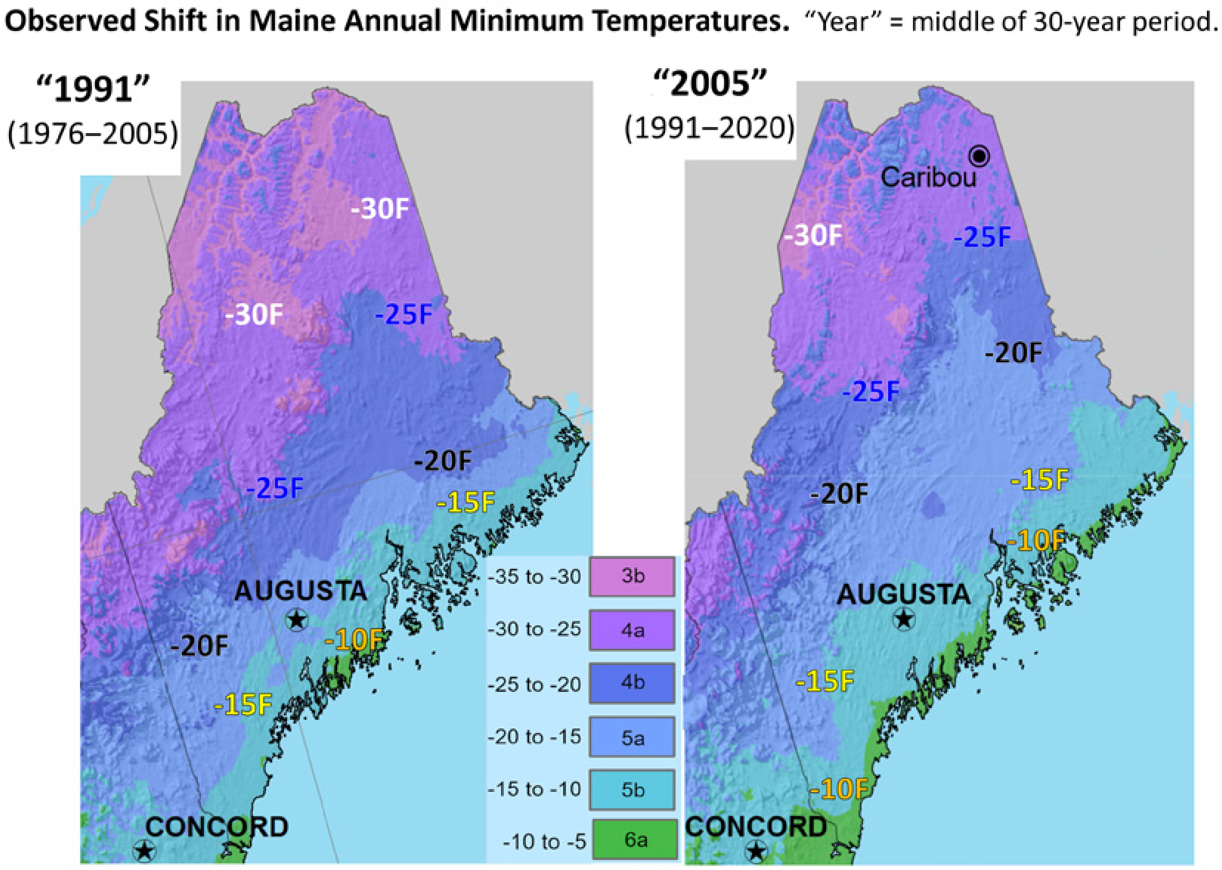


Figure 5. USDA Plant Hardiness Zone Maps for Maine. Each map shows the average annual minimum temperature zones for a 30-year period. The map on the left shows the average annual minimum temperature for 1976-2005, the map on the right for 1991-2020. The 5b zone which was restricted to coastal areas in the "1991" map expands further into interior Maine in the "2005" map, and the 5a zone expands north into areas that had previously been 4b. The area of northwest Maine that was classified as 3b in the "1991" map is greatly diminished in the "2005" map. The "1991" map is modified from USDA & PRISM 2012, and the "2005" map is from USDA 2023d.

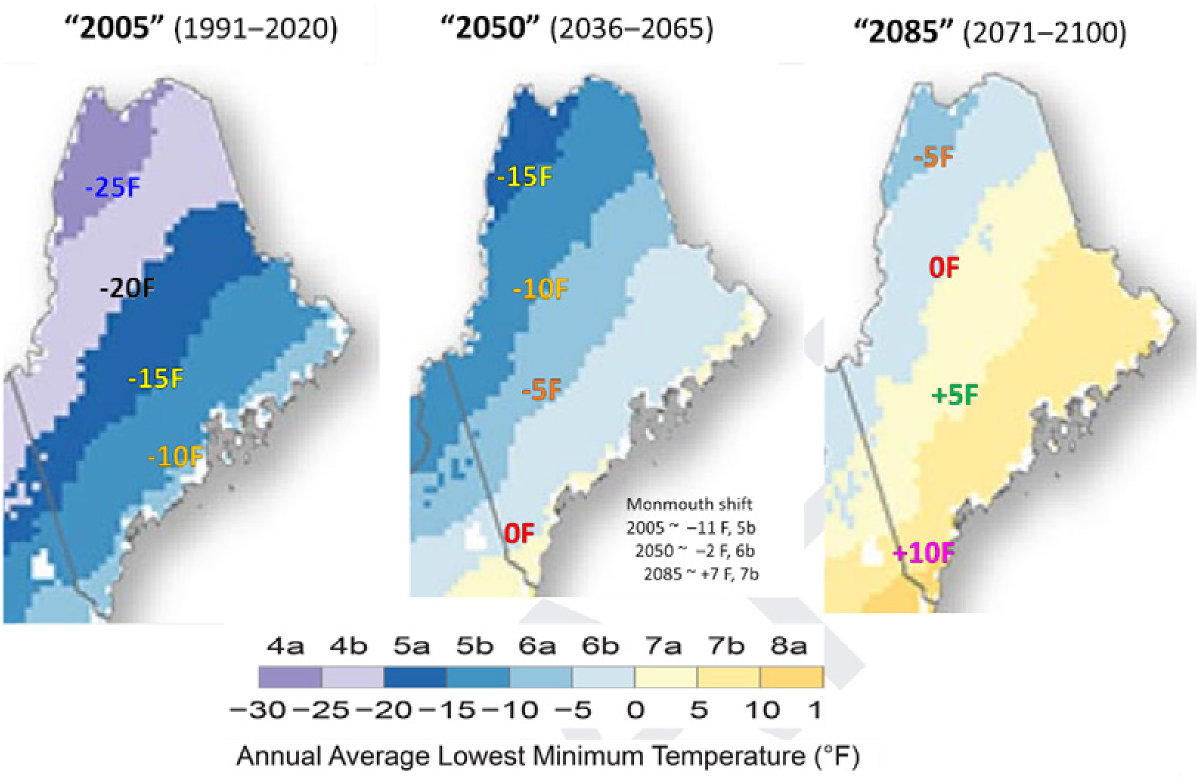


Figure 6. USDA Plant Hardiness Zone Maps for Maine in 2005, 2050, and 2085. Modified from Bolster et al., 2023.

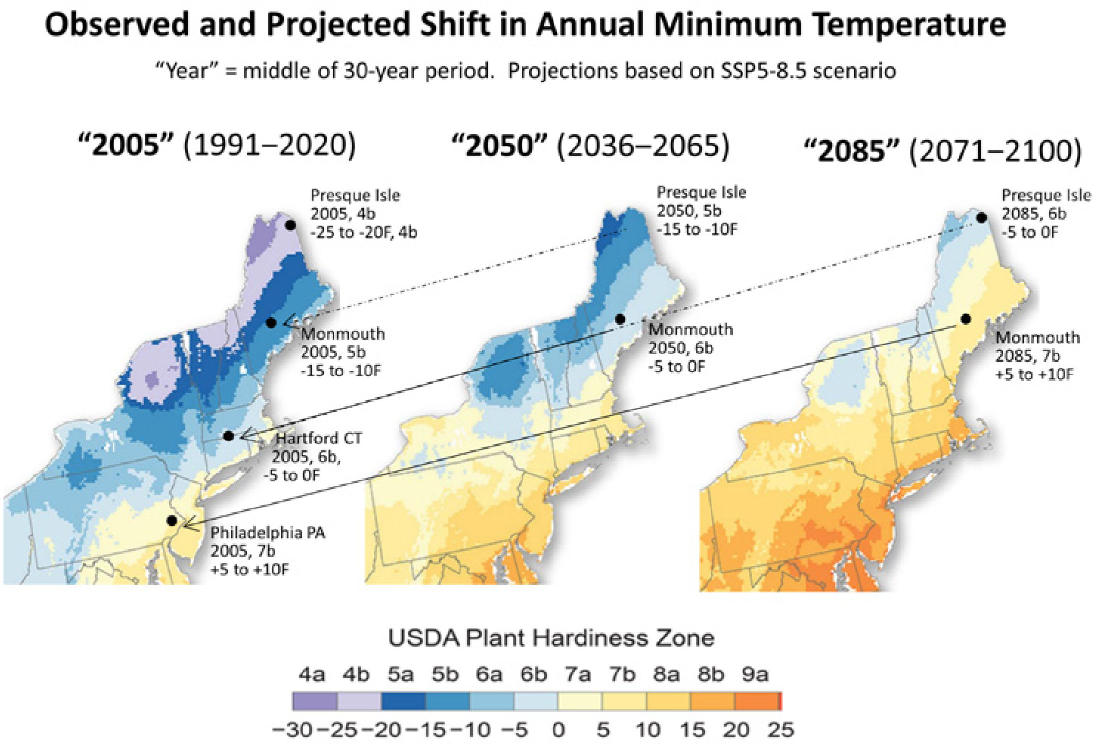


Figure 7. Observed and anticipated shifts in USDA Plant Hardiness Zones in Maine. Modified from Bolster et al., 2023.

Maple Production and Climate

The majority of Maine maple syrup production is concentrated in northern and western Maine. Many producers reported 50% of an average yield in 2023 (J. Lilley, personal communication, March 2023). The low production was due to an earlier-than-normal spring warm-up. Conversely, southern and coastal areas of Maine were able to collect sap earlier and for a longer period in 2023, resulting in record high total syrup production for many operations. Even so, the prolonged 2023 harvest at those locations required more time, energy, and labor to boil down sap collections over a longer period (**Figure 8**).

Figure 8. A sensor station monitoring sap flow, internal tree pressure, internal tree temp, soil temp, soil moisture, and ambient conditions in East Dixfield, Maine. Data are being uploaded in real time to a portal used by researchers showing results from a small network of sensors across the maple producing region. (Photo Credit: Jason Lilley, UMaine Cooperative Extension)

Climate change poses a substantial risk to U.S. agricultural yields. Using corn and soybeans as model crops, climate change is expected to have negative impacts on crop production nationally (Keane & Neal, 2020; Kirk, 2020; Zhu et al., 2016). These studies are not specific to Maine, but given that Maine imports 90% of its food, the national market directly impacts Maine food pricing and security. Modeling by Keane and Neal (2020) projected that optimistic models of advances in technology, combined with moderate or greater greenhouse gas emissions reductions and adaptation, could achieve yield growth roughly in line with population growth according to the mean climate model projection. However, this scenario deteriorated quickly under even slightly less optimistic technology projections. They concluded that climate change poses a substantial risk to U.S. agricultural yields.

Effective adaptation requires decades to implement and faces constraints, but can be 90% effective if warming remains under 2.7°F (1.5°C). Another global analysis (Theokritoff et al., 2023) found that agricultural and water management adaptation options are on average 90% effective in reducing risks up to 2.7°F (1.5°C) of warming, but with increased warming (3.6, 5.4, or 7.2°F (2, 3, or 4°C) above pre-industrial levels), effectiveness declines across all options and regions, with the decline in effectiveness most pronounced for agricultural options such as change in cropping patterns to accommodate warmer temperatures. Effective adaptation also takes decades to implement and is subject to constraints (financial, institutional, socioeconomic, cultural). Despite seemingly conducive conditions for agricultural adaptation (high GDP, educational level, gender equity, governance), the U.S. and Canada were ranked in the middle group of nations as having higher constraints to adaptation than western Europe, Greece, Turkey, Brazil, South Korea, New Zealand, and three others.

Higher concentrations of CO_2 can also reduce the nutritional quality of some staples such as wheat (Bloom et al., 2010). Plants in the C_3 group, including corn, do not benefit from higher atmospheric CO_2. Only crop plants with C_4 type metabolism benefit from increased CO_2 under controlled conditions where all other conditions are non-restricting. In addition to CO_2, plants need a steady water supply (absence of drought and flooding), an absence of high or low-temperature stress, and a supply of soil nutrients. Increasing CO_2 concentration for plant growth is only beneficial in controlled conditions such as greenhouses where temperature, moisture, and fertility are fully optimized (Kirk, 2020). A CO_2 fertilization effect has often been cited as a potential boon to crop plant productivity, but recent observations indicate that an initial positive effect of CO_2-induced climate change on vegetation carbon uptake shifted to negative in the early 21st century, especially in higher latitudes, in part due to widespread land drying which is expected to be exacerbated with future global warming (Chen et al., 2024; Yuxi et al., 2024).

Agricultural Emissions

Agriculture accounted for 9.4% of total United States greenhouse emissions in 2022 (USEPA, 2024), but that number is not representative of Maine. **Agriculture accounted for about 2% of total Maine statewide emissions in 2019** (S. Knapp, personal communication, March 2024). An updated analysis through 2021 will be available in the 10th Biennial Report on Progress toward Greenhouse Gas Reduction Goals due in 2024.

Sources of Maine's agricultural emissions

From 2010–2021, total emissions from Maine agriculture decreased; methane from the digestion process of ruminants (i.e., cattle) is down, and methane from manure is up. Total greenhouse gas (GHG) emissions from Maine agriculture declined slightly from 2010 to 2021 after a period of higher emissions from 1996–2010 (see **Figure 9**). Enteric methane emissions have been on a slow but steady decline since 1996. Conversely, methane emissions from manure have increased over that same period. Different manure treatment and storage methods affect the amount of CH_4 and N_2O emissions produced (USEPA, 2024a).

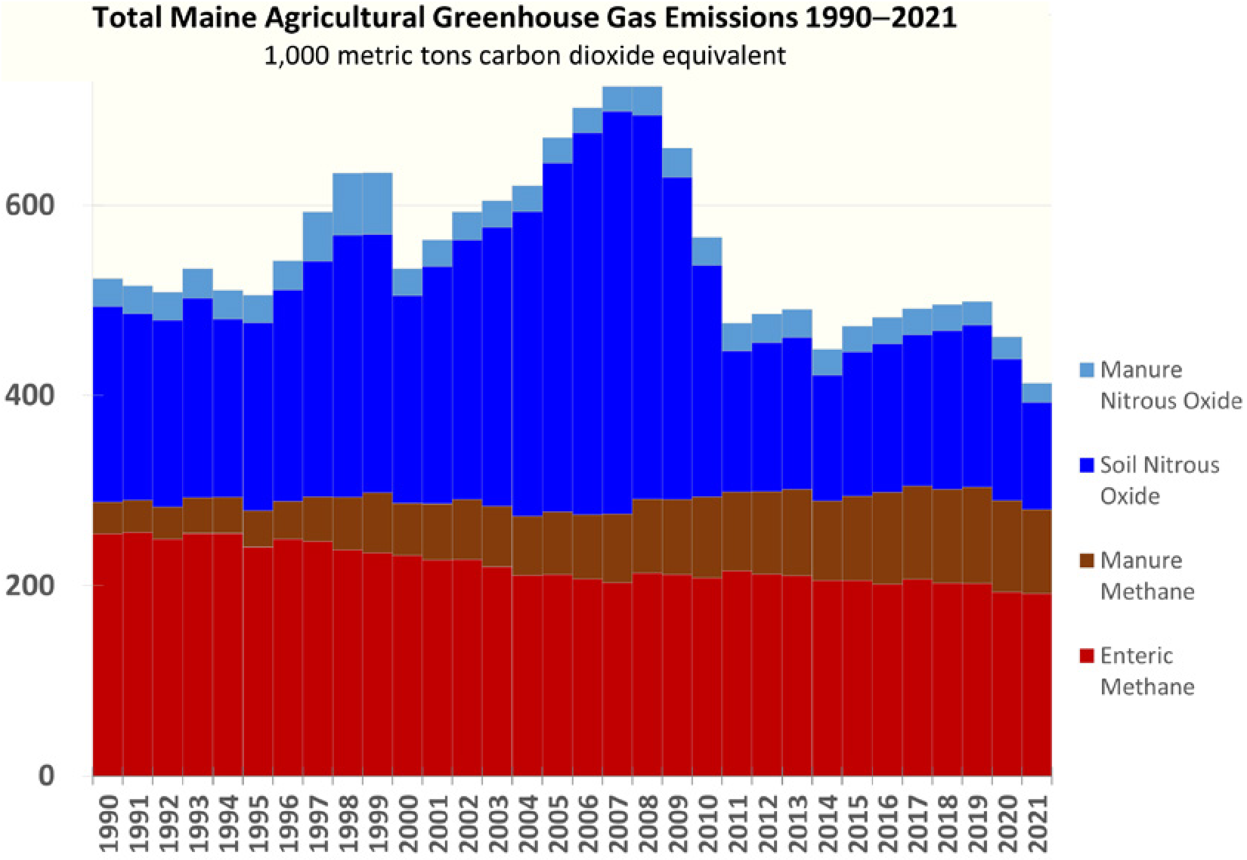


Figure 9. Maine agricultural greenhouse gas emissions 1990-2021. Data from Stacy Knapp, Maine Department of Environmental Protection. Summarization and graph by Glen Koehler, UMaine Cooperative Extension.

The major sources are methane (CH_4) from ruminant (e.g. cattle) digestion (46%), methane and nitrous oxide from cattle, poultry and other livestock manure (40%), and nitrous oxide (N_2O) from synthetic (non-manure) fertilizer losses from soil due to leaching and runoff (12%) (Knapp 2024). The remaining 2% are from soil N_2O released by nitrogen-fixing plants, crop residues, and by carbon dioxide (CO_2) from urea fertilizers (**Figure 10**). Methane has become the dominant component of Maine agricultural greenhouse gas emissions, overtaking nitrous oxide emissions that have declined since peaking in 2005-2009. In Maine, agricultural emissions of CO_2 from liming and urea application and CH_4 and N_2O from burning crop residues account for less than 0.3% of reported statewide emissions in 2021.

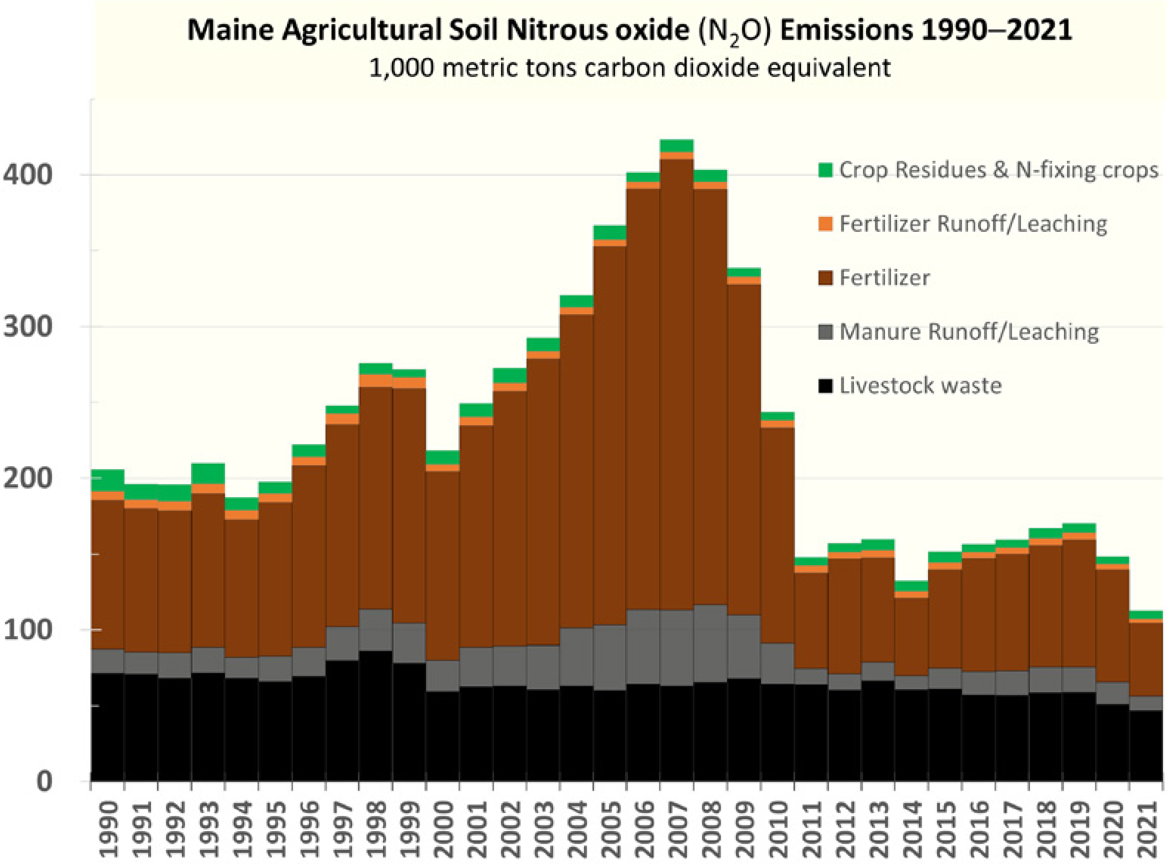


Figure 10. Contributing sources to nitrous oxide (N_2O) emissions from Maine agricultural soils. Data from Stacy Knapp, Maine Department of Environmental Protection. Summarization and graph by Glen Koehler, UMaine Cooperative Extension.

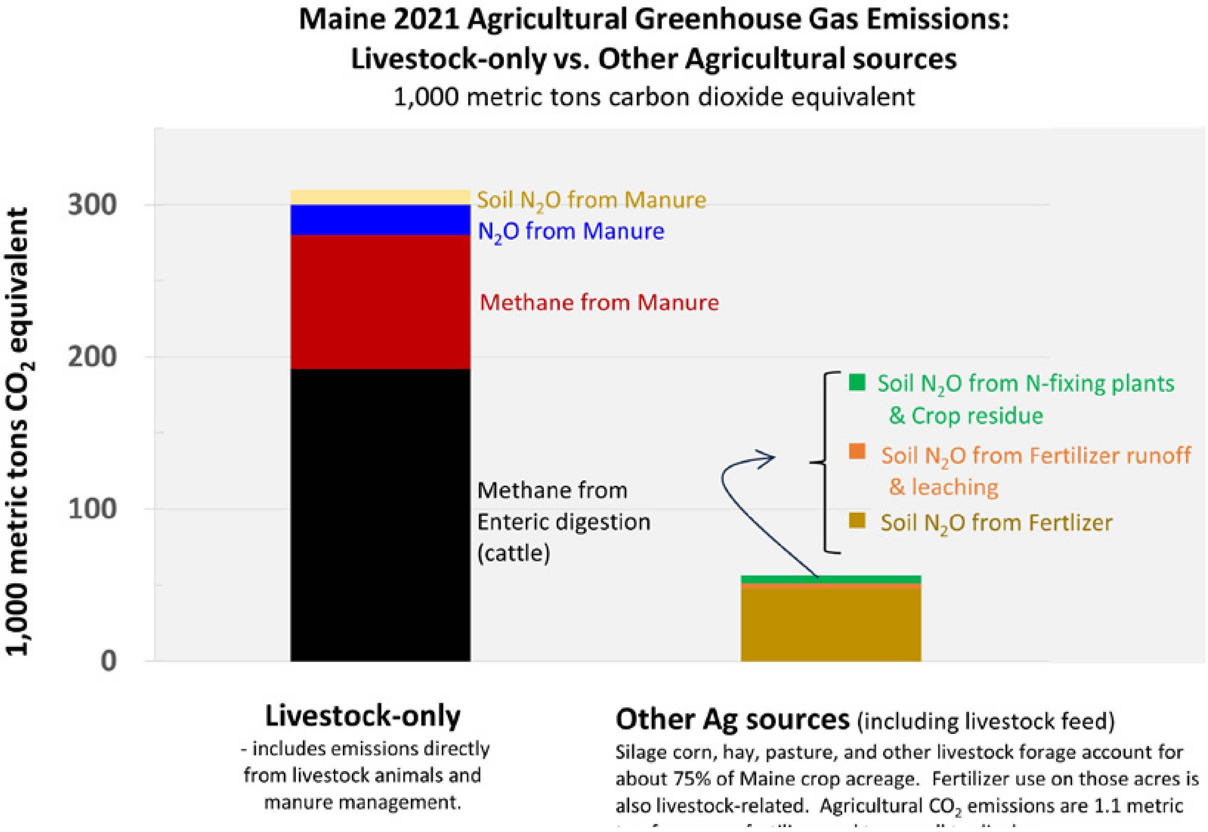


Figure 11. Maine agricultural greenhouse gas emissions in 2021 directly attributable to livestock versus those due to livestock forage production and other crops for human consumption. Data from Stacy Knapp, Maine Department of Environmental Protection. Summarization and graph by Glen Koehler, UMaine Cooperative Extension.

In 2021, livestock accounted for more than 86% of Maine's agricultural emissions, primarily from enteric methane and methane emitted from livestock manure (**Figure 11**) (Knapp, 2024; Soder & Brito, 2023; Tedeschi et al., 2022). The remaining 14% is due to soil N_2O arising from fertilizer applications made to grow crops for human consumption and forage and hay crops for consumption by livestock, and also from soil tillage. While livestock contributes the majority of agricultural emissions, Maine livestock industries account for less than 1% of total statewide emissions,

Globally, livestock methane emissions represent the largest agricultural contribution to climate change (Kelly & Kebreab, 2023; Steinfeld et al., 2006; Ungerfeld, 2022; Wuthmann, 2022). In a comprehensive 2006 FAO report on livestock agriculture, Steinfeld et al. (2006) stated that globally, livestock accounted for 37% of anthropogenic methane (83% of that from enteric digestion,17% from manure) and 65% of anthropogenic nitrous oxide (82% of that from manure).

Livestock emissions can be reduced through feed additives, including locally harvested seaweed. Research on multiple strategies for enteric methane mitigation has greatly increased in the last 20 years (Soder & Brito, 2023). Ongoing trials suggest opportunities to reduce beef and dairy cattle enteric methane production by the use of small amounts of feed additives, including locally harvested seaweed. Results vary widely by seaweed type and more study is warranted (Vijn et al., 2020). Methane-reducing feed supplements combined with grazing have shown mixed responses (Vargas et al., 2022).

Tradeoffs With Anaerobic Digesters

Manure digesters are a closed system that captures the biogas created when microorganisms break down manure. On livestock farms, they offer many benefits, including: reducing odors; protecting animal and human health by reducing pathogens; converting nutrients in manure into a form that is more accessible for plants than raw manure; recycling nutrients on the farm; reducing greenhouse gas emissions; producing heat, electricity, or biogas fuel, which can be used on-farm or sold; and providing animal bedding or peat moss replacement from digested solids. On-farm digesters can accept grassy biomass, wastewater biosolids, and food waste. The addition of food waste increases digester efficiency and reduces the amount of food waste being sent to landfills. In addition to potential income from tipping fees, this service increases farm-community connection. (Iowa State University 2022; USEPA 2023a; 2023b). Maine has a large natural gas production facility in Clinton that uses manure from several thousand cows in the region (Summit Utilities, 2023).

While anaerobic digesters offer opportunities in a world struggling to reduce greenhouse gas (GHG) emissions, there are concerns about promoting anaerobic digesters: 1) they may increase reliance on larger concentrated animal feeding operations that generate more waste; 2) they address a symptom but not the core problem of high GHG from livestock, 3) they reduce the incentive to decrease use of animal protein, and 4) they perpetuate continued reliance on methane as an energy source. The tradeoffs involved in these technologies require further analysis (NASEM, 2023; Wilcox, 2023).

Over half of Maine's organic dairy producers surveyed were familiar with, and a third were already using, red seaweed (aka "Irish moss," *Chondus crispus*) as a feed supplement to reduce enteric methane emissions (Reyes et al., 2023). Research suggests that methane emission from beef and dairy cattle can be reduced by 50% (Cowley & Brorsen 2018; McCabe et al., 2023; Melgar et al., 2020), and with some non-native seaweed species (e.g., tropical/subtropical *Asparagopsis taxiformis)* up to 98% with minimal effects on livestock health, productivity, or food quality (Camer-Pesci et al., 2023; Machado et al., 2016; Sena et al., 2023). Research is underway to identify seaweed and microalgae native to the Northeast that could be used to reduce livestock methane emissions (Wuthmann, 2022). Feed additive dosage levels and mitigation potential will need to be standardized before they are incorporated as a regular part of ruminant diets (Kelly & Kebreab, 2023). Preliminary research suggests that seaweed feed additives can also reduce methane emissions from cow manure (Ramin et al., 2023; Pitta et al., 2022). Another emergent strategy is the use of essential oils as a feed additive to reduce the methane intensity of cows (Carrazco et al., 2020).

Other important considerations for livestock methane reduction are safety, impacts on emissions of other greenhouse gases, plus economic, regulatory, and societal aspects that are key to implementation (Beauchemin et al., 2022). Successful implementation of locally appropriate and effective strategies will require delivery mechanisms and adequate technical support for producers, as well as consumer involvement and acceptance (Ibid).

New federal funding delivered through the Natural Resources Conservation Service (NRCS) promotes the installation of roofs over manure storage (USDA NRCS, 2023). Covering solid manure heaps with fixed roofs has been shown to reduce runoff losses and the escape of greenhouse gases, particularly ammonia (Chadwick et al., 2011; Hou et al., 2015; Sommer et al., 2013). Cover and flare manure pits are another option (Cornell CALS, 2020).

Debate Around Measuring Emissions from Livestock

The livestock industry has a different perspective on whether animal agriculture is a major driver of climate change. Beef and milk are often cited as the foods with the highest GHG emissions (e.g., Poore & Nemecek 2018; Xu, 2021). Livestock (primarily dairy cows) are the primary source of Maine agricultural GHG emissions. However, a peer-reviewed alternative perspective is that ruminant emissions in the form of methane are part of a natural atmosphere-plant-animal biogenic carbon cycle, and thus not an external source of GHG (Muñoz & Schmidt, 2016). In this view, the carbon released by livestock originates from, and is subsequently absorbed by, the plants used as livestock feed; therefore, livestock emissions do not add carbon to the atmosphere but simply recycle it. Part of this debate also centers on how the efficacy of methane as a GHG is calculated (Cain et al., 2019). In a counter-reaction to two leading sources of publications, websites, and statements that minimize the role of livestock GHG emissions, Morris & Jacquet (2024) point to under-reported industry funding and other factors resulting in biased science used to minimize the perceived need for livestock emission regulations, influence climate change policy and discourse, and promote industry-led climate "solutions" for which the real purpose is to maintain profitability.

Greenhouse Gas Mitigation

Mitigation potential of biochar

Evidence suggests that biochar, a form of charcoal, may enhance soil carbon sequestration. Globally, there is increasing interest in biochar as an agricultural soil amendment, with numerous basic and applied research studies (e.g., the International Biochar Initiative). Composting with biochar has been found to reduce nutrient and leachate losses from treated agricultural soils (Gao et al., 2023). However, only limited research has been done in New England demonstrating how these technologies could be applied to Maine. Regional interest and research in commercial biochar production and agricultural utilization is at an early stage. Biochar development is challenged by variability in the composition and characteristics of materials identified as biochar (Bai et al., 2022). Further study is necessary to understand how biochar influences soil properties and to identify appropriate management and economic strategies for biochar application across a diverse range of environmental and agronomic conditions.

How Does Biochar Sequester Carbon in Soil?

Biochar can sequester carbon in soil through multiple interacting mechanisms: 1) biochar is a high carbon material that is resistant to decomposition, thus soil amendments with biochar directly increase overall soil carbon stock; 2) biochar protects against microbial decomposition of soil organic matter, reducing carbon mineralization and prolonging carbon sequestration in the soil; 3) biochar provides numerous colonization sites and serves as a substrate for soil microbes, that, in turn, result in enhanced soil aggregate formation and stability; and 4) due to its physical structure (high porosity and surface area), biochar increases water and nutrient retention because it has both a high cation exchange capacity (CEC) and is slightly alkaline, which can help conserve both nutrients and water resources (Li & Tasnady, 2023).

Renewable energy on farms

Maine farmers are installing renewable energy infrastructure on agricultural land to increase farm economic viability. Of the 7,036 farms in Maine in 2022, 861 had solar panels, up from 709 in 2017, and 52 farms had wind turbines, down from 69 in 2017 (USDA RMA, 2024). This includes wind turbines on actively producing wild blueberry land (Calderwood et al., 2022). Good communication between the farmer and energy contractors is essential to ensure minimal damage to the crop during installation (Calderwood et al., 2023). Solar panels have been installed on less productive wild blueberry land that has been taken out of production. Growers cannot profitably manage wild blueberries under a solar array at the standard eight foot row spacing because of the 91–93% reduction in sunlight and the inability to spray, fertilize, and harvest under panels using current equipment (Calderwood et al., 2023).

Dual-use solar arrays in agricultural fields have so far only been economically feasible in Maine on pastures grazed by sheep (King, 2023). Solar co-location models for farms in other states suggest the potential for dairy cow grazing, and field corn, cranberry, and vegetable production (USDA, 2021). However, dual use for solar arrays and grazing is not recommended for cows, pigs, horses, or goats (ASGA, 2024). Only a small portion of Maine land is deemed suitable for crop production, and there is concern about solar array installations removing acreage from agricultural production (Cough, 2022; Kirk Hall et al., 2023).

Soil Carbon Sequestration

There are multiple constraints on soil carbon sequestration, including ecological and socioeconomic factors and the lack of standardized monitoring and measuring methods. While there is a great deal of enthusiasm for the potential of soil carbon sequestration globally (Lal et al., 2018), recent studies have pointed to the ecological, biogeochemical, and socioeconomic challenges of achieving enhanced carbon sequestration in soils (e.g., Davidson, 2022; Janzen et al., 2022; Ogle et al., 2023; Schlesinger, 2022), raising questions about the potential scale, overlooked constraints and other uncertainties.

Assigning "carbon credits" for soil carbon sequestration has limitations and is not equivalent to, or a substitute for, permanent reduction of fossil fuel-based GHG emissions. Measuring, reporting, and verifying soil carbon data in a way that can be used by stakeholders, regulators and policymakers requires improved coordination and methods assessment (Lawrence et al., 2023). Research indicates that regional-scale networks to coordinate the collection and use of soil carbon data could be accomplished through multi-state and institutional cooperation.

Emerging technologies

Research indicates that crushed rock mineralization, also known as enhanced silicate weathering (EW), could remove billions of tons of CO_2 per year if implemented on a global scale (Beerling et al., 2020; 2024). Research has found that adding crushed silicate rocks to agricultural land also increased corn and soybean yields by 12–16%, and had beneficial effects on soil nutrients and pH (Beerling et al., 2020; 2024). EW is becoming commercialized and appears much closer to wide-scale deployment than it did four years ago (NASEM, 2023).

ADAPTATION IN AGRICULTURE

Crop insurance in Maine

Crop insurance policies designed for diversified farms have low utilization rates by the Maine farmers that they are intended to serve. New climate-related crop insurance policies are becoming available. 5.5% of Maine farms were enrolled in crop insurance programs in 2022 (USDA, 2024c), up slightly from 5% in 2017. Frequent extreme weather events are impacting payment claims and premiums charged by crop insurance programs, making crop insurance protection more expensive (Crane-Droesch et al., 2019; J. Lilley, personal communication, March, 2023). New options include coverage for damage caused by tropical storms not categorized as hurricanes. The Whole-Farm Revenue Protection program (USDA, 2024b) allows eligible producers to purchase catastrophic coverage level policies for individual crops, makes policies more affordable for single commodity producers, and allows farmers to choose how other federal crop insurance policies are integrated into premium and claims calculations (USDA, 2024b).

Priority Information Needs

The top three information needs for agriculture that arose during this climate science assessment process included two urgent needs and a medium term need with a statewide focus:

1. **Access to more accurate, short, intermediate, and long range weather forecasts tuned to agricultural needs, and weather information analysis and delivery to translate conditions into guidance for agricultural management decisions.** This can be accomplished through better use of existing meteorological data, analyses, and delivery platforms. Funding for staff to identify needs, what is known, and conduct literature review and develop programs and products to fill gaps. Temperature and precipitation forecasts can be interpreted for the impact on crop and livestock management needs and timing for environmentally-driven precision agriculture already common elsewhere in the U.S. Soil moisture forecasting is more important than the simple precipitation amount. For agricultural drought, the default USDA Drought Monitor and Palmer Drought Severity Index (PDSI) are less useful than shorter term measures such as SPEI (standardized precipitation and evapotranspiration index) and EDDI (evaporative demand drought index). Soil saturation and field workability crop drying indices can improve yields, efficiency, and farm profitability. Information is needed on climatic shift and real time immediate conditions relative to phenological balance between late winter-early spring degree days and dates of final spring frost, and site specific trends in growing season length, in particular the date shift for the first fall frost. New agricultural opportunities will require knowledge from regions already experienced with those crops and livestock. This information is broadly applicable, especially for forestry, fisheries, and other natural resource industries.

2. **Programs designed to provide technical and financial support to increase Maine farm resilience and recovery to extreme and variable weather (e.g. drought and flooding, heat stress and freeze events), including mental health services to address farmer stress.** This can be accomplished first by reviewing existing programs to reduce bureaucratic hurdles, analyzing programs for farm climate resilience in other states and federal agencies, and reviewing ag-related components in emergency preparedness and recovery plans. These literature reviews and client needs surveys would support needed legislative action. Ag-focused programs would crosscut with municipal resilience planning and human health.

3. **Information relevant to instituting policies, programs and technology to reduce food waste and enhance food security.** Legislation could reduce liability concerns around food donations, and education would support sustainability actions for food usability and spoilage. This need crosscuts with the Human Dimensions chapter and further addresses municipal landfill issues.

A list of all of the priority information needs beyond those addressed here can be found in Report Appendix I.

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BIODIVERSITY

LAND CONSERVATION

Maine would need to add approximately 200,000 acres of conserved land per year to reach the national and state goal of 30% of land conserved by 2030 ("30x30"); however, Maine is not currently on track to meet this goal. The goal of protecting, restoring, and effectively managing 30% of land and water by 2030 was recently endorsed by the Convention on Biological Diversity (2022) as an important step towards reducing population declines, species extinctions, and disruption of ecological systems, and it is part of the 2020 Maine Won't Wait climate action plan.

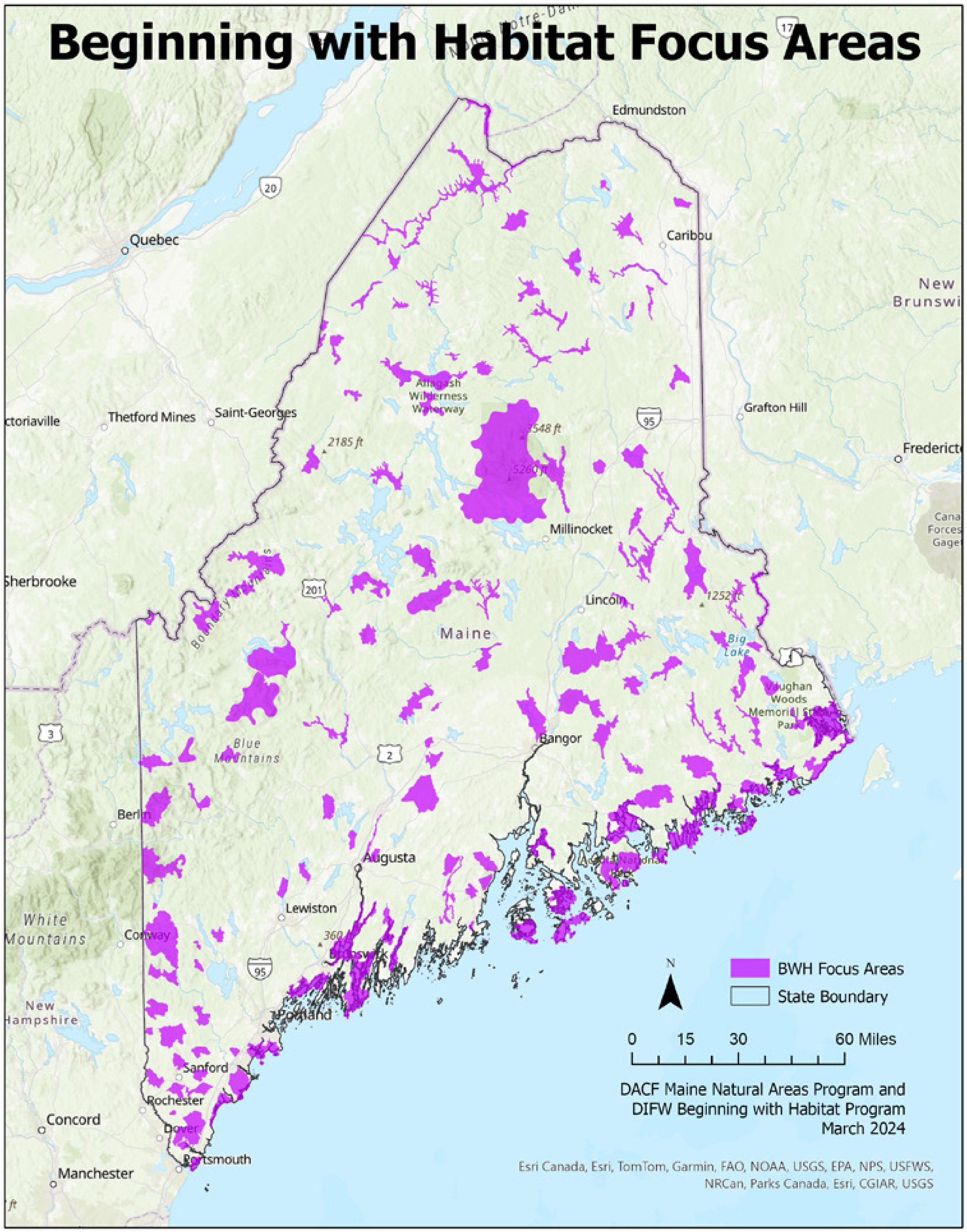
Though Maine's overall conserved area (22%) is low relative to most states in the Northeast, rates have recently increased. The state is projected to reach 30% land conserved in 2047 and would need to triple the current rate of conservation to meet the 2030 goal (Kannel et al., 2023, **Table 1**). Although region-wide state ownership makes up the largest proportion of conservation lands, lands held in conservation easement (primarily as working forest) are the predominant form of conservation (54% of conserved lands), followed by state ownership (23%) (Kannel et al., 2023).

Maine's Beginning with Habitat program identifies areas where a disproportionate concentration of at-risk species and habitats are located. These "Focus Areas" of statewide ecological significance (**Figure 1**) are collaboratively identified by partners within the state's Beginning with Habitat program administered by the Maine Department of Inland Fisheries and Wildlife (DIFW) and the Maine Natural Areas Program (MNAP) and distributed to municipalities, landowners, and land trusts with the goal of encouraging voluntary conservation measures

			Proportion of State Conserved		
State	**Total Land (Acres)**	**Total Conserved Land - this Study (Acres)**	**This Study**	**PAD-US**	**NEPOS**
Maine	19,751,680	4,389,364	22.2%	21.6%	21.6%
New Hampshire	5,729,696	2,009,985	35.1%	33.1%	33.8%
Vermont	5,898,662	1,687,534	28.6%	23.2%	26.5%
Massachusetts	4,992,038	1,453,232	29.1%	27.3%	30.6%
Rhode Island	661,638	171,588	35.9%	22.1%	24.1%
Connecticut	3,099,110	618,513	20.0%	19.5%	20.0%
New York	30,160,896	5,867,995	19.5%	20.4%	
New Jersey	4,706,701	1,394,180	29.6%	28.8%	
Pennsylvania	28,635,328	6,113,276	21.3%	19.3%	
Maryland	6,212,633	1,562,879	25.2%	23.4%	
Delaware	1,247,066	343,579	27.6%	27.6%	
Virginia	23,273,658	5,118,524	20.3%	17.0%	
Total Region	136,369,106	30,730,648	22.5%	21.1%	

Table 1. Progress of states towards the 30 by 30 goal by the Appalachian Mountain Club (this study) compared with estimates from Protected Areas Database of the United States (PAD-US) and the New England Protected Open Space (NEPOS) dataset maintained by Harvard Forest (from Kannel et al., 2023).

(Maine Department of Inland Fisheries and Wildlife, n.d.). The biodiversity elements in Maine's Focus Areas are vulnerable to threats such as habitat loss and fragmentation, invasive species, pollution, and more recently, climate change. Directing "30 by 30" land conservation efforts at unprotected portions of Maine's Focus Areas could both increase the viability and resilience of Maine's biodiversity and serve as a natural climate solution for protecting natural areas' carbon stocks.



DACF Maine Natural Areas Program and DIFW Beginning with Habitat Program March 2024

Esri Canada, Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS, NRCan, Parks Canada, Esri, CGIAR, USGS

Figure 1. Map of Focus Areas statewide (in purple) identified by partners in Maine's Beginning With Habitat Program. Identified areas contain a disproportionately high number of at-risk species and habitats.

Climate change is predicted to cause unprecedented species loss and range shifts. As climate drives species movements, conserving diverse geophysical settings and strategically located resilient and connected landscapes can protect biodiversity (Anderson & Ferree, 2010; Anderson et al., 2023; Zhu et al., 2023)**.** Complementing the focal area approach above, protecting a diversity of geophysical settings ("the stage") and strategically located resilient and connected landscapes (via large undeveloped habitat blocks) is a strategy promoted to protect biodiversity, even as climate changes and species move (Anderson and Ferree 2010, Zhu et al. 2023, Anderson et al. 2023). Geophysical settings are unique combinations of geology, soils, and elevation zones that have been identified as predictors of current and future species diversity (Anderson & Ferree, 2010). In the Northeast, Anderson et al. (2023) found that habitat loss exceeds conservation three fold in low elevation settings. These settings also have experienced the highest fragmentation, with decreases in connectivity continuing through the last decade. Globally, 20% of the species listed under the Convention on the Conservation of Migratory Species of Wild Animals (CMS) are at risk of extinction, further highlighting the need to conserve ecological connectivity in the form of unfragmented habitat across large landscapes to facilitate species' safe movement within and between states and nations (UNEP-WCMC, 2024).

Old growth (older than 170 year old) forests support the largest carbon pools of all Northeast forest types while concurrently supporting the highest biodiversity (Finzi et al., 2020). Old growth forests provide ecological benefits beyond carbon storage, including soil development, nutrient cycling, clean water, oxygen, and biodiversity (Anderson et al., 2019; McMahon, 2021). Forests that have evolved with little or no drastic human intervention typically are more physically and biologically diverse than younger forests (Haskell, 2017; Lapin, 2005; Maloof, 2016), including a greater variety of microclimates and microhabitats above ground (Martin et al., 2021) and below ground (Haskell, 2017).

Severe disturbances (e.g., clearcutting or infestation by invasive insects) have the potential to convert forests from a carbon sink to a source at least temporarily if disturbance severity increases (Finzi et al., 2020)**.** This is largely the result of disturbance induced increases in forest litter and soil organic matter decomposition (i.e., microbial respiration releasing CO_2) and declines at least temporarily in the photosynthetic capture of atmospheric CO_2, shifting the ecosystem from sink to source.

Young forest stands (younger than 15 years) sequester carbon quickly and provide important habitat for species that rely on early successional forests (Catanzaro & D'Amato, 2022). Young forest stands are more common, especially in northern Maine, than older forests. Forests with a mix of young and old trees typically have the highest carbon sequestration of all age classes, and a mix of young, medium, and old patches are important for sustaining a diversity of species (Catanzaro & D'Amato, 2022). More generalized biodiversity impacts of different management strategies are difficult to define, because species will respond to management differently depending on their habitat needs (Daigneault et al., 2024). Maine's conservation lands are estimated to contain 23% of the State's carbon stock, across both fee and easement lands (Anderson et al., 2023). Approximately 48% of Maine's carbon stock is located within a resilient climate landscape "network" that is not conserved, highlighting opportunities for conservation action that would benefit biodiversity, climate resiliency, and carbon sequestration (Ibid).

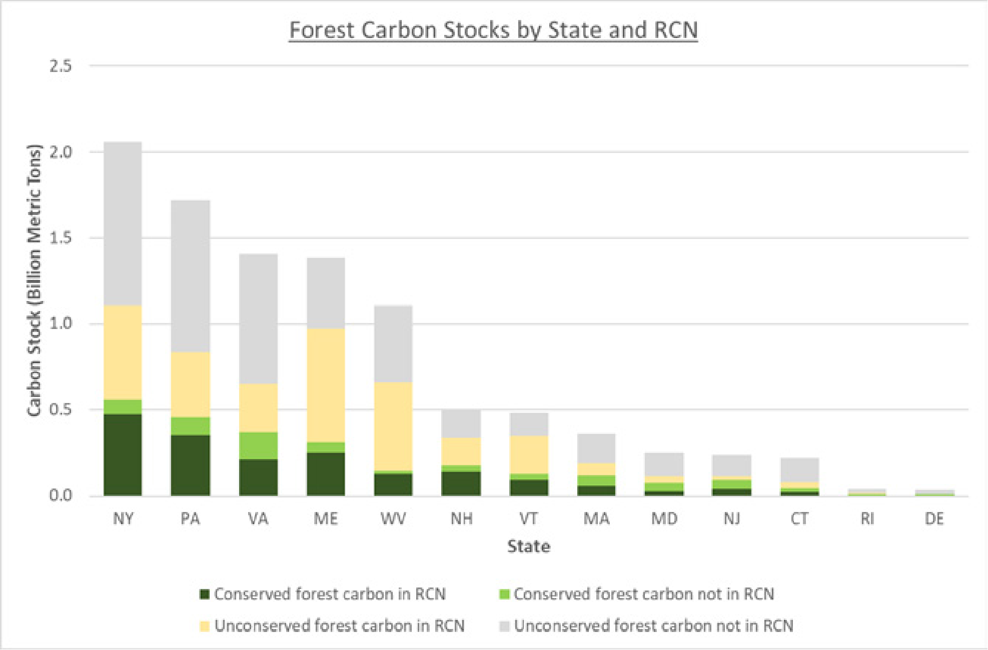


Figure 2. Conserved and nonconserved forest carbon stocks inside and outside of The Nature Conservancy's (TNCs) Resilient and Connected Network in the northeastern U.S. Total carbon stocks for each state vary in size depending on the state's area and forest cover. Adapted from Anderson et al. 2023.

Protecting biodiversity can serve as Nature-based solutions (NbS) use natural ecosystems and their processes or mimics of natural systems to protect natural and human infrastructure (MacKinnon et al., 2008). For example, protecting riparian buffers, particularly forested buffers and those along headwater streams, can protect water quality and stabilize streambanks, provide shading that limits water temperature increase, intercept non-point source pollution, decrease intensity of flooding, and provide habitat and climate refuge for wildlife (Graziano et al., 2022). These nature-based buffers also create high-quality habitat for aquatic species such as brook trout (*Salvelinus fontinalis*) (**Figure 3**) (Albertson et al., 2018), amphibians (Mitchell et al., 2006), and macroinvertebrates (Milner & Gloyne-Phillips, 2005).

Figure 3. Brook Trout (*Salvelinus fontinalis*) are a cold-water species that is vulnerable to warming of freshwaters. They are one example of a species that could benefit from nature-based climate solutions such as riparian restoration.

Author: Gary Delise; Source: https://www.inaturalist.org/observations/136644453; License: CC-BY-NC https://creativecommons.org/licenses/by-nc/4.0/legalcode.en

Rare and Endangered Species

Ecologists agree that human-accelerated climate change will have a profound effect on the status of biota worldwide (Kannan & James, 2009; Pecl et al., 2017). Undoubtedly there will be climate winners and losers among Maine's biota with some species increasing in abundance and distribution and others declining, potentially to the point of state extirpation. Among those species likely to be most vulnerable to the compounding stress of climate change are those with low population abundance, narrow ranges, and/or specialized habitat requirements. Many of these species are already formally designated as state species of conservation concern.

A quarter of Maine's at-risk butterflies are threatened by climate change (deMaynadier et al., 2023). One example of a group of Maine animals whose conservation status was recently assessed in significant depth is the taxonomic order Lepidoptera, or butterflies. As a result, 25 (21%) of Maine's 120 resident and visiting butterfly species are listed as state endangered, threatened, special concern, or extirpated. And while habitat loss to development ranks first as the leading cause of species endangerment, seven (28%) of the state's 25 at-risk butterfly species are also considered imminently threatened by climate change (deMaynadier et al., 2023). In most cases this threat is likely to manifest as changes in the quality and quantity of specific climate-vulnerable habitats that support narrow species specialists, such as alpine tundra (Katahdin Arctic, *Oeneis polixenes katahdin*), boreal forest (Arctic Fritillary, *Boloria chariclea*), and northern bogs (Frigga Fritillary, *Boloria frigga*).

Figure 4. Katahdin and other high peaks are examples of rare alpine and subalpine habitat that support at-risk species such as the Katahdin Arctic butterfly (*Oeneis polixenes katahdin*). Photo credit: Devon Fernandez, used with permission.

Figure 5. The Wood Turtle (*Glyptemys insculpta*) is a species found in Maine that is under consideration for listing on the federal list of Threatened and Endangered Species.

Author: Logan Parker; Source: https://www.inaturalist.org/observations/47427479; License: CC-BY-NC https://creativecommons.org/licenses/by-nc/4.0/legalcode.en

Eight new wildlife species were added to the Maine State List of Endangered and Threatened Species in 2023, many of which are additions driven in full or part by climate change (Latti, 2023). Four species are directly impacted by climate change: Saltmarsh Sparrows (*Ammospiza caudacuta*) require high saltmarsh grass habitat for nesting and are losing ground to sea level rise and storm surge; Bicknell's Thrush (*Catharus bicknelli*) preferred breeding habitat is impacted by shifts and potential shrinkage of subalpine fir habitat; Blackpoll Warbler (*Setophaga striata*) is a semi-boreal species closely tied to changes in the availability of high elevation spruce-fir forest and spruce budworm outbreaks; and the Margined Tiger Beetle (*Ellipsoptera marginata*) relies on back dune mudflats and salt marshes threatened by sea level rise (Ibid). Cliff (*Petrochelidon pyrrhonota*) and Bank (*Riparia riparia*) Swallows are suffering from loss of habitat and declining insects, the latter likely partly driven by climate change (Latti 2023). White-nose syndrome, in combination with climate change (USFWS, 2021) has caused dramatic declines in the Tricolored Bat (*Perimyotis subflavus*) in Maine, and Ashton's Cuckoo Bumblebee (*Bombus ashtoni*), once thought to be extirpated from the state after widespread bumblebee declines in the early 2000s, exists in one known population in Aroostook County (Latti, 2023). Of these eight species, the Saltmarsh Sparrow and Ashton's Cuckoo Bumblebee are designated as Endangered, while the other six are Threatened (Latti, 2023).

Maine species being considered for federal ESA listing with listing decisions coming in 2024 include Northern Bog Lemming (*Synaptomys borealis*), Wood Turtle (*Glyptemys insculpta*), Spotted Turtle (*Clemmys guttata*), and Saltmarsh Sparrow (*Ammospiza caudacuta*) (A. Cross, personal communication, February 2024).

Additional species not listed but vulnerable to climate change include bats, amphibians, turtles, salmonid fish and moose. Examples of other species not listed as endangered or threatened but impacted by climate change include: bats, which are vulnerable to declining flying insects and warming caves (Rodenhouse et al., 2009, Rustad et al., 2012); amphibians vulnerable to changing hydroperiods and flow in marshes, vernal pools, and streams (Rustad et al., 2012); turtles with temperature dependent sex determination in which the sex of developing embryos is determined by nest temperature, not genetics (Valenzuela et al., 2019); salmonid fish vulnerable to increasing water temperatures (Bonney, 2007); and moose (*Alces alces*), which are susceptible to heat stress, changing vegetation, and increased parasites such as Winter Ticks (*Dermacentor albipictus*) (Rodenhouse et al., 2009; Rustad et al., 2012).

Figure 6. Moose (*Alces alces*) culturally important species that is threatened directly and indirectly by climate change

Author: catskillbob; Source: https://www.inaturalist.org/observations/171090942; License: CC-BY-NC https://creativecommons.org/licenses/by-nc/4.0/legalcode.en

Impacts

Biodiversity Loss

Many of Maine's species have already been impacted by climate-driven changes to climate niche space and ecosystem structure. Ecosystem structure is the complex interaction between plants and animals at all levels of the food web. Specific examples include the loss of Eelgrass (*Zostera sp.*) (ME DEP, 2023) and kelp (Order: Laminariales) beds (Dijkstra et al., 2017), and the loss of forest understory plant diversity due to invasive species. In Maine, the range of Common (*Rhamnus cathartica*) and Glossy (*Rhamnus frangula*) Buckthorn, for example, has expanded due to warming temperatures, contributing to the loss of native species through overcrowding the forest understory and shading out natural regeneration (Fagan et al. 2004, ME DACF, n.d.a, ME DACF n.d.b), decreased carbon sequestration, and increases in invasive earthworms (Knight et al., 2007, ME DACF n.d.a).

Species distribution in the Northeast depends more on habitat characteristics and factors related to precipitation than temperature. While temperatures are important limits to species distributions, the Vermont Atlas of Life (Hallworth et al., 2023) identifies factors describing physical habitat, such as soil and geological factors, and precipitation to be slightly more important than temperature for defining species distributions. The report also projects a loss of at least 6% (386 species) of current species by 2100 under the RCP 8.5 scenario.

Almost all bird taxa are declining; wetland bird populations have benefited from adaptive management and long-term wetland protection (Rosenberg et al., 2019). Birds are one taxonomic group that show declines across taxa and the continent, likely due to multiple stressors including habitat degradation and loss, increases in intensive agriculture, coastal habitat loss and disturbance, and direct taking by humans, all of which are made worse by climate change (Rosenberg et al., 2019). It is notable that despite declines in all other biomes, wetland bird populations have gone up since 1970, likely as a result of adaptive management via harvest regulations and enormous financial investment in wetland protection and restoration (Ibid).

Climate change impacts on biodiversity are expected to increase, but are currently less impactful than habitat loss. Across terrestrial vertebrate extinctions since 1900, there were three to 11 times more extinctions due to habitat loss than for climate change. The impacts of habitat loss and overexploitation manifest more rapidly than those of climate change, especially in the case of local extirpations (Caro et al., 2022). However, climate change is expected to contribute more directly and immediately to extinctions in the future, with specific effects varying by species and location. Current projections estimate 5% of species globally to be at risk of extinction due to climate change at 3.6° F (2.0° C) warming and 16% at 7.7° F (4.3° C) warming (Urban, 2015).

In the Northeast, models suggest that many common and culturally important species will decrease (Rodenhouse et al., 2009). About two thirds of resident species in the Northeast are projected to increase in population as more southern species move northward; among the one third that will decrease are culturally important species such as the Ruffed Grouse (*Bonasa umbellus*), Black-capped Chickadee (*Poecile atricapillus*), and Moose (*Alces alces*) (Ibid). Conversely, about two-thirds of short-distance migrant birds are projected to decrease, including the Baltimore Oriole (*Icterus galbula*) and Hermit Thrush (*Catharus guttatus*), and about half of neotropical migrants are projected to decrease, including the Blackburnian Warbler (*Setophaga fusca*), Rose-breasted Grosbeak (*Pheucticus ludovicianus*), Wood Thrush (*Hylocichla mustelina*), and Veery (*Catharus fuscescens*) (Ibid). These population changes are attributed to geographic shifts or shrinkages of biologically and climatically suitable areas (Ibid). Species reliant on high-elevation forests (i.e., Bicknell's Thrush [*Catharus bicknelli*], Blackpoll Warbler [*Setophaga striata*], and Northern Bog Lemming [*Synaptomus borealis*]) are especially vulnerable because such forests are limited in their ability to move upslope with warming (Ibid). Montane spruce-fir forests are also limited in distribution in the Northeast, covering less than 1% of the landscape, and most bird taxa that rely on these forests for breeding are already considered of conservation concern (Ibid).

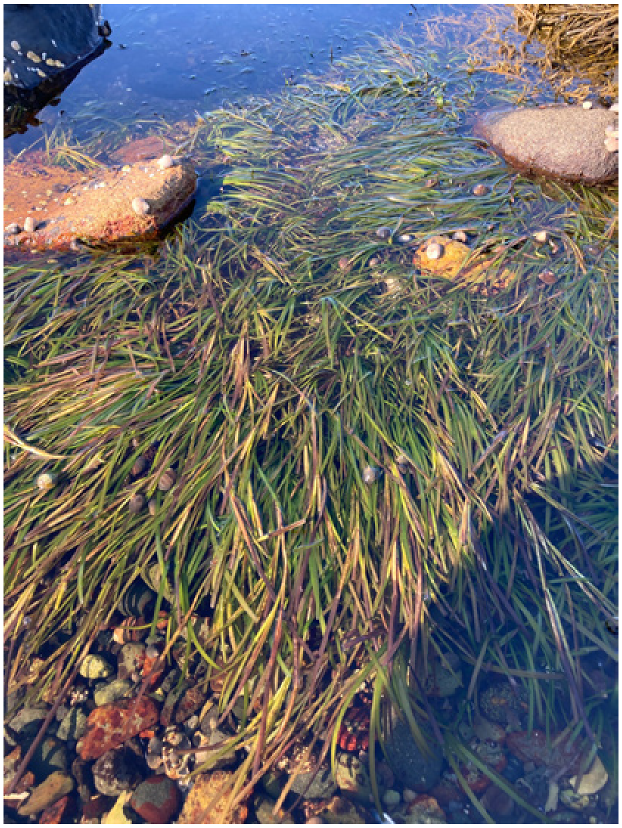


Figure 7. Eelgrass (*Zostera sp.*) meadows, such as those pictured here, have declined by 54% since 2018.

Author: Hannah Webber; Source: https://www.inaturalist.org/observations/88252528; License: CC-BY-NC https://creativecommons.org/licenses/by-nc/4.0/legalcode.en

Climate change continues to affect species' numbers and distributions in diverse ways

Eastern Bluebirds (*Sialia sialis*) are a more "southern" species expanding its range northward. The southern counts are reporting higher numbers consistently each year, and the advance of smaller (approximately <25 individuals) wintering populations are continuing in a north-northeastly direction (Hitchcox, 2019). Boreal Chickadee (*Poecile hudsonicus*) is an example of a species experiencing a particularly steep decline in the state and the region. Increases in mean winter precipitation and variability in winter precipitation, as well as rising summer temperatures, are the climatic factors with negative effects on Boreal Chickadee populations (Glennon et al. 2019)

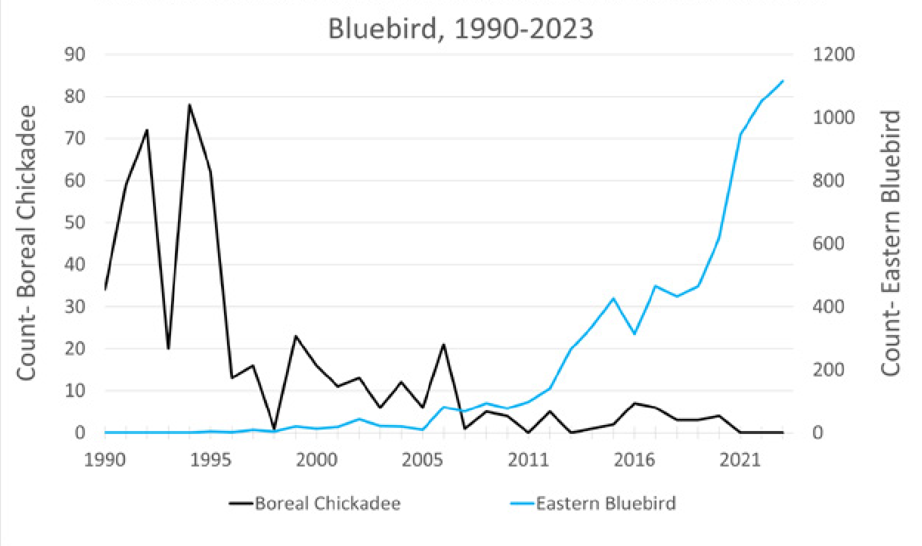


Figure 11: Counts of Boreal Chickadee (*Poecile hudsonicus*, black) and Eastern Bluebird (*Sialia sialis*, blue) from Christmas Bird Counts between 1990 and 2023. Data from National Audubon, compiled and graphed by Doug Hitchcox (bluebird) and Val Watson (chickadee).

Shifts in Range and Phenology

Due to climate change, Maine birds are on the move, expanding or shifting their ranges. Results from the five-year Maine Breeding Bird Atlas that concluded in 2022 document new birds moving into Maine since 1983, including the Red-bellied Woodpecker (*Melanerpes carolinus*), Carolina Wren (*Thryothorus ludovicianus*), Merlin (*Falco columbarius*), Sandhill Crane (*Antigone canadensis*), and American Oystercatcher (*Haematopus palliatus*) (Maine Bird Atlas, 2023). Several warblers and grassland birds have lost parts of their range (i.e., Cape May Warbler (*Setophaga tigrina*) and Bobolink (*Dolichonyx oryzivorus*), while other species' ranges are expanding (i.e., Indigo Bunting [*Passerina cyanea*], Eastern Bluebird [*Sialia sialis*], and Prairie Warbler [*Setophaga discolor*]*).* Still other species are moving south (i.e., Merlin [*Falco columbarius*] and Fox Sparrow [*Passerella iliaca*]) or north (e.g., Boreal Chickadee [*Poecile hudsonicus*] and Olive-sided Flycatcher [*Contopus cooperi*]) (Ibid Hitchcox, 2023).

Shifting ranges can lead to concerning interspecific interactions and decreased nesting success. For example, movement of the more territorial Swainson's Thrush (*Catharus ustulatus*) into higher elevation montane habitat occupied by state endangered Bicknell's Thrush (*Catharus bicknelli*) (Freeman & Montgomery, 2016). The combination of increased heavy precipitation events and temperature increases can lead to a decrease in nesting success as birds attempt to avoid unfavorable conditions, especially in montane breeding birds (Deckel et al., 2024).

An Audubon study projects that with 5.4° F (3.0° C) warming, more than 100 North American bird species could experience population and range shifts during both the breeding and non-breeding season, albeit with different responses for each (Bateman et al., 2020), including losses in Maine's Common Loon (*Gavia immer*) population (MCC STS, 2020).

Figure 9. The Bicknell's Thrush (*Catharus bicknelli*) is a new addition to Maine's List of Endangered and Threatened Species due to shifts and potential shrinkage of its subalpine fir breeding habitat.

Author: Matt Felperin; Source: https://www.inaturalist.org/observations/170184898; License: CC BY https://creativecommons.org/licenses/by/4.0/legalcode.en

Many of Maine's insects, foundational to most ecosystem food webs, will respond to climate change by altering their flight periods. Significant shifts toward earlier adult emergence and flight have already been documented in Massachusetts (Polgar et al., 2013) and Maine (deMaynadier et al., 2023). One conservation implication of this dynamic is the potential for trophic mismatch, whereby ecologically associated species do not respond to climate-related changes at the same rate (e.g., Schmidt et al., 2016). This can affect caterpillar survival if adult oviposition is no longer timed for optimal nutrition, as during host plant senescence. A trophic mismatch of this kind can cascade through food webs in complex ways with implications for insectivores, such as song birds and bats, that require healthy populations of butterfly and moth populations as prey, especially for feeding their young (Damien & Tougeron, 2019; Renner & Zohner, 2018).

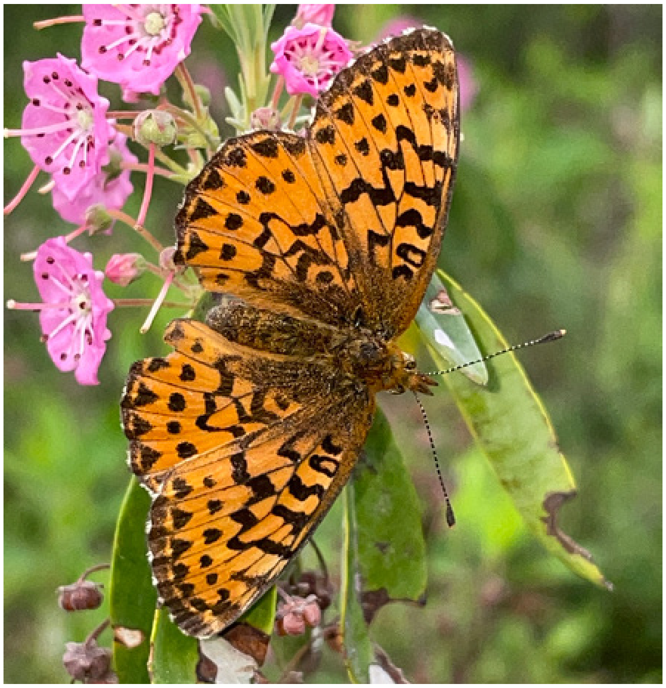


Figure 8. The Arctic Fritillary (*Boloria chariclea*) is a boreal forest specialist whose highly specific habitat needs make it especially vulnerable to climatic change.

Author: John V. Calhoun; Source: https://www.inaturalist.org/observations/173866091; License: CC-BY-NC https://creativecommons.org/licenses/by-nc/4.0/legalcode.en

Another expected response to a warming climate is a shift in the geographic range of individual butterfly species and other insects. This too appears to be already underway in Massachusetts (Breed et al., 2012) and Maine (deMaynadier et al., 2023). Several skippers (i.e., Black Dash [*Euphyes conspicua*] and Mulberry Wing [*Poanes massasoit*]) have expanded their northern ranges into Maine recently, while Arctic Fritillary (*Boloria chariclea*) and Hoary Comma (*Polygonia gracilis*) appear to have contracted their ranges northward. These semi-boreal species approach the southern limits of their distribution here, possibly making them more susceptible to the effects of warming (deMaynadier et al., 2023).

A climate vulnerability assessment conducted in Maine involving over 100 biologists identified alpine tundra, boreal and montane forest, peatlands, and coastal marshes as among the most vulnerable ecosystems based on climate projections for the state (Whitman et al., 2014). Unfortunately, these same systems are known to host many of the Acadian region's most specialized and unique biota, including, for example, the American Pipit (*Anthus rubescens*) and Katahdin Arctic butterfly (*Oeneis polixenes katahdin*) (alpine tundra), Canada Lynx (*Lynx canadensis*) and Arctic Fritillary butterfly (*Boloria chariclea*) (boreal forest), Quebec Emerald dragonfly (*Somatochlora brevicincta*) and Bog Elfin butterfly (*Callophrys lanoraieensis*) (northern bogs), and Saltmarsh Sparrow (*Ammospiza caudacuta*) and Margined Tiger Beetle (*Ellipsoptera marginata*) (northern salt marshes).

The impacts of climate change on some specialized invertebrates (and other less mobile biota) are compounded by the destruction and fragmentation of habitat from development, which can reduce the likelihood for successful dispersal to climatically suitable areas (deMaynadier et al., 2023). The pace of development remains high in parts of central and south-coastal Maine, an area with significant concentrations of imperiled insects and other at-risk species (McCollough et al., 2003; deMaynadier et al., 2023).

Changes in precipitation and hydrology, especially of ephemeral or vernal pools, are likely impacting the state's amphibians (Rustad et al., 2012, Hunter et al., in press). Amphibians in the Northeast rely on damp habitats, and most breed in water, making them especially vulnerable to changes in temperature and precipitation. Hydroperiod of vernal pools is particularly important, as drought and high temperatures can cause pools to dry or reduce in volume before frogs and salamanders can complete their juvenile aquatic life stages, leading to mortality (Rustad et al., 2012). Low moisture levels can directly kill terrestrial adult salamanders, and those that live in streams are vulnerable to low flow events (Rodenhouse et al., 2009).

Along with changes in seasonal emergence, highly variable late winter and spring freeze-thaw events are impacting regional amphibians. Similar to the bird and insect examples discussed above, warmer winters and springs are expected to lead to changes in the seasonality of amphibian emergence, activity, and reproduction (Hunter et al., in press). Climate warming has already advanced the calling activity of frogs in New York where Spring Peeper (*Pseudacris crucifer*), Wood Frog (*Lithobates sylvaticus*), American Bullfrog (*Lithobates catesbeianus*), and Gray Treefrog (*Dryophytes versicolor*) were calling one to two weeks earlier by the end of the 20th century (Gibbs & Breisch, 2001). A related concern is the growing number of reports in the Northeast of late-winter amphibian movements followed by sudden freezing temperatures that can kill breeding adults and Wood Frog (*Lithobates sylvaticus*) egg masses (Klemens et al., 2021). Highly variable late winter and spring freeze-thaw events are a new stressor with which Maine's pool-breeding amphibians must increasingly contend.

Figure 10. Amphibians like this Wood Frog (*Lithobates sylvaticus*) are especially vulnerable to changes in precipitation patterns and vernal pool hydroperiod.

Author: Fiana; Source: https://www.inaturalist.org/observations/193685091; License: CC-BY-NC https://creativecommons.org/licenses/by-nc/4.0/legalcode.en

Broad Trends

The pace of change to natural systems over the past 50 years is unprecedented and accelerating, in part a function of climate change, causing significant losses in biodiversity and ecosystem function and health. A recent study of population trends of over 71,000 species from all five vertebrate taxonomic groups plus insects across the globe found declines in 48% of those species (Finn et al., 2023). Species that occur in isolated or small populations are particularly vulnerable due to the combination of climate change and fragmentation impacts on the landscape.

Climate change exacerbates the worldwide decline of species and worsens the impacts of habitat loss. Between 1970 and 2014, multiple classes of forest-living vertebrates worldwide declined by 53%, on average (WWF, 2020). Even with mitigation policies in place, climate change could directly drive extinctions of as many as 20% of all land species by 2100 (Ibid). Endemic (locally specialized) species are even more vulnerable: climate change could directly cause the extinctions of up to 40% of endemic species in the same period (Ibid). Climate change also exacerbates the effects of other stressors, like land-use change. A 2019 analysis by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) found that climate change worsened effects of habitat loss over the next 25 years in every metric they examined (IPBES, 2019). For example, construction and development can divide large and continuous patches of habitat into many small, disconnected fragments, impeding the movement of species trying to track their resource needs as the climate changes (WWF, 2020).

The globe experienced its first documented climate-driven extinctions of this era, along with widespread localized extirpations: a quarter of all species on earth are at risk of extinction. Climate change has been identified as the cause of at least two species extinctions, the Golden Toad (*Incilius periglenes*) of Costa Rica in 1990 and the Bramble Cay melomys (*Melomys rubicola*, a rodent) of the Great Barrier Reef, Australia in 2016 (IPCC, 2022). These are the world's first documented cases of climate change-driven species extinction. However, an additional 5% of extant (currently living) species are at risk for climate-driven extinction with 3.6° F (2.0° C) warming and 16% at 7.7° F (4.3° C)warming (Urban, 2015). Research shows that one million species, or 25% of all the world's known species, are threatened with extinction due to other reasons alone or in conjunction with climate change (IPBES, 2019).

Climate change is causing local species extinctions, often driven by increases in annual high temperatures. A far more common outcome of climate changes is extirpation, or local extinction, of species. In these scenarios, a local population of a species is permanently lost, but other individuals of the species remain elsewhere. Climate change is causing local species loss and increased disease (IPCC, 2022). Worldwide, local extinctions tend to be driven by large increases in annual high temperatures rather than changes in mean annual temperature (Román-Palacios & Wiens, 2020). In Maine, climate impacts have led to mass mortality in North Atlantic Shrimp (*Pandalus borealis*) in the Gulf of Maine's warming waters, resulting in an indefinite moratorium on the decades-old Maine shrimp industry (Richards & Hunter 2021).

Climate warming is expected to facilitate the establishment and spread of more invasive species in the Northeast, and Maine's biodiverse river shores and floodplains are particularly vulnerable. Already an important threat to native biota, invasive species contributed to 60% of global extinctions, and were the primary driver in 16%. Examples of invasive species impacts interacting with climate change in Maine include Common (*Rhamnus cathartica*) and Glossy Buckthorn (*Rhamnus frangula*) (discussed above) and Green Crabs (*Carcinus maenas*), which flourish in warmer winters and are a significant contributor to the decline in native soft-shell clam populations (Tan & Beal, 2015). Two of Maine's exceptionally biodiverse ecosystems, river shores and floodplains, are particularly vulnerable to the proliferation of invasive plants. Compounded by sprawling impervious development, increasing climate-associated flood severity can exacerbate the downstream colonization of aggressive exotic plants such as Japanese Knotweed (*Fallopia japonica*).

Priority Information Needs

The top information needs for biodiversity that arose during this science assessment process have multiple cross cutting applications. These top priority information needs include:

1. **Summary of, and projections for, tidal marsh elevation and biological response to sea level rise based on long term monitoring data and validation of current projection efforts.** This effort would collate existing data and provide a report, and create a state sentinel site monitoring plan. The initial report could be discreet and near-term, with ongoing (long-term) support for continued monitoring, coordination and reporting. Tidal marshes store significant carbon and hold tremendous ecosystem service and biodiversity values, providing cross cutting benefits to sea level rise and marine and coastal ecosystem monitoring.

2. **Projections for time scale of significant forest composition changes in Maine due to climate and pest stressors.** Forest type is foundational to biotic composition, and this would cross cut forest monitoring and the forestry industry.

3. **Improved hydrologic data and growing season models for wetlands.** This includes updated and improved understanding of changes in hydrology to palustrine wetlands through growing season models that predict drought frequency and intensity, and through field data from reference sites statewide. This would require developing a hydrologic monitoring protocol that can be repeated across remote areas and over long term. Drought and changes in precipitation patterns and heat are significant stressors for wetlands, especially peatland communities. which store significant amounts of carbon.

4. **Conduct social science research to identify resource and policy bottlenecks limiting efficient implementation of the highest priority recommendations of the MCC's Natural and Working Lands Committee.** Interviews across state agencies and related stakeholders, followed by analysis and synthesis, could be presented in a report. Methods and foundational theory overlap with the human dimensions chapter.

5. **Updated and improved winter season snow accumulation and temperature pattern monitoring and modeling.** This need overlaps directly with climate monitoring needs.

6. **Projections of the magnitude of human climate refugees predicted to migrate to Maine by 2050.** These projects should include most likely settlement areas, as this movement could magnify existing habitat loss and fragmentation stressors. This topic is further addressed in human dimensions, with more information needed.

A list of all of the priority information needs beyond those addressed here can be found in Report Appendix I.

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FRESHWATER

WETLANDS

Maine's wetlands are a bright spot for biodiversity, with some of the highest quality and quantity across New England, but remain at risk from poorly planned development and climate impacts (Dahl, 1990, U.S. EPA, 2023a). Maine has lost up to 20% of its wetlands since the 1780s (Dahl, 1990). Conservation can play a critical role in protecting wetlands in Maine and across New England. For example, recent field surveys and remote assessments have demonstrated that Maine has some of the most intact and extensive floodplain forests remaining in the northeastern U.S. (Cameron & Schlawin, 2022). Maine's temperate floodplain wetlands, especially within the watersheds of the Penobscot, St. John, and coastal rivers had among the best average ecological integrity among northeastern states (Cameron & Schlawin, 2022).

Peatlands make up 3% of Earth's landmass yet store a third of global soil carbon (IUCN, 2019). Maine hosts an exceptional number and diversity of bogs and fens, covering 500,000-750,000 acres (MGS, 2019). Maine's peatlands also store the most carbon of all wetland types (Kolka et al., 2018), but are at risk of switching from a sink to a source with climate warming (Hanson et al., 2020).

Salt marshes in Maine currently store more carbon than salt marshes in all other states except Massachusetts (Colarusso et al., 2023), but are threatened by sea level rise (Burdick et al., 2020). Calculations based on sea level rise projections suggest **over 75% of the region's marsh area could be lost to inundation unless the habitat is able to migrate landward into undeveloped natural areas** (Anderson et al., 2023). In addition to serving as important carbon sinks, Maine's peatlands and coastal marshes are home to many specialized species, including several at-risk plants, insects, and birds (Whitman et al., 2014).

Although wetlands are recognized for their important role in carbon sequestration and storage, accurate assessments of their carbon sequestration ability and greenhouse gas (GHG) emissions and sinks are limited. Wetlands only store carbon when they are wet; they are at high risk of becoming carbon sources to the atmosphere if high water levels are not sustained (Li et al., 2023).

Figure 1: Saltmarsh. Photo credit: ME DIFW.

Impacts to Freshwaters

In streams and rivers, increased frequency and greater magnitude of floods can erode stream banks, reshape stream channels, accelerate the spread of invasive species, and increase sediment deposition in other parts of a river system. In urban areas with increased floods intensified by impervious surfaces, stream channels often become incised, widened, and disconnected from floodplains. In addition, riffles can become embedded and smothered by sediment, pools diminish in size, and overall habitat complexity and quality is reduced (eg, Hale et al., 2016; Vietz et al., 2016). Similar habitat changes may begin to occur in non-urban streams (e.g., Vidon et al., 2018; Wicherski et al., 2017). These changes can significantly degrade habitat quality for fish, amphibians, wood turtles, and freshwater mussels and other macroinvertebrates.

In addition to affecting stream and river geomorphology and habitat quality, intense floods can directly impact aquatic life by killing some organisms and washing others downstream (Calderon et al., 2017)**.** While healthy aquatic ecosystems are resilient and can recover over time, urban and other stressed aquatic ecosystems may be less capable of doing so (e.g., Linares et al., 2021), especially if both droughts and extreme rain events become common (Palmer et al., 2009).

Climate-induced fish declines are often coupled with anthropogenic threats. Freshwater fish, especially coldwater species, are vulnerable to the combined threats of warming water temperatures and decreasing summer flows (Rustad et al., 2012). For example, projected warming in streams by 2100 could make 50-100% of current Brown (*Salmo trutta*), Brook (*Salvelinus fontinalis*), and Rainbow Trout (*Oncorhynchus mykiss*) habitat in the U.S. uninhabitable (Michaels et al., 1995).

Maine's Eastern Brook Trout (*Salvelinus fontinalis*) population is especially important for long-term conservation of the entire species (EBTJV, 2018) because Maine is predicted to be a regional stronghold for suitable habitat. Maine has watersheds where water temperature models suggest that even with 4°C or more of mean annual air temperature increase, some streams are still predicted to have temperature regimes suitable for brook trout occupancy (Walker et al., 2020).

Significant rain events in late winter and early spring on frozen ground can increase stream scouring when larval Brook Trout (*Salvelinus fontinalis*) and Atlantic Salmon (*Salmo salar*) are sac fry in the loose gravels and cannot evade these conditions (Andrew et al., 2022; Blum et al., 2018, Valentine et al., 2023). This is a significant concern, especially when coupled with extreme low flow and much warmer summer conditions that impact adult spawning success (Xu et al., 2010). Over time, less total spawning success coupled with an increased rate of young-of-the-year recruitment loss due to late winter and early spring weather variability is dangerous for long-term maintenance of brook trout populations (Andrew et al., 2022; Blum et al., 2018; Valentine et al., 2023, Xu et al., 2010). Recent research provides guidance for the identification, conservation, and protection of coldwater refugia across jurisdictions (Mejia et al., 2023).

Figure 2: Sunday River Access Road, Newry, Maine, during December 2023. Photo Credit: MaineDOT.

A key problem for Brook trout and Atlantic Salmon is likely to be range expansion of introduced non-native species as waters warm. Cooler water temperature is a limiting factor for expansion of Smallmouth Bass (*Micropterus dolomieu*) and other warm-water species into Brook Trout (*Salvelinus fontinalis*) and Atlantic Salmon (*Salmo salar*) habitat (Rubenson et al., 2020). Maine biologists have observed Smallmouth Bass farther upstream than in the past, in both the Sandy and the Piscatquis watersheds (J. Reardon, Atlantic Salmon Federation, personal communication, 2024). Expansion of Smallmouth Bass may profoundly reduce the suitability of salmonid habitats modeled to be thermally suitable in part via competition (Ramberg-Pihl et al., 2023; Valois et al., 2009).

For coldwater fish species, earlier onset of ice-out conditions means a longer open water season with more opportunity for water temperature increase and a longer duration of stressful or lethal summer temperatures (Caldwell et al., 2020; Ellis & Greene, 2019)**.** This is exacerbated in drought years that would already stress coldwater fish species.

Lake conditions are changing to the advantage of warmer water species moving northward, often to the detriment of smaller resident, native forage species, such as rare minnows (Wu et al., 2023). At the same time, many temperate lakes are experiencing darkening waters from increased dissolved organic carbon levels, a phenomenon that may be attributable to decreased acid rain and increased temperatures (Evans et al., 2005; Nelson et al., 2021). This "browning" of water rapidly depletes dissolved oxygen levels, which in combination with already increasing water temperatures, greatly limits suitable summer habitat for lake dwelling, coldwater specialists like the whitefishes and Arctic Char (*Salvelinus alpinus*) (Jane et al., 2024).

Figure 3: Arctic char. Photo credit: ME DIFW.

Climate change, changes in air quality, and human impacts interact to drive regional changes in lake water quality in Maine. Trends for increasing dissolved organic carbon in Maine lakes, coupled with warming water and declines in acid deposition interact to alter the quality of lake habitats. Recent research has shown how lake depth influences the interaction of these trends (Gavin et al., 2023). Dykema et al. (2022) looked at 143 lakes across the Northeast, including Maine, and reported a 22% decrease in sulfate concentrations between 1986 and 2004 reflecting recovery from acid rain. However, climate change and land use (particularly road salt) as well as rising concentrations of dissolved organic carbon precluded a return to pre-acidification status for these lakes, with demonstrable impacts on zooplankton as an indicator of biological impact.

Overnight recovery of water temperatures in lakes and streams from extreme high temperatures are reduced when overnight temperatures remain at or near the thermal tolerance limits for coldwater species. Increasingly frequent overnight lows of 65°F or higher, especially over several consecutive days, can eliminate overnight low water temperatures that would otherwise allow for periods of reduced thermal stress and likely reduce feeding that will not occur if temperatures remain high for 24 hours (J. Reardon, personal communication, October 2023).

Hydrology

The STS 2020 Hydrology chapter continues to be a relevant assessment of the state of the science for hydrological impacts of climate change (MCC STS, 2020)**.** In summary, annual peak streamflows have increased in magnitude in Maine's rivers and streams over the last century. Future changes in larger, less-frequent peak flows such as the 100-year peak flow are uncertain but may increase with increased precipitation or decrease with increased temperatures and decreased snowpacks. In the last 50-100 years, snowpack depths have decreased for selected dates in late winter and snowpack densities have increased. Snowmelt-related runoff (MCC STS, 2020, p. 39, **Figure 1**) and lake ice-out dates have become earlier in recent decades. These changes are likely to continue into the future with ongoing warming, however, future changes in summer/fall low stream flows are less clear. Groundwater levels and low stream flows have increased in recent years or not changed significantly. However, there may be an increase in the length of the warm low-flow season in the future for high-emission scenarios. Competing water demands in some Maine watersheds during low-flow periods have the potential to become more problematic during future droughts.

Freshwater Quality

Recent studies pertaining to the effects of climate change on freshwater resources continue to support those presented in the STS 2020 Fresh Water Quality chapter. Climate change issues that affect Maine's rivers, streams, lakes, and wetlands identified in that report include: increased temperatures; changes to ice-cover thickness and duration, extended open-water seasons in lakes; increases in dissolved organic carbon export from watersheds to fresh waters; increased stormwater runoff transporting nutrients to fresh waters; increased cyanobacteria blooms and cyanotoxin production that threatens drinking water and recreational uses; and increases in bacterial and pathogen contamination of swimming areas (MCC STS, 2020). All of these can alter native plant and animal communities, particularly sensitive cold-water species; result in deep water oxygen depletion in lakes; threaten human and animal health; result in economic impacts to water-dependent businesses; and, decrease shoreline property values and associated property tax revenue (MCC STS, 2020).

Saltwater Intrusion

Sea level rise not only causes nearshore inundation and erosion but can also increase the risk of saltwater contamination of coastal surface water and groundwater resources. Salt can contaminate freshwater bodies through storm surge flooding and inundation by tides. Groundwater aquifers near the coast are susceptible to lateral and vertical movement of saltwater through the ground due to the greater density of saltwater compared to freshwater and changes in ocean depth, coastline position, precipitation, and water withdrawals from wells (Ferguson & Gleeson, 2012). The intrusion of salty water into freshwater aquifers not only contaminates fresh water with salt but can change the chemistry of groundwater reservoirs and groundwater discharges in a variety of significant ways (Moore & Joye, 2021).

Globally, saltwater intrusion is expected to have severe consequences for 60 million people by 2100 (Zamrsky et al., 2024), especially in regions with low coastal elevations and low aquifer recharge rates (Jasechko et al., 2020). Jasechko (2020) points to regions of concern within the continental United States concentrated along the mid-Atlantic and southern East Coast, the Gulf Coast, and isolated areas of coastal California; however, saltwater intrusion has been documented in Maine as well (see below). Panthi et al. (2022), in reviewing investigation approaches and monitoring networks across the U.S., recommend increased monitoring of saltwater intrusion across the country, including the northeastern U.S., where rates of sea-level rise are high relative to other regions.

Inundation of land surface during storm surges can infiltrate an aquifer from above and elevate the freshwater table. Groundwater can be contaminated by salt during direct inundation of the land surface by storm surges, during which seawater infiltrates into the aquifer from above (Ataie-Ashtiani et al., 2013; Cantelon et al., 2022). Furthermore, the intrusion of saltwater into the lower portion of aquifers can elevate the freshwater table that lies above it, potentially flooding road beds, septic systems, and other buried infrastructure (Walter et al. 2016; Bosserelle et al., 2022). Vulnerability of coastal aquifers is geographically complicated by the slope and elevation of the shore, shape of the coastline, local and regional freshwater hydrology, precipitation, surficial geology, bedrock geology, bedrock fractures, and human groundwater use (Barlow, 2003).

The potential of inland reach of saltwater intrusion has not been systematically studied. There have been few investigations of saltwater intrusion completed in Maine. In Maine, there are both bedrock and surficial (sand and gravel) aquifers that can be affected by saltwater intrusion (Caswell, 1987; 1979). Fractures in Maine's bedrock act as reservoirs of groundwater and conduits for groundwater migration, and private wells drilled into bedrock supply domestic water for many coastal residents. Even in the absence of sea level rise, coastal bedrock wells can become contaminated by saltwater if the fracture pattern allows seawater to be drawn inland under the influence of pumping wells. This has been described for a set of domestic wells in Harpswell located within 250 feet of shore (Caswell, 1979; Barlow, 2003). A series of studies (described in De Wet, 2007) located and sampled wells in the island town of Vinalhaven and mapped geologic structures in the bedrock that might be associated with seawater intrusion at high-salinity wells. In general, private bedrock wells with high salinity have been reported all along Maine's coast, but the frequency and extent of the problem is not known, partly because of the sensitivity homeowners have about reporting and sharing information about their private water sources. Salty wells are most often observed within several hundred feet of the coastline, but the maximum potential inland reach of saltwater intrusion in Maine has not been established by research. Guiang & Allen (2016) modeled the impacts of future sea-level rise, increases in precipitation, and changes in population on the saltwater interface below Sebascodegan Island, Harpswell. The authors found that precipitation patterns had greater control over future saltwater intrusion than sea-level rise, and pumping rates had the least impact. In their worst-case scenario for the year 2070, about 11% of modeled bedrock wells became salty, all of which were located on narrow peninsulas or within 300 feet from the shore.

Sand and gravel aquifers at the coast are also susceptible to saltwater intrusion, and they are used in some areas by some coastal homeowners and public systems, although not as widely as the bedrock aquifer. Popham Beach State Park (Phippsburg, Maine) uses 2 million gallons of water per year from a sand aquifer between a salt marsh and an ocean beach. As sea level rises, saltwater has the potential to both impinge upon the freshwater aquifer, threatening the source of drinking water, and to push the freshwater table higher in elevation, which could flood the Park's septic system, reducing its effectiveness. The Maine Geological Survey investigated these vulnerabilities and found that the septic system may be at risk at about 2.5 feet (0.76 m) of sea-level rise (Gordon and Dickson, 2016). In a larger scale modeling study in coastal New Hampshire (Knott et al., 2019; NH Coastal Flood Risk STAP, 2019; Wake et al., 2019), sea level rise of up to 6.5 feet (2 m) was investigated and was found to threaten buried infrastructure via water table rise farther inland than areas of potential coastal flooding.

Watershed Resilience

Lane et al (2022) define watershed resilience as "the ability of a watershed to maintain its characteristic system state while concurrently resisting, adapting to, and reorganizing after hydrological (e.g., drought, flooding) or biogeochemical (e.g., excessive nutrient) disturbances." Freshwater systems are commonly viewed as individual ecosystems with boundaries ending at the land-water interface, but in reality they are an integral component of their respective watersheds and landscapes (Carpenter & Cottingham, 1997). Over geologic time, lakes transition from oligotrophic (low nutrient high oxygen) to eutrophic (high nutrient low oxygen) systems, and eventually become wetlands (Wetzel, 1975). Anthropomorphic watershed activity and disturbance can accelerate this process; climate change can intensify it (Suresh et al, 2023). Managing for resilient watersheds is a necessity in the face of uncertain climate challenges (Pelletier et al., 2020; Lane et al., 2022).

Freshwater resources can be supported with planning that encompasses climate, human activities, uses, and economies, and lake characteristics. To better understand watershed and water quality indicators, Suresh et al. (2023) reviewed the literature to identify pressure and driver indicators and establish a conceptual cause and effect model for use by decision makers. Although they focused on lake trophic status, most often controlled by nutrient loading, their results consider multiple watershed activities and can be generally applied to all freshwater resources. Seven categories of trophic drivers or themes were identified (hydroclimatic, socio-economic, land use, lake characteristics, crop farming/livestock, hydrology/water management, and fishing/aquaculture) encompassing 30 relevant indicators (**Figure 4**). This comprehensive set of indicators, including those capturing changes at the global level, is proposed as a useful eutrophication planning and resource management framework.

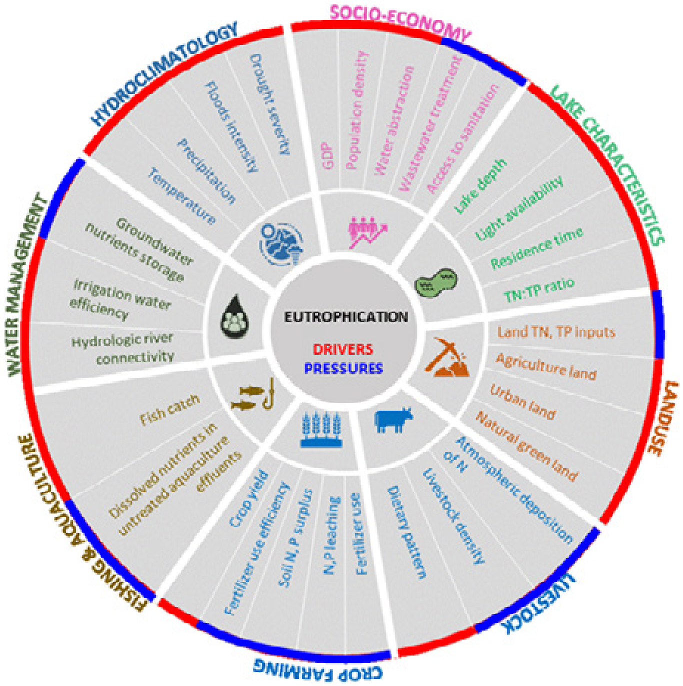

Figure 4. Graphic representation of 30 indicators and seven cross-cutting indicator themes: (i) hydro-climatology, (ii) socio-economy, (iii) land use, (iv) lake characteristics, (v) crop farming and livestock, (vi) hydrology and water management, and (vii) fishing and aquaculture] relevant to watershed management (From Suresh et al, 2023).

Socioecological resilience requires consideration of ecological principles as well as input from all stakeholders to assure equity in the process of establishing an adaptive management plan (Pelletier et al., 2020). Future challenges include balancing societal expectations with ecosystem services, as social conflict is likely to arise from the tradeoffs required to utilize these services (Pelletier et al., 2020). If the goal is to optimize equitable services, stakeholder understanding of ecological processes and services can support collaborative and adaptive management plans (Pelletier et al., 2020).

Table 1. Factors affecting resilience in aquatic systems, as summarized in Pelletier et al, 2020.

Decreasing Resilience	Context Dependent Direction	Increased Resilience
Increasing stressor loads (e.g., nutrients and contaminants)	*Disturbance (+/- diversity –> timing, magnitude, frequency)*	*Connectivity (recruitment, access to habitat/refugia)*
Urbanization and associated land use changes	*Life history characteristics*	*Functional redundancy (multiple species able to perform same function)*
Overharvesting (e.g., fish, apex predators)	*Scale issues (local, regional)*	*Diversity (species)*
Climatic changes (e.g., wind, rain/ drought, intense storms, temp)		*Habitat heterogeneity*
Multiple stressors (interacting effects)		*Strong linkages between the social and ecological systems*
Lack of equity (in the socioecological system)		

Vulnerable waters, or the often unregulated headwater streams, intermittent flows, and isolated wetlands, buffer disturbances to watersheds. Allen et al. (2018) estimated that 89% of the world's total length of streams worldwide are vulnerable headwaters based on work by Downing et al. (2012); Lane and D'Amico (2016) estimated that vulnerable non-floodplain wetlands comprise 16-23% of wetlands in the conterminous United States. Lane et al. (2022) define 'vulnerable waters' as headwater streams, intermittent flows, and isolated non-floodplain wetlands, which are often poorly mapped and tend to escape regulation and highlight the need for increased protection of these resources in far reaches of aquatic networks. They provide hydrological and biogeochemical functions that "affect the magnitude, frequency, timing, duration, storage, and rate of change of material and energy fluxes among watershed components and to downstream waters, thereby maintaining watershed states and imparting watershed resilience." These functions impart resilience to watersheds by buffering effects of disturbance and providing 'self-regulating' feedback mechanisms (Lane et al., 2022).

Mapping vulnerable waters, determining their hydrological thresholds, and managing adaptively can support watershed resilience. Watershed development (e.g., urbanization, agricultural intensification, industrialization) often provides short-term benefits to society often without consideration to longer term, cumulative costs. Lane et al. (2022) recognize that planning for watershed resilience "is hindered by conflicting management objectives, interests, existing policies, inflexible infrastructure design and a lack of quantitative tools and data to facilitate critical decision-making." They suggests planners "(1) Comprehensively map the extent, spatial arrangement, dynamic networked connectivity, and function of vulnerable waters; (2) determine state-changing hydrological and biogeochemical thresholds; (3) identify drivers of change and prioritize management activities; and (4) adaptively manage watersheds."

Building resilience into watersheds can be supported with risk assessments, integrative implementation, and monitoring with indicators of effectiveness. Lane et al (2022) touched on social aspects that must be considered in building watershed resilience. Because resilient watersheds are a global need, the United Nations has produced *Building Resilience into Watersheds* (FAO, 2023), a sourcebook of information on how to build resilience and reduce disaster risk into the Watershed Management Process. The publication addresses the importance of having an 'enabling environment' in place to maximize success including support policies, legislation, communications, and finances. To be effective, stakeholder involvement that recognizes the diversity of needs and concerns is foundational. Risk assessments, both on the ground and with use of GIS tools, must be conducted, then integrative implementation strategies crafted. Effectiveness indicators are identified to monitor and guide progress. Similarly, US-EPA has launched the Equitable Resilience Builder (Maxwell et al., 2023) to provide a "toolkit of activities for local government agencies or non-profit organizations to carry out in conjunction with robust community engagement. Users can select relevant activities to inclusively assess local hazards, equity, and resilience of built, natural, and social environment systems, then use the results to collaboratively prioritize actions to build community resilience in an equitable way."

Priority Information Needs

The top three information needs for freshwater that arose during this climate science assessment process were projects that involve monitoring and data analysis. These top priority information needs include:

1. Additional riverine and coastal gages relevant to populated flood prone areas, which would provide ongoing, continuous and long term data to answer important climate questions. For example, when gauges data is used in combination with flood inundation maps, emergency managers and the public will be able to better predict when the riverine or coastal peaks will occur, how big it will be, and what that will look like on the ground. This need overlaps with sea level rise and marine monitoring needs.

2. Expanded snowpack monitoring network. This statewide monitoring effort could be achieved by expanding the existing state cooperative snow survey in frequency over individual winters and in more locations, and would support information needs in climate, agriculture, human dimensions, and biodiversity.

3. Riverine flood inundation maps. Discrete studies could combine existing hydraulic models, flood forecast streamgages and lidar to create flood inundation map libraries for analysis. When used in combination with flood forecast gauges, emergency managers and the public will be able to predict when the riverine peak will occur, how big it will be, and what that will look like on the ground.

A list of all of the priority information needs beyond those addressed here can be found in Report Appendix I.

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FORESTS AND FORESTRY

CURRENT & FUTURE CLIMATE IMPACTS

Impacts on Forest Physiology

Treelines are shifting upslope due to climate change, and some treelines are shifting faster. Research on the impact of climate-related treeline changes in the northeastern U.S. found that regional treelines have significantly shifted upslope over the past several decades (on average by three meters (m) / decade) and that when the transition zone for maximum tree elevation is gradual (characterized by declining tree density) there were significantly greater upslope shifts (five m/decade) compared to other treeline forms (Tourville et al., 2023). This suggests that both climate warming and treeline demography (the study of tree life cycles and populations) are important correlates of treeline shifts in the region.

Elevated atmospheric carbon dioxide (CO_2) has had a strong and consistently positive effect on wood volume. Although higher atmospheric CO_2 concentrations drive global warming, the higher concentrations of CO_2 represent extra carbon in the atmosphere that plants can use to drive photosynthesis and grow better, and thus this phenomenon is referred to as "CO_2 fertilization." He et al. (2023) evaluated the impacts of climate change on northern temperate and boreal forests and found that CO_2 fertilization is the dominant driver of the observed forest biomass increase over recent decades across the study area. Specifically, inventory- and satellite-based evidence suggested that CO_2 fertilization increased forest biomass by 54 ± 18% and 64 ± 21%, respectively. They noted that eventually, the positive effect of CO_2 fertilization may slow down and saturate reducing tree contributions to achieving carbon neutrality.

CO_2 fertilization can increase growth and yield. Future CO_2 fertilization could increase total forest carbon by 0.8% to 5.1% compared to the no-CO_2 fertilization scenarios (Zhao et al., 2023). Further, increased growth and yield from CO_2-fertilization could increase harvests by up to 20% compared to the no-fertilization scenarios. Using empirical analysis to estimate the effect of elevated CO_2 on aboveground wood volume in temperate forests of the United States, including Maine, research showed that elevated CO_2 has had a strong and consistently positive effect on wood volume while other environmental factors yielded a mix of both positive and negative effects (Davis et al., 2022).

The growing season is lengthening in North America. The length of the growing season increased by 4 days per decade since 1985 in North America, which was primarily due to an extended end of growing season (Fang et al., 2022).

The timing of peak fall foliage is now occurring almost two weeks later than 1950, and future climate projections predict that the timing of peak fall foliage will occur between October 30th and November 2nd by 2060. Spera et al. (2023) evaluated the effects of climate change on the timing of peak fall foliage in Acadia National Park, finding that minimum temperatures, maximum temperatures, precipitation, and the number of warm nights, hot nights, warm days, hot days, and downpour days have all significantly increased over time.

Impacts to Forest Management

Among the climate impacts to Maine's forests, increased frequency of winter freeze-thaw cycles is disrupting forest harvesting. The frequency of winter freeze-thaw cycles has increased, leading to difficulties in scheduling and implementing forest harvesting (typically done on frozen soils) and management at times of the year that were historically more predictable. This impact is likely to constrain the harvesting of wood products, lead to harvesting under less favorable conditions and potentially change the carbon mitigation potential of forests. Burakowski et al. (2022) project that New England winters will continue to warm with coincident increases in days above freezing, decreases in days with snow cover, and fewer nights below freezing. Deep snowpacks will become increasingly short-lived, decreasing from a historical baseline of two months of subnivium (under the snow) habitat for organisms to less than one month under the warmer, higher-emissions climate scenario.

A spatially explicit vulnerability assessment of the forest industry in Maine to climate change found that each Maine county had its own unique combination of exposure, sensitivity, and adaptive capacity indicators, with overall vulnerability highest in the rural northern and western parts of the state, where forest industry activities are most prevalent (Soucy et al., 2021a). However, results also indicate that although increased stress from climate-related changes can negatively affect Maine's forest via high exposure, reduced forest sensitivities and an increased capacity to adapt to a changing climate have the potential to largely decrease overall vulnerability in many parts of the state. Soucy et al. (2021b) found that experts prioritized the greatest and most likely climate change impacts on the forest industry as forest health threats imposed by insects and pathogens, extreme precipitation events, shifts in forest composition, invasive species, and changes in forest productivity. Specifically, winter freeze thaw cycles have increased, leading to difficulties related to forest harvesting and management.

Challenges persist in the development of forest ecosystem research on climate change to support effective science informed management. Nelson et al. (2022) identified three key priorities related to forest ecosystems and management in New England mountain ecosystems: 1) improving communication strategies to get relevant research to land managers and decision makers; 2) providing funding sources for research that better match the needs of forest managers and decision makers; and 3) creating a conservation landscape that embraces the value of actively managed and unmanaged forests.

Projections

Projections show that socioeconomic factors are a greater driver of harvest and carbon stocks than climate change. Zhao et al. (2023) investigated alternative futures of Maine's forests under a range of climate and socioeconomic conditions and found that socioeconomic factors had much larger effects on total harvest and carbon stocks than climate change. Harvest volume was projected to increase by 9–29% between 2020 and 2100 for favorable (i.e., high/sustainable growth) socioeconomic development scenarios and decrease by 3–29% for unfavorable socioeconomic development scenarios (i.e., low/unequal growth). Modeling of alternative socioeconomic futures on Maine's forest carbon stocks found large variance driven by assumptions about land use change, economic growth and wood product demand (Zhao et al., 2022).

Climate change, coupled with increased pressure from non-native pathogens, insect pests and invasive plants, will change Maine forests. As discussed in the 2020 STS report (MCC STS, 2020), climate and pest-related vulnerabilities vary greatly by species and forest type. While some species may be favored by the changing climate, others are not. Tree species that occur south of Maine today are likely to migrate into the state, creating novel forest types. Some tree species are also especially vulnerable to pests that target only one or few tree species (e.g., the emerald ash borer). Pest vectors are likely to be amplified by climate change. Either directly or indirectly, these environmental changes can lead to tree loss, ecosystem destabilization, altered forest composition, changes in forest productivity and vulnerabilities to other stresses. These changes are likely to have corresponding impacts on the forest products industry and the capacity of Maine forests to sequester and store carbon.

Cedar and fir may be sensitive to future temperature and precipitation changes. Schulz (2022) evaluated the impact of climate change on northern white-cedar (*Thuja occidentalis*) and balsam fir (*Abies balsamea*), and found that both cedar and fir may be at risk due to climate change. They suggested that if future moisture regimes favor cedar over fir, climate change may reduce the need for population management strategies for reducing density of fir competition.

Predicted species ranges show more suitable habitat remains when modeling includes historical data and seasonal climate variables. By modeling current northern New England tree species distributions with climate projections, Andrews et al. (2022) found that seasonal climate variables that emerged as most important for cold-adapted tree species all included interactions that reflected sensitivity to colder temperatures, and preferences for wet weather concentrated in the winter months. Under moderate climate warming, or representative concentration pathway (RCP) 6.0, the northeastern U.S. retained additional suitable habitat when historical data were included through 2060 for three of the four species: red spruce (*Picea rubens*), black spruce (*Picea mariana*) and balsam fir (*Abies balsamea*), while white spruce (*Picea glauca*) habitat contracted into Canada. In contrast, future predictions from models that used contemporary data alone forecast extirpation for all four species from the northeastern United States. Overall, these findings highlight that prediction of species ranges in transitional ecosystems that span geopolitical boundaries and gradients of intense land use are improved when historical data and seasonal climate interactions of both temperature and precipitation variables are incorporated.

Recent research using national forest inventory data suggests that climate change strongly influences productivity trends across the U.S. (Hogan et al., 2024). These researchers showed that the western U.S. is showing negative productivity trends while the eastern U.S. is showing positive productivity trends, strongly influenced by climate change. They suggest the future of the land carbon balance will be strongly influenced by the geographic extent of drought and heat stress.

Wildfire in Maine

Recent record-breaking wildfires, especially in Canada, have raised concerns about increasing risk of wildfire in Maine. Large-scale, catastrophic wildfire in the state remains a low probability event, but, like a powerful hurricane, it would be a high impact event with severe consequences for the state.

Maine's extensive wildland-urban interface makes Maine vulnerable if a large wildfire were to occur. Wildfires pose direct risks to people, property, and ecosystems, but also can indirectly degrade air quality (Jaffe et al., 2020) and emit high levels of CO_2 that contribute to climate change (Liu et al., 2014). Maine has many houses in the wildland-urban interface (WUI), and 19% of the state's more than 17 million forest acres are considered WUI (Woodall et al., 2023). These patterns make Maine particularly vulnerable if a large, severe wildfire were to occur.

Recent climate change projections for the Northeast predict intensification of conditions conducive to wildfire: warmer temperature, more variation in precipitation, more lightning, and longer periods of high-fire risk (Gao et al., 2021; Kerr et al., 2018). Accordingly, these models predict an earlier fire season (Kerr et al. 2018) and more than a doubling of fire probability (Gao et al. 2021). Nevertheless, the Northeast is expected to continue to be one of the least fire-prone regions in the USA and Canada (Gao et al. 2021).

While large-scale, catastrophic wildfires are unlikely in Maine for a range of future climatic conditions, some Maine forests have characteristics that are similar to the Canadian Acadian forests that recently burned. There are lessons to be learned for Maine from the 2023 Canadian wildfires, which burned nearly 50 million acres (a historic record) and resulted in the evacuation of more than 150,000 people (A.P., 2023; CWFIS, n.d.: Government of Canada, n.d.). The vast majority of these fires occurred in coniferous boreal forest, which differs from forests occurring in Maine. The coniferous forest in Maine—the Acadian forest type—has a different mix of tree species and is much less fire-prone than the true boreal forest. However, wildfires did burn in Acadian forests in the Maritime provinces of Canada. For example, in May and June 2023, a wildfire burned 60,000 acres in Nova Scotia in forests similar to those found in northern and Downeast Maine. This record-breaking wildfire season in the province was driven largely by extreme short-term drought in May and June. The Nova Scotia wildfires provide a glimpse of future fire risk in Maine.

Increased fire risk in Maine's future can potentially be reduced by efforts to minimize human ignitions, employ prescribed fire where appropriate, and increase wildland fire-fighting preparedness. The vast majority of Maine wildfires are of human origin, not lightning, meaning that they are, to some extent, under human control. This is a lesson that is embedded in the decline in wildfires over the past century in Maine. Prescribed fire has been used extensively across the world to achieve a variety of goals, including reducing fire risk (Hiers et al., 2020). Although small in area, New England's most fire-prone habitats, such as coastal sand plains, have increasingly been managed with prescribed fire for habitat management by agencies, conservation non-governmental organizations, and tribal nations (Bois et al., 2023).

Mitigation: Carbon sequestration

Maine forests and wood products are a net carbon sink, and are the largest contributor to the state's carbon neutrality target. The most recent data available for Maine suggest that the state's forest ecosystem is sequestering approximately 14.8 million metric tons of CO_2 equivalent per year ($MMTCO_2e/yr$). Numbers are based on analysis of the U.S. Forest Service's Forest Inventory and Analysis (FIA) database and estimate the change in carbon stock among the five major forest carbon pools between 2017 and 2021 (see **Table 1**). This rate of sequestration represents an offset of approximately 91% of Maine's gross GHG emissions

The History of Wildfire in Maine

With some exceptions, wildfire has not been a prominent component of Maine's history. Before Euro-American settlement in the lands today called Maine, lightning-ignited wildfire was not a major ecological disturbance, due mainly to moist conditions (Barton et al., 2012) and low lightning density (Mäkelä et al., 2011). There is evidence of Indigenous fire management in Maine (Francis, 2008), although probably not as extensive as in other regions, and some ecosystem types, such as red pine, did support frequent fires, according to recent research (Abadir et al., 2019; Engstrom & Mann, 1991). This is an active area of research by institutions, agencies, and Wabanaki nations that should soon provide a more complete picture of pre-contact (i.e., before European settlement) indigenous fire management. Massive fires did occur after Euro-American settlement in the 19th and first half of the 20th centuries (Coolidge, 1963). These were driven largely by the widespread use of fire as a tool, forest management practices, and periodic dry conditions. Wildfire incidence and acreage burned in Maine has decreased dramatically from the first half of the 20th century and has not increased in recent years despite warmer temperatures (Office of the Maine State Fire Marshal, 2022). A recent comparison of large wildfires between 1984–1993 and 2011–2020 in the eastern U.S. found very few wildfires in Maine and no increase over that period (Donovan et al., 2023).

Despite the lack of a history of frequent wildfire, the state has distinct vulnerabilities to wildfire, including high densities of forest fuels (live trees and dead woody debris), many houses in close proximity to forests, and less wildland-fire-fighting infrastructure than states that experience frequent wildfires. Unlike more fire-prone states, Maine has no regular dry season, but the historic record suggests that large fires can burn during periods of drought (Patterson et al., 1983), even very short-lived ones. In 1947, for example, Palmer Drought Severity Index readings were normal during late spring and much of the summer, but rapidly intensified because of lack of rainfall in September and October (NCEI, n.d.), creating conditions that promoted the rapid spread of the 1947 wildfires that burned 213,547 acres in Maine.

over that time period (16.4 MMTCO2e/yr) (S. Knapp, Maine Department of Environmental Protection, Personal communication, 2024). About 74% of the carbon sequestration in the forest ecosystem is in live biomass, with the remaining in deadwood and litter pools, although the inventories show a loss of carbon from Maine's forest soils over this time period. State harvest data and modeling of the life of harvested wood products suggests that about an additional 1.6 MMTCO$_2$e/yr is sequestered in wood products during this period (Li et al., 2022; Wei et al., 2023). Overall, forests and wood products are estimated to be acting as a net sink of 16.4 MMTCO$_2$e/yr between 2017 and 2021, offsetting about 101% of Maine's total gross GHG emissions.

(MMT CO$_2$ e / year)	2007-2011	2012-2016	2017-2021
Forest Carbon Pools	**-10.37**	**-14.86**	**-14.8**
Live Aboveground Biomass	-8.67	-14.2	-9.32
Live Belowground Biomass	-1.51	-2.59	-1.6
Dead Wood	-0.95	-1.42	-5.59
Litter	-0.05	0.23	0.04
Soil Organic	0.81	3.14	1.68
Wood Products Pools	**-1.54**	**-1.17**	**-1.6**
In Use	-1.16	-0.8	-0.9
Solid Waste Disposal Sites	-0.38	-0.37	-0.7
TOTAL	**-11.91**	**-16.03**	**-16.4**

Table 1. Maine forest ecosystem and harvested wood product annual average carbon stock change for the last three FIA inventory periods (MMTCO$_2$e/yr) based on EVALIDAator v.2.1.0 (D. Hayes, University of Maine, personal communication, March, 2024).

While there is limited new research on the effects of climate change on Maine's forest pests and pathogens since 2020, recent studies (e.g., Quirion et al., 2021) highlight the increasing prevalence of many stressors that could reduce the resilience of Maine's forests, thereby affecting its potential to sequester and store carbon, and therefore the forest ecosystem's climate change mitigation potential. Also where land is newly forested or there are significant changes in forest composition, the alteration in the albedo of the vegetated surface can offset some of the carbon sequestration benefits relative to atmospheric warming if the surface color is darker (Weber et al., 2024).

Carbon sequestration could be greatly increased by managing forests using a 'triad' approach consisting of harvesting to create uneven age continuous cover, intensive plantations, and permanent set-asides. Forest management practices can increase carbon storage by 20% or more. The Maine Governor's Task Force on the Creation of a Forest Carbon Program Final Report (Saffeir, 2021) identified a number of recommendations on increasing forest carbon sequestration, particularly on small woodland areas (10 to 10,000 acres). The Forest Carbon for Commercial Landowners Report (Walker et al., 2023) found that Maine's commercial timberlands could adjust the distribution of silvicultural practices and increase carbon sequestration by 20% or more without reducing timber harvest (**Table 2**). The practices that would most likely help achieve this include a mix of uneven age continuous cover to intensive plantations (Daigneault et al., 2024). Giffen et al. (2022) modeled the effect of employing improved forest management (IFM) across the region and estimated that doing so on privately owned timberland across the Acadian Forest of New England could increase carbon storage by 26% compared to current stocks.

Achieving forest carbon objectives requires attention to the choice of species cultivated and overall species diversity. Maass and Laustsen (2022) evaluated the impact of planting hybrid larch in Maine and found that, over the 34-year period, larch hybrids sequestered 2.4 times as much CO_2e as the untreated plots. Puhlick et al. (2022) evaluated the effect of implementing different forest management treatments in mixed-species stands in northern Maine and emphasized the importance of leveraging multiple harvesting strategies to achieve carbon objectives, including consideration of forest reserves and using targeted yet operationally feasible silvicultural treatments that promote forest resilience relative to climate change.

Clark et al. (2023) note that although reforestation has long been central to forest management, the desired outcomes of traditional and emerging tree-planting strategies face barriers linked to a lack of ecological diversity in forest nurseries. Faison et al. (2023) evaluate USDA Forest Inventory and Analysis (FIA) plots in Maine and find that aboveground carbon is 34% higher in "wildland" areas that are protected from harvest compared to those which are not protected, where recent harvesting intensity and differences in stand age between protection categories were highest. Their results highlight the adaptation and mitigation benefits of allowing natural processes to predominate in strictly protected areas.

The amount of time since harvest is likely the largest influence on CO_2 flux rates. Read et al. (2022) examined the change in CO_2 emissions over time from red spruce (*Picea rubens Sarg.*) stumps using a 32-year chronosequence derived from detailed harvesting records in a northern conifer forest in central Maine that has experienced repeated partial harvests. They found low initial CO_2 flux followed by a rapid increase, peaking eight years post-harvest, and followed by a decrease to very low rates by two decades from harvest. They found no clear relationship between CO_2 emissions and any of the environmental or stump variables tested (wood temperature, wood moisture, soil moisture, and/or stump volume), suggesting that time since harvest was the overriding influence on CO_2 flux rates.

Since the 2020 STS assessment, several studies have been published that looked at the impacts of forest management or disturbance on soil organic carbon (SOC) (i.e., Puhlick et al., 2016; Puhlick et al., 2019; Puhlick & Fernandez 2023; Tattersall Smith et al., 2022). Given the complexity of forest response and the high variability of forest ecosystems, no clear conclusions emerge from this limited body of research. A series of meta-analyses (a statistical method

Estimate	Business as Usual	Expanding Uneven-Aged Silviculture	Expanding Plantations & Unharvested Areas	Maximizing Sequestration & HWP Storage
C Sequestration (tCO_2e/y)	3,613,497	4,350,475	4,555,255	5,110,665
Forest Area (ac)	7,583,441	7,583,441	7,583,441	7,583,441
Annual Net Revenue ($/y)	$77,466,139	$65,838,942	$67,851,458	$85,964,970
Annual Harvest (tCO_2e/y)	7,340,000	7,340,000	7,340,000	7,340,000
Change From Business as Usual				
C Sequestration (tCO_2e/y)	-	$736,978	$911,480	$1,466,890
Annual Harvest (tCO_2e/y)	-	$0	$0	$0
Annual Net Revenue ($/y)	-	-$11,627,197	-$9,614,681	$8,498,831
Break Even Carbon Price ($/$tCO_2e$)	**-**	**$15.78**	**$10.21**	**-$5.68**
Break Even Implementation Cost ($/ac)	**-**	**$151.43**	**$108.58**	**-$85.79**
% Change Carbon Sequestration	**-**	**20.4%**	**26.1%**	**41.4%**

Table 2. Northern Maine commercial forest's carbon sequestration potential under alternative management scenarios and constraints (from Walker et al., 2023).

for analyzing the results of multiple studies) providing syntheses of research has been conducted in recent years to look at the effects of forest management on SOC stocks by region (e.g., Nave et al. 2010; Nave et al., 2019). They find that there is a wide range of responses and high variability in forest soil response, but their analyses support common trends in this area of research where O horizon SOC losses occur most commonly with harvesting and fire, and SOC gains occur with reforestation. Nave et al. (2024) recently published a similar analysis for the Northeast, reinforcing the themes from this research in other regions, but finding limited potential for forest harvesting to alter forest SOC in either direction. There are significant limitations in forest SOC monitoring for decision-making, with no soil carbon monitoring programs across all land use types including here in Maine (Lawrence et al., 2023).

Another disturbance to Maine forest soils is the arrival and spread of invasive earthworms in Maine forests that poses a risk to forest carbon stocks and forest resilience to climate change. Puhlick et al. (2021) reported on the first evidence of invasive earthworms in northern Maine forest soils, adding to the body of evidence emerging of the spread of these invasive species throughout Maine. While there is extensive reporting on this issue here in Maine with the growing threat of these organisms, there is limited published scientific literature yet to draw upon. Invasive earthworms have a clear negative impact on soils because of their rapid acceleration of SOC and nutrient loss.

Soil organic carbon and nitrogen processes can be impacted by changes in winter climate. Little is yet demonstrated about the effects of changing climate on SOC stocks and processes in Maine soils. One clear trend in the climate system has been warming and increased variability in Maine winters. Patel et al. (2018) looked at processes of soil carbon (C) and nitrogen (N) cycling as a result of freeze-thaw cycles in a Maine forest over a two-year study period. While they found no effects on total SOC stocks in that short time from freeze-thaw dynamics, they did identify impacts on soil C and N processes, with particular impacts from a rain on snow event resulting in 'concrete' frost formation that had significant soil impacts.

In light of growing interest in carbon markets, valuing soil carbon will be increasingly important. Mikhailova et al. (2023) analyzed the effect of land use change on Maine's Climate Action Plan on the value of soil carbon (C) regulating ecosystem services and disservices and estimated that the total estimated monetary midpoint value for total soil carbon stocks in Maine was $295.9 billion, which is comprised of soil organic carbon stocks ($270.3B) and soil inorganic carbon stocks ($25.6B). Most of the soil carbon stocks in Maine are in forests. (For more, see Soil Carbon Sequestration in Agriculture).

Research in Maine has recently looked at environmental factors influencing the export of dissolved organic carbon (DOC) largely derived from soils through riverine transport to the ocean. They report that factors such as temperature, fire, changing atmospheric nitrogen and sulfur deposition, landscape factors, wetland abundance, and particularly precipitation all influence the export of C as DOC in rivers providing increasing insight into the dynamics of the carbon cycle here in Maine (Wei et al., 2021a; Wei et al., 2021b, Wei et al., 2021c).

Adaptation

Active and passive management strategies can enhance, maintain, and restore the mitigation value of forests (Ontl et al., 2019). Research identifying adaptation strategies and approaches for managing forest carbon sequestration and storage found that forest carbon management informed by climate change vulnerability tied to existing adaptation concepts of resistance, resilience, and transition support both active and passive management strategies (Ontl et al., 2019).

The research in the 2020 STS report remains relevant for considering barriers and perceptions of climate change among forest managers (MCC STS, 2020). Since 2021, COVID-19 has also impacted forest management (e.g. supply chains, personnel, staffing, etc.) which can also impact landowners ability to respond to climate change (Jayasundara et al.,2024).

Forest Conservation

Climate change is only one aspect of forest management considerations, and public perceptions of silvicultural alternatives remain the greatest barrier to harvesting. A qualitative study among conservation practitioners in Maine found that climate change remains a priority for management; however, adapting to climate change is only one consideration for forest managers as those making decisions are also balancing increased public use on conserved lands alongside the impacts of climate change (Soucy et al., 2023). Together, recent literature is pointing to the growing complexities of managing for climate change on conserved lands where managers are facing novel threats. Public opposition to harvesting is a critical barrier faced by many forestry professionals to implementing adaptation. Foresters' use of different strategies to increase public acceptance of management in the Northeast included education, political advocacy and public collaboration (McGann et al., 2023).

Among interviewed rural respondents in New England and New York, warming winters and declining tree vigor from a host of stressors were most often mentioned as environmental drivers of change, while adjusting harvesting practices to increase age class, stand structure, and tree species diversity within forest stands were the most commonly mentioned adaptation approaches implemented (McGann et al., 2022). The most cited barriers to adaptation included changing weather patterns, public perceptions of invasive species treatments and silvicultural prescriptions, and costs associated with adaptation treatments. Urban foresters most often cited extreme weather events and safety hazards posed by flooding and storm-damaged trees. Similar to rural foresters, urban foresters discussed increasing diversity as the most common adaptation approach, although this is implemented through increased species, cultivar and age-class diversity by planting trees. Urban foresters most frequently named lack of time and money as the most significant challenges to meeting management goals (McGann et al., 2023).

Priority Information Needs

The top three information needs for forests and forestry that arose during this climate science assessment process were all medium term projects that involve monitoring, data analysis and research. These top priority information needs, in no specific order, include:

1. **Improved availability, resolution, and mapping of key data and projected forest impacts like temperature, precipitation, forest health, pest, disease, land use change, pre-contact fire, biomass, dieback, and carbon stocks by species and geographic area.** Ideally, these data would be collected in a **consistent format across all of Maine**. Methods to gather these data include FIA analysis, field collection, and model simulation. This information can feed into an economic impact of benefit-cost analysis, and the impacts have follow-on effects to many other groups, and some data could be sourced from other subgroups (e.g., climate variables).

2. **Improved monitoring and mapping of forest soil attributes, including forest soil carbon flux and stock over time and as a result of forest management, ideally collected in a consistent format across Maine.** Methods to gather these data include FIA and other federal/state data agency analyses, field collection, and model simulation. This information would have applications in the agriculture sector, and may also have implications for freshwater.

3. **Evaluating distributional impacts of climate change plus adaptation and mitigation practices on forest-dependent communities.** These data could be collected across Maine, particularly in forest-industry communities, using field collection, data analysis, and stakeholder engagement. Implications include multiple sectors captured in the Human Dimensions chapter, including health, community resilience, and economic systems.

A list of all of the priority information needs beyond those addressed here can be found in Report Appendix I.

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HOPE

HOPE—A FRAMEWORK FOR ACTION IN THE FACE OF CLIMATE CHANGE

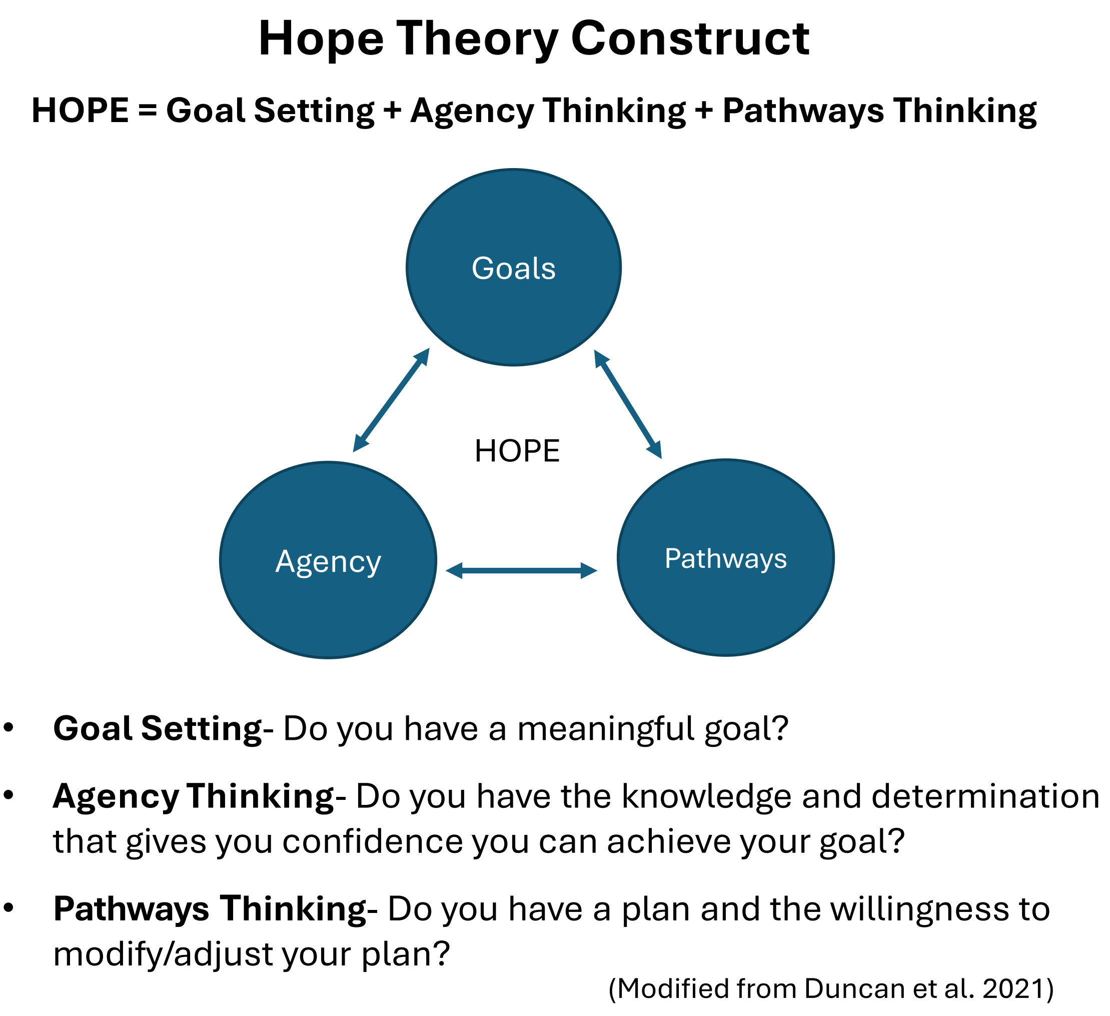
Hope can be learned and it can be restored. Emerging psychological studies show that hope theory, defined by Snyder et al. (1991) as a dynamic motivational experience derived from two cognitive tools, pathways and agency thinking, can be useful when applied broadly to achieve goals (Duncan et al., 2021). Importantly, just as scientists can measure changes in climate variables, scientists also measure hope and have been doing so for over 30 years.

Hope theory provides specific and systematic actions to reduce anxiety and increase well-being. Climate anxiety has been documented worldwide; in Maine, physicians report that climate change is worsening the mental health and well-being of their patients (Carlson, 2023)**.** Globally, climate change is taking a mental-health toll on society (Pearson, 2024): more than half of people aged 16-25 reported feeling sad, anxious or powerless about climate change in a 2021 global survey (Hickman et al., 2021). These feelings are often occurring in people who care deeply (Pearson, 2024). Clinical psychologists suggest that those suffering from climate anxiety (also called eco-anxiety or eco-distress) limit their 'doom-scrolling', or intake of bad news about climate change. Yet the evidence presented in the previous pages of this report will likely pose significant changes and challenges for humanity and the ecosystems on which we depend. How can scientists, teachers, practitioners and Maine residents and visitors navigate sharing factual information about accelerating climate impacts without contributing to a culture of distress and apathy?

Science communications that result in action rely on agency and clear paths to action. Simply sharing facts about a situation does not result in action (Bergquist et al., 2023). In fact, providing data alone can be counter productive, leading to anxiety and paralysis (Sangervo et al., 2022). Rather, communications models that promote engagement involve the head (understanding climate change), the heart (hope through empowerment and efficacy), and the hands (intentions to participate in action) (Bonnano et al., 2021). To address these needs, the Maine Climate Council provides a framework to incorporate the science detailed in this report with pathways to action via a relatively comprehensive, robust, and diverse process leading to Maine's Climate Action Plan, Maine Won't Wait, and its implementation. That process is not static, but guides ongoing implementation, measures progress towards specific goals, and provides a update every four years.

Hope theory provides a systematic framework for promoting engagement. Hope theory is made up of three primary components:

1. **goal setting** (having a personally meaningful goal),
2. **agency thinking** (having the knowledge and determination to achieve the goal), and
3. **pathways thinking** (having a plan and a willingness to tweak the plan) (Snyder et al., 1991).



Hope Theory Construct

HOPE = Goal Setting + Agency Thinking + Pathways Thinking

- **Goal Setting**- Do you have a meaningful goal?
- **Agency Thinking**- Do you have the knowledge and determination that gives you confidence you can achieve your goal?
- **Pathways Thinking**- Do you have a plan and the willingness to modify/adjust your plan?

(Modified from Duncan et al. 2021)

Figure 1. Hope theory construct.

These three components can bolster each other along with well-being (Duncan et al., 2022). Research finds that perceptions of higher goal attainment, independent of the kind of goal, were significantly associated with hope; that social support elevated hope and pathways thinking; and that perceived higher social standing raised hope and agency thinking (Duncan et al., 2022).

Hope differs from optimism: while optimism implies confidence in a successful outcome, hope does not; consequently, one can "hoping against hope" even when optimism has been lost (Milona, 2020). Hope, instead of optimism, has often been cited as the driving psychological force behind survival against the odds (Milona, 2020). Dispositional optimism, or the individual personality trait to tend to see things positively, can provide motivation and health benefits, especially cardiovascular health and healthy lifestyle habits; however, it is a risky strategy because it can leave people open to crushing disappointment and losses incurred from overconfidence of success (Milona, 2020). Hope can equally inspire demotivation when placed in a specific person or outcome; however, hope can be learned, engages with individual desire, and provides the instrumental value of increasing the likelihood of the desired outcomes (Milona, 2020). Hope is seen as essential to the existence of democratic political life: policies that undermine hope are perceived as oppressive, and institutions that enhance hope prove desirable. Hope not only begets hope: it increases the odds of individual success (Milona, 2020).

Hope theory moves beyond philosophical discussions of hope as an emotion, personal identity, or means to address moral challenges to faith (as in religion), to an actionable approach employing pathways thinking.

Pathways thinking, a core component of hope theory, has been implemented from the local to national level to address complex climate challenges, such as planning for sea level rise. Adaptation pathways can illustrate how to meet short and long-term adaptation needs; promote collaborative learning, adaptive planning and adaptive capacity; and account for the potential need for transformative change, breaking down long term complexity (Werners et al., 2021). Dynamic adaptive pathways provide concrete planning options under deep uncertainty, a strategic vision of the future in which a planner commits to short-term actions and establishes a framework to guide future actions–building flexibility into the plan for unforeseen circumstances (Haasnoot et al., 2013).

Social connectedness, built through discussion, agency and community events, nurture hope and action. Social outlets are an important part of developing hope. Climate anxiety, particularly in young people, can be alleviated through the creation of opportunities for discussion, agency and meaningful action (Whitlock, 2023). Community events also build social capital, or strong relationships, which make communities better situated for disaster preparedness and response (Johnson et al., 2019; Pörtner et al., 2022). Researchers are now studying mental-health improvements related to empowering communities in the design of their own climate action plans (Pearson, 2024).

Maine's Climate Action Plan has specific goals, empowers agency thinking and utilizes pathways thinking. Hope theory is a framework for action. Put into context of the work of the Maine Climate Council, the goals are outlined in the Climate Action Plan. The Scientific and Technical Subcommittee alongside the Working Groups provide the agency thinking and pathways to achieve these goals. Dr. Chan Hellman from University of Oklahoma at Tulsa said, "imagination is the instrument of hope". Hope helps people cast a vision of what future success will look like. Having an accessible visual map, such as Maine Won't Wait, is a key strategy for nurturing hope. Every success is an opportunity to show that the future we want is possible. Hope begets hope.

Hope levels are positively correlated with goal setting and attainment (Snyder et al., 1991). Thus, the continued challenge is to be hope-givers in science communications, motivating people to take successful action on climate to preserve things they value.

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APPENDICES

Earth Science and Remote Sensing Unit, Lyndon B. Johnson Space Center, Public domain, via Wikimedia Commons

APPENDIX A (CLIMATE)

Growing season (May–September) trends

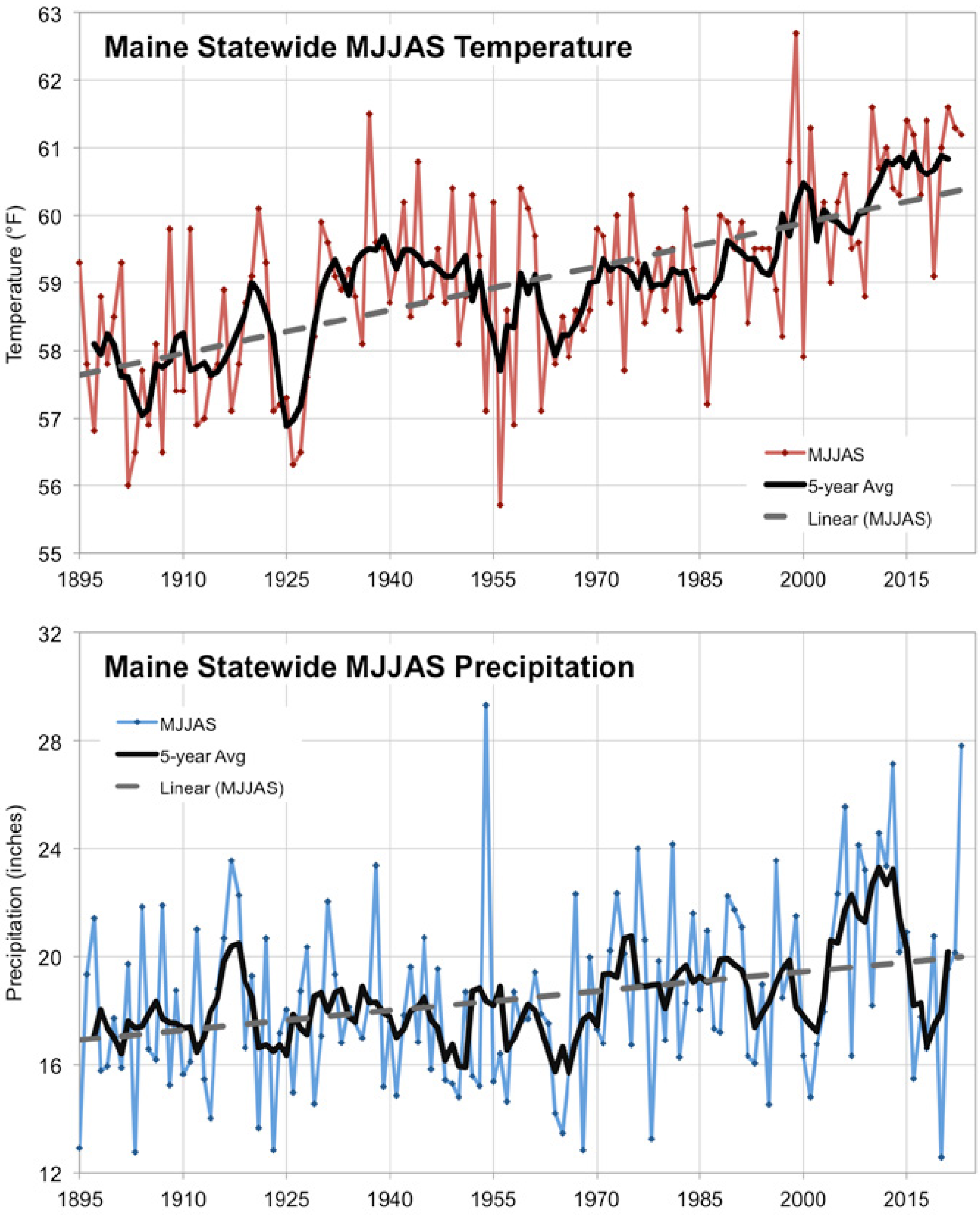


Figure A1. Maine's May–September (MJJAS) mean temperature (top) and cumulative precipitation (bottom) 1895–2023 based on data from the National Centers for Environmental Information (NCEI, 2024a). The dashed linear trendlines show temperature and precipitation increases of 2.7°F and 3 inches (1.5°C and 7.6 cm), respectively, across the record period. Bold black lines represent five-year running averages.

APPENDIX B (CLIMATE)

Anomalous atmospheric blocking pattern, May 2023

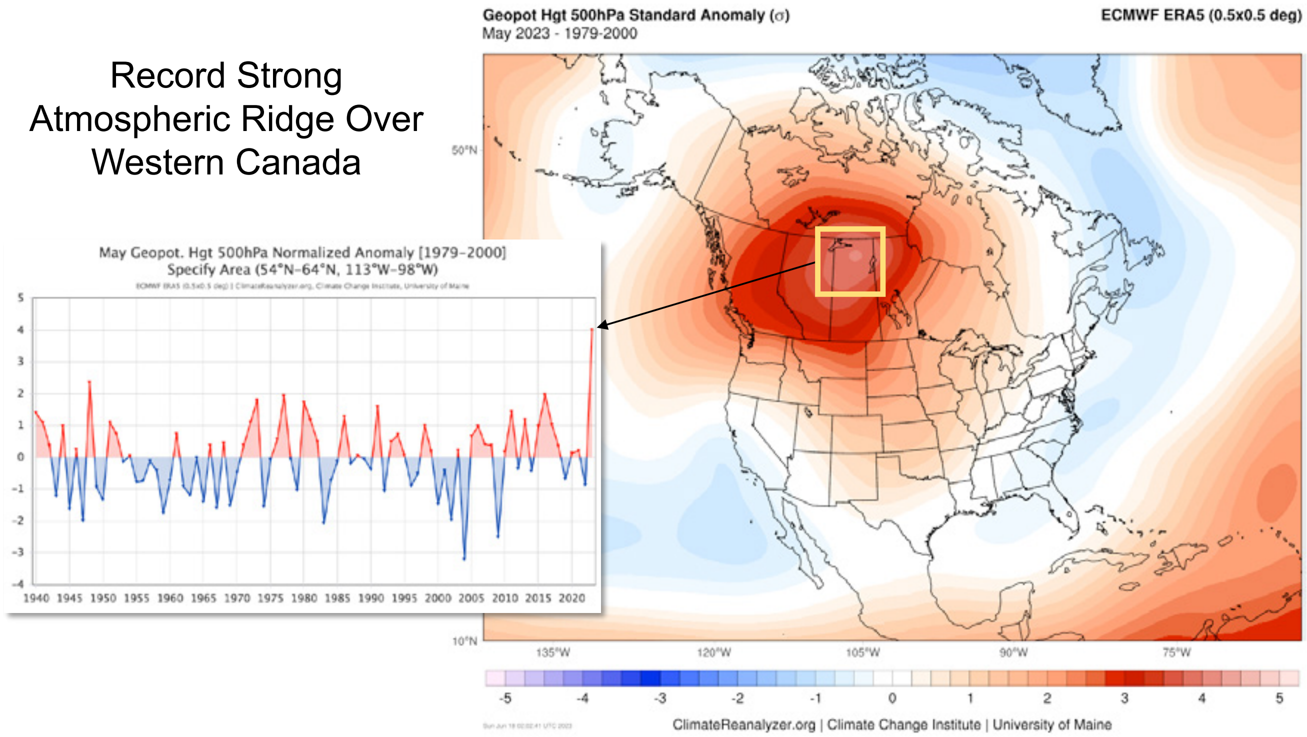


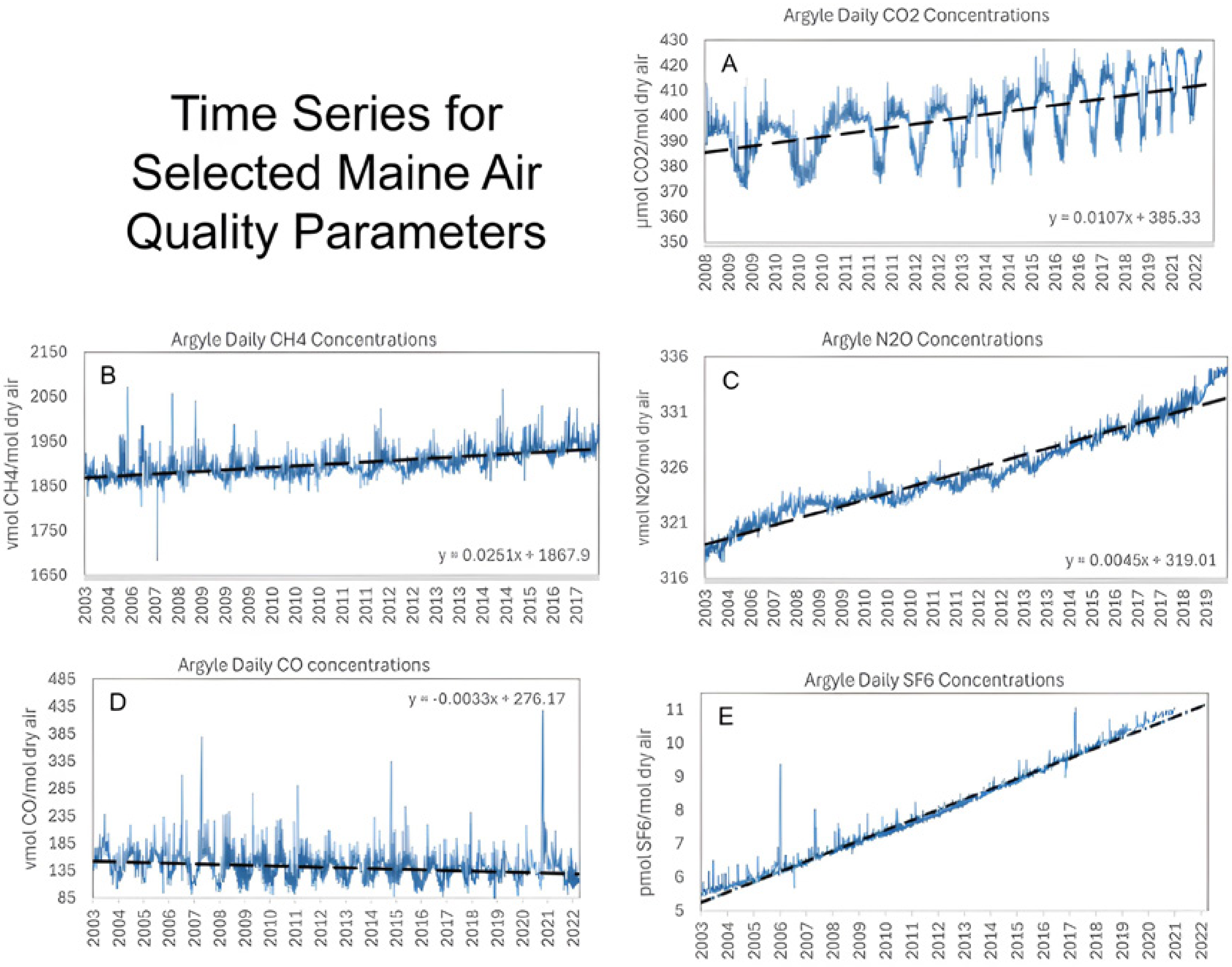
Figure B1. Time series of 500 hPa geopotential height anomalies for May, 1940–2023 (left) averaged across the area marked with a yellow box on the map (right). The map shows 500 hPa geopotential height anomalies for May, 2023. Geopotential height refers to the physical height of a pressure surface above sea level. 500 hPa is a diagnostic surface for identifying ridges and troughs in the jet stream. Strongly positive height anomalies are indicative of a blocking pattern in which the usual zonal (west-to-east) atmospheric flow is interrupted by persistent meridional (south-to-north) flow. The anomalies shown here are standardized such that the values represent standard deviations from the mean of a normal distribution, where values +/- 3 sigma are considered extreme events. The geopotential height anomaly for May, 2023 is +4 sigma. The anomalies are calculated against a 1979-2000 climatology. Chart and map from Climate Reanalyzer (2024) with ECMWF Reanalysis version 5 (ERA5) data from C3S (2024).

APPENDIX C (AIR QUALITY)

Maine Air Quality

Legend:

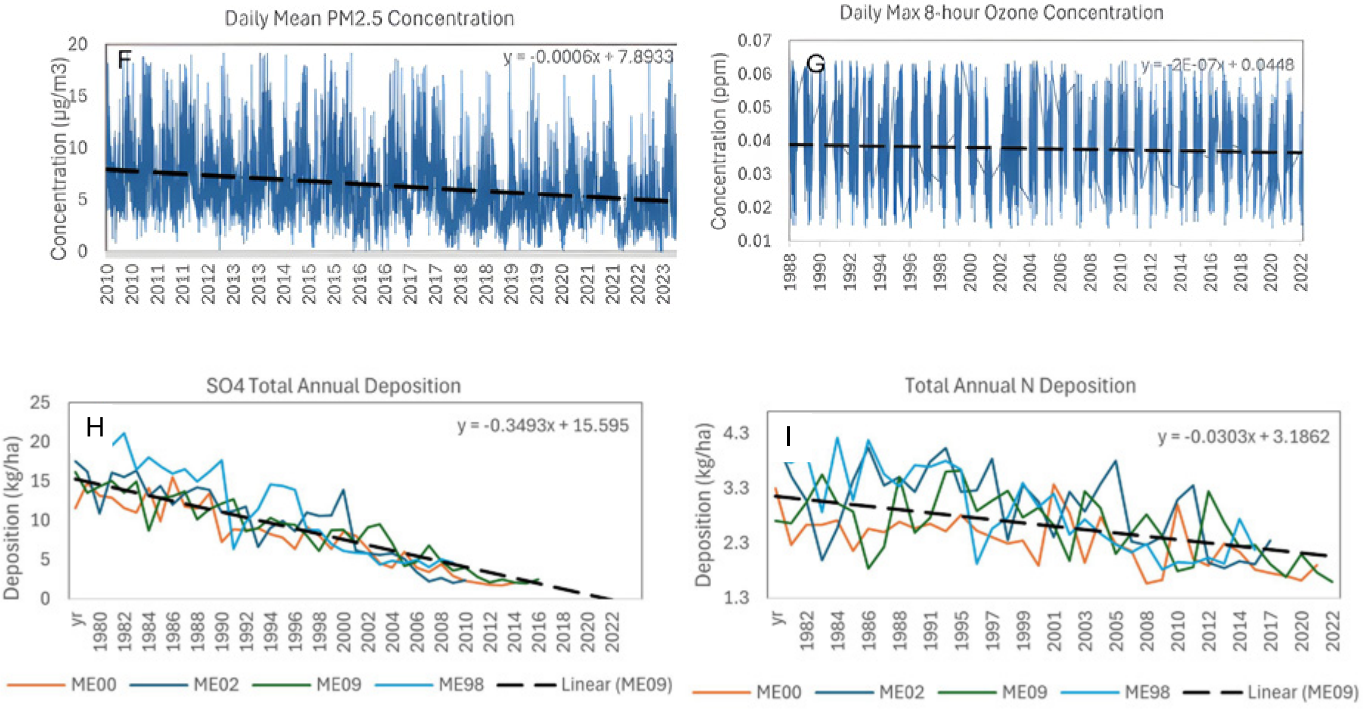
- **A–E:** Greenhouse gas concentrations measured at the Argyle, Maine National Oceanographic and Atmospheric Administration (NOAA) Global Monitoring Laboratory Earth System Research Laboratories. Data for carbon monoxide (CO), sulfur hexafluoride (SF_6), nitrous oxide (N_2O), and methane (CH_4) were collected from 09-18-2003 through 12-29-2022. CO_2 data were collected from 11-23-2008 through 12-23-2022. Data from the Global Monitoring Lab: https://gml.noaa.gov/dv/data/index.php?frequency=Discrete&site=AMT&category=Greenhouse%2BGases. Data above and below two standard deviations were excluded from the plots and considered outliers.



Time Series for Selected Maine Air Quality Parameters

- **F:** PM 2.5 particulate matter from station 230010011, “COUNTRY KITCHEN BAKERY PARKING LOT”, in Lewiston, Maine. Data from the United States Environmental Protection Agency: https://www.epa.gov/outdoor-air-quality-data/download-daily-data.

- **G:** Ozone (O_3) concentrations measured from stations 230112001 and 230112005 “Gardiner, Pray Street School (GPSS)”. Data from site 230112005 were collected from 04-04-1991 through 09-30-2019. Data from station 230112001 were collected from 04-08-1988 through 10-02-1998, and from 03-01-2020 through the present. Data from the United States Environmental Protection Agency: https://www.epa.gov/outdoor-air-quality-data/download-daily-data.



- **H and I:** Atmospheric Deposition of Total Inorganic Nitrogen (= NH_4 + NO_3) and SO_4. Site ME00 is located in Caribou, Maine; Site ME02 in Bridgton, Maine; Site ME09 in Greenville, Maine; and Site ME98 is on McFarland Hill in Acadia National Park, Maine. Trend line shown is for the Greenville, Maine site. Data from National Trends Network: https://nadp.slh.wisc.edu/networks/national-trends-network/

APPENDIX D (SEA LEVEL RISE):

Observed Water Levels

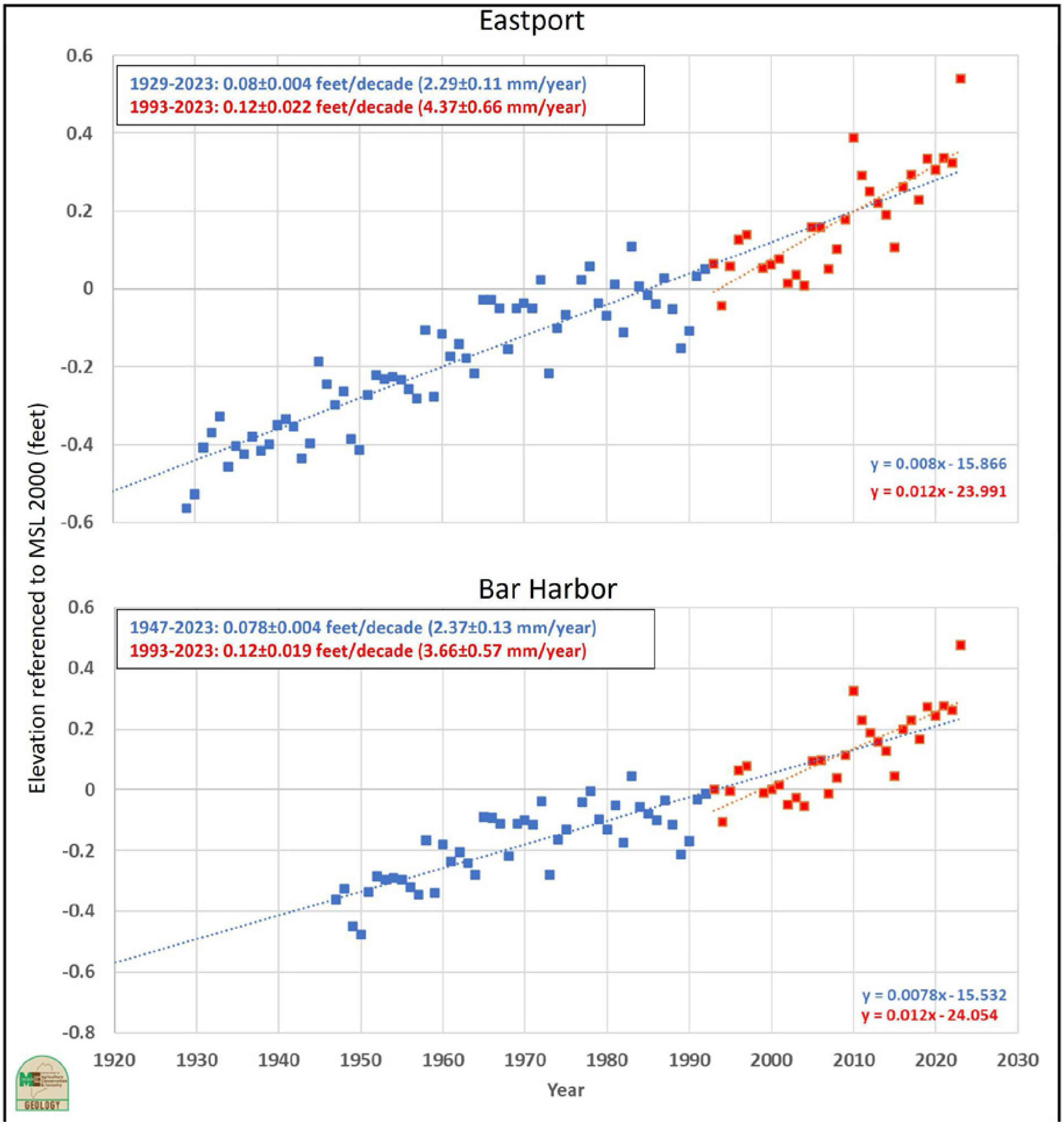


Figure D1. Observed annual mean sea level (blue and red dots), with long-term (blue line) and short-term (1993–2023; red line) sea level rise trends at the Bar Harbor and Eastport NOAA tide gauge. Note the anomalous high sea level years of 2010 and 2023.

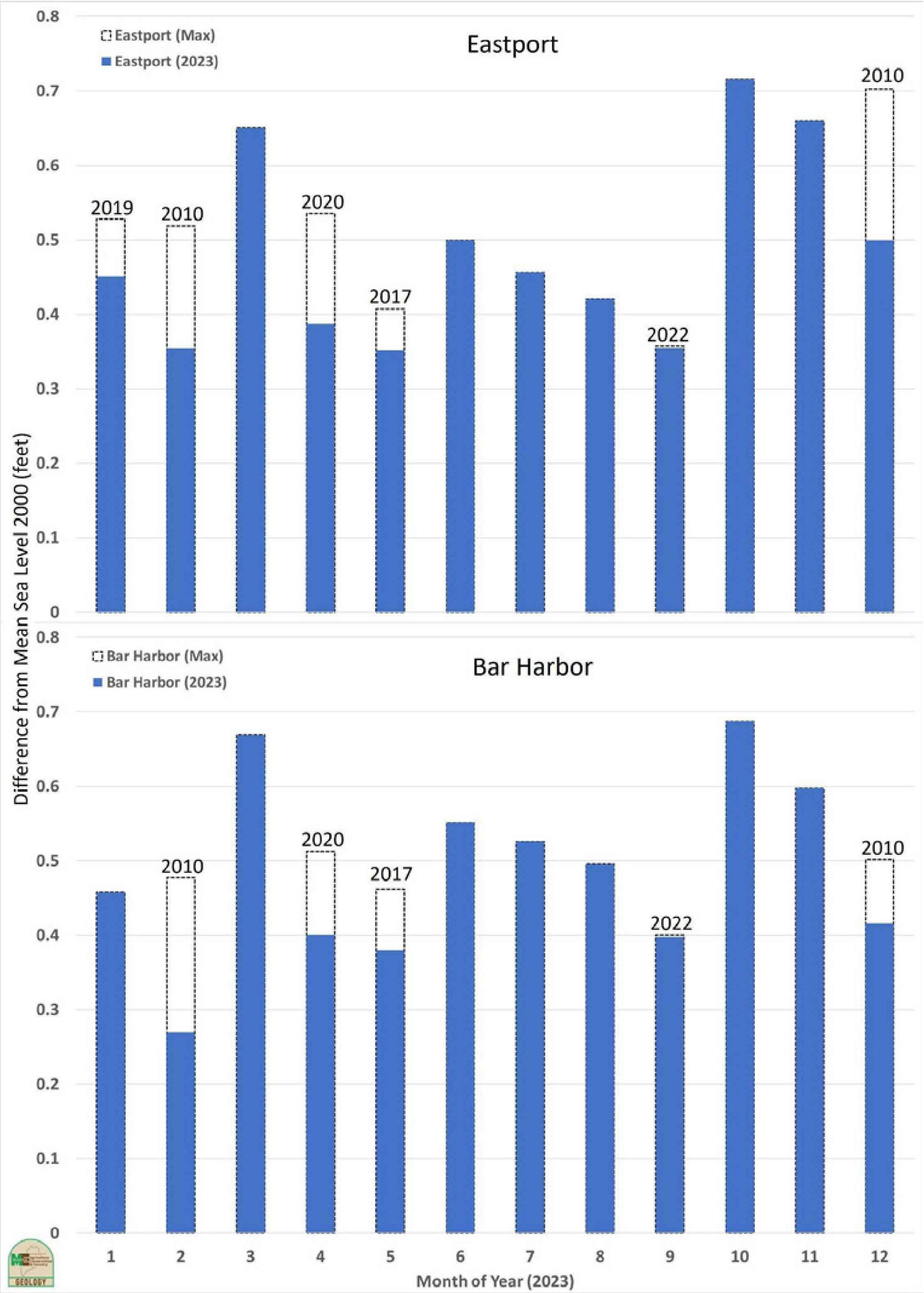


Figure D2. Monthly mean sea levels in 2023 for Eastport and Bar Harbor referenced to 2000 mean sea level (MSL). 2023 set records in June through November, and aside from one month (February), was within the top 3 highest recorded monthly water levels for the remaining months since data collection initiated (1929 for Eastport and 1947 for Bar Harbor). Months where 2023 did not set records are labeled with the maximum year.

Converting among datums

	Elevation, in feet above 1983-2001 (NTDE) Mean Lower Low Water (MLLW)		
	Portland	Bar Harbor	Eastport
1983-2001 (NTDE) MSL	4.94	5.67	9.70
1991-2009 (central year 2000) MSL[1]	4.99	5.73	9.75
Present-day (2024) MSL	Likely ~3-4 inches higher than 1991-2009 MSL[2]		
NAVD88	5.26	5.95[3]	9.93
1983-2001 (NTDE) MHHW	9.91	11.37	19.27
1983-2001 (NTDE) HAT	11.97	13.69	22.76

[1] Baseline for sea level rise projections **Table 3** and Appendix **Table A1**. The offset between NTDE and 1991-2009 MSL was directly calculated at each tide gauge as the average of all hourly measurements 1991-2009, minus the average of all hourly measurements 1983-2001.

[2] Sea level has risen since 2000 (the baseline used for projections). More time must pass to know exactly how much warming-driven sea level rise has occurred since 2000 because fluctuations in temperature, salinity, wind, atmospheric pressure, and ocean currents also cause sea level to vary year-to-year. However, applying the average rate of sea level rise measured over the past 30 years (**Figure 1**), sea level likely rose 3 to 4 inches between 2000 and 2024.

[3] NOAA has not conducted a detailed elevation survey to measure the NAVD88 elevation of the Bar Harbor tide gauge. However, the relationship between NAVD88 and the MLLW tidal datum for Bar Harbor is estimated through the use of the NOAA VDatum tool.

Table D1. Datum conversions at the Portland, Bar Harbor, and Eastport tide gauges. At locations without tide gauges, NOAA's VDatum tool (https://vdatum.noaa.gov/) can be used to convert among NAVD88 and most NTDE tidal datums. Maine Geological Survey's Highest Astronomical Tide Line tool (https://www.maine.gov/dacf/mgs/hazards/highest_tide_line/index.shtml) provides conversions between NAVD88 and NTDE HAT along Maine's entire coastline.

APPENDIX E (SEA LEVEL RISE)

Sea Level Rise Projections

Gridded Sea Level Rise Projections

The Sweet et al. (2022) gridded projections provide more locally accurate estimates in areas far from long-term tide gauges. Under both the Intermediate and High scenarios, sea level rise projections only vary by 1.5 inches along the entire Maine coast through the year 2050. Spatial variability in sea level rise emerges later this century, with 3.2 inches of variation by 2100 under the Intermediate scenario and 3.7 inches of variation by 2100 under the High scenario. The lowest projected sea level rise along Maine's coast is in the region from Saint George to Camden, and the highest projected sea level rise is from Harpswell to Saint George and Millbridge to Lubec.

Through 2050, this spatial variation in sea level rise is similar to the average variation in seasonal mean sea level, which ranges between 1.1 and 2.8 inches in Maine. It is smaller than the largest observed interannual (year-to-year) variation in mean sea level. For example, in Portland, annual mean sea level abruptly increased by 3 inches from 2009 to 2010, then fell by 2 inches the following year.

	Intermediate				
	1	2	3	4	5
2030	0.58 (0.39, 0.78)	0.63 (0.44, 0.82)	0.58 (0.39, 0.77)	0.61 (0.42, 0.81)	0.64 (0.45, 0.84)
2040	0.85 (0.60, 1.11)	0.91 (0.67, 1.18)	0.84 (0.59, 1.10)	0.88 (0.64, 1.15)	0.93 (0.69, 1.20)
2050	1.13 (0.83, 1.47)	1.21 (0.91, 1.56)	1.12 (0.81, 1.46)	1.18 (0.87, 1.52)	1.24 (0.93, 1.58)
2060	1.46 (1.09, 1.87)	1.56 (1.19, 1.98)	1.45 (1.08, 1.86)	1.52 (1.15, 1.94)	1.59 (1.22, 2.01)
2070	1.84 (1.41, 2.33)	1.96 (1.53, 2.46)	1.82 (1.39, 2.32)	1.90 (1.47, 2.40)	1.99 (1.56, 2.50)
2080	2.30 (1.79, 2.85)	2.44 (1.92, 3.00)	2.28 (1.75, 2.83)	2.38 (1.84, 2.94)	2.48 (1.94, 3.04)
2090	2.87 (2.21, 3.48)	3.03 (2.36, 3.67)	2.83 (2.17, 3.48)	2.95 (2.28, 3.60)	3.07 (2.39, 3.72)
2100	3.49 (2.59, 4.23)	3.67 (2.76, 4.45)	3.44 (2.53, 4.23)	3.58 (2.66, 4.36)	3.71 (2.79, 4.50)
2110	4.21 (3.02, 5.22)	4.42 (3.21, 5.45)	4.17 (2.97, 5.20)	4.31 (3.10, 5.36)	4.46 (3.24, 5.52)
2120	4.86 (3.42, 6.48)	5.09 (3.64, 6.75)	4.80 (3.34, 6.46)	4.97 (3.50, 6.64)	5.13 (3.65, 6.82)
2130	5.45 (3.80, 8.20)	5.72 (4.03, 8.49)	5.42 (3.73, 8.16)	5.59 (3.89, 8.35)	5.77 (4.06, 8.56)
2140	5.95 (4.16, 10.30)	6.25 (4.41, 10.63)	5.91 (4.08, 10.24)	6.11 (4.25, 10.48)	6.30 (4.43, 10.70)
2150	6.51 (4.49, 12.82)	6.82 (4.73, 13.18)	6.45 (4.39, 12.75)	6.65 (4.58, 13.02)	6.86 (4.78, 13.28)

	High				
	1	2	3	4	5
2030	0.61 (0.40, 0.86)	0.66 (0.44, 0.91)	0.61 (0.39, 0.85)	0.64 (0.42, 0.88)	0.68 (0.46, 0.92)
2040	0.97 (0.64, 1.36)	1.040 (0.7, 1.43)	0.96 (0.63, 1.35)	1.00 (0.67, 1.40)	1.05 (0.72, 1.45)
2050	1.42 (1.01, 1.95)	1.51 (1.09, 2.03)	1.41 (0.98, 1.93)	1.47 (1.04, 1.99)	1.53 (1.10, 2.05)
2060	2.06 (1.50, 2.69)	2.17 (1.59, 2.81)	2.03 (1.45, 2.67)	2.11 (1.52, 2.75)	2.19 (1.60, 2.83)
2070	2.88 (2.12, 3.68)	3.00 (2.24, 3.83)	2.82 (2.05, 3.65)	2.92 (2.14, 3.73)	3.01 (2.22, 3.84)
2080	3.84 (2.83, 4.83)	3.99 (2.97, 5.02)	3.76 (2.74, 4.80)	3.87 (2.83, 4.92)	3.97 (2.92, 5.04)
2090	4.93 (3.60, 6.15)	5.11 (3.76, 6.34)	4.81 (3.46, 6.07)	4.93 (3.57, 6.22)	5.06 (3.68, 6.36)
2100	5.98 (4.40, 7.35)	6.19 (4.61, 7.59)	5.88 (4.27, 7.30)	6.03 (4.39, 7.46)	6.16 (4.50, 7.61)
2110	7.18 (5.19, 8.78)	7.42 (5.38, 9.06)	7.03 (5.02, 8.72)	7.19 (5.15, 8.90)	7.35 (5.28, 9.07)
2120	8.22 (5.94, 10.30)	8.49 (6.14, 10.58)	8.07 (5.74, 10.16)	8.25 (5.90, 10.36)	8.43 (6.05, 10.56)
2130	9.29 (6.45, 12.40)	9.60 (6.71, 12.73)	9.13 (6.35, 12.26)	9.34 (6.51, 12.50)	9.53 (6.72, 12.70)
2140	10.10 (6.95, 14.47)	10.41 (7.28, 14.89)	9.91 (6.84, 14.43)	10.14 (7.01, 14.69)	10.36 (7.16, 14.91)
2150	10.82 (7.5, 16.74)	11.12 (7.81, 17.21)	10.59 (7.37, 16.69)	10.85 (7.56, 16.97)	11.06 (7.75, 17.20)

Table E1. Gridded sea level rise projections for the Sweet et al. (2022) Intermediate and High scenarios, in feet above 2000 mean sea level. The central (median) estimate is provided, followed by the statistically likely range (17th to 83rd percentile) in parentheses. Numbers 1 through 5 in the header of the table refer to the five 1 degree latitude x 1 degree longitude regions that cover the Maine coast, where 1 = Kittery to Freeport (43-44°N, 71-70°W); 2 = Harpswell to St. George (43-44°N, 70-69°W); 3 = St. George to Camden (44-45°N, 70-69°W); 4 = Lincolnville to Gouldsboro (44-45°N, 69-68°W); and 5 = Millbridge to Lubec (44-45°N, 68-67°W).

Future Extreme Water Level Probabilities

Recurrence Interval (Years)		1		5		10		25		50		100		200	
Sea level rise scenario		Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High
Year	Quantile														
2020	17	12.5	12.5	13.0	13.0	13.4	13.4	13.6	13.6	13.8	13.8	14.2	14.2	14.3	14.3
	50	12.6	12.6	13.2	13.1	13.5	13.5	13.7	13.7	13.9	13.9	14.3	14.3	14.4	14.4
	83	12.8	12.8	13.3	13.3	13.6	13.6	13.8	13.8	14.1	14.1	14.4	14.4	14.5	14.5
2030	17	12.7	12.7	13.2	13.2	13.5	13.5	13.7	13.7	14.0	14.0	14.3	14.3	14.5	14.5
	50	12.9	12.9	13.4	13.4	13.7	13.7	13.9	14.0	14.2	14.2	14.5	14.5	14.7	14.7
	83	13.1	13.1	13.6	13.7	13.9	14.0	14.1	14.2	14.4	14.5	14.7	14.8	14.8	14.9
2040	17	12.9	12.9	13.4	13.4	13.7	13.8	14.0	14.0	14.2	14.2	14.5	14.6	14.7	14.7
	50	13.1	13.3	13.6	13.8	14.0	14.1	14.2	14.3	14.4	14.6	14.8	14.9	14.9	15.0
	83	13.4	13.7	13.9	14.2	14.2	14.5	14.4	14.7	14.7	15.0	15.0	15.3	15.2	15.4
2050	17	13.1	13.3	13.6	13.8	14.0	14.1	14.2	14.4	14.4	14.6	14.8	14.9	14.9	15.1
	50	13.4	13.7	13.9	14.2	14.3	14.5	14.5	14.8	14.7	15.0	15.1	15.3	15.2	15.5
	83	13.8	14.2	14.3	14.7	14.6	15.1	14.8	15.3	15.1	15.5	15.4	15.9	15.5	16.0
2060	17	13.4	13.8	13.9	14.3	14.2	14.6	14.4	14.8	14.7	15.1	15.0	15.4	15.2	15.6
	50	13.8	14.3	14.3	14.9	14.6	15.2	14.8	15.4	15.1	15.6	15.4	16.0	15.5	16.1
	83	14.2	15.0	14.7	15.5	15.0	15.9	15.2	16.1	15.5	16.3	15.8	16.7	15.9	16.8
2070	17	13.7	14.4	14.2	14.9	14.5	15.2	14.8	15.4	15.0	15.7	15.3	16.0	15.5	16.2
	50	14.1	15.2	14.6	15.7	15.0	16.0	15.2	16.2	15.4	16.5	15.8	16.8	15.9	16.9
	83	14.6	16.0	15.1	16.5	15.5	16.8	15.7	17.0	15.9	17.3	16.3	17.6	16.4	17.7
2080	17	14.1	15.1	14.6	15.6	14.9	15.9	15.1	16.1	15.4	16.4	15.7	16.7	15.9	16.9
	50	14.6	16.1	15.1	16.6	15.4	17.0	15.7	17.2	15.9	17.4	16.2	17.8	16.4	17.9
	83	15.1	17.1	15.7	17.6	16.0	18.0	16.2	18.2	16.4	18.4	16.8	18.8	16.9	18.9
2090	17	14.5	15.8	15.0	16.3	15.3	16.6	15.6	16.9	15.8	17.1	16.1	17.4	16.3	17.6
	50	15.2	17.2	15.7	17.7	16.0	18.0	16.2	18.2	16.5	18.5	16.8	18.8	16.9	19.0
	83	15.8	18.4	16.3	18.9	16.6	19.2	16.8	19.5	17.1	19.7	17.4	20.0	17.6	20.2
2100	17	14.9	16.6	15.4	17.1	15.7	17.4	15.9	17.6	16.2	17.9	16.5	18.2	16.7	18.4
	50	15.8	18.2	16.3	18.7	16.6	19.1	16.8	19.3	17.1	19.5	17.4	19.9	17.6	20.0
	83	16.5	19.7	17.1	20.2	17.4	20.5	17.6	20.7	17.9	21.0	18.2	21.3	18.3	21.4
2110	17	15.3	17.4	15.8	17.9	16.1	18.2	16.3	18.5	16.6	18.7	16.9	19.1	17.1	19.2
	50	16.5	19.4	17.0	19.9	17.3	20.2	17.5	20.4	17.8	20.7	18.1	21.0	18.3	21.1
	83	17.5	21.0	18.0	21.5	18.4	21.9	18.6	22.1	18.8	22.3	19.2	22.7	19.3	22.8
2120	17	15.7	18.1	16.2	18.6	16.5	19.0	16.7	19.2	17.0	19.4	17.3	19.8	17.5	19.9
	50	17.1	20.5	17.6	21.0	18.0	21.3	18.2	21.6	18.4	21.8	18.8	22.1	18.9	22.3
	83	18.8	22.6	19.3	23.1	19.7	23.4	19.9	23.7	20.1	23.9	20.5	24.3	20.6	24.4
2130	17	16.1	18.7	16.6	19.2	16.9	19.5	17.1	19.7	17.4	20.0	17.7	20.3	17.9	20.5
	50	17.7	21.5	18.3	22.0	18.6	22.4	18.8	22.6	19.0	22.8	19.4	23.2	19.5	23.3
	83	20.5	24.6	21.0	25.1	21.3	25.4	21.6	25.6	21.8	25.9	22.2	26.2	22.3	26.4
2140	17	16.4	19.2	17.0	19.7	17.3	20.1	17.5	20.3	17.7	20.5	18.1	20.9	18.2	21.0
	50	18.3	22.3	18.8	22.8	19.1	23.1	19.3	23.4	19.6	23.6	19.9	23.9	20.1	24.1
	83	22.6	26.8	23.1	27.3	23.5	27.6	23.7	27.8	23.9	28.1	24.3	28.4	24.4	28.6
2150	17	16.8	19.8	17.3	20.3	17.6	20.7	17.8	20.9	18.1	21.1	18.4	21.5	18.6	21.6
	50	18.8	23.0	19.3	23.5	19.6	23.8	19.9	24.1	20.1	24.3	20.4	24.7	20.6	24.8
	83	25.1	29.0	25.7	29.5	26.0	29.8	26.2	30.0	26.4	30.3	26.8	30.6	26.9	30.8

Table E2. Future extreme water level probabilities for the Intermediate and High sea level rise scenarios through the year 2150 at the Portland tide gauge. Values are provided in feet above 1983-2001 (NTDE) MLLW because this is the datum currently used for tide predictions and flood forecasting in Maine (see callout box "Water level datums and baselines" in main text). For each return period, year, and sea level rise scenario, we provide the 17th, 50th, and 83rd quantile estimate for extreme water level. The only source of uncertainty included here is sea level rise uncertainty; statistical uncertainty and interannual variation in sea level and tidal range are not included.

Recurrence Interval (Years)		1		5		10		25		50		100		200	
Sea level rise scenario		Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High
Year	Quantile														
2020	17	14.2	14.2	14.7	14.7	14.9	14.9	15.2	15.2	15.3	15.3	15.6	15.6	16.0	16.0
	50	14.3	14.3	14.8	14.8	15.0	15.0	15.3	15.3	15.4	15.4	15.8	15.7	16.1	16.1
	83	14.4	14.4	14.9	14.9	15.1	15.1	15.4	15.4	15.5	15.5	15.9	15.9	16.2	16.2
2030	17	14.4	14.4	14.9	14.9	15.1	15.1	15.4	15.4	15.5	15.5	15.8	15.8	16.1	16.1
	50	14.6	14.6	15.0	15.1	15.3	15.3	15.5	15.6	15.7	15.7	16.0	16.0	16.3	16.3
	83	14.8	14.9	15.2	15.3	15.4	15.5	15.7	15.8	15.9	15.9	16.2	16.3	16.5	16.6
2040	17	14.6	14.7	15.1	15.1	15.3	15.3	15.6	15.6	15.7	15.7	16.0	16.1	16.4	16.4
	50	14.9	15.0	15.3	15.4	15.5	15.6	15.8	15.9	15.9	16.1	16.3	16.4	16.6	16.7
	83	15.1	15.4	15.6	15.8	15.8	16.1	16.1	16.3	16.2	16.5	16.5	16.8	16.9	17.1
2050	17	14.9	15.0	15.3	15.5	15.5	15.7	15.8	16.0	15.9	16.1	16.3	16.4	16.6	16.8
	50	15.2	15.4	15.6	15.9	15.8	16.1	16.1	16.4	16.3	16.5	16.6	16.8	16.9	17.2
	83	15.5	16.0	16.0	16.4	16.2	16.7	16.5	16.9	16.6	17.1	16.9	17.4	17.2	17.7
2060	17	15.1	15.5	15.6	16.0	15.8	16.2	16.1	16.5	16.2	16.6	16.6	16.9	16.9	17.2
	50	15.5	16.1	16.0	16.6	16.2	16.8	16.5	17.1	16.6	17.2	16.9	17.5	17.3	17.8
	83	15.9	16.8	16.4	17.2	16.6	17.4	16.9	17.7	17.0	17.9	17.3	18.2	17.7	18.5
2070	17	15.5	16.1	15.9	16.6	16.1	16.8	16.4	17.1	16.6	17.2	16.9	17.5	17.2	17.9
	50	15.9	16.9	16.4	17.4	16.6	17.6	16.9	17.9	17.0	18.0	17.3	18.3	17.6	18.6
	83	16.4	17.7	16.8	18.2	17.1	18.4	17.3	18.7	17.5	18.8	17.8	19.1	18.1	19.4
2080	17	15.8	16.8	16.3	17.2	16.5	17.5	16.8	17.7	16.9	17.9	17.3	18.2	17.6	18.5
	50	16.4	17.8	16.8	18.3	17.1	18.5	17.3	18.8	17.5	18.9	17.8	19.3	18.1	19.6
	83	16.9	18.9	17.4	19.4	17.6	19.6	17.9	19.9	18.0	20.0	18.3	20.3	18.7	20.7
2090	17	16.3	17.5	16.8	18.0	17.0	18.2	17.3	18.5	17.4	18.6	17.7	18.9	18.0	19.2
	50	17.0	18.9	17.4	19.4	17.6	19.6	17.9	19.9	18.0	20.0	18.4	20.3	18.7	20.6
	83	17.6	20.2	18.1	20.7	18.3	20.9	18.6	21.2	18.7	21.3	19.0	21.6	19.3	21.9
2100	17	16.7	18.3	17.1	18.7	17.3	18.9	17.6	19.2	17.8	19.4	18.1	19.7	18.4	20.0
	50	17.6	20.0	18.1	20.5	18.3	20.7	18.6	21.0	18.7	21.1	19.0	21.4	19.3	21.7
	83	18.4	21.5	18.8	21.9	19.1	22.1	19.3	22.4	19.5	22.5	19.8	22.9	20.1	23.2
2110	17	17.1	19.1	17.6	19.6	17.8	19.8	18.1	20.1	18.2	20.2	18.5	20.5	18.8	20.9
	50	18.3	21.1	18.8	21.6	19.0	21.8	19.3	22.1	19.4	22.2	19.7	22.6	20.1	22.9
	83	19.4	22.8	19.8	23.3	20.1	23.5	20.3	23.8	20.5	23.9	20.8	24.3	21.1	24.6
2120	17	17.5	19.9	18.0	20.3	18.2	20.6	18.5	20.8	18.6	21.0	18.9	21.3	19.2	21.6
	50	19.0	22.3	19.4	22.8	19.7	23.0	19.9	23.3	20.1	23.4	20.4	23.7	20.7	24.0
	83	20.7	24.4	21.1	24.9	21.3	25.1	21.6	25.4	21.8	25.5	22.1	25.8	22.4	26.2
2130	17	17.9	20.5	18.4	21.0	18.6	21.2	18.9	21.5	19.0	21.6	19.3	21.9	19.7	22.2
	50	19.6	23.3	20.1	23.8	20.3	24.0	20.6	24.3	20.7	24.4	21.0	24.7	21.3	25.0
	83	22.4	26.4	22.9	26.9	23.1	27.1	23.4	27.4	23.5	27.5	23.8	27.8	24.1	28.1
2140	17	18.3	21.0	18.8	21.4	19.0	21.6	19.3	21.9	19.4	22.0	19.7	22.4	20.0	22.7
	50	20.2	24.1	20.6	24.6	20.8	24.8	21.1	25.1	21.2	25.2	21.6	25.6	21.9	25.9
	83	24.5	28.6	25.0	29.1	25.2	29.3	25.5	29.6	25.6	29.7	25.9	30.0	26.3	30.3
2150	17	18.6	21.5	19.1	22.0	19.3	22.2	19.6	22.5	19.7	22.6	20.0	23.0	20.4	23.3
	50	20.7	24.9	21.2	25.3	21.4	25.5	21.7	25.8	21.8	26.0	22.1	26.3	22.4	26.6
	83	27.1	30.8	27.5	31.3	27.7	31.5	28.0	31.8	28.2	31.9	28.5	32.2	28.8	32.6

Table E3. Future extreme water level probabilities for the Intermediate and High sea level rise scenarios through the year 2150 at the Bar Harbor tide gauge. Values are provided in feet above 1983-2001 (NTDE) MLLW because this is the datum currently used for tide predictions and flood forecasting in Maine (see callout box "Water level datums and baselines" in main text). For each return period, year, and sea level rise scenario, we provide the 17th, 50th, and 83rd quantile estimate for extreme water level. The only source of uncertainty included here is sea level rise uncertainty; statistical uncertainty and interannual variation in sea level and tidal range are not included.

Recurrence Interval (Years)		1		5		10		25		50		100		200	
Sea level rise scenario		Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High	Intermediate	High
Year	Quantile														
2020	17	23.1	23.1	23.5	23.5	23.8	23.8	24.0	24.0	24.2	24.2	24.4	24.4	24.7	24.7
	50	23.2	23.2	23.6	23.6	23.9	23.9	24.1	24.1	24.3	24.3	24.5	24.5	24.8	24.8
	83	23.3	23.3	23.7	23.7	24.0	24.0	24.2	24.2	24.4	24.4	24.6	24.6	24.9	24.9
2030	17	23.2	23.2	23.7	23.7	24.0	24.0	24.1	24.1	24.3	24.3	24.5	24.5	24.8	24.8
	50	23.4	23.5	23.9	23.9	24.2	24.2	24.3	24.3	24.5	24.5	24.7	24.7	25.0	25.1
	83	23.6	23.7	24.1	24.1	24.3	24.4	24.5	24.6	24.7	24.8	24.9	25.0	25.2	25.3
2040	17	23.5	23.5	23.9	23.9	24.2	24.2	24.3	24.4	24.5	24.6	24.7	24.8	25.1	25.1
	50	23.7	23.8	24.1	24.2	24.4	24.5	24.6	24.7	24.8	24.9	25.0	25.1	25.3	25.4
	83	24.0	24.2	24.4	24.7	24.7	24.9	24.8	25.1	25.0	25.3	25.3	25.5	25.6	25.8
2050	17	23.7	23.8	24.1	24.3	24.4	24.6	24.6	24.7	24.8	24.9	25.0	25.1	25.3	25.4
	50	24.0	24.3	24.4	24.7	24.7	25.0	24.9	25.1	25.1	25.3	25.3	25.5	25.6	25.9
	83	24.3	24.8	24.8	25.2	25.1	25.5	25.2	25.7	25.4	25.9	25.6	26.1	25.9	26.4
2060	17	24.0	24.3	24.4	24.7	24.7	25.0	24.8	25.2	25.0	25.4	25.3	25.6	25.6	25.9
	50	24.3	24.9	24.8	25.3	25.1	25.6	25.2	25.8	25.4	26.0	25.6	26.2	25.9	26.5
	83	24.7	25.6	25.2	26.0	25.5	26.3	25.6	26.5	25.8	26.7	26.0	26.9	26.3	27.2
2070	17	24.3	24.9	24.7	25.3	25.0	25.6	25.2	25.8	25.4	26.0	25.6	26.2	25.9	26.5
	50	24.7	25.7	25.2	26.1	25.4	26.4	25.6	26.6	25.8	26.8	26.0	27.0	26.3	27.3
	83	25.2	26.5	25.6	26.9	25.9	27.2	26.1	27.4	26.3	27.6	26.5	27.8	26.8	28.1
2080	17	24.7	25.5	25.1	26.0	25.4	26.3	25.5	26.4	25.7	26.6	25.9	26.8	26.2	27.1
	50	25.2	26.6	25.6	27.0	25.9	27.3	26.1	27.5	26.3	27.7	26.5	27.9	26.8	28.2
	83	25.7	27.7	26.2	28.1	26.5	28.4	26.6	28.6	26.8	28.8	27.0	29.0	27.3	29.3
2090	17	25.1	26.2	25.5	26.6	25.8	26.9	25.9	27.1	26.2	27.3	26.4	27.5	26.7	27.8
	50	25.8	27.6	26.2	28.1	26.5	28.4	26.6	28.5	26.8	28.7	27.0	28.9	27.4	29.2
	83	26.4	28.9	26.8	29.4	27.1	29.7	27.3	29.8	27.5	30.0	27.7	30.2	28.0	30.5
2100	17	25.4	27.0	25.9	27.4	26.2	27.7	26.3	27.9	26.5	28.1	26.7	28.3	27.0	28.6
	50	26.4	28.7	26.8	29.2	27.1	29.4	27.3	29.6	27.5	29.8	27.7	30.0	28.0	30.3
	83	27.2	30.2	27.6	30.6	27.9	30.9	28.0	31.0	28.2	31.2	28.4	31.5	28.8	31.8
2110	17	25.9	27.8	26.3	28.2	26.6	28.5	26.7	28.7	26.9	28.9	27.2	29.1	27.5	29.4
	50	27.1	29.9	27.5	30.3	27.8	30.6	28.0	30.7	28.2	30.9	28.4	31.2	28.7	31.5
	83	28.2	31.6	28.6	32.0	28.9	32.3	29.0	32.4	29.2	32.6	29.4	32.9	29.8	33.2
2120	17	26.3	28.6	26.7	29.0	27.0	29.3	27.1	29.5	27.3	29.7	27.5	29.9	27.9	30.2
	50	27.7	31.0	28.2	31.4	28.5	31.7	28.6	31.8	28.8	32.0	29.0	32.2	29.3	32.6
	83	29.4	33.1	29.9	33.6	30.2	33.8	30.3	34.0	30.5	34.2	30.7	34.4	31.0	34.7
2130	17	26.7	29.2	27.1	29.6	27.4	29.9	27.5	30.0	27.7	30.2	27.9	30.5	28.2	30.8
	50	28.3	31.9	28.8	32.4	29.1	32.7	29.2	32.8	29.4	33.0	29.6	33.2	29.9	33.5
	83	31.1	35.1	31.6	35.5	31.8	35.8	32.0	35.9	32.2	36.1	32.4	36.3	32.7	36.7
2140	17	27.0	29.6	27.4	30.1	27.7	30.4	27.9	30.5	28.1	30.7	28.3	30.9	28.6	31.2
	50	28.9	32.8	29.3	33.2	29.6	33.5	29.8	33.6	30.0	33.8	30.2	34.1	30.5	34.4
	83	33.3	37.2	33.7	37.7	34.0	37.9	34.1	38.1	34.3	38.3	34.5	38.5	34.9	38.8
2150	17	27.3	30.2	27.8	30.6	28.1	30.9	28.2	31.0	28.4	31.2	28.6	31.4	28.9	31.8
	50	29.4	33.5	29.8	33.9	30.1	34.2	30.3	34.3	30.5	34.5	30.7	34.7	31.0	35.1
	83	35.8	39.4	36.2	39.9	36.5	40.1	36.7	40.3	36.9	40.5	37.1	40.7	37.4	41.0

Table E4. Future extreme water level probabilities for the Intermediate and High sea level rise scenarios through the year 2150 at the Eastport tide gauge. Values are provided in feet above 1983-2001 (NTDE) MLLW because this is the datum currently used for tide predictions and flood forecasting in Maine (see callout box “Water level datums and baselines” in main text). For each return period, year, and sea level rise scenario, we provide the 17th, 50th, and 83rd quantile estimate for extreme water level. The only source of uncertainty included here is sea level rise uncertainty; statistical uncertainty and interannual variation in sea level and tidal range are not included.

APPENDIX F (SEA LEVEL RISE)

Contributions of Ice Sheet Loss to Future Sea Level Rise

This section summarizes significant new literature on ice sheet instabilities that may contribute to rapid late-21st century acceleration in sea level rise.

Greenland Ice Sheet

Estimates for the amount of warming, relative to pre-industrial levels, that would cause the Greenland Ice Sheet to reach a critical threshold where the entire ice sheet would melt over the next several millennia range from 0.8°C to 3°C, with a central estimate of 1.5°C (Lenton et al., 2023). This complete melting would raise global sea level by about 23 feet (7 meters; Morlighem et al., 2017), and the speed the ice sheet melts would depend on how much Earth warms beyond the critical temperature threshold (Robinson et al., 2012). This critical threshold would be reached when the melt-elevation lowers creating a positive feedback, or the process by which melting the ice sheet brings it into contact with warmer air at lower elevations, becomes strong enough to support self-accelerating ice mass loss that continues without additional warming (Huybrechts, 1994; Levermann & Winkelmann, 2016; Ridley et al., 2010; Robinson et al., 2012).

Millan et al. (2023) observed an increase in basal melting rates of several of the largest Greenland ice shelves, resulting in an estimated 35% loss in ice shelf volume over the last 45 years. Ice shelves are thick plates of floating ice, so although breakup of the ice shelves themselves does not raise sea level, they stabilize land-based ice that does contribute to sea level rise. Complete collapse of Greenland's three major ice shelves could raise sea levels by 3.6 feet alone over the next few centuries.

East and West Antarctic Ice Sheets

Recent estimates of critical thresholds for self-sustained ice retreat range from 1°C to 3°C of warming for the marine basins of the West Antarctic Ice Sheet and 1°C to 8°C for marine basins of the East Antarctic Ice Sheet (Lenton et al., 2023). Marine basins refer to parts of the ice sheet that are grounded on bedrock that lies below sea level. Large-scale ice loss from parts of East Antarctica grounded on bedrock above sea level may be reached with warming of 6°C or greater (Garbe et al., 2020).

DeConto et al. (2021) found that sustained warming above 2°C may lead to extreme sea level rise over the coming centuries that is irreversible on human timescales. In model simulations where warming was limited to 2 °C or less, Antarctic Ice Sheet loss continued through the 21st century at a rate similar to today. With 3°C of warming, there was rapid and sustained ice loss, regardless of simulated removal of greenhouse gases from the atmosphere after reaching 3 °C of warming (representing a scenario where mitigation, sequestration, etc. lower atmospheric concentrations of greenhouse gasses after warming 3°C). This rapid ice loss was mainly triggered by the breakup of ice shelves that buttress the ice sheet and cannot regrow in a warmer ocean.

Stokes et al. (2022) found that the East Antarctic Ice Sheet, which has typically been viewed as less susceptible to ice loss than the West Antarctic Ice Sheet, is presently losing mass, despite models indicating that it should be accumulating over the 21st century. They also found that beyond 2100, high-emissions scenarios that exceed 2 °C of warming could lead to several meters of sea level rise within a few centuries.

Naughten et al. (2023) found that Earth is likely already committed to rapid ocean warming over the 21st century (triple the historical rate), and that this committed warming will lead to widespread increases in ice shelf deterioration that ultimately destabilize ice sheets. Internal climate variability and greenhouse gas mitigation strategies may not be able to prevent ocean warming that could lead the West Antarctic Ice Sheet to collapse.

The Thwaites Glacier (part of the West Antarctic Ice Sheet) has been retreating at an accelerating rate over the past 20 years (Alley et al., 2021; Bevan et al., 2021; Miles et al., 2020). It is particularly susceptible to large-scale retreat from ocean warming, and its collapse would raise global sea level by over 0.5 meters and destabilize neighboring glaciers that would raise sea level an additional 3 meters (Scambos et al., 2017).

APPENDIX G (SEA LEVEL RISE)

Coastal Flooding

Components of extreme water levels and the 18.6-year nodal cycle

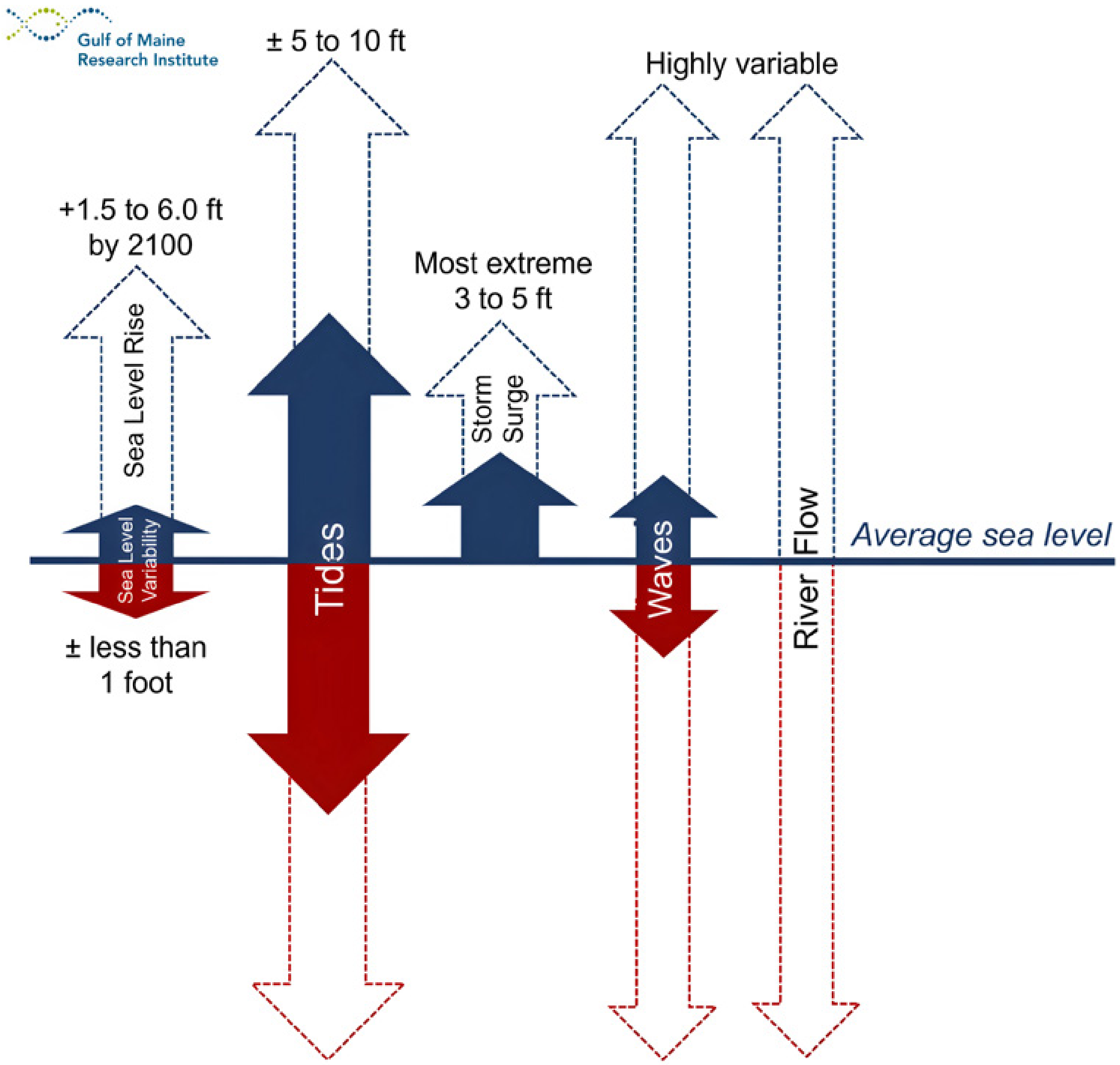


Figure G1. Physical processes that raise and lower water level along Maine's tidally-influenced coast, contributing to extreme floods. Average sea level varies by less than a foot on seasonal-to-annual timescales, and long-term warming-driven sea level rise will increase sea level 1.5 to 6 ft by 2100. Tides raise and lower water level twice per day by approximately 5-10 ft, depending on location. High tides tend to be larger than storm surge, as extreme surges along Maine's coast are between 3 and 5 ft; thus, the height of the tide on the day a storm hits has a major influence on the severity of flooding. Depending on location, waves and river flow range from having no impact on water level to being the most significant factor in determining water level. Figure by Hannah Baranes, GMRI.

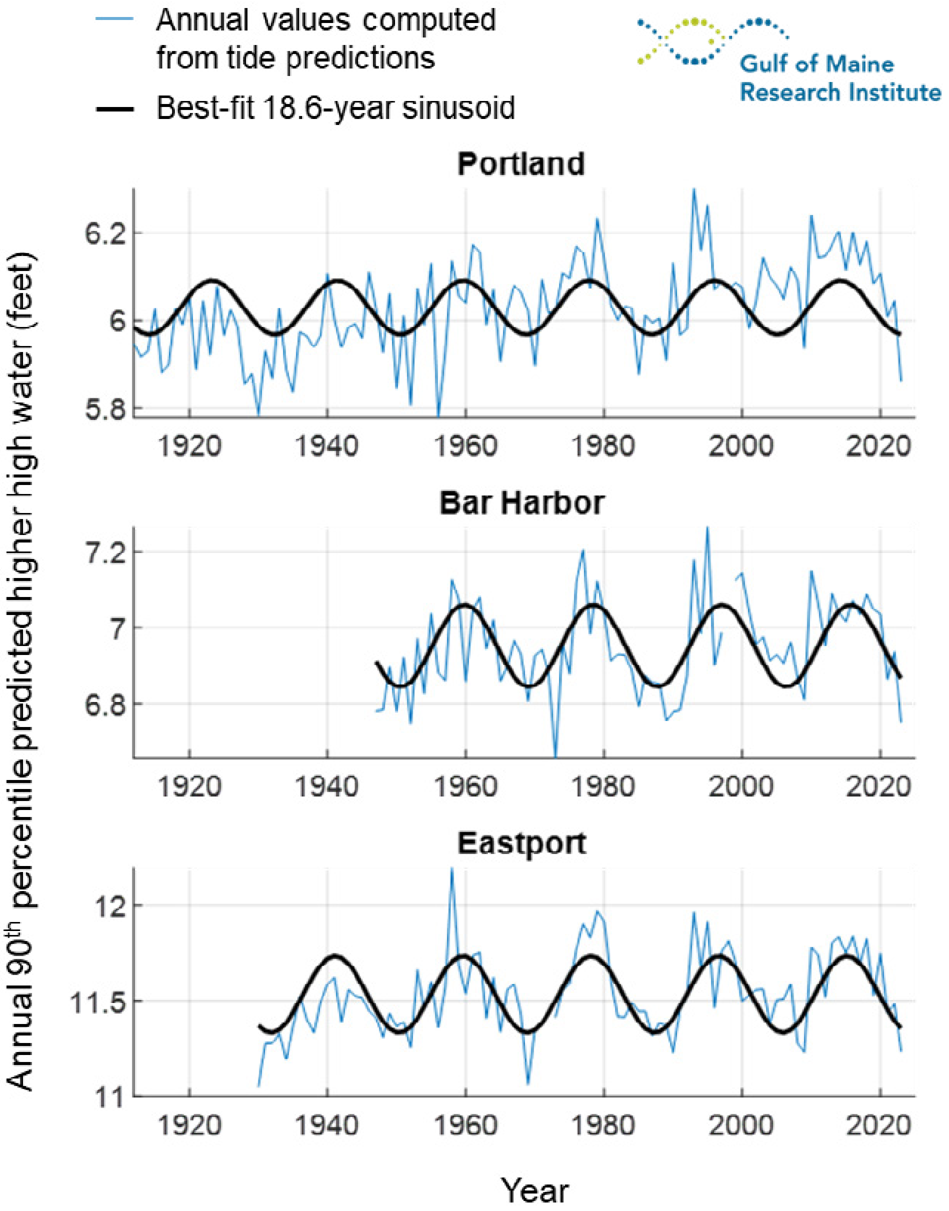


Figure G2. Annual 90th percentile predicted higher high water at Portland, Bar Harbor, and Eastport. Values computed from annual tide predictions are plotted in blue, and a best-fit 18.6-year period sinusoid is plotted in black. The best-fit sinusoid shows that the 18.6-year nodal cycle causes the 90th percentile higher high water to vary by about 1.2 inches (0.1 feet) in Portland, 2.4 inches (0.2 feet) in Bar Harbor, and 4.8 inches (0.4 feet) in Eastport. Figure by GMRI.

Dynamic flood models

Maine Silver Jackets Portland, South Portland, and Damariscotta Model

Since the 2020 STS report, the US Army Corps of Engineers' Maine Silver Jackets Team released a new flood model for Portland, South Portland and Damariscotta. The purpose of this model was to provide detailed maps of present and future flooding from coastal storms and sea level rise to aid in municipal planning efforts for the cities of Portland and South Portland and the Town of Damariscotta. South Portland is using model results to inform their comprehensive planning efforts. Portland is using model results to develop flood resilience overlays and rewrite their land use code for the first time in 50 years as a part of their Recode Portland effort.

This model simulated three historical storms with five sea level scenarios (15 total model runs). Storms selected for the model were the Patriots' Day Storm of 2007 (April 16, 2007; representative of the "10-year" or 10% annual chance event), Winter Storm Grayson (January 4, 2018; representative of the "25-year" or 4% annual chance event), and the Blizzard of 1978 (February 7, 1978; representative of the "100-year" or 1% annual chance event). Storms were modeled on top of present day sea level and 1.5 feet, 3.0 feet, 3.9 feet, and 8.8 feet of sea level rise (consistent with Maine's targets based on the 2020 STS and Portland and South Portland's joint climate action plan, One Climate Future). Limitations of this model are that select events may not represent an extreme scenario everywhere (for example, coastal geometry determines whether a location is impacted more by Nor'easters or Southeasters), and the probability of the event is unknown for every location. This model also does not include all wave processes that impact exposed coastal areas.

Selected model results have been made available to the City of South Portland and are available for the public to view at this page via an ArcGIS StoryMap. Results from all three communities will eventually be presented on the MGS Hazards page.

The Maine Coastal Flood Risk Model

The Maine Coastal Flood Risk Model (ME-CFRM) is currently being developed to assess present and future flood hazard along the state's entire intertidal coastline. MaineDOT is leading the project, and the consulting firm Woods Hole Group is leading model development. The model is scheduled for release in 2025.

The ME-CFRM is a coupled ADCIRC-UnSWAN model that includes the impacts of sea level, tides, storm surge, wave setup, wave runup and overtopping, and river flows on coastal flooding. It models a large set of tropical and extratropical cyclones with various tidal alignments, river flows, and sea level scenarios to provide water depth, water surface elevation, flood duration, wave characteristics, flood pathways, flood volumes, and currents for events of various return periods (not just the 1%) under present and future conditions along the entire coastline.

APPENDIX H (MARINE)

Lobster status, projections, and pressures

Lobsters are being directly impacted by warming waters as well as climate-driven changes to the zooplankton community, effects that have important implications for the future of Maine's lobster industry. For the Gulf of Maine and Georges Bank, hindcasting models have been used to assess recruitment and annual fishing mortality (Tanaka et al., 2019). Independent predictions that Maine's lobster harvest would peak in the 2015-2020 time frame and begin to decline thereafter (Le Bris et al., 2018; Oppenheim et al., 2019) have been borne out by subsequent trends in landings and fishery-independent surveys (Kim et al., 2023; ME DMR, 2024). Research outlined in the following paragraphs suggests climate related change in both temperature and planktonic food supply are key drivers of larval lobster settlement, which influences how many lobsters mature and can be harvested by the fishery six to eight years later.

By the mid-late 2000s along the eastern Maine coast, more frequent summer temperatures above a critical 12°C threshold for larval development promoted a northeastward expansion of settlement and subsequent recruitment to the fishery (toward the Bay of Fundy (Le Bris et al., 2018; Goode et al., 2019). The newly populated nurseries in eastern Maine drove a historic boom in landings (**Figure 5** in main text) that elevated the combined U.S. lobster fishery to its status as the nation's most valuable single-species fishery by 2015. Despite the more favorable temperatures in the northeast, by 2010 the Gulf was already undergoing a regime shift stemming from the waning influence of the cold, nutrient-rich Labrador Current and the increasing supply of warm, salty, nutrient poor Gulf Stream water. Declines in larval settlement over the past decade (2010-2023) are strongly correlated with basin-wide changes in the abundance and phenology of cold-water zooplankton, in particular, the copepod *C. finmarchicus* (Carloni et al., 2018; Carloni et al., 2024; Wahle et al., 2021).

Beyond the correlative evidence, new research is providing insight into the mechanism of the predator-prey interaction between larvae and their zooplankton prey (**Figure A1**). Using novel DNA sequencing tools, Ascher (2023) found that larval lobster stomachs reveal a diversity of planktonic prey, mostly crustaceans, with a disproportionately high number of larvae containing *C. finmarchicus,* suggesting preferential feeding. Laboratory feeding experiments further reveal the relative vulnerability of early stage larvae compared to the more robust later stages, especially when zooplankton densities are low (Ascher, 2023; Layland, 2023, Layland et al. 2024, in review).

Additional research shows that warming waters cause lobsters to mature at a smaller size and that larvae from smaller females are more vulnerable than those from larger females. The length at which female lobsters reach maturity has decreased (by 5mm) over the last 25 years in Maine (Waller et al., 2019). Further, research by Ascher et al. (in review) suggests smaller females produce smaller eggs, less well invested with lipids and proteins resulting in less robust larvae that do not endure starvation as well as those from larger females.

Figure H1. Stage III American lobster larva consuming the copepod *Calanus finmarchicus*. (Photo: D.M. Fields, Bigelow Laboratory)

Several recent studies have contributed to our understanding of the effects of ocean acidification on the biology of the American lobster. Experimentally evaluating the effects of warming and acidification together–the two major effects of rising atmospheric CO_2–is most informative because they enable the evaluation of change in one factor while controlling the other. While the study of temperature change on lobster biology has a long history, meaningful studies of acidification effects have only recently come to light. In less than a decade new studies have spanned the larval to adult life stages and measured a range of biological variables including behavior, growth, heart rate, metabolism, and gene expression (Harrington & Hamlin, 2019; Menu-Courey et al., 2019; Niemisto et al., 2020; Waller et al., 2017). In general, the biological response of the lobster to end-century levels of acidification anticipated for the Gulf of Maine is considerably more subtle than to end-century warming. **The American lobster also appears to be relatively resistant to OA effects compared to other more vulnerable commercially valuable shellfish, such as oysters and clams** (Gledhill et al., 2015). These findings are filling an important empirical gap in the development of models predicting the impact of climate change on lobster population dynamics (e.g., Tai et al. 2021). Still missing and more challenging are multi-generational studies and comparisons among subpopulations that will provide more insight into the potential for local adaptation to changing conditions.

Taken together, the results from these different lines of research suggest that **climate-related changes in the reproductive performance of lobsters and the supply of planktonic foods have contributed to declines in lobster settlement over the past decade with important implications for the future of Maine's iconic lobster fishery.**

In the years since the 2020 STS assessment, the Maine lobster industry has been beset by challenges that ultimately relate to the increasingly tangible direct or indirect effects of climate change on the state's fishing grounds and working waterfront, raising concern over the economic and social well being of the state's coastal fishing communities. Five climate-related issues face the lobster industry:

1. **Projected declines in lobster stock abundance and landings: Maine's lobster harvest in 2022 declined by 26% in volume from its historic highs in 2016** (ME DMR, 2024) in keeping with recent short term predictive models based on larval settlement strength (Oppenheim et al., 2019). Three recently developed multi-decadal projection models that use different approaches agree in their prediction of a continuing downward trend in statewide lobster production by 2050. One model (Le Bris et al., 2018; **Figure A2**) is based on an understanding of thermal effects on lobster life history and changes in the predator environment that span the Gulf of Maine stock. It suggests that the lobster population abundance will decline approximately 40% by 2050 under projected mean temperatures from the RCP8.5 scenario in the CMIP5 climate model ensemble. A second model (Tai et al. 2021; **Figure A3**) that encompasses the entire geographic range of the species, starkly depicts the northward shift in maximum catch potential relative to 2010 levels by end of the 21st century under RCP8.5 conditions. This model is noteworthy in parsing out the relatively small but widespread adverse impact (mostly <1%) of ocean acidification across lobster life stages. It is important to distinguish ocean acidification effects, a result of elevated atmospheric CO_2, depicted here from the more localized effects of coastal acidification. The third, fine-scale model (Kim et al. 2023; **Figure A4**), is based on a statistical association between lobster landings, abundance and environmental data collected in state waters by the Maine-New Hampshire trawl survey. Under both RCP4.5 and 8.5 climate change models this model consistently predicts downward trends in habitat suitability and landings through 2055 for eastern Maine, the area producing the largest boom over the past two decades, but more mixed outcomes for the midcoast and southwestern zones. It is noteworthy that these results differ from other modeled projections of change in lobster distributions that indicate the potential for declines in habitat suitability in many areas of the Gulf of Maine, with projected increases in suitability in offshore waters (Tanaka et al., 2020) and from mid-coast Maine to the Bay of Fundy (Allyn et al., 2020).

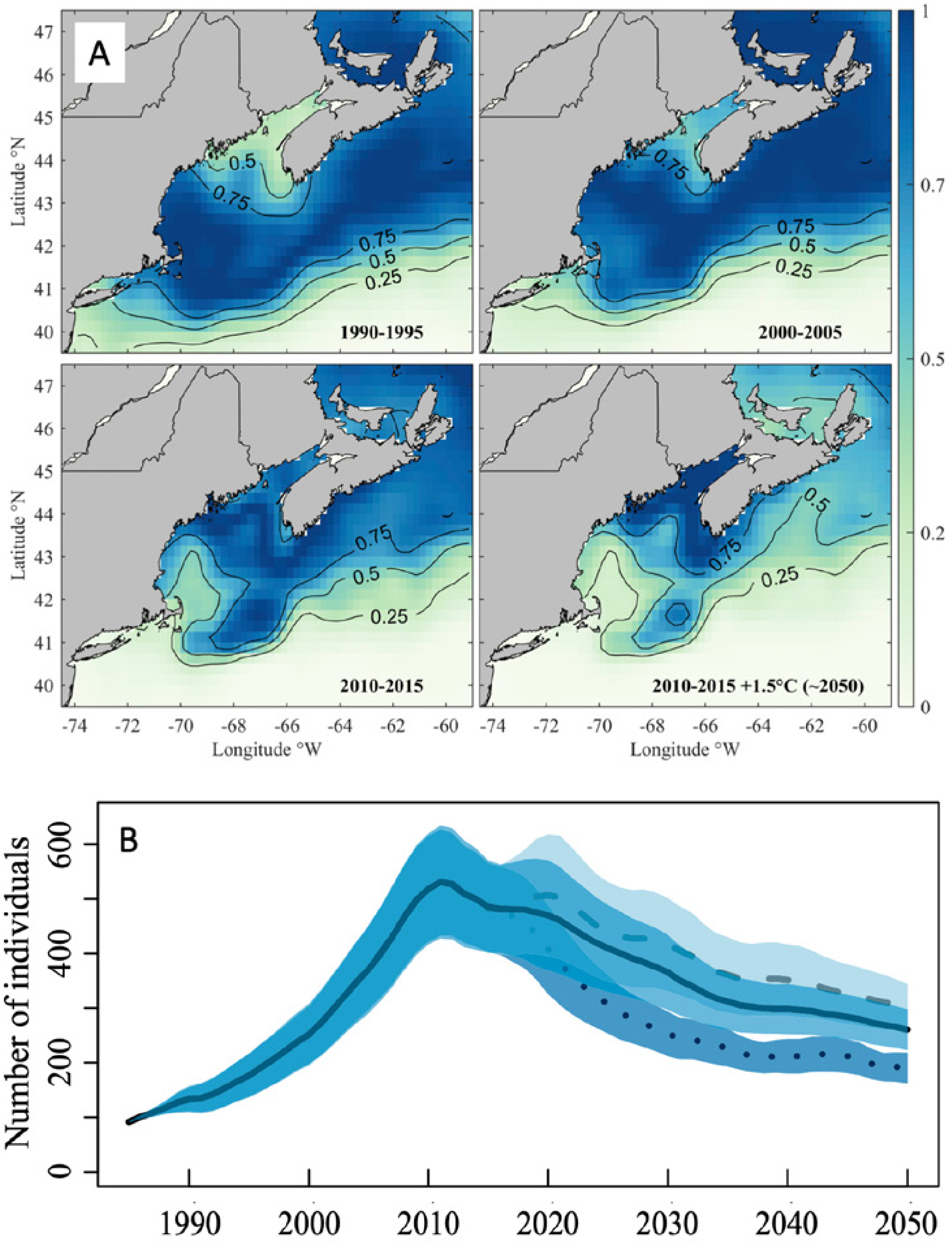


Figure H2. Gulf of Maine scale lobster abundance projections from Le Bris et al. (2018). (**A**) Historic and projected lobster recruitment index normalized across years and across the spatial domain of the Gulf of Maine and adjacent waters of southern New England and Atlantic Canada, with the last panel showing recruitment projections assuming a 1.5°C increase in temperature above that observed for 2010-2015. (**B**) Estimated lobster abundance from 1985 to 2050 for the Gulf of Maine. Projections use the mean (solid lines), the 5th percentile (dashed lines), and the 95th percentile (dotted lines) of temperature projections from the CMIP5 ensemble of climate projections using RCP 8.5. Colored areas show 95% confidence intervals.

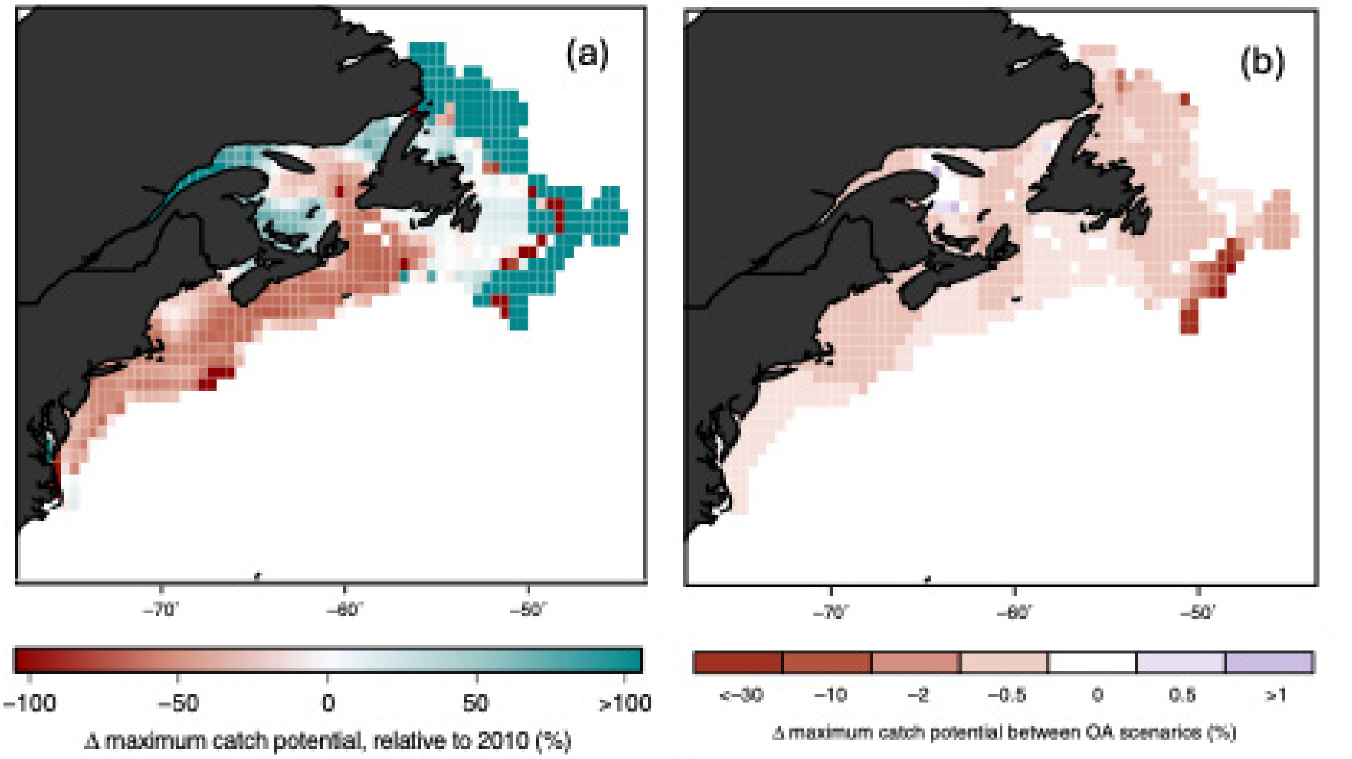
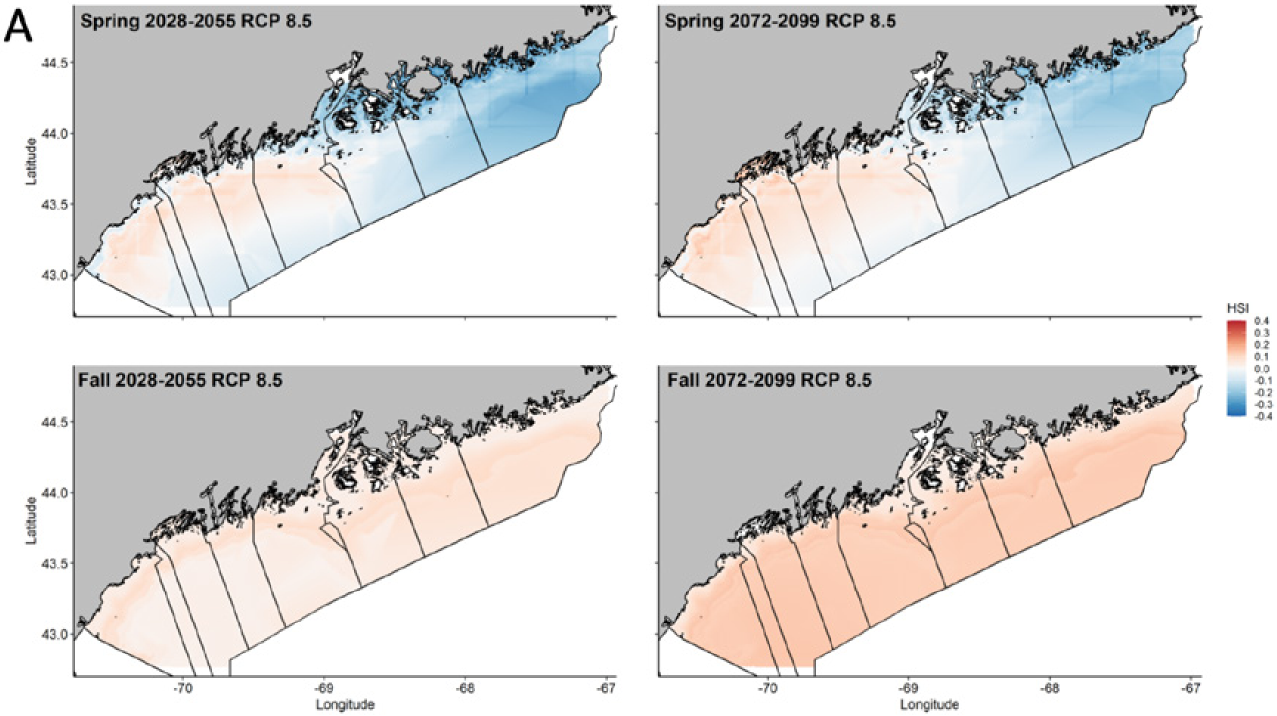


Figure H3. (**a**) Predicted change in the distribution of maximum catch potential relative to 2010 for the American lobster over its geographic range by 2100 under the RPC 8.5 scenario without OA effects. (**b**) Change in catch potential due to the added effect of OA based on empirical studies over all life stages (modified from Tai et al., 2021).



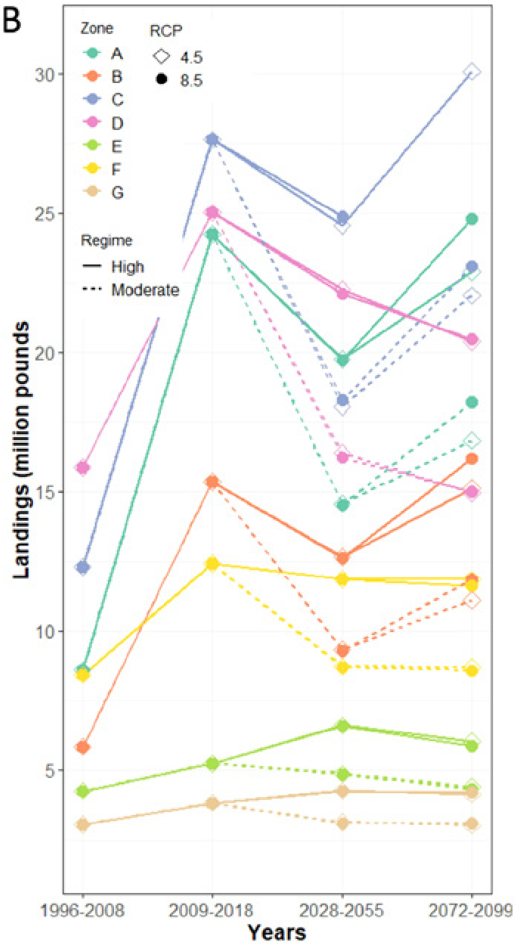


Figure H4. Lobster habitat suitability and landings projections at the scale of Maine's seven lobster fishing zones modified from Kim et al. (2023). **(A)** Change in interpolated lobster habitat suitability index (HSI) from the 2004-2017 baseline to the time periods 2028-2055 (maps on left) and 2072-2099 (maps on right) for the seasons spring (top row) and fall (bottom row) for RCP scenario 8.5. HSI values range from 0 (lowest) to 1 (highest). Lines depict Maine's seven lobster management zones from A (northeast) to G (southwest). **(B)** Total interpolated landings from the Landings-HSI model for historical (1978-2005), baseline (2004-2017), and forecasted (2028-2055; 2072- 2099) time periods and RCP 4.5 and 8.5 scenarios and under modeled high and low abundance regimes.

2. **An over-dependence on the lobster fishery:** In the wake of depleted fisheries in groundfish, shrimp and sea urchin, Maine's coastal communities have become increasingly dependent on the lobster fishery, which contributes over two thirds of the combined fishery generated revenue in the state (ME DMR, 2023). The economic dependency on lobster is especially acute in eastern Maine. A downturn in the fishery is likely to be most consequential because fewer alternative sources of income exist. Continuing socio-economic research and modeling under way at the University of Maine and Gulf of Maine Research Institute aims to better document regional indicators of economic resiliency along the state's coast so as to provide policy makers and businesses tools to mitigate vulnerabilities (Burnham et al., in preparation; see Vulnerability and Resilience section).

3. **Anticipating sea level rise and storm damage to working waterfront:** The devastating damage of back-to-back storms of January 10 and 13, 2024, brought home the realities of climate change to those making a living on Maine's waterfront. On the heels of 2023, the year with the highest recorded sea levels, January strong winds, large storm surge and waves coincided with high astronomical tides to cause widespread damage to wharves, docks and storage facilities serving the lobster industry (see Sea Level Rise chapter). Many working waterfront structures were built decades ago, exposing their vulnerability to accelerating sea level rise. Given the forecasted accelerating rate of SLR, structures will continue to face impacts if not rebuilt with Maine's "commit to manage" and "prepare to manage" sea levels guiding development. Improvement projects may also be an opportunity to incentivize and integrate climate-ready infrastructure such as charging stations to facilitate electrification down the road. Although pure battery electric propulsion systems are not yet feasible for Maine's inshore and offshore fleets, parallel hybrid (diesel and electric) systems may be able to reduce boat emissions by 30-40% or more with current technology while meeting the duty cycle needs of Maine's fleet (Hagan & Nelson, 2022).

4. **Minimizing interaction between the North Atlantic right whale and lobster fishing:** With only some 350 individuals remaining in the population, the North Atlantic right whale is classified as an endangered species. Under pressure from conservation organizations to enforce the Endangered Species Act, in 2021 the National Marine Fisheries Service announced a federal rule that the lobster industry must take significant measures to reduce the risk of entanglement of right whales in lobster gear (Federal Register, 2021). The regulations required a 98% reduction in the risk of entanglement implemented through a combination of area closures, reductions in the number of vertical buoy lines on traps, adopting weak links and rope, marking the gear to be traceable to its origin, and the adoption of on-demand, or so called "ropeless" gear. A recent report commissioned by the Massachusetts Division of Marine Fisheries summarizes the ongoing and anticipated issues and challenges of using on-demand gear in lobster fisheries, including environmental, regulatory, and socioeconomic impacts (Oppenheim, 2022; Oppenheim et al. 2023).

   Maine's lobster industry and state fishery regulators saw the conservation targets as unrealistic, unenforceable, and a threat to the lobster industry and coastal communities that depend on it. In December 2022, the Maine Lobstermen's Association, Maine Department of Marine Resources, in partnership with other state officials and Maine's Congressional delegation, secured a six year delay in the implementation of these rules. And in 2023, a federal appeals court sided with the lobster industry and sent the regulations back to the National Marine Fisheries Service to be reworked by applying more realistic rather than worst-case-scenario modeling approaches. The delay includes the appropriation of federal funds to test the new fishing methods (especially on-demand gear), improve technology to track right whales, and improve models to predict their movements as influenced by changes in the ocean environment.

   Recent studies have demonstrated that climate-related shifts in ocean productivity have resulted in reductions in the right whale's primary food, the copepod *Calanus finmarchicus*, which in turn has adversely affected growth rates and calving rates, and forced movement to more productive feeding grounds in Canadian waters (Meyer-Gutbrod et al., 2021). The decline of North Atlantic Right Whales is complex and attributable to multiple causes, with certain industries in the U.S. (lobstering) bearing a disproportionate burden of the processes and policies to remediate right whale impacts. Federal funding is supporting new research, staff and infrastructure in Maine and throughout New England to mitigate the interaction of the lobster fishery and right whales, and to study environmental and economic impacts of the gear in further detail.

5. **Offshore wind energy development:** In March 2024, the Bureau of Ocean Energy Management made public its draft plan for siting wind energy development in the Gulf of Maine (Randall et al., 2024). The plan includes approximately two million acres of offshore area. Responding to fishing industry concerns, the plan avoids most of the Gulf of Maine's most productive offshore lobster fishing grounds in federal waters (NOAA's Lobster Management Area 1), while still aligning with the Maine legislature's mandate to produce 3GW of offshore wind energy by 2040. Where fishing overlaps with potential wind energy development there will be a need to assess the interaction of the proposed floating turbine arrays with lobsters and lobster fishing activity. To the extent they are comparable, lessons may be learned from impact studies conducted in southern New England (e.g., Wilber et al., 2024), the Mid-Atlantic (e.g., Munroe et al., 2022; Scheld et al., 2022), and the Irish Sea (i.e., Thatcher et al., 2023). A small experimental / non-commercial area for as many as 12 turbines has been set aside for this purpose. Floating turbines are being designed and tested by the University of Maine's College of Engineering and Computing specifically for use in the deeper waters of the Gulf of Maine and have never been used elsewhere in the United States.

APPENDIX I

Priority Information Needs

Maine Climate Council 2024 Scientific and Technical Subcommittee Worksheet on Information Needs as part of the climate science assessment process.

This is a worksheet used by subgroups of the STS in discussing and identifying information needs as part of the 2024 STS climate science assessment deliberations. This information should be viewed as a work product of these deliberations, and one that builds on the Information Needs identified in the 2020 STS climate science assessment document.

SECTOR	WHAT?	HOW?	WHEN?	WHERE?	TYPE?	CROSSCUTTING?
	Information need: summarized in as few and specific words as possible	**What specific methods or approaches could be used to address this information need**	**Timeline: ongoing, discreet years, urgent, short/long-term?**	**Are there specific location needs? If so, where?**	**Monitoring, research, data analysis, surveys, other?**	**Is this information need for this sector also applicable to other or all sectors? (e.g., B/C analysis)**
Agriculture	Access to more accurate, short, intermediate, and long range weather forecasts tuned to agricultural needs. In addition, there is need for weather information analysis and delivery to translate conditions into guidance for	Better use of existing meteorological data, analyses, and delivery platforms. Funding for staff to identify needs, what is known, and conduct literature review and develop programs and	Urgent, ongoing.	Statewide, but primarily in the agricultural production areas of southern/central Maine.	Literature review, assessment of existing capabilities in and beyond Maine. Surveys	Broadly applicable, especially for forestry, fisheries, and other natural resource industries
Agriculture	Program designs to provide technical and financial support for to increase Maine farm resilience and recovery to extreme and variable weather (e.g. drought and flooding, heat stress and freeze events). Including mental health services to address farmer stress.	Review existing programs to reduce bureaucratic hurdles. Study programs for farm climate resilience in other states and federal agencies. Review ag related components in emergency preparedness and recovery plans.	Urgent, ongoing.	Statewide, but especially farm locations prone to flooding and drought.	Literature review. Client need surveys. Legislation.	Largely specific within agricultural commodities and economic scale, but crossover with municipal resilience planning.
Agriculture	Information relevant to instituting policies, programs and technology and to reduce food waste and enhance food security.	Legislation to reduce liability concerns around food donations. Education on food usability and spoilage.	Medium term	Statewide	Surveys, Data analysis	Human dimensions, Municipal land fill issues.
Agriculture	Analysis of the economics, impacts, and logistics of carbon sequestration, biochar, enhanced weathering, and other methods being considered for greenhouse gas reduction	Ongoing monitoring of test plots to evaluate different methods.	Ongoing, long term	Statewide, National. Programs to incentivize carbon sequestration are likely to be managed at the Federal level. Similarly the research needed does not necessarily have to originate in Maine, though it should be validated in Maine. Given the national breadth of the issue, it is not in our top 3 priorities for information needs in Maine.	Data analysis, Monitoring	May have high degree of site specificity, thus requiring high resolution validation.
Agriculture	Effective program designs to support on-farm energy efficiency and transitioning from fossil fuel to electrical farm equipment and facilities.	USDA ag support programs, Maine tax policy. UMaine Extension and DACF for educational outreach.	Medium/long term	Statewide	Surveys. Legislation.	Energy, Transportation.
Agriculture	Analysis of the economics, efficacy, and community logistics for enteric methane digesters to reduce methane emissions from agriculture in concert with municipal waste streams .	Monitoring input and output of existing digesters. Cost accounting.	Medium/long term	Statewide	Surveys	Municipal governments.
Agriculture	Monitor pest pressure from invasive species issues related to climate change	Continued communication with other state and Federal partners.	Ongoing	Statewide, but especially locations bordering other states and near high traffic flows and out-of-state importation.	Monitoring	Forestry

Agriculture	Information relevant to instituting policies, programs and technology and to reduce food waste and enhance food security.	Legislation to reduce liability concerns around food donations. Education on food usability and spoilage.	Medium term	Statewide	Surveys, Data analysis	Human dimensions
Agriculture	Life cycle analysis of harvesting, drying/transporting and feeding of algal based supplements, especially those that can be harvested in Maine, to reduce methane emissions from dairy and beef cattle.	Continue and augment ongoing research.	Medium/long term	Coastal for sourcing, statewide for implementation	Field and Lab studies, on farm trials.	Marine resources
Air Quality	Ozone and particulate matter monitoring	Continued monitoring by Maine DEP, Micmac Environmental Health Department (MEHD), and the Passamaquoddy Tribe in Sipayik, Pleasant Point; surface monitoring stations should be in every county. Could be enhanced via satellite monitoring.	Ongoing	Counties without current ozone monitoring: Franklin Lincoln Piscataquis Somerset Waldo Counties without current PM monitoring: Franklin Knox Lincoln Piscataquis Sagadahoc Somerset Waldo York	monitoring	
Air Quality	Pollen monitoring	Both a traditional rotation impaction method (e.g. a rotorod sampler) and a cutting edge technology using digital images that are analyzed by artificial intelligence (e.g. a Pollen Sense sampler) will be used in Maine's aeroallergen monitoing network.	Anticipated pollen monitoring start date is 4/1/24	Initial site locations are anticipated to be located at: Cape Elizabeth - Two Lights State Park Augusta - East Side Campus Rumford - Rumford Avenue Parking Lot Bangor - Mary Snow School	monitoring	
Biodiversity	Summary of, and projections for, tidal marsh elevation and biological response to sea level rise based on long term monitoring data and validation of current projection efforts [tidal marshes store significant carbon and hold tremendous ecosystem service and biodiversity values]	Collate existing data and report; create state sentinel site monitoring plan	Initial report could be discreet, near-term; ongoing (long-term) support for continued monitoring, coordination and reporting also needed	coastwide	Data analysis, monitoring	Yes

Biodiversity	Comprehensive hub for information about existing invasive species in Maine, with tools for management, and modeled projections for emerging threats. Including current maps, analysis of potential expansions or changes in impacts/severity due to CC [invasive species are a threat to native biodiversity, and expected to expand in range and abundance due to climate related changes such as temperature]	Compilation of existing resources including iMapinvasives data, paired with on-going monitoring and literature review	Near-term, and on-going	statewide	ling, Data Analysis, Mon	Maybe
Biodiversity	Better data on changes in range and population size of climate-sensitive at-risk (ETSC) flora and fauna [CC is a compunding stressor for ETSC species already at risk of extirpation]	Rigorous monitoring protocols; collaboration between partners	On-going	statewide	Monitoring	Maybe
Biodiversity	Projections for time scale of significant forest composition changes in Maine due to climate and pest stressors [forest type is foundational to biotic composition]		An update could be discreet, near-term	statewide	Research, data analysis	Yes
Biodiversity	Updated/improved understanding of changes in hydrology to palustrine wetlands by initiating better growing season models for prediciting drought frequency and intensity and through field data collection of hydrological data from reference sites statewide [drought and changes in precipitation patterns and heat are significant stressors for wetlands, especially peatland communities which store significant amounts of carbon, and their associated priority species]	Develop hydrologic monitoring protocal that can be repeatable across remote areas and over long term	Ongoing monitoring as well as modeling update which could be discreet, near-term	statewide	rch, data analysis, mon	Yes
Biodiversity	Social & Political Science: What are some of the resource and policy limitations currently preventing State Government from efficiently implementing the highest priority recommendations of the MCC's Natural and Working Lands Committee?	An interview with NWLC representatives from MDIFW, MDACF, and GOPIF	Discreet, short-term	statewide	Survey	Yes
Biodiversity	Improved conservation design and associated strategies to identify and protect important landscape-level features connecting areas of biodiversity importance. To include both terrestrial and aquatic features. [Will provide important targets for where working forest and farmland will contribute to Maine's biodiversity and climate resiliency/species migration benefit].	Landscape analysis, modeling, use of existing modeling	With appropriate resources, analysis could be discreet and near-term	statewide	Data analysis	Maybe
Biodiversity	Updated/improved winter season snow accumulation and temperature pattern monitoring and modeling [reduced snowpack and warmer temps are a significant stressor for some priority species]		An update could be discreet, near-term	statewide	Research, data analysis	Yes
Biodiversity	Identify a way to track natural community or ecosystem changes in composition or extent over time [Plant community assemblages are expected to shift or transition to novel types in response to climate change, impacting wildlife and habitat functions]	Evaluate current mapping and monitoring methods, identify additional research results, query other Heritage programs	On-going	statewide	Analysis, Monitoring, Mo	Maybe

Biodiversity	Ice out monitoring [Impacts to lake temperature impacting cold water species as well as food web]	Collate historic data, identify monitoring stations	On-going	statewide	analysis, surveys, monit	Maybe
Biodiversity	Better information on the status and trends of Maine's insect populations [a group foundational to the foodweb of most natural ecosystems]	Refer to growing body of scientific literature on subject	On-going	statewide	Monitoring	Maybe
Biodiversity	Dissolved oxygen monitoring during summer [warming surface water pushes thermocline deepr plus inceased DOC, threatens lake-dwelling cold water fish-see Jane et al 2024]	Thermocline/DO profile lake monitoring; including citizen science	On-going, start short term	statewide	Monitoring	Maybe
Biodiversity	Projections of the magnitude of human climate refugees predicted to migrate to Maine by circa 2050 and where they are most likely to settle [could magnify existing habitat loss/fragmentaion stressors]		On-going	statewide	Research	Yes
Biodiversity	An updated Maine-specific species and habitat vulnerability analysis (sensu Whitman et al.2013) [helps inform conservation community and state listing decisions]	Could follow same methodology as Whitman et al 2013	Discreet, near-term	statewide	Research	Maybe
Biodiversity	Address gaps in biodiversity assessments to include census of cryptic or lesser known species (e.g. fungi, bryophytes, lichens, cerain inverts?) [these groups play important roles in forest biomes yet ecology and diversity is still poorly understood]	Identify taxonomic experts, identify and collate species lists (state/regional)	On-going	statewide	eys and existing data re	Maybe
Climate	Better understanding of the frequencies and trends of high-impact storm events in the historical record, and improved future projections. The events are those with high winds (e.g., > 50 mph), heavy precipitation (e.g., > 3 in per day or number of hours).	Historical analyses using weather station observations, gridded data, and reanalysis products. Future projections based on historical trends, climate models, and plausible scenarios.	ongoing, medium term		research, data analysis	generally applicable to all
Climate	Improved real-time drought information	Includes gathering existing data and conducting new monitoring for precipitation, streamflow, groundwater, soil moisture, snowpack/snow water equivalent, and temperature.	medium to long term		monitoring	agriculture, forestry
Climate	Cloud cover & sunshine monitoring	Establish new observation stations or utilize existing obs for understanding changes in cloud cover and solar radiation in support of solar projects	long term		data analysis, monitoring	agriculture, forestry
Climate	Better understanding of future projected drought frequency, intensity, and seasonality.	Analyses using weather station observations, gridded data, reanalysis products, and climate models to establish trends and plausible scenarios.	ongoing, medium term		research, data analysis	generally applicable to all

Climate	Expand winter lake monitoring to include ice-on and thickness in addition to ice-off.	Duration and thickness of ice cover on lakes has important climatological, ecological, recreational, and economic implications. The Bureau of Parks and Lands currently monitors ice-out dates for an array of lakes across Maine as does Lake Stewards of Maine, but there is not yet a concerted effort to monitor ice-on or ice thickness. Monitoring these lake ice parameters would help to better characterize broader changes in Maine's winter climate as well as changes in in-lake biological processes.	long term			freshwater quality
Climate	Enhance snowpack monitoring to include early-season snow depth and snow water equivalent data in addition to late winter and spring measurements	Monitoring snow depth and snow water equivalent during late fall, early winter, and mid-winter in addition to the measurements that typically take place during late winter and early spring could provide valuable insights into how the length of the snow season is changing as well as the amount of snow present during extreme winter storm events that can cause flooding, particularly winter rainfall that occurs as rain-on-snow	ongoing, long-term, weekly to bi-monthly	could be added to existing snow survey locations, though there might be benefit in comparing current locations with need for new stream and river gauges in flood-prone areas	monitoring, data analysis, research	related to flood forecasting, impact impacts of changing snow season lengths on winter recreation and tourism as well as changes in forest harvest patterns
Forests	Better availability, resolution, and mapping of key data and projected forest impacts like temperature, precipitation, forest health, pest, disease, land use change, pre-contact fire, biomass, dieback, and carbon stocks by species and geographic area	FIA analysis, field collection, model simulation	medium term	All of Maine, ideally in a consistent format across entire area	monitoring, data analysis, research	Can feed into an economic impact of benefit-cost analysis. Impacts have flow on effects to many other groups; Some data could be sourced from other subgroups (e.g., climate variables)
Forests	Improved monitoring and mapping of forest soil attributes, including forest soil carbon flux and stock over time and as a result of forest management	FIA and other federal/state data agency analysis, field collection, model simulation	medium term	All of Maine, ideally in a consistent format across entire area	monitoring, data analysis, research	Agriculture; potentially freshwater?
Forests	Better mapping of tree species distributions and assessing the impacts of harvesting, insects and disease, storms, and other disturbances on forest resources, including use of remote sensing	FIA and other federal/state data agency analysis, field collection, model simulation	short term	All of Maine, ideally in a consistent format across entire area	monitoring, data analysis, research	
Forests	Develop new and revise existing Best Management Practices, particularly as it relates to roads, water-crossing, and culverts	Field collection, data analysis, stakeholder engagement	medium term	All of Maine, particularly in forests most vulnerable to changing conditions	monitoring, data analysis, research	Freshwater
Forests	Identify the potential impacts of prescribed burning as an adaptation practice for Maine's forests	Field collection, data analysis, stakeholder engagement	medium term	All of Maine, particularly in forests most suited for prescribed burns	monitoring, data analysis, research	Biodiversity

Forests	Improved understanding and application of indigenous/cultural knowledge of and impacts to Maine's forests	Field collection, data analysis, stakeholder engagement	medium term	All of Maine	monitoring, data analysis, research	Human dimensions, biodiversity, climate
Forests	Distributional impacts of climate change + adaptation and mitigation practices on forest-dependent communities	Field collection, data analysis, stakeholder engagement	medium term	All of Maine, particularly forest-industry communities	monitoring, data analysis, research	Human dimensions
Freshwater HABs	Improved evaluations of lakes, rivers and streams to determine sensitivity to HABs	Identify parameters and characteristics of waterbodies that make them susceptible to HABs including nutrient concentrations, pelagic and benthic algal flora, sediment geochemistry and redox potential in lakes and wetlands, and, flow characteristics in rivers and streams.			research	
Freshwater HABs	Improved methods to evaluate algal toxin concentrations (microcystin, anatoxin, cylindrospermopsin, others)	Current technology is limited to lab-based ELISA techniques and multistep rapid ELISA tests. Simple, inexpensive, rapid tests are needed so that real-time conditions can be evaluated. Evaluate the effectiveness of passive samplers such as Solid Phase Adsorption Toxin Tracking (SPATT) devices, as well as the usefulness of eDNA/qPCR testing for determining if an algal population has the genetic capacity to produce toxins, is needed.			research	
Freshwater HABs	Evaluation of algal toxin movement through freshwater food chain	Research of this nature has only recently begun, for the most part outside of Maine. Determination of algal toxin concentrations in fish tissue will provide insight into consumption risk to humans and wildlife.			research	
Freshwater HABs	Expand capacity to characterize toxin (microtoxin, anatoxin) concentrations IN and effects FROM HABs	Maine needs to invest in technology to efficiently and effectively determine toxin levels in water, algal biomass, humans and pets. Standard reporting of human illness suspected to be related to ingestion of an algal toxin needs to be implemented. A free mail-in blood sample testing program for pets suspected of dying from toxin ingestion is also needed.			monitoring	
Freshwater HABs	Expand monitoring of freshwaters for algal toxins	Algal toxin concentrations should be evaluated at a regular frequency whenever pelagic bloom conditions or benthic mats of species are observed in Maine freshwaters. Results will allow identification of sites where algal toxins occur annually to better inform the public regarding risk.			monitoring	

Freshwater HABs	Adopt Federal criteria or establish Maine criteria so public can evaluate risk	Presently Maine is applying Federal criteria to evaluate microcystin results. These criteria could be adopted by Maine or modified to reflect regional considerations. Swimming and drinking water risk communication through an advisory process will become more important as HABs increase.			monitoring	
Freshwater Quality	Accurate spatial characterization of intense storms across state	Intense, localized storms result in stream crossing washouts and other highly erosive events. Proper crossing resizing and stabilization is critical to prevent washouts and silt/nutrient delivery to rivers, streams, lakes & wetlands, which impairs water quality, fuels algal growth, and increases the risk of Harmful Algal Blooms (HABs).			research	
Freshwater Quality	Evaluate effectiveness of statewide standards (Shoreline Zoning, NRPA, Site Location of Development, others) for protecting freshwater resources from erosion related to stormwater runoff	Erosion results in silt & nutrient delivery to rivers, streams, lakes and wetlands. Most of the current development standards originated 30-45 years ago under much different climate conditions and likely need to be adjusted to current conditions to protect water quality in freshwater and downstream marine waters.			research	
Freshwater Quality	Ecosystem modeling of freshwater species' ranges and temperature tolerances, and, eDNA characterization of current species assemblages	Species shifts are expected as a result of warming temperatures. Knowing which species are where, as well as their temperature tolerances will allow accurate modeling to predict changes in the geographic range of species and prioritize regional waters for protection.			research	
Freshwater Quality	Establish permanent monitoring stations on a range (size, depth, relief) of each water type, across the entire state	A few permanent monitoring stations exist in a few water types, but the parameters measured are limited. A more extensive network, with coordinated data acquisition will allow for a better understanding of long-term changes in our freshwater resources.			monitoring	

Freshwater Quality	Expand agency and citizen monitoring of rivers, streams, lakes and wetlands	Current agency and citizen monitoring needs to be expanded to allow for a more comprehensive understanding of changes in water quality in Maine. Citizen scientists provide an effective front-line means of tracking changes in our freshwater systems. Programs designed specifically for citizens, specific to each water type using low-cost measures and sensors, have the potential to provide critical information to researchers.			monitoring	
Freshwater Quality	Implement regular use of satellite imagery and aerial imagery to evaluate siltation events following intense storms	Remote monitoring will provide insight into damage done to Maine waterways as a result of intense storms. Knowing where issues arise will help locate sites requiring stabilization to prevent future erosion events.			monitoring	
Human Dimensions	Tourism statistics relative to CC: changes in Maine recreation where the number of ATV trips has 2X since ~2000 from 44K to 82K Maine registered ATVs. My _guess_ is that Maine is likely to experience a significant net increase in tourism in the next 50 years.					
Human Dimensions	Effect of temperature and humidity extremes and variation on tick activity and survival using both lab and field experiments (lipids, diapause/molecular hormonal cascade, accounting for pathogens infecting ticks that might enhance survival); not just adults and nymphs but also oviposition/eclosion and larvae.					
Human Dimensions	Effects of climate on suburban development/creation of new tick habitat; interaction of warming winters with planned management to increase the deer population in northern counties.					
Human Dimensions	Effects of climate migration to NE and Maine (population is a major driver in Maine GHG emissions, tax revenues, etc.)	This may require a speific study by scenarios: migration & economic development in the NE, with housing prices and union workforce as significant control variables compared to the Southern and western states	2030 is the lates forecast, accuracy will fall greatly, but a 2050 forecast by scenario would be very helpful			
Human Dimensions	Impact of CC on Tourism sector - winter, shoulder and summer seasons	May need to commission a study				

Human Dimensions	**Better information on regional differences in vulnerability and readiness:** Build on existing analyses of differential vulnerability with more information about the relationship between: 1) the types of climate risks communities face (coastal flooding, inland flooding, sea level rise, drought); 2) sensitivty to those risks including economic and infrastructural dependencies; 3) community demographics; and 4) levels of readiness. These differences can be mapped and utilized to inform state investments, community readiness efforts, and strategies to communicate with those most vulnerable.	mapping, community surveys, economic analyses	ongoing	sampling across the state	mixed method social science (surveys, interviews, spatial analysis)	yes
Human Dimensions	**Improved understanding of mental health impacts, prevention and treatment:** we need to build upon important insights into the mental health impacts of extreme climatic events and disasters to include the impact of loss of culture/heritage as well as the potential impacts of the inability to adapt in place. This information is necessary to research and inform effective public health interventions/healthcare responses to address the mental health impacts of climate change in Maine.	case studies, experimental design, clinical trials	ongoing	state-wide	mixed methods and synthetic analysis	yes
Human Dimensions	**Develop a stronger understanding of potential migration patterns and population shifts:** more information to enable projections of climatic impacts on population - including settlement patterns and migration to and within the state. This information is necessary to understand the impacts of shifting populations and settlement patterns on a wide range of human systems including housing, transport, electrical grids, healthcare systems, tourism and tax revenues.	Demographic projections, **build out scenarios, real estate data**	ongoing, long term	state-wide	theoretical models	yes
Human Dimensions	**Develop a stronger understanding of insurance markets**: stronger understanding of insurance markets in a wide range of sectors (crop, home, business, municapality, eg) and the relationship between these markets and risk assesements under a changing climate. This information is necessary to inform adaptation policies including decisions about, for example, coastal "hardening" or "planned retreat".	systemic analysis, economic models, qualitative collection with insurance specialists	ongoing	state-wide	synthesis	yes
Hydrology/Freshwater	Additional riverine and coastal gages relevant to populated flood prone areas	Install USGS streamgages. NWS would then adopt gages as flood forecast gages	Ongoing, continuous, and long term to answer important climate questions.	Populated town/city centers. Coastal communities. Headwater streams.	Monitoring	Marine (for coastal streamgages)
Hydrology/Freshwater	Expanded snowpack monitoring network	Expand existing state cooperative snow survey in frequency over individual winters and in more locations	Ongoing. Weekly to monthly in winter months to answer climate questions. Continuous over many winters for trends.	Statewide	Monitoring	Agriculture, Forestry, Human Dimensions, Biodiversity

Hydrology/Freshwater	Riverine flood Inundation maps	Combine existing hydraulic models, flood forecast streamgages and lidar to create flood inundation map libraries.	Discrete studies	Populated town/city centers. Coastal communities,	Data Analysis	Human Dimensions
Hydrology/Freshwater	More comprehensive riverine water quality monitoring network		Ongoing, continuous, and long term to answer climate questions.	Statewide	Monitoring	Agriculture, Biodiversity, Human Dimensions
Hydrology/Freshwater	Trends in lake ice, snowmelt timing, and snowpack	Redo trends studies to include more recent data.	Discrete studies	State and potentially adjacent areas	Research. Data Analysis.	Human Dimensions, Biodiversity, Agriculture, Marine (coastal), Forestry
Hydrology/Freshwater	Watershed models for winter/spring flooding		Discrete studies	Statewide	Research. Data Analysis.	Human dimensions
Marine	Continue to expand on community initiatives to monitor Maine's complex coastline, with special emphasis on bottom waters that are difficult to monitor with remote sensing products. For example, expand collaboration between the lobster industry and oceanographers through the electronic Monitoring of Lobster Traps (eMOLT) program.	eMOLT	Ongoing	Bottom waters, lobstering, expansion into undersampled areas in Eastern GoM and deep water.	Temperature, conductivity, dissolved oxygen	Potentially with SLR
Marine	Expand initiatives to measure water quality. Community initiatives such as the Maine Coastal Observing Alliance and existing governmental and municipal water quality monitoring programs to determine if warming coastal waters are more susceptible to nutrient loading, eutrophication, harmful algal blooms, bacteria runoff, and other water quality perturbations.	Total nitrogen, E. coli, HABs	Ongoing	Shellfish harvesting and aquaculture locations		
SLR/Storm	Develop technical guidance that supports waterfront decision-makers and property owners in using tide predictions, coastal flood forecasts, extreme water scenarios, and sea level rise projections to inform adaptive short and long-term management.	Guidance documents, checklists, etc.	urgent post-storm recovery, but also short and long-term	working waterfronts but also along entire coast	guidance documents	
SLR/Storm	Continue to expand Maine's network of water level sensors to support flood forecasting of local thresholds and establishment of local tidal datums that inform coastal planning and ecological restoration.	installation of local monitoring gauges, determination of local thresholds	ongoing	coast	monitoring and data analysis	
SLR/Storm	Complete erosion hazard modeling that accounts for future SLR along Maine's varied coastline (e.g., bluff, dune, wetland)	modeling that follows protocol established by FEMA contractors in Region 1		coast	research and data analysis	
SLR/Storm	Conduct investigations on increasing frequency and/or intensity of southeast storm events and the ongoing sea level rise anomaly impacting Maine		ongoing	coast	research and data analysis	Yes
SLR/Storm	Continue to establish high water marks throughout the State, especially post-storm 2024		urgent short term	coast	monitoring	
SLR/Storm	Establish a statewide network of wells to monitor for saltwater intrusion		ongoing	coast	monitoring	Yes
SLR/Storm	Incorporate updated tidal datums to account for SLR since last datum		2026	coast		

SLR/Storm	Continue to acquire high-quality topobathy LIDAR data		ongoing	coast	monitoring	
SLR/Storm	Continue monitoring coastal erosion and update bluff maps		ongoing and short term	coast	monitoring	
SLR/Storm	Further investigate SLR impacts on marshes and intertidal habitats including mudflats, including sedimentation rates and sediment flux	modeling needed along with ongoing monitoring	ongoing	coast	monitoring and modeling	Yes
SLR/Storm	Develop a plan for sharing results and educating the public and practitioners on the Maine Flood Risk Model		post-model completion	coast	education and outreach	Yes

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