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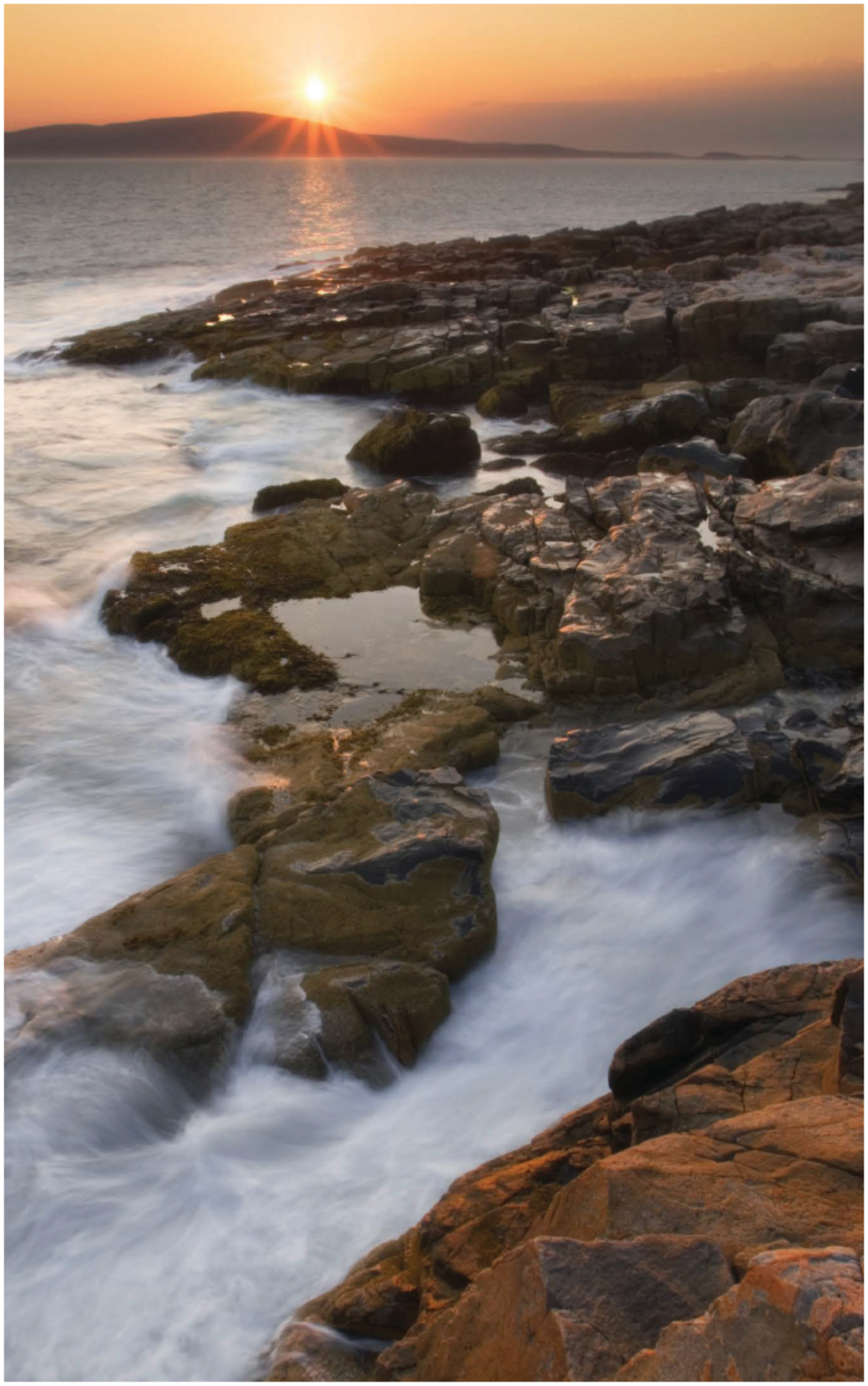
COASTAL MAINE CLIMATE FUTURES



CLIMATE CHANGE INSTITUTE

1865 THE UNIVERSITY OF MAINE

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Executive Summary

- This report examines historical climate trends, explores impacts on select commodities, and identifies large-scale climate connections to coastal Maine in order to develop plausible future climate scenarios for local planning over the next 20 years.

- The coastal region, like elsewhere in Maine, is adjusting to rising atmospheric temperatures, more intense rain events, a longer growing season, and increasing temperature extremes.

- Agricultural production in coastal areas, using the example of blueberries, is strongly correlated to summer sea surface temperature (SST) in the Gulf of Maine, and summer atmospheric pressure across the eastern U.S. Blueberry yield increases with increasing SST (more warm, moist onshore flow) and decreasing atmospheric pressure (more rainfall).

- The amount of summer precipitation across coastal Maine and statewide is linked strongly to large-scale atmospheric patterns spanning the Arctic and North Atlantic. Maine summers are wettest when high pressure anomalies develop across Greenland and the Arctic Basin in conjunction with low pressure anomalies across the eastern U.S. An unusually wet interval from 2005–2014 is attributed in part to this teleconnection.

- Maine fisheries are impacted by changes in the Gulf of Maine, where surface waters have warmed considerably since the 1990s. Future prediction is complicated by decade-scale variability linked to the broader North Atlantic. A correlation between lobster landings and SST suggests that warming is beneficial to the species, at least below some maximum temperature threshold.

- Maine's coastal climate is strongly influenced by a number of factors that will determine future short and long-term changes in climate, notably: El Niño/Southern Oscillation (ENSO), volcanic eruptions, and warming in the Arctic. ENSO is a particularly important feature, whereby El Niño brings warm/dry and La Niña brings cool/wet conditions to Maine.

- Five plausible future climate scenarios are developed to facilitate planning for the 2020–2040 timeframe, including: 1) The "New Normal" Currently Experienced with No Additional Change, 2) Moderate Warming, 3) Another Abrupt Arctic Warming and Even Greater Arctic Sea Ice Collapse, 4) Cooling from Increased Volcanic Activity, and 5) Drying from More Frequent and Extreme El Niño Events.

- In conclusion, Maine should expect significant environmental changes as human and other factors create increased instability in the climate system. The best approach in adapting to uncertainty is to consider a variety of plausible outcomes in all planning capacities.

Introduction

Climate and weather exert a critical influence on the health of Maine's people, ecosystems and economy. Across coastal communities, where fishing, forestry, tourism, and agriculture serve as the economic backbone, the changing climate poses near and long-term challenges. These challenges include warming ocean temperatures, a longer growing season and shorter snow season, more frequent extreme precipitation events, drought, soil moisture deficits, storm surges, and rising sea level. Insights into possible changes in climate over the next 20 years – between now and 2040 – are offered in this report to help community, commerce, non-governmental, and government planning efforts.

Why Coastal Maine Climate Futures? Most climate predictions project many decades out and rely on output from computer models, such as those utilized by the Intergovernmental Panel on Climate Change (IPCC) **(Ref. 1)**. Although predictive climate models are extremely useful for simulating long-term trends under different industrial emission scenarios, they do not necessarily resolve regional variability sufficiently to make reliable predictions only a few years out. Coastal Maine Climate Futures builds upon previous reports released by the Climate Change Institute at the University of Maine **(Refs. 2, 3)** and examines the local historical climate record for trends and associations, while also identifying climate-commodity relationships. These insights are then translated into a series of plausible future climate scenarios that provide guidance for planning at annual and longer time scales. Insights include the potential for unexpected changes in climate that could result from, for example, a major volcanic event, or widespread loss of summer sea ice over the Arctic.

In conjunction with Coastal Maine Climate Futures, the Climate Change Institute (CCI) has developed online data tools for plotting maps and time series of temperature and precipitation data for coastal, central, and northern Maine climate divisions from 1895 to present. This and other information is available through CCI's Maine Climate Office (https://mco.umaine.edu) and CCI's website (https://climatechange.umaine.edu). Further access to a variety of climate and weather data at local, national, and global scales is also available through CCI's Climate Reanalyzer (https://ClimateReanalyzer.org). By utilizing these resources, this document serves in part as a template for how Maine stakeholders can, for themselves, explore climate data to better understand the past, and to glean insights into what will likely characterize Maine's climate in the future.

Coastal Climate

Observations of daily temperature and precipitation in coastal Maine and elsewhere in the state are available from individual station records and from monthly gridded data products. The latter provide reliable, continuous measurements from January 1895 to present. Over this period, average annual temperature across coastal Maine has increased ~3°F while total annual precipitation has increased ~6 inches **(Fig. 1)**. Both temperature and precipitation show considerable variability with time. In particular, the temperature record is marked by significant decade-scale changes between relatively cool (late 1800s–1920s and 1960s–1990s) and warm (1930s–1950s and late 1990s–present) conditions.

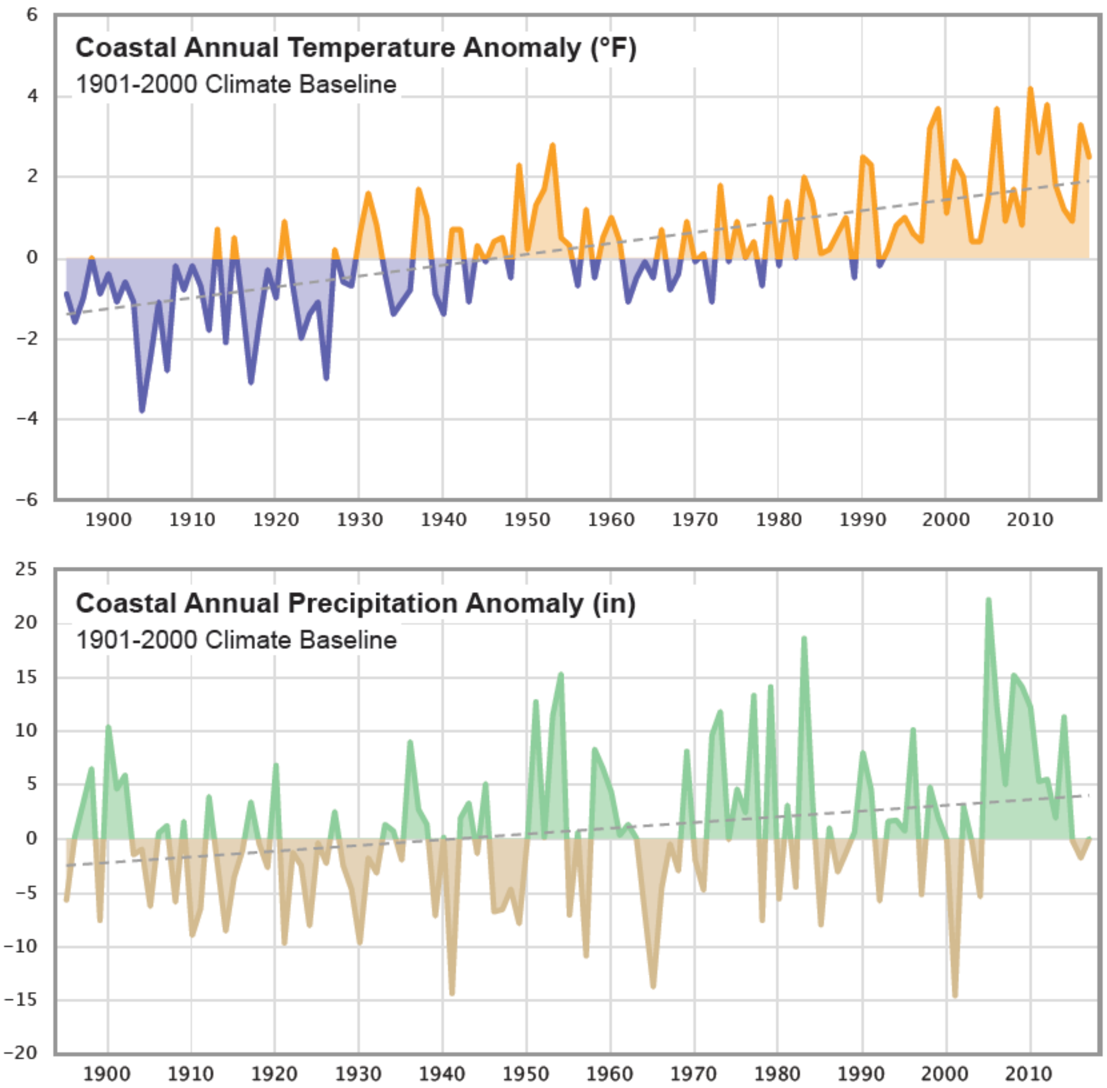

Figure 1. Maine coastal climate division annual temperature and precipitation 1895–2017. Dashed gray lines show long-term linear trends. Data from the NOAA U.S. Climate Divisional Dataset (https://www.ncdc noaa.gov/cag/).

Agricultural Impacts and Associations

Maine's commercial coastal agriculture, which is predominantly blueberry, apple, and cranberry, can be impacted in both positive and negative ways by the changing climate. For instance, since ~2000 the growing season has increased by about two weeks in comparison to the 20th century average **(Fig. 2)**. August and September have also warmed 2–3°F. Potential benefits from this longer growing season, however, are balanced by a number of negative impacts of the changing weather, including the northward migration of pests, extreme rainfall events **(Fig. 3)** that can damage newly planted seeds and cause erosion, sedimentation in associated surface waters from the accelerated soil loss, as well as more frequent "blocking" patterns in the atmosphere that increase the likelihood of heat waves and seasonal drought **(Fig. 4)**. Moreover, in recent years there has been greater temperature variability in late winter/early spring that can cause early crop development before the last freeze. This affected apple and other crops in 2012 and 2016 **(Ref. 4)**.

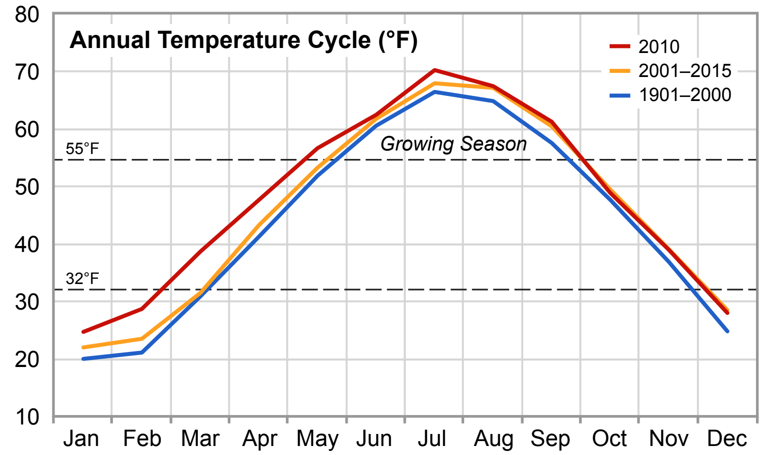

Figure 2. Maine coastal climate division annual temperature cycle for the periods 1901-2000 (blue) and 2001-2015 (orange), and for the record warm year 2010 (red). Dashed horizontal lines delineate 32°F and 55°F, where the latter can be used to estimate the growing season length. Data from the NOAA U.S. Climate Divisional Dataset (https://www.ncdc.noaa.gov/cag/).

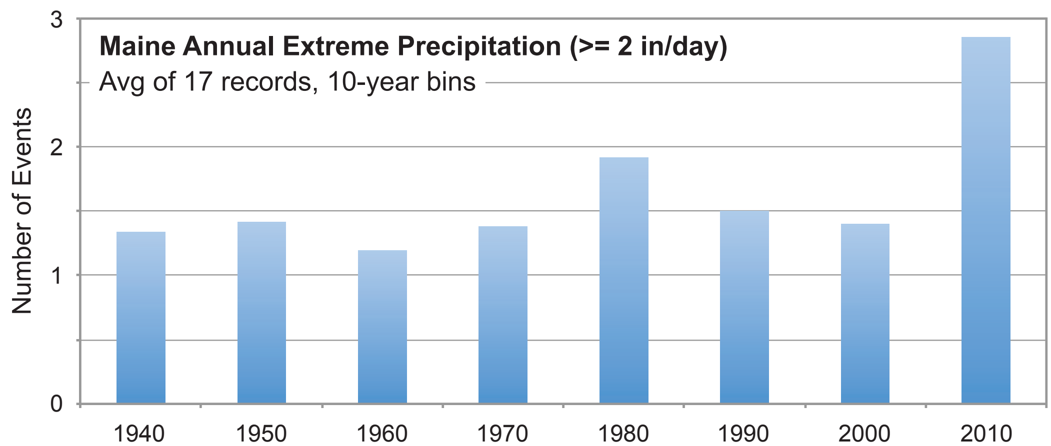

Figure 3. Mean annual incidence of extreme precipitation events for a 2 in/day threshold calculated from 17 long-term observation sites across Maine. Values are in 10-year average bins. The record sites are: Acadia N.P., Belfast, Bangor, Bar Harbor, Brassua Dam, Bridgton, Caribou, Farmington, Gardiner, Lewiston, Machias, Millinocket, Newcastle, Presque Isle, Portland, Rangeley, and Rumford. Data from the NOAA Global Historical Climatology Network (https://www.ncdc noaa.gov/ghcn-daily-description).

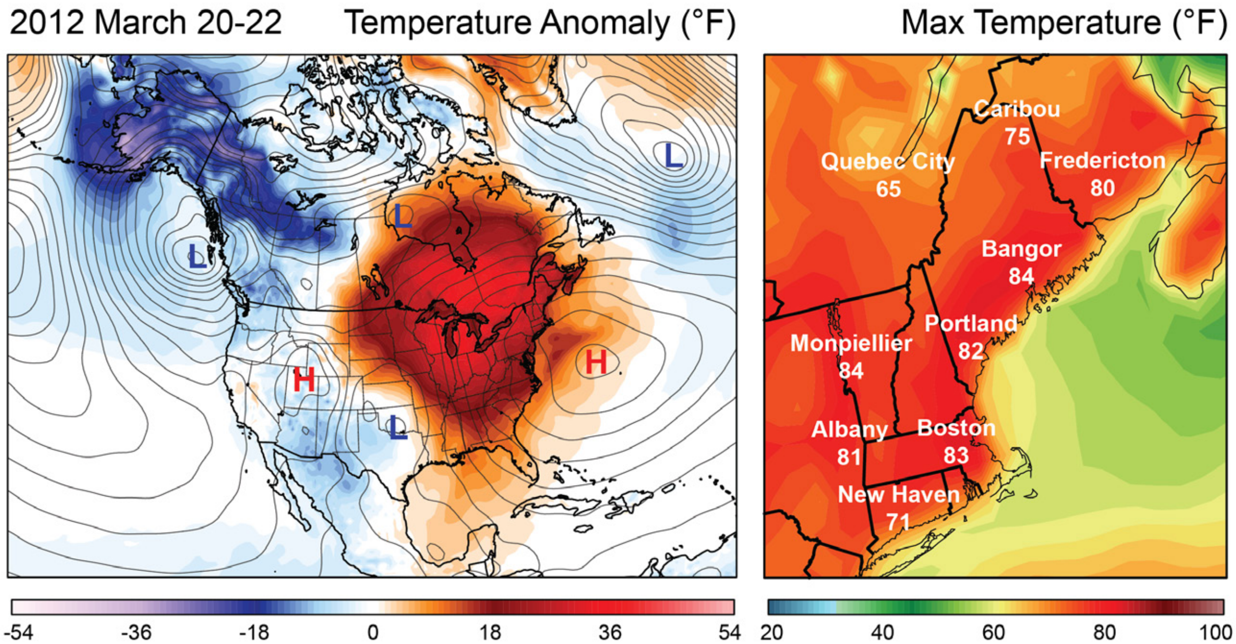

Figure 4. A record heatwave developed over eastern North America in March 2012 associated with a subtropical high pressure system that stalled for several days. Across New England, the event culminated between March 21 and 22 with temperatures climbing into the low to mid 80s. Historical daily high temperature records were beaten by as much as 15°F in some places. The maps above show temperature anomaly (departure from 1979–2000 climatology) and maximum temperature attained during the event. The large-scale blocking pattern associated with this heat wave also brought unseasonable cold to Alaska and the Pacific Northwest. Data from NCEP CFS[3].

Data time series and correlation analyses are useful for establishing possible links between commodity yields[1] and changes in regional or large-scale climate patterns. For example, we analyzed annual blueberry yield data from the University of Maine Cooperative Extension[2] and found significant positive correlation to summer sea surface temperature (SST) in the Gulf of Maine, and negative correlation to mean sea level pressure (MSLP) over the eastern U.S. **(Fig. 5)**. The SST correlation could reflect increased onshore flow of warm, moist air that could be beneficial to blueberry growth. MSLP is associated with rainfall, such that summers with lower-than-usual MSLP tend to be wetter. In all, the correlation analysis suggests that blueberry yield is higher when summer conditions favor warm, moist air flow and more rainfall than usual.

1. Agricultural commodity data are available from the USDA Economics, Statistics and Market Information System: http://usda mannlib.cornell.edu/MannUsda/homepage.do
2. University of Maine Cooperative Extension, Wild Blueberry Crop Statistics: https://extension.umaine.edu/blueberries/factsheets/statistics-2/statistics/
3. NCEP Climate Forecast System: http://cfs ncep noaa.gov/

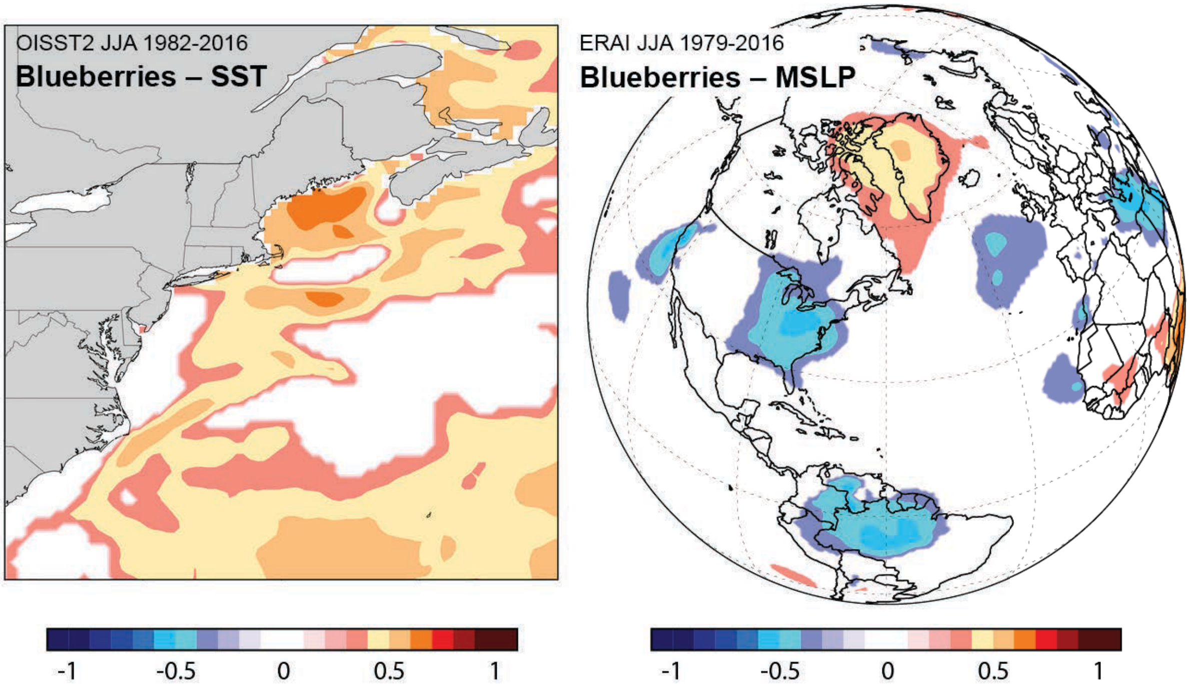

Figure 5. Maps showing linear correlation values for Maine annual blueberry yield compared against summer (June-August) sea surface temperature (SST) (left panel) and mean sea level pressure (MSLP) (right panel). Positive values (warm tones) indicate that the commodity increases/declines with correlated variable, whereas negative values (cool tones) indicate the opposite. SST data from NOAA OISST[1] and atmospheric data from ECMWF ERA-Interim Reanalysis[2].

The Blueberry-MSLP correlation map in **Fig. 5** is particularly interesting, because the pattern, with distinct nodes over Greenland, the eastern U.S., and Brazil, can be linked to variability across the North Atlantic. By better understanding this large-scale teleconnection it may be possible to improve future summer rainfall predictions for our region. This is discussed further in the "Climate Connections" section on page 13.

We caution that correlation does not necessarily equal causation, and that many other factors should be considered that change over time (e.g., tillage practices, irrigation, fertilization regimes, and pests). However, commodity measures such as production and area yield are influenced by weather, and the implications of a changing climate are extremely important to consider.

1. NOAA Optimum Interpolated SST: https://www ncdc noaa.gov/oisst
2. ECMWF ERA-Interim Reanalysis: https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim

Gulf of Maine Climate

The historical record of sea surface temperature (SST) across the Gulf of Maine is available from gridded data products that assimilate ship, buoy, and satellite measurements. Much like the inland temperature record, the Gulf of Maine SST record shows an overall warming trend (~3°F since 1895) marked with considerable decade-scale variability with periods of relatively cool (late 1800s–1920s and 1960s–1990s) and warm (1930s–1950s and late 1990s–present) conditions **(Fig. 6)**. The recent warm interval in the Gulf of Maine began ca. 1999, followed by a minor respite 2003–2004. By 2012, and then again in 2016, SSTs reached about 1°F warmer than a previous warm peak in 1951. In addition, local sea level, as measured at Portland, has risen by ~7 inches since 1912.

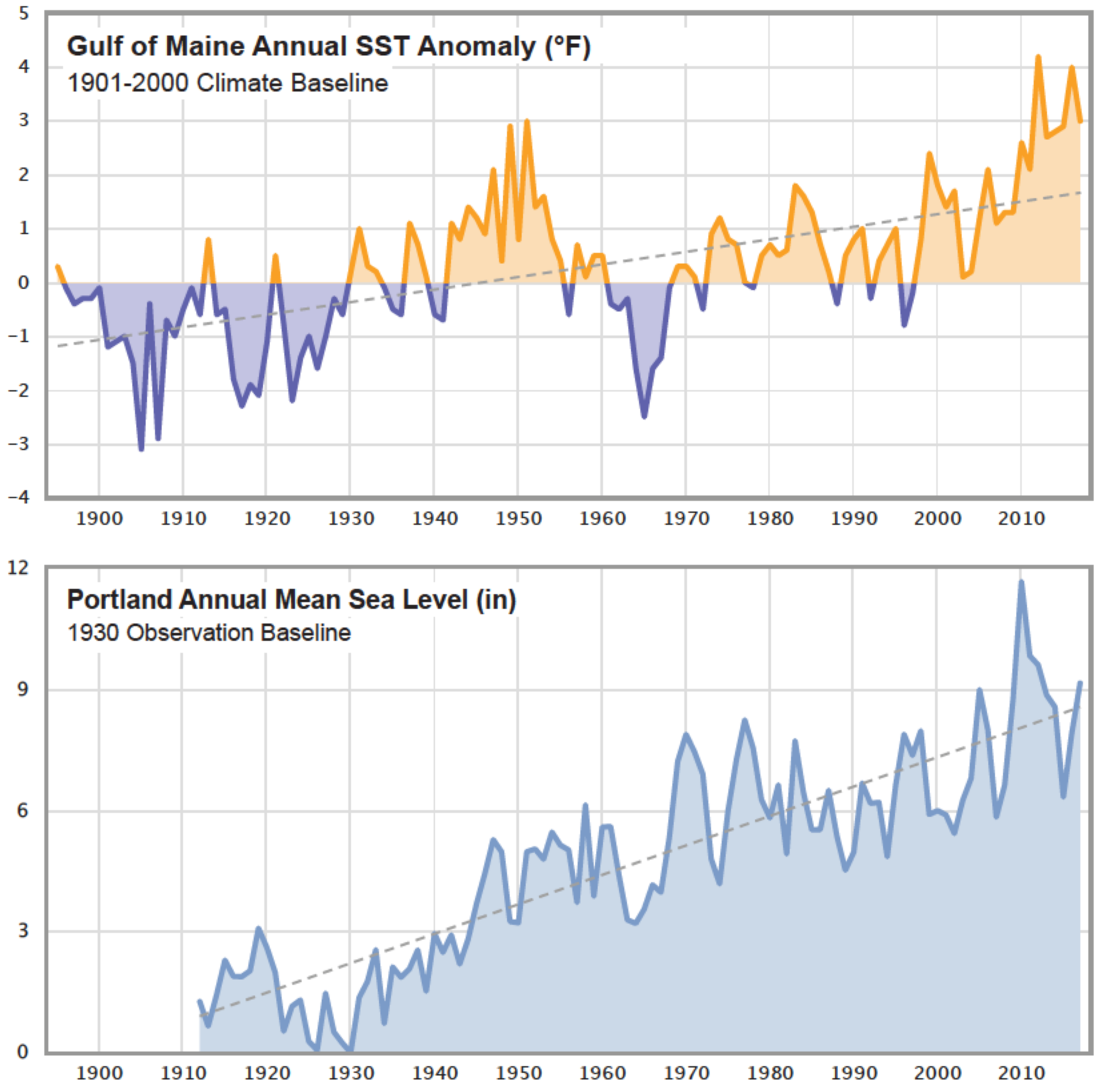

Figure 6. Gulf of Maine annual SST 1895–2017 and Portland, ME sea level 1912–2017. Dashed gray lines show long-term linear trends. Data from NOAA ERSST[1] and PSMSL[2].

Fisheries Impacts and Associations

The Gulf of Maine is a biologically productive marginal ocean resulting from the interplay between cool freshwater inputs (i.e., rivers and the Labrador Current) and warm salty water from the Gulf Stream **(Ref. 5)**. Fishery commodities in the Gulf of Maine, including lobster and cod, have undergone dramatic changes in association with climate and other factors since the 1980s **(Figs. 7, 8)**. The cod fishery collapsed primarily due to overfishing. Subsequent recovery efforts, however, failed to rebuild the population, as waters warmed above the temperature range in which cod is tolerant **(Ref. 6)**. Lobster abundance in Maine has meanwhile increased four-fold since the late 1980s due to both the decline of cod (predators of juvenile lobsters) and warming waters that are favorable to the species at least to a threshold. As found during summer in coastal waters off southern New England, lobster mortality increases significantly if SSTs exceed ~68°F **(Ref. 7)**.

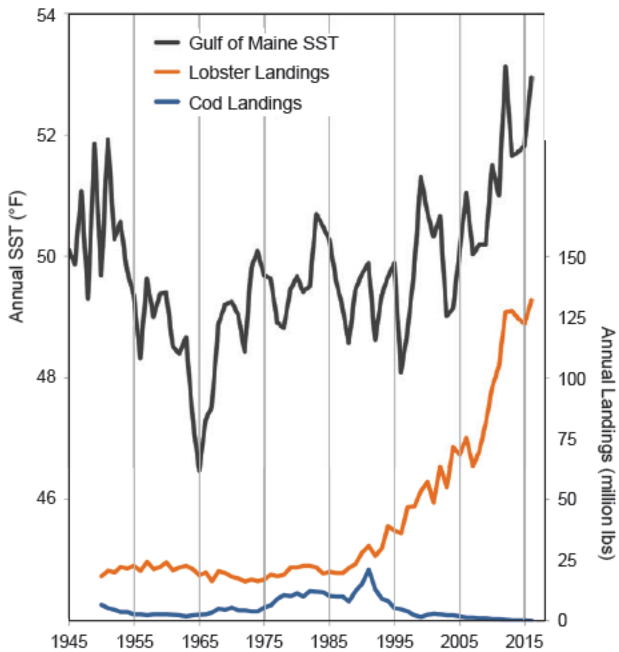

Figure 7. Comparison of annual SST for the Gulf of Maine and landings of cod and lobster 1945–2016. Data from NOAA ERSST[1] and the Maine Dept. of Marine Resources[3]. Note the longer time series used here than in a recent study on warming in the Gulf of Maine **(Ref. 6)**.

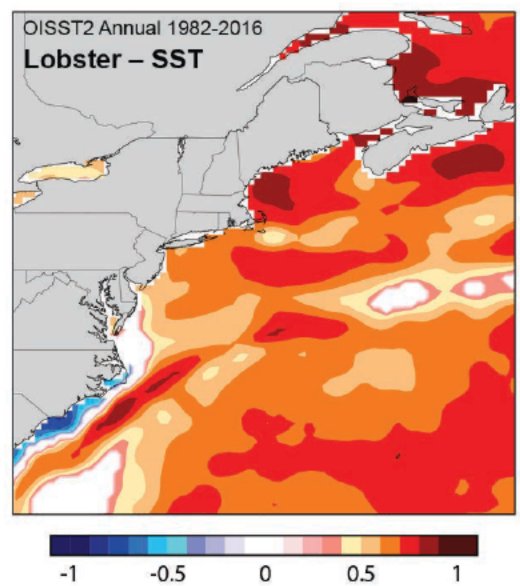

Figure 8. Map showing linear correlation values between annual lobster landings and SST. The strong positive correlations support a linkage between expanding lobster populations over recent decades and warming ocean waters. Data from NOAA OISST and the Maine Dept. of Marine Resources[3].

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1. NOAA Extended Reconstructed SST: https://www ncdc noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v5
2. Permanent Service for Mean Sea Level: http://www.psmsl.org/
3. Maine Department of Marine Resources landings: https://www maine.gov/dmr/commercial-fishing/landings/index html

Although it has been reported that the Gulf of Maine has warmed faster than most of the world's oceans in recent decades **(Ref. 6)**, the future predictability of temperature in the Gulf of Maine is complicated by multiple dynamical interactions that involve the Gulf Stream, Labrador Current, and the atmosphere. It is notable that a previous warm interval occurred in the region during the 1940s and 1950s, followed by a cooling in the 1960s, and then moderate conditions for the next two decades. The current record warming began in earnest in the late 1990s in conjunction with greater influx of Gulf Stream waters both near the surface and at depth **(Ref. 5)**. The Gulf Stream is a wind-driven current that can change strength in relation to shifts in large-scale wind patterns that develop across the North Atlantic. Recent intensification of the Gulf Stream and warming of the Gulf of Maine coincides with both a warming of the broader North Atlantic Ocean, and also a strengthening of south-westerly winds along the eastern seaboard **(Fig. 9)**. It is conceivable that a weakening of these winds, such as through natural variability expressed in the historical record, could lead to the propagation of cool or moderate conditions during some years, but superimposed on a continuing warming trend driven by global changes.

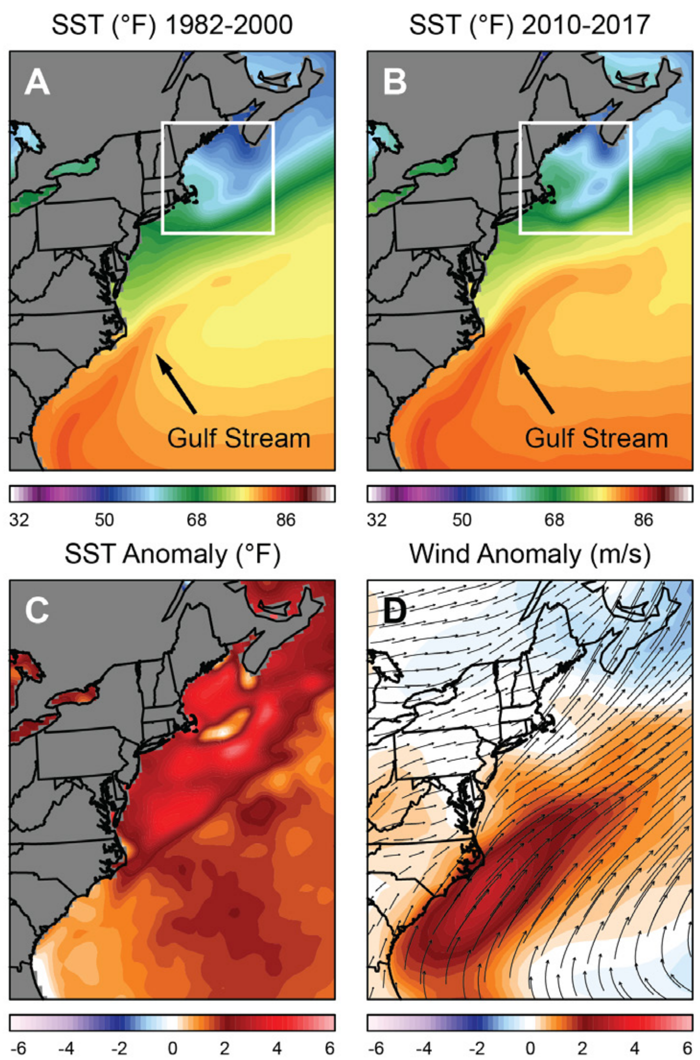


Figure 9. Maps showing (A, B) mean summer (June-August) SST for the periods 1982–2000 and 2010–2017, (C) the SST increase between those periods, and (D) the associated increase in near-surface wind speed. The Gulf Stream is labeled, and a white box is placed around the Gulf of Maine to help the reader distinguish differences between A and B. Data from NOAA OISST and ECMWF ERA-Interim Reanalysis.

Climate Connections

El Niño/Southern Oscillation

The exchange of heat and moisture across the equatorial Pacific Ocean varies in a phenomenon known as the El Niño/Southern Oscillation (ENSO). ENSO plays an important role in modulating global climate on a time scale of 3–5 years. ENSO phases are commonly identified from indices representing temporal changes in equatorial sea surface temperature. El Niño, the warm phase of ENSO, is known for temporarily raising global temperature (such as recently in 2016), bringing rains to California, and causing unusual or "wild" weather elsewhere across the globe due to increased moisture in the atmosphere and associated changes in large-scale atmospheric circulation. La Niña brings the opposite – cooler temperatures and generally less storminess. ENSO tends to have the greatest effect on global weather patterns during the Northern Hemisphere winter, but impacts can extend several months or longer depending on the the timing and intensity of the event.

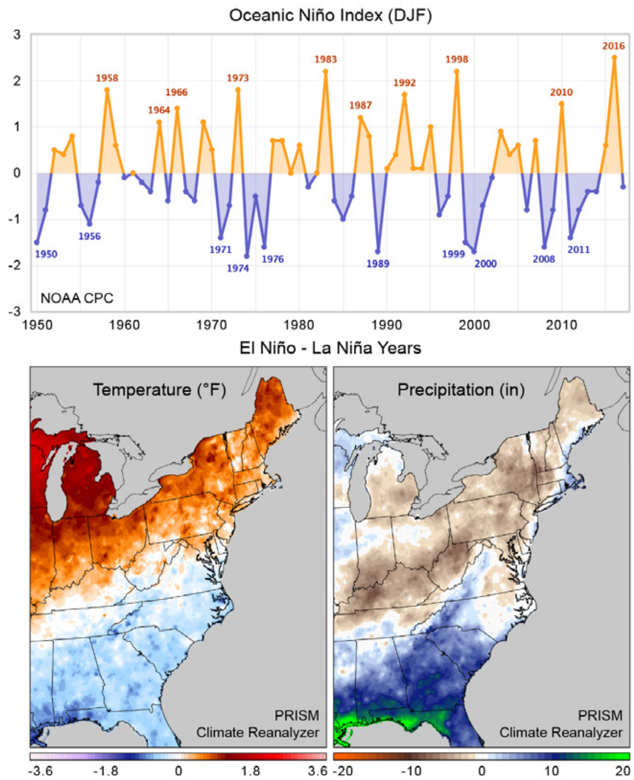


Figure 10. The Oceanic Niño Index (ONI) (top), and temperature and precipitation maps (bottom) showing the difference between the 10 strongest El Niño and La Niña years. The winter (December-February) ONI is a common measure of ENSO. Data from NOAA (http://cpc.ncep.noaa.gov/) and PRISM (http://prism.oregonstate.edu/).

How does ENSO affect Maine? One way to answer this question is to compare temperature and precipitation anomalies found on average for the ten strongest El Niño and La Niña years **(Fig. 10)**. In doing this exercise, we find that that Maine tends to be ~1°F warmer and ~10% drier on average statewide during El Niño, and cooler and wetter during La Niña. While the temperature response to ENSO is consistent across the entire state, the precipitation tendency is different for coastal Maine, where near-normal or wetter conditions are expected during El Niño, and drier conditions are expected during La Niña. This pattern develops in response to changes in the jetstream, where during some El Niño years, the Maine coast will tend to be at the northern edge of a southward-shifted storm track.

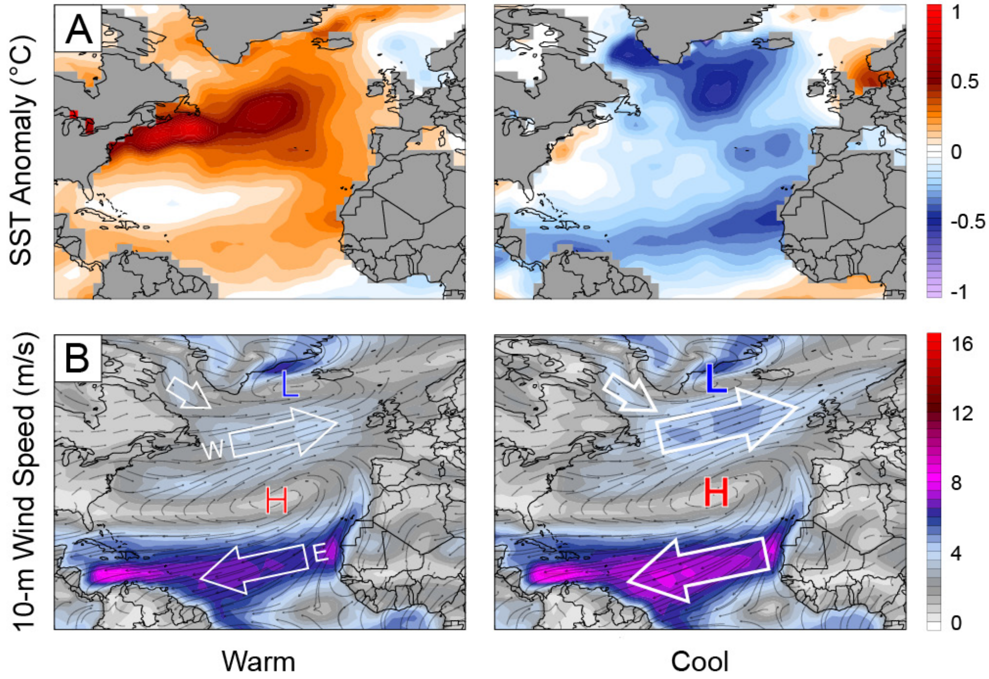
The most recent El Niño – the strongest on record – developed in late 2015 and persisted through early 2016. The 2015–16 winter was the warmest on record statewide, and the 2016 summer saw the first significant drought in a decade – likely in connection with El Niño.

Volcanic Activity

Major volcanic eruptions that inject material into the lower stratosphere are capable of cooling climate for several years on a regional, hemispheric, or global scale. Cooling develops directly from the formation of aerosol clouds that act like a veil to reduce the sunlight reaching the earth surface, and indirectly from secondary effects linked to changes in atmospheric circulation and ocean response.

The 1991 eruption of Mt. Pinatubo. Photo courtesy of the USGS.

In the Northern Hemisphere, volcanic eruptions tend to strengthen the winds across the subpolar and tropical North Atlantic Ocean **(Fig. 11) (Ref. 8)**. Increased wind speeds in turn drive an oceanic response, whereby sea surface temperatures (SSTs) decline from evaporative cooling, shoaling, advection, and other processes.



Figures 11. Comparison of mean annual (A) SST anomaly and (B) wind speeds for warm (1951–1960) (left panels) and cool (1971–1976) (right panels) intervals across the North Atlantic. Strong westerly and easterly winds are associated with cool SST anomalies, whereas weak circulation relates to the opposite. The labels "H" and "L" represent the Azores High and Icelandic Low pressure centers, respectively. SST anomalies are made against a 1951–1980 climate baseline. Data from NOAA ERSST and NCEP/NCAR Reanalysis[1]. Modified from Birkel et al., 2018 **(Ref. 8)**.

A comparison of stratospheric aerosol and North Atlantic SST measurements over the past century reveals cool conditions during two distinct intervals of frequent volcanic activity, namely 1880s–1920s and 1960s–1990s **(Fig. 12)**. Conversely, the 1930s–1950s and 2000s onward are non-volcanic intervals marked by warmer-than-normal conditions. The last major eruption was that of Mt. Pinatubo in 1991, which impacted global climate for ~5 years. In Maine, the effects of the Mt. Pinatubo eruption can be linked to three years of cooler (~2°F) and drier (~10%) weather compared to normal, with the greatest impacts felt in 1992 **(Fig. 13)**.

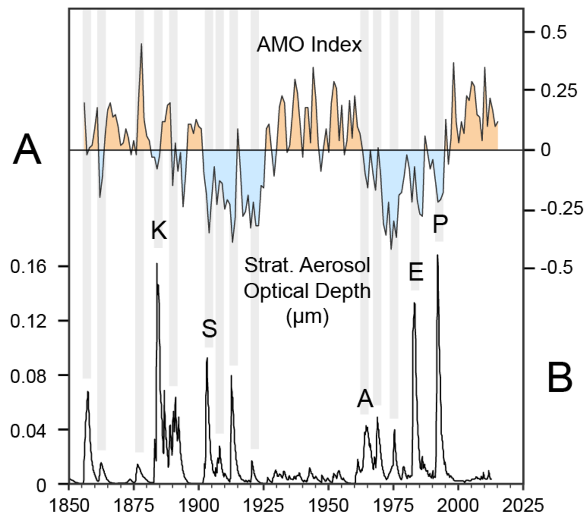


Figure 12. Time series comparison of (A) the Atlantic Multidecadal Oscillation (AMO) Index[2] and (B) stratospheric aerosol optical depths[3]. The AMO Index represents the detrended, normalized North Atlantic SST signal. Spikes in aerosol optical depths result from explosive volcanic activity. Well known volcanic events are labeled: K = 1883 Krakatau, S = 1902 Santa María, A = 1963 Agung, E = 1982 El Chichón, and P = 1991 Pinatubo. Modified from Birkel et al., 2018 **(Ref. 8)**.

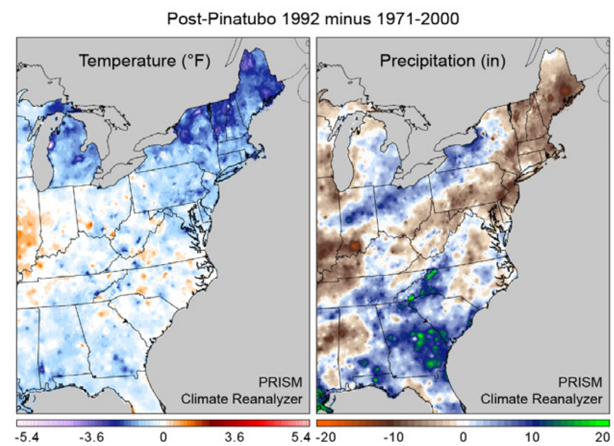


Figure 13. Maps showing the 1992 annual temperature (left) and precipitation (right) anomalies following the 1991 Mt. Pinatubo eruption. The anomalies are in reference to 1971–2000 climatology. Data from PRISM (http://prism.oregonstate.edu/).

It is important to emphasize that changes in annual temperature across Maine – and also across the surface of the Gulf of Maine – generally mimic temperature swings across the North Atlantic Ocean that are associated with intervals of volcanic activity as shown above. Thus, one plausible future climate scenario for the 2020–2040 timeframe is temporary cooling, if significant volcanic activity happens to emerge in the next few years.

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1. NCEP/NCAR Reanalysis: https://www.esrl noaa.gov/psd/data/gridded/data ncep.reanalysis html
2. AMO Index: https://www.esrl noaa.gov/psd/data/timeseries/AMO/
3. NASA GISS Stratospheric Aerosol Optical Depths: https://data.giss.nasa.gov/modelforce/strataer/

The Arctic and Maine's Climate

One of the most significant and widely reported aspects of recent changes in climate relate to the dramatic ~5°F mean annual warming that has taken place on average across the Arctic since about 1980. This warming has been accompanied by more than 50% reduction in the area of ocean covered by sea ice at the end of the summer melt season **(Fig. 14)**. Arctic warming and associated sea-ice loss is thought to underlie an observed rise in extreme weather events across the Northern Hemisphere **(Ref. 9)**, owing to changes in atmospheric patterns resulting from what is now a smaller difference in temperature between the equator and pole.

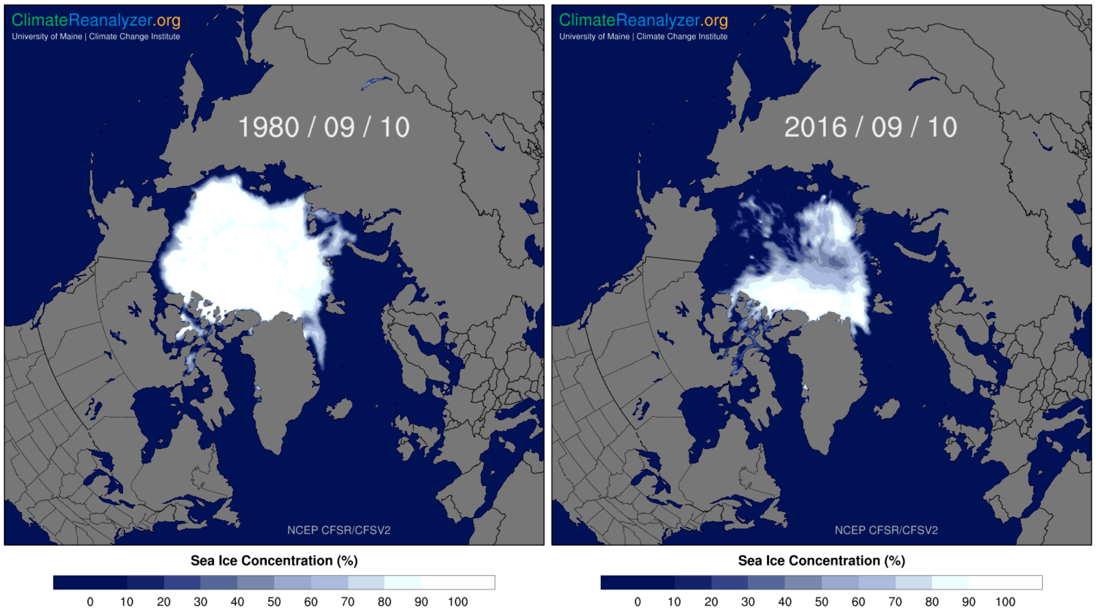

Figure 14. Comparison of sea ice extent at the end of the Arctic summer in 1980 and 2016. Satellite-derived ice concentration data from NCEP CFSR/CFSV2. Images from CCI Climate Reanalyzer (https://ClimateReanalyzer.org).

But how is Arctic warming impacting Maine? In order to answer this question it is useful to examine extremes within the climate record. We will focus on summer because of its relevance to agriculture and extreme rainfall events that occur primarily during the warm season. Arctic sea ice has been declining since at least the early 1980s, but the most significant declines have occurred since 2000, particularly after ~2005 **(Fig. 15A)**. With the eastern Arctic mean annual temperature having warmed as much as 8°F in less than 5 years, this climate shift is as dramatic as the abrupt change from ice-age to modern climate that took place 11,500 years ago **(Ref. 10)**. Maine's historical climate record also shows rapid warming since ~2000, especially in the overnight temperatures in summer and fall. The record furthermore shows a nearly 30% increase in summer precipitation during 2005–2014 compared to the 20th century mean. This same interval has also seen a rise in the number of extreme rainfall events as noted earlier **(Fig. 3)**.

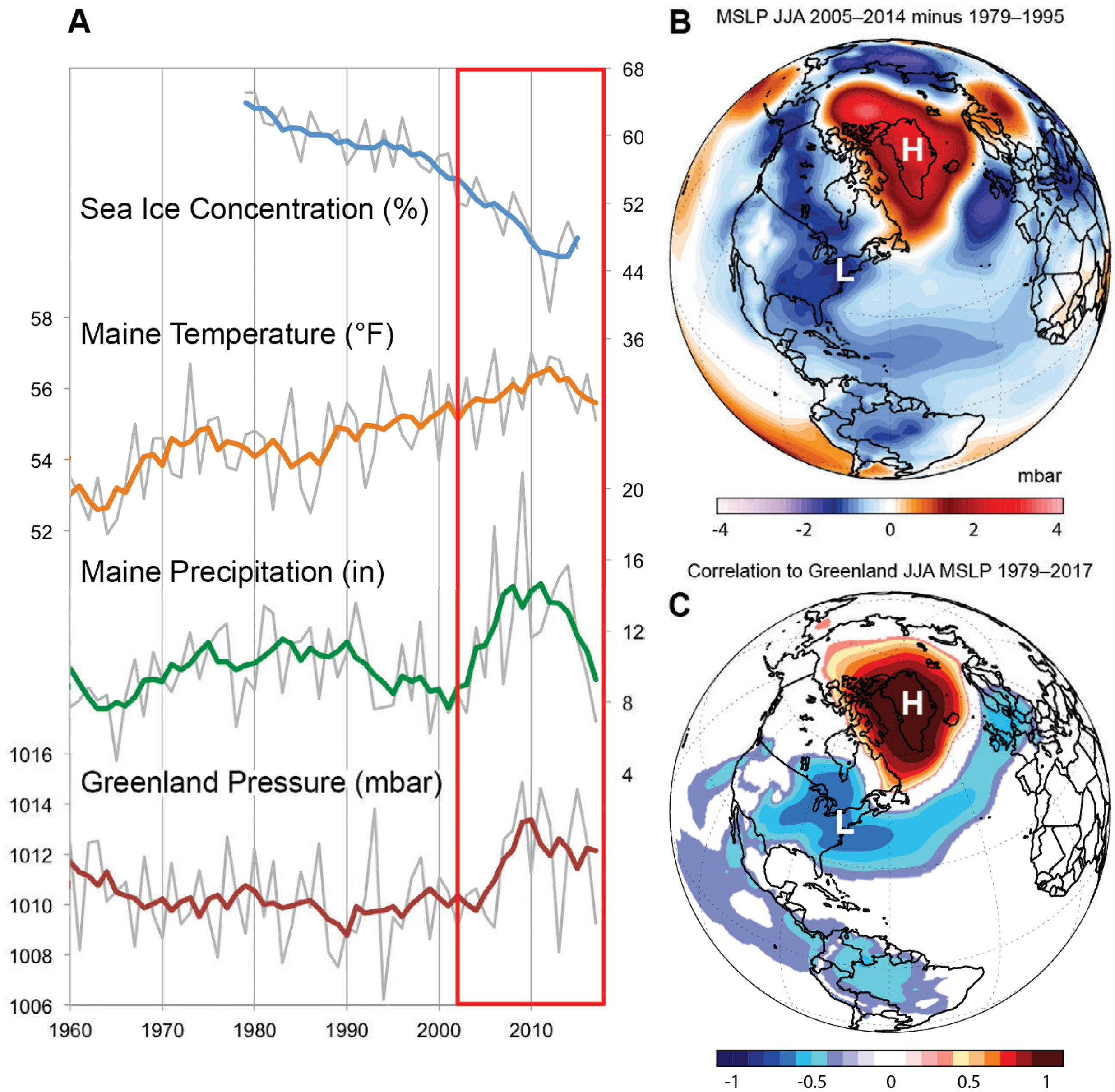

Figure 15. Connections between the Arctic and coastal Maine's summer (June-August) climate. (A) Timeseries stack of Arctic sea ice concentration, Maine costal climate division temperature and precipitation, and mean sea level pressure (MSLP) over the Greenland Ice Sheet. The red box highlights the interval of steep sea-ice decline, rising Maine temperature and precipitation, and increased high pressure over Greenland. (B) Map showing the difference in summer MSLP for 2005–2014 minus 1979–1995. This illustrates that the recent interval of extreme events has occurred in conjunction with anomalous high MSLP over the Arctic during summer. (C) Map showing linear correlation between Greenland summer MSLP timeseries and MSLP over North America. In both B and C the "H" and "L" mark high and low pressure centers, respectively. The low pressure over the eastern U.S. facilitates rainfall over Maine. Data from NCEP/NCAR Reanalysis and ECMWF ERA-Interim.

An Arctic connection to these climate signals in Maine can be discerned by using reanalysis to make a difference map of mean sea level pressure for the recent interval, 2005–2014, minus a long-term interval preceding the most severe changes in the Arctic. The resultant map shows a broad area of higher-than-normal pressure extending across Greenland and the Arctic Basin, flanked by areas of lower-than-normal pressure across North America, Europe, Asia, and the Amazon **(Fig. 15B)**. Mean sea level pressure, which refers to the weight of the atmosphere if air is at sea level, is an indicator of atmospheric motion and whether precipitation and clouds can develop. The map in **Fig. 15B** by itself suggests that major changes in atmospheric circulation have taken place between the intervals in question.

A further step can be taken to identify whether Maine's climate is linked to changes in the Arctic. Namely, the summer mean sea level pressure over Greenland can be correlated against pressure elsewhere across the globe **(Fig. 15C)**. This analysis reveals a strong negative correlation between pressure over Greenland and pressure over the eastern U.S. and Canada. The latter area of low pressure is associated with rainfall over Maine. Thus, when anomalous high pressure develops over Greenland, Maine should get wetter as pressure in our region would tend to decrease. Likewise, Maine should see drier weather for summers when the pressure dipole between Greenland and eastern North America is reversed. This same basic relationship is also found by comparing Maine annual blueberry yield to mean sea level pressure – two nodes of significant correlation, one over the eastern U.S. and the other over Greenland **(Fig. 5)**. This demonstrates the supposition that future changes in the Arctic, as they affect pressure over Greenland and the broader North Atlantic via blocking patterns, can propagate to Maine and affect our weather. Understanding this linkage better could help improve future predictability of summer precipitation across our region.

Plausible Future Climate Scenarios, 2020–2040

Complex non-linear interactions between natural and human-sourced forcings within the global climate system preclude a single answer to how Maine's weather and climate will evolve between now and 2040. Plausible future climate scenarios can therefore provide an important guide for sustainable commerce and environmental resource planning. The data analysis and climate insights developed in this report lend to five such plausible future climate scenarios for coastal Maine. These scenarios consider cases from the mundane – no change from the recent past – to significant "climate surprises" such as what might arise from abrupt sea-ice collapse and warming in the Arctic, increased major volcanic activity, and changes in the frequency of the El Niño/Southern Oscillation.

Scenario 1 — The "New Normal" Currently Experienced with No Additional Change

Although projections from nearly all global climate models predict continued warming from rising greenhouse gases, Scenario 1 assumes little to no increase in annual or seasonal temperature occurs over the coastal interior or Gulf of Maine compared to the post-2000s climate baseline. Precipitation varies year-to-year, but without a discernable trend over the next decade. Extreme events that have come to mark the past decade and a half – increased atmospheric blocking patterns that bring unusual cold waves, heat waves, and extreme rainfall events – effectively become the "new normal" during this period. Sea level increases another inch in accord with the century-long trend, as the Greenland Ice Sheet continues to shrink and seeks equilibrium with the modern climate.

Scenario 2 — Moderate Warming

This scenario follows the vast majority of global climate model predictions and assumes that coastal Maine warms about 1 °F over the next decade. Although that amount of warming may not seem like much, it is sufficient to increase the growing season length by about 1 additional week over the next 20 years from what has been experienced to date. The winter season would likewise shrink by the same amount. The uptick of extreme weather patterns observed in the late 2000s and the 2010s continues to increase in severity. The Arctic continues to warm, and summer sea-ice extent continues to decline short of complete collapse. Warming in the Gulf of Maine continues, as North Atlantic atmospheric patterns in the warm climate mode promote intensified influx of Gulf Stream waters.

Scenario 3 — Another Abrupt Arctic Warming and Even Greater Arctic Sea Ice Collapse

By 2012, sea ice at the end of the summer melt season had diminished across the Arctic Ocean to an extent initially projected by climate models for ca. 2040. Scenario 3 in turn assumes that all seasonal sea ice melts away in late summer by 2030 – two decades earlier than a 2050 timeframe predicted by models. The major collapse event is driven largely by continued carbon dioxide emissions in addition to release of methane (30x higher heat trapping potential than carbon dioxide) from melting permafrost. With the Arctic Ocean now ice-free from at least early August until late October, atmospheric patterns become drastically altered across the Northern Hemisphere every season of the year. Average temperature across coastal Maine warms 3°F or more, comparable to the warming observed over all of the 20th century. The growing season lengthens by two additional weeks, and winters diminish such that most storms bring rain, and any snow that does fall melts within a day. A much warmer Arctic means a reduced temperature gradient between the equator and pole; this in turn produces a slow-moving, highly embayed jet stream with more frequent extreme weather events, and more total annual precipitation than observed during the early 2010s.

Scenario 4 — Cooling from Increased Volcanic Activity

Major volcanic eruptions, such as the 1991 Mt. Pinatubo event, in isolation can cool climate for 1–3 years. If two or more major eruptions occur only years apart, then the climate impact can last a decade or longer. Scenario 4 assumes the latter – that two major volcanoes erupt and cause a cool decade. Atmospheric circulation strengthens across the North Atlantic, yielding several severe winters comparable to those of the 1990s where coastal Maine sees more snow than rain. The growing season shortens by 1–2 weeks, and there is a reduction in total rainfall. The Gulf of Maine temporarily cools to where conditions, again, are comparable to the 1990s. Although it is impossible to estimate when the next major volcanic event will occur, examination of past events such as Pinatubo provide excellent analogs for the expected climate response.

Scenario 5 — Drying from More Frequent and Extreme El Niño Events

After several years of cool surface waters dominating the equatorial Pacific from 2006–2014, the record 2015–16 El Niño marks a shift towards more frequent moderate to strong El Niños. As a consequence, warmer-than-normal conditions develop across Maine each season of the year, with the greatest impact seen in winter and spring. Precipitation is less straightforward: most of the state is drier on a mean annual basis, but coastal areas see near to above-normal rainfall due to a southward shift of storm tracks. Drought conditions become more common statewide in the fall. Coastal mainland communities are affected by reduced groundwater level and streamflow originating from the dry interior, despite the possibility of increased precipitation from storms passing across the Gulf of Maine. Coastal winters are reliably warm with more rain than snow.

Conclusions

This report examines modern climate in Maine, climate-commodity relationships, and sources of climate variability resulting in five plausible future climate scenarios for the coastal region for the period 2020–2040 to aid community, commerce, non-governmental, and government planning efforts. Future scenarios range from "no change" from recent climate extremes to major disruption from the collapse of Arctic sea ice, volcanic eruptions, and changes in the frequency of El Niño.

In a climate-commodity example of blueberries, strong correlations are found between blueberry yield and both summer sea-surface temperature (SST) across the Gulf of Maine, and summer atmospheric pressure across the eastern U.S. In turn, it is inferred that blueberry yield increases with more warm, moist onshore flow and increased rainfall. Summer precipitation across Maine is linked strongly to large-scale atmospheric patterns, where wet conditions are associated with high pressure anomalies over Greenland and the Arctic Basin, and low pressure anomalies across the eastern U.S.

General application of the plausible future climate scenarios to agriculture is simplified by considering changes in temperature (as associated with growing season length) and precipitation. Scenarios 1–3 ("no change", moderate warming, and collapse of Arctic sea ice) and 5 (more El Niños) envision warming temperatures that would result in a longer growing season, and therefore provide a benefit to agricultural production. Of these cases, Scenarios 1–3 also yield increases in precipitation, meaning an overall benefit to most agriculture. In contrast, Scenarios 4 (volcanic eruption) and 5 (more El Niños) see precipitation declines and likely drought. The volcanic scenario yields cooling and a shortened growing season. Thus, the latter two cases, Scenarios 4 and 5, afford overall detrimental conditions for agriculture.

Maine fisheries are impacted by changes in the Gulf of Maine, where surface waters have warmed considerably since the 1990s to temperatures exceeding that of a lesser warm interval in the 1950s. Barring any significant change in the flux of Gulf Stream water into the basin, such as driven by large-scale variability and redistribution of surface winds, the Gulf of Maine is likely to remain warmer than the historical average. However, one or more major volcanic eruptions, as outlined in Scenario 4, could lead to a cooling in the Gulf of Maine for a few years. The response of lobster and other fisheries to SST changes are complicated by population and harvest dynamics. However, the recent dramatic expansion of lobster facilitated by warm water could become reversed, as it has already in southern New England, if summer water temperatures begin to exceed ~68°F.

Underlying the plausible scenarios presented in this report is some predictability. It can be expected in the long term that the inexorable rise of greenhouse-gas concentrations from industrial activity will warm the oceans and atmosphere. However, superimposed on this warming trend are patterns of variability arising from natural processes operating over decadal and shorter timescales **(Fig. 16)**. For instance, major volcanic eruptions have impacts lasting 1–3 years or longer, leading to cooler and drier conditions than usual in Maine. Given the historical frequency of major eruptions **(Fig. 12)**, and that nearly 30 years have elapsed since the 1991 Pinatubo event, the likelihood of at least one major eruption in the next 20 years seems high. Events associated with the El Niño/Southern Oscillation (ENSO) occur more frequently, every 3–5 years. The warm phase of ENSO is El Niño, which tends to cause warming and drying statewide, especially in winter. Moderate El Niños develop about four times a decade, whereas the last three major El Niños (1982–83, 1997–98, and 2015–16) were each separated by ~15 years.

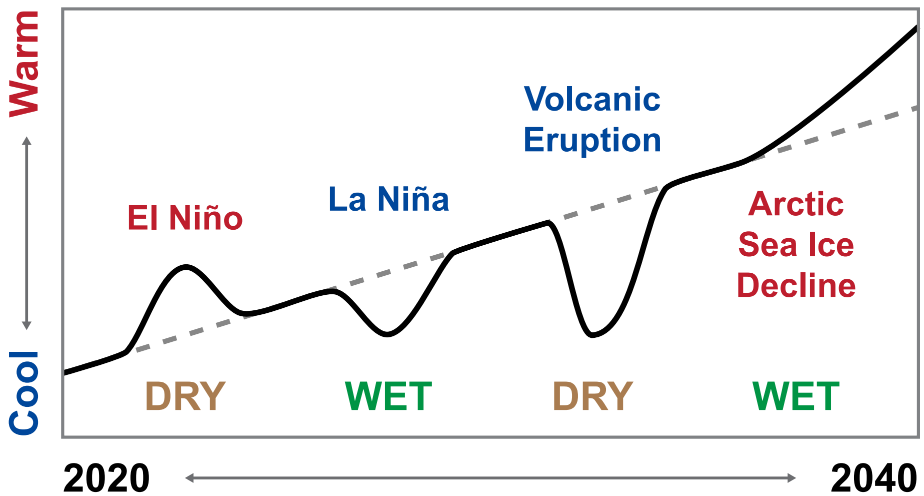

Figure 16. An idealized schematic diagram showing the relative temperature and precipitation impacts on Maine from El Niño, La Niña, volcanic eruptions, and Arctic sea ice decline. These features are superimposed on a generalized warming trend projected by models (dashed line). It is not possible to know with certainty how many, and at what magnitude these these events will occur decades out. That said, ENSO in particular is one of the best understood climate phenomena on the planet, and reasonable predictions of El Niño development can be made several months in advance.

In closing, the key message is that Maine should expect significant environmental changes as human and other factors create increased instability in the climate system. We suggest that the best approach to planning, adapting to and operating successfully within uncertainty is to be prepared for a variety of changes ranging from a general warming trend to occasional annual scale diversions to cooler and drier weather associated with volcanic and El Niño events, respectively.

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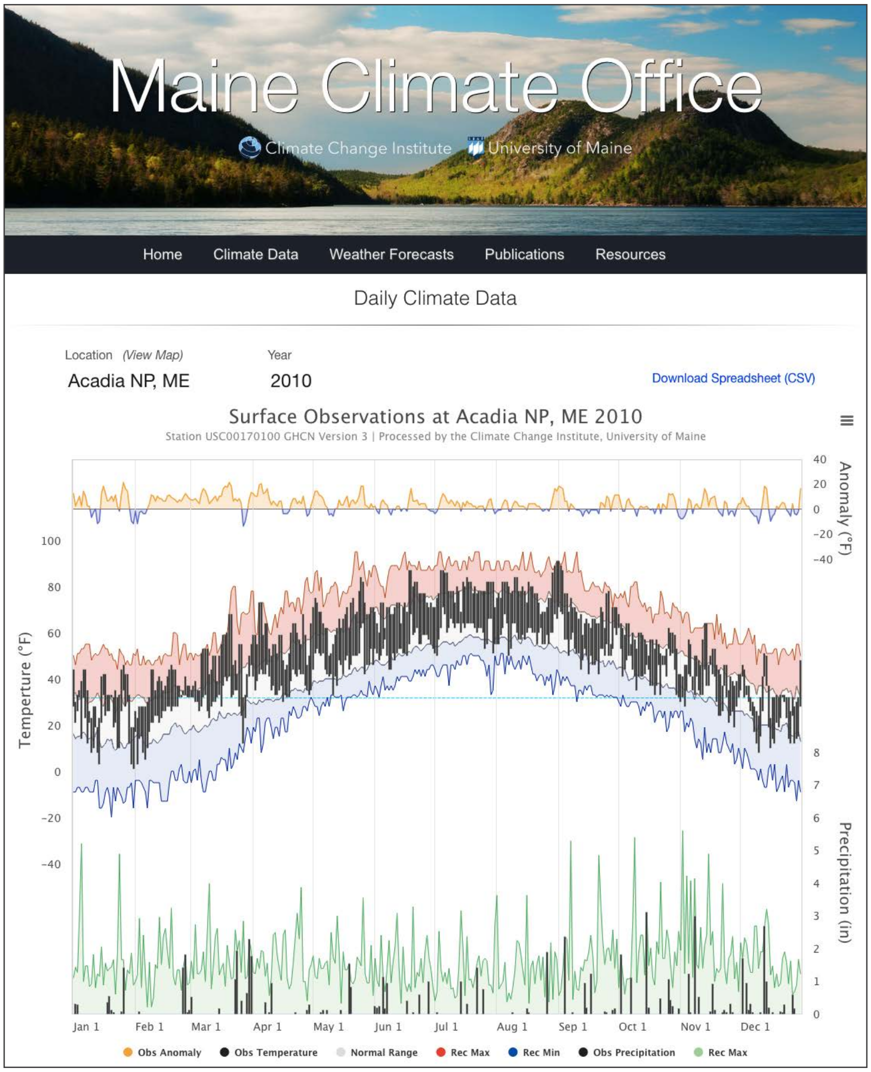
Coastal Maine Climate Futures is available in PDF from the Climate Change Institute (CCI) website at https://climatechange.umaine.edu. CCI also maintains the Climate Reanalyzer and Maine Climate Office websites for accessing and visualizing a variety of climate and weather data. See screen captures below and on the opposite page.



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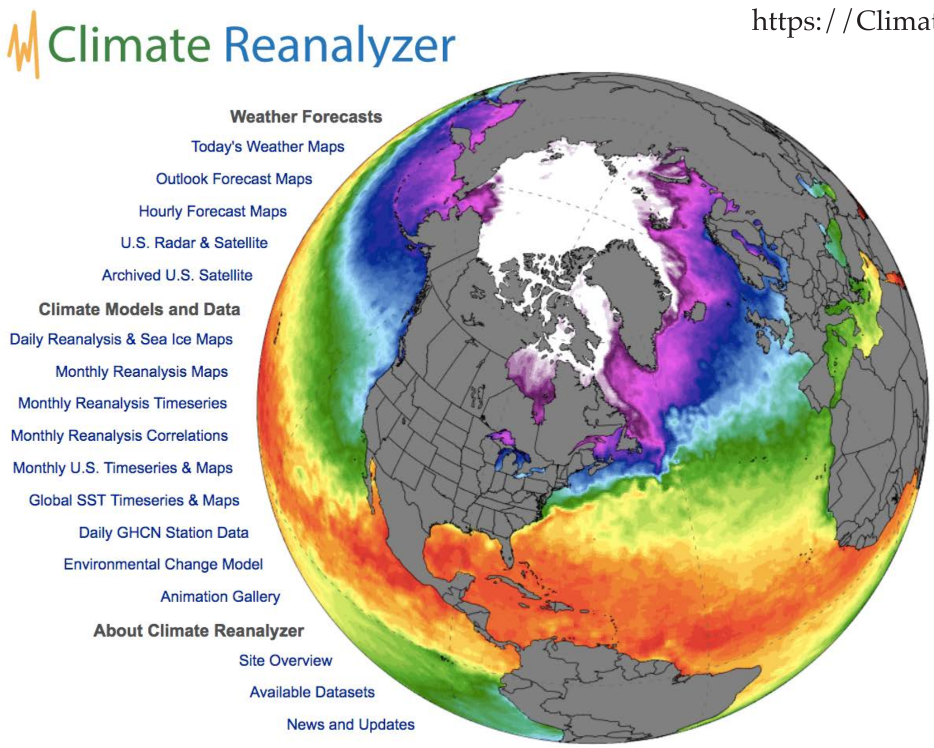

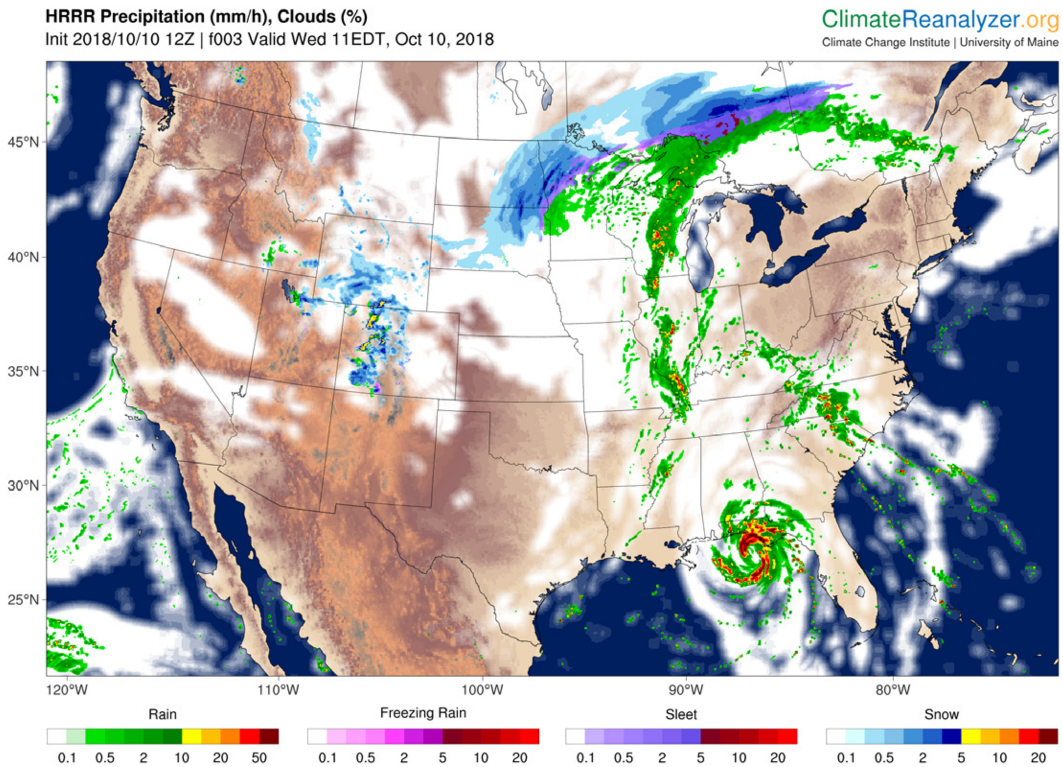

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