Temperature and Circulation Conditions in the Gulf of Maine in 2050 and their Expected Impacts

Andrew Pershing[1], Michael Alexander[2], Damian Brady[3], Dave Brickman[4] , Enrique Curchitser[5], Tony Diamond[6], Loren McClenachan[7], Katherine Mills[1], Owen Nichols[8], Dan Pendleton[9], Nicholas Record[10], Jamie Scott[11], Michelle Staudinger[12], Yanjun Wang[13]

1. Gulf of Maine Research Institute, Portland, ME USA
2. NOAA/Earth System Research Laboratory, Boulder, CO USA
3. Darling Marine Center, University of Maine, Walpole, ME 04573, USA
4. DFO/Bedford Institute of Oceanography, Dartmouth, NS, Canada
5. Rutgers University, New Brunswick, NJ USA
6. University of New Brunswick, Fredericton, NB Canada
7. Colby College, Waterville ME USA
8. Center for Coastal Studies Provincetown, MA USA
9. New England Aquarium, Boston, MA USA
10. Bigelow Laboratory for Ocean Sciences, East Boothbay Harbor, ME USA
11. University of Colorado, CIRES / NOAA Earth System Laboratory, Boulder, CO USA
12. DOI Northeast Climate Adaptation Science Center, Amherst MA USA
13. St. Andrews Biological Station, Fisheries and Oceans Canada, NB Canada

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Abstract: The Gulf of Maine has recently experienced its warmest five-year period in the instrumental record. This warming was associated with a decline in the signature subarctic zooplankton species, *Calanus finmarchicus.* The recent period also saw a decline in Atlantic herring recruitment and an increase in novel harmful algal species, although these have not been attributed to the recent warming. The temperature changes have also led to impacts on commercial species such as Atlantic cod and American lobster and protected species including Atlantic puffins and northern right whales. An ensemble of numerical ocean models were used to downscale global climate projections to estimate temperature, salinity, and ocean circulation in 2050. Under business as usual carbon emissions, the average temperature in the Gulf of Maine is expected to increase 1.1°C to 2.4°C relative to the 1976-2005 average. Surface salinity is expected to decrease, leading to enhanced water column stratification. These physical changes are likely to lead to additional declines in subarctic species including *C. finmarchicus*, lobster, and cod and an increase in temperate species. The ecosystem changes have already impacted human communities. Continued warming will lead to a loss of heritage and culture and will require adaptations such as shifting from traditional fisheries to harvesting temperate species.

Introduction

The ecosystems in the Gulf of Maine have provided food, recreation, and economic opportunities for centuries. Recently, the Gulf of Maine has experienced one of the fastest rates of warming of any ocean ecosystem (Pershing et al 2015). The recent warming has elevated concerns within the region about how marine resources and communities around the Gulf of Maine will fare as global warming progresses. These concerns prompted the creation of the Gulf of Maine 2050 Symposium.

The Symposium is designed to bring together a broad section of the Gulf of Maine community to consider how to prepare for the future. The Symposium is organized around three main drivers of change: ocean warming and circulation changes, ocean and coastal acidification, and sea level rise and changes in storm frequency and intensity. For each of these drivers, we asked a group of scientists to synthesize current understanding of these drivers and how conditions are likely to change over the next thirty years. This paper will consider the impact of warming and circulation.

The year 2050 was not selected at random. It is around this time that the different carbon emission scenarios begin to diverge from one another. In other words, many of the changes that we expect over the next 30 years are inevitable, regardless of how much carbon dioxide is emitted in the next few years. By focusing on 2050, the hope is that the community in the region can identify tangible goals that inform choices over the next few decades.

Because the signal of warming has been so strong, this paper begins by reviewing what we have learned by studying the ecosystem impacts from recent changes in temperature. We will then introduce two independent efforts to develop high-resolution projections for conditions in 2050. Finally, we will consider what the future changes may mean for ecosystems. We will also present four case studies that offer an integrated perspective on the future of some highly visible and commercially important species.

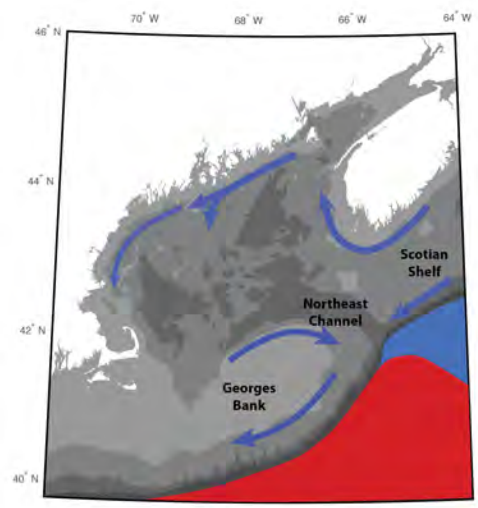


Figure 1. Map of the Gulf of Maine with major currents highlighted. The red and blue areas off the continental shelf represent the cold and warm water masses that can enter the Gulf of Maine at depth (see MERCINA 2001).

Past and Current Conditions

The Newfoundland/Labrador Shelf, Gulf of St. Lawrence, Scotian Shelf, and Gulf of Maine form an interconnected shelf sea along the eastern seaboard of the US and Canada. The circulation in the region is characterized by a general northeast-southwest flow of water from the Labrador and Newfoundland Shelf areas through the Gulf of St. Lawrence, Scotian Shelf, and Gulf of Maine to the Mid-Atlantic Bight (1). The region off the shelf is the confluence zone between the warm northeastward flowing Gulf Stream and the cold southwestward flowing Labrador Current (Loder et al 1998). These two currents interact at the tail of the Grand Banks (south of Newfoundland) resulting in east-to-west flows that affect ocean variability downstream on the Scotian Shelf and Gulf of Maine. Ocean properties in the Gulf of Maine are also directly influenced by Gulf Stream variability (i.e warm-core rings), inflows of water from the Scotian Shelf, and local effects like river inputs and interaction with the atmosphere.

Despite having a mean latitude of 41°N, the Gulf of Maine has a distinctive subarctic ecosystem. It has a strong spring phytoplankton bloom typical of the North Atlantic that is fueled by nitrate that mixes into the surface waters by the cold winters or, in places like Georges Bank, by the strong tides (Townsend 1991). The copepod *Calanus finmarchicus* (hereafter, *Calanus*) is the signature invertebrate animal of the North Atlantic subpolar ecosystem (Pershing & Stamieszkin 2019). It is adapted to the intense seasonality of this region. In particular, it accumulates reserves of lipids during the spring and summer and then uses these reserves to sustain itself through several months of winter dormancy (Johnson et al 2007). *Calanus* is very abundant in the Gulf of Maine—some of the highest concentrations ever measured are from this region, even though the Gulf is near the southern limit of its range (Melle et al 2014, Pershing & Stamieszkin 2019).

The spring bloom and *Calanus* support a community of iconic North Atlantic species, and it is likely that a large proportion of the carbon fixed during the spring bloom passes to higher trophic levels through *Calanus*. *Calanus* is an important food source for larval cod (*Gadus morhua*) and for adult Atlantic herring (*Clupea harengus*), sand lance (*Ammodytes* spp.), and right whales (*Eubalaena glacialis*). Small fish like herring and sand lance are key seasonal prey for larger fish like adult cod and bluefin tuna (*Thunnus thynnus*) and for marine mammals and seabirds (Golet et al 2015, Smith et al 2015, Staudinger et al 2019a).

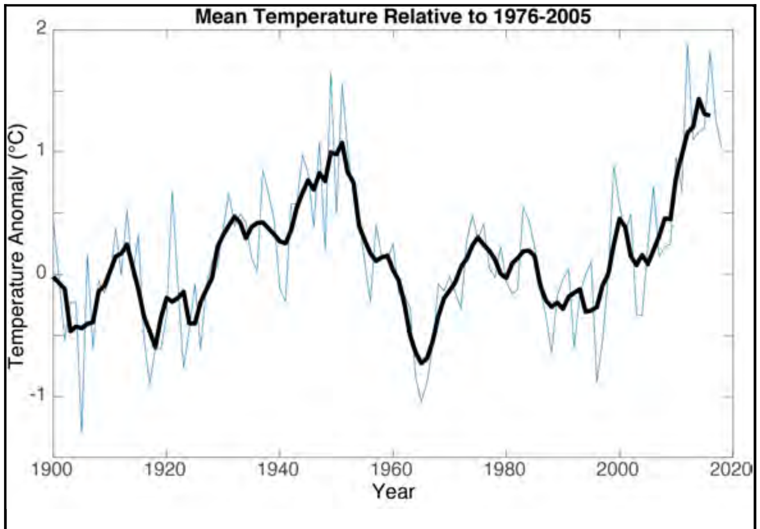


Figure 2. Gulf of Maine temperature anomalies relative to 1976-2005 baseline. Thin line = annual average temperature. Thick line = five year running mean. Data from NOAA Extended Reconstruction Sea Surface Temperature.

Observed Impacts of Warming on the Gulf of Maine Ecosystem

Temperature in the Gulf of Maine varies from year to year and from decade to decade (Figure 2). Mean surface temperatures in the late 1940s and early 1950s were well above the 1976-2002 mean, and 1949 and 1951 had annual anomalies above 1°C. The 1960s were particularly cold. Temperatures rose in 1999 and then entered a period of rapid warming around 2005. The warming has been strongest in the summer and fall, with summer-like conditions extending a more than a month later into the year (Thomas et al 2017). The warming was punctuated by heatwaves in 2012 (Mills et al 2013), 2016 (Pershing et al 2018b) and 2018 (A. Pershing *pers. obs.*). The mean temperature over the last five years is now the highest on record. The recent warming has been linked to inflows of warm, salty water at depth through the Northeast Channel beginning in 2010 (Townsend et al 2015; Record et al. 2019; Brickman et al., 2018). This subsurface oceanographic pathway is highly sensitive to changes in the Atlantic Meridional Overturning Circulation (Sherwood et al. 2011), which has been weakening due to Arctic warming (Caesar et al. 2018).

In addition, warmer winters with more precipitation falling as rain rather than snow has affected ice pack conditions and shifted the timing and amount of freshwater runoff and delivery to coastal waters (Hodgkins et al. 2003; Huntington & Billmire, 2014). As a result, seasonal stratification has become more variable, with a general trend towards earlier strengthening in the eastern portion of the Gulf of Maine basin (Li et al., 2015).

The recent warming is causing the Gulf of Maine ecosystem to lose some of its subarctic characteristics. As a result, *Calanus* abundance, especially in the eastern Gulf of Maine has declined during the summer and autumn, causing right whales to spend more time in the Gulf of St. Lawrence (Record et al 2019) (see Case Study: Right Whales). Stocks near the southern limit of their range such as the Gulf of Maine stocks of northern shrimp (Richards 2012, Richards et al. 2012, 2016) and cod (Pershing et al 2015) and southern New England lobster (Le Bris et al 2018) have declined. Recent herring recruitment has also been very low (NEFSC 2018). While the decline in herring recruitment has not been attributed to temperature or to the changes in *Calanus*, it is certainly consistent with the general decline in the subarctic community. Many Northeast U. S. fishery stocks are moving northward and to deeper depths with long-term temperature changes across the region (Nye et al 2009, Pinsky et al 2013).

The flip side of the decline in subarctic species is the increased prominence of mid-Atlantic species in the Gulf of Maine. Longfin squid, which are typically ephemeral off of Maine, moved into and stayed in coastal Maine waters during the 2012 marine heatwave (Mills et al. 2013 and see Case Study: Squid). Black sea bass have extended their range from Cape Cod Bay into the northern Gulf of Maine (McMahan 2017, McBride et al. 2018) as have Atlantic mackerel (Overholtz et al. 2011) and silver hake (Nye et al 2011). American lobster, which prefers warmer temperatures, is rapidly increasing across the Scotian Shelf and expanding its distribution to the Eastern Scotian Shelf and into deeper water (Bernier et al. 2018). Some new species, like American John Dory and armored sea robin are now being more frequently observed on the Scotian Shelf (Bernier et al. 2018). The shift away from a subarctic fish community has impacted the diet and breeding success of seabird species such as puffins and terns that nest during the summer months on islands in the Gulf of Maine (see Case Study: Seabirds).

In addition to distribution shifts in fishery-relevant species, warming waters are affecting a variety of other species in the Gulf of Maine. For example, non-native species of tunicates (e.g., *Botrylloides violaceus*) have proliferated in the Gulf of Maine, altering communities that occupy rocky bottoms and settling on piers, fishing gear, and even seaweeds (Dijkstra et al. 2010). Diseases that affect local species are also increasing in prevalence. Two diseases--MSX (*Haplosporidium nelsoni*) and Dermo (*Perkinsus marinus*)--that can cause mortality in oysters have become more prevalent in the Gulf of Maine as ocean temperatures have warmed (Marquis et al. 2015, Robledo et al. 2018). While there is no evidence to date that harmful algal blooms are increasing in the Gulf of Maine, blooms of species previously unreported in the Gulf of Maine like *Karenia mikimotoi* and *Pseudo-nitzschia australis* have occurred in the last several years (Clark et al. 2019). Outbreaks of these organisms have been linked to fish and wildlife mortality events in other regions (e.g., Pacific coast) and represent an emerging potential threat if changing conditions in the Gulf of Maine support them (de la Riva et al 2009).

The warming, both directly and potentially through stresses to native populations, is increasing the opportunities for invasive species like green crabs. While green crabs have been present in the Gulf of Maine for more than 100 years, their abundance has increased dramatically during the warm period in the 1950s (Glude 1955; Welch 1969). During recent warming, green crabs have caused considerable damage to eelgrass beds and to populations of soft-shell clams (Congleton et al. 2006; Whitlow 2009; Neckles 2015; Belknap and Wilson 2015). They are one possible explanation for the observed decline in mussels throughout the Gulf of Maine (Sorte et al 2017) and have the potential to impact native rock crabs (Griffen and Riley 2015).

The distribution shifts reported above can occur through a variety of mechanisms. Highly mobile species like squid, butterfish, and right whales can shift rapidly by actively tracking the environmental conditions they need to survive. For less mobile species and for plankton, shifts occur through differences in productivity. For example, Le Bris et al. (2018) attributed the decline of the lobster population in southern New England and the increase in abundance in the northern Gulf of Maine to temperature-dependent recruitment.

Shifts also occur in the timing of when species are abundant or when processes like phytoplankton blooms occur. Seasonal changes in the environment such as the timing of transition from winter to spring and fall to winter are lengthening the duration of summer and shortening the duration of winter (Thomas et al 2017). The fact that summer and fall temperatures have risen faster than those in the winter implies the likelihood of rapid drops in temperature during the late fall and early winter. This pattern may explain the recent increase in cold-stun stranding events of Kemp's Ridley sea turtles; Griffin et al., 2019).

All of these physical changes in the seasonal conditions of the Gulf of Maine affect the timing of recurring life events, known as phenology, of marine fauna, including foraging and growth conditions, and environmental cues that prompt breeding and migration.

The greatest evidence for phenological shifts in the Gulf of Maine have been observed at the base of the food web including later spring and fall phytoplankton blooms (Record et al 2018) and earlier and higher peaks in spring abundance of *Calanus* and other zooplankton (Record et al 2019, Runge et al 2015) (Staudinger et al. 2019). Larval fishes show varying responses, with earlier occurrence of larval stages of some benthic fishes (e.g., haddock, winter flounder) and later occurrence in species such as sand lance, pollock and mackerel; however, most larval fish (e.g., Atlantic cod, silver hake) have showed no detectable changes (Walsh et al. 2015). Evidence for shifts in phenology of higher level species is scarce. A few notable examples include earlier adult migrations of anadromous fishes such as Atlantic salmon and alewife from marine to freshwater spawning habitats (Huntington et al 2003; Juanes et al 2004; Ellis and Vokoun 2009), later reproduction and fledging of Atlantic puffins on Machias Seal Island (Whidden 2016) and increased duration of the spawning period for some commercially important macro-invertebrates including northern shrimp (Richards 2012; Richards et al 2016). The timing of large whales in Cape Cod Bay, which is known as a critical spring foraging habitat, has changed but in variable ways; peak abundance of North Atlantic right whales and humpback whales in the bay has shifted later by approximately one month and 1-2 weeks, respectively, while fin whale abundance has shifted earlier by 1-2 weeks (Pendleton et al., in prep). Although relatively few examples of shifts in phenology have been documented to date in marine habitats, there is much concern that they are happening and put species at risk for ecological mismatches that can affect fitness and survival (Staudinger et al. 2019).

Physical Conditions in 2050

The main tools for understanding future climate conditions are coupled global atmosphere-ocean-sea ice-land (increasingly, ecosystem) climate models, run by numerous international institutes. The Intergovernmental Panel on Climate Change (IPCC) coordinates the simulation, analyses, and reporting of these future climate simulations in a series of “Coupled Model Intercomparison Projects” (CMIP) of which CMIP5 forms the basis of the most recent IPCC reports (Taylor et al 2012). CMIP6 has been completed and will be reported on soon.

While climate models are incredibly complex, often with several million lines of computer code, they are still a simplification of the real climate system. This means that they will always imperfectly represent key processes like clouds in the atmosphere and fine scale processes in the oceans. Another simplification is that computer models divide the atmosphere and ocean into discrete boxes and layers and assume conditions are constant within each cube. The horizontal resolution of the CMIP5 ocean models is considered to be coarse -- ranging from about 1/2° to 2° – which translates into a resolution of (at least) 100 km in the northwest Atlantic Ocean. This presents a challenge in our region as the main current systems (e.g. the Gulf Stream and Labrador Currents) are not properly resolved and thus not accurately simulated in these models. The result is that there are large biases (errors) in these models of the present day climate, which reduces the confidence in the future climate simulations. More precisely, the position of the Gulf Stream is typically too far north which results in a warm bias in the Gulf of Maine and off-shelf region.

One often-used method to address model biases is to apply the “delta method”. The first step in the delta method is to select a common period from the simulations and in the real world (for example, 1976-2005). Then the difference, or delta, between this period and the target period (in this case, 2050) is computed for variables of interest in the simulations. The delta values are then added to the observed values for the reference period from the real world, removing the mean model bias. The delta method assumes that while the models may get the baseline conditions wrong (say, by putting the Gulf Stream too far north), the change through time is correct. This approach has been used to support several ecosystem projections for the Gulf of Maine (e. g. Hare et al 2010, Kleisner et al 2017, Le Bris et al 2018).

An improvement on the simple delta method is to use the output from the low-resolution CMIP models to force a high-resolution model for a portion of the globe. Two modeling groups have applied this dynamical downscaling approach over domains that include the Gulf of Maine. NOAA’s Earth System Research Laboratory used output from three different CMIP5 models: GFDL, IPSL, and HadGEM (see Appendix I) to drive a high resolution ocean model that extended from the Gulf of Mexico to Greenland. Using the three different global models provides a way of capturing some of the range of possible future conditions.. Each of the global models used the “business as usual” RCP8.5 emission scenario. We will refer to the output from this model as the ROMS (Regional Ocean Modeling System) simulations.

Canada’s Department of Fisheries and Oceans used a similar procedure for a high resolution ocean model that extended from 7-75°N. This regional model was forced with the average output from six IPCC models run under both the business as usual scenario and a lower emissions scenario (RCP4.5). We will

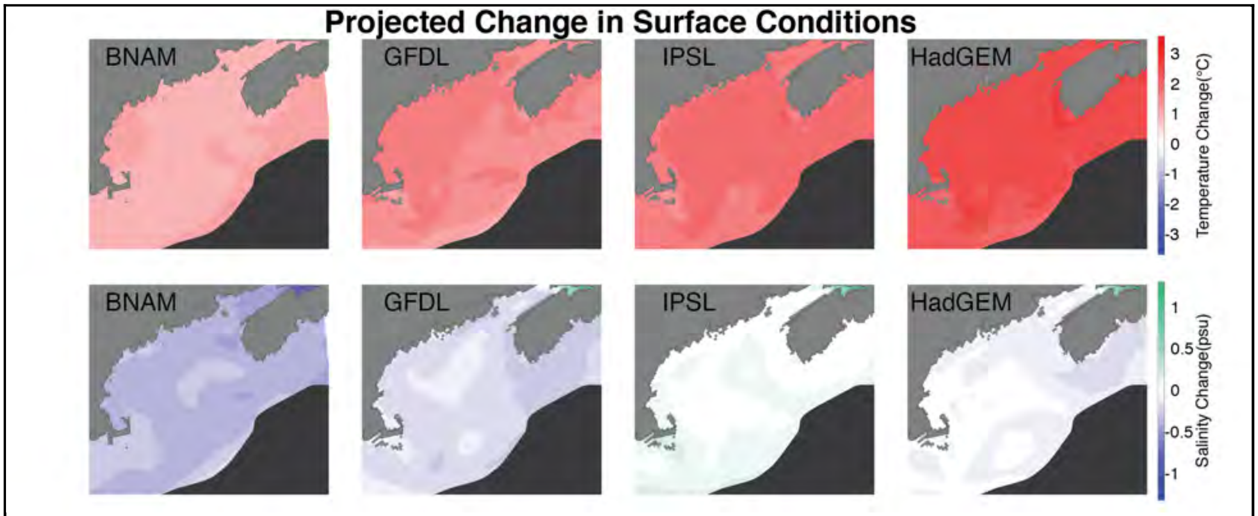


Figure 3. Projected changes in surface temperature (top panels) and surface salinity (bottom panels) in 2050 relative to the 1976-2005 baseline. The four models that used RCP8.5 are sorted left-to-right by their mean surface temperature

refer to these as the BNAM (Bedford Institute of Oceanography North Atlantic Model) simulations. Technical details on both the ROMS and BNAM approaches are described in Appendix I.

Ensemble Predictions for 2050

Together, the ROMS and BNAM simulations provide five different views of the future state of the Gulf of Maine. These differ due to the sensitivity of their respective global models to carbon dioxide levels, and in the BNAM simulations, due to differences in carbon emission pathways. Some of the differences may also be due to the two distinct modeling approaches. For example, the BNAM simulations include more detailed treatment of Greenland melting (see the Box "Why are the projections different?").

The four models run under business-as-usual carbon dioxide emissions (RCP8.5) all show warming throughout the Gulf of Maine (Figure 3). The BNAM simulation suggests warming of about 1°C above the 1976-2005 baseline. The strongest warming occurs in the ROMS-HadGEM simulation. There is very little spatial structure in the surface temperature anomalies, however, the three ROMS simulations show generally stronger warming in the Gulf of Maine compared with Georges Bank and the southern New England Shelf.

Surface salinity anomalies are generally inversely related with the amount of warming in the simulations (Figure 3). The cooler BNAM model projects stronger freshening, while the very warm ROMS-HadGEM shows only slight freshening. The ROMS-IPSL projection is the only one that shows increased surface salinities. Taken together, all of these simulations suggest that the future Gulf of Maine will be more stratified, and both warming and changes in salinity likely to play a role.

All of the simulations show increased temperature and salinity in the deep basins of the Gulf of Maine (Figure 4). This is consistent with the Saba et al. (2016) high-resolution model projection that shows strong warming in the Gulf of Maine associated with an inflow of warm salty water at depth.

Although temperature is clearly a controlling variable on ecosystem function in the Gulf of Maine, the model projections indicate an increase in current speed, particularly in the Gulf of Maine Coastal Current (GMCC) system, which includes the Eastern and Western Maine Coastal Currents. Originally described by Townsend et al. (1987), this coastal current system is an important transport system in the Gulf of Maine for dissolved inorganic nutrients, phytoplankton, and grazers. For example, this cold plume of water is tidally mixed to the surface where nitrate can be utilized by primary producers (Townsend et al, 1987) and can influence downstream systems such as Massachusetts Bay (McManus et al. 2014).

To put the projections in context, we plotted the mean change in Gulf of Maine temperature relative to the historical conditions (Figure 5). Because each of the simulations represents the mean

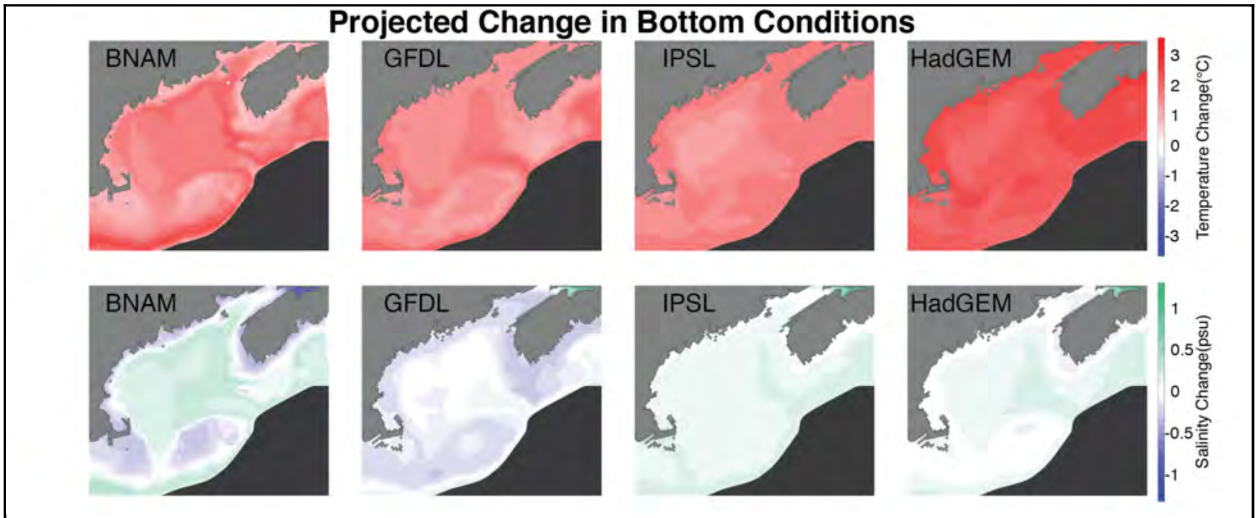


Figure 4. Projected changes in bottom temperature (top panels) and bottom salinity (bottom panels) in 2050 relative to the 1976-2005 baseline.

climate state (~30-year average) around 2050, it is most appropriate to compare the projections with the 30-year average of the observations (heavy black line). At the 30-year scale, the recent period of very warm conditions (2010-2018) is averaged against the cooler conditions of the 1990s. This means that the "climate" of the Gulf of Maine is only now approaching the mean conditions around 1950. However, it is clear that each of the downscaled projections suggest a climate that is significantly warmer than what the Gulf of Maine has experienced.

While the 30-year climate may be different, the Gulf of Maine has already experienced conditions like those indicated by the climate models, albeit only for brief periods. We think that these comparisons are instructive for picturing what conditions are likely to be in the future.

1) **BNAM RCP4.5**: This simulation is the most optimistic. It assumes aggressive carbon emission reductions and shows a temperature anomaly of 0.8°C. This temperature anomaly is comparable to those in 1999 (0.89°) and 2010 (0.95°). The climate implied by this simulation is quite similar to the most recent decade. In this climate, 2008 would be a cool year and 2012 would be a very warm, but not necessarily extreme year.
2) **BNAM RCP8.5**: This simulation is slightly warmer than the previous simulation: 1.11°C above the 1976-2005 baseline. This temperature anomaly is identical to what we experienced in 2013 (1.11°C). In this climate, cold conditions like those in the 1990s or in 2004 would be very unlikely. Years like 2012 and 2016 that now seem remarkable would feel like merely warm years. The very slight 0.3°C difference between BNAM RCP4.5 and RCP8.5, underscores the insidious delay between when carbon is released into the atmosphere and when its effects are fully felt in the climate system.
3) **ROMS GFDL:** This is the coolest of the ROMS simulations but it is still much warmer than the BNAM simulations. The 1.55°C change in mean temperature is only slightly below the temperature anomaly in 2016 (1.82°C). In this climate, 2012 and 2016 would be ordinary years, and extremely warm years would have temperatures well beyond historical experiences.
4) **ROMS IPSL:** The 1.89°C change in mean temperature corresponds almost exactly to the anomaly during the record year of 2012 (1.88°C). We would expect that this climate could produce years with a mean temperature anomaly more than 2° above the baseline.
5) **ROMS HadGEM**: The world pictured in this simulation is hard for people in 2019 to fathom. The 30-year average would be 2.38° above the baseline, almost 0.5°C above the warmest year recorded. In this climate, a cold year would feel like 2012. This is a very different future that approaches many end-of-century simulations.

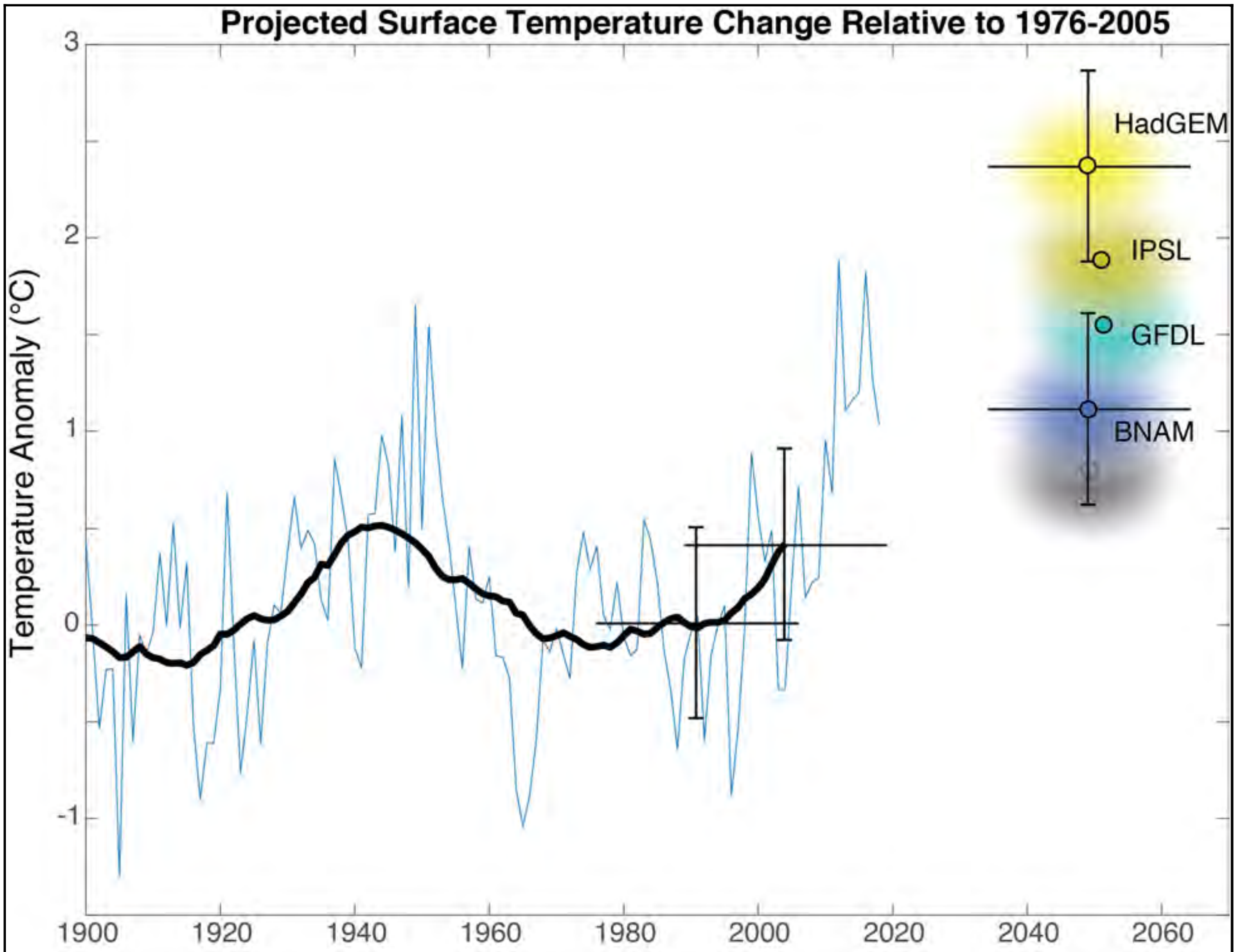


Figure 5. Observed and projected Gulf of Maine temperature anomalies relative to 1976-2005 baseline. Thin line = annual average temperature as in Figure 2. Thick line = 29 year running mean. The colored circles denote the mean projections from the five downscaled climate projections. The projections represent the 30 year climate centered on 2050. The colored ellipses convey the range of annual temperatures that could occur during the projection period under RCP8.5. The crosses denote the 30 year period represented by the reference period, the most recent observations, and the projections with the least and most warming. The vertical extent of the crosses show variability of +/- 0.5°C consistent with the observations. The gray ellipse is the BNAM RCP4.5 projection.

The projections assembled for this study offer a view of the potential future for the Gulf of Maine. At this point, we cannot determine whether one of these is more likely than the others. We can also say little about how the mean climate will vary between now and 2050. For example, it is possible that we could encounter several average or even cool years even if conditions like those depicted in HadGEM come to pass. However, it is important to note that all of these model runs show a Gulf of Maine that is warmer than the recent 30-year climate.

Ecosystem Conditions in 2050

Quantitative models relating temperature to distribution and/or abundance are available for a few important Gulf of Maine species. Climate model projections of temperature can then be used to drive these models, providing an estimate of the future abundance or distribution.

Projected Impacts on Calanus

For *Calanus*, projections into future climate conditions have so far generally relied on statistical models. Using a model built on surface conditions, Reygondeau and Beaugrand (2011) predicted a disappearance of *Calanus* from the Gulf of Maine by 2050. Grieve et al. (2017) included bottom conditions—important because of the extended diapause period at depth—and predicted a more modest decline of around 50% by the end of the century. As yet, statistical models do not incorporate two key processes relevant to plankton: advection, which strongly influences *Calanus* abundance along coasts and continental shelves (Ji et al 2017, Speirs et al 2006), and life history dynamics, for which a number of mechanistic models exist (reviewed in Record et al 2013) but have not been used in projections. Wilson et al. (2016) did project one mechanistic *Calanus* model to end-of-century conditions, and reported some of the largest decreases in diapause duration (~75%) to occur in the Gulf of Maine, but it is not clear the impact this will have on overall abundance. Statistical models also do not capture the adaptive capacity of *Calanus* to adjust behavior and other inherent traits to changing conditions (Beever et al., 2016) or interactions among *Calanus* and other species within the food web, which could have either positive or negative effects (Moritz and Agudo 2013; Selden et al. 2018). The persistence of *Calanus* in recent years despite the rapid warming that has already occurred implies a need for improved models (Runge et al 2015).

Projected Impacts on fish species

In the Gulf of Maine, continued warming is expected to create extensive ecosystem changes by 2050. For overfished stocks near the upper thermal limit of their range, distribution and abundance will be most subject to change and vulnerable to further impacts. Hare et al. (2016) conducted a climate vulnerability assessment for 82 fish and invertebrate species in the Northeast U.S. Shelf. Their methods indicated that the overall climate vulnerability is high to very high for half the species assessed, with bivalves (i.e. bay scallop, ocean quahog, northern quahog) and an endangered fish (i.e., Atlantic salmon) rated the most vulnerable. In addition, the majority of species have a high potential for a change in distribution in response to projected changes in climate. Negative effects are expected for half of the species assessed, and many of those species are currently important to commercial fisheries in the Gulf of Maine. Some species moving in to the Gulf of Maine, such as black sea bass and longfin squid, are expected to be positively affected (e.g., increase to productivity and abundance) over the Northeast Shelf region. A similar vulnerability assessment of marine species on the Scotian Shelf predicts that 45% of populations may be vulnerable under a severe (+3°C) warming scenario (Stortini et al., 2015). Populations in the southwest portion of the domain are found to be more vulnerable than those in the northeast. Some key commercial populations on the western Scotian Shelf (adjacent to the Gulf of Maine) that are vulnerable under the severe warming scenario include snow crab, cod, pollock, and red hake.

Projected warming also affects thermal habitats for species occurring in the Gulf of Maine. Shackell et al. (2014) used temperature projections (3.0° C for depths < 100m and 1.5° C for depths > 100 m) to evaluate thermal habitat changes for US and Canadian species. These temperature changes are consistent with the ROMS and BNAM projections for 2050. This level of warming is expected to modify the realized thermal habitats of 76% of the fishery target species in Canada (55% contract, 21% expand) and 85% of those in the U.S. (65% contract, 20% expand) (Shackell et al., 2014). These changes include substantial reductions in suitable thermal habitat for key northern species such as red crab, Atlantic cod, Atlantic herring, and American plaice, but potential gains for some species including summer flounder, American lobster, and shortfin squid. Kleisner et al. (2017) used temperature projections from a high-resolution climate model (Saba et al 2016), with average increases of 3.9° C (surface) and 4.3° C (bottom) that are above those for our 2050 downscaling study. Species projections indicated that more southern species (e.g., striped bass, Atlantic croaker, smooth dogfish) would experience stable or increasing thermal habitat by moving northward or deeper, yet species in northern areas like the Gulf of Maine (e.g., cod, haddock, redfish) would experience declines in thermal habitat (Kleisner et al. 2017).

Projections tailored to individual species indicate more nuanced ways in which warming may affect suitable habitats and species distributions. Fragmentation of habitats is one concern. For an increase of 1°C in bottom temperature (the low end of our 2050 projections), cusk habitat in the Gulf of

Maine region will shrink and fragment as a result of a spatial mismatch between high complexity seafloor habitat and suitable temperatures. With temperature increases above 1.5°C (i.e. the ROMS-HadGEM simulation), half of the surface area classified as cusk habitat will disappear, and fragmentation is exacerbated with temperature increases between 1° C and 4° C (Hare et al. 2012). In addition, the effects of warming on habitat suitability for a species may vary with sex, life stage, and other characteristics, as demonstrated for lobster in the inshore waters of the Gulf of Maine (Tanaka et al. 2018). Finally, while most habitat projections consider individual species in isolation, changes in overlap between predators and prey are also expected to occur as temperatures warm (Selden et al. 2018) and seasonality changes (Pershing et al. 2015; Staudinger et al., 2019). The ability of species to find suitable and sufficient prey as well as the risks they may face from changing predator fields can both affect the habitats they actually occupy as well as their potential population productivity. Thus, there is the potential for novel mixes of species, a concern highlighted in the recent US National Climate Assessment (Pershing et al 2018a; Lipton et al 2018).

Commercial fishing has a long history in the Gulf of Maine, and fishing remains one of the most tangible services provided by this ecosystem. Until recently, Atlantic cod was the mainstay of the fisheries in this region. The 1-2°C increase in bottom temperature in the ROMS and BNAM projections would imply that the 12°C threshold above which cod occurrence declines dramatically (Drinkwater 2005, Fogarty et al. 2008) will be exceeded on Georges Bank in 2050.

Cod recruitment in the Gulf of Maine and Georges Bank declines with increasing temperature (Drinkwater 2005, Fogarty et al 2008, Pershing et al 2015). With an increase of 3°C, the stocks in Georges Bank, Gulf of Maine, and Browns Bank/Bay of Fundy would all decline, and a 4°C increase would extirpate cod from Georges Bank (Drinkwater, 2005) and possibly the Gulf of Maine (Selden et al., 2018). These higher levels of temperature could occur sporadically during the 2050 climate and more frequently later in the century. More detailed projections suggest that the 1°C increase depicted in the BNAM simulation would reduce the spawning stock biomass of Gulf of Maine cod that produces the maximum sustainable yield to 30,000 mt, slightly more than half the current estimate of this value (Pershing et al 2015). Warming above 2°C as in ROMS-HadGEM would reduce the value to 20,000 mt. While much lower than what the stock has historically produced, these values would represent a marked improvement over the current estimate of only 5,000 mt of spawning cod. The level of fishing that is sustainable also declines with rising temperature. At the higher temperature level, the stock is predicted to go extinct at fishing mortality rates in excess of 1.6, a level which is sustainable (though far from optimal) under a 1°C increase in temperature (Fogarty et al 2008).

While cod have traditionally been the most important fishery in the Gulf of Maine, the lobster fishery is currently the most valuable fishery in both the U.S. and Canada. Le Bris et al. (2018) estimated the future trajectory of lobster in the Gulf of Maine. Their study used the CMIP5 RCP8.5 ensemble which has temperature changes of 1°-2°C by 2050. At these levels of warming, lobster abundance in the Gulf of Maine will decline 42-62% relative to the recent peak in abundance. This would imply a scale of the fishery similar what existed in around 2000. However, the spatial distribution could be different, with higher recruitment in the eastern Gulf of Maine/Bay of Fundy and reduced recruitment in the western Gulf of Maine and on the Scotian Shelf.

As climate drives shifts in the spatial distribution of predators relative to their prey, trophic interactions will likely amplify the direct effects of climate warming. Under a CO2 doubling scenario, range expansion for spiny dogfish and silver hake resulted in enhanced overlap with prey, likely increasing their relative importance and replacing cod as piscivores in the U.S. Northeast Shelf ecosystem (Selden et al., 2018). For the next 50 years, the combined climate effects associated with changes in temperature (increasing by about 1°C), pH, oxygen, decreased primary productivity and shifts in zooplankton size structure, the western Scotian Shelf is projected to experience a reduction in biomass of 19% to 29%, an associated decrease in catches of 20% and 22%, and a 50% decrease in exploitation rate (Guénette et al., 2014).

Changes in suitable thermal habitat of important commercially fished species will impact local fishing communities and may affect major fishing ports (Kleisner et al 2017). One social-ecological risk assessment shows that 64 of 85 New England and Mid-Atlantic (USA) fishing communities will be exposed to increased risk by mid-century of declines in future fishing opportunities based on current practices (Rogers et al. 2019). Communities of small trawlers in Maine are most vulnerable because of their historical dependence on Atlantic cod and witch flounder, which are expected to lose habitat suitability in the future (Rogers et al., 2019). Even communities with fisheries that may benefit from warming can be impacted by climate change in other ways. For example, lobster fishing communities in Atlantic Canada are projected to experience increases in a key resource, but vulnerabilities to other climate-related factors, such as sea level rise, will shape community impacts and adaptation needs (Greenan et al. 2019).

Fishers view warming waters as associated with decreased fishing opportunities, indicating that fishing communities are currently finding the prospect of climate adaptation difficult (McClenachan et al 2019a). However, many do have plans to adapt. For example, Maine lobster fishers indicated that strategies for adaptation include fisheries diversification; supplementing income with non-fishing activities; changing gear use, location, or timing; and becoming more involved in fisheries management and local politics (McClenachan et al 2019b). However, adaptation is constrained by social, economic and historical factors (Pinsky & Fogarty 2012). For example, only 12% of Maine fishers have license holdings that would allow them to access emerging species (Stoll et al. 2017).

For sustainable commercial fisheries management, warming-induced distribution shifts, productivity changes, and diversity trends should be closely monitored. At the population level, simulation studies show that changes in mortality rates are exert particularly strong effects on spawning biomass and catch targets, while maturity and recruitment are also influence fishing mortality targets (Thorson et al., 2015). It will be important to incorporate both fishing and climate impacts when evaluating the efficacy of management strategies and developing novel solutions to emerging problems. In addition, considering the impacts of climate change on transboundary species distributions and access by neighboring coastal communities in Canada and the U.S., effective bilateral cooperation between the two country's scientists and fishery managers is required in the pursuit of sustainable fisheries in the Gulf of Maine (VanderZwaag et al., 2017).

Conclusions

All of the resulting environmental and ecological changes described in this paper have implications for the ecosystem services that human communities and economies around the Gulf of Maine depend on for food, livelihoods, recreation, heritage and culture. Changes in the timing, distribution and abundance of commercially and recreationally important populations will affect their availability to the fishing industry, in many cases increasing costs of operations (e.g., the distance and associated costs to travel offshore to find and harvest the species). However, increased availability of warm-water species such as black sea bass, summer flounder, and longfin squid could provide new opportunities for fishing communities if state and regional policies are able to adapt to facilitate harvesting opportunties where and when they occur relative to fishing ports.

Recreational and tourism industries will also experience changes based on whether certain activities diminish or increase in duration (or are eliminated completely) due to changing seasonal conditions. For example, ice fishing for species like smelt may become less profitable as ice cover decreases and reduces the time when activities can occur. Conversely, wildlife (e.g., whale watching and seabird) viewing and recreational fishing opportunities may increase with more pleasant summer and fall conditions lasting longer. Still, if species of interest move out of traditional areas and away from the region, or if their populations decline due to changes in forage and thermal habitats, declines or shifts in tourism and recreational opportunities may occur.

Finally, tribal nations and other coastal communities that depend on climate-affected species will suffer due to losses of economic and subsistence harvests (Jantarasami et al. 2018). While possibilities remain for communities to shift to new (warm-water associated) species as they move into the region, many communities that identify with certain species or places will experience a loss of heritage and culture that can further impacts human health and well-being in the region.

Interdisciplinary Case Studies

Case Study: Seabirds

A variety of seabirds nest in large colonies during summer on nearshore and offshore islands located along the Gulf of Maine coastline. Notable species include common, roseate, Arctic and least terns (*Sterna* sp.) and alcids such as Atlantic puffins (*Fratercula arctica*) and razorbills. Seabirds remain close to these islands during the critical period when they breed and raise their young. They are therefore highly dependent on the timing and spatial occurrence of forage resources around these islands as they can only hunt within a limited radius to provision food for their growing chicks. For many of these species, the Gulf of Maine is the southern edge of their biogeographic range.

Long-term diet data of Common, Roseate, Arctic and Least terns (*Sterna* sp.) shows terns have historically specialized on a few key forage fishes, including sand lance, Atlantic herring, and hake (*Urophycis* sp., *Merluccius* sp., and *Enchelyopus* sp.) (Hall et al. 2000; Yakola 2019). This specialization makes these species more vulnerable to shifts in foraging conditions mediated by climate change. Over the last 30 years, at most locations, hake have been generally declining in common tern diets, while sand lance has been increasing at varying magnitudes. The occurrence of hake in common tern diets appears to be most sensitive to changes in seasonal timing (earlier onset of spring) and seasonal sea surface temperatures (Yakola 2019).

Atlantic puffins act as a tourism magnet wherever they occur and support a substantial tourist industry, especially in Maine. Puffin breeding phenology seems to be sensitive to sea surface temperature at a North Atlantic scale (Diamond & Devlin 2003). Puffin chick diets have changed significantly since 2000 (Scopel et al. 2019), corresponding with reductions in a variety of demographic indicators (occupancy, breeding success, chick growth and fledging condition) since 2005 in eastern (Whidden 2016, Diamond 2017) and 2010 in western colonies (Kress et al. 2016). A shift in 2010 to generally lower-quality prey coincided with a shift in plankton communities, nutrient concentrations, increased stratification and above-average ocean temperatures on the Scotian Shelf at the entrance to the Gulf of Maine (Johnson et al. 2018). Juvenile herring dominated puffin diets in the late 1990s but were largely replaced by sand lance (*Ammodytes* spp. (often as larvae) and white hake, and from 2010 by juvenile haddock (*Melanogrammus aeglefinus*) and Acadian redfish (*Sebastes fasciatus*).

Temperatures in 2012-2013 and 2016 were close to 2°C above normal, roughly the anomaly expected in 2050, allowing experiences in these years to be used as an analogue for 2050. Breeding success was catastrophically low in 2013 and 2016 (Kress et al. 2016, Scopel et al. 2019). Prey availability and puffins' hunting abilities are clearly important; as temperatures increase, prey will move deeper (Pinsky et al. 2013) and will be more difficult for puffins to catch because fish increase their burst speed in warmer water (Cairns et al. 2007, Grady et al. 2019). Reduced breeding success and condition of fledging chicks will likely result, causing reduced recruitment of young. As long-lived birds with high annual survival (89-96%, Breton & Diamond 2014) populations may not decline measurably for some time despite extremely low reproductive success.

Case Study: Lobsters

American lobster (*Homarus americanus*) supports commercial fisheries worth over $US1.2 billion in the Northeast U. S. and Maritime Canada (2016 values in $US: Fisheries and Oceans Canada 2019, NOAA Fisheries 2019). These fisheries provide income and sustain cultural identities for many small coastal communities. Rising ocean temperatures have affected the productivity, abundance, and distribution of American lobster. In the U. S., warming ocean waters have contributed to declines in the southern New England and increases in the Gulf of Maine lobster populations (Le Bris et al. 2018). These divergent trajectories have been attributed to a reduction in thermal habitat for juvenile lobsters (<20° C) in the south and an expansion in the Gulf of Maine (Steneck and Wahle 2013, Wahle et al. 2015, Tanaka and Chen 2016), increased prevalence of epizootic shell disease in the south (Glenn and Pugh 2006), and an associated northward shift in recruitment success (Le Bris et al. 2018). As a result of changes in productivity and abundance, the centroid of the spatial distribution of American lobster has shifted northward (Pinsky et al 2013).

While warming trends have influenced the population dynamics of lobster, lobster fisheries were also substantially affected by a marine heatwave in 2012. During this heatwave, sea surface temperature was 1-3° C warmer than the long-term average—and on par with end-of-century climate projections (Mills et al. 2013). As temperatures warmed earlier in the spring, high-volume landings in the U. S. fishery began so early that they overlapped with the Canadian lobster season. Processing capacity could not keep pace with landings, and ultimately, a flood of product led to a price collapse that affected both U. S. and Canadian fisheries (Mills et al. 2013).

With continued warming, the Gulf of Maine lobster population is projected to decline by 50% between now and 2050 under the mean warming expected under the RCP 8.5 climate scenario (Le Bris et al. 2018). Multiple studies indicate that suitable thermal habitat for lobsters in U. S. and Canadian Maritime waters will increase in the future (Shackell et al. 2014, Kleisner et al. 2017, Morley et al. 2018, Greenan et al., 2019), but the warming scenarios used and magnitude of the projected increase varies substantially among the studies.

Case Study: Squid

The longfin squid (*Doryteuthis pealeii*) and shortfin squid (*Illex illecebrosus*), support important fisheries in the western North Atlantic for decades (from Cape Hatteras to Cape Cod; Arkhipkin et al., 2015). Squid fisheries are notoriously "boom and bust" due to the species' sensitivity to environmental and ecosystem conditions (Rodhouse et al., 2014). Distribution and abundance of both species varies from year to year along the continental shelf (Black et al., 1987), and have been linked to water temperature and circulation at multiple spatiotemporal scales (Dawe et al., 2007,Manderson et al., 2011).

Longfin squid have experienced episodic northward distributional shifts in the past (Dow 1977, Dawe et al. 2007), and in recent years, they have been occurring in harvestable abundances northward of the historical range of the fishery, including within the Gulf of Maine during very warm years (Mills et al., 2013). Shortfin squid landings have been increasing over the last few years (NOAA Fisheries 2019), and fishermen and beachgoers are reporting large numbers of the species in nearshore waters and stranded on beaches in the Gulf of Maine (O. Nichols, *pers. obs.*). This trend in increased abundance is also reflected in the diets of many commercially important large pelagic fishes (e.g., tunas) that forage in offshore and Gulf Stream waters (Teffer et al. 2015).

In general, warming temperatures associated with climate change can be beneficial for squid populations due to plasticity in life history and temperature-dependent growth (provided there is no limitation in food). Notably, many squid species are able to rapidly shift their distributions in response to warming. The sudden appearance of longfin squid in the Gulf of Maine during the 2012 heatwave is similar to the rapid northward expansion of Humboldt squid during El Niño conditions (Zeidberg & Robison 2007), as well as the episodic northward range extensions of the sympatric *Doryteuthis opalescens* along the US West Coast (Wing and Mercer 1990). Squids have also expanded northward in the northeast Atlantic (van der Kooij et al., 2016).

Increases in squid abundance in the Gulf of Maine will have implications for both predators and prey. It is difficult to predict the future ecological role of squids in the Gulf of Maine ecosystem, but it is worth noting that they serve as a conduit between upper and lower trophic levels and are important as forage for a variety of marine species, including many of commercial importance (Staudinger, 2006; Staudinger et al 2010; Teffer et al. 2015) as well as of conservation concern (Staudinger 2006; Staudinger et al 2014). In bioenergetics terms, smaller squid perform optimally at higher temperatures (Pecl and

Jackson, 2008), while in a trophodynamics context, larger squid tend to demonstrate higher rates of piscivory (Hunsicker and Essington, 2006).

The primary means of squid harvest is small-mesh trawl gear, which can result in high levels of bycatch (Hendrickson, 2011). Should squid distribution shift further into the Gulf of Maine, this may present new fishery management challenges while incentivizing bycatch reduction methods. Squid processing requires substantial shoreside infrastructure, of which there is currently little in Gulf of Maine ports. Expansion of squid fishing in this region will require new investments in such infrastructure.

Case Study: Right Whales

North Atlantic right whales (*Eubalaena glacialis*) are one of the most endangered marine mammals in the world, with only around 400 individuals remaining (Pettis et al., 2018). Marine mammal surveys (CETAP 1982, Mayo et al. 2004, Cole et al. 2007) established that all core right whale feeding habitats are in and around the Gulf of Maine. Ecosystem studies revealed that the predictable seasonal occurrence of right whales was linked to high concentrations of their prey, the lipid-rich *Calanus* and other copepods (Mayo and Marx 1990, Baumgartner et al 2003, Pendleton et al. 2009). Recovery efforts have focused on reducing human-caused mortality due to ship strikes and fishing gear entanglements. Conservation measures have included moving shipping lanes away from right whale core areas, establishing speed limits for large vessels, and modifying fishing gear. These measures have been applied in a manner that follows the annual migratory path of right whales, from one Gulf of Maine feeding habitat to another. Reduced mortality due to improved management (Laist et al., 2014) and increased calf production associated with elevated *Calanus* abundance (e.g. Meyer-Gutbrod et al. 2015) allowed the population to build from 350 whales in the late 1990s to over 400 whales.

In 2010, a shift occurred. Right whale occurrences in the Bay of Fundy feeding habitat in the eastern Gulf of Maine dropped sharply (Davis et al. 2017). The drop in right whales coincided with a decline in *Calanus* in the eastern Gulf of Maine, which was strongly correlated with warming in deep waters entering through the Northeast Channel beginning in 2010 (Record et al. 2019).These climate-driven circulation changes have undermined a previously reliable feeding habitat for right whales. The right whale population has responded by moving to other areas during this time of year, presumably to find other feeding grounds. Their appearance in areas where protective measures are not in place, such as the Gulf of St. Lawrence, has led to a sharp increase in mortalities (Davies & Brilliant 2019). Meanwhile, calving rates have also declined, as whales struggle to find new feeding grounds (Meyer-Gutbrod and Greene 2018). The result is that since 2010, after many years of slow population growth, the right whale population has been in steady decline (Kraus et al., 2016; Pace et al., 2017).

Maintaining right whale protections as conditions change is a challenge. The loss of a reliable seasonality to their habitat use has made management actions reactive rather than proactive. Protective measures sometimes have economic impacts on fisheries, such as the New England lobster fishery, and management now requires international cooperation. At the same time, whales are not simply following an isotherm, but rather hunting for good feeding grounds which depend on temperature, ocean productivity, and complex currents. In spring, for example, a new feeding ground has appeared in southern New England, outside of the thermal niche of *Calanus*. If the seasonal patterns eventually stabilize into a nearly regular cycle, then new regular feeding grounds could be the targets of new protections. On the other hand, there is a good chance that there will be substantial year-to-year variability for the foreseeable future. This decreases the chances that a protective measure that works one year will work the next year. For the right whale population to recover, predictive and dynamic management strategies (e.g. Pendleton et al. 2012) need to be developed as more drastic changes to shipping and fishing practices (e.g., ropeless fishing) are pursued and eventually adopted.

Box: Why are the projections different?

Figures 3-5 show that there is a wide range of results from projections of how the climate may change in the Gulf of Maine. Why does this occur? Three main factors cause climate projections to diverge: 1) the amount of greenhouse gases that will be released into the atmosphere, 2) differences in how models are formulated and 3) variability that arises naturally in the climate system (Hawkins and Sutton 2009). The uncertainty of the first has been tested using different climate change scenarios and the second can be tested by using different climate models. However, natural variability can complicate isolating human-induced climate change, especially for small regions of the globe such as the Gulf of Maine. Natural variability can be seen in long observed time series, with periods of both rapid increases but also decreases in temperature (Figure 2 shows a long time series, and it is likely that natural variability contributed to the very warm temperatures that occurred recently.) In addition, it was often assumed that changes over decades or longer due to natural variability were small. However, there are very long time scale fluctuations that occur due to slow changes in ocean currents, especially the thermohaline circulation.

A method for examining natural variability in a changing climate has recently been developed in which a large set of climate model simulations are performed using the same scenario and model but with different initial conditions for each simulation. The differences at the start of the runs causes changes in the temperature, winds, currents, and other factors to vary, resulting in each simulation having a different evolution of the atmosphere, ocean and sea ice. The average of all the simulations gives the model's response to climate change, and the spread among the simulations indicates the influence of natural variability. Results from these large ensembles of simulations are eye opening: even over 50 year periods, natural variability could strongly influence regional trends, especially for variables such as precipitation and sea level pressure (Deser et al. 2012 and 2014). Results from a large ensemble for sea surface temperatures in the Gulf of Maine suggest inherent variability of about +/- 0.5°C.

Appendix I: Downscaling Methodology

ROMS Methods

The effects of climate change on the northwest Atlantic was investigated using the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams 2003, 2005). The version used here, configured by Kang and Curchitser (2013), has a horizontal grid spacing of 7 km and 40 vertical levels. The model domain extends along the entire US east coast to Newfoundland and including the Gulf of Maine.

A control (**CTRL**) ROMS simulation was performed using observationally-based fields at the surface and along the side boundaries in the ocean with radiational conditions for flow out of the domain and nudging of temperature, salinity and in-flowing currents as a function of depth at the boundary. The CTRL simulation (upper left panel of Figure S1) represents the observed climate over the period 1976—2005 and well simulates the mean path of the Gulf Stream (Kang and Curchitser 2013, 2015), the circulation in the Gulf of Maine (Shin and Alexander 2019), and temperatures on the Northeast US Shelf (Chen et al. 2018).

Climate change simulations were performed using the delta method, obtained by subtracting the monthly mean values during 1976-2005 from those in 2070-2099, where the future period is simulated based on RCP8.5, representing the “business-as-usual” scenario assuming continued strong greenhouse gas emissions through 2100.

Since we used the 2070-2099 period for the future climate forcing, the ROMS experiments need to be adjusted to estimate the changes in 2050. We explored several ways to accomplish this and one that appeared to work well was to use the global average change in radiative forcing from the RCP8.5 scenario. The change in forcing from 1976-2005 to 2050 is 3.1 Wm^{-2} and to 2085 is 5.68 Wm^{-2}. So, the differences between the CTRL and climate change simulations presented here are scaled by 0.546 (3.1/5.68) to estimate the changes that occur by 2050.

Three future simulations were conducted in which the delta values were obtained from global climate models used in the fifth IPCC assessment: the GFDL ESM2M, Institute Pierre Simon Laplace (IPSL) CM5A-MR, and the Hadley Center HadGEM2-CC (HadGEM). The three models differed in terms of how they simulated the present-day climate (e.g. strength of the Gulf Stream) and how strongly they responded to greenhouse gases.

BNAM Methods

The Fisheries and Oceans Canada (DFO) future climate modelling was done using the BIO North Atlantic Model (Brickman et al., 2016, 2018; Wang et al., 2019). BNAM is a high resolution (1/12-deg) model of the North Atlantic Ocean based on the NEMO-OPA code (Madec, 2008). The z-level model has 50 vertical levels, partial cells for the bottom layer, and a horizontal resolution in the Gulf of Maine region of about 5km. BNAM was designed specifically to resolve the interaction of the Gulf Stream and Labrador Current at the tail of the Grand Banks which is required to simulate changes in Maritime Canadian waters, including the Gulf of Maine. BNAM is run in present and future climate modes.

Forcings for the BNAM future climate simulations are derived as anomalies from an ensemble of six IPCC coupled atmosphere-ocean future climate runs for two future periods (2055 (2046-2065) and 2075 (2066-2085)), and two RCPs: 8.5 & 4.5. The four future climate scenarios also include predictions of future river runoff, and a representation of the expected increase in melting of the Greenland glacier (the latter has a noticeable effect).

The present ocean climate is simulated using the (repeat cycle) CORE Normal Year atmospheric forcing (Large and Yeager, 2004). Future climate anomalies are added to the present climate forcing to create the 4 future climate forcings. The resulting ocean model simulations produce climatologies for the future periods 2055 and 2075 for RCPs 8.5 & 4.5. Results are typically presented as spatial fields of future climate anomalies, i.e. as differences between the model future and present climates. This allows the model output to be added to present climate fields derived from a variety of sources (Delta method).

Appendix II: Detailed Downscaling Results

ROMS Results

All three ROMS simulations indicate warming of the annual mean SST over the entire Gulf of Maine, ranging from 1.5-2.0 °C, 1.75-2.25°C and 2.25-2.75°C (relative to 1976-2005 baseline) in the simulations driven by the GFDL, IPSL and HadGEM climate models, respectively (Fig. S1 b, c, d). This ordering is consistent with the overall sensitivity of the three climate models: the Hadley model has the strongest global warming and warmest temperatures over North America and the Arctic, followed by IPSL and then GFDL. Although the exact location of the strongest warming varies among the models, the greatest warming occurs at or near the Maine coast and over shallower areas south and east of Cape Cod including Georges bank in all three simulations (Figure S1). The warming varies with the seasons, with the strongest warming occurring in late summer-early fall when the mixed layer is shallow and heating from the atmosphere resides closer to the surface (Figure S2a).

The annual mean surface salinity response (Figure S3) differs among the three simulations, with a decrease in the ROMS-GFDL simulation and ROMS-HadGEM but an increase in ROMS-IPSL. However, all show a decrease in salinity on the Scotian Shelf extending into the eastern edge of the Gulf of Maine. The freshening is especially strong in ROMS-GFDL resulting from a strong decrease in salinity over the whole North Atlantic and stronger southeastward coastal currents on the Scotian Shelf, both of which lead to fresher water being transported to the Gulf of Maine (Alexander et al. 2019; Shin and Alexander 2019). The annual cycle of surface salinity response (Figure S2b) is opposite to that of temperature with the strongest decreases occurring in summer in all three simulations, when even the ROMS-IPSL values are negative.

The simulated bottom temperature change indicates warming on the order of 1.0-2.0 °C in the ROMS-GFDL and ROMS-IPSL and 2.0-2.75 °C in the ROMS-HadGEM by 2050 (Figure S4). The warming varies by depth among the three models (Figure S5). The warming is greatest at depth in ROMS-GFDL and enters the Gulf of Maine via the deep northeast channel. The maximum warming occurs higher in the water column and intersects the bottom on the shallower parts of the shelf around the Gulf in ROMS-HadGEM and to a lesser degree in ROMS-IPSL.

The bottom salinity in both the present day and the future is strongly influenced by the complex bathymetry (structure in the ocean’s bottom depth) in the Gulf of Maine. In the present day, relative salty water enters the Gulf via the Northeast Channel and is ringed by less saline water in shallower portions of the Gulf (Figure S6). A similar process occurs to varying degrees in the climate change simulations. The increase in the salinity is confined to the vicinity of the Gulf of Maine in ROMS-GFDL but is much more expansive in the other two simulations. The shallower parts of the Gulf of Maine exhibit a decrease in salinity in ROMS-GFDL and to a much lesser degree in ROMS-HadGEM, in concordance with the freshening at the surface in these two models.

BNAM Results

The BNAM future climate simulation for RCP 8.5, (~)2050, is summarized below. Annual averages were chosen for variables as they provide an overview of the expected changes. Predicted changes in surface temperature and salinity show a fairly uniform spatial pattern. Temperature changes are uniformly positive and range from about 1.0 to 1.5 degrees (Figure S7a), while salinity changes are uniformly negative with a range from -0.2 to -0.3 PSU (Figure S7b).

Predicted changes in bottom temperatures range from 1.5-3° in the deeper waters, and 0.5-1.5° in the shallower coastal waters and on Georges Bank (Figure S8a). Changes in bottom salinity show an interesting pattern with freshening in the shallower coastal waters and on Georges Bank by about -0.25 PSU while the deeper waters show an increase in salinity of about 0.25 PSU (Figure S8b). This indicates that the deeper waters are influenced by intrusions of warm salty offshelf waters (through the Northeast Channel), while the shallower waters are affected by BNAM’s prediction of increased river inputs and precipitation in the Gulf of Maine region.

Spatial mean, annually averaged, vertical profiles of temperature and salinity were computed for the deeper waters (200m or deeper) of the Central Gulf of Maine. The temperature profile shows a uniform increase with depth ranging from 1-2° with a maximum at mid-depth (Figure S9a). Spatial variability was about 0.25+/-0.05° for all depths so is not shown. The vertical salinity profile predicts fresher water in the top ~60m but saltier water at greater depths, with a range from -0.25 to +0.25 PSU (Figure S9b). Spatial variability was about 0.15+/-0.05 PSU for all depths so is not shown. This is consistent with Figures S7 and S8 and indicates, as mentioned above, the predicted presence of warm, salty offshore waters penetrating into the Gulf of Maine at depth, counteracting the general freshening trend in the upper layers.

To see if the coastal zone behaved differently, spatial mean, annually averaged, vertical profiles of temperature and salinity were computed for the coastal waters (inside the 100m isobath, exclusive of Georges Bank) (Figure S10). In general, the temperature and salinity differences with depth are similar to those of the central Gulf of Maine, with the surface layer very slightly cooler and fresher than the central Gulf of Maine in both the present and future climate simulations. The switching to saltier waters at depth relative to the present climate is also evident in the coastal zone below ~70m. This indicates the degree to which the offshelf intrusions which enter through the Northeast Channel flood the entire deeper layers of the Gulf of Maine.

BNAM seasonal changes in surface temperature and salinity over the Gulf of Maine were computed as in Figure S2. Surface temperature changes in BNAM show weak seasonal variability, with greatest spatial variability from late summer to early winter (Figure S11-a). Surface salinity changes (Figure S11-b) also show weak seasonal variability, with greatest spatial variability from late summer to early winter.

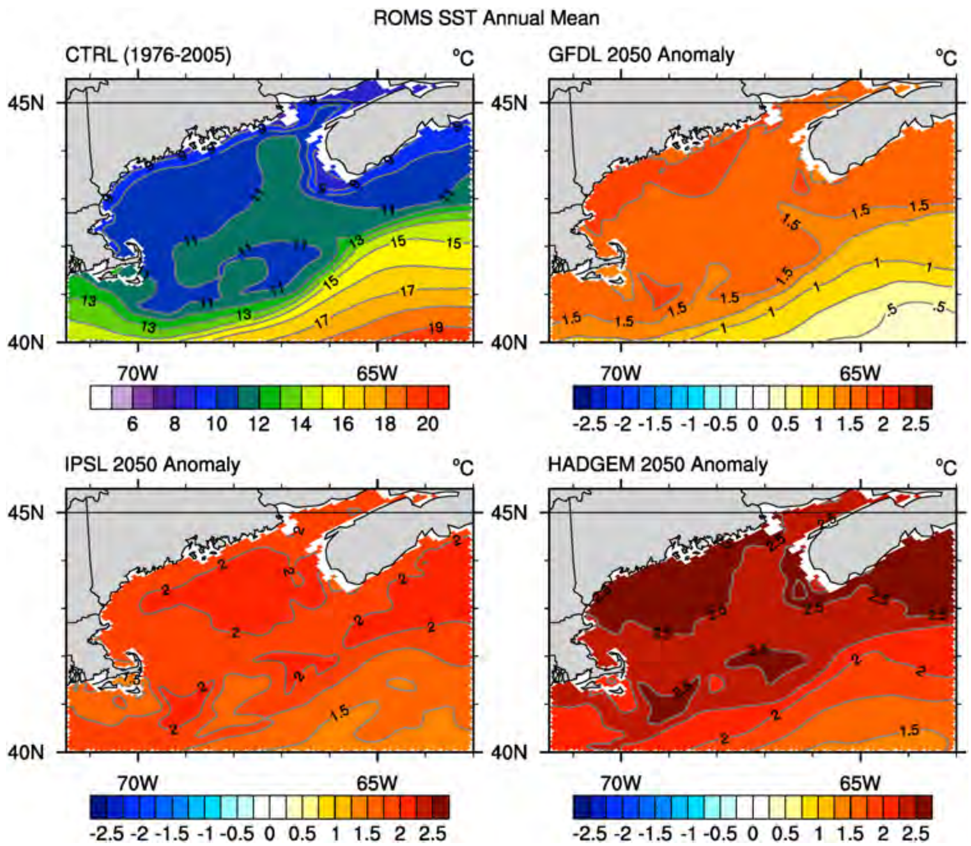
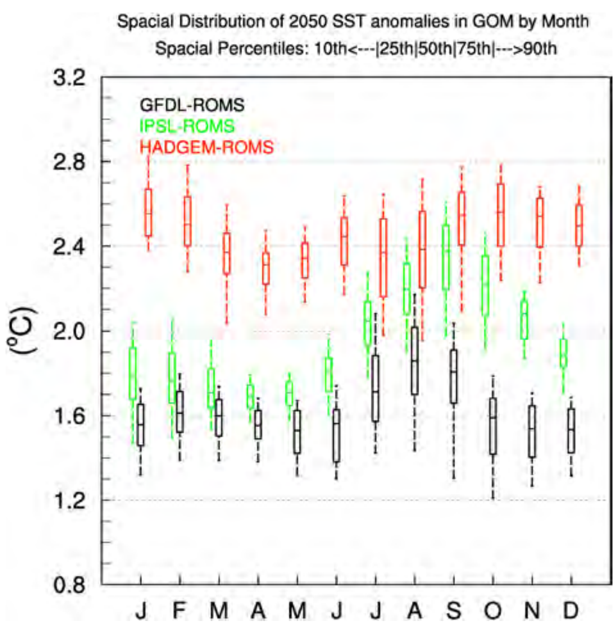


Figure S1. Annual mean SST in the a) CTRL (interval 1˚C) and the SST response in 2050 to climate change (RCP8.5 – CTRL, interval 0.25˚C) in the (b) ROMS-GFDL, (c) ROMS-IPSL, and (d) ROMS-HadGEM simulations.



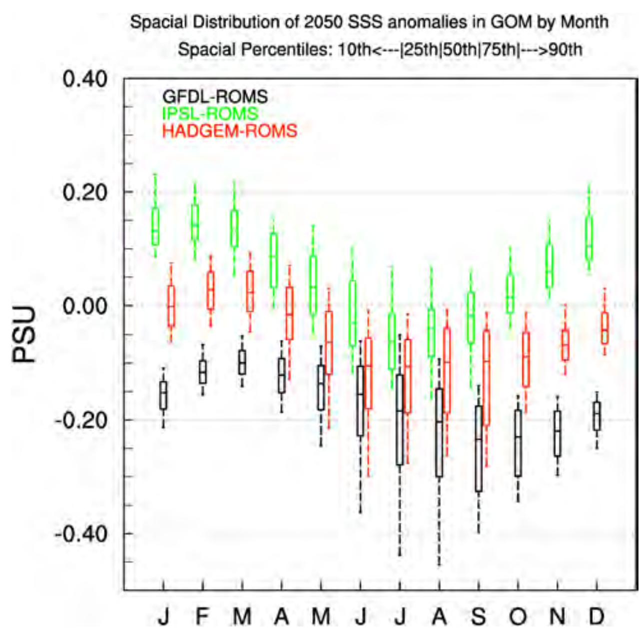


Figure S2. Bar and whiskers plot for the change in sea surface a) temperature (°C) and b) salinity (PSU) in the ROMS-GFDL, ROMS-IPSL and ROMS-HadGEM as a function of calendar month. The values are obtained from the individual grid points in the Gulf of Maine region shown in Fig. 1, where the point closest (farthest) from zero at the end of the dashed line represents the 10th (90th) percentile, the inner (outer) point of the box indicates the 25th (75th) percentile and the line in the middle of the box indicates the median – the 50th percentile.

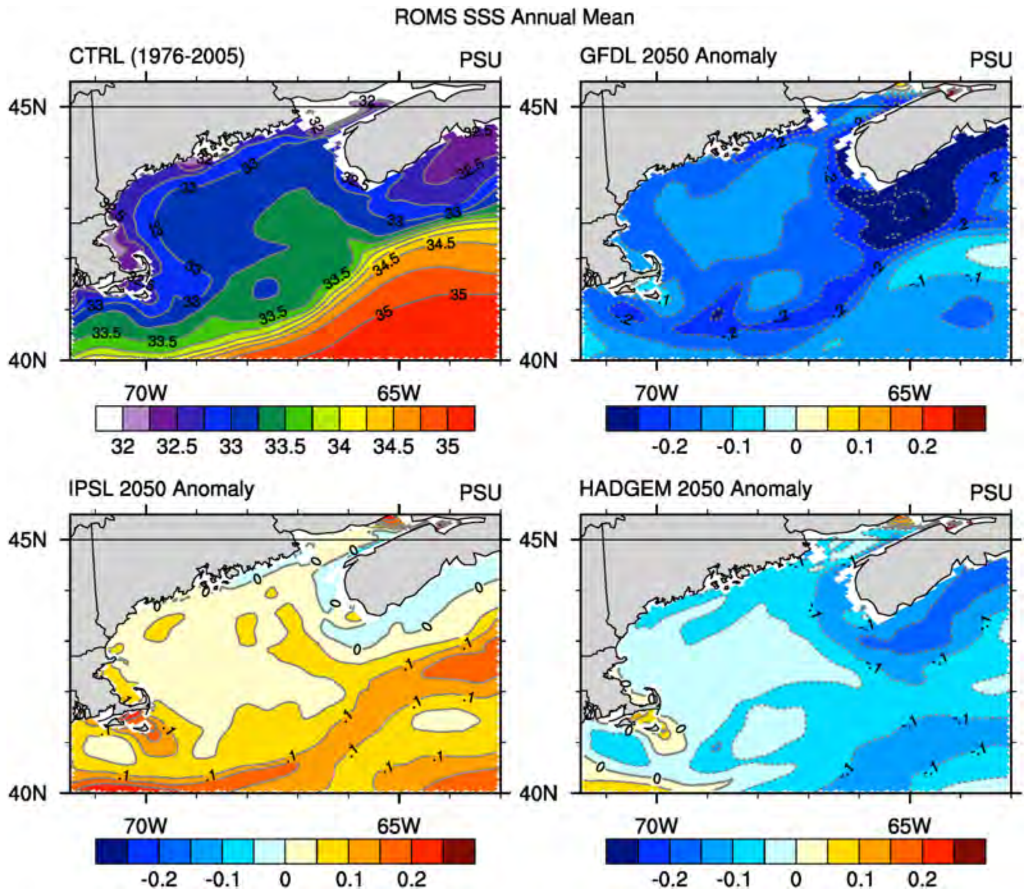


Figure S3. Annual mean surface salinity in the a) CTRL (interval 0.25 PSU) and the SST response in 2050 to climate change (interval 0.05 PSU) in the (b) ROMS-GFDL, (c) ROMS-IPSL, and (d) ROMS-HadGEM simulations. PSU stands for practical salinity unit and is similar to part per thousand.

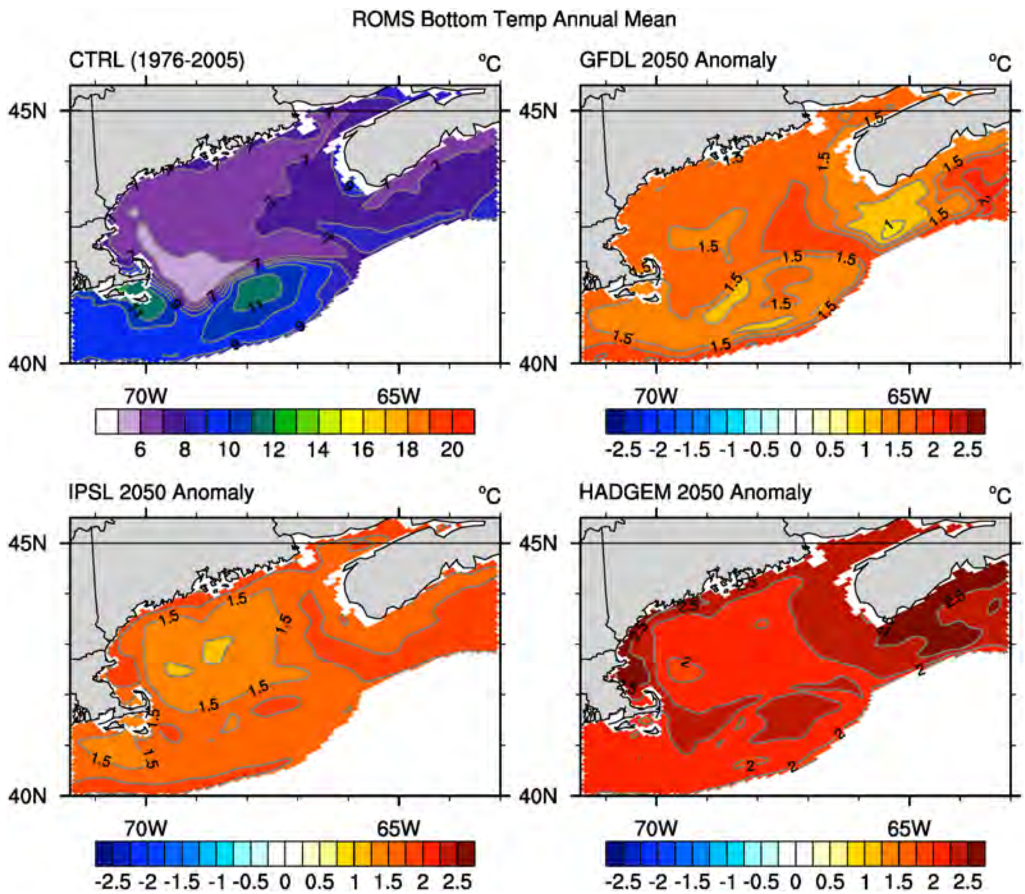


Figure S4. Bottom temperature (temperature of the model layer that is in contact with the sea bed) Only values at depth shallower than 300 m are shown.

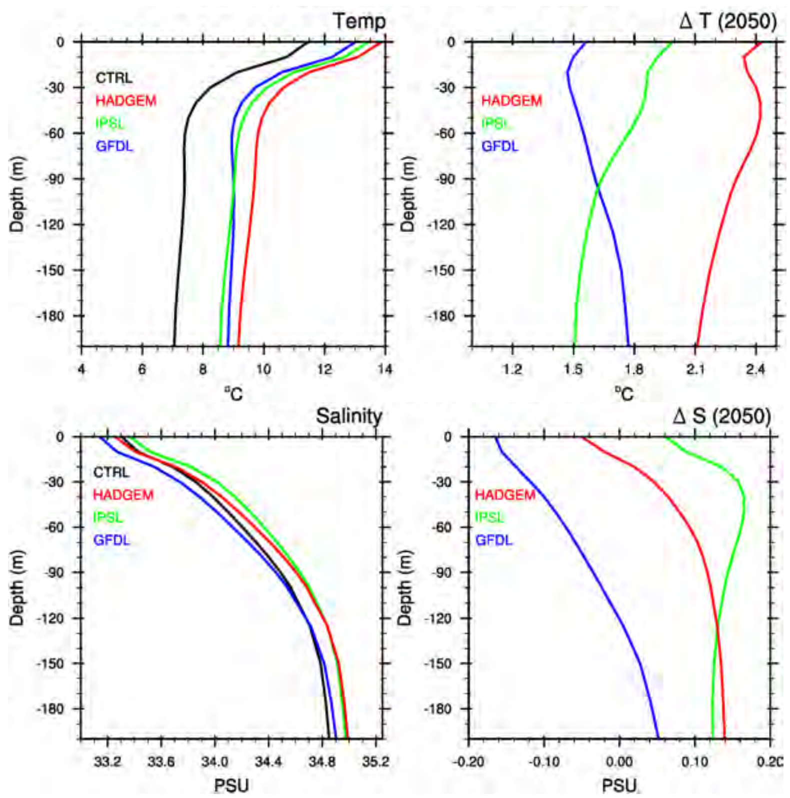


Figure S5. Vertical profiles of (a) temperature and (b) salinity in the central Gulf of Maine from the ROMS projections. In each of the left panels, the black line is the profile in the present climate (CTRL) and the colored lines are the future profiles from the three climate models in 2050. The panels on the right show the difference between future and the present.

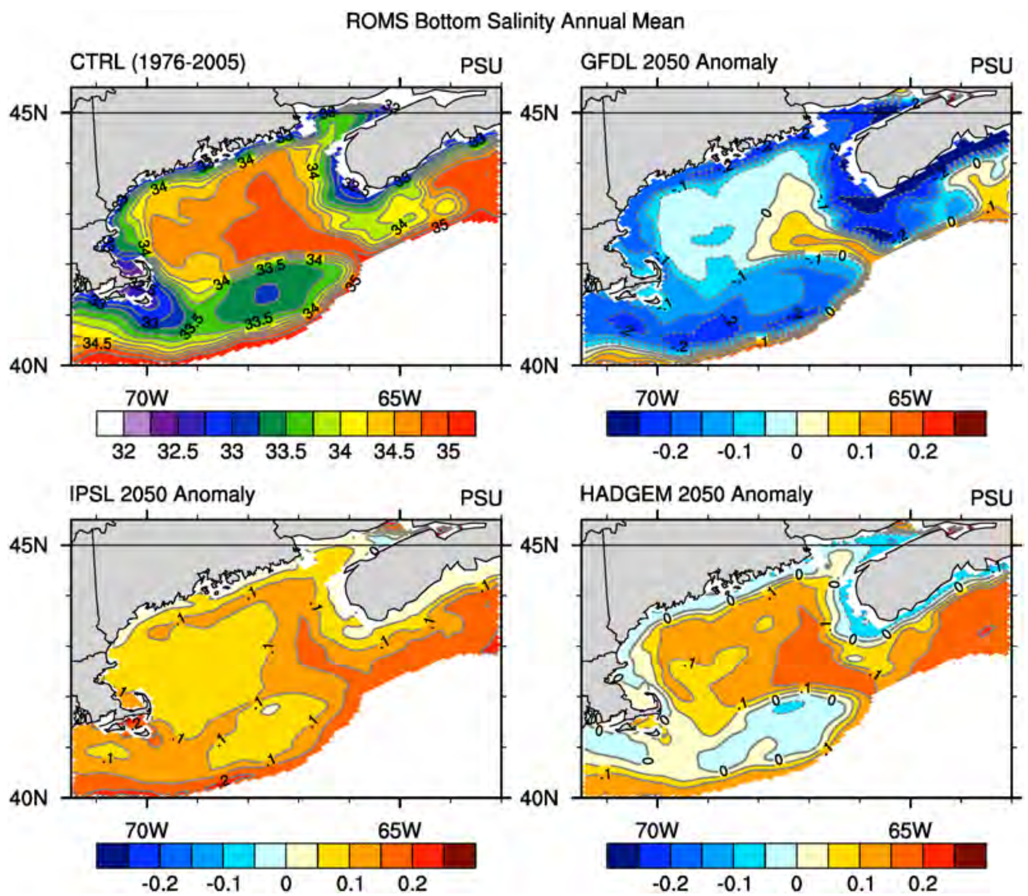


Figure S6. Same as Figure S4 but for bottom salinity anomaly

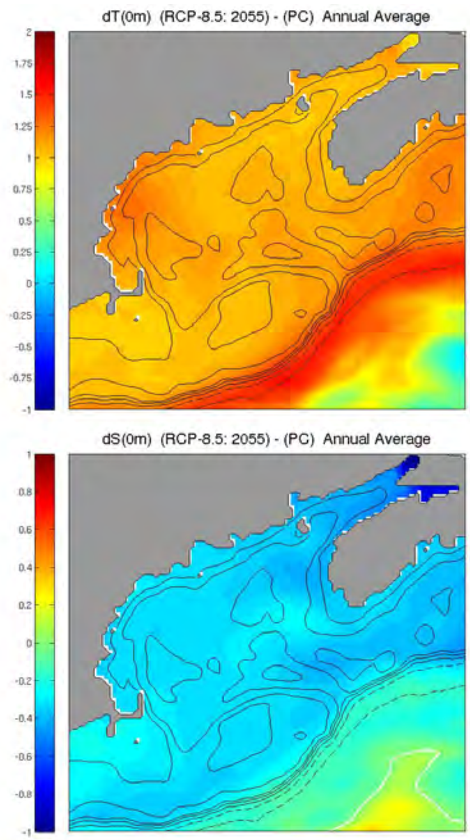


Figure S7. Surface (a) temperature and (b) salinity change in the BNAM projection

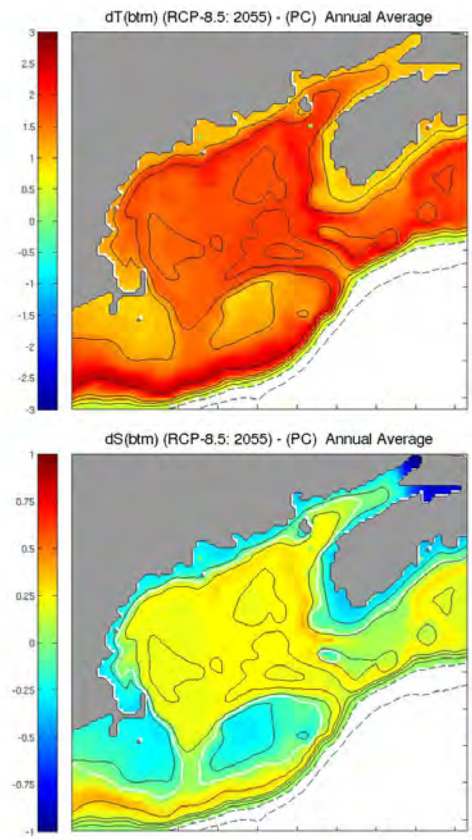


Figure S8. Bottom (a) temperature and (b) salinity from the BNAM projection.

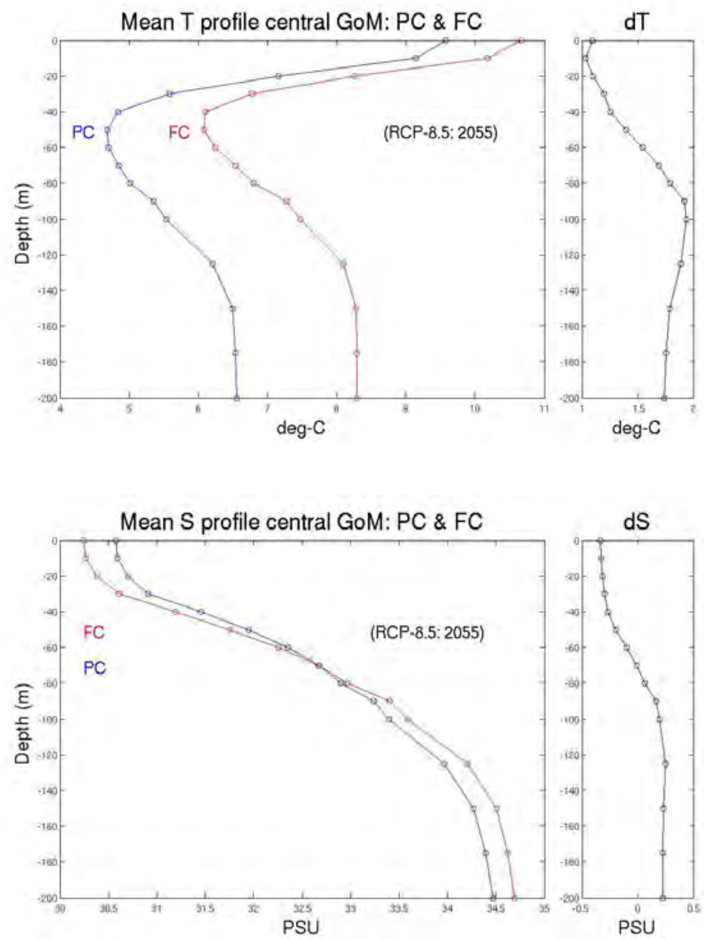


Figure S9. Vertical profiles of (a) temperature and (b) salinity in the central Gulf of Maine from the BNAM projections. In each of the left panels, the blue line is the profile in the present climate (PC) and the red line is the future climate (FC). The panels on the right show the difference between future and the present.

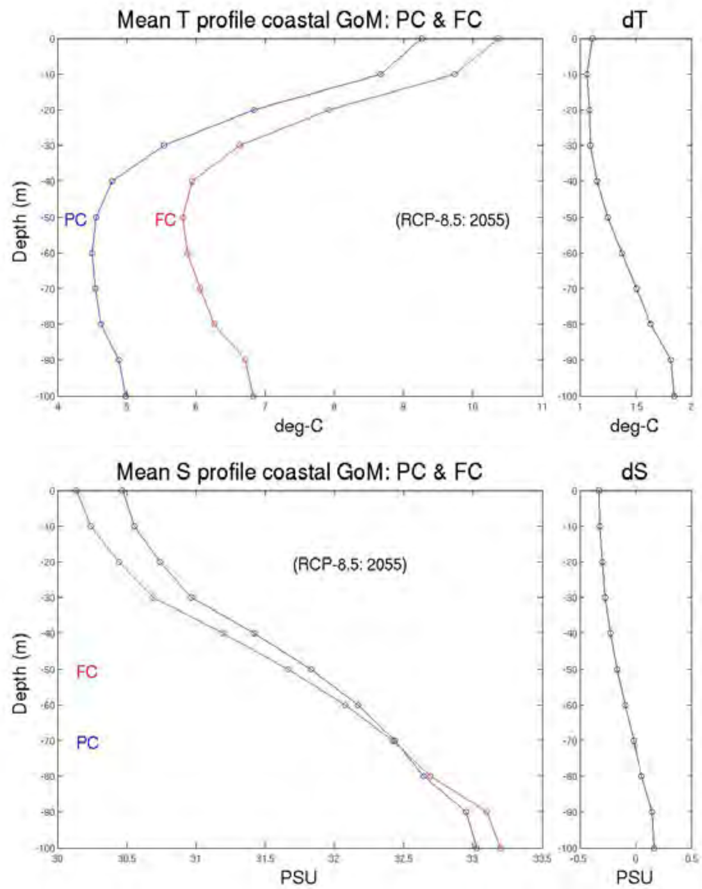


Figure S10. Same as Figure S9 but for the coastal Gulf of Maine.

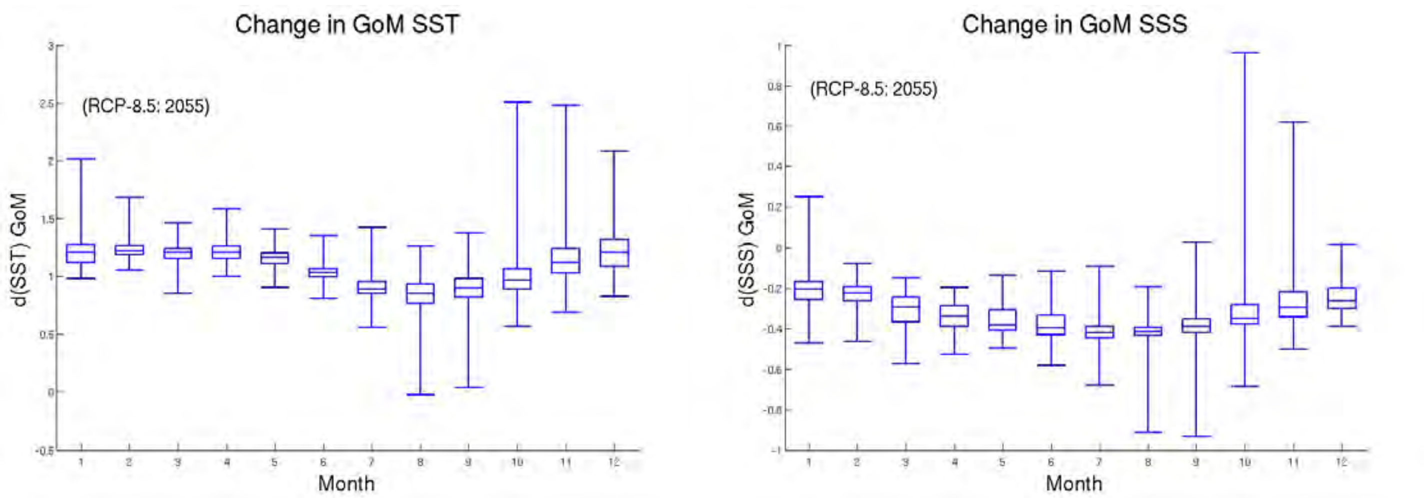


Figure S11. Bar and whiskers plot for the change in sea surface a) temperature (°C) and b) salinity (PSU) in the BNAM simulation for RCP8.5, 2055, as a function of calendar month. The values are obtained from the individual grid points in the Gulf of Maine region, where the point closest (farthest) from zero at the end of the dashed line represents the 10th (90th) percentile, the inner (outer) point of the box indicates the 25th (75th) percentile and the line in the middle of the box indicates the median – the 50th percentile.

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