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Key Points:
- Northwest Atlantic benthic temperatures will increase under future climate scenarios
- Benthic warming is likely to impact the American Lobster population
- Under either business as usual or climate policy scenarios, Southern New England's nearshore lobster fishery will likely decline further

Supporting Information:
- Supporting Information S1

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Implications of Future Northwest Atlantic Bottom Temperatures on the American Lobster (*Homarus americanus*) Fishery

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Abstract Sea surface temperatures of the northwest Atlantic have warmed dramatically over the last several decades, while benthic temperatures have increased at a slower pace. Here we analyze a subset of the CMIP5 global Earth system model ensemble using a statistical downscaling approach to determine potential future changes in benthic temperatures on the northwest Atlantic continental shelf and slope (<500 m). We put future changes in the context of possible impacts of ocean warming on the high-value, wild-caught American Lobster (*Homarus americanus*) fishery. Future bottom temperatures of the northwest Atlantic under a business-as-usual (RCP8.5) and a climate-policy (RCP4.5) scenario are projected to increase by 0–1.5°C and 1.2–2.4°C by 2050 and 0–1.9°C and 2.3–4.3°C by the end of the century for RCP4.5 and RCP8.5, respectively. *H. americanus* experiences thermal stress at temperatures above 20°C, and projected increases in temperature is likely to result in changes in the distribution of optimal thermal egg hatching and settlement indicators. Inshore regions of southern New England, where *H. americanus* biomass and catch have been declining historically, will likely become inhospitable under either future scenario, while thermal egg hatching and settlement indicators will expand offshore and in the Gulf of Maine. These changes imply that members of the fishery based in southern New England may need to recapitalize to larger vessels to prepare for potential changes brought on by future climate warming. Results from the downscaling presented here can be useful in preparing for potential changes to other fisheries or in future climate vulnerability analyses.

1. Introduction

Since the beginning of the satellite era, global sea surface temperatures (SSTs) have warmed by nearly 0.03°C/yr (Pershing et al., 2015). During the past decade or so, both global and regional SSTs have continued to break records, and warming rates have increased when compared to the long-term trend since the early 1980s (Forsyth et al., 2015; Mills et al., 2013; Pershing et al., 2015). SST is an ecologically relevant proxy of thermal conditions for many pelagic marine species occupying shallow waters. However, there is commonly a decoupling between surface and bottom temperatures, even on the continental shelf, either due to lateral current flow or seasonal stratification. This decoupling means that SST is not always the best measure to determine the impacts of warming on benthic organisms, including ecologically and commercially important species such as lobster, sea scallop, and groundfish. Additionally, the relationship between surface and benthic temperatures can vary across less than 100 km due to circulation and bathymetry. Understanding the spatial and temporal variability in future bottom water temperatures is critical to appropriately manage both benthic and pelagic ecosystems in a changing environment.

The northwest Atlantic has experienced ocean warming rates in the top 1% globally (Pershing et al., 2015), and warming SST in this region is linked to a northward shift in both fish species distribution and commercial fishing industry catch (Nye et al., 2009, Pinsky & Fogarty, 2012). The Northeast Shelf Large Marine Ecosystem contains a number of high-value and ecologically important fisheries including one of the top-grossing wild-caught fisheries in the United States, the American Lobster (*Homarus americanus*). The *H. americanus* fishery has recently grossed more than $500 million (USD) in ex vessel revenue in 2014 and 2015, employs thousands of people, and leads to substantial regional economic benefits (NMFS Commercial

Landings; National Marine Fisheries Service, 2014). This bottom dwelling, cold-water loving species also shows high sensitivity to warmer water temperatures. *H. americanus* actively avoids temperatures greater than 18°C (Atlantic States Marine Fisheries Commission (ASMFC), 2015; Crossin et al., 1998) and shows signs of biological stress under temperatures greater than 20°C (Crossin et al., 1998; Dove et al., 2005; Reynolds & Casterlin, 1979).

Regional warming is already impacting *H. americanus*, which typically uses coastal estuaries as a nursery habitat (Wahle, 1993; Wahle et al., 2009b, 2015). Because of ocean warming, many of these habitats critical to juvenile development and recruitment at the southern end of the *H. americanus* latitudinal range have become inhospitable (Wahle et al., 2009a, 2015). As a result, the productivity of many common lobster fishing grounds of southern New England has declined markedly over the past several decades (Pearce & Balcom, 2005; ASMFC, 2010, 2015). Although increasing temperatures have negatively impacted the *H. americanus* fishery toward the southern limit of the species, in the Gulf of Maine, populations have increased in size and experienced northward expansion likely due to warming waters (ASMFC, 2015). In addition, increased temperatures are linked to the onset of epizootic shell disease, a bacterial degradation of *H. americanus* shells that impacts behavior, growth, and mortality rates, reproductive success, and marketability (Glenn & Pugh, 2006; Castro et al., 2012) and implicated as playing a role in the decline of the southern New England lobster fisheries. Further north, in the Gulf of Maine, fishery yield has increased along with water temperatures (ASMFC, 2015); however, climate variability and individual warming events can alter the phenology (seasonal timing) of biological processes that may have industry-wide consequences. In 2012, an unusually warm year led to negative economic impacts when the lobster industry was ill prepared to handle the glut of landings (Mills et al., 2013).

Given both the environmental and fishery changes already observed in the northwest Atlantic, quantifying potential future changes will be important to successfully manage a sustainable fishery. Although global climate models are useful in projecting the broader-scale impacts of future greenhouse gas emissions, coastal regions are not well described by the typical resolution of IPCC-class Earth system models (e.g., 1–3° ocean horizontal resolution). In many models, the nearshore environment to a considerable span of the continental shelf is either not resolved at all or the low-resolution bathymetry does not adequately describe nearshore physical oceanography (Saba et al., 2016). As a result, projecting the influence of climate change on nearshore environments is challenging with global-scale models alone, and some form of regional downscaling is required. This work, intended to describe future potential changes to the nearshore northwest Atlantic bottom temperatures, details a case study using regional downscaling on the potential impacts of warming on the American Lobster, *Homarus americanus*, one of the top-grossing, wild-caught fisheries in the United States.

2. Methods

2.1. Historical Data

A description of the data used is given in the supporting information of this work, and described in detail in a companion paper (Kavanaugh et al., 2017). In summary, we quantified surface and benthic temperatures from CTD casts from the Northeast Fisheries Science Center's Oceanography Branch (NEFSC) (n.d.) and supplemented the NEFSC data set with high-resolution CTD casts from the World Ocean Database (WOD; Boyer et al., 2013). Surface and benthic temperatures were binned to a 34 km grid to maximize spatial resolution and data density. The region analyzed in this study, north of 36°N, had 67,717 unique CTD casts.

2.2. Climate Model Output

We analyzed model output from the 10 Earth system models used in Bopp et al. (2013) from the fifth Coupled Model Intercomparison Project (CMIP5). Model output was taken from a server hosted at WHOI (cmip5.whoi.edu) from the CMIP5 historical simulation and the RCP8.5 and RCP4.5 projections to analyze two contrasting future scenarios, a business-as-usual, and a climate policy scenario, respectfully. Each model has a different spatial and vertical extent (reported in Bopp et al., 2013, Table 1a). Full 3-D monthly potential temperature fields were first interpolated to the 34 km grid, and grid cells within our coastal domain impacted by land masks were interpolated in the zonal direction (e.g., van Hooidonk et al., 2015). Benthic potential temperatures were then extracted for each pixel.

We used the delta method to downscale the low spatial resolution, global model output to the Northeast Shelf using historical high-resolution observational data (Hamlet et al., 2010, 2012; Greive et al., 2016). The present-day historical climatology (1982–2006) from the regridded modeled hindcasts was removed from the future projections to calculate the pixel-specific change in temperature over the projection, termed the "delta," or climate perturbation. The delta value is then added to the high-resolution climatology from the gridded CTD measurements to estimate bottom temperatures from each model for the two future scenarios.

Simulated bottom-temperature trajectories from the future scenarios were used to infer potential biological impacts of climate change on both *H. americanus* recruitment and distribution. Numerous studies have quantified temperature thresholds for *H. americanus* that suggest conditions optimal for recruitment are between 12 and 18°C (ASMFC, 2015), below which eggs are less likely to hatch (Annis, 2005; Annis et al., 2013; MacKenzie, 1988) and above which juveniles and adults tend to actively avoid (Crossin et al., 1998). Temperatures above 20°C induce physiological stress across all *H. americanus* life stages (Dove et al., 2005; Glenn et al., 2007; Powers et al., 2004; Steenbergen et al., 1978; summarized in ASMFC, 2015). ASMFC (2015) found that both juvenile indices, such as young-of-year abundance, and recruit size showed a strong, positive correlation to the number of days between 12 and 18°C, but a strong, negative correlation to days above 20°C. Warmer waters have also been linked to increased incidence of epizootic shell disease (Glenn & Pugh, 2006).

The seasonal duration of temperature optima and extremes are important to understand climate impacts on *H. americanus*. Because we downscaled temporally coarse monthly model output, sinusoids were fit to mean monthly potential temperature projections using nonlinear least squares regression. Each year, the number of days between 12 and 18°C and above 20°C, maximum, and minimum temperatures were quantified from the sinusoid regressions. As this work focuses on the decadal time scale changes in future bottom temperature, we quantified 20 year running means of temperatures and phenology variables using locally

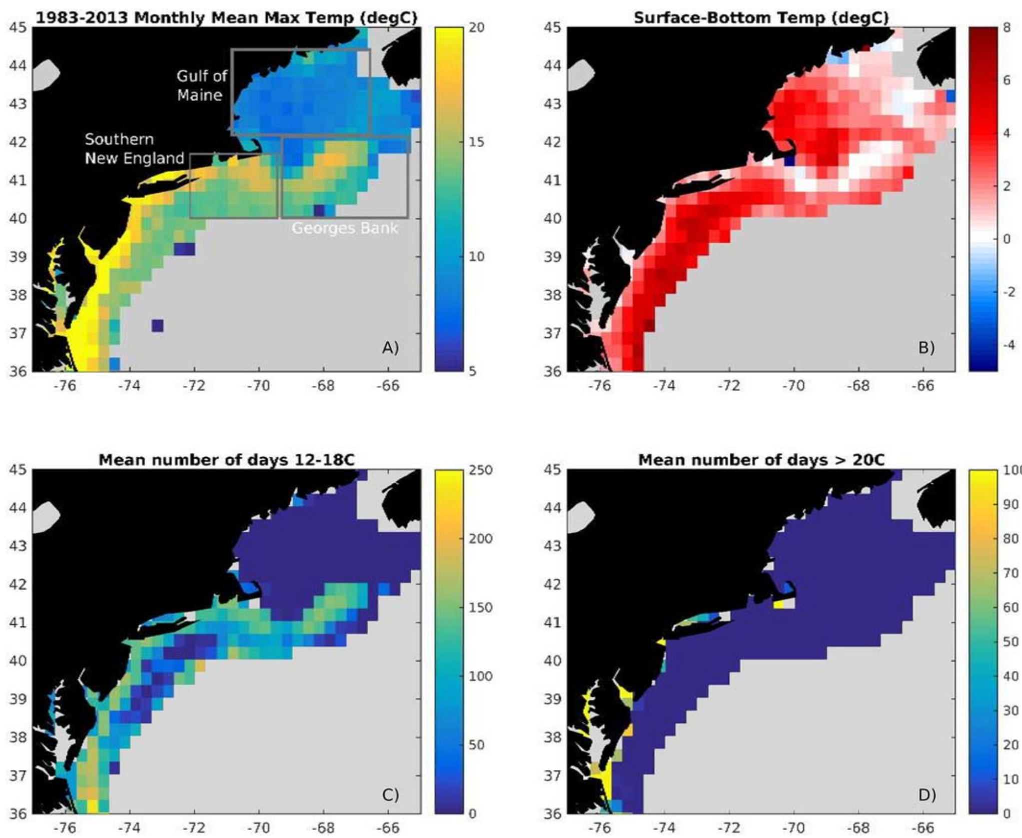

Figure 1. (a) Monthly mean maximum bottom temperature over the 1983–2014 period from the spatially interpolated data set described in Kavanaugh et al. (2017). (b) The 1983–2014 mean thermal stratification during August illustrated as the difference between surface and bottom temperatures. The 1983–2014 mean number of days between (c) 12 and 18°C and (d) >20°C.

weighted scatterplot smoothing (LOWESS). Because of differences among the individual models, we analyzed the changes in bottom temperatures and phenology on the model ensemble mean, treating the individual models as replicates to estimate uncertainty. Future downscaled bottom potential temperature projections were analyzed for long-term trends using linear regression. The three regions highlighted in this study, southern New England, Georges Bank, and the Gulf of Maine, are shown as boxes in Figure 1.

3. Results

3.1. Historical Data

A detailed analysis of statistically interpolated historical bottom temperatures for the Northeast shelf can be found in a companion paper (Kavanaugh et al., 2017; draft in supporting information). For the sake of context, we summarize the major patterns observed in the historical data set (Figure 1; Kavanaugh et al., 2017). Maximum monthly bottom temperatures ranged from ~7°C in the Gulf of Maine to >20°C in coastal waters across the study region (Figure 1a). Waters ranged from vertically well mixed during winter months, to strongly thermally stratified during summertime, with the exception of the central portion of Georges Bank, which remained tidally mixed throughout the year (Figure 1b, example field from August). Historical biological thermal indicators for *H. americanus* (e.g., number of days between 12 and 18°C, and number of days > 20°C), derived using the data described in Kavanaugh et al. (2017), varied across the study region, both with latitude and with bathymetry (Figures 1c and 1d). Rates of change in benthic temperatures over the 1982–2014 period ranged from −0.028 to 0.058°C yr^{-1} with the fastest rates in shallow regions and in the well-mixed portions of Georges Bank (supporting information Figure S5; see Kavanuagh et al., submitted, 2017).

We compared the downscaled historical model hindcasts plus 9 years of the RCP8.5 future projection (1982–2014) to the statistically interpolated bottom temperature measurements described in Kavanaugh et al. (2017). Although we used some data from a future projection, the model forcings, specifically atmospheric CO_2, used for the projections over the 2006–2014 period are very similar to measured conditions. Total spatiotemporal root mean square errors (RMSE) among the model ensemble, calculated as in Lima and Doney (2004), varied from 1.51 to 2.05°C averaged across the Northeast shelf. The model ensemble mean best described the binned bottom temperatures with total spatiotemporal RMSE of 1.50°C. With the exception of three pixels, model bias in ensemble mean historical bottom temperatures ranged from a minimum of −1.29°C to a maximum of 1.85°C, with a mean ± standard deviation of 0.21 ± 0.42°C. RMSE calculated over time for individual pixels for the downscaled hindcast varied spatially (supporting information Figure S3) from ~1 to 4°C with relatively low values in the Gulf of Maine and higher values in the southern mid-Atlantic bight. Model-data temporal correlations at the pixel scale were statistically significant over much of the grid, particularly on the inner shelf along the Mid-Atlantic Bight and in the Gulf of Maine (supporting information Figure S4 model-data-correlations).

We also compared long-term trends in the modeled and observed deviations from the monthly seasonal cycle. The hindcasts showed consistent increasing long-term trends across the full study region, while the interpolated observational data set showed mixed increasing and flat trends (Kavanuagh et al., submitted, 2017). Long-term trends in the modeled hindcast were consistently larger than those from the historical data set but the spatial patterns in trends were fairly consistent with larger warming rates in nearshore waters in the Mid Atlantic Bight and throughout the Gulf of Maine as well as, to a lesser extent, along the southern and northern edges of Georges Bank (supporting information Figure S5).

3.2. Future Projections

Downscaled ensemble mean annual bottom temperatures are projected to increase compared to a baseline of the historical mean (1982–2005) by between 0–1.5°C and 1.2–2.4°C by 2050 and 0–1.9°C and 2.3–4.3°C by the end of the century for RCP4.5 and RCP8.5, respectively. Both scenarios showed a high degree of spatial variability in warming rates but agreed that the Gulf of Maine region has the largest projected warming rates across the entire study area regardless of future scenario (Figure 2). The magnitude of the warming trends in the RCP8.5 scenario exceeded the modeled historical trends on average; RCP4.5 and modeled historical trends were more similar. However, in both scenarios, the north-south spatial warming pattern for the future projections (Figure 2) differed qualitatively from the onshore-offshore pattern in the modeled historical hindcast (supporting information Figure S5).

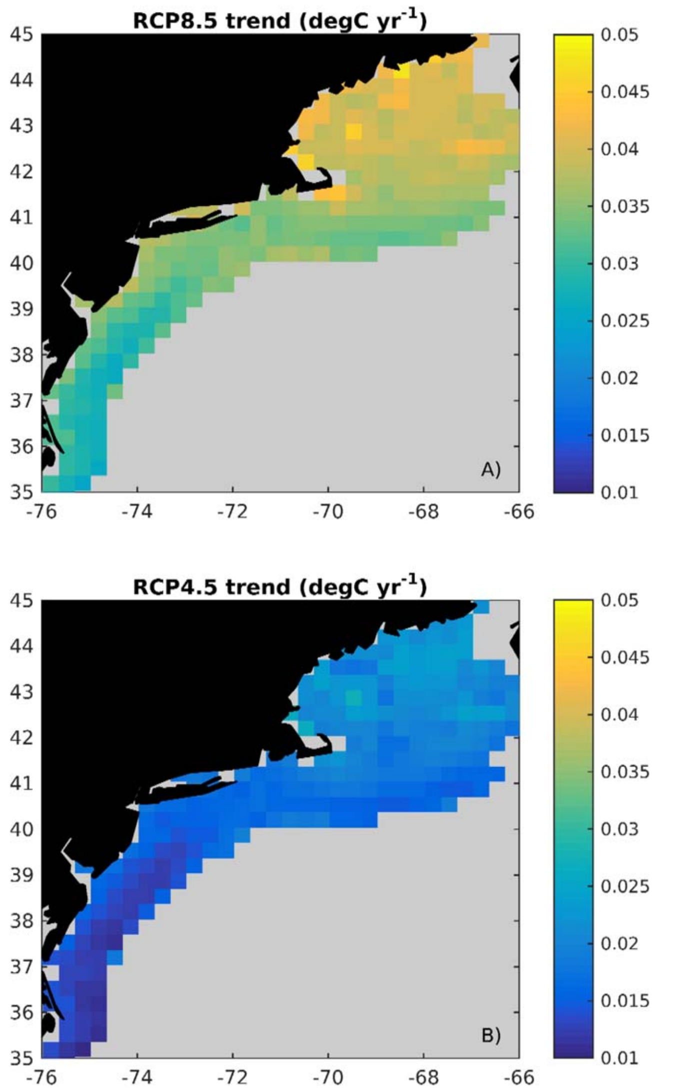

Figure 2. Projected annual mean bottom temperature linear rate of change (°C yr^{-1}) from 2006 to 2100 for (a) RCP8.5 and (b) RCP4.5. Greyed regions are not analyzed.

Benthic recruitment indices for *H. americanus*, defined as areas with sufficient time between 12 and 18°C to induce egg hatching and larval survival (ASMFC, 2014), varied regionally and with time over the Northeast Shelf. Consistent across both RCP4.5 and RCP8.5, thermal egg hatching and larval settlement indices in inshore areas in the southern New England region ($<$40 km from the coast) declined over the projection, while indices in southern New England offshore areas increased (Figures 3 and 5). There was a corresponding increase in the length of high-stress periods, indicated by increase in the annual number of days $>$ 20°C for inshore areas of southern New England in both future projections (Figures 4 and 5). Under both RCP4.5 and RCP8.5, biological indicators in offshore regions of southern New England and Georges Bank increased (Figures 3 and 5), and the number of days $>$ 20°C increased only in the region of Georges Bank (Figure 5) that remains relatively well mixed throughout the year (Figure 1b, also see Kavanaugh et al., 2017). For the Gulf of Maine region, thermal biological indices increased only in portions of the nearshore areas under RCP4.5 (Figures 3 and 5), while thermal biological indices increased for nearly all of the Gulf of Maine, both inshore and offshore areas, under RCP8.5. The annual number of days $>$ 20°C did not increase in the Gulf of Maine under either future scenario. Although there was considerable variability among the model ensemble (shaded regions of Figures 3 and 4), all models agreed that there is likely to be northward and offshore habitat expansion along with reductions in habitat in nearshore southern regions.

4. Discussion

Historical benthic temperatures increased for much of the northwest Atlantic over the 1982–2014 period for the region north of 35° (Kavanaugh et al., 2017, supporting information Figure S5). The fastest rates were observed in nearshore waters (0.05 $>$ °C yr^{-1}, Kavanaugh et al., 2017) and on Georges Bank (0.03°C yr^{-1}, Kavanaugh et al., 2017), agreeing well with high-resolution model results from Saba et al. (2016). Our estimates of the historical modeled warming rates and results from Kavanaugh et al. (2017) also agreed well with recent analyses of shelf trends off the New Jersey shoreline (e.g., 0.028–0.037°C yr^{-1}, modeled hindcast; 0.011–0.026, Kavanaugh et al., 2017; 0.005–0.04°C yr^{-1}; Forsyth et al., 2015).

The historical model ensemble mean presented here generally agreed with our analysis of observational CTD data in terms of the spatial pattern of warming, with greatest increases nearshore and on Georges Bank (supporting information Figure S5a). Although the modeled hindcast reproduced spatial patterns in historical warming rates, the simulated magnitude of the warming rate deviated with the model showing, on average, warming rates that were twice as large as observed in the interpolated data set (supporting information Figure S5b). Additionally, the interannual variability in modeled bottom temperature was also $\sim$50% smaller than the historical interpolated data set. It is not completely surprising that our simplified downscaling technique has some difficulty reproducing historical trends and interannual variability in the study region given the complexity in bathymetry, variations in performance for individual models within the ensemble (Saba et al., 2016), vertical decoupling of surface and bottom temperatures, and the relatively short comparison period that includes natural variability as well as secular trends. Nevertheless, analyses of future change relative to historical baselines are useful to plan and prepare for a changing future and have been identified as necessary strategy elements in regional climate plans (Hare et al., 2016a, 2016b).

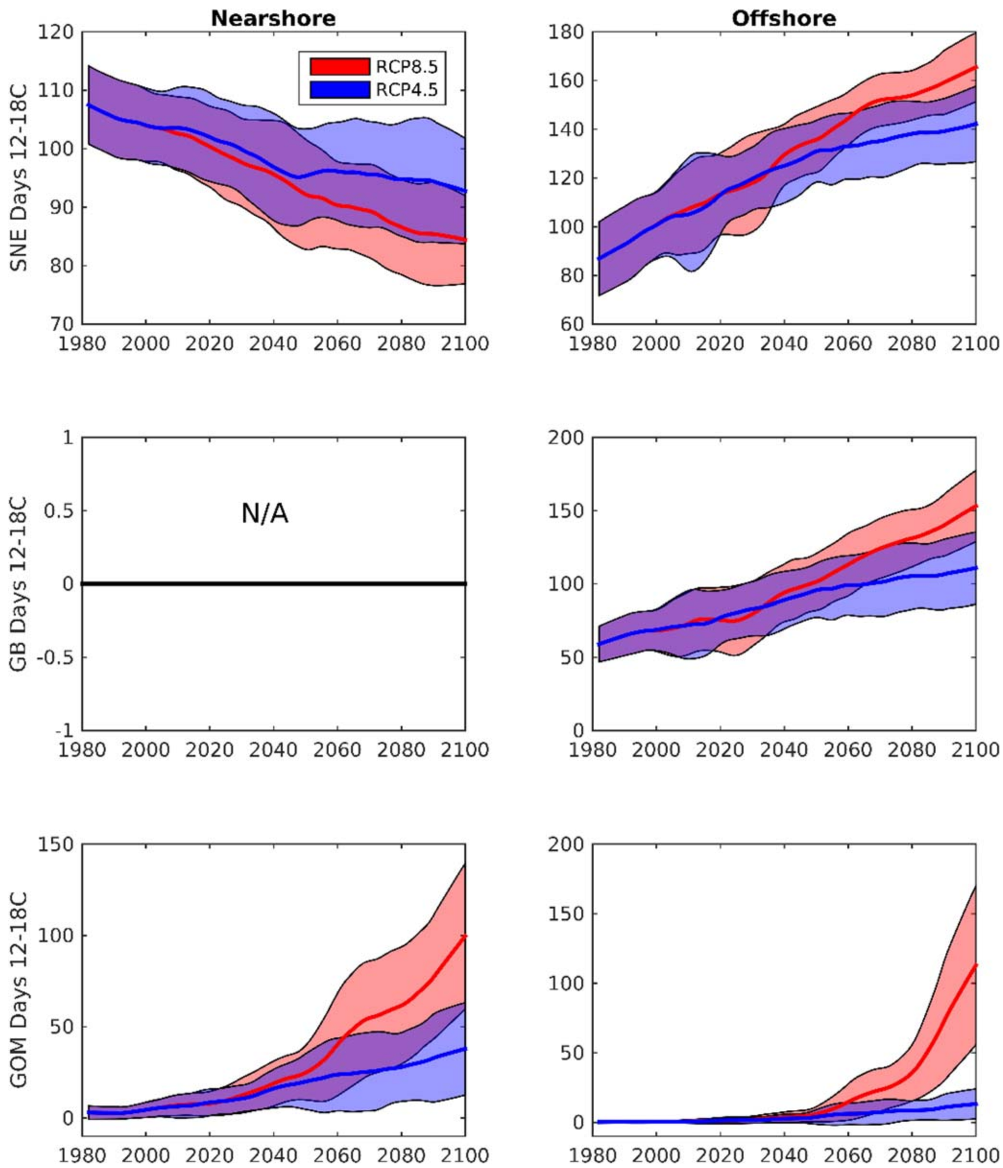

Figure 3. Nearshore and offshore number of days annually between 12 and 18°C under RCP8.5 (red) and RCP4.5 (blue) for southern New England (SNE), Georges Bank (GB), and the Gulf of Maine (GOM). There is no nearshore region in GB (panel left blank). The thick lines are the model ensemble mean, and shading shows ±1 standard deviation. Model projections have been smoothed using 20 year locally weighted scatterplot (LOWESS) smoothing.

Regionally, our downscaled temperatures agreed well with end of century model projections from several recent studies (Greive et al., 2016; Kleisner et al., 2017; Maynard et al., 2016; Saba et al., 2016). Greive et al. (2016) used a high-resolution regional model of the U.S. East Coast to analyze future habitat of lionfish under two climate scenarios. Although Greive et al. (2016) did not specifically analyze bottom temperatures within our study region, they note bottom temperature changes of up to 3°C in nearshore areas south of the Delmarva Peninsula, while the largest increases in projected bottom temperatures occurred in the Gulf of Maine region. Maynard et al. (2016) applied similar downscaling techniques to data from the northwest Atlantic that suggests that year-round, well-mixed regions of Georges Bank may see increases in maximum monthly mean bottom temperature to above 12°C as soon as 2020. These results are consistent with our projections of 2.4–4.3°C increases by the end of the century under the RCP8.5 scenario.

Finally, Saba et al. (2016) and Kleisner et al. (2017) utilized a new, high-resolution (0.1°) version of the GFDL global climate model (CM2.6) to simulate changes associated with a doubling of preindustrial atmospheric

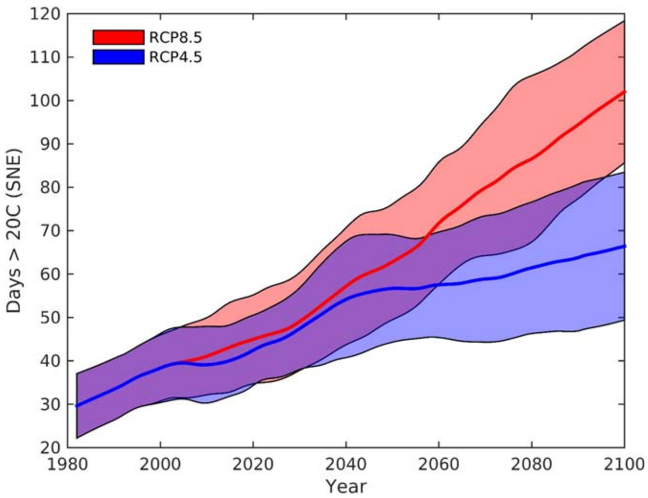

Figure 4. Number of days annually with bottom temperatures greater than 20°C in the nearshore southern New England (SNE) region for RCP8.5 (red) and RCP4.5 (blue) future projections. The thick lines are the model ensemble mean, and shading shows ±1 standard deviation. Model projections have been smoothed using 20 year locally weighted scatterplot (LOWESS) smoothing.

CO_2. CM2.6 better captures the historical changes in bottom temperature, and resolves the complex bathymetry of the Gulf of Maine, while low-resolution GCMs do not (Saba et al., 2016). As such, low-resolution GCMs tend to underestimate future bottom temperatures in this region because they do not capture intrusions of Gulf Stream water into the Gulf of Maine (Saba et al., 2016). Our statistical downscaling technique, while likely an improvement on biased GCM output, still may not reflect these increases, as illustrated by larger increases in bottom temperature predicted using climate projections from CM2.6 (up to 5.0°C on average across the northwest Atlantic shelf; Kleisner et al., 2017).

Warming is likely to impact both the *H. americanus* stock and fishery. The two contrasting climate scenarios, business-as-usual (RCP8.5) and climate policy (RCP4.5), both show large changes to the potential habitat of *H. americanus* on the Northeast continental shelf and slope. Under either future climate scenario, our results suggest the nearshore fishery of the southern New England region may not be viable by the end of century. The extent of optimal thermal egg hatching and settlement indicators (12–18°C) declines in inshore regions from the Delmarva Peninsula through Cape Cod as these areas warm under increased radiative forcing and thermal stress increases as the number of days > 20°C lengthens (Figure 4). The inshore *H. americanus* fishery of the southern New England region has already declined due to recruitment failure attributed in part to increases in thermal stress (ASMFC, 2012, 2015; Howell, 2012).

Egg bearing *H. americanus* females often migrate into coastal environments such as Long Island Sound, Narragansett Bay, and Buzzards Bay that provide critical habitat for larval development and juvenile settlement (Wahle et al., 2015). Our downscaling results do not fully capture the physics of smaller coastal estuaries

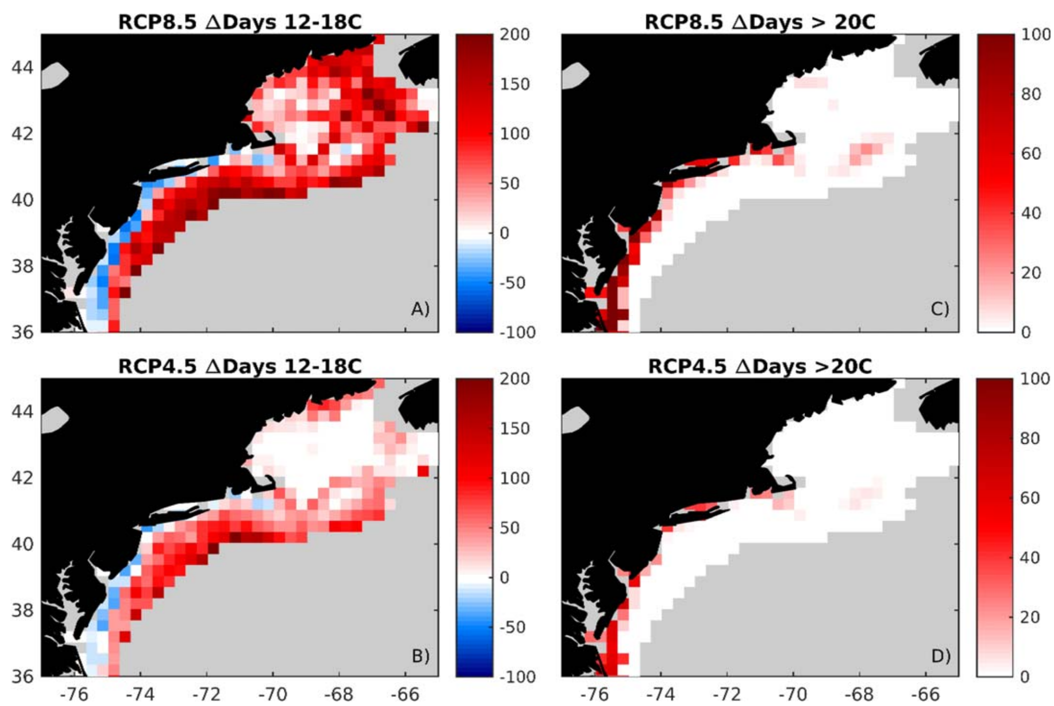

Figure 5. Change in potential habitat indicators from the mean 1982–2002 period to the 2080–2100 period under (top) RCP8.5 and (bottom) RCP4.5. (a and b) The ensemble mean change in number of days between 12 and 18°C. (c and d) The ensemble mean change in number of days > 20°C.

used by *H. americanus* females and thus may underestimate estuarine warming due to data limitations, the simplicity of the delta method, and hydrodynamics that differ substantially from open-ocean conditions simulated in Earth system models. Recent warming over the past several decades has reduced nursery habitat in nearshore waters, but thermal refugia do exist in deeper, seasonally stratified waters (Glenn et al., 2007; Wahle et al., 2015). Surveys in Narragansett Bay and Buzzards Bay show *H. americanus* females and juveniles in increasing numbers toward the cooler mouths of the estuaries, and reduced numbers or even absence from the warmer, upper reaches of the bays (ASMFC, 2010; Wahle et al., 2015). Temperature monitoring in shallow coastal areas suggests that even in stratified areas, these regions are nearly always considerably warmer during summer months than habitats on the continental shelf (Fulweiler et al., 2015; Goldstein & Watson, 2015; Oczkowski et al., 2015). Thus, it is reasonable to assume that temperatures in the relatively shallow coastal environment may be enhanced compared to nearby waters on the continental shelf (Fulweiler et al., 2015; Oczkowski et al., 2015).

Under future climate change, both RCP4.5 and RCP8.5 project increases in the number of days $> 20^\circ$C in nearshore areas of southern New England by nearly 20–80 days by the end of century (Figure 4). Increased thermal stress that drives aggregations of egg bearing females in the outer portions of nursery habitat increases the likelihood that oceanographic conditions may move larvae away from coastal nurseries of southern New England and further reduce settlement and recruitment (ASMFC, 2010; Wahle et al., 2015) with future warming in the region. Using continuous surface water monitoring and *H. americanus* survey data reported in ASMFC (2015, Tables 2.3.2 and 5.2.3.2C—CT-Fall), 5 year lagged recruitment indices were negatively correlated to the length of thermal stress (ASMFC, 2010, 2012, 2015; see supporting information). As recruitment indices were proportional to the length of thermal stress (ASMFC, 2010, 2012, 2015), the increase in number of days $> 20^\circ$C under both RCP4.5 and RCP8.5 suggests potential declines in recruitment indices by up to 90% by end of century relative to present-day conditions.

Although warming under both climate scenarios suggests further declines in the fishery toward the southern and inshore limits of the species, downscaled projections imply that the thermal egg hatching and larval settlement indicators further offshore in southern New England and Georges Bank and within the Gulf of Maine will continue to expand without the added stress of temperatures above 20°C during summer (Figure 5). Our results utilize the critical thresholds for egg hatching and larval settlement (e.g., 12–18°C). Adult individuals are more tolerant of low temperatures, and individuals are typically found within the thermal range of 5–18°C (ASMFC, 2015), agreeing with our historical bottom temperature maps (e.g., Figure 1).

These future trends describe a worsening of current conditions in the southern New England lobster fishery. Much of the current lobster fishery of southern New England has already been pushed toward cooler waters of the shelfbreak, likely related to warming impacts on traditionally rich inshore fishery grounds (Wahle et al., 2015). Regional surveys of the U.S. Northeast Large Marine Ecosystem during spring and fall clearly show a migration of the lobster resource both northward and offshore (Pinsky et al., 2013, oceanadapt.rutgers.edu), and future projections based on fall and spring temperatures using GFDL's CM2.6 model show similar movement with increases in suitable habitat in the Gulf of Maine without added stress during summer (Kleisner et al., 2017, https://www.nefsc.noaa.gov/ecosys/climate-change/projected-thermal-habitat/american-lobster.html). Although these potential future trends are already occurring, it is important to highlight that these species migrations are likely to continue, or even amplify under future climate scenarios. If all else remains equal, e.g., food availability, fishing pressure, predator abundance, etc., the northward movement of optimal conditions for egg hatching and larval survival suggests that in U.S. waters, the fishery will be largely located within the Gulf of Maine by the latter half of the century (e.g., Kleisner et al., 2017) for either future scenario, or a completely offshore fishery in the Georges Bank and southern New England regions (Figure 5). This implies continuing increasing costs of fishing due to longer steam times or a wholesale recapitalization to larger vessels capable of fishing offshore or steaming to the Gulf of Maine for existing fishermen based in southern New England. Or, if this is not possible, there could be a complete loss of economic benefits to southern New England as the fishery migrates further northward.

Current trends in inshore trawl surveys suggest increasing trends in *H. americanus* stocks in Cape Cod Bay and the Gulf of Maine (Massachusetts Division of Marine Fisheries, 2016) that is consistent with our analysis of increasing optimal habitat below thermal stress limits. However, through short-term stock assessment modeling and annual monitoring of larval settlement and young-of-year lobster juveniles from southern New England through Canadian maritime waters, there are also indications that lobster stocks and landings in the Gulf of Maine may begin declining in the near term (Wahle & Oppenheim, 2015). More data are necessary to determine if this projected decline reflects simply interannual variability in recruitment due to other factors than thermal indicators. Additionally, links between warmer waters and epizootic shell disease (Glenn & Pugh, 2006), although still uncertain, also suggest this problem could become more prevalent in waters of the Gulf of Maine under either future scenario (Maynard et al., 2016). Epizootic shell disease is more common under water temperatures greater than 12°C, thus the widespread increase in bottom temperatures between 12 and 18°C projected here in the Gulf of Maine (Figures 3 and 5) may also lead to expansion of disease range (Maynard et al., 2016) in addition to *H. americanus* habitat.

Linking our bottom temperature projections to stock assessment models of the *H. americanus* fishery would provide long-term guidance for fisheries management under changing environmental conditions. The results from multiple Earth system models all agree that under either scenario, nearshore environments south of Cape Cod are likely to become too warm for *H. americanus* with both increases in maximum temperature (1–2°C and 2–4°C among models for RCP4.5 and RCP8.5, respectively) and increases in the length of time *H. americanus* experiences thermal stress (Figures 4 and 5). These findings hold even given the wide range of uncertainty across the model ensemble shown by the envelope ($\pm$1 SD) for the thermal lobster biological indicators (Figures 3 and 4). Among the model ensemble, the standard deviation in estimated maximum benthic temperatures at the end of the 21st century ranged from 0.21 to 3.67°C depending on location, with the largest uncertainty in the tidally mixed portion of Georges Bank. While it is impossible to predict future emissions pathways, the good agreement among models for the future trajectory of *H. americanus* habitat under both contrasting business-as-usual and climate policy scenarios suggests members of the fishery should prepare for expected changes brought on by future climate warming.

The results of the downscaling presented here provide a simple framework for exploring the impact of warming on fisheries of the northwest Atlantic, though the analysis is limited by a number of assumptions. First, our downscaling of global Earth system models requires a large amount of data to develop an accurate present-day climatology of bottom temperatures for the delta method. Although there is a considerable amount of historical data available (supporting information Figures S1 and S2), the data density is low during several months of the year that may be more logistically challenging to sample (e.g., January and December). The lack of data during winter months may reduce our confidence in developing a consistent climatological bottom temperature for parts of the study region. Summer months, when stressful conditions are most likely to occur, were well sampled across the full study area. Thus, a lack of wintertime data is not likely to impact our analysis of the *H. americanus* fishery, but this issue would need to be considered for species with critical thresholds during winter months.

Second, we acknowledge that our simplified statistical downscaling method cannot fully capture the complexity of the oceanographic conditions in the northwest Atlantic. Rather, this analysis is designed to provide a prospective view on higher spatial resolution potential long-term change in this region, given how poorly low spatial resolution global models capture regional dynamics (Saba et al., 2016). We also acknowledge that while this analysis downscales monthly data, the hindcast poorly captures the interannual variability in bottom temperatures when compared to the historical data. This bias toward smaller interannual variability may affect results if investigating the impacts of interannual or episodic warming events, because the downscaled future projection would not capture or predict these infrequent events. However, this analysis focuses on the long-term means by analyzing the 20 year smoothed average temperatures over the next century and is thus not likely to be impacted by biased interannual variability. A more sophisticated downscaling technique, such as dynamical downscaling using regional model nesting or grid refinement, or more complex empirical relationships used to downscale model output, would likely provide both a higher spatial resolution, reduced bias, and more details regarding the potential mechanisms of change.

It is important to note, however, that these results may be a conservative projection of future bottom temperatures, especially in the Gulf of Maine as low-resolution GCMs may not resolve the complex bathymetry and currents of the study region. Although low-resolution GCMs have been shown to underestimate projected future temperatures under climate change scenarios (Saba et al., 2016), an underestimate of future bottom temperatures in the Gulf of Maine would not dramatically change the conclusions of this work. An additional 0.5–1.5°C would still mean expansion of the number of days between 12 and 18°C without the added stress of temperatures above 20°C. For other species however, this additional increase in temperature may exceed negative thermal thresholds, and this potential cool bias would need to be considered.

Third, this analysis simplified *H. americanus* biology by considering only the impacts of warming on egg hatching and larval settlement indicators. Future iterations of this work could include more complex approaches to *H. americanus* biology by incorporating adult thermal habitat indices. Finally, in this manuscript, we focus only on the potential impacts of future warming on a single, high-value fishery. These downscaling results could be applied to any benthic species of interest (e.g., Greive et al., 2016; Hare et al., 2016b) of the northwest Atlantic. For example, *Placopecten magellanicus*, the Atlantic sea scallop, is another benthic, cold-water loving, top-grossing fishery of this region. Given the southern range limit of *P. magellanicus* is on the continental shelf off Virginia Beach, USA, where the potential warming is prominent, *P. magellanicus* is likely be influenced by future changing bottom temperatures (Cooley et al., 2015). The discussion of the implications of warming bottom temperatures presented here assumes that other environmental factors such as dissolved oxygen, primary productivity, ocean acidification (Gehlen et al., 2014; Gledhill et al., 2015), or predator-prey ranges remain constant over the next century. This highly simplifies the potential impacts of multiple stressors as ocean physics and biogeochemistry are projected to change under future emissions scenarios (e.g., Boyd et al., 2015; Breitburg et al., 2015). However, given that major stressors tend to become worse over time under these climate scenarios (Bopp et al., 2013), it is likely that the northward and offshore movement of *H. americanus* habitat reported here is conservative.

5. Conclusions

The model downscaling presented in this study projects increases in northwest Atlantic bottom temperatures of up to 4.3°C under a business as usual climate scenario by the end of century that will likely alter the thermal range of *H. americanus* and other high-value fisheries. Our results suggest that regardless of future scenario, there will likely be declines in nearshore habitat that should be considered in future management of the *H. americanus* fishery. More broadly, regionally downscaled bottom temperatures could be used in the next iteration of climate vulnerability analyses (Hare et al., 2016b) or as environmental drivers in fisheries management models. A warm bias in historical downscaled modeled trends might imply slower future change than projected here; however, this study is intended as a first pass on higher-resolution future projections, and future iterations of this work will reduce mean biases and improve forecasts. These downscaled projections could be used to help guide fishing industry in preparation of northward movements following fish populations (e.g., Pinsky & Fogarty, 2012). A natural extension of this work would be to incorporate these changes into an ecosystem-based framework that would include multiple species interactions in the future projections (e.g., Link et al., 2010). Given the large projected changes to the northwest Atlantic under both a business-as-usual and a climate policy scenario, these results will be useful for the fisheries management community to prepare for habitat changes under future climate change.

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