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Trends and change points in surface and bottom thermal environments of the US Northeast Continental Shelf Ecosystem

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Abstract

Temperature is an important factor in defining the habitats of marine resource species. While satellite sensors operationally measure ocean surface temperatures, we depend on in situ measurements to characterize benthic habitats. Ship-based measurements were interpolated to develop a time series of gridded spring and fall, surface and bottom temperature fields for the US Northeast Shelf. Surface and bottom temperatures have increased over the study period (1968–2018) at rates between 0.18–0.31°C per decade and over a shorter time period (2004–2018) at rates between 0.26–1.49°C per decade. A change point analysis suggests that a warming regime began in the surface waters in 2011 centered on Georges Bank and the Nantucket Shoals; in following years, most of the Northeast Shelf had experienced a shift in surface temperature. A similar analysis of bottom temperature suggests a warming regime began in 2008 in the eastern Gulf of Maine; in following years, change points in temperature occurred further to the west in the Gulf of Maine, finally reaching the Middle Atlantic Bight by 2010. The spatial pattern in bottom water warming is consistent with well-known oceanographic patterns that advect warming North Atlantic waters into the Gulf of Maine. The varying spatial and temporal progression of warming in the two layers suggests they were actuated by different sets of forcing factors. We then compared these trends and change points to responses of lower and higher trophic level organisms and identified a number of coincident shifts in distribution and biomass of key forage and fisheries species.

KEYWORDS
climate change, ecosystem, regime shift, resource species, temperature

1 | INTRODUCTION

Decadal scale change in temperature has had dramatic effects on the productivity and organization of marine ecosystems, in particular, continental shelf ecosystems, which are responsible for much of the world's food security (Free et al., 2019). Temperature, and the associated effects on thermohaline stratification and circulation, plays a major role in the distribution and productivity of marine biota. Marine ecosystems depend on thermally influenced vertical mixing to resupply nutrients in surface waters, which initiates blooms and sustains primary productivity (Checkley, Asch, & Rykaczewski, 2017). Seasonal variability in currents and vertical mixing can affect the survivorship of early life history stages of fish and invertebrates (Rijnsdorp, Peck, Engelhard, Mollmann, & Pinnegar, 2009). The organisms within this dynamic environment have thermal tolerances that define where they can grow, survive, and reproduce (Brett, 1979; Neill et al., 2004). Collectively, these responses to temperature can result in shifts in community structure, which for temperate ecosystems has been termed tropicalization (Cheung et al., 2012). It is therefore critical to understand the temporal and spatial progression of temperature change in these ecosystems.

It is important to recognize that change in thermal conditions will not always progress in a monotonic fashion and that rapid non-linear change, or regime level change, can occur. Change in climate parameters by either small or large increments has been found to produce a mixture of responses (Feher et al., 2017), suggesting that the non-linear behavior of climate is compounded by the non-linear responses. Furthermore, change in climate parameters can often actuate, or are influenced by, synergistic effects of other parameters (Hewitt, Ellis, & Thrush, 2016) that complicate the interpretation of observations and confidence in predictive assessments of resource species. There is a need to understand and anticipate non-linear dynamics in our management planning, as it is highly likely that resource species will respond in a way that reflects the complexity of the underlying system (Burkett et al., 2005). Though used in many different contexts, the term regime change is usually associated with a change in conditions that have been established for a substantial period of time, represents an oscillation between stable states, and involves change in state of multiple levels of the ecosystem (Mollmann, Folke, Edwards, & Conversi, 2015). Change in thermal conditions may be indicative of regime change, but it is desirable to examine other aspects of the ecosystem before concluding whether a change in regime has truly occurred.

The Northeast U.S. Shelf (NES) is a transitional biome between ecoregions of distinctly different physical and biological characteristics, making any change in its thermal environment critical to understanding its ability to support ecosystem services. The NES has been labeled a cold temperate or boreal system (Spalding et al., 2007), bounded to the south by the confluence of the dominant current systems of the western boundary of the Atlantic Basin (Talandier et al., 2014). The NES also serves as the latitudinal boundary of many taxa, including both lower and higher trophic level species. The copepod *Calanus finmarchicus*, which has a trans-basin distribution, is abundant on the NES, which is the southern extent of its range in the western North Atlantic. It is a key component of the NES food web and may be vulnerable to latitudinal shifts in thermal habitat (Ji et al., 2017). Similar concerns exist with upper trophic level species such as Atlantic cod and American lobster. In contrast, the taxa typical of the warm temperate or Carolinian ecosystems to the south are finding expanding habitat on the NES, displacing native species (Friedland et al., 2020) and impacting human communities that exploit these species (Colburn et al., 2016). At a more fundamental level, the primary production of the NES is expressed as a two bloom system in the northern end of the ecosystem and a single bloom elsewhere (Friedland et al., 2016). Considering the importance of bloom dynamics to the benthic coupling that drives fisheries production (Friedland et al., 2012; Stock et al., 2017), latitudinal shifts in thermal conditions, and their potential impacts on bloom initiation and development, may affect the productivity of the NES.

The benthic living marine resources of the NES support productive and valuable fisheries in the region. These include the historic groundfish fishery that targets a suite of demersal fish (Thunberg & Correia, 2015) and invertebrate fisheries including those for sea scallop (Truesdell, Hart, & Chen, 2016) and American lobster (Steneck, 2006). Change in the benthic thermal regime has been associated with shifting regional productivity affecting recruitment dynamics in groundfish species such as Atlantic cod (Fogarty, Incze, Hayhoe, Mountain, & Manning, 2008), mediation of the predation pressure on scallops (Shank, Hart, & Friedland, 2012), and differential patterns of disease onset in lobster (Steneck et al., 2011). The bottom thermal environment of this ecosystem has been studied in its own right (Kavanaugh, Rheuban, Luis, & Doney, 2017) and is expected to experience changes that might affect the spatial distribution of benthic species and fishery activities (Hare et al., 2012; Rheuban, Kavanaugh, & Doney, 2017). The surface thermal regime is more closely associated with pelagic species that include some of the historically most abundant species in the region such as Atlantic herring and Atlantic mackerel (Overholtz, Link, & Suslowicz, 2000). These species have also experienced dramatic distributional changes (Turner, Hare, Richardson, & Manderson, 2017), which can be compared to the synoptic patterns of surface temperature from satellites. However, these two thermal environments play interacting roles in the function of this ecosystem and warrant examination both in isolation and concurrently.

The NES is among the fastest warming ecosystems worldwide and is expected to continue to warm through the balance of this century (Saba et al., 2016). Change in the thermal environment has been characterized in a number of different ways including estimates of long- and short-term temperature trends, but also in terms of change in seasonal dynamics and thermal phenology. The rate of warming has not proceeded equally between seasons (Friedland & Hare, 2007; Kavanaugh et al., 2017), and changes in temperature have resulted in changes in thermal phenology (Thomas et al., 2017). Regional studies provide decadal scale estimates of warming for segments of the NES and often make note of rapid warming occurring within recent decades. In the Gulf of Maine, sea surface temperature increased at rate of 0.3°C per decade over multiple decades; however, warming rate exceeded 2°C per decade from 2004–2013 (Pershing et al., 2015). In the Middle Atlantic Bight, water column integrated temperature increased at a rate of 0.23°C per decade annually, but rates ranged from 1.1–2.4°C per decade depending on the choice of contemporary years used in the calculation (Forsyth, Andres, & Gawarkiewicz, 2015). Kavanaugh et al. (2017) provided a more systematic characterization of the thermal environment of the NES by developing an analysis based on mixed data sources. They characterized bottom temperature with a regression analysis of in situ measurements and surface temperature with satellite data. The time series was constrained to the length of the satellite measurements. Benthic warming over the course of the year ranged from 0.1–0.4°C per decade with faster rates in shallower water and during winter months. More recently, temperature trends for the NES were studied by binning spatial data over eight subareas and three seasonal compartments and computing volume weighted temperatures (Wallace, Looney, & Gong, 2018). Estimates of warming rate varied by subarea with the highest rates of approximately 0.5°C per decade observed in the southern end of the ecosystem, which were nearly twice the rate of the northern end. When examining rates over different time periods, these investigators did not find any significant trends in temperature over the most recent years of the study, in contrast to other studies.

Because temperature is a key parameter in the change observed in the physical dynamics and biota of the NES ecosystem, we felt it would be timely to study both the linear and non-linear change in surface and bottom thermal environments. Specifically, we examine temperature time series for non-linear change points, which may be an indication that a regime shift has occurred (Deyoung et al., 2008). The analyses are carried out on both the temperature signal for the ecosystem as a whole and for subareas of the ecosystem to test whether change points occur in distinct spatial and temporal patterns.

2 | METHODS

2.1 | Study system

We investigated the surface and bottom thermal environments of the NES ecosystem. Surface and bottom temperatures were estimated over a 0.1° latitude/longitude grid, termed the estimation grid (Figure 1a) composed of 3,227 cells. To facilitate a more manageable summary of some aspects of the data, we analyzed data binned to a 0.5° latitude/longitude grid, termed the sample grid, also shown in Figure 1a. The sample grid contains 145 cells. The extent of these grids reflects the resource management monitoring programs that are the primary sources of the data. Ecosystem features referred to in the course of describing the results are shown in Figure 1b.

2.2 | Data Sources

The main source of temperature data was ongoing resource and ecosystem surveys of the NES conducted by the Northeast Fisheries Science Center (NEFSC) of the National Marine Fisheries Service. Water column temperatures have been collected contemporaneously to tows associated with a fall seasonal bottom trawl survey beginning in 1963; collection began five years later for the spring surveys (Desprespatanjo, Azarovitz, & Byrne, 1988). In addition, multiple sampling programs with varying designs have surveyed the ecosystem. The two most comprehensive surveys over the study period were the Marine Resources Monitoring Assessment and Prediction program or MARMAP (1977–1987) and the Ecosystem Monitoring program or EcoMon (1992-present), both providing shelf-wide surveys (Kane, 2007; K. Sherman, Solow, Jossi, & Kane, 1998). Temperature measurements were made with a mix of conductivity, temperature, and depth (CTD) instruments, analog expendable bathythermographs (XBT), digital XBTs, mechanical BT (MBT), glass thermometers (bottle temperatures), and trawl mounted temperature loggers collecting either water column profiles or temperatures measured at targeted depths. Surface and bottom temperatures were identified from these measurements; bottom temperature

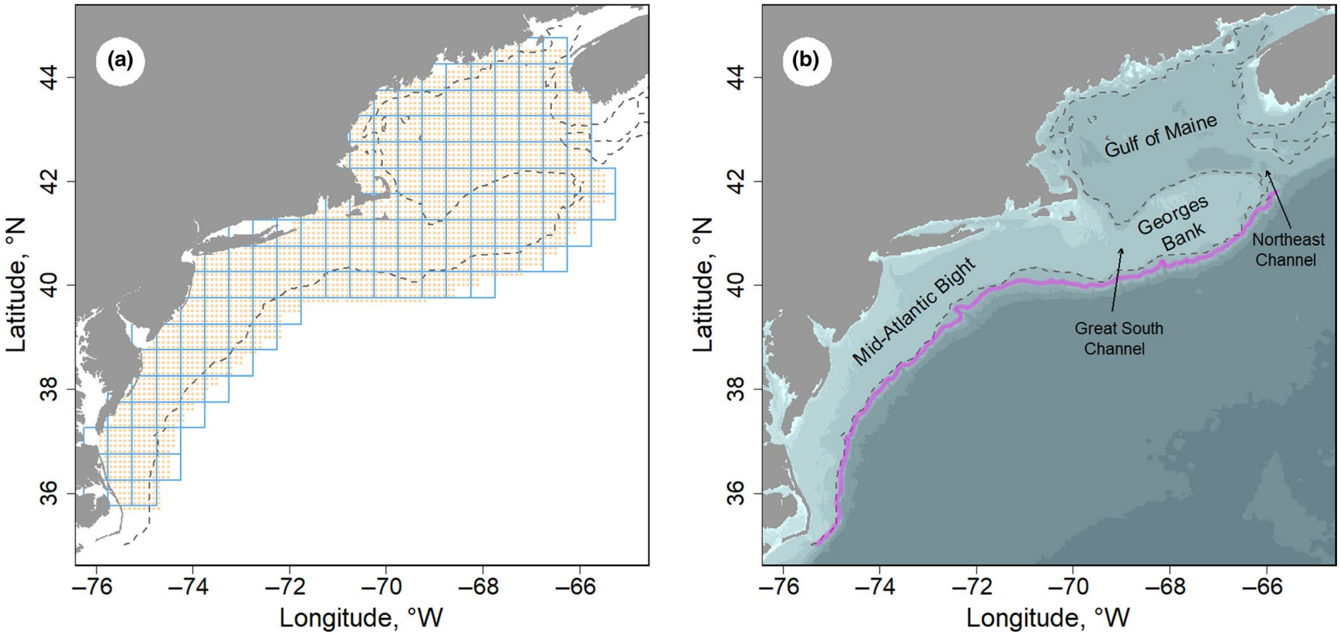


FIGURE 1 Map of the study system with half-degree sample grid (blue lines) and extent of estimation grid shown in beige points (a). Major features of the study system with shelf break marked in purple line (b). Dashed line marks 100m depth contour [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Variance explained (%), mean absolute error (°C), bias (°C), and root mean square error (°C) for surface and bottom interpolation procedure temperature estimates by season

Depth	Season	Variance Explained	Median Absolute Error	Bias	Root Mean Square Error
Surface	Spring	85	0.395	−0.085	1.11
	Fall	85	0.406	0.025	1.23
Bottom	Spring	83	0.389	−0.008	1.01
	Fall	89	0.661	−0.007	1.35

was the deepest measurement within 10 meters of the bottom. Temperatures representing the spring period were drawn from data collected during the months of February to June, and the fall period was September to December. The total number of NEFSC surface temperature measurements was 14,774 and 16,193 for spring and fall, respectively, and, 15,167 and 16,231 for spring and fall bottom temperatures, respectively. Because these sampling programs were based on random stratified designs, stations were located in different locations for each annually.

In addition to data collected by the NEFSC, we considered data collected by other institutions available from the NOAA National Centers for Environmental Information's World Ocean Database (WOD). We extracted surface and bottom temperature from the Ocean Station (OSD), CTD, XBT, and MBT WOD data sets using the same selection criteria for a surface and bottom observations used for the NESFC survey data. We also constrained the selection of observations in time and space to the distribution of the NEFSC data. For a given season and depth, the OSD, CTD, XBT, and MBT data added approximately 2000, 1,200, 2,400, and 3,200 records, respectively, for model testing.

2.3 | Interpolation procedure

Using the interpolation procedure described in Friedland, McManus, Morse, and Link (2019), we estimated annual temperature fields over the estimation grid by season (spring and fall) and depth layer (surface and bottom). We first adjusted all of the temperature data to a common collection date of April 3 for the spring data and October 11 for fall data using linear regression (see Figures S1 and S2). A temperature field for season/depth was constructed by combining what we term an annual temperature field (AT) and a compiled temperature field (CT). We created an AT field for a given year using universal kriging ("automap" r package, version 1.0–14) of the observed point data for that year with station depth as a covariate. The interpolation was cast over the estimation grid. Typically, these interpolations were informed by 300–400 observations from the main data source (NEFSC) and observations from the WOD.

Next, we constructed the CT field by first calculating time series of annual shelf-wide mean temperatures for a given season/depth. We first binned the data to the sample grid, and only those data within sample grid members with at least 80% coverage of the time series were used to estimate the time series of annual shelf-wide means. The shelf-wide mean temperature for a year at a given season/depth (m^{yr}) was subtracted from the temperature observations for that year (t), which was repeated over all years of the time series. The total number of anomalies generated over the time series for an estimation grid location ($n_{x,y}$) was divided into the sum of the anomalies.

$$aCT_{x,y} = \sum_{yr=1968}^{51} t_{x,y}^{yr} - m^{yr} - n_{x,y} \tag{1}$$

The mean of the anomalies by grid location ($aCT_{x,y}$) for the given season/depth was assembled onto the estimation grid; missing values were filled using ordinary kriging. The anomaly field was transformed to the final CT field for a particular year by adding back the mean shelf-wide temperature for that year. Hence, the CT field was informed by all the data for the season/depth being analyzed.

A final annual temperature field for a given season/depth was a mathematical combination of the AT and CT fields. These fields were combined by taking the weighted mean between them by grid location. The weighting was based on the variance field from the AT field kriging interpolation for the year being analyzed. We weighted the temperature estimates higher for the AT data in areas of low variance because these data would be most reflective of the actual observations for that year. In areas of higher variance, the CT field received greater weight. This weighting was implemented by dividing the grid into quartiles from low to higher error based on the kriging variance with the weighting ratio of AT:CT temperatures of 4:1, 3:1, 2:1, and 1:1, respectively. Hence, the final temperature at an estimation grid location (tx,y) can be represented by:

$$t_{x,y} = \left(AT_{x,y} \times w_{x,y}^{AT} + CT_{x,y} \times w_{x,y}^{CT}\right) / w_{x,y}^{AT} + w_{x,y}^{CT} \tag{2}$$

where $AT_{x,y}$ and $CT_{x,y}$ are the temperature from the AT and CT fields, respectively, and w^{AT} and w^{CT} are the weights for the respective fields.

As noted above, we extended the interpolation procedure by considering the data from the WOD. We evaluated the addition of these data by testing the sensitivity of the estimates to different combinations of the sensor types. We found that the addition of OSD, CTD, and XBT data produced the lowest errors in the bottom temperature data yielding median absolute errors of 0.389 and 0.661 in the spring and fall, respectively (see Table S1 and Table 1). The addition of CTD and XBT data produced the lowest errors in the surface temperature data with median absolute errors of 0.395 and 0.406°C in the spring and fall, respectively. The final fits for the spring and fall surface temperature models were informed by 18,153 and 19,552 observations, respectively, and the spring and fall bottom temperature models were informed by 20,356 and 22,239 observations, respectively. The number of temperature measurements averaged 375 by season, depth layer, and year.

2.4 | Analysis of trend and change points

The time series trends in temperature were analyzed on spatial scales associated with the estimation grid. Trend at each grid location was estimated using the generalized least squares model selection approach described in Hardison et al. (2019). This approach fits trend models with Gaussian, AR(1), and AR(2) correlation structures prior to selection by small sample AIC (Sugiura, 1978) and reduces estimation bias due to autocorrelated residuals when compared to linear regression or the Mann–Kendall test alone. We estimated trend at grid locations over the time series of 1968–2018, but we also evaluated trend over the more contemporary period of 2004–2018. The start year of our contemporary period matches the start year used by Pershing et al. (2015), which also quantified temperature trends in the NES ecosystem.

The identification of time series change points or potential regime shifts in the data was done with the sequential averaging algorithm called STARS or "sequential *t*-test analysis of regime shifts" (Rodionov, 2004, 2006; Thomson & Emery, 2014). The STARS algorithm parameters were specified a priori to detect change in thermal regime (alpha level $\alpha = 0.1$; the length criteria was set to 10; and the Huber weight was set to 1). We applied change point detection to time series of mean temperature, which provided a determination of the year in which a change point occurred and an index of the magnitude of the change termed the regime shift index (RSI), which is unitless. To be consistent with the terminology associated with the STARS algorithm, the change in temperature level before and after a change point is referred to as the change in regime means, which has units of °C. We also applied the change point detection to temperature time series for sample grid cells. The sum of the number of sample grid cells with a change point was quantified for each depth and season along with the mean RSI scores for that year sorted by positive and negative change in temperature. Finally, we examined the spatial distribution of change points among samples from the sample grid for those events identified in the analysis of the mean temperature series for the study area.

3 | RESULTS

3.1 | Ecosystem trends in thermal conditions

Surface temperatures of the NES increased over most of the ecosystem during the fifty-one-year time series of the study. Spring surface temperatures ranged from 1.7–15.7°C, roughly arrayed by latitude, but also influenced by bathymetry (Figure 2a). Spring long-term trends in temperature were nearly all positive, with weaker trends in the Middle Atlantic Bight (Figure 2b). The mean trend over the entire grid was 0.214°C decade^{-1}, and only half (49%) of the trends associated with grid locations were significant (Table 2). Short-term (past 15 years) trends in spring surface temperature varied by region; in the Gulf of Maine and Georges Bank areas trends were positive whereas in the Middle Atlantic Bight there was cooling (Figure 2c). Despite the regional difference in sign of the trend estimates, the mean trend for this field was 0.262°C decade^{-1} and only 7% of the trend estimates in this field were significant. Surface temperature patterns in fall were similar to spring but with a temperature range of 10.7 to 23.0°C, which represents approximately a 10°C difference from spring (Figure 2d). Long- and short-term trends in fall surface temperature were overwhelmingly positive over most of the ecosystem, with the percentage of significant trends by grid cells at 85 and 86%, respectively (Figure 2e,f). The decadal rates of warming averaged 0.311 and 1.488°C decade^{-1} for the long- and short-term fields, respectively.

The bottom temperature environment was influenced by bathymetry and was inversely arrayed with depth between spring and fall. In spring, bottom temperature was warmer in deeper regions ranging from 3.1–12.7°C (Figure 3a). Long-term trends were nearly all positive during spring (Figure 3b), averaging 0.178°C decade^{-1}, lower than observed in the surface layers (Table 2). Short-term trends in spring bottom temperature were mostly positive, with the exception of some portions of the Middle Atlantic Bight, which had negative trends, providing evidence of cooling (Figure 3c). Spring cooling in the bottom water was not nearly as developed as in the spring surface water trends. In fall, bottom temperature was warmer in shallow regions ranging from 4.9–21.0°C, which represents approximately a 5°C difference from spring (Figure 3d). As in the surface water, long- and short-term trends in fall bottom water temperature were overwhelmingly positive. The long-term trends in fall bottom water averaged 0.306°C decade^{-1}, with 77% of the field grid cell trends statistically significant (Figure 3e). The short-term trends in fall bottom water averaged 1.269°C decade^{-1}, with 68% of the field grid cell trends statistically significant (Figure 3f). However, it is worth noting that a band of cooling trends exists along the southern portion of the Middle Atlantic Bight. A general summary is that fall rates of warming tended to be greater than spring rates and short-term rates tended to be much greater than long-term rates.

3.2 | Trend and change points in ecosystem temperature

The ecosystem as a whole experienced positive temperature trends over the study period; however, change points in these time series varied by season and depth. Decadal time series trends over the study period ranged from 0.176 to 0.321°C decade^{-1}, with the lower trends observed in the spring and higher trends in the fall (Table 3). Seasonal trends in surface temperatures do not appear to be significantly different as the upper limit of the spring

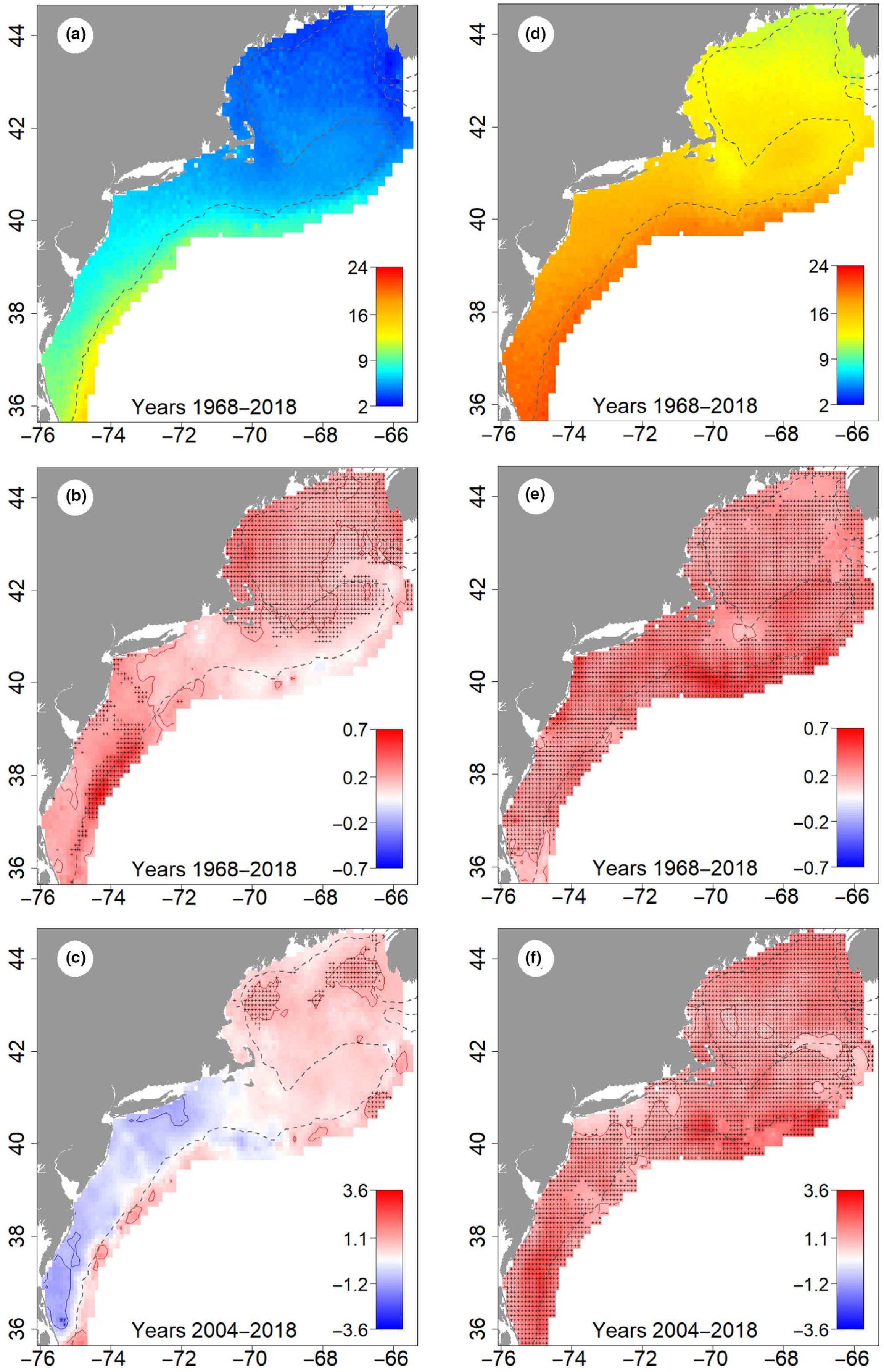

(a)
Years 1968–2018
24
16
9
2
(b)
Years 1968–2018
0.7
0.2
−0.2
−0.7
(c)
Years 2004–2018
3.6
1.1
−1.2
−3.6
(d)
Years 1968–2018
(e)
Years 1968–2018
(f)
Years 2004–2018
44
42
40
38
36
−76
−74
−72
−70
−68
−66

FIGURE 2 Spring surface temperature mean field in °C (a), decadal trend in °C decade^{-1} over the full time period 1968–2018 (b),and decadal trend over a recent time period 2004–2018 (c). The same fields for fall (d, e, and f, respectively). "+" mark grid locations with trends with $p < .05$. In full time period trend plots ± 0.2°C decade^{-1} contours marked with solid lines, in recent time period trend plots ± 1.0°C decade^{-1} contours marked. The dashed line marks the 100m depth contour [Colour figure can be viewed at wileyonlinelibrary.com]

confidence interval includes the fall trend estimate and the fall lower confidence interval includes the spring trend estimate. This is not the case for seasonal trends in bottom temperatures where the trend estimates were outside the confidence intervals of the other season.

The change point analysis found shifts in temperature or regime mean in each of the seasonal and depth layer time series. In the spring surface data, there was a change point in 1983 (Figure 4a); though the trend in these data over the entire time series was significant, the trends before and after the change points were not significant and both were negative trends indicating cooling (Table 3). For spring bottom temperatures, a change point was identified in 2016; however, since this shift occurred so late in the time series, it may not be a reliable indicator of change in regime mean (Figure 4c). The fall surface temperature experienced shifts in 1999 and 2011 (Figure 4b); the trends before and after these change points were not significant, noting that the later trends were estimated with a small sample size. Finally, the fall bottom temperature experienced a shift in 2008 (Figure 4d); like in the fall surface temperature, neither trend before or after the change point was significant.

3.3 | Spatial and temporal distribution of change points within the ecosystem

The change points detected at the sub-ecosystem level represent more complex patterns of spatial and temporal shifts than detected at the ecosystem level. For spring surface temperatures, 46 sample grid cells had positive change points in 1983 (Figure 5a) and the RSIs associated with these change points averaged 0.35 (Figure 5b). These change points correspond to the 1983 event in the whole ecosystem temperature analysis (Figure 4a); however, other change points are also evident in the spring surface data, notably cooling change points that occurred in 2013–2014. The positive change points that occurred in 1983 were located in two separate areas, one in the southern end of the ecosystem and the other on Georges Bank (Figure 6a). More detail regarding the 1983 event is evident by visualizing the location of change points in 1984 and 1985; the location of these change points were distributed between the 1983 clusters. The mean temperature for sample grid locations that had change points in 1983, 1984, and 1985 confirms the progression of change points by year (Figure 7a,b,c). The change in regime means was 0.97, 1.22, and 1.1°C, respectively. For fall surface temperatures, 22 sample grid cells had positive changes in 1999 and 53 cells had positive change points in 2011 (Figure 5c) and the RSIs associated with these change points averaged 0.77 (Figure 5d). The positive changes points that occurred in 1999 were located in the Georges Bank/Gulf of Maine area (Figure 6b). The positive change points that occurred in 2011 were located mostly in the Georges Bank area (Figure 6c). The 2011 event is further characterized by also plotting the location of change points in 2012; the location of these change points was distributed both north and south of the 2011 cluster suggesting that most of the ecosystem was enveloped in a step change in temperature. The mean temperature for sample grid locations that had change points in 1999 and 2011–2012 confirm the progression of change points by year (Figure 7d,e,f). The change in regime means was 0.70°C in 1999 and 1.32 and 1.71°C in 2011 and 2012, respectively.

The temporal and spatial progression of bottom water change points differed from those in the surface water. For spring bottom water, the highest number of change points occurred in 2016 (Figure 5e) and the RSIs associated with these change points averaged 0.25 (Figure 5f). These change points correspond to the 2016 event in the whole ecosystem temperatures analysis (Figure 4c). The 2016 positive change points were dispersed between the Middle Atlantic Bight and the Gulf of Maine (Figure 6d). For sample grid locations with change points in 2016, the mean temperature had a change in regime means of 0.98°C (Figure 7g). For fall bottom water, 47 sample grid cells had positive change points in 2008 (Figure 5g) and the RSIs associated with these change points averaged 0.60 (Figure 5h). These change points correspond to the 2008 event in the whole ecosystem temperatures analysis

TABLE 2 Mean trend in °C decade^{-1} with standard deviation (*SD*) by depth layer and season over both long (1968–2018) and short (2004–2018) time series. Count is the grid locations with significant trends ($p < .05$), and percent is the percentage of grid locations that were significant

Layer	Season	Time	Mean	*SD*	Count	Percent
Surface	Spring	Long	0.214	0.097	1591	49
		Short	0.262	0.666	210	7
	Fall	Long	0.311	0.074	2,759	85
		Short	1.488	0.425	2,784	86
Bottom	Spring	Long	0.178	0.072	1,406	44
		Short	0.835	0.520	1,229	38
	Fall	Long	0.306	0.112	2,486	77
		Short	1.269	0.619	2,208	68

(Figure 4d). It is also evident there are other change points in the fall bottom data, notably warming change points that occurred in 2009–2011. The positive change points that occurred in 2008 were located in the eastern Gulf of Maine (Figure 6e). The 2008 event is further characterized by also plotting the location of change points in 2009–2011; the locations of these change points appear to follow a counterclockwise progression in the Gulf of Maine. The 2009 change points were mostly in locations in the western Gulf of Maine, followed by the 2010 and 2011 change points that mostly occurred to the south. The mean temperature for sample grid locations that had change points in 2009–2011 confirms the progression of change points by year (Figure 7h,I,j,k). The change in regime means was in excess of 1.2°C in all four of these time series.

4 | DISCUSSION

4.1 | Change in the thermal environment

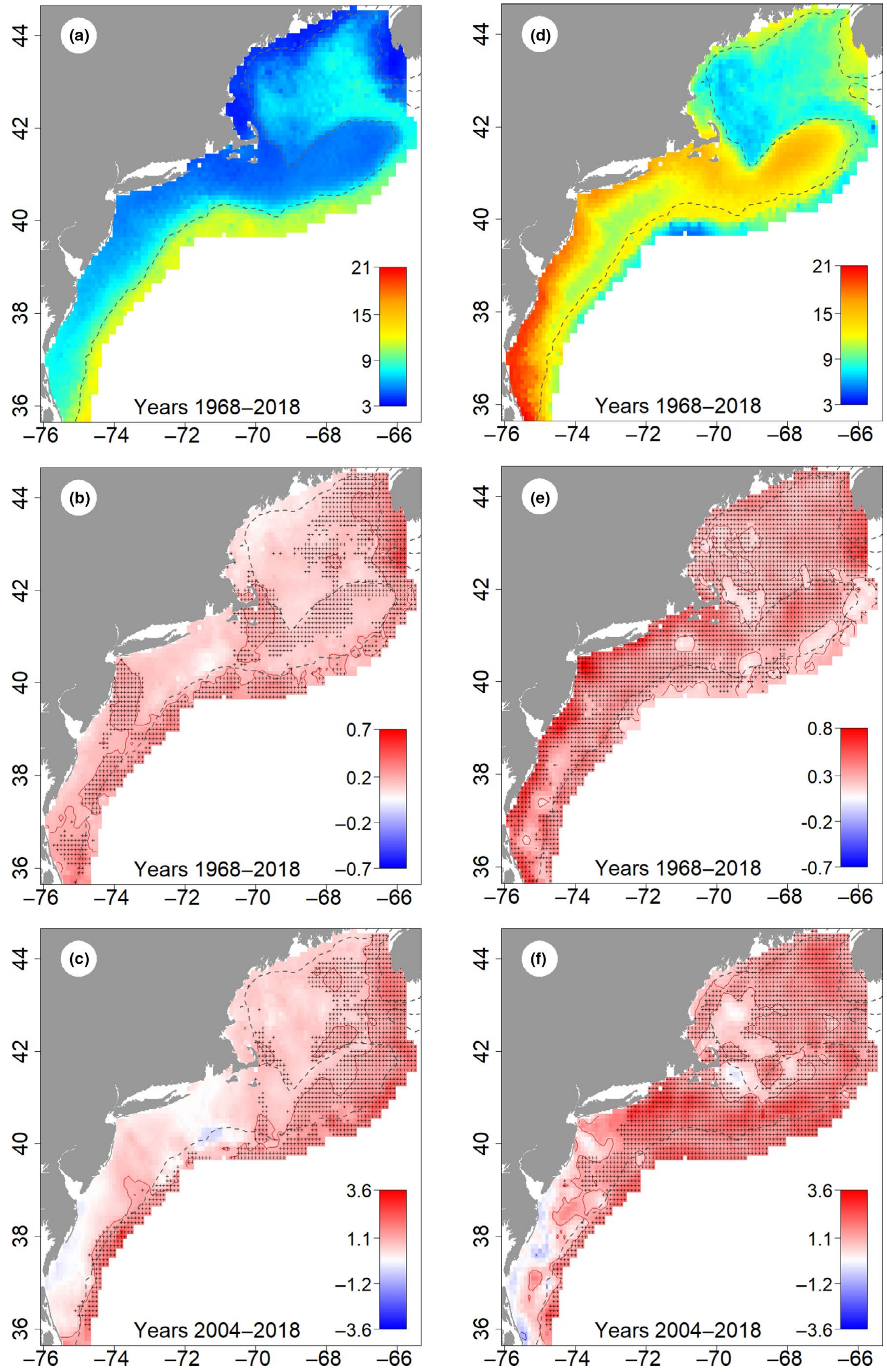
Surface and bottom temperatures in the NES have trended higher over the past half-century, with shifts in thermal conditions that were marked by distinct change points. These change points progressed differently in time and space in these two depth layers suggesting differing roles for advective and atmospheric effects. Due to its mid-latitude, western boundary location, the NES ecosystem receives strong thermal forcing from multiple processes (Townsend, Thomas, Mayer, Thomas, & Quinlan, 2006). Cold bottom waters are maintained by advection from the north over the relatively shallow Scotian Shelf (Li et al., 2014; Loder, Shore, Hannah, & Petrie, 2001) and at the shelf break through changes in position and volume of Labrador Slope water (Townsend et al., 2015). These movements are in turn related to basin scale forcing in the Northwest Atlantic (Greene et al., 2013; Xu, Kim, Nye, & Hameed, 2015). The pattern of change in fall bottom temperatures may be more heavily influenced by changing advection of Labrador slope water due to the upstream effects of the Gulf Stream on Labrador flow (Brickman, Hebert, & Wang, 2018). The factors influencing the changes in fall surface water temperature may be more complex. Spring surface temperatures are influenced by atmospheric forcing related to global teleconnections and local conditions, whereas later seasons are more influenced by oceanic effects (Chen, Curchitser, Chant, & Kang, 2018). For example, the marine heat wave of 2012, which is associated with the fall surface water change point, was the product of both advective and atmospheric processes (Chen, Gawarkiewicz, Lentz, & Bane, 2014; Chen et al., 2018). It is difficult to ignore the possibility that the change points in temperature we observed may be an indication of a regime shift in ecosystem state. Clearly, the temperature changes observed have been established for a substantial period, but we recognize that a regime shift is a more complex process than simply a change in temperature (Mollmann et al., 2015). It will be incumbent on the research community to test for change in other aspects of the ecosystem and evaluate whether change in thermal conditions is directional or oscillatory.

Our analysis expands the current understanding of linear trends in temperature in the NES by more clearly differentiating temperature change by season and spatially within the ecosystem. Our analysis suggests the rate of spring warming is substantially less than the rate of fall warming in both the surface and bottom depth layers. This has been reported previously based on surface observations (Friedland & Hare, 2007; Thomas et al., 2017) and viewed as evidence that winter conditions have remained more constant over time due to the dominant effects of advective versus atmospheric forcing during this segment of the year. However, these observations are not strictly comparable to other characterizations of seasonal differences in warming rates. Kavanaugh et al. (2017) make the comparison of seasonal rates by computing a ratio of winter warming to the rest of the year and concludes that in winter, bottom water is warming faster than surface water. We also observed differences in trend by latitude during spring with greater warming in the northern segment of the ecosystem, in particular the Gulf of Maine and Georges Bank, compared with the southern segment, the Middle Atlantic Bight. These differences were strong enough to result in negative temperature trends or cooling in the Middle Atlantic Bight. Using other seasonal demarcations, Wallace et al. (2018) suggest the northern segment of the ecosystem is warming at a slower pace than the southern segment. We are able to differentiate fall bottom water cooling along the Middle Atlantic coast, which would be consistent with recent changes in wind and upwelling patterns in that region (Forsyth, Gawarkiewicz, Andres, & Chen, 2018), suggesting our analysis is attuned to fine scale change in the thermal dynamics of the ecosystem. However, inconsistencies between the results from different studies underscore the complexity of change in temperature on the NES, likely due to strong spatial and temporal variability. We suggest that observational products, particularly focused on spatial dynamics in bottom water, need to be systematically used to validate process level hydrodynamic models in the region.

4.2 | Response to changing thermal trends

Progressive warming of the NES and adjacent water bodies has impacted the ecosystem in many ways. Some of the most demonstrative impacts of the decadal scale shifts in temperature have been changes in the distribution of fish and macroinvertebrates species (Kleisner et al., 2017; Pinsky, Worm, Fogarty, Sarmiento, &

FIGURE 3 Spring bottom temperature mean field in °C (a), decadal trend in °C decade^{-1} over the full time period 1968–2018 (b), and decadal trend over a recent time period 2004–2018 (c). The same fields for fall (d, e, and f, respectively). "+" mark grid locations with trends with $p < .05$. In full time period trend plots ± 0.2°C decade^{-1} contours marked with solid lines, in recent time period trend plots ± 1.0°C decade^{-1} contours marked. The dashed line marks the 100m depth contour [Colour figure can be viewed at wileyonlinelibrary.com]


(a)
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44
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Years 1968–2018
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21
15
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3
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–0.2
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3.6
1.1
–1.2
–3.6

TABLE 3 Trends in °C decade^{-1} with 95% confidence interval (CI) and test probability (p) by depth layer, season, and time period. Test with *p* < .05 are in bold, tests with low sample size marked with *

Layer	Season	Time	Trend	CI	*p*
Surface	Spring	1968–2018	0.216	(0.063 to 0.369)	**.007**
		1968–1982	−0.311	(−1.144 to 0.523)	.437*
		1983–2018	0.019	(−0.24 to 0.277)	.883
	Fall	1968–2018	0.321	(0.115 to 0.526)	**.015**
		1968–1998	−0.120	(−0.335 to 0.096)	.266
		1999–2010	−0.500	(−1.22 to 0.22)	.153*
		2011–2018	1.261	(−0.197 to 2.72)	.077*
Bottom	Spring	1968–2018	0.176	(0.048 to 0.304)	**.008**
		1968–2015	0.145	(0.003 to 0.286)	**.045**
	Fall	1968–2018	0.305	(0.181 to 0.429)	**<.001**
		1968–2007	0.128	(−0.047 to 0.304)	.146
		2008–2016	0.601	(−0.318 to 1.519)	.174*

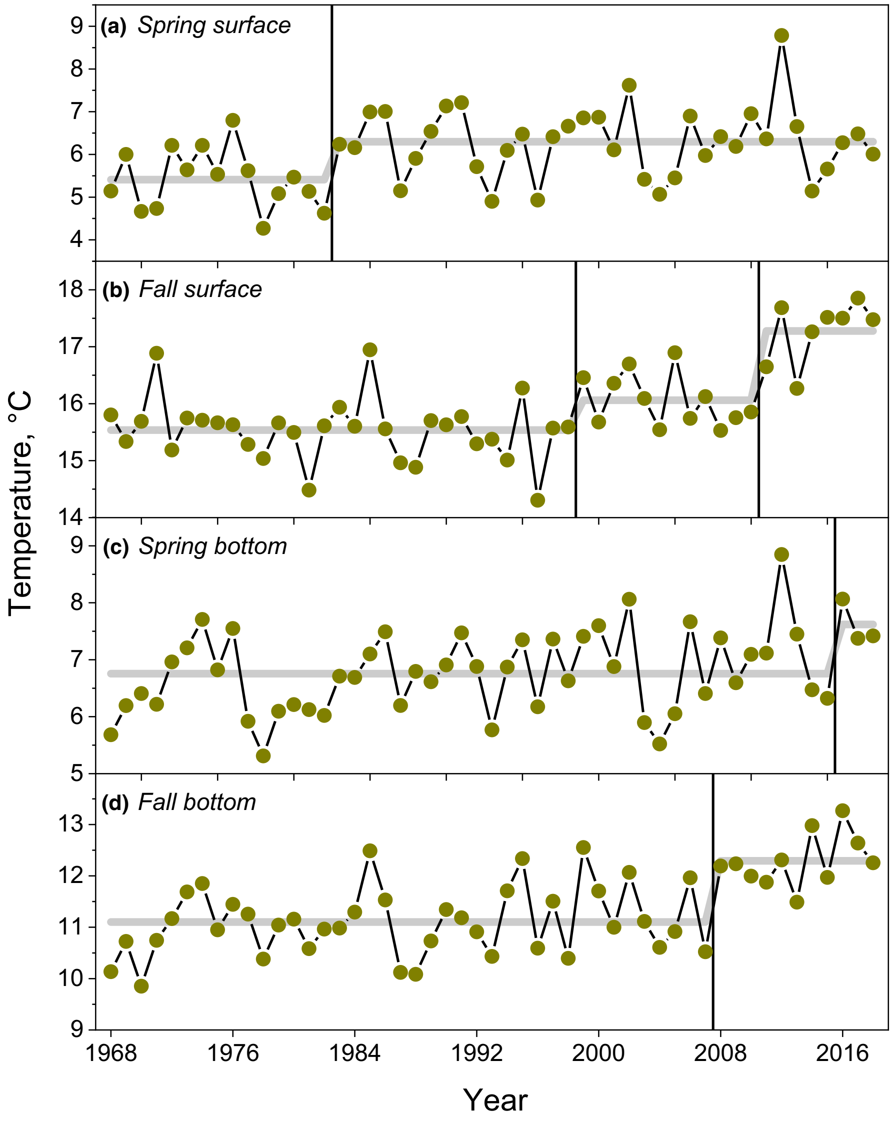


FIGURE 4 Spring (a) and fall (b) surface temperature on the Northeast Shelf ecosystem, and the same data for spring (c) and fall (d) bottom temperature. Regimes level means shown as gray lines, vertical lines mark change points or shifts in regime means [Colour figure can be viewed at wileyonlinelibrary.com]

Levin, 2013). In response to shifting distribution of their thermal habitats, species have moved to higher latitudes and into deeper water. There is also evidence of shifting distributions of lower trophic level organisms such as benthic infauna (Hale, Buffum, Kiddon, & Hughes, 2017) and copepods (Friedland et al., 2019). Of particular concern is the potential fate of the copepod *Calanus finmarchicus*, which plays a pivotal role as forage for fish and marine mammals. Warming of bottom waters in the Gulf of Maine could have severe impacts on the survival of diapausing *C. finmarchicus* copepods as survivorship is inversely related to ambient temperature during diapause (Melle et al., 2014). Additionally, the abundance of *C. finmarchicus* in Wilkinson Basin has been linked to transport from areas along eastern Maine and the Bay of Fundy through advective transport (Ji et al., 2017; Runge et al., 2015). Increasing temperatures in these source waters may decrease development time of copepodite stages, which may affect the progression into diapause in the fall months. For American lobster, *Homarus americanus*, the NES is the southern extent of their range in North America. Increasing water temperature represents two physiological threats to population demography of lobsters. First, inshore nursery habitats have retracted (Wahle, Dellinger, Olszewski, & Jekielek, 2015) as temperatures exceed a maximum thermal physiological threshold of 20°C (Glenn & Pugh, 2006; McLeese & Wilder, 1958; Pearce & Balcom, 2005). Secondly, epizootic shell disease has become more prevalent and severe at higher temperatures (Castro, Factor, Angell, & Landers, 2006; Steneck et al., 2011). Both thermally mediated factors have been implicated in the collapse of American lobster populations in the Middle Atlantic Bight. Interestingly, the current set of oceanographic conditions in the Gulf of Maine appears to have increased the available habitat within their optimal settling range and resulted in a population expansion (Goode, Steneck, Wahle, & Brady, 2019).

4.3 | Change points in the thermal environment

Abrupt changes in temperature appear to be an important characteristic of this ecosystem. Most of the change in both surface

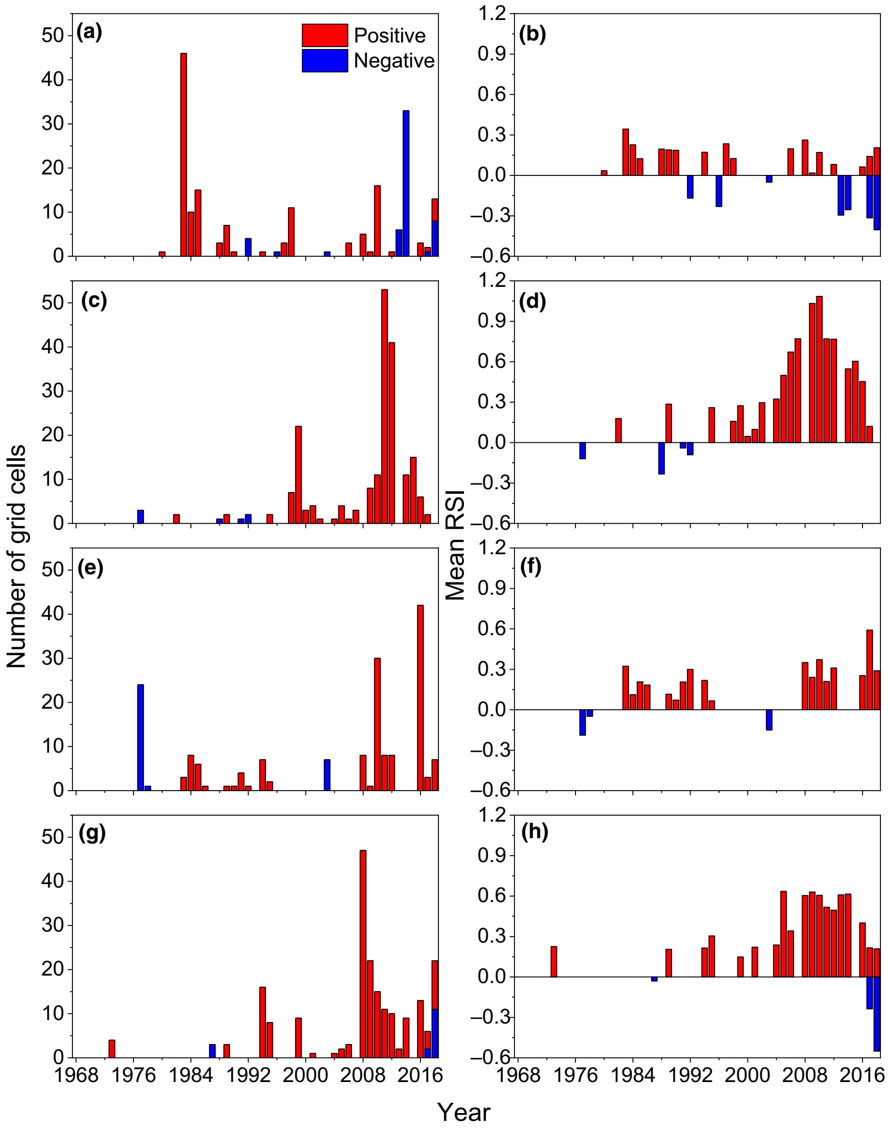


FIGURE 5 Number of grid cells with significant change points or shift in regime means by year for spring (a) and fall (c) surface temperature, and spring (e) and fall (g) bottom temperature. Mean Regime Shift Index (RSI) associated with change points by year for spring (b) and fall (d) surface temperature, and spring (f) and fall (h) bottom temperature [Colour figure can be viewed at wileyonlinelibrary.com]

and bottom temperature has occurred in the last decade or so, underscoring how consistent the bottom thermal environment has been over most of the time series. This is reinforced by trend analyses for time series before and after temperature change points. The different time and spatial scales of the change points in surface and bottom thermal environments suggest they are driven by different forcing factors. When and where the surface temperature change points developed and progressed is consistent with a relatively strong response to atmospheric forcing. The surface water temperature change began in a latitudinal band associated with the predominant path of the jet stream across the ecosystem and is associated with continental warming marked by record high temperatures in 2012 (Chen, Gawarkiewicz, Kwon, & Zhang, 2015). This change point appears to be distinct from the change observed in the bottom water where advective processes seem to dominate. The progressive change in fall bottom water temperatures starting in 2008 in the eastern Gulf of Maine and moving westward in a counterclockwise manner consistent with to an increase in the contribution of warm slope water entering the system via the Northeast Channel and remarkably consistent with what is known about Gulf of Maine circulation (Pettigrew et al., 2005; Townsend et al., 2015). This water originates from the south and tends to be higher in salinity than water masses originating from the north including Labrador slope and Scotian Shelf waters. If the contribution of warm slope water is related to basin scale forcing reflected in the position of the Gulf Stream and Atlantic meridional overturning circulation (AMOC), the recent changes in AMOC would be consistent with the progressive increase of warm water intrusions into the Gulf of Maine during summer (Caesar, Rahmstorf, Robinson, Feulner, & Saba, 2018). Spring bottom water does not reflect the changes so evident in the fall time series suggesting a seasonal aspect of the progression of warming at depth. The repeated warm water intrusions likely starting in summer and remaining evident into the fall would appear to be ameliorated by winter mixing conditions. However, the change point in spring bottom water in 2016 may be related to advective warming that developed the following year in the Middle Atlantic Bight (Gawarkiewicz et al., 2019).

4.4 | Responses to change points in temperature

Change points in temperature, which occurred at different spatial and temporal scales in surface and bottom water, will impact species differently depending on where in the water column critical life stages reside. The abrupt change in fall bottom temperature potentially impacted a number of species in the Gulf of Maine area. The American lobster, *Homarus americanus*, exhibits specific thermally mediated settlement behavior (Annis, 2005), and thermal habitat regime shifts influence the settlement-driven demography (Palma, Steneck, & Wilson, 1999). Northeastward expansion of recruitment within the Gulf of Maine attributed to warming (Le Bris et al., 2018), and rapid expansion of thermally suitable (>12°C) nursery habitat (Goode et al., 2019) has coincided with the rapid expansion of the American lobster fishery. Our results corroborate that the northeastern Gulf of Maine inshore bottom water habitat for juvenile American lobster has been approaching this critical temperature and a significant amount of benthic habitat may have crossed this restricting thermal threshold starting in 2008–2009. Importantly, this shift coincided with a significant peak in larval settlement in the northeastern Gulf of Maine (Jaini, Wahle, Thomas, & Weatherbee, 2018; Oppenheim, Wahle, Brady, Goode, & Pershing, 2019) and has since resulted in fishery-independent surveys reporting a 2.5 to 4-fold increase in abundance across multiple life stages (Sherman, Stepanek, Pierce, Tetrault, & O'Donnell, 2015). Essentially, an increasing body of evidence is supporting the contention that a step change in temperature in the eastern Gulf of Maine substantially increased suitable habitat for lobster larval settlement. Therefore, the positive, rapid thermal regime shift in benthic habitats in the Gulf of Maine since 2008, combined with non-linear demographic responses to changing temperature, may have resulted in a cascading response of increased larval settlement, juvenile abundance, and landings to date.

The shift in fall bottom water temperature began in 2008 in the eastern Gulf of Maine, but continued and were evident in the Great South Channel and Georges Bank area by 2010. The abundance of North Atlantic right whales, *Eubalaena glacialis*, an endangered species of baleen whale, has shown a marked decline since 2010, that may be associated with shifting conditions on its summer feeding grounds around the Great South Channel area (Pace, Corkeron, & Kraus, 2017). Our analysis shows that the progression of substantive bottom water thermal change would have arrived in this area starting in 2010, potentially affecting the main forage species for these whales, *Calanus finmarchicus*, which exists in the Gulf of Maine at the southern boundary of its distribution. Indeed, Sorochan et al. (2019) demonstrate a regime shift in *C. finmarchicus* abundance and biomass concomitant with an increase in bottom temperature in both eastern and western Gulf of Maine. This decline in *C. finmarchicus* aligns with a decrease in the calving rate of right whales and a low presence in the Gulf of Maine and Scotian Shelf after 2010.

The general spatial pattern of warming in temperate ecosystems has been to proceed from low to high latitudes; however, the progression of warming from north to south in the bottom water will also have consequences for marine resources. Although the prevailing view of climate-induced species movement on the NES has been in a northeasterly direction (Friedland et al., 2019; Nye, Link, Hare, & Overholtz, 2009; Pinsky et al., 2013), it has also been observed that some species have made distinct movements in the opposite direction to the southwest. This is demonstrated by the movement of species into deeper, cooler water available in multiple Gulf of Maine basin areas (Kleisner et al., 2016). The time and location of these movements coincide with the change in bottom temperature beginning in 2008, which progressed from east to west and would have the potential to force fish species movement in the southwest direction.

The main shifts in surface water temperature occurred in the spring of 1983 and the fall of 2011. There is little documentation of

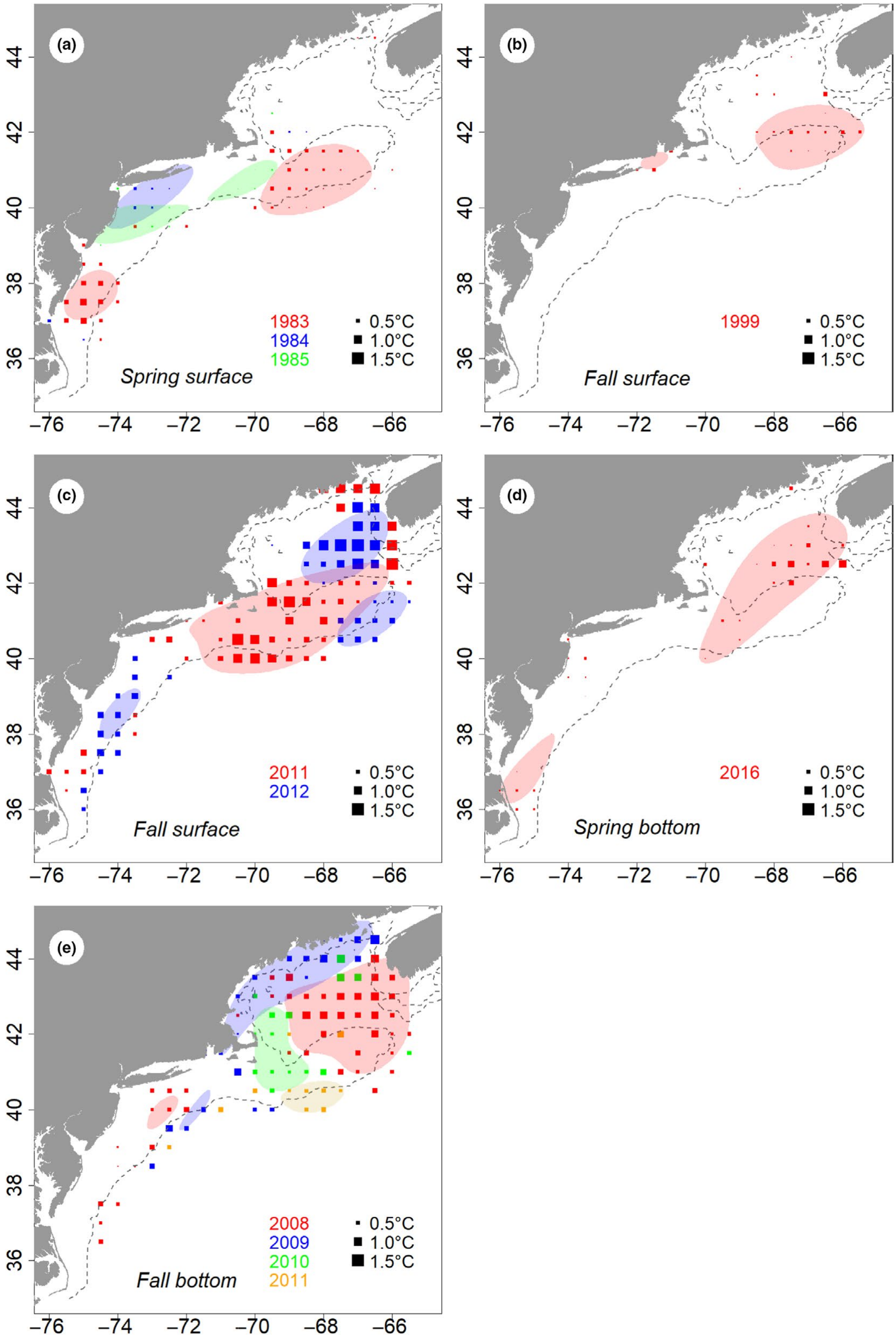
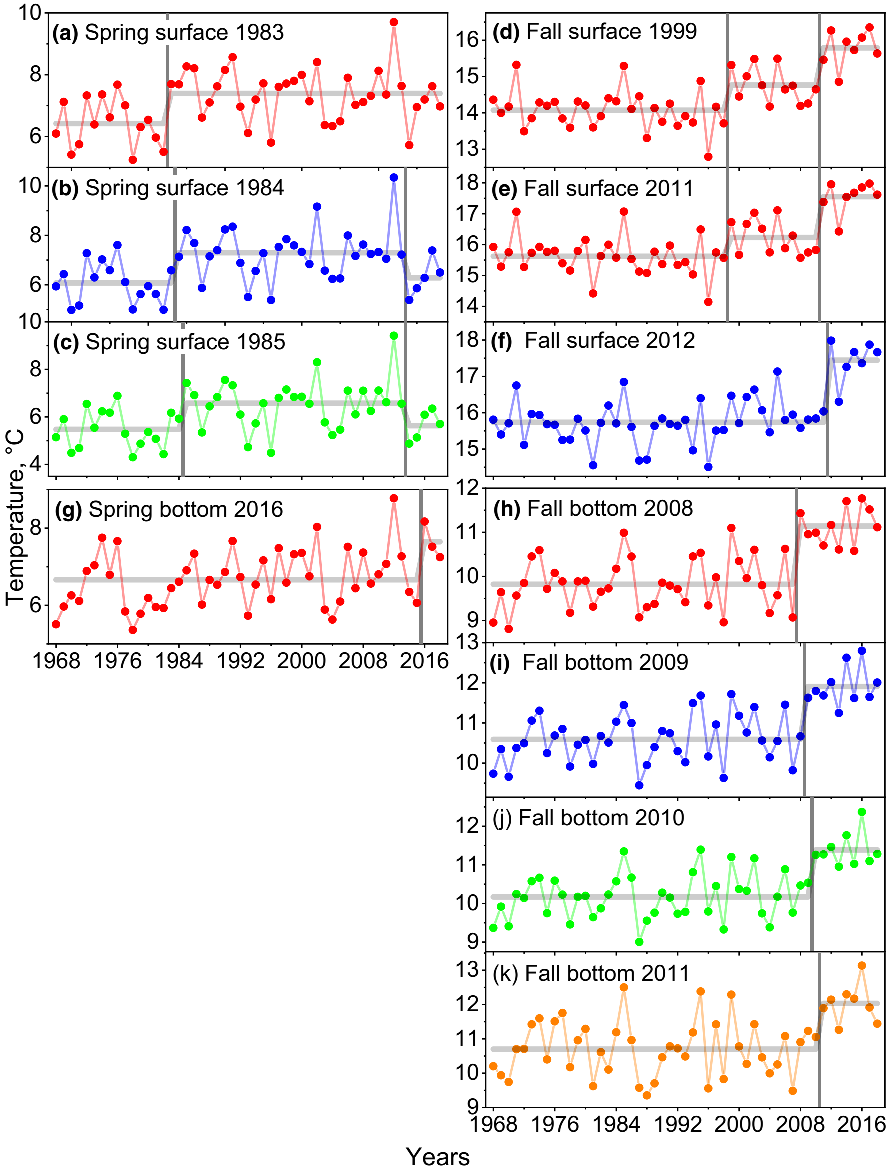


FIGURE 6 Map locations of grid cells with change points or shifts in regime mean in spring surface temperature in 1983–1985 (a), fall surface temperatures in 1999 (b) and 2011–2012 (c), spring bottom temperature in 2016 (d), and fall bottom temperature in 2008–2011 (e). Symbol size is proportional to Regime Shift Index (RSI). Shaded areas are 50% kernel density contours color coded to location by year [Colour figure can be viewed at wileyonlinelibrary.com]

either shift, the former was of low magnitude and the later so recent that it is not well studied. However, the more limited shift we document around 1999 in fall surface water appears to have had a significant impact on the ecosystem. There was a reorganization of the zooplankton community around 1999–2000 (Morse, Friedland, Tommasi, Stock, & Nye, 2017; Mountain & Kane, 2010), and we

FIGURE 7 Mean temperature for the grid cell locations with change points or a shift in regime means in spring surface waters in 1983–1985 (a,b,c, respectively), fall surface waters in 1999 and 2011–2012 (d, e, f, respectively); spring bottom waters in 2016 (g), and fall bottom waters in 2008–2011 (h, i, j, k, respectively). See Figure 5 for the number of grid cells used to compute each mean and Figure 6 for grid locations; note that the color coding of grid cells and time series coordinates are the same between Figures 6 and 7. Regime level means shown as gray lines, vertical lines mark change points or shifts in regime means [Colour figure can be viewed at wileyonlinelibrary.com]



also see evidence of a change in the body size and condition of many fish taxa (EAP, 2009), also around the year 2000, suggesting that the change in the physical environment affected system-wide energy flow. In addition to changes in the biological community, other changes in the physical environment have been noted such a shift in the generation of warm core rings of the Gulf Stream (Gangopadhyay, Gawarkiewicz, Silva, Monim, & Clark, 2019). In addition to the changes observed in mobile taxa, this shift appears to have had an impact on benthic infauna. The substantive increase in fall water temperatures is particularly significant in that most Mid-Atlantic biomass dominant infauna are cold temperate and boreal species with southerly range limits delimited by temperature. Atlantic surfclams (*Spisula solidissima*), for example, experienced a large-scale mortality event between 1999 and 2002 in the southern portion of the Mid-Atlantic Bight off Delmarva (Hofmann et al., 2018; Weinberg, 2005). Surfclam feeding is particularly sensitive to water temperature (Munroe, Powell, Mann, Klinck, & Hofmann, 2013); temperatures above 21°C reduce scope for growth and ultimately impact survival (Narváez et al., 2015). Observations of surfclam condition along the Delmarva mortality line showed that starvation was the primary agent of mortality (Kim & Powell, 2004; Marzec, Kim, & Powell, 2010). Following the circa-2000 event, the range of surfclams expanded offshore throughout much of their alongshore range. Weinberg (Weinberg, 2005) identified an offshore shift in distribution off New Jersey by 2002. Timbs, Powell, and Mann (2019) found that the core of the surfclam range shifted 20 km east and 30 km north off New Jersey and 20 km east and 40 km north off Delmarva over the 1990–2011 time period. Documentation of newly colonized areas in the deeper water off Nantucket Shoals, for example, show that earliest settlers appeared by 2004, only a few years after the Delmarva mortality event (Powell, Mann, Kuykendall, Long, & Timbs, 2019). Interestingly, growth rates off Nantucket were initially low, but by the year 2008 had reached regional norms, consistent with the rapidly warming bottom water temperatures observed during this time in this region.

4.5 | Approaches to characterizing thermal conditions

The differences in the progression of temperature change in the surface and bottom depth layers underscore the need for better data collection systems to characterize the benthic environment. As well-documented in Li, Tanaka, Chen, Brady, and Thomas (2017), modeling bottom temperatures is difficult even with a well-developed high-resolution coastal circulation model. There is promise in alternative data collection methods expected in the coming decade that combine the use of both dedicated collection systems and platforms of opportunity. Loggerhead turtles have diving behavior that is well understood, making them serviceable observation platforms (Patel et al., 2018). Increased engagement by the fishing industry has led to a substantial increase in water column measurements. A continuing challenge is the spatially and temporally clustered nature of these data in regions targeting specific fishery resources. Direct scientific measurements have traditionally been limited by the time and expense of sending research vessels to sea. This paradigm is rapidly shifting as the technology of unmanned collection devices expands. Highly capable autonomous vehicles have demonstrated the potential to approach the time and space requirements necessary for near-continuous characterization of a system like the NES (Castelao et al., 2008; Glenn et al., 2016; Schaeffer et al., 2016). Given the complex challenges facing resource managers, which are amplified by climate change, the improved understanding of ecosystems afforded by these approaches should prove to be very valuable.

5 | CONCLUSION

The thermal environment of the NES ecosystem has changed significantly, with water temperatures warming at an average rate of 0.24°C per decade from 1968 to 2018 and at 0.95°C per decade between 2004 and 2018. The rates of change in temperature vary with season and depth layer, with generally higher rates in the fall season. The differences in long- and short-term trends are driven by distinct change points in the temperature time series. The most prominent change points in surface conditions started in 2011 in the center of the ecosystem and expanded both north and south the following year. In the bottom temperatures, the most prominent change points began in the Gulf of Maine in 2008 and progressed west and south in subsequent years. The differences in timing and spatial distribution of surface and bottom temperature change points suggest they are the result of different forcing factors. These change points may indicate a regime shift in ecosystem has occurred; however, further investigation into whether other aspects of the ecosystem have shifted with thermal conditions is needed. Change in thermal regime of the NES has affected resource species on the shelf, and in particular, non-linear or abrupt changes in temperature have strongly influenced both the distribution and fitness of biota on the NES.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTION

K.F. conducted statistical analyses, produced figures, and drafted initial and revised versions of the manuscript. All authors provided comments and suggestions on revisions.

ETHICAL APPROVAL

Consent was received for all research conducted in this manuscript, with all participants voluntarily involved. We ensure quality and integrity of the research involved, and we are independent and impartial to the results.

DATA AVAILABILITY STATEMENT

The database of NES water column properties observations is available at ftp://ftp.nefsc.noaa.gov/pub/hydro/matlab_files/yearly/. The World Ocean Database holdings are available at https://www.nodc.noaa.gov/OC5/WOD/pr_wod.html.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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