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Trends in Physical Properties at the Southern New England Shelf Break

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Key Points:

- The New England continental shelf warmed at a rate of 0.26 °C yr^{-1} from 2003–2013 during late June
- The near-surface warming leads to a significant increase in stratification over this time period
- There are statistically significant increases in temperature and salinity over the upper continental slope over this time period

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Abstract We analyze 11 years (2003–2013) of repeat temperature and salinity sections from across the New England shelf break south of Cape Cod during early summer (June–July). The mean sections resolved the shelf break front which supports the Shelf Break Jet, a vital component of the regional circulation. Individual sections showed a great deal of variability associated with meanders in the shelf break front consistent with previous studies in the region. Over the 11 year record, the shelf region (inshore of the 100 m isobath) warmed by 0.26 °C yr^{-1}, with the majority of this warming occurring shallower than 20 m (0.58 °C yr^{-1}). The full-depth trend agrees well with previous studies of shelf warming to the north and the south of our study region. The temperature and salinity of the offshore edge of the Cold Pool Water on the shelf did not change significantly during this period. The surface warming on the shelf resulted in a decrease in near-surface density of 0.12 kg m^{-3} yr^{-1} and an increase in stratification between 10 and 15 m of 6.7×10^{-5} s^{-2} yr^{-1}. Offshore of the shelf break, the Slope Water also warmed and became more saline by 0.21 °C yr^{-1} and 0.04 yr^{-1} respectively, resulting in a maximal reduction in density of 0.01 kg m^{-3} yr^{-1}. In the Shelf Break Front, there is some evidence of freshening and a reduction in density, which may have resulted from an offshore shift in the Cold Pool but the statistical significance is small.

Plain Language Summary The ocean is getting warmer along the coast of New England. This has already impacted major fisheries including lobster but may have larger implications for temperatures on land and the path and intensity of storms. However, we lack a full picture of these changes and what is driving them, mostly due to a limited supply of measurements in similar parts of the coastal ocean. Fortunately, a collaboration between the Woods Hole Oceanographic Institution and the Sea Education Association measured the ocean at exactly the same points in late June between 2003 and 2013 to the south of Cape Cod. We found that the surface ocean was getting hotter quickest by more than 5 °C over this decade. This has made the surface water more buoyant and will likely limit the amount of vital nutrients that can reach the surface. There was also warming and an increase in salinity deeper in the ocean, over the upper continental shelf, possibly due to an increased presence of Gulf Stream water. These warming trends are similar to those seen to the north and south of this region.

1. Introduction

The northeastern continental shelf of the United States, comprising the Gulf of Maine and the southern New England shelf, is among the most rapidly warming regions in the world oceans (Mills et al., 2013; Pershing et al., 2015). This has impacted the continental shelf ecosystem (Record et al., 2019; Walsh et al., 2015) with important economic consequences for the commercial fishing industry. Future projections of bottom temperature for this region indicate significant effects for the lobster industry in particular (Rheuban et al., 2017).

Despite increasing public and academic awareness of this issue, we lack a full understanding of how this region is changing due, in part, to the limited number of data sets with repeat hydrographic stations at the same location and time of year for an extended period of time. Those that do exist are largely limited to surface or subsurface temperature measurements and have not been able to account for changing salinity and density throughout the water column. For example, Forsyth et al. (2015) used data from a NOAA Ship of Opportunity Program vessel, the CMV Oleander, which sampled using expendable bathythermographs from 1977 to the present. The use of the expendable bathythermographs, which are important for resolving the temperature structure, does not measure salinity, and thus, changes in both the salt content over the continental shelf as well as the stratification and density field were not collected. The ECOsystem

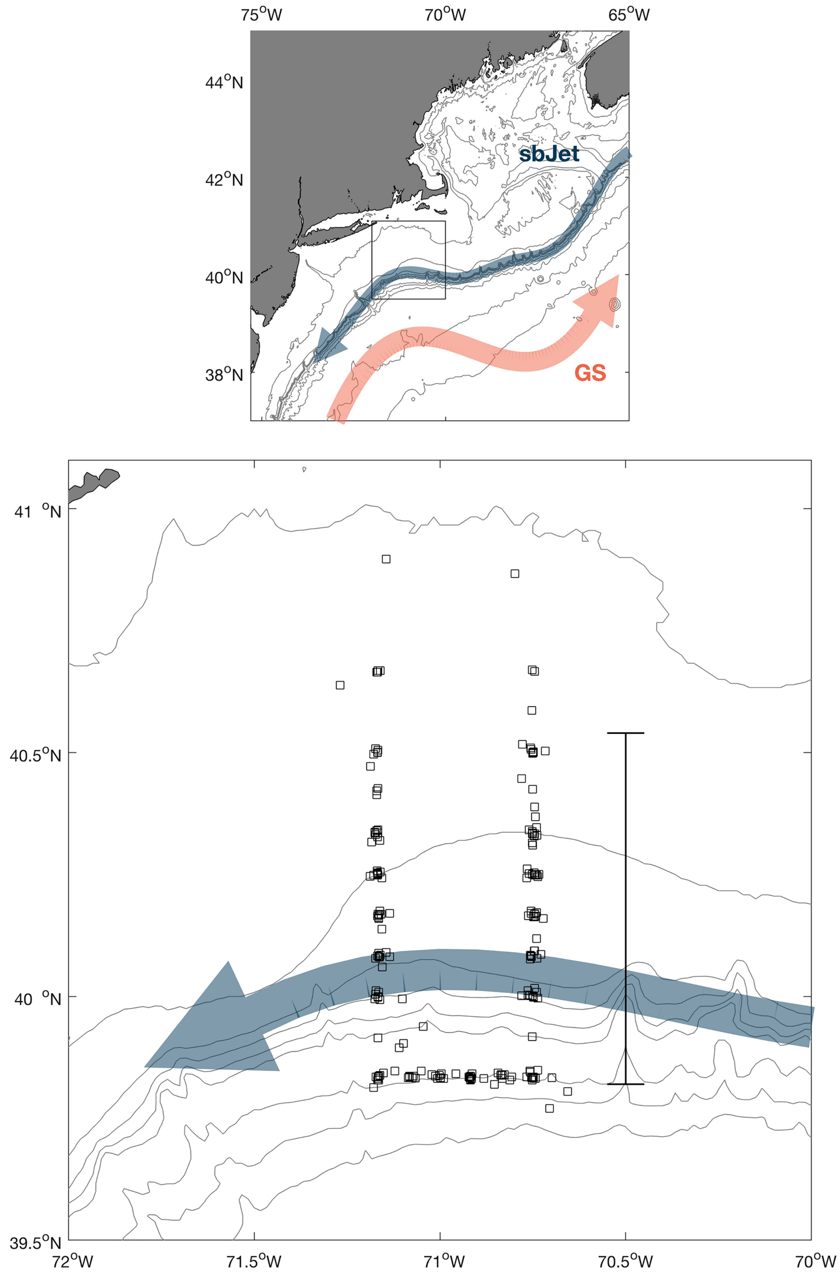

Figure 1. Top: overview map of the study region showing schematics of the Shelf Break Jet (sbJet) and Gulf Stream (GS). Bottom: close-up of study region (see box in top panel) with locations for all CTD measurements used in this study (black squares). The approximate location of the Shelf Break Jet is shown with a blue arrow. The portion of the array over which we gridded the individual CTD measurements is shown with the black end-barred line.

MONitoring (ECOMON) program for the northeast continental shelf, which does have sampling over an extended period of time with CTD profiles, uses random stratified sampling and is limited to the 200 m isobath and so does not normally resolve shelf break current structures.

The changes in the salinity and density fields south of New England are of particular importance because of the presence of the Shelf Break Front (Fratantoni et al., 2001; Linder & Gawarkiewicz, 1998). The along-shelf flow in the associated Shelf Break Jet is primarily in geostrophic balance (Gawarkiewicz et al., 2004; Zhang et al., 2011), and so knowledge of the changes in the density gradients across the Shelf Break Front directly impacts the strength of the Shelf Break Jet as well as the strength of the upwelling along the front driven by the bottom boundary layer convergence (Benthuysen et al., 2014; Gawarkiewicz & Chapman, 1992;

Table 1
Overview Table of the Cruises and Data Collected

Cruise ID	Year	Start date	End date	Number of stations Total	West	East	Comments
C187B	2003	28 June	02 July	19	7	7	Two casts in western section not used
C193A	2004	25 June	29 June	21	9	10	
C199A	2005	23 June	29 June	18	7	7	
C205G	2006	22 June	25 June	17	7	5	
C211A	2007	24 June	27 June	19	8	6	
C218A	2008	26 June	30 June	20	8	7	
C223A	2009	27 June	30 June	18	7	7	
C230A	2010	26 July	27 July	7	0	7	Cruise in late July
C235A	2011	30 June	01 July	15	5	7	
C241A	2012	29 June	04 July	20	9	9	
C248B	2013	05 July	07 July	19	8	7	

Houghton & Visbeck, 1998). To date, there have been no studies that have been able to determine how this front might be changing on a decadal scale due to lack of consistent temperature and salinity sections and the strong synoptic variability of the front.

Fortunately, an educational partnership in the Woods Hole community between the Woods Hole Oceanographic Institution (WHOI) and the Sea Education Association (SEA) allowed for annual sampling of the outer continental shelf and upper continental slope for the time period 2003–2013. This effort occurred due to the Orientation Cruises of the WHOI-MIT Joint Program, during which incoming graduate students were introduced to shipboard life and at-sea data collection during a cruise aboard the Sailing School Vessel (SSV) Corwith Cramer. Science activities were overseen by a scientist from WHOI, but the shipboard operations were directed by chief scientists from SEA.

This study describes 11 years of hydrographic sampling during early summer south of New England during these cruises and the trends in the water mass properties observed near the shelf break. The study area was near the current position of the National Science Foundation Ocean Observatories Initiative Pioneer Array and thus represents baseline early summer conditions before the Observatory was constructed and deployed in 2014.

The outline of this paper is as follows. Section 2 describes the sampling, instrumentation, and the opportunities and limitations of hydrographic sampling using a sailing ship. The mean fields across the shelf break are presented in section 3 along with the magnitude of the interannual variability. Interpretations of shelf break processes evident in the cross-shelf transects are also discussed. Trends for the temperature, salinity, and density fields, including cross-frontal density contrasts, appear in section 4. The results and implications for shelf break exchange are discussed in section 5. Finally, conclusions appear in section 6.

2. Methods

Data for this study come from the WHOI-MIT Joint Program student orientation cruises aboard the Sea Education Association's SSV Corwith Cramer. These cruises are typically 10 days in length and occurred every year from 2003 to 2013 in late June or early July to the south of Cape Cod (see Figure 1 and Table 1 for details). The primary goals of the cruises were for students to experience underway sampling methods and to build a community, but the cruises maintained a standard sampling plan between years so a unique data set has emerged.

The sampling on these cruises occurred along standard sections forming a "U" shape off the New England shelf break (see Figure 1). The unique nature of sampling under sail produced some variability in precise sampling locations depending on the year. The two cross-shelf transects are separated by 40 km and typically consisted of seven to eight casts each with a typical spacing of approximately 8 km (see Table 1 for full information). For the purposes of this paper we will refer to the two sections in any single year as "west" and

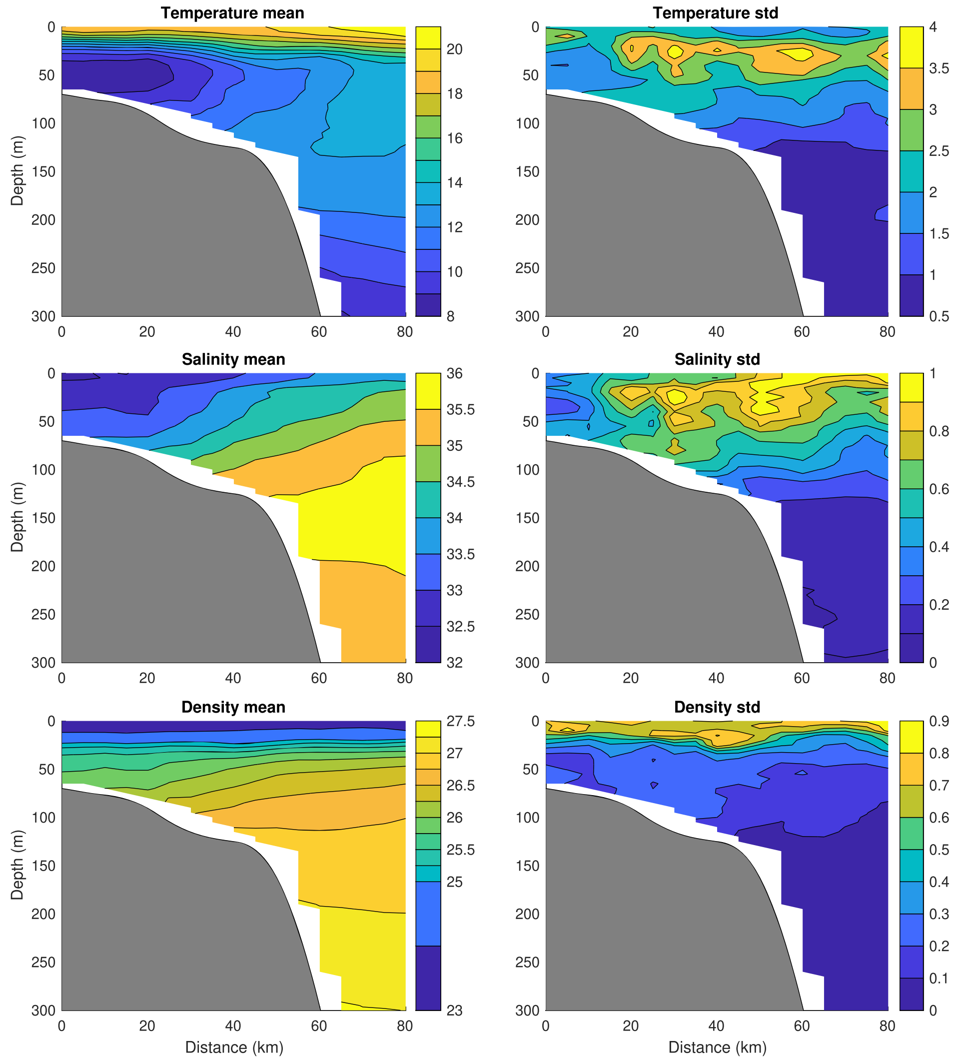

Figure 2. Mean (left column) and standard deviation (right column) sections from the gridded data over the region shown in Figure 1. Top panels: potential temperature (°C). Middle panels: salinity. Bottom panels: potential density (kg m^{-3}). Bathymetry is a from an underway echosounder.

"east." The along-slope section will be referred to as the slope section although we do not work specifically with this data for this study.

For this study we use CTD data from these sections to look at the mean structure, variability, and trends across the shelf break. All CTD casts were conducted using Seabird SBE SEACAT Profilers (of different models depending on the year) from a J-frame mounted on the port side of the SSV Corwith Cramer, which was hove-to on a port tack during deployments. We processed all cast data to a vertical resolution of 1 dbar and removed data spikes using a moving median window method (Kelley & Richards, 2019).

In addition, we produced standard gridded sections across the shelf break. Each section was objectively mapped on to a standard section (see Figure 1) and gridded using a Laplacian spline interpolator (e.g., Nikolopoulos et al., 2009) with vertical and horizontal resolutions of 5 m and 5 km, respectively.

3. Results

3.1. Mean Sections

The 11-year mean sections (combining both east and west sections) show patterns typical of the region in the early summer (Figure 2) with a basic structure consistent with the climatological pattern initially described in Linder and Gawarkiewicz (1998).

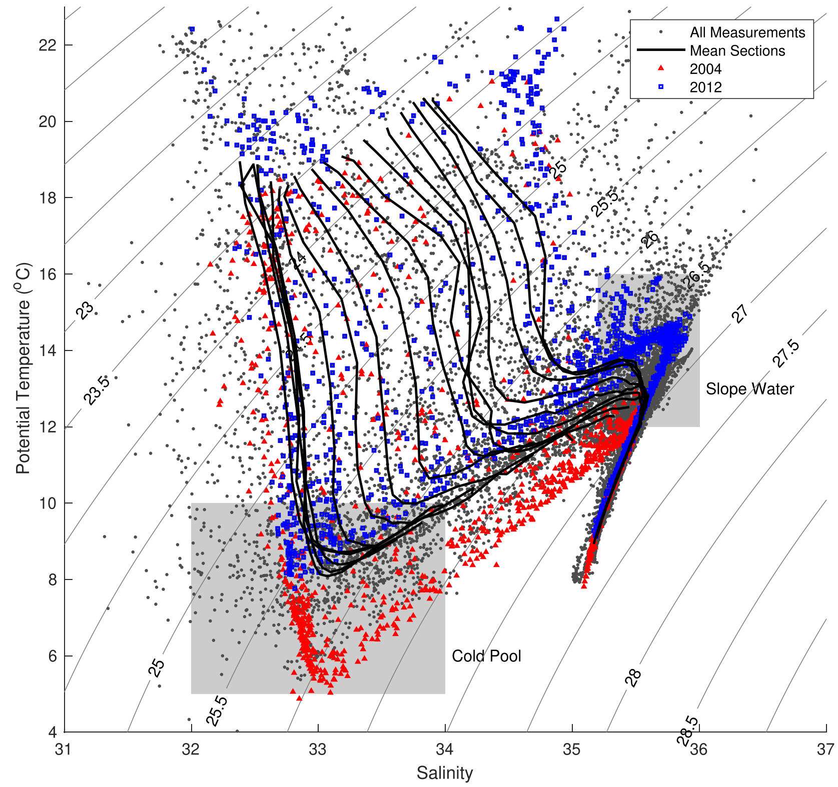

Figure 3. θ-S diagram showing all CTD data used in this study (gray dots). Overlaid are the data from the mean sections (Figure 2, plotted as profiles (black lines)). Two example years are also shown: 2004 (red triangles) and 2013 (blue squares). The two major water masses discussed in this study, the Cold Pool and Slope Water are shown with gray boxes.

The surface waters are warm due to heating throughout the spring and form a strong pycnocline between 10 and 30 m largely due to temperature. The temperature in the surface layer increases offshore due to the increased presence of warmer Gulf Stream water masses. The salinity of this surface layer increases as we move away from shore due to the reduced influences of local and remote shelf freshwater sources.

Below the surface layer on the shelf, we can see a well-defined Cold Pool. This is the remnant of winter water that formed locally due to intense cooling and vertical mixing over the winter months (Forsyth et al., 2015; Houghton et al., 1982). The Cold Pool has a pronounced cold and fresh signature (Figures 2 and 3) and typically sits shallower than the 100 m isobath along much of the Northeast U.S. continental shelf. Our sections capture just the northern, offshore edge of the Cold Pool.

Offshore and downslope from the Cold Pool is the local salinity and temperature maximum associated with Slope Water. This has a non-local source to the north and is transported southward along the New England Slope as part of the shelf break current system. The θ-S properties of this region have been defined by Wright and Parker (1976), and factors affecting the structure and interannual variability of the slope currents and water masses in this region have been discussed by the MERCINA project (Greene et al., 2013).

Between the Cold Pool and Slope Water, we see a subsurface cross-shelf density gradient from a depth of 20 m to the bottom (Figure 2). This front supports the south flowing Shelf Break Jet at the 100 m isobath. Above 20 m, the front is weak or nonexistent. The mean cross-shelf width of the frontal zone is approximately 20 km, which is most noticeable in the near-bottom salinity and density fields.

3.2. Interannual Variability

The variability in the physical properties from the sections displays similar patterns to one another (Figure 2). There is least variability in the deeper Slope Water region and most at the seasonal thermocline (20–40 m) near the Shelf Break Front. This is consistent with previous climatological analyses of the standard deviation fields (Linder et al., 2006). The most likely cause of the spatial structure of the standard deviation fields is

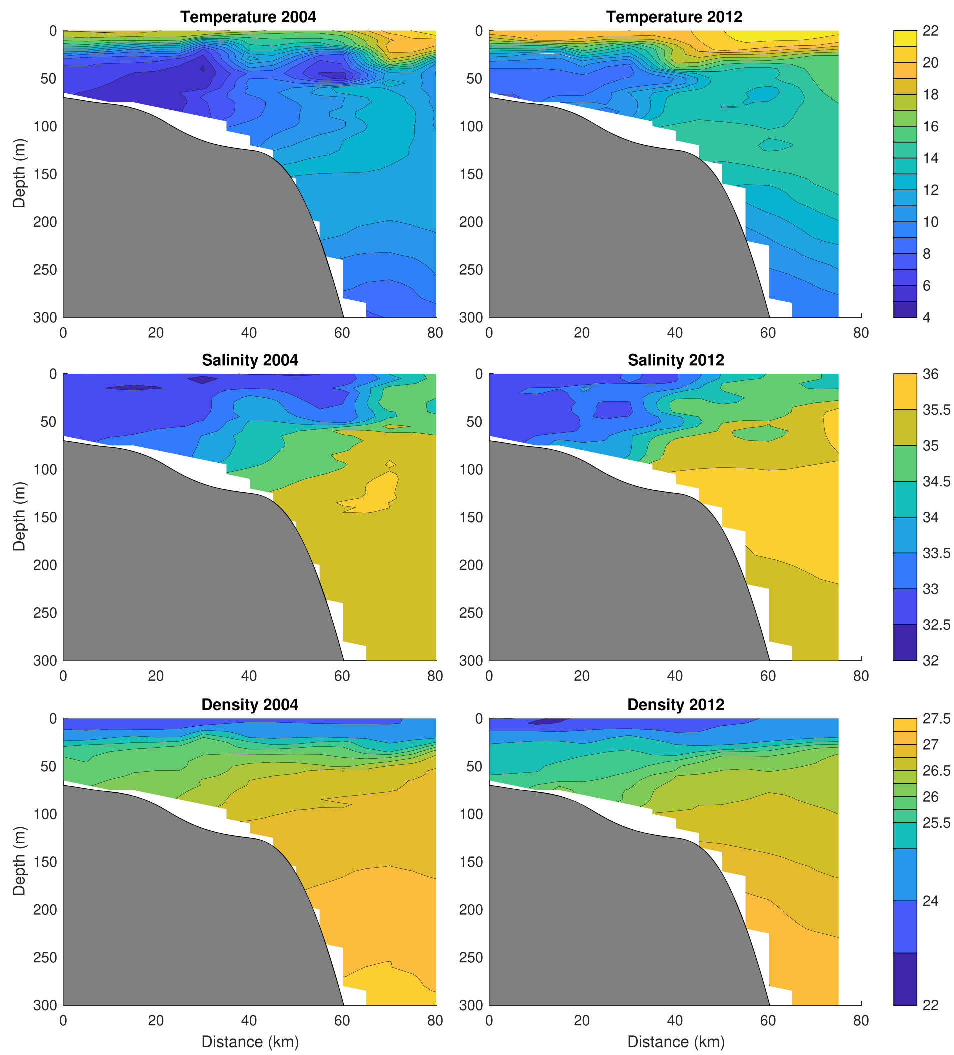

Figure 4. Example gridded sections from two years: 2004 (left column) and 2013 (right column). Top panels: potential temperature (°C). Middle panels: salinity. Bottom: potential density (kg m^{-3}). Example years are the same as used in Figure 3.

the frequent frontal meanders, which have their maximum cross-shelf extent just beneath the thermocline (Gawarkiewicz, 1991; Gawarkiewicz et al., 2004).

Our individual sections clearly show signatures of these large-amplitude frontal meanders. Here, we simply present the western sections from 2004 and 2012 as representative examples to demonstrate some of these features and how water mass properties change between years. (Figures 3 and 4). From analysis of Cold Pool variability off the New Jersey shelf, 2004 was a cold year and 2012 was the warmest year on record for 150 years of data (Chen et al., 2015; Forsyth et al., 2015; Mills et al., 2013).

The section in 2004 shows strong evidence of large-amplitude frontal meandering. Both the temperature and salinity fields show a detached parcel of shelf water within a depth range of 20–50 m. This is the offshore limb of a frontal meander, similar to parcels described in Garvine et al. (1988). The Lagrangian nature of the flow around these meanders is described in Garvine et al. (1989). The core of this parcel has a temperature minimum of less than 6 °C and a minimum salinity of around 33 (Figure 3). The cross-shelf scale of this offshore limb is 15 km, consistent with other measurements of frontal meanders (Gawarkiewicz et al., 2004). Note that there is a weak reversal of density gradients between 55 and 60 km consistent with an expected flow reversal near the offshore limb of detached water. Both the offshore edge of the Cold Pool and the maximum cross-shelf salinity gradients along the bottom occur at the 100 m isobath.

The primary difference in 2012 is the much warmer minimum temperature of the Cold Pool: about 8°C. This is more than 2 °C warmer than 2004. The warming is consistent with temperature anomalies calculated from nearby NDBC buoy 44008 by Chen et al. (2014). There is a much weaker indication of a possible offshore limb of a frontal meander, but its minimum temperature and salinity are different from the core properties of the Cold Pool and so it has either undergone mixing processes or may not be part of a meander at all.

Offshore of the shelf break, the water is warmer and saltier at all depths in 2012 compared with 2004. The near-surface water in both sections is over 20 °C at the offshore edge of the transect but remains seaward of the 300 m isobath in 2014 and was 20 km further inshore in 2012. This indicates a larger influence of Gulf Stream water in the 2012 section compared with 2004.

The differences in water mass properties between the 2 years are made evident in the θ-S diagram (Figure 3). Minimum temperatures for the Cold Pool were 5 °C in 2004 and 8 °C in 2012. Salinities at the minimum temperature were similar in the 2 years at 33. The influence of the offshore Gulf Stream water mass is indicated by the high temperature and salinity in the Slope Water in 2012 relative to 2004. The Slope Water in the offshore stations in 2012 had a temperature of 14 °C and salinities as high as 35.9. In contrast, offshore Slope Water in 2004 was 12.2 °C and 35.6. The presence of water masses with salinity greater than 35.5 is an indication of Warm Core Ring or Gulf Stream water masses. While this was present in both years, it is clear that the influence was much greater in the section from 2012.

4. Property Trends

The 11 year record allows us to investigate the trends in the physical properties in this region (Figure 5). To do this, we computed the linear trends in all properties at all locations and calculated the significance of the slopes by Monte Carlo analysis using 2,000 random permutations. Only trends that were significant with 95% confidence are shown in the section maps of Figure 5. We note that the timing of the cruises gradually moved later in June through the 11 years, with a shift of around a week from the first to last cruise. We do not believe that this change in timing significantly biases the estimates of the trends.

A clear trend exists in the temperature and density of the surface waters across the section but particularly on the shelf. The average temperature trend on the shelf (inshore of 100 m isobath) shallower than 20 m is 0.58 $°C\,yr^{-1}$, with a maximum in this region of 0.79 $°C\,yr^{-1}$ (see black outlined region in Figure 5). The salinity does not exhibit a significant trend suggesting that the temperature change is driven by local heat fluxes. The increased temperature reduces the surface density by 0.12 $kg\,m^{-3}\,yr^{-1}$ in the same region. This surface region of the section has some of the largest variability for the region (see Figure 2), so it is all the more striking that these trends can be extracted in an area where synoptic variability is very high.

The resulting change in stratification is a significant increase in maximum buoyancy frequency of $6.7 \times 10^{-5}\ s^{-2}yr^{-1}$ at 10–15 m depth inshore of the shelf break (Figure 6). There is no corresponding trend for a change in the depth of this maximum stratification.

The sharp increase in near-surface temperatures over the 11 year span might be expected to increase Cold Pool temperatures in a systematic manner due to winter mixing. We attempted to isolate any trends in the Cold Pool properties using objective criteria. The water depth range was chosen to be deeper than 30 m with a salinity of less than 34 (see Figures 2 and 3 for why these criteria effectively isolate the Cold Pool). This captured both Cold Pool waters on the shelf and intrusions found offshore. There was a weakly increasing trend in both temperature and salinity, but the year-to-year variability was large enough that these trends were not quite significant at 95% confidence.

The upper slope region, which exhibits naturally lower levels of variability, also exhibits trends with high confidence levels. The core of the Slope Water saw a significant increase in both temperature and salinity of 0.21 °C and 0.04 yr^{-1}, respectively. This resulted in a weakly declining density of 0.01 $kg\,m^{-3}\,yr^{-1}$, showing that the increase in temperature and salinity was not entirely density compensating.

The only other region to show a significant trend is an isolated patch at middepth in the Shelf Break Front. Here, the significant salinity trend (part of a large region that was not significant at 95 % confidence) was $-0.11\,yr^{-1}$ and resulted in a reduction in density of 0.05 $kg\,m^{-3}\,yr^{-1}$. The temperature in this region also appears to be decreasing, but this did not test as statistically significant. The reduction in salinity (and maybe temperature) could imply that the Cold Pool has moved further offshore over the course of the period of study potentially shifting the location and strength of the Shelf Break Front.

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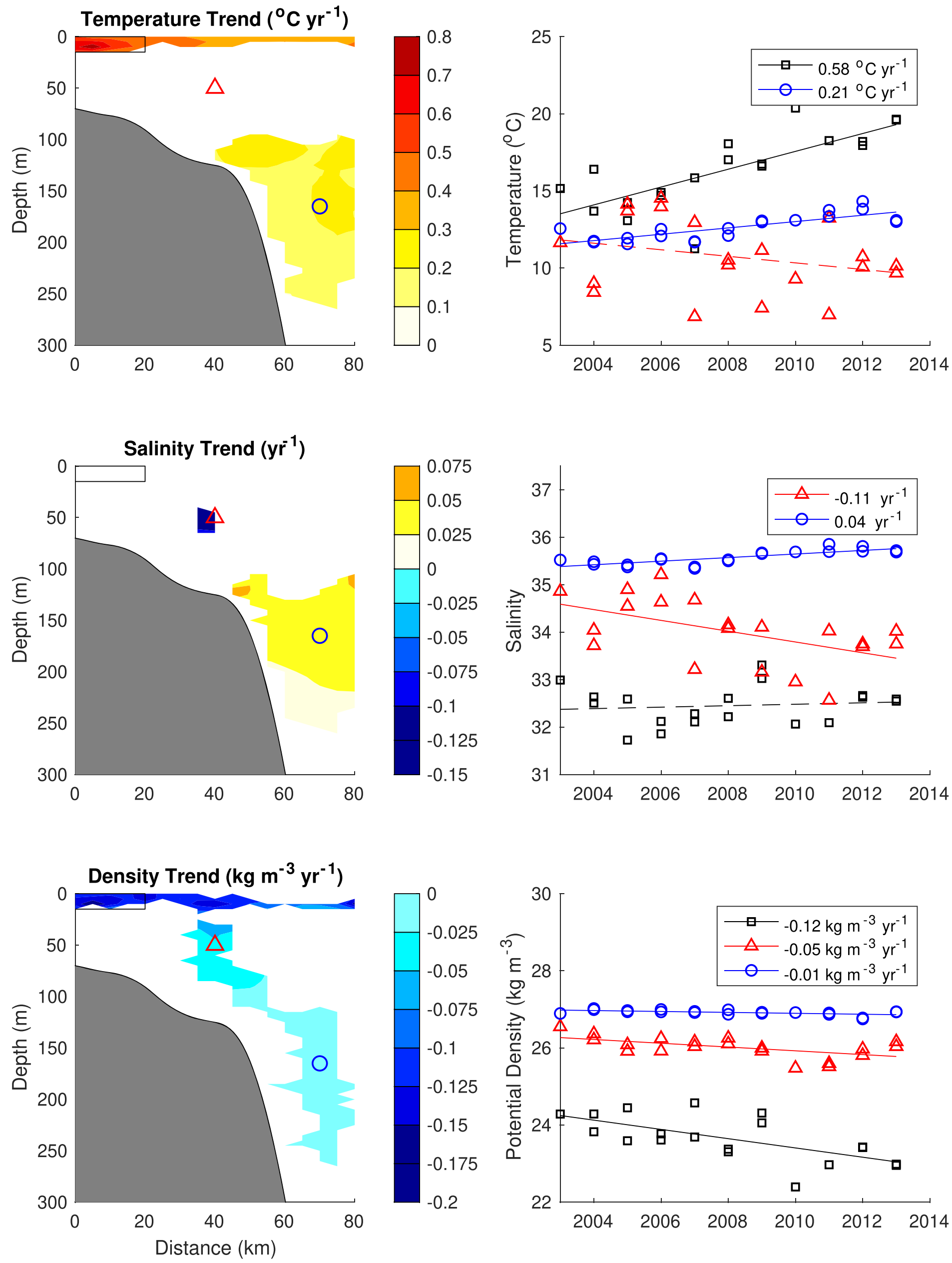

Figure 5. Left column: Linear trends for properties at all locations in the gridded data. Top panels: potential temperature ($^\circ$C yr^{-1}). Middle panels: salinity (yr^{-1}). Bottom: potential density (kg m^{-3} yr^{-1}). Only trends that are significant at 95% confidence (using a Monte Carlo analysis with 2,000 random samples) are shown. Right column: Linear trends from three locations in the gridded domain: Black squares: Surface Shelf Water (trend in average shallower than 20 m inshore of 100 m isobath). Red triangles: maximum in Shelf Break Front trend. Blue circles: maximum in Slope Water trend. See left column for regions/locations. Trends which are significant at 95% confidence are shown with solid lines and enumerated in the panel legends. Nonsignificant trends are plotted with a dashed line.

5. Discussion

We can compare our temperature results to those obtained by Forsyth et al. (2015) in the same current system further south, offshore of New Jersey, and those from Mills et al. (2013) from the Gulf of Maine further to the north. To facilitate comparison, we computed the linear trends over the 11 year period averaged for all depths inshore of the 100 m isobath (Figure 7).

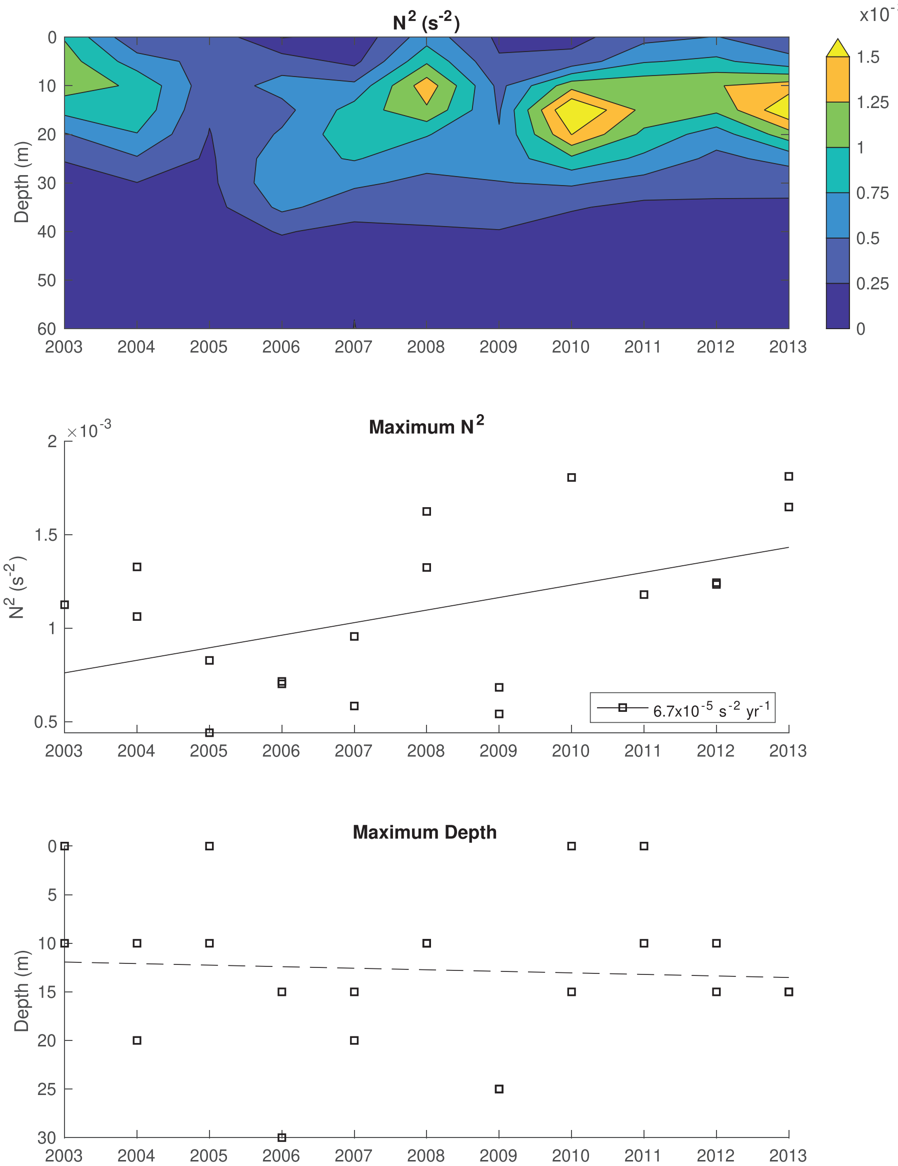

Figure 6. Top: mean buoyancy frequency each year shoreward of the 100 m isobath. Middle: maximum value of the mean buoyancy frequency inshore of the 100 m for each section in each year. Bottom: depth of the maximum buoyancy frequencies shown in middle panel. Linear trend lines are shown for two lower panels, but only maximum buoyancy frequency trend is significant with 95% confidence.

Temperature is the only property to show a significant trend of 0.26 °C yr^{-1} over our measurement period (early summer, 2003–2013). The density trend is weakly negative but not quite significant at 95% confidence. Despite not reaching this confidence level, the change in density is of interest. Given that typical cross-frontal density differences are on the order of 0.5 kg m^{-3}, the change in depth-averaged density of 0.4 kg m^{-3} over the course of this decade is important and bears further investigation in more recent years.

Our temperature trend agrees well with that found by Forsyth et al. (2015) from the New Jersey shelf who showed a trend of 0.126 °C yr^{-1} for spring months and 0.188 °C yr^{-1} for summer months between 2002 and 2013. Switching their calculating period to 2004–2012 (extremum years) increases these values as high as 0.357 °C yr^{-1}, so our value falls within these bounds given the slightly different reporting periods. Given that Forsyth et al. (2015) also see large interanual variability, we need to continue our measurements in all locations in order to quantify statistically significant trends in the presence of high levels of synoptic variability.

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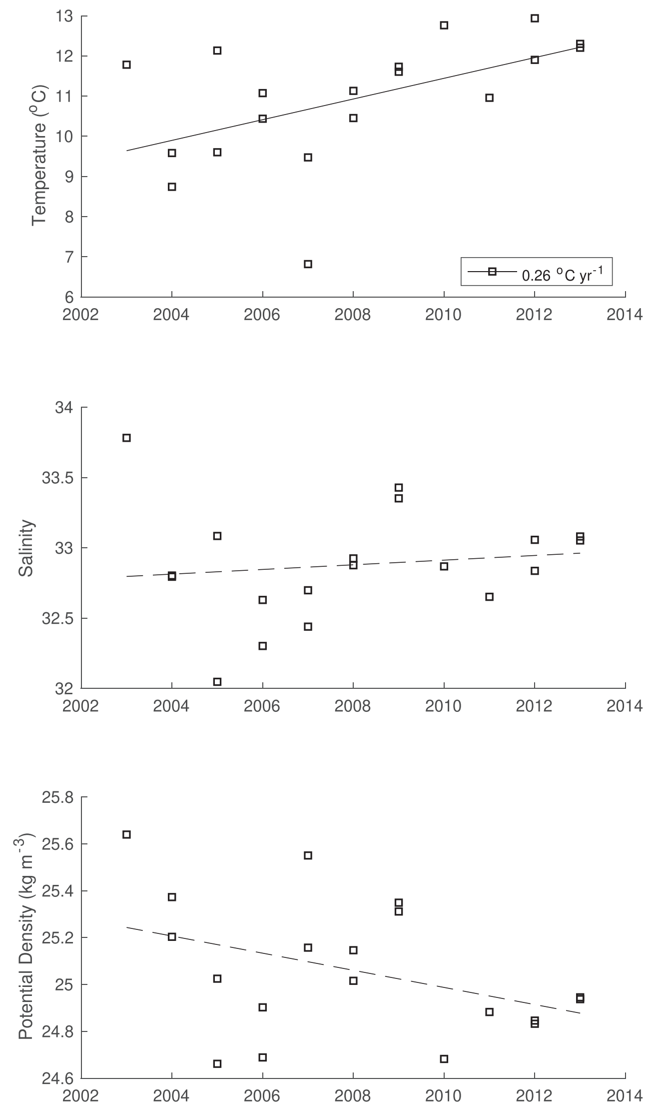

Figure 7. Depth-averaged properties form inshore of the 100 m isobath with linear trend lines added. Top: potential temperature (°C yr^{-1}). Middle panels: salinity (yr^{-1}). Bottom: potential density (kg m^{-3} yr^{-1}). Only the temperature trend is significant at 95% confidence.

Forsyth et al. (2015) show that the increase in temperature of New Jersey has a clear surface expression, which we also see in our study. However, they also show a significant increase in temperature at middepth in the Shelf Break Front which is absent (or even possibly opposite) in our study (Figure 5). Future work must include quantifying the relative contributions of large-scale atmospheric forcing, local shelf break processes, and offshore forcing from the Gulf Stream.

We can also compare our shelf temperature trends to those further to the north in the Gulf of Maine. Mills et al. (2013) report a recent increase of 0.26 °C yr^{-1} between 2004 and 2012 which agrees well with our value off New England. As in the Forsyth et al. (2015) study, this period is between low and high temperature extremums so is probably the upper bound of the true trend.

Returning to the regional trends we observed in this paper, the increasing temperature and salinity of the Slope Water may be the result of the increasing influence of offshore forcing from features generated by the Gulf Stream such as Warm Core Rings. The upper slope has been shown from analysis of data from the Ocean Observatories Initiative Pioneer Array gliders to be significantly more salty than in the 1970s to 1990s (Gawarkiewicz et al., 2018), which is also supported by our findings. Recent analysis of meandering patterns of the Gulf Stream (Andres, 2016) shows that the initiation of large-amplitude meanders of the Gulf

Stream has been steadily shifting westward since the early 1990s and large-amplitude meanders may reach the shelf break south of New England (Gawarkiewicz et al., 2012). At the same time, the Gulf Stream is shifting northward both in observations (Seidov et al., 2019) and climate models (Saba et al., 2016). Increasing influence of Gulf Stream features on the shelf break is also reflected in the increasing number of Warm Core Rings since 2000 (Gangopadhyay et al., 2019).

We also observe an increase in near-surface stratification, predominantly on the shelf. This could have important ecological implications as an increase in surface stratification may limit the vertical fluxes of nutrients to the surface mixed layer, which are vital to sustain healthy ecosystems.

The presence of the OOI Pioneer Array will hopefully allow examination of these patterns in more recent years. The combination of high-resolution observations and extended duration (more than 5 years) should allow much more detailed analysis of specific oceanographic processes contributing to the trends described above.

6. Summary

We have examined 11 years of repeat cross-shelf hydrographic sections across the Shelf Break Front south of New England to determine trends in water mass properties. Individual sections show considerable synoptic variability including the influence of shelf break frontal meandering, but the mean and standard deviation fields are consistent with prior climatological studies.

Water mass properties show considerable year-to-year differences in both the minimum temperature of the Cold Pool and the characteristics of Slope and Warm Core Ring waters at the offshore edge of the transects. The most statistically significant trends over the full 11 year record were warming across the near-surface layer as well as warming and increased salinity in the subsurface layer over the upper continental slope. The average water column properties shoreward of the 100 m isobath warmed by 0.26 °C yr^{-1}. This is comparable to warming estimates for the same time period from the Gulf of Maine and the New Jersey continental shelf.

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