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Atmospheric and Offshore Forcing of Temperature Variability at the Shelf Break

Observations from the OOI Pioneer Array

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ABSTRACT. Knowledge of heat balance and associated temperature variability in the Northwest Atlantic coastal ocean is important for understanding impacts of climate change such as how ocean warming will affect the management of fisheries. Heat balances are particularly complicated near the edge of the continental shelf, where the cross-shelf temperature gradients within the shelf-break front complicate the competing influences of air-sea flux anomalies versus ocean advection. We review the atmospheric and oceanic processes associated with heat balance over the Northwest Atlantic continental shelf and slope, with an emphasis on the scale-dependent nature of the heat balance. We then use data from the Ocean Observatories Initiative (OOI) Pioneer Array to demonstrate heat balance scale dependence at the southern New England shelf break, and the capability of the array to capture multiscale ocean processes. Comparison of the cumulative effects of air-sea heat fluxes measured at the OOI Pioneer Array from May 2015 to April 2016 with the actual temperature change shows the importance of advective processes in overall heat balance near the shelf break.

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INTRODUCTION

The coastal ocean of the Northwest Atlantic is affected by both subtropical and subpolar gyres and thus is subject to influences from the Gulf Stream and the Labrador Current. Circulation over the continental shelf includes an equatorward mean flow, which originates in the Labrador Sea (Chapman et al., 1986; Chapman and Beardsley, 1989). Separating the cold/fresh shelf water from the warm/saline slope water are the shelf-break front and the shelf-break jet, which are accompanied by complex shelf-slope exchanges across the shelf break (e.g., Loder et al., 1998). The shelf-break region supports a highly productive ecosystem and commercially valuable fisheries. The importance of understanding the region's ecosystem dynamics and its response to the physical environment has long been recognized (e.g., Fogarty and Murawski, 1998; Ji et al., 2008; He et al., 2011; Mills et al., 2013).

Ocean temperature is a fundamental environmental variable that profoundly influences marine ecosystems. Thus, understanding of the ocean's heat balance and its temperature variability is a long-standing research topic (Beardsley et al., 1985; Lentz et al., 2003a; Brink et al., 2009; Lentz, 2010; Fewings and Lentz, 2011; Connolly and Lentz, 2014). Growing evidence reveals long-term warming of Northwest Atlantic coastal waters (Shearman and Lentz, 2010; Forsyth et al., 2015; Pershing et al., 2015) and extreme warming events such as the ocean heat wave of 2012 (Chen et al., 2014a, 2015). Major shifts across the marine food web associated with such physical changes (e.g., Link and Ford, 2006; Greene and Pershing, 2007; Nye et al., 2009; Lucey and Nye, 2010; Walsh et al., 2015) further challenge ecosystem management (e.g., Mills et al., 2013; Pershing et al., 2015). Better understanding of the heat balance and temperature anomalies has societal and economic importance.

The main processes controlling the Northwest Atlantic coastal ocean heat balance include air-sea heat exchange, along-shelf advective flux, and cross-shelf advective flux. Each of these three contributions to the heat balance operates on different temporal and spatial scales. This scale-dependent nature of the heat balance often complicates understanding, particularly near the shelf break, where lateral gradients are present.

Fortunately, the Ocean Observatories Initiative (OOI) Pioneer Array (Figure 1) provides observations relevant to the coastal ocean heat balance on the small cross-shelf spatial scales typical of the shelf-break front south of New England. In this article, we briefly review the atmospheric and oceanic processes controlling the heat balance in the Northwest Atlantic coastal ocean, particularly the outer continental shelf and shelf break, with a focus on discussing recent extreme events and interannual variability. Then, we examine a year's worth of data from contrasting locations relative to the shelf-break front to consider both the seasonal cycle and processes contributing to intraseasonal variability. Finally, we discuss future science questions and research opportunities relating to OOI Pioneer Array data.

THE HEAT BALANCE OVER THE OUTER CONTINENTAL SHELF AND SHELF BREAK

Here, we briefly review the processes that affect the heat budget and the temperature variability over the outer continental shelf and shelf break in the Northwest Atlantic coastal ocean, including the Middle Atlantic Bight and the Gulf of Maine, as well as their relationships to large-scale atmospheric and oceanic forcings. These processes include surface air-sea heat flux, along-shelf advection, and shelf-slope exchange. Progress in this area has been limited by the absence of longer-term direct measurements of air-sea fluxes and reliance on reanalysis products with known uncertainty.

Surface air-sea heat flux and along-shelf advective heat flux are the primary drivers of heat balance and temperature variability in the Northwest Atlantic coastal ocean. However, the relative importance of these two processes in driving temperature changes and the dependence on timescales need clarification. For example, using historical temperature profiles and atmospheric reanalysis products, Lentz (2010) tested the hypothesis that the climatological mean heat balance on the Middle Atlantic Bight continental shelf is between the surface heat flux and the along-shelf advective heat flux resulting from the mean equatorward along-shelf flow. However, he noted that the validity of this simple balance is sensitive to the choice of the meteorological heat flux product. This sensitivity highlights uncertainties associated with the cross-shelf advective flux in the mean heat budget in the Middle Atlantic Bight.

Cross-shelf exchange processes are also important to the heat budget, particularly on an individual event timescale of days to weeks. Note that the mean cross-shelf heat flux in the Middle Atlantic Bight is small (e.g., Lentz, 2010), but the eddy flux (deviation from the mean) over an event timescale can be large. Gulf Stream warm core rings can induce significant cross-shelf transport of shelf water when they impinge upon the shelf break (e.g., Cenedese et al., 2013). Smaller eddies generated by instabilities of the shelf-break front (e.g., Garvine et al., 1988) and frontal meanders (e.g., Gawarkiewicz et al., 2004) can also entrain shelf water. A data-assimilative modeling study by Chen et al. (2014b) shows that one single warm core ring can cause cross-shore heat (and salt) flux much larger than the mean value (Chen and He, 2010). In a companion article, Gawarkiewicz et al. (2018, in this issue) discuss warm core ring intrusions onto the continental shelf observed by the OOI Pioneer Array.

Increasing attention is being given to long-term warming trends in the Middle Atlantic Bight and the increasing influence of offshore forcing that is bringing warmer waters onto the continental shelf because of the potential impacts on fisheries. Examples of such forcing include an increased number of warm core rings on the continental shelf (Monim, 2017), shifts in the meander pattern of the Gulf Stream (Andres 2016), and the north wall of the Gulf Stream pressing close to the shelf break (Gawarkiewicz et al., 2012; Ullman et al., 2014). Pershing et al. (2015) report accelerated warming of sea surface temperature in the Gulf of Maine during the last decade, which has affected the Atlantic cod fishery. Using XBT data, Forsyth et al. (2015) found accelerated warming of shelf water over the continental shelf off New Jersey. (Interested readers are referred to Figure 1 in Pershing et al., 2015, and Figure 5 in Forsyth et al., 2015, for the long-term warming trends.) Although the exact mechanisms for the accelerated warming in both the Gulf of Maine and the Middle Atlantic Bight remain to be investigated, the Pershing et al. (2015) and Forsyth et al. (2015) papers suggest that both atmospheric and oceanic processes are involved in the accelerated warming. For example, Pershing et al. (2015) showed there was a significant correlation between Gulf of Maine sea surface temperatures and large-scale climate indices, including the Gulf Stream Index, the Atlantic Multidecadal Oscillation, and the Pacific Decadal Oscillation. Forsyth et al. (2015) showed enhanced warming around the shelf break, indicating the possible role of offshore forcing in displacing the shelf-break front further onshore.

Focusing on the relative contributions of air-sea flux anomalies relative to advective processes, Chen et al. (2016) investigated the interannual variability of winter-spring temperature in the Middle Atlantic Bight using a realistic regional model (5–10 km resolution). They found that seasonal mean temperatures in winter and spring can be estimated using a combination of the initial temperature of the season and mean cumulative air-sea flux. The relative contributions of air-sea flux and ocean advective flux to the evolution of the temperature anomaly (with seasonal cycle removed) varies in each individual year (Chen et al., 2016). Nine of the 12 years considered had temperature anomalies resulting from air-sea flux anomalies, and the other three years had temperature anomalies primarily resulting from advective processes. It is an open question as to how these relative contributions may change moving forward, given changes in the motions of both the Jet Stream and the Gulf Stream in recent years.

In addition to the long-term warming trend, extreme events have become increasingly common in the Middle Atlantic Bight. The best example is the record warming in 2012. Sea surface temperature in the region was the highest ever recorded (Chen et al. 2015), with a 3°–4°C anomaly that exceeded three standard deviations in both the Middle Atlantic Bight and the Gulf of Maine. The temperature change significantly affected the marine ecosystem (Mills et al., 2013); for example, a northward shift in the distribution of Atlantic cod was observed (Friedland, 2012). Commercial fishermen also reported an increased abundance of squid in the summer of 2012, as well as the appearance of warm-water species not previously seen off southern New England, such as cobia and grouper (Gawarkiewicz et al., 2013). Such an extreme event in the Middle Atlantic Bight was attributed to anomalous atmospheric forcing, which was linked to a northward shift in the Jet Stream position (Figure 2; Chen et al. 2014a, 2015). The anomalously warm atmospheric conditions in the winter of 2011–2012 increased the ocean heat content (and heat content anomaly) and facilitated extreme warm ocean temperatures in spring 2012 (Chen et al. 2014a, 2015), with winter cooling reduced by 50% relative to the mean heat loss from 2000 to 2010. Ocean advection played a secondary role, as it partially damped the heat content anomaly created by the air-sea heat flux (Chen et al., 2015).

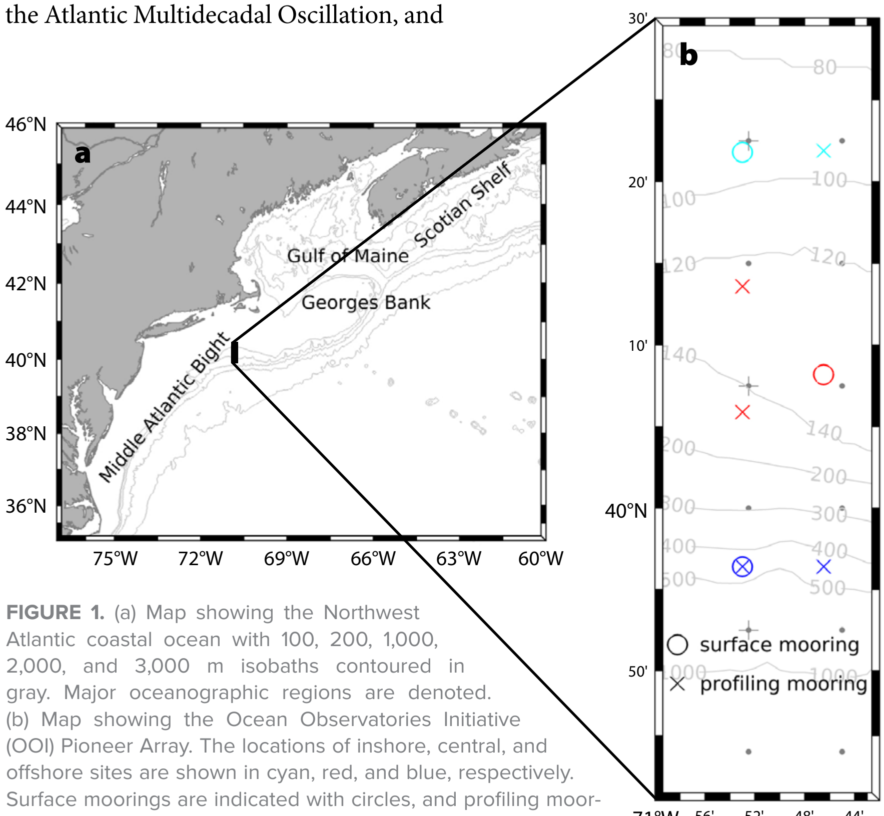

FIGURE 1. (a) Map showing the Northwest Atlantic coastal ocean with 100, 200, 1,000, 2,000, and 3,000 m isobaths contoured in gray. Major oceanographic regions are denoted. (b) Map showing the Ocean Observatories Initiative (OOI) Pioneer Array. The locations of inshore, central, and offshore sites are shown in cyan, red, and blue, respectively. Surface moorings are indicated with circles, and profiling moorings with crosses. Dots and pluses denote the locations of air-sea heat flux grid points for ERA-Interim and temperature/salinity climatology from the World Ocean Atlas.

OBSERVATIONS FROM THE PIONEER ARRAY

The Pioneer Array and Data Processing

The OOI Pioneer Array (Figure 1 and Smith et al., 2018, in this issue) is located off the coast of southern New England. Designed to capture multiscale, interdisciplinary processes in the shelf-break region, the Pioneer Array covers the outer shelf, shelf break, and upper slope with three surface moorings, seven profiler moorings, six coastal gliders, and intermittent sections by autonomous underwater vehicles (AUVs). A description of the science motivation and design principles for the Pioneer Array will be available in a forthcoming paper by authors Gawarkiewicz and Plueddemann.

The data used here are from the moored array, including three surface moorings and four profiler moorings at three isobaths near the shelf break: inshore, central, and offshore. The Figure 1 map shows the locations of the moorings. Net air-sea heat flux is collected by bulk meteorology instrument packages (using the COARE v3.5 bulk formula) at three surface moorings, and the depth-averaged temperature is calculated by averaging temperature profiles from the wire-following profilers at corresponding sites: upstream inshore, central inshore, central offshore, and offshore. The CTD on the wire-following profiler takes temperature measurements from 28 m below the surface to 28 m above the bottom (the upper and lower limits are dictated by the mooring design. The surface moorings also record surface water temperature, subsurface temperature at 7 m below surface, and bottom temperature one meter above the seabed. The OOI Data Portal provides two data delivery methods: recovered and telemetered. For each variable at each site, we merge recovered and telemetered data so that the recovered data are prioritized and the telemetered data fill in where the recovered data are not yet available. The net air-sea flux and surface temperature data are averaged to hourly values, and the profiling temperature data are interpolated to the same hourly intervals so that contributions of tidal and other variability are included.

Examination of the availability of heat flux, temperature, and velocity data shows that the inshore and central offshore moorings from May 2015 to April 2016 have the best data coverage. In the following, we will only focus on the observations from these two sites during this time period.

Heat Flux and Temperature, 2015–2016

The net air-sea heat flux exhibits a strong seasonal cycle, with positive flux into the ocean during the warm months, and negative flux during the cold months (Figure 3). The daily averaged values from the inshore surface buoy (95 m isobath) range from −775 W m^{-2} to 323 W m^{-2}. The buoy flux compares well with the heat flux from European Centre for Medium-range Weather Forecasts (ECMWF) ERA-Interim global reanalysis at the closest grid point (70.875°W, 40.375°N).

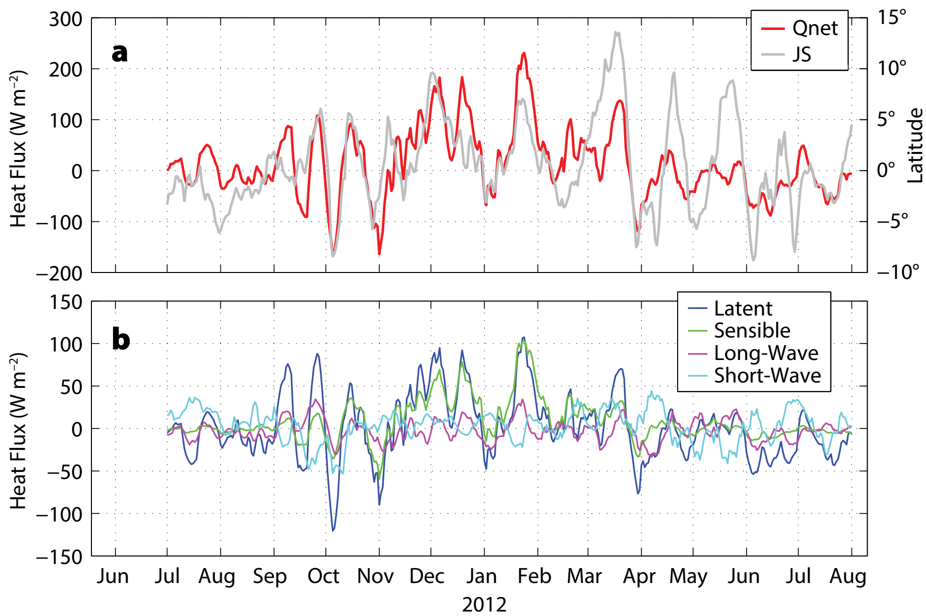

FIGURE 2. (a) The Jet Stream (JS) latitude anomaly (gray) during 2011–2012 and net atmospheric heat flux anomaly from North America Regional Reanalysis (Qnet, red, averaged at National Data Buoy Center buoys 44008, 44025, and 44099 in the Middle Atlantic Bight). (b) Different components of the air-sea heat flux anomaly, including latent heat flux (blue), sensible heat flux (green), long-wave radiation (magenta), and short-wave radiation (cyan). The positive direction is defined as downward (into the ocean). *Figure adapted from Chen et al. (2014a)*

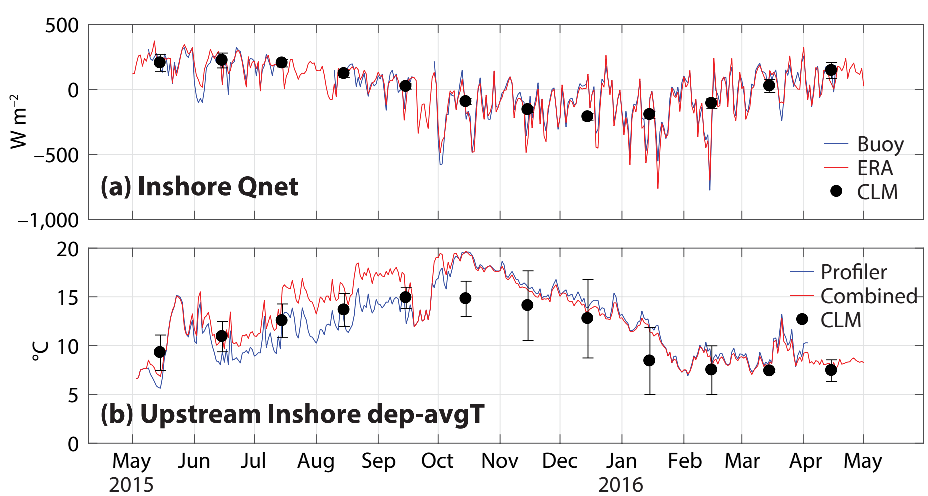

FIGURE 3. (a) Air-sea flux (positive downward) from the inshore surface buoy (blue) and ERA-Interim (red). Black dots indicate the monthly climatology based on ERA-Interim (1979–2016), with the error bar representing one standard deviation for all years. (b) Depth-averaged temperature at the upstream inshore profiler mooring without (blue) and with (red) the combination of surface temperature. Monthly climatology of depth-averaged temperature from WOA 2013 version 2 with the error bar representing one standard deviation during the depth averaging.

The seasonal variation of heat flux from May 2015 to April 2016 generally follows the climatological mean from 1979 to 2016, with larger departures on synoptic timescales during fall and winter, and less so during spring and summer. The strong fluctuations of heat flux during the cooler months are most likely associated with storm activity in the region.

The depth-averaged temperature at the upstream inshore site (9.2 km to the east of the inshore site along the same isobath) has a large seasonal variation, which is consistent with the typical seasonal cycle over the New England shelf (e.g., Beardsley and Boicourt, 1981; Lentz et al., 2003b, 2010). Over the seasonal scale, the depth-averaged temperature rises from April until October, and decreases to the annual minimum in March. To include the surface variability in the depth-averaged temperature, we also combine the surface water temperature from the inshore surface buoy with the profiling temperature at the upstream inshore site. Linear interpolation was used to fill the values between the surface and the uppermost valid measurement of the profiling temperature (Figure 4) at the same vertical resolution. Depth averaging then considers all data values for each vertical realization at an hourly interval. As expected, the inclusion of surface temperature increases the depth-averaged value in warmer, stratified months (June through October) by 2°–3°C, and does not change the depth-averaged value in cooler, less stratified months. The depth-averaged temperature at this site is similar to the World Ocean Atlas (WOA) climatology during 2005–2012 at the nearest grid point (70.875°W, 40.375°N) to the west of the upstream inshore site (70.775°W, 40.365°N), although there are notable departures from the climatology during fall and winter (Figure 3b).

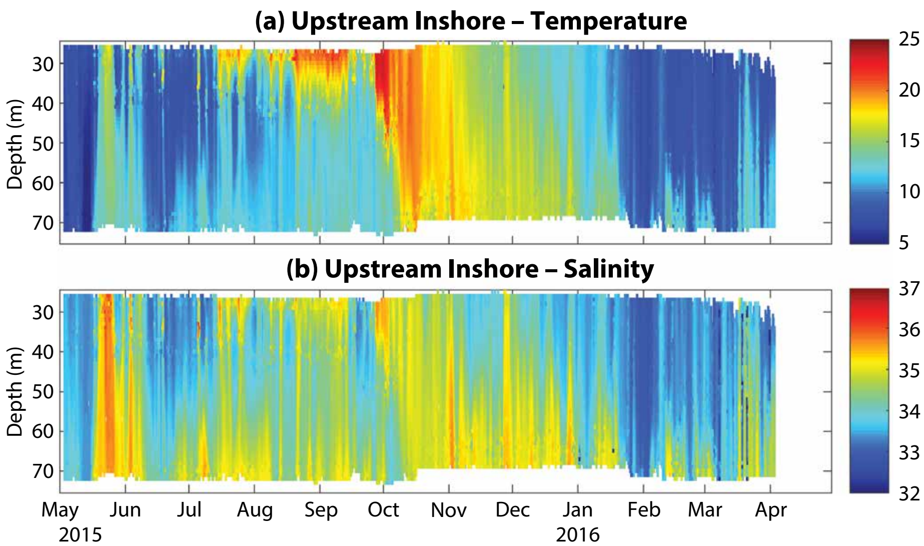

FIGURE 4. Temperature (°C) and salinity record from the upstream inshore wire-following profiler. Data are processed to hourly averages with vertical resolution of one meter.

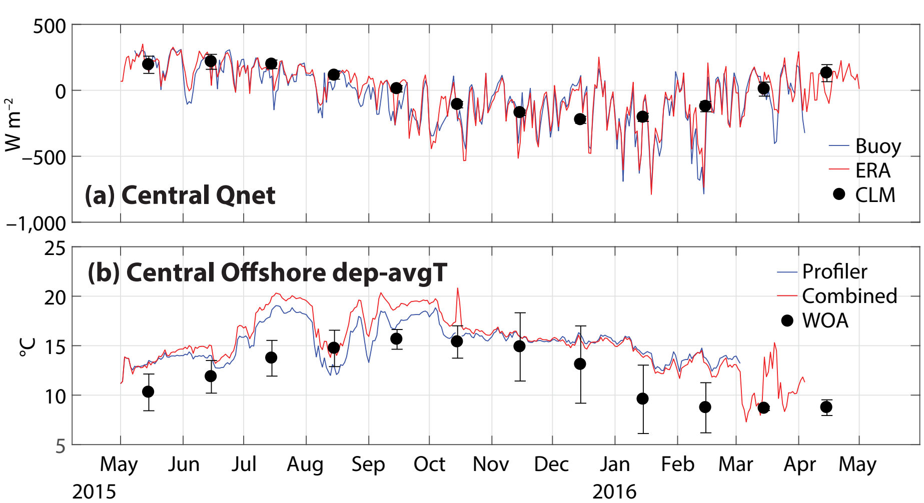

FIGURE 5. (a) Air-sea flux (positive downward) from the central surface buoy (blue) and ERA-Interim (red). Black dots indicate the monthly climatology based on ERA-Interim (1979–2016), with the error bar representing one standard deviation for all years. (b) Depth-averaged temperature at the central offshore profiler mooring without (blue) and with (red) the combination of surface temperature. Monthly climatology of depth-averaged temperature from the World Ocean Atlas with the error bar representing one standard deviation during the depth-averaging.

At the central site (135 m isobath), net air-sea heat flux exhibits a seasonal cycle similar to that at the inshore site (Figure 5). The buoy air-sea flux values agree well with the ERA-Interim counterpart at the nearest grid point (70.750°W, 40.125°N). The depth-averaged temperature (a combination of profiling temperature at the central offshore mooring and sea surface temperature at the central surface mooring) at the central offshore site (147 m isobaths; 10.2 km from the central site) also shows seasonal variability, although not as significant as that at the inshore site. One notable feature from the depth-averaged temperature record is the anomalously warm temperature in July 2015. The peak temperature is 18°–20°C, about 5°C higher than the climatology (at 70.875°W, 40.125°N) and temperature at the upstream inshore site. Further examination of satellite sea surface temperature imagery reveals that the warm anomaly was associated with a warm core ring, which brought warm and salty water to the outer shelf (Figures 6 and 7). A similar process also occurred in September 2015 when a warm core ring dramatically increased the temperature and salinity at the central offshore site (Figures 6 and 7).

The other notable feature is the anomalously warm temperature from December 2015 to February 2016. The depth-averaged temperature did not go through the typical seasonal cooling (black dots), in contrast with the variability at the upstream inshore site. Chen et al. (2014a) show that reduced cooling in the winter of 2011–2012 caused the extreme warm anomaly in early 2012 over a large region in the Northwest Atlantic coastal ocean. However, the three-month warm anomaly at the central offshore site is less likely to be explained by large-scale reduced cooling (i.e., air-sea heat flux anomaly) because the upstream inshore site, which is only 30 km away, does not exhibit a similar signal. Instead, the long-standing warm anomaly was due to intrusion of warm slope water associated with the Gulf Stream meander and warm core rings (Figure 7), which significantly warmed the continental slope and outer shelf. Considering the small spatial distance, such a contrast in the temporal evolution of the temperature field is remarkable. This contrast explains how the variability of a regional mean (temperature or flux) could be different from that of a single point. The contrasting observations at the inshore and central sites also highlight the importance of resolving the cross-shelf scale of the shelf-break front and frontal processes at the southern New England shelf break, as also suggested by earlier studies (e.g., Lentz et al., 2003b). Local heat balance is critically dependent on the cross-shelf position of the shelf-break front, which may be strongly affected by offshore forcing from warm core rings.

HEAT BALANCE

The time integrated heat balance for the depth-averaged temperature can be written as:

$$\overline{T} = T_0 + Q_{airT} + Q_{hadvT} + Q_{vadvT}, \quad (1)$$

where is the depth-averaged temperature, T_0 is the initial temperature at the beginning of the integration, Q_{airT} is the cumulative air-sea heat flux, Q_{hadvT} is the cumulative horizontal advective flux, and Q_{vadvT} is the cumulative vertical advective flux. For the details of the equation and the data processing, please see the online supplementary material.

Here, we focus on investigating the one-dimensional balance between the temperature change (the first two terms in Equation 1) and air-sea flux (the third term in Equation 1) and attribute the discrepancies to ocean advective processes. Although the absence of advective fluxes prevents us from closing the budget (we note that velocity data have not yet been quality controlled; this analysis will be performed in the future), a diagnostic calculation using only atmospheric forcing sheds light on the relative importance of the atmosphere and the ocean in determining temperature variability in the shelf-break region. Over the seasonal timescale, air-sea flux certainly plays an important role in modulating the depth-averaged temperature at both

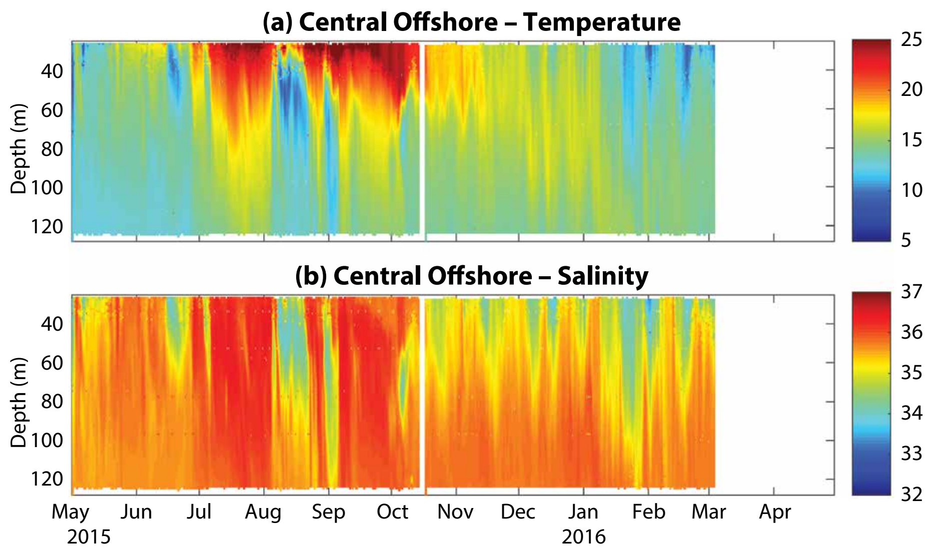

FIGURE 6. Temperature (°C) and salinity record from the central offshore wire-following profiler. Data are processed to hourly averages with vertical resolution of one meter.

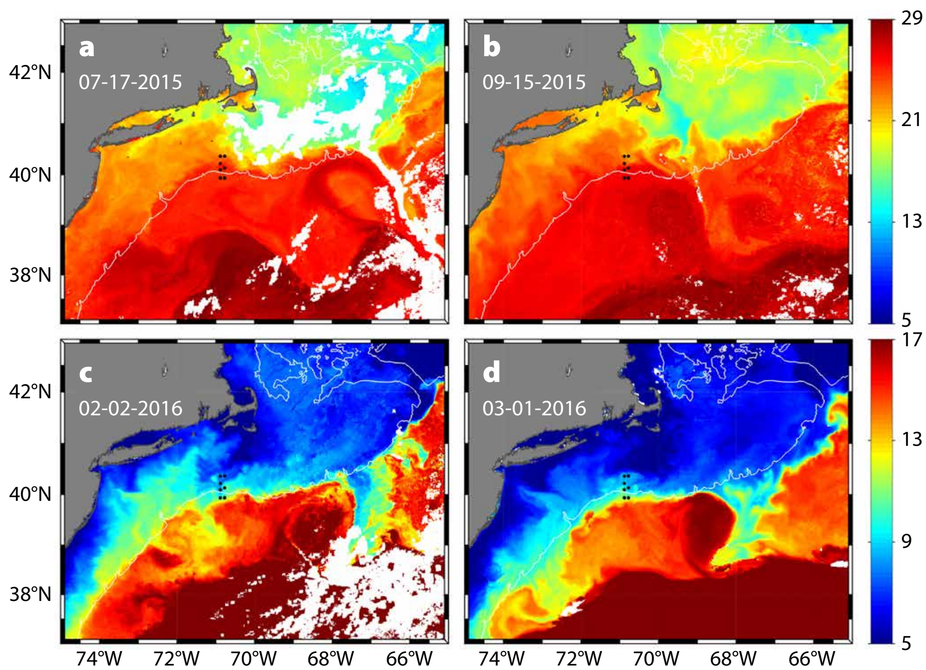

FIGURE 7. Satellite sea surface temperature images showing the impact of warm core rings at the OOI Pioneer Array (black dots). Sea surface temperature data (°C) are Advanced Very High Resolution Radiometer (AVHRR) daily averages composite on (a) July 7, 2015, (b) September 15, 2015, (c) February 2, 2016, and (d) March 1, 2016. The white contour is the 200 m isobath. Different color bars (in °C) are used for the upper and lower panels.

the upstream inshore and central offshore moorings (Figure 8), consistent with earlier studies over the continental shelf (e.g., Lentz et al., 2003a, 2010; Brink et al. 2009; Chen et al. 2014a). Within a seasonal timescale, the ocean advective flux likely dominates the variability of water column temperature at both the inshore and the central sites. For example, at the central offshore site, the warm anomalies in July 2015 and in early 2016 are primarily the result of advective fluxes associated with warm core ring interactions. Despite the uncertainties in the calculation of depth-averaged temperature and the fact that we did not calculate advective fluxes, the one-dimensional diagnostic calculation in Figure 8 suggests that ocean advective flux can be very important to the heat balance. In particular, intraseasonal variability is dominated by advective processes associated with warm core rings. The calculation of advective fluxes requires depth-dependent along- and cross-shelf temperature gradients and velocities, which are potentially available from the Pioneer Array. Further analysis is needed to better understand the complex ocean advective fluxes in the shelf-break region.

SUMMARY AND FUTURE OUTLOOK

Knowledge of the temperature variability and the heat budget of the outer continental shelf and shelf-break region is important for understanding how climate change is affecting the coastal ocean, in particular, its direct economic impact on the harvesting of living marine resources. Understanding the heat balance relies on the ability to differentiate the underlying atmospheric and oceanic processes, which in this region involves both shelf-break meandering and large-scale forcing from the Jet Stream and the Gulf Stream. The primary drivers of temperature variability depend on the timescale studied, for example, daily, intraseasonal, annual, interannual, or decadal, and the spatial scale, for example, one point to a large control volume. Therefore, interpretation of results needs to consider the appropriate temporal and spatial scales upon which the processes act, which, in the vicinity of the shelf break, may be very small.

The OOI Pioneer Array will undoubtedly provide further insights into the drivers of the heat balance and the role of advective influences, such as warm core ring interactions, on the heat balance at intraseasonal, seasonal, and interannual timescales. We anticipate gaining a much deeper understanding of heat balance contributions on smaller spatial and temporal scales as oceanographers combine different components of the OOI Pioneer Array data set, such as those from gliders and moored acoustic Doppler current profilers. Even initial analyses are showing that the OOI Pioneer Array resolves the necessary spatial and temporal scales to explore the influences of large-scale atmospheric forcing as well as local shelf-break processes such as frontal meandering.

In addition to improving our understanding of the heat balance in the Northwest Atlantic coastal ocean, data from the OOI Pioneer Array will provide sustained observations of air-sea fluxes necessary for evaluating heat flux products such as OAFlux (Yu and Weller, 2007) and SeaFlux (Curry et al., 2004). Furthermore, keeping a close eye on shelf and slope ocean temperatures is vitally important to understanding changes in the shelf ecosystem and associated fisheries, as well as to examining ocean response and feedbacks to storms affecting the coastal ocean and coastal communities.

Finally, we also hope that a new generation of graduate students and young scientists can be inspired and invigorated by the questions and challenges stimulated by the OOI Pioneer Array.

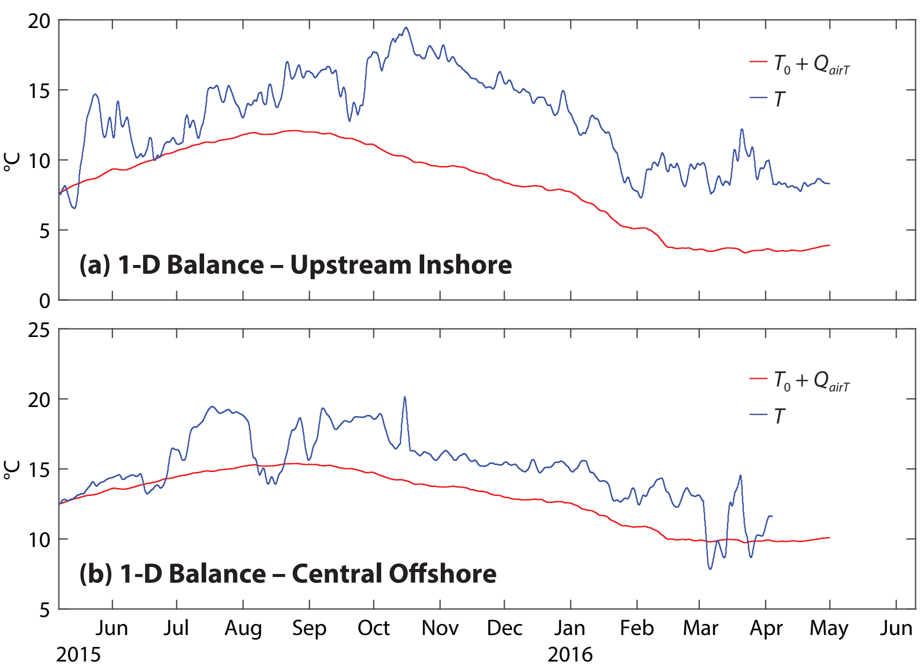

FIGURE 8. Depth-averaged temperature (blue) and the combination of initial temperature and cumulative air-sea heat flux (red) at inshore and central sites from May 2015 to April 2016. All units are °C.

SUPPLEMENTARY MATERIALS

The Supplementary Materials are available online at https://doi.org/10.5670/oceanog.2018.112.

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