THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Gawarkiewicz, G., R.E. Todd, W. Zhang, J. Partida, A. Gangopadhyay, M.-U.-H. Monim, P. Fratantoni, A. Malek Mercer, and M. Dent. 2018. The changing nature of shelf-break exchange revealed by the OOI Pioneer Array. *Oceanography* 31(1):60–70, https://doi.org/10.5670/oceanog.2018.110.

DOI

https://doi.org/10.5670/oceanog.2018.110

The Changing Nature of Shelf-Break Exchange Revealed by the OOI Pioneer Array

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> "Observations from the OOI Pioneer Array suggest that coastal ocean dynamics are changing rapidly south of New England, with important implications for commercial fisheries, ecosystems, and future storm intensities from both hurricanes and nor'easters."

ABSTRACT. Although the continental shelf and slope south of New England have been the subject of recent studies that address decadal-scale warming and interannual variability of water mass properties, it is not well understood how these changes affect shelf-break exchange processes. In recent years, observations of anomalous shelf and slope conditions obtained from the Ocean Observatories Initiative Pioneer Array and other regional observing programs suggest that onshore intrusions of warm, salty waters are becoming more prevalent. Mean cross-shelf transects constructed from Pioneer Array glider observations collected from April 2014 through December 2016 indicate that slope waters have been warmer and saltier. We examine shelf-break exchange events and anomalous onshore intrusions of warm, salty water associated with warm core rings located near the shelf break in spring 2014 and winter 2017 using observations from the Pioneer Array and other sources. We also describe an additional cross-shelf intrusion of ring water in September 2014 to demonstrate that the occurrence of high-salinity waters extending across the continental shelf is rare. Observations from the Pioneer Array and other sources show warm core ring and Gulf Stream water masses intrude onto the continental shelf more frequently and penetrate further onshore than in previous decades.

SHELF-BREAK EXCHANGE AND THE OCEAN OBSERVATORIES INITIATIVE PIONEER ARRAY

Shelf circulation south of New England consists primarily of westward along-shelf flow bounded on the offshore edge by the shelf-break front and jet. The shelf-break front is the boundary between cool, fresh shelf water and warm, salty slope water. The shelf-break front is baroclinically unstable and is frequently populated by large-amplitude frontal meanders (Zhang and Gawarkiewicz, 2015a). A number of recent studies document decadal- to century-scale warming of continental shelf and slope waters in this region, including research in fisheries oceanography and meteorology that focuses on the impacts of warming on commercial fisheries and the potential for storms to strengthen.

An important contributing factor to warming of the continental shelf is the influence of shelf-break exchange processes, particularly those that bring warm, salty water masses from the Slope Sea or Gulf Stream warm core rings onto the continental shelf. These exchange processes have been difficult to study because decorrelation scales near the shelf break are extremely small both spatially (~10 km) and temporally (~1 day), necessitating high-resolution sampling in both space and time to capture them (Gawarkiewicz et al., 2004). Additionally, variability of the cross-shelf fluxes at the shelf break is much larger than the long-term mean (Chen and He, 2010); thus, long-duration observations are needed to obtain statistically robust estimates of heat and salt fluxes between the continental shelf and the adjoining deep ocean.

Despite its complexity, two important practical applications make this topic important: (1) fisheries management, and (2) storm forecasting and associated public warnings/evacuations. Specifically, the timing and magnitude of episodic warming related to shelf-break exchange events or the cumulative impact of a string of events over a single season could alter critical habitat and affect recruitment success of commercially important species (Sullivan et al., 2005; Bell et al., 2014). Likewise, significant cumulative warming could affect the intensity and severity of storms striking the eastern seaboard (Glenn et al., 2016).

The record warm year of 2012 (Mills

et al., 2013; Chen et al., 2014a) as well as documented warming over decadal timescales (e.g., Forsyth et al., 2015; Pershing et al., 2015) in the Middle Atlantic Bight and Gulf of Maine system raise many important questions regarding shelf-break exchange processes. Increased shelf-break exchange can contribute to continental shelf warming. Warming of the shelf in turn affects cross-shelf density gradients that can change the nature of individual shelf-break exchange processes. This may increase the influence of ocean advective processes relative to air-sea fluxes in contributing to interannual fluctuations of shelf temperatures (e.g., see the discussion of relative contributions between air-sea flux anomalies and ocean advective heat flux anomalies in Chen et al., 2016).

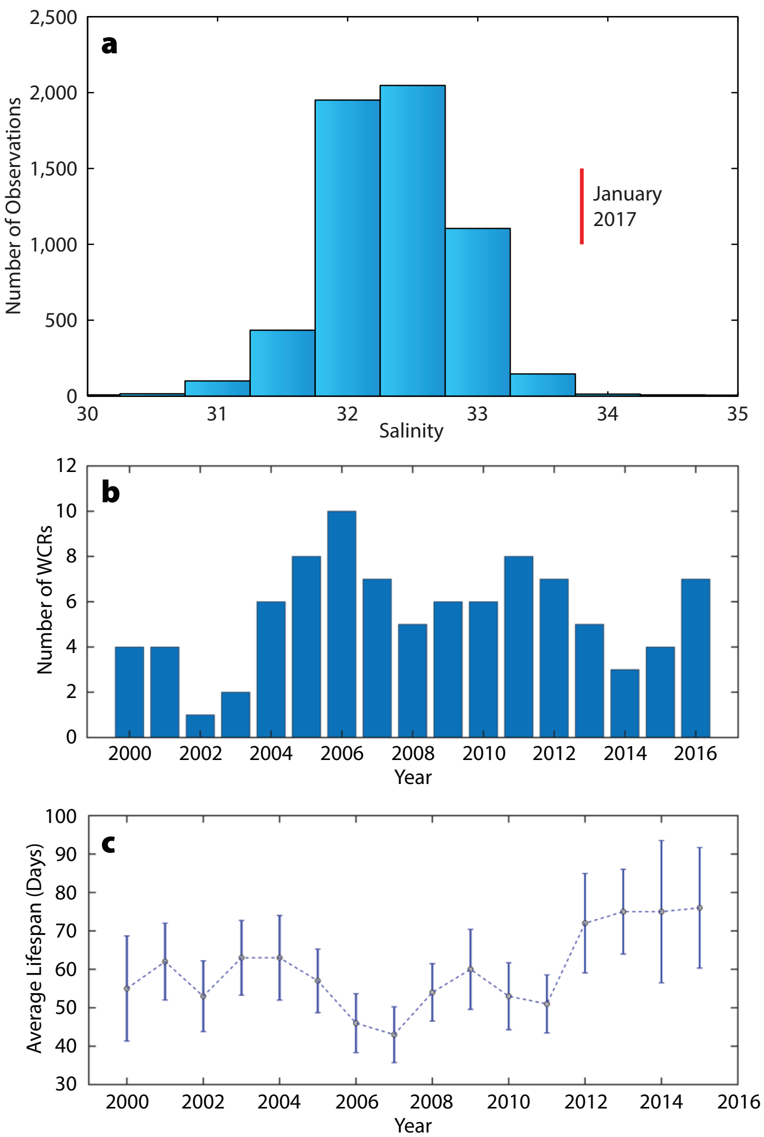

FIGURE 1. (a) A histogram of all salinity observations between 41°N and 41°15'N and 70°W and 72°W. The vertical red line denotes the salinity measured in January 2017. (b) The number of warm core rings (WCRs) passing through the Pioneer Array region with a ring center north of 39°30'N and within 70°W to 72°W each year from 2000–2016. This census is derived from the Gulf Stream analysis charts published each week by Jenifer Clark (http://users.erols.com/gulfstrm). (c) The average lifespan of all rings that pass through the slope region (75°W to 55°W), including the Pioneer Array, is shown with the standard error of the mean lifespan. Note that the warm core rings in the middle panel are a subset of all the warm core rings that were used for the average lifespan computation.

Ocean warming is not the only factor potentially affecting the dynamics of shelf-break exchange in this region. The large-scale spatial pattern of Gulf Stream meandering has changed over the past 20 years. Andres (2016) found that the longitude at which meander amplitudes exceed a specific threshold has been shifting westward since 1995, and large-amplitude meanders now frequently influence the upper continental slope south of New England (e.g., Gawarkiewicz et al., 2012; Ezer et al., 2013). Similarly, a recent census of Gulf Stream warm core rings shows that the average number of warm core rings formed annually from 2000 to 2016 was roughly double that for the time period 1977 to 1999 (Monim, 2017). Surprisingly, the annual frequency of warm core ring formation in the recent period was not correlated with the North Atlantic Oscillation. This is in sharp contrast to the earlier period when the number of rings was well correlated with the phase of the North Atlantic Oscillation (Chaudhuri et al., 2009).

The westward shift in the destabilization point of the Gulf Stream and the increasing number of warm core rings suggest that offshore forcing of the shelf-break region and increasing frequency of ring-shelf interactions may be playing a role in the recent warming of the continental shelf and changes to the continental shelf and slope ecosystem (Hare et al., 2016). Consistent with increasing influence from offshore forcing on the continental shelf, recent hydrographic observations reveal onshore intrusions of salty waters that are at the upper limits of observed values or exceed the range of previously observed values. For example, Ullman et al. (2014) describe a shoreward intrusion of salty bottom water that exceeded the range of historical salinity observations in the vicinity by 1.0 psu. Observations from the Commercial Fisheries Research Foundation (CFRF) Shelf Research Fleet (http://www.cfrfoundation.org/shelf-research-fleet) in January 2017 showed salinities in the upper 0.41% of historical observations between latitudes of 41°N and 41°15'N and longitudes of 70°W and 72°W (Figure 1a). The historical data were compiled by Christopher Linder of Woods Hole Oceanographic Institution and Maureen Taylor of the National Marine Fisheries Service and are described in Linder et al. (2006). This intrusion of ring water is described further in a later section of this paper.

Since its initial partial deployment in late 2013 and its subsequent commissioning in January 2016, the Ocean Observatories Initiative (OOI) Pioneer Array has collected sufficient observations to begin examining how various physical processes associated with shelf-break exchange may be evolving. A description of the Pioneer Array appears in Smith et al. (2018, in this issue), and recent work of author Gawarkiewicz and Al Plueddemann will soon yield a detailed discussion of both the final configuration of the array and the scientific motivation for the design choices.

Further examination of Monim's (2017) warm core ring census offers insight into offshore forcing of the shelf-break front. In recent years, a large number of warm core rings, ranging from four to nine per year from 2006 to 2016, have passed through the vicinity of the Pioneer Array (i.e., the ring center was located north of 39°30'N, and within 70°W to 72°W), frequently affecting the shelf-break front and jet (Figure 1b). The average lifetime of rings along the continental slope (75°W–55°W), including those passing through the Pioneer Array region, has increased in recent years (Figure 1c), allowing for the possibility of longer duration interactions between the rings and the shelf-break jet. (See Gawarkiewicz et al., 2001, for an example of a small ring interacting with the shelf-break jet, and Chen et al., 2014b, for a detailed analysis of a large ring interacting with the shelf-break front in 2006.)

Here, we present new perspectives on the changing nature of shelf-break exchange south of New England. We characterize the mean structure of the shelf-break front using Pioneer Array glider observations and compare the mean during this period to previous studies on decadal variations in slope water mass properties. We then focus on a warm core ring interacting with the shelf-break front in the spring of 2014 when Pioneer Array observations captured a new shelf-deep ocean exchange process (the Pinocchio's Nose Intrusion previously detailed by Zhang and Gawarkiewicz, 2015b), a subsequent rapid shift in shelf-break front location and circulation, and a subsurface filament of shelf-origin water adjacent to the warm core ring. We next combine Pioneer Array observations with measurements collected over the continental shelf by commercial fishermen to characterize the anomalous onshore penetration of warm core ring waters in early 2017. We use observations collected routinely since 1981 by the National Marine Fisheries Service Ecosystem Monitoring (EcoMon) Program to place September 2014 anomalous shelf conditions in a longer-term context. The final section looks ahead to possible impacts of future analyses using Pioneer Array observations.

THE SHELF-BREAK FRONT: A NEW PORTRAIT USING PIONEER ARRAY GLIDER OBSERVATIONS

Before examining recent shelf-break exchange events, it is instructive to consider the mean cross-shelf structure of the shelf-break front from April 2014 to December 2016, a period for which observations from autonomous underwater gliders are available on the Pioneer Array Eastern Boundary (EB) line (Figure 2). The primary science goal of the EB gliders is to measure the inflow of shelf and slope waters, which can be used as upstream boundary conditions for regional circulation and biogeochemical models. The typical EB glider mission goes back and forth between the 70 m isobath and the 3,000 m isobath (roughly 40°24'N to 39°50'N). Individual cross-shelf transects are completed in approximately one week. Further details of the glider missions, their scientific justification, and technical attributes may be found in Smith et al. (2018, in this issue) and are evident in recent work of author Gawarkiewicz and Al Plueddemann. A total of 78 distinct glider transects along the EB line are used here to construct mean potential temperature, salinity, and potential density fields. We average observations from individual glider profiles into 5 m vertical bins, then average individual glider transects into horizontal bins of 1 min extent by latitude (1 nm, or 1.852 km), and finally average across transects. The resulting mean fields (Figure 2) are shown only at latitudes occupied by at least 50% of individual transects.

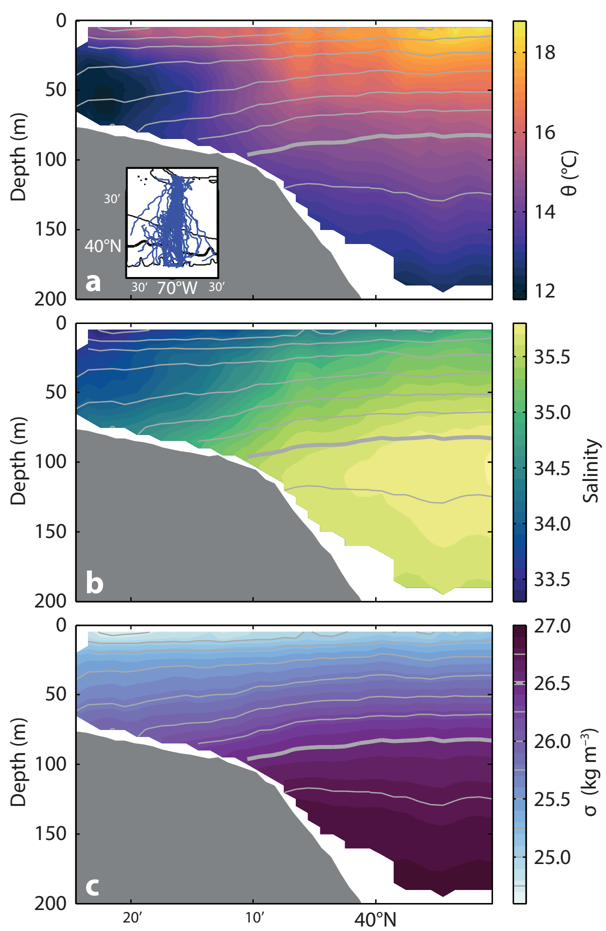

FIGURE 2. Mean transects across the Middle Atlantic Bight shelf break near 70°W of (a) potential temperature (θ), (b) salinity, and (c) potential density (σ) constructed by averaging observations from gliders surveying along the Pioneer Array's Eastern Boundary line from April 2014 through December 2016. Mean values are shown only at locations where at least 50% of identified glider transects yielded observations. Gray contours in all panels are isopycnals, with a contour interval of 0.25 kg m^{-3} and the 26.5 kg m^{-3} isopycnal bold. The inset in panel a shows the trajectories of the gliders from which observations were used.

Shoreward of the shelf break, the mean temperature, salinity, and density fields from EB glider observations capture expected features of the Middle Atlantic Bight shelf-break frontal region. The shelf-break front itself appears as a transition from cooler, fresher shelf waters to warmer, saltier slope waters, with isopycnals sloping upward offshore to form a retrograde front (i.e., the slope of the isopycnals is in the opposite direction of the slope of the bathymetry). The foot of the shelf-break front, identified as the location at which the 26.5 kg m^{-3} isopycnal (Linder and Gawarkiewicz, 1998) intersects the seafloor, is found near the 100 m isobath (approximately 40°12'N), in general agreement with previous, longer-term climatologies (e.g., Linder and Gawarkiewicz, 1998). More recent studies (e.g., Pickart, 2000; Linder et al., 2004; Fratantoni and Pickart, 2007) suggest that the frontal upwelling associated with the shelf-break front is centered on the 26.0 isopycnal, which intersects the seafloor near the 80 m isobath (approximately 40°20'N). The "cold pool" (Houghton et al., 1982), a region of cold water between the seasonal thermocline, the seafloor, and the shelf-break front is apparent shoreward of 40°15'N (Figure 2a), with minimum temperature below 12°C. Salinities within the cold pool range from 33.7 to 34.5 (Figure 2b), which is more saline than the typical salinities near 33 reported previously (e.g., Linder et al. 2006).

Farther offshore over the upper continental slope, the upper 50 m has the warmest temperatures in the region (16°–18°C). Beneath this layer, potential temperatures fall from 16°C to 13°C toward 200 m depth, and salinities reach a local maximum of more than 35.7 near 100 m. Wright and Parker (1976) previously identified these waters as the "upper slope thermostad," but found temperatures to be 10°–13°C and salinities to be 35–35.6. That these waters were on average warmer and saltier during the April 2014 to December 2016 period suggests more frequent presence over the upper continental slope of waters originating in the Gulf Stream.

> "The increase in temperature and salinity over the continental slope is consistent with both the westward shift in the destabilization point of the Gulf Stream and the increase in the number of warm core rings since 2000."

The increase in both temperature and salinity over the upper slope is surprising. Greene et al. (2013) and Pickart et al. (1999) describe how two different source regions, from the subpolar north and subtropical south, influence upper slope waters south of New England (see Figure 1 of Greene et al., 2013, for a schematic of the spatial distribution of the various water masses over the slope). The mean fields produced from glider observations along the Pioneer Array EB line (Figure 2) suggest that the subtropical waters of Gulf Stream origin have been dominant over the last several years. This has important consequences for zooplankton distributions and ecosystem dynamics of the shelf-slope system (e.g., Pershing et al., 2015). The increase in temperature and salinity over the continental slope is consistent with both the westward shift in the destabilization point of the Gulf Stream and the increase in the number of warm core rings since 2000.

RING INTERACTIONS AND SHELF-BREAK EXCHANGE PROCESSES REVEALED BY PIONEER ARRAY OBSERVATIONS

The persistent high-resolution observations provided by the Pioneer Array reveal new aspects of warm core ring interactions with outer shelf circulation. This is illustrated by Pioneer Array observations during the spring of 2014 when warm core ring water masses moved onto the outer continental shelf and shelf water masses extended over the continental slope along the periphery of a warm core ring.

Zhang and Gawarkiewicz (2015b) demonstrated the great potential of the observatory for studying a new form of shelf-break exchange process. By examining observations from the first Pioneer Array glider deployment along the EB line together with satellite-based sea surface temperature measurements, they identified a direct intrusion of warm core ring water onto the outer continental shelf in April–May 2014. The onshore intrusion of ring water represented a type of exchange process that had not been reported previously in the scientific literature, although a similar event was apparent in satellite-based sea surface temperature images from summer 2006. Zhang and Gawarkiewicz (2015b) named this process a Pinocchio's Nose Intrusion (PNI), as the intrusion had a unique elongated pattern in sea surface imagery that grew in the alongshelf direction.

The Pinocchio's Nose Intrusion in April–May 2014 measured roughly 30 km wide in the cross-shelf direction and extended at least 150 km alongshelf in two weeks (e.g., Figure 3a). Glider measurements captured the subsurface characteristics of the intrusion, showing that intruding ring water occupied almost the entire water column over the outer shelf (e.g., Figure 3c,e) and was not a surface-trapped feature entrained by the shelf-break jet. By combining these observations with idealized numerical simulations, Zhang and Gawarkiewicz (2015b) demonstrated that the dynamics of a PNI are inherently nonlinear and that it results from topographically induced vorticity variations of the ring water as it is carried into shallower water. As the ring water moves onshore, it is compressed vertically, and conservation of potential vorticity dictates that the ring water gains anticyclonic vorticity. This causes an enhanced outward-pointing centrifugal force that pushes the ring water further onto the shelf and generates the onshore intrusion. The westward elongation of the PNI is due to the alongshelf advection of momentum, as the intrusion does not form when nonlinear advective terms are neglected (see details of the momentum balances in Zhang and Gawarkiewicz, 2015b). This process represents a new mechanism for warm core rings interacting with the continental shelf circulation. It is a significant exchange process, as the associated onshore transport of ring water is of the same order of magnitude as shelf-break frontal jet transport. These intrusions of warm, salty ring water may have important biogeochemical implications and could facilitate migration of subtropical marine species across the shelf-break barrier and transport low-nutrient surface Gulf Stream ring water into the otherwise productive shelf-break region (Zhang et al., 2013).

A subsequent glider transect along the EB line demonstrates the rapid shifts in shelf-break hydrography and circulation following the 2014 Pinocchio's Nose Intrusion event (Figure 3d,f). Within the week between repeat glider crossings of the shelf break near 40°10'N in mid-May 2014, warm salty waters from the PNI were replaced by typical cool and fresh waters as the shelf-break front returned to approximately its mean position (Figure 3d,f) after having been pushed shoreward by the PNI (Figure 3c,e). Vertically averaged currents measured by the gliders indicate a simultaneous shift from westward flow within the PNI near 40°10'N (Figure 3a) to strong eastward flow south of 40°N a week later (Figure 3b) as the anticyclonic flow of the warm core ring impinged upon the upper

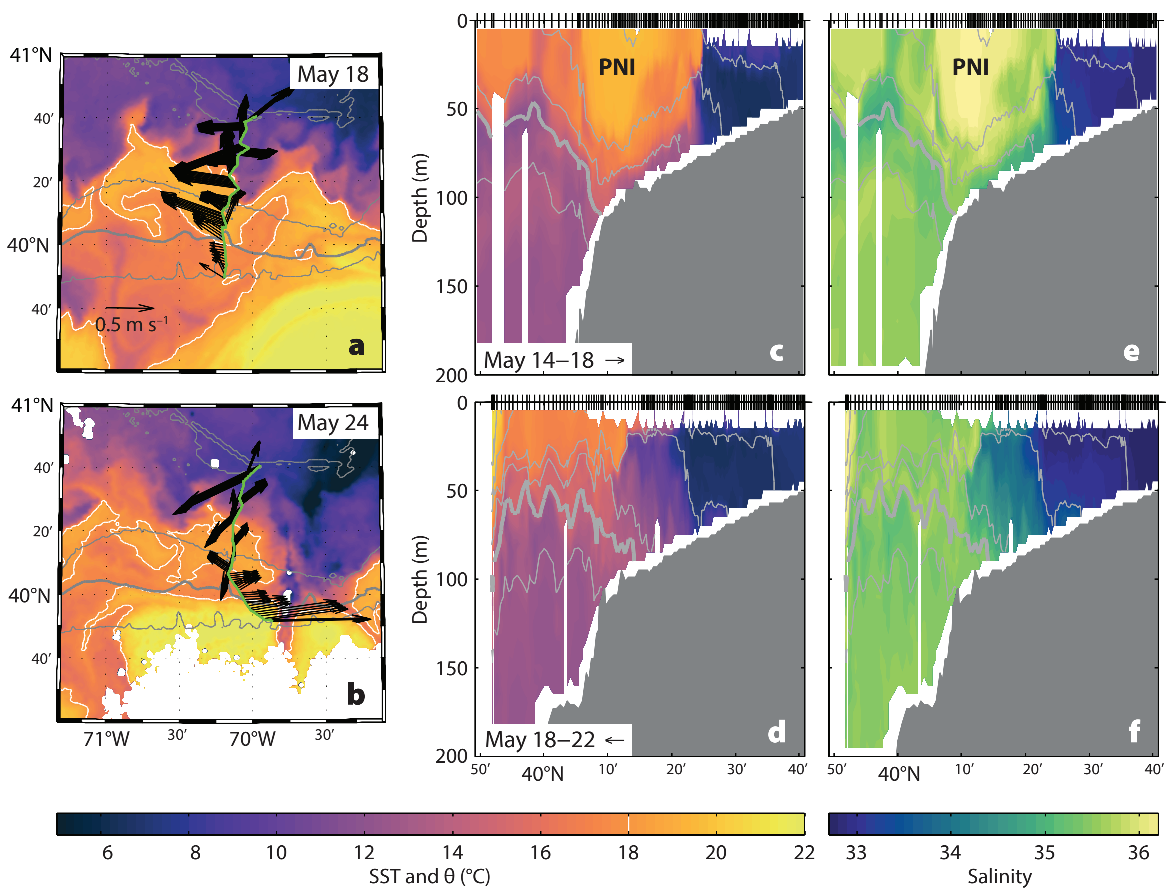

FIGURE 3. Rapid evolution of temperature and salinity near the Middle Atlantic Bight shelf break following the Pinocchio's Nose Intrusion (PNI) in May 2014. Top panels show (a) sea surface temperature with the 18°C isotherm drawn in white to delineate warm core ring water and cross-shelf break distributions of (c) potential temperature and (e) salinity from a Pioneer Array glider while the intrusion was active. PNI denotes the intrusion in (c,e). Lower panels (b,d,f) show the same properties a few days later. In (a) and (b), the trajectory of the glider along the Eastern Boundary line is shown (green), with vectors (black) indicating vertically averaged currents along the glider's trajectory. Gray contours are the 50, 100, 200, and 1,000 m isobaths, with the 200 m isobath bold. In (c–d), isopycnals are shown in gray, with a contour interval of 0.25 kg m^{-3} and the 26.5 kg m^{-3} isopycnal bold. Tick marks on the upper axes denote locations of glider profiles, and arrows show direction of glider motion during the indicated dates.

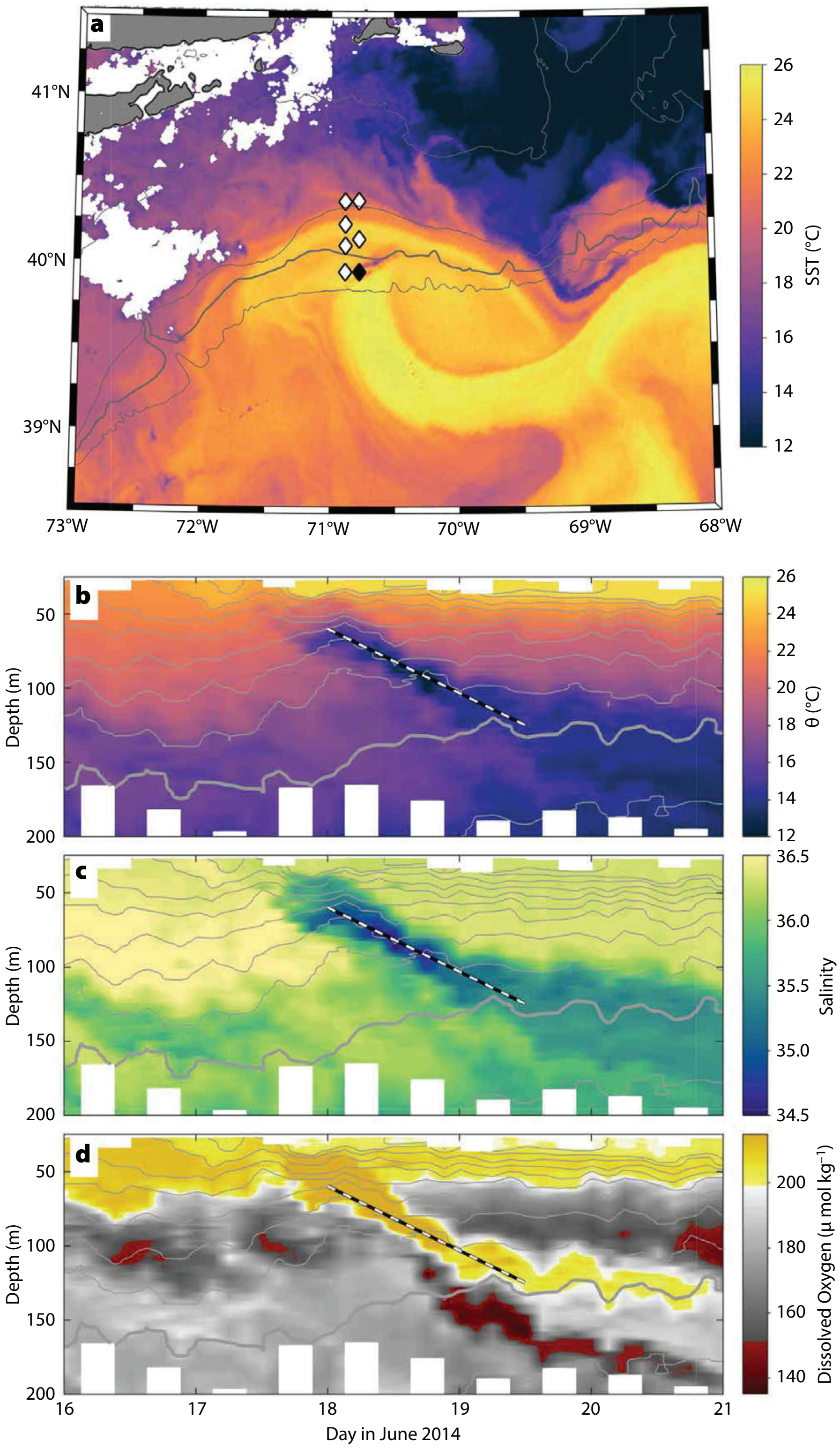

FIGURE 4. (a) Sea surface temperature on June 28, 2014, showing a warm core ring present near the Pioneer Array moorings (diamonds). The location of the Upstream Offshore mooring is shown in black. Time series of (b) potential temperature, (c) salinity, and (d) dissolved oxygen from the Upstream Offshore mooring during June 16–21, 2014, as a filament of shelf water was advected past the mooring. Gray contours in (b–d) are isopycnals, with a contour interval of 0.25 kg m^{-3} and the 26.5 kg m^{-3} isopycnal bold.

continental slope. These observations, together with those discussed by Zhang and Gawarkiewicz (2015b), indicate that the full timescale over which the PNI affected the shelf-break front was approximately one month.

As the same warm core ring continued to impinge upon the shelf break in June 2014, a subsurface filament of shelf-origin water was advected past the Pioneer Array moorings by the complex flows over the upper continental slope that were associated with the warm core ring-shelf-break front interaction (Figure 4b–d). Unlike the surface-visible shelf water streamer transport that is carried around the eastern periphery of the warm core ring (e.g., near 40°N, 69°20'W in Figure 4a), this subsurface filament of shelf water cannot be seen by satellite.

Moored profiler observations from the upstream-offshore mooring (Figure 4a, black diamond) show the relatively cold, fresh, and high-oxygen signature of shelf waters first reaching the mooring site near 60 m depth on June 18; it is then found at subsequently deeper depths until it arrives at the mooring site near 125 m depth about 1.5 days later (Figure 4b–d, dashed lines) as the northwestern edge of the warm core ring reaches the Pioneer Array moorings. The relatively low temperatures (<15°C) and salinities (<35) within the filament indicate that those waters originated shoreward of the shelf-break front, and the relatively high dissolved oxygen concentration serves as a useful additional tracer that distinguishes shelf waters from slope and ring waters. Note that the upstream-offshore mooring is located near the 500 m isobath and so is seaward of where shelf waters are typically found. The relatively fresh, cold, and oxygen-rich shelf water is eventually found beneath the warmer, saltier, and low-oxygen ring water. The descending signal of shelf water in Figure 4 crosses isopycnals, but this should not be interpreted as observational evidence of a water parcel moving downward across isopycnals. Such cross-isopycnal motion would require substantial mixing to modify the density of a parcel; however, the temperature, salinity, and oxygen signatures of the shelf water remain intact and do not suggest mixing with adjacent water masses. A likely explanation for the observed descending signal of shelf water is that the mooring sampled the three-dimensional structure of a tilted shelf-water filament as that filament was advected past the mooring by the combined ring and shelf-break flows. Vertically sheared flow, such as that in the shelf-break front, in warm core rings, and in other baroclinic eddies, is effective at producing tilted filaments (e.g., Smith and Ferrari, 2009).

A WARM CORE RING INTRUSION IN WINTER: COMBINING PIONEER ARRAY OBSERVATIONS WITH FISHERMEN-COLLECTED DATA FOR DEEPER INSIGHTS

A warm core ring intrusion onto the Middle Atlantic Bight shelf in the winter of 2017 offered an opportunity to combine Pioneer Array observations with additional in situ observations to examine the shoreward extent of anomalously warm waters over the continental shelf. Sea surface temperature imagery from January 25, 2017, showed an intrusion of warm (10°–11°C) waters as far north as 40°40'N from a warm core ring centered near 39°N, 71°20'W (Figure 5a). A subsequent sea surface temperature image on February 6 indicated that filaments with surface temperatures of 10°C extended as far north as 41°15'N, in the vicinity of Block Island in Rhode Island Sound (not shown). Block Island is approximately 115 km north of the 100 m isobath, the long-term mean position of the foot of the shelf-break front.

In late January 2017, a Pioneer Array glider surveying along the shelf break near 40°N (the northern edge of the Frontal Zone [FZ] glider survey pattern; Figure 5a) measured temperatures of

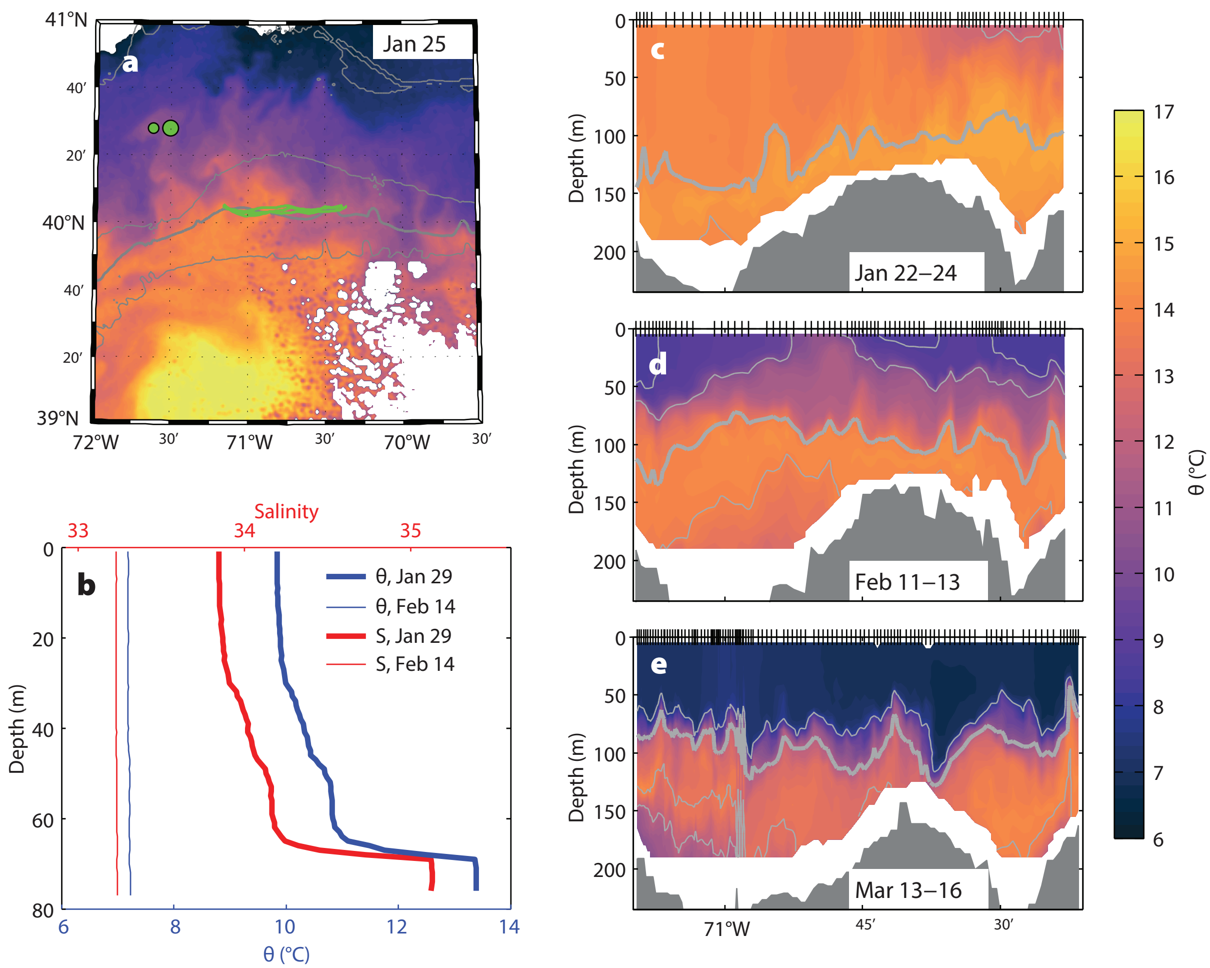

FIGURE 5. The evolution of anomalous conditions on the Middle Atlantic Bight shelf in winter 2017 resulting from a nearby warm core ring. (a) Sea surface temperature for the Pioneer Array region on January 25, 2017. The warm core ring is evident along the southern boundary, with warm water (>12°C) extending north of 40°20′N. (b) Potential temperature θ (blue) and salinity (red) profiles over the shelf north of the Pioneer Array from the Commercial Fisheries Research Foundation (CFRF) Shelf Research Fleet during January (thick lines) and February (thin lines) 2017. Warm, salty waters extended onto the shelf, particularly near the bottom, in late January, but not in mid-February. Locations of the CFRF profiles are shown by green circles in (a), with the larger circle corresponding to the January profiles. (c–e) Potential temperature (along the shelf break from Pioneer Array gliders during (c) January, (d) February, and (e) March 2017, showing substantial cooling as the warm core ring influence diminished. Tick marks on the upper axes in (c–e) denote the locations of individual glider profiles. Glider trajectories, which proceeded westward, are shown in green in (a). Contour lines denote isopycnals.

13°–15°C throughout the water column (Figure 5b). As part of the CFRF Shelf Research Fleet, Rhode Island fishermen collected temperature and salinity profiles near 40°30'N, 71°30'W on January 29 (Figure 5b; thick profiles). These profiles reveal a layer of unusually warm (10°–11°C) and salty (near 34) water in the upper 65 m that overlies a very warm (13.4°C) and salty (35) layer within 10 m of the seafloor. The near-bottom layer is slope water, and the sharp thermal gradient is the shelf-break front near the foot of the front where the high-gradient region intersects the bottom.

It is useful to compare a recent monthly, three-dimensional climatology built from all observations available from 1864 to 2009 (Fleming, 2016) with the observed shelf water mass properties in January 2017. The climatological temperature for the continental shelf for January is 5°C, and the climatological salinity is 33.0. Relative to this climatology, the January 2017 ring intrusion resulted in anomalies of 5°–6°C and 0.8–1.1 salinity units that extended as far north as 41°15'N. As such, the ring intrusion substantially impacted both shelf-water temperature and salinity across virtually the entire continental shelf.

Subsequent Pioneer Array observations and shelf profiles from CFRF fishermen indicate that shelf water properties returned toward normal as the winter of 2017 progressed. By February 14, the water column near 40°30'N, 71°30'W over the mid-shelf was well mixed with a temperature of 7.2°C and salinity of 33.2 (Figure 5b, thin profiles), and a nearly concurrent reoccupation of the glider transect along the shelf break (Figure 5d) showed waters in the upper 50 m around 9°C. Salinity measured at the offshore surface mooring indicated a rapid increase to 35.5 in early January 2017 that slowly decreased to 35.0 in mid-February as the ring intrusion drifted westward toward Hudson Canyon. By mid-March, another occupation of the along-shelf break glider transect showed further cooling throughout the water column, including a surface mixed layer with temperature near 7°C through the upper 60 m of the water column (Figure 5e).

One consequence of this warm intrusion was the appearance of warm-water fish species that were presumably carried onto the continental shelf in January 2017 as part of this event. A Rhode Island fishermen, Michael Marchetti (F/V *Mister G*, Point Judith, RI), recorded observations and photographs of unusual catch around Block Island in approximately 30 m of water, well inshore of the shelf break. Observed species included Gulf Stream flounder (*Citharichthys arctifrons*) and juvenile black sea bass (*Centropristis striata*), which are not typically found in shallow New England waters during the winter months. Fishermen also reported dramatic changes in Jonah crab (*Cancer borealis*) catch during the warm intrusion. Standardized fisheries surveys (NOAA Northeast Fisheries Science Center trawl survey and Northeast Area Monitoring and Assessment Program trawl survey) do not operate in the winter months, and thus are unable to provide further insights into the biological impacts of this mid-winter warm intrusion. Given the scale of the warm intrusion in January 2017, however, it is likely that the event had major, short-term impacts on ecosystem structure and function. Further research is needed to substantiate these specific ecosystem impacts of the ring intrusion.

HOW UNUSUAL ARE THE RING INTRUSIONS?

The Pioneer Array provides important new perspectives on shelf-break exchange, and observations from the array clearly show that onshore intrusions of warm core ring water masses are penetrating farther onshore than previously noted in historical data or the scientific literature. This is consistent with recent studies described earlier that indicate larger-amplitude Gulf Stream meanders and more frequent warm core rings since the year 2000. However, because the Pioneer Array has only been collecting observations since late 2013, it is difficult to quantify how unusual the recent ring intrusion events have been since 2013 using Pioneer Array observations alone.

The NOAA National Marine Fisheries Service's EcoMon program has been collecting CTD profiles over the Middle Atlantic Bight shelf between Hudson Canyon and the eastern end of Long Island, New York, since 1981; these long-term measurements allow us to place recent events in context. EcoMon observations are mapped onto a cross-shelf grid based on distance from the 100 m isobaths. Only observations collected during the months of September from 1981 to 2010 were used to calculate the climatological mean values and standard deviations (Figure 6a,b).

A significant intrusion event was identified in observations collected during the September 2014 EcoMon cruise (Figure 6c,d). The 34.0 isohaline outcropped at the 50 m isobath, 70 km shoreward of the shelf break (Figure 6c). In contrast, the surface outcrop of the 34.0 isohaline was located 20 km seaward of the shelf break in the EcoMon climatology (Figure 6a). Note that the slope of the 34.0 isohaline is in the opposite direction in September 2014 (downward offshore) compared to the climatology (upward offshore in the shelf-break front). The 34.0 isohaline intersected the seafloor at the 60 m isobath in September 2014, 50 km shoreward of the shelf break and roughly 30 km shoreward of its climatological position. This shoreward shift in the isohaline surfaces resulted in the mid-shelf salinity being five standard deviations above the climatological mean value in September 2014.

The shelf waters were also much warmer than average during the same time period, with much of the sub-thermocline water mass ranging from 14°–16°C, compared to climatological averages of 10°–12°C. Thus, the entire shelf was substantially warmer and saltier than average in late summer 2014, consistent with other ring intrusions documented by the OOI Pioneer Array.

LOOKING FORWARD—FUTURE IMPLICATIONS OF OOI PIONEER ARRAY SCIENCE

The OOI Pioneer Array has measured a number of significant shelf-break exchange events from the precommissioning deployments in late 2013 to the present. Some of the anomalous water mass properties measured over the continental shelf have rarely been observed in the past. The significant onshore penetration of warm core ring water is particularly likely to have important impacts on the continental shelf ecosystem and the seasonal movements of fish. By combining observations from the Pioneer Array, the CFRF Shelf Research Fleet, and the EcoMon program, we see that extreme or outlier events with warm, salty intrusions onto the shelf are occurring more frequently and penetrating further onshore than data from historical hydrographic archives would suggest.

We have presented primarily data on the thermohaline signatures of the exchange events. The next stage of Pioneer Array data analysis and modeling is processing and quality control of the velocity measurements from moorings and gliders and the computation of cross-shelf fluxes to characterize heat, salt, and buoyancy fluxes from these events. The ultimate goal will be to parameterize these fluxes based on dynamically important parameters such as the Rossby and Burger numbers, the maximum jet velocity in the shelf-break jet, and the maximum azimuthal velocities and spatial scales of warm core rings (e.g., Cenedese et al., 2013).

Observations from the OOI Pioneer Array suggest that coastal ocean dynamics are changing rapidly south of New England, with important implications for commercial fisheries, ecosystems, and future storm intensities from both hurricanes and nor'easters. There is an urgent need for focused numerical modeling studies to investigate the dynamics of shelf-break exchange. It is vital to explore the influence of larger, more frequent, and longer-lived warm core rings on the shelf-break front and on continental shelf circulation and ecosystems. Changes to shelf-break exchange may significantly affect nutrient transport between the deep ocean and the continental shelf, with consequences for higher trophic level productivity, including commercially harvested fish.

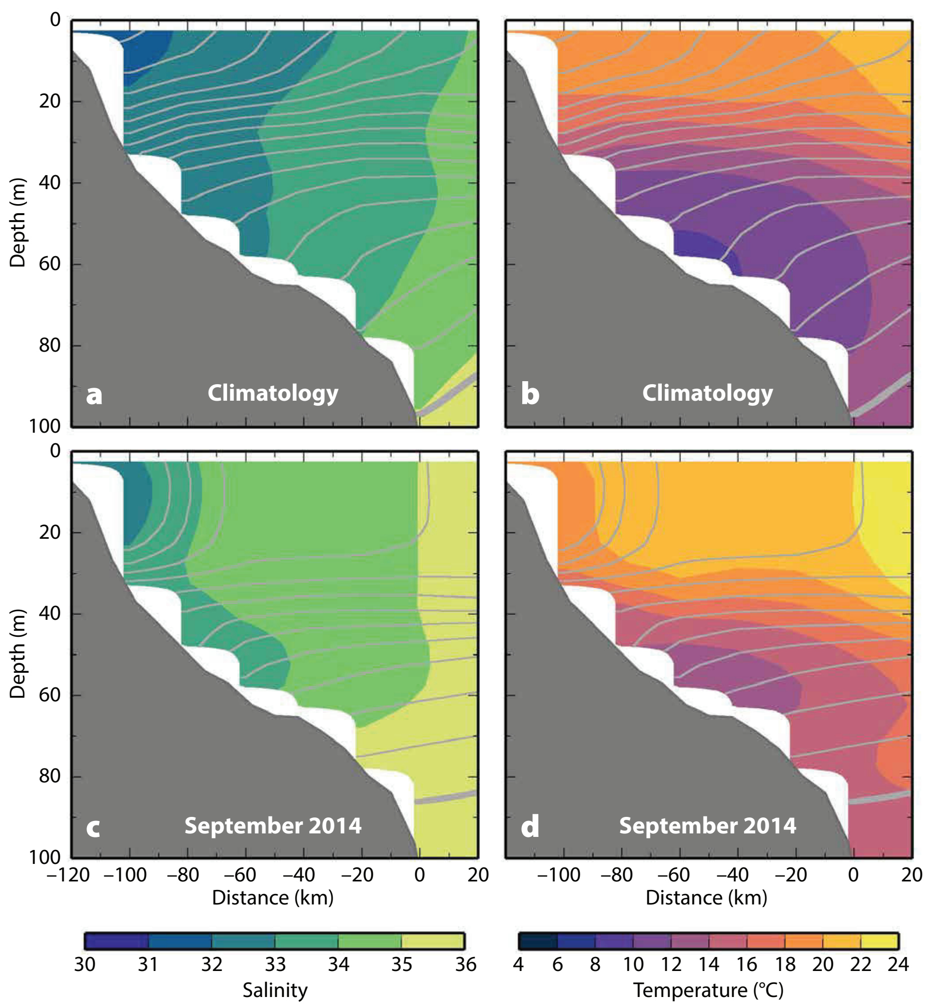

FIGURE 6. Cross-shelf transects of salinity (left panels) and temperature (right panels) from the Ecosystem Monitoring (EcoMon) cruises from NOAA's Northeast Fisheries Science Center. (a–b) Climatological mean fields constructed using observations collected from September cruises from 1981 to 2010. (c–d) Observations collected in September 2014. Gray contours are isopycnals with a contour interval of 0.25 kg m^{-3} and the 26.5 kg m^{-3} isopycnal bold.

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ACKNOWLEDGMENTS

GG, WZ, RT, and MD were supported by the National Science Foundation under grant OCE-1657853. WZ was also supported by grant OCE-1634965. JP is grateful for the support of the Woods Hole Oceanographic Institution Summer Student Fellow Program. AMM was supported by a grant from the MacArthur Foundation. GG and AMM were also supported by a grant from the van Beuren Charitable Foundation for collection and analysis of hydrographic data collected by the CFRF Shelf Research Fleet. Data from the OOI Pioneer Array was obtained from the NSF Ocean Observatories Initiative Data Portal, http://ooinet.oceanobservatories.org, as well as from the OOI raw data archive. AG and MM were partially supported by NOAA Grant No. NA11NOS0120038 for implementation of the Mid-Atlantic Regional Association Coastal Ocean Observing System. AG acknowledges the support of Jenifer Clark for the GS-WCR charts, which enabled the census results reported here. Data collected by the CFRF Shelf Research Fleet is available at http://science.whoi.edu/users/seasoar/cfrfwhoi. PF acknowledges the NOAA scientists and technicians who coordinated the collection and processing of EcoMon data used in this analysis. The authors thank Frank Bahr and Aubrey Ellertson for their efforts in coordinating and processing Shelf Fleet data as well as the fishermen who collect these data while at sea. We also thank the many dedicated scientists, engineers, and administrators who have worked so hard over more than a decade to make the Pioneer Array a reality.

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ARTICLE CITATION

Gawarkiewicz, G., R.E. Todd, W. Zhang, J. Partida, A. Gangopadhyay, M.-U.-H. Monim, P. Fratantoni, A. Malek Mercer, and M. Dent. 2018. The changing nature of shelf-break exchange revealed by the OOI Pioneer Array. *Oceanography* 31(1):60–70, https://doi.org/10.5670/oceanog.2018.110.

The Changing Nature of Shelf-Break Exchange Revealed by the OOI Pioneer Array

By Glen Gawarkiewicz, Robert E. Todd, Weifeng Zhang, Jacob Partida, Avijit Gangopadhyay, Mahmud-Ul-Hasan Monim, Paula Fratantoni, Anna Malek Mercer, and Margaret Dent

Photo credit: Ellen Roosen

> "Observations from the OOI Pioneer Array suggest that coastal ocean dynamics are changing rapidly south of New England, with important implications for commercial fisheries, ecosystems, and future storm intensities from both hurricanes and nor'easters."

ABSTRACT. Although the continental shelf and slope south of New England have been the subject of recent studies that address decadal-scale warming and interannual variability of water mass properties, it is not well understood how these changes affect shelf-break exchange processes. In recent years, observations of anomalous shelf and slope conditions obtained from the Ocean Observatories Initiative Pioneer Array and other regional observing programs suggest that onshore intrusions of warm, salty waters are becoming more prevalent. Mean cross-shelf transects constructed from Pioneer Array glider observations collected from April 2014 through December 2016 indicate that slope waters have been warmer and saltier. We examine shelf-break exchange events and anomalous onshore intrusions of warm, salty water associated with warm core rings located near the shelf break in spring 2014 and winter 2017 using observations from the Pioneer Array and other sources. We also describe an additional cross-shelf intrusion of ring water in September 2014 to demonstrate that the occurrence of high-salinity waters extending across the continental shelf is rare. Observations from the Pioneer Array and other sources show warm core ring and Gulf Stream water masses intrude onto the continental shelf more frequently and penetrate further onshore than in previous decades.

SHELF-BREAK EXCHANGE AND THE OCEAN OBSERVATORIES INITIATIVE PIONEER ARRAY

Shelf circulation south of New England consists primarily of westward alongshelf flow bounded on the offshore edge by the shelf-break front and jet. The shelf-break front is the boundary between cool, fresh shelf water and warm, salty slope water. The shelf-break front is baroclinically unstable and is frequently populated by large-amplitude frontal meanders (Zhang and Gawarkiewicz, 2015a). A number of recent studies document decadal- to century-scale warming of continental shelf and slope waters in this region, including research in fisheries oceanography and meteorology that focuses on the impacts of warming on commercial fisheries and the potential for storms to strengthen.

An important contributing factor to warming of the continental shelf is the influence of shelf-break exchange processes, particularly those that bring warm, salty water masses from the Slope Sea or Gulf Stream warm core rings onto the continental shelf. These exchange processes have been difficult to study because decorrelation scales near the shelf break are extremely small both spatially (~10 km) and temporally (~1 day), necessitating high-resolution sampling in both space and time to capture them (Gawarkiewicz et al., 2004). Additionally, variability of the cross-shelf fluxes at the shelf break is much larger than the long-term mean (Chen and He, 2010); thus, long-duration observations are needed to obtain statistically robust estimates of heat and salt fluxes between the continental shelf and the adjoining deep ocean.

Despite its complexity, two important practical applications make this topic important: (1) fisheries management, and (2) storm forecasting and associated public warnings/evacuations. Specifically, the timing and magnitude of episodic warming related to shelf-break exchange events or the cumulative impact of a string of events over a single season could alter critical habitat and affect recruitment success of commercially important species (Sullivan et al., 2005; Bell et al., 2014). Likewise, significant cumulative warming could affect the intensity and severity of storms striking the eastern seaboard (Glenn et al., 2016).

The record warm year of 2012 (Mills

et al., 2013; Chen et al., 2014a) as well as documented warming over decadal timescales (e.g., Forsyth et al., 2015; Pershing et al., 2015) in the Middle Atlantic Bight and Gulf of Maine system raise many important questions regarding shelf-break exchange processes. Increased shelf-break exchange can contribute to continental shelf warming. Warming of the shelf in turn affects cross-shelf density gradients that can change the nature of individual shelf-break exchange processes. This may increase the influence of ocean advective processes relative to air-sea fluxes in contributing to interannual fluctuations of shelf temperatures (e.g., see the discussion of relative contributions between air-sea flux anomalies and ocean advective heat flux anomalies in Chen et al., 2016).

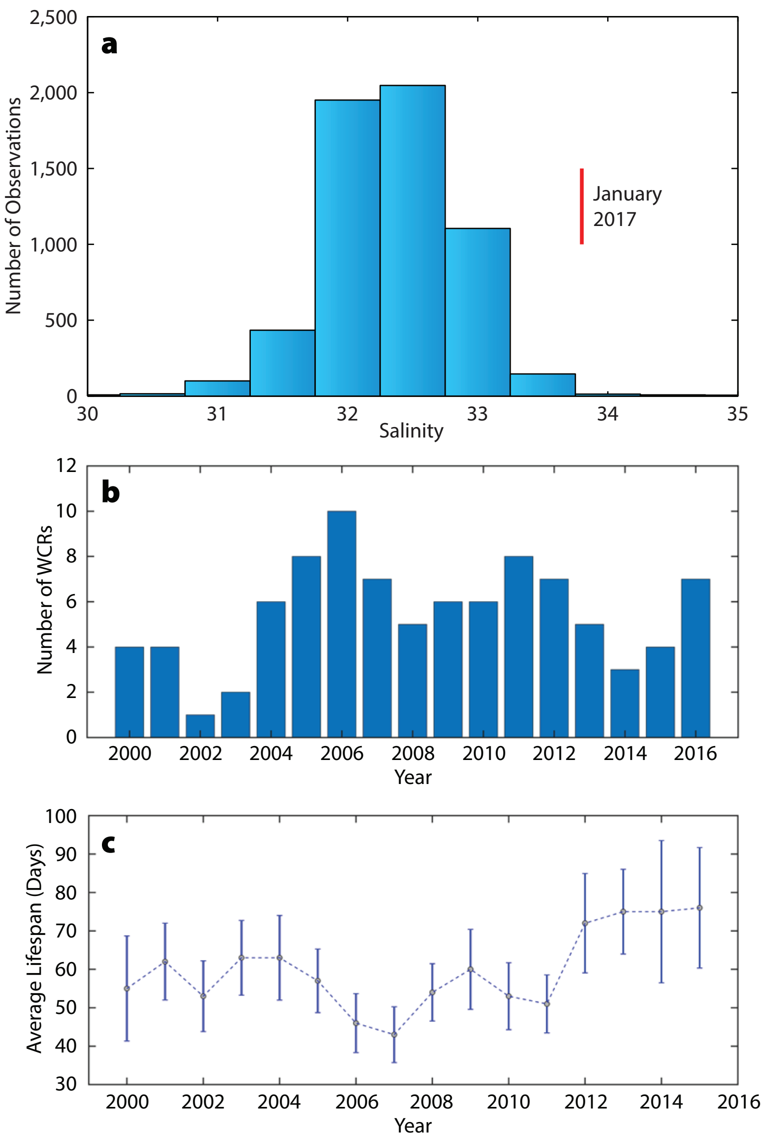

FIGURE 1. (a) A histogram of all salinity observations between 41°N and 41°15'N and 70°W and 72°W. The vertical red line denotes the salinity measured in January 2017. (b) The number of warm core rings (WCRs) passing through the Pioneer Array region with a ring center north of 39°30'N and within 70°W to 72°W each year from 2000–2016. This census is derived from the Gulf Stream analysis charts published each week by Jenifer Clark (http://users.erols.com/gulfstrm). (c) The average lifespan of all rings that pass through the slope region (75°W to 55°W), including the Pioneer Array, is shown with the standard error of the mean lifespan. Note that the warm core rings in the middle panel are a subset of all the warm core rings that were used for the average lifespan computation.

Ocean warming is not the only factor potentially affecting the dynamics of shelf-break exchange in this region. The large-scale spatial pattern of Gulf Stream meandering has changed over the past 20 years. Andres (2016) found that the longitude at which meander amplitudes exceed a specific threshold has been shifting westward since 1995, and large-amplitude meanders now frequently influence the upper continental slope south of New England (e.g., Gawarkiewicz et al., 2012; Ezer et al., 2013). Similarly, a recent census of Gulf Stream warm core rings shows that the average number of warm core rings formed annually from 2000 to 2016 was roughly double that for the time period 1977 to 1999 (Monim, 2017). Surprisingly, the annual frequency of warm core ring formation in the recent period was not correlated with the North Atlantic Oscillation. This is in sharp contrast to the earlier period when the number of rings was well correlated with the phase of the North Atlantic Oscillation (Chaudhuri et al., 2009).

The westward shift in the destabilization point of the Gulf Stream and the increasing number of warm core rings suggest that offshore forcing of the shelf-break region and increasing frequency of ring-shelf interactions may be playing a role in the recent warming of the continental shelf and changes to the continental shelf and slope ecosystem (Hare et al., 2016). Consistent with increasing influence from offshore forcing on the continental shelf, recent hydrographic observations reveal onshore intrusions of salty waters that are at the upper limits of observed values or exceed the range of previously observed values. For example, Ullman et al. (2014) describe a shoreward intrusion of salty bottom water that exceeded the range of historical salinity observations in the vicinity by 1.0 psu. Observations from the Commercial Fisheries Research Foundation (CFRF) Shelf Research Fleet (http://www.cfrfoundation.org/shelf-research-fleet) in January 2017 showed salinities in the upper 0.41% of historical observations between latitudes of 41°N and 41°15'N and longitudes of 70°W and 72°W (Figure 1a). The historical data were compiled by Christopher Linder of Woods Hole Oceanographic Institution and Maureen Taylor of the National Marine Fisheries Service and are described in Linder et al. (2006). This intrusion of ring water is described further in a later section of this paper.

Since its initial partial deployment in late 2013 and its subsequent commissioning in January 2016, the Ocean Observatories Initiative (OOI) Pioneer Array has collected sufficient observations to begin examining how various physical processes associated with shelf-break exchange may be evolving. A description of the Pioneer Array appears in Smith et al. (2018, in this issue), and recent work of author Gawarkiewicz and Al Plueddemann will soon yield a detailed discussion of both the final configuration of the array and the scientific motivation for the design choices.

Further examination of Monim's (2017) warm core ring census offers insight into offshore forcing of the shelf-break front. In recent years, a large number of warm core rings, ranging from four to nine per year from 2006 to 2016, have passed through the vicinity of the Pioneer Array (i.e., the ring center was located north of 39°30'N, and within 70°W to 72°W), frequently affecting the shelf-break front and jet (Figure 1b). The average lifetime of rings along the continental slope (75°W–55°W), including those passing through the Pioneer Array region, has increased in recent years (Figure 1c), allowing for the possibility of longer duration interactions between the rings and the shelf-break jet. (See Gawarkiewicz et al., 2001, for an example of a small ring interacting with the shelf-break jet, and Chen et al., 2014b, for a detailed analysis of a large ring interacting with the shelf-break front in 2006.)

Here, we present new perspectives on the changing nature of shelf-break exchange south of New England. We characterize the mean structure of the shelf-break front using Pioneer Array glider observations and compare the mean during this period to previous studies on decadal variations in slope water mass properties. We then focus on a warm core ring interacting with the shelf-break front in the spring of 2014 when Pioneer Array observations captured a new shelf-deep ocean exchange process (the Pinocchio's Nose Intrusion previously detailed by Zhang and Gawarkiewicz, 2015b), a subsequent rapid shift in shelf-break front location and circulation, and a subsurface filament of shelf-origin water adjacent to the warm core ring. We next combine Pioneer Array observations with measurements collected over the continental shelf by commercial fishermen to characterize the anomalous onshore penetration of warm core ring waters in early 2017. We use observations collected routinely since 1981 by the National Marine Fisheries Service Ecosystem Monitoring (EcoMon) Program to place September 2014 anomalous shelf conditions in a longer-term context. The final section looks ahead to possible impacts of future analyses using Pioneer Array observations.

THE SHELF-BREAK FRONT: A NEW PORTRAIT USING PIONEER ARRAY GLIDER OBSERVATIONS

Before examining recent shelf-break exchange events, it is instructive to consider the mean cross-shelf structure of the shelf-break front from April 2014 to December 2016, a period for which observations from autonomous underwater gliders are available on the Pioneer Array Eastern Boundary (EB) line (Figure 2). The primary science goal of the EB gliders is to measure the inflow of shelf and slope waters, which can be used as upstream boundary conditions for regional circulation and biogeochemical models. The typical EB glider mission goes back and forth between the 70 m isobath and the 3,000 m isobath (roughly 40°24'N to 39°50'N). Individual cross-shelf transects are completed in approximately one week. Further details of the glider missions, their scientific justification, and technical attributes may be found in Smith et al. (2018, in this issue) and are evident in recent work of author Gawarkiewicz and Al Plueddemann. A total of 78 distinct glider transects along the EB line are used here to construct mean potential temperature, salinity, and potential density fields. We average observations from individual glider profiles into 5 m vertical bins, then average individual glider transects into horizontal bins of 1 min extent by latitude (1 nm, or 1.852 km), and finally average across transects. The resulting mean fields (Figure 2) are shown only at latitudes occupied by at least 50% of individual transects.

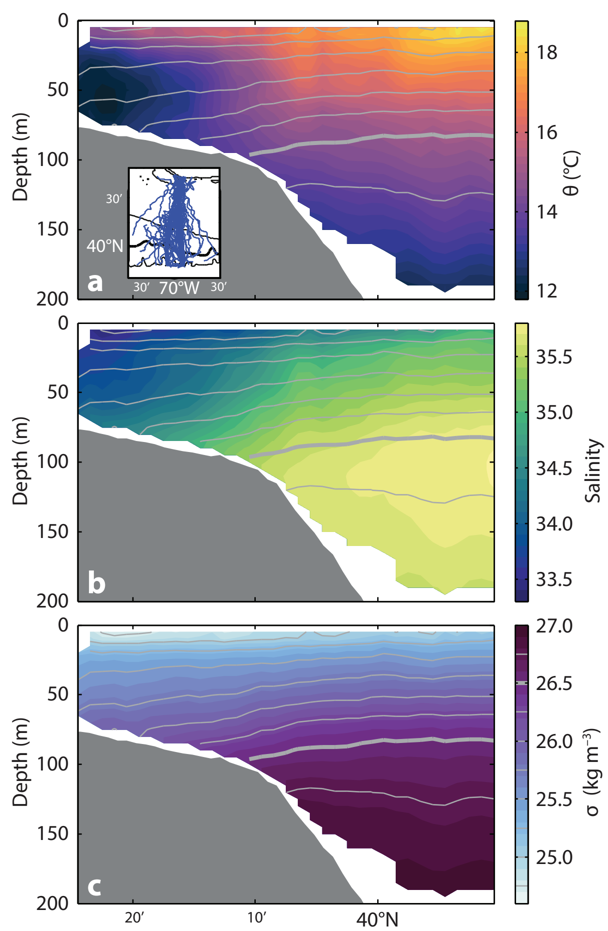

FIGURE 2. Mean transects across the Middle Atlantic Bight shelf break near 70°W of (a) potential temperature (θ), (b) salinity, and (c) potential density (σ) constructed by averaging observations from gliders surveying along the Pioneer Array's Eastern Boundary line from April 2014 through December 2016. Mean values are shown only at locations where at least 50% of identified glider transects yielded observations. Gray contours in all panels are isopycnals, with a contour interval of 0.25 kg m^{-3} and the 26.5 kg m^{-3} isopycnal bold. The inset in panel a shows the trajectories of the gliders from which observations were used.

Shoreward of the shelf break, the mean temperature, salinity, and density fields from EB glider observations capture expected features of the Middle Atlantic Bight shelf-break frontal region. The shelf-break front itself appears as a transition from cooler, fresher shelf waters to warmer, saltier slope waters, with isopycnals sloping upward offshore to form a retrograde front (i.e., the slope of the isopycnals is in the opposite direction of the slope of the bathymetry). The foot of the shelf-break front, identified as the location at which the 26.5 kg m^{-3} isopycnal (Linder and Gawarkiewicz, 1998) intersects the seafloor, is found near the 100 m isobath (approximately 40°12'N), in general agreement with previous, longer-term climatologies (e.g., Linder and Gawarkiewicz, 1998). More recent studies (e.g., Pickart, 2000; Linder et al., 2004; Fratantoni and Pickart, 2007) suggest that the frontal upwelling associated with the shelf-break front is centered on the 26.0 isopycnal, which intersects the seafloor near the 80 m isobath (approximately 40°20'N). The "cold pool" (Houghton et al., 1982), a region of cold water between the seasonal thermocline, the seafloor, and the shelf-break front is apparent shoreward of 40°15'N (Figure 2a), with minimum temperature below 12°C. Salinities within the cold pool range from 33.7 to 34.5 (Figure 2b), which is more saline than the typical salinities near 33 reported previously (e.g., Linder et al. 2006).

Farther offshore over the upper continental slope, the upper 50 m has the warmest temperatures in the region (16°–18°C). Beneath this layer, potential temperatures fall from 16°C to 13°C toward 200 m depth, and salinities reach a local maximum of more than 35.7 near 100 m. Wright and Parker (1976) previously identified these waters as the "upper slope thermostad," but found temperatures to be 10°–13°C and salinities to be 35–35.6. That these waters were on average warmer and saltier during the April 2014 to December 2016 period suggests more frequent presence over the upper continental slope of waters originating in the Gulf Stream.

The increase in both temperature and salinity over the upper slope is surprising. Greene et al. (2013) and Pickart et al. (1999) describe how two different source regions, from the subpolar north and subtropical south, influence upper slope waters south of New England (see Figure 1 of Greene et al., 2013, for a schematic of the spatial distribution of the various water masses over the slope). The mean fields produced from glider observations along the Pioneer Array EB line (Figure 2) suggest that the subtropical waters of Gulf Stream origin have been dominant over the last several years. This has important consequences for zooplankton distributions and ecosystem dynamics of the shelf-slope system (e.g., Pershing et al., 2015). The increase in temperature and salinity over the continental slope is consistent with both the westward shift in the destabilization point of the Gulf Stream and the increase in the number of warm core rings since 2000.

> "The increase in temperature and salinity over the continental slope is consistent with both the westward shift in the destabilization point of the Gulf Stream and the increase in the number of warm core rings since 2000."

RING INTERACTIONS AND SHELF-BREAK EXCHANGE PROCESSES REVEALED BY PIONEER ARRAY OBSERVATIONS

The persistent high-resolution observations provided by the Pioneer Array reveal new aspects of warm core ring interactions with outer shelf circulation. This is illustrated by Pioneer Array observations during the spring of 2014 when warm core ring water masses moved onto the outer continental shelf and shelf water masses extended over the continental slope along the periphery of a warm core ring.

Zhang and Gawarkiewicz (2015b) demonstrated the great potential of the observatory for studying a new form of shelf-break exchange process. By examining observations from the first Pioneer Array glider deployment along the EB line together with satellite-based sea surface temperature measurements, they identified a direct intrusion of warm core ring water onto the outer continental shelf in April–May 2014. The onshore intrusion of ring water represented a type of exchange process that had not been reported previously in the scientific literature, although a similar event was apparent in satellite-based sea surface temperature images from summer 2006. Zhang and Gawarkiewicz (2015b) named this process a Pinocchio's Nose Intrusion (PNI), as the intrusion had a unique elongated pattern in sea surface imagery that grew in the alongshelf direction.

The Pinocchio's Nose Intrusion in April–May 2014 measured roughly 30 km wide in the cross-shelf direction and extended at least 150 km alongshelf in two weeks (e.g., Figure 3a). Glider measurements captured the subsurface characteristics of the intrusion, showing that intruding ring water occupied almost the entire water column over the outer shelf (e.g., Figure 3c,e) and was not a surface-trapped feature entrained by the shelf-break jet. By combining these observations with idealized numerical simulations, Zhang and Gawarkiewicz (2015b) demonstrated that the dynamics of a PNI are inherently nonlinear and that it results from topographically induced vorticity variations of the ring water as it is carried into shallower water. As the ring water moves onshore, it is compressed vertically, and conservation of potential vorticity dictates that the ring water gains anticyclonic vorticity. This causes an enhanced outward-pointing centrifugal force that pushes the ring water further onto the shelf and generates the onshore intrusion. The westward elongation of the PNI is due to the alongshelf advection of momentum, as the intrusion does not form when nonlinear advective terms are neglected (see details of the momentum balances in Zhang and Gawarkiewicz, 2015b). This process represents a new mechanism for warm core rings interacting with the continental shelf circulation. It is a significant exchange process, as the associated onshore transport of ring water is of the same order of magnitude as shelf-break frontal jet transport. These intrusions of warm, salty ring water may have important biogeochemical implications and could facilitate migration of subtropical marine species across the shelf-break barrier and transport low-nutrient surface Gulf Stream ring water into the otherwise productive shelf-break region (Zhang et al., 2013).

A subsequent glider transect along the EB line demonstrates the rapid shifts in shelf-break hydrography and circulation following the 2014 Pinocchio's Nose Intrusion event (Figure 3d,f). Within the week between repeat glider crossings of the shelf break near 40°10'N in mid-May 2014, warm salty waters from the PNI were replaced by typical cool and fresh waters as the shelf-break front returned to approximately its mean position (Figure 3d,f) after having been pushed shoreward by the PNI (Figure 3c,e). Vertically averaged currents measured by the gliders indicate a simultaneous shift from westward flow within the PNI near 40°10'N (Figure 3a) to strong eastward flow south of 40°N a week later (Figure 3b) as the anticyclonic flow of the warm core ring impinged upon the upper

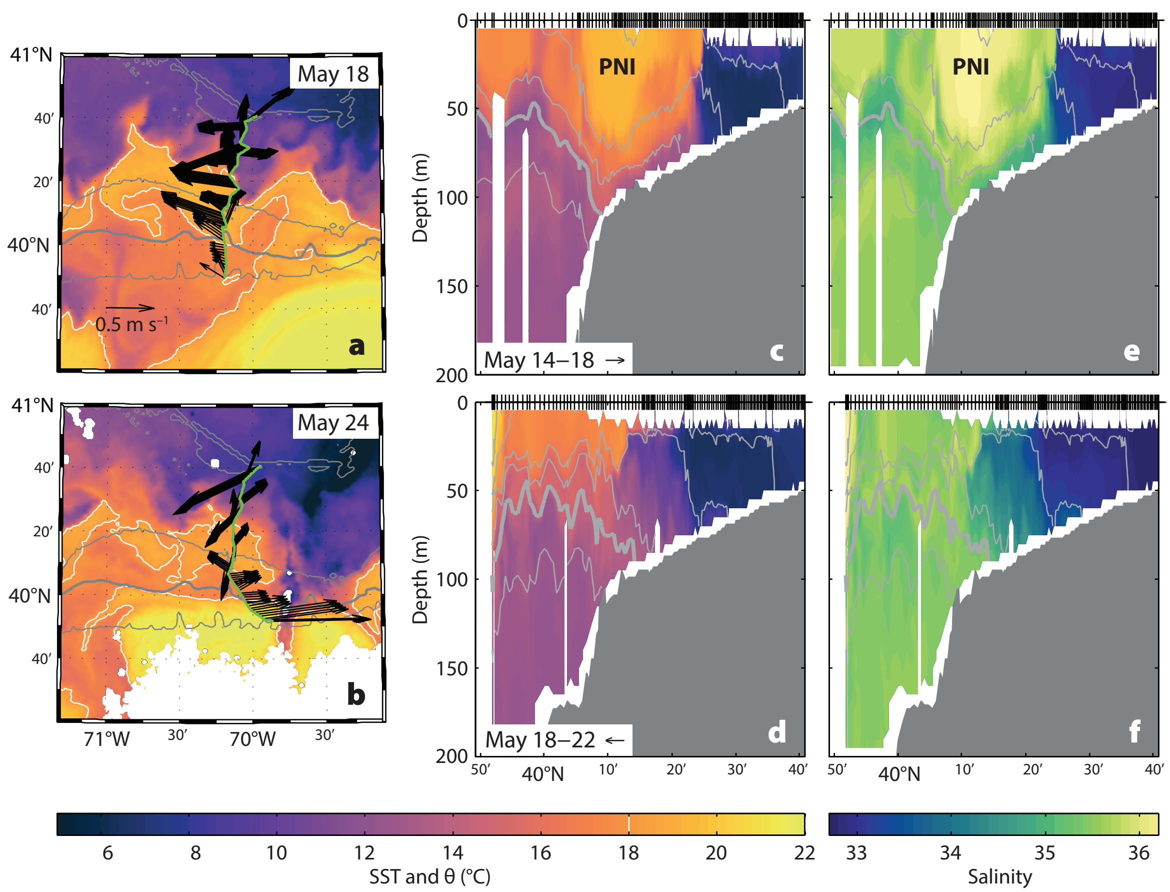

FIGURE 3. Rapid evolution of temperature and salinity near the Middle Atlantic Bight shelf break following the Pinocchio's Nose Intrusion (PNI) in May 2014. Top panels show (a) sea surface temperature with the 18°C isotherm drawn in white to delineate warm core ring water and cross-shelf break distributions of (c) potential temperature and (e) salinity from a Pioneer Array glider while the intrusion was active. PNI denotes the intrusion in (c,e). Lower panels (b,d,f) show the same properties a few days later. In (a) and (b), the trajectory of the glider along the Eastern Boundary line is shown (green), with vectors (black) indicating vertically averaged currents along the glider's trajectory. Gray contours are the 50, 100, 200, and 1,000 m isobaths, with the 200 m isobath bold. In (c–d), isopycnals are shown in gray, with a contour interval of 0.25 kg m^{-3} and the 26.5 kg m^{-3} isopycnal bold. Tick marks on the upper axes denote locations of glider profiles, and arrows show direction of glider motion during the indicated dates.

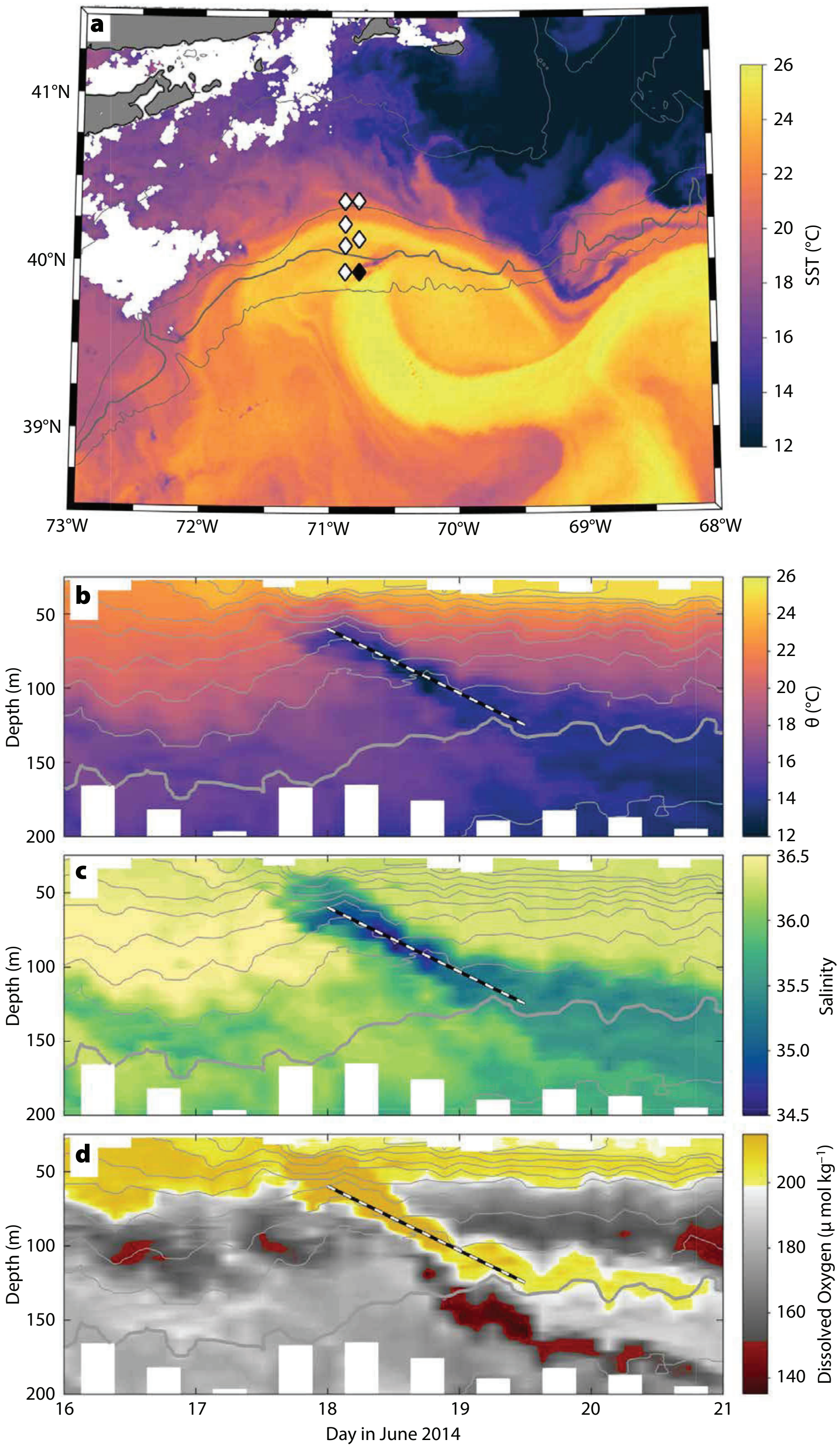

FIGURE 4. (a) Sea surface temperature on June 28, 2014, showing a warm core ring present near the Pioneer Array moorings (diamonds). The location of the Upstream Offshore mooring is shown in black. Time series of (b) potential temperature, (c) salinity, and (d) dissolved oxygen from the Upstream Offshore mooring during June 16–21, 2014, as a filament of shelf water was advected past the mooring. Gray contours in (b–d) are isopycnals, with a contour interval of 0.25 kg m^{-3} and the 26.5 kg m^{-3} isopycnal bold.

continental slope. These observations, together with those discussed by Zhang and Gawarkiewicz (2015b), indicate that the full timescale over which the PNI affected the shelf-break front was approximately one month.

As the same warm core ring continued to impinge upon the shelf break in June 2014, a subsurface filament of shelf-origin water was advected past the Pioneer Array moorings by the complex flows over the upper continental slope that were associated with the warm core ring-shelf-break front interaction (Figure 4b–d). Unlike the surface-visible shelf water streamer transport that is carried around the eastern periphery of the warm core ring (e.g., near 40°N, 69°20'W in Figure 4a), this subsurface filament of shelf water cannot be seen by satellite.

Moored profiler observations from the upstream-offshore mooring (Figure 4a, black diamond) show the relatively cold, fresh, and high-oxygen signature of shelf waters first reaching the mooring site near 60 m depth on June 18; it is then found at subsequently deeper depths until it arrives at the mooring site near 125 m depth about 1.5 days later (Figure 4b–d, dashed lines) as the northwestern edge of the warm core ring reaches the Pioneer Array moorings. The relatively low temperatures (<15°C) and salinities (<35) within the filament indicate that those waters originated shoreward of the shelf-break front, and the relatively high dissolved oxygen concentration serves as a useful additional tracer that distinguishes shelf waters from slope and ring waters. Note that the upstream-offshore mooring is located near the 500 m isobath and so is seaward of where shelf waters are typically found. The relatively fresh, cold, and oxygen-rich shelf water is eventually found beneath the warmer, saltier, and low-oxygen ring water. The descending signal of shelf water in Figure 4 crosses isopycnals, but this should not be interpreted as observational evidence of a water parcel moving downward across isopycnals. Such cross-isopycnal motion would require substantial mixing to modify the density of a parcel; however, the temperature, salinity, and oxygen signatures of the shelf water remain intact and do not suggest mixing with adjacent water masses. A likely explanation for the observed descending signal of shelf water is that the mooring sampled the three-dimensional structure of a tilted shelf-water filament as that filament was advected past the mooring by the combined ring and shelf-break flows. Vertically sheared flow, such as that in the shelf-break front, in warm core rings, and in other baroclinic eddies, is effective at producing tilted filaments (e.g., Smith and Ferrari, 2009).

A WARM CORE RING INTRUSION IN WINTER: COMBINING PIONEER ARRAY OBSERVATIONS WITH FISHERMEN-COLLECTED DATA FOR DEEPER INSIGHTS

A warm core ring intrusion onto the Middle Atlantic Bight shelf in the winter of 2017 offered an opportunity to combine Pioneer Array observations with additional in situ observations to examine the shoreward extent of anomalously warm waters over the continental shelf. Sea surface temperature imagery from January 25, 2017, showed an intrusion of warm (10°–11°C) waters as far north as 40°40'N from a warm core ring centered near 39°N, 71°20'W (Figure 5a). A subsequent sea surface temperature image on February 6 indicated that filaments with surface temperatures of 10°C extended as far north as 41°15'N, in the vicinity of Block Island in Rhode Island Sound (not shown). Block Island is approximately 115 km north of the 100 m isobath, the long-term mean position of the foot of the shelf-break front.

In late January 2017, a Pioneer Array glider surveying along the shelf break near 40°N (the northern edge of the Frontal Zone [FZ] glider survey pattern; Figure 5a) measured temperatures of

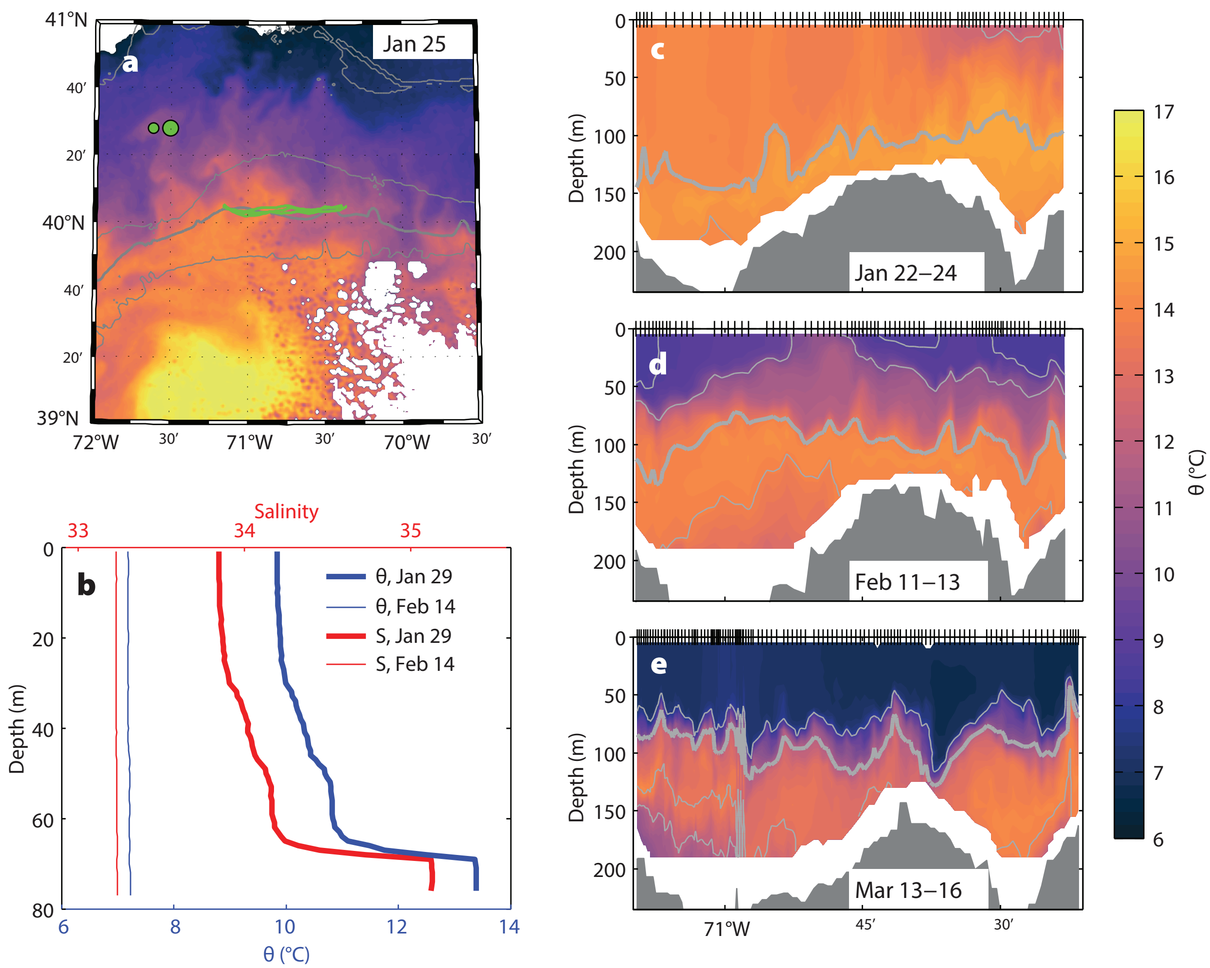

FIGURE 5. The evolution of anomalous conditions on the Middle Atlantic Bight shelf in winter 2017 resulting from a nearby warm core ring. (a) Sea surface temperature for the Pioneer Array region on January 25, 2017. The warm core ring is evident along the southern boundary, with warm water (>12°C) extending north of 40°20'N. (b) Potential temperature θ (blue) and salinity (red) profiles over the shelf north of the Pioneer Array from the Commercial Fisheries Research Foundation (CFRF) Shelf Research Fleet during January (thick lines) and February (thin lines) 2017. Warm, salty waters extended onto the shelf, particularly near the bottom, in late January, but not in mid-February. Locations of the CFRF profiles are shown by green circles in (a), with the larger circle corresponding to the January profiles. (c–e) Potential temperature (along the shelf break from Pioneer Array gliders during (c) January, (d) February, and (e) March 2017, showing substantial cooling as the warm core ring influence diminished. Tick marks on the upper axes in (c–e) denote the locations of individual glider profiles. Glider trajectories, which proceeded westward, are shown in green in (a). Contour lines denote isopycnals.

13°–15°C throughout the water column (Figure 5b). As part of the CFRF Shelf Research Fleet, Rhode Island fishermen collected temperature and salinity profiles near 40°30'N, 71°30'W on January 29 (Figure 5b; thick profiles). These profiles reveal a layer of unusually warm (10°–11°C) and salty (near 34) water in the upper 65 m that overlies a very warm (13.4°C) and salty (35) layer within 10 m of the seafloor. The near-bottom layer is slope water, and the sharp thermal gradient is the shelf-break front near the foot of the front where the high-gradient region intersects the bottom.

It is useful to compare a recent monthly, three-dimensional climatology built from all observations available from 1864 to 2009 (Fleming, 2016) with the observed shelf water mass properties in January 2017. The climatological temperature for the continental shelf for January is 5°C, and the climatological salinity is 33.0. Relative to this climatology, the January 2017 ring intrusion resulted in anomalies of 5°–6°C and 0.8–1.1 salinity units that extended as far north as 41°15'N. As such, the ring intrusion substantially impacted both shelf-water temperature and salinity across virtually the entire continental shelf.

Subsequent Pioneer Array observations and shelf profiles from CFRF fishermen indicate that shelf water properties returned toward normal as the winter of 2017 progressed. By February 14, the water column near 40°30'N, 71°30'W over the mid-shelf was well mixed with a temperature of 7.2°C and salinity of 33.2 (Figure 5b, thin profiles), and a nearly concurrent reoccupation of the glider transect along the shelf break (Figure 5d) showed waters in the upper 50 m around 9°C. Salinity measured at the offshore surface mooring indicated a rapid increase to 35.5 in early January 2017 that slowly decreased to 35.0 in mid-February as the ring intrusion drifted westward toward Hudson Canyon. By mid-March, another occupation of the along-shelf break glider transect showed further cooling throughout the water column, including a surface mixed layer with temperature near 7°C through the upper 60 m of the water column (Figure 5e).

One consequence of this warm intrusion was the appearance of warm-water fish species that were presumably carried onto the continental shelf in January 2017 as part of this event. A Rhode Island fishermen, Michael Marchetti (F/V *Mister G*, Point Judith, RI), recorded observations and photographs of unusual catch around Block Island in approximately 30 m of water, well inshore of the shelf break. Observed species included Gulf Stream flounder (*Citharichthys arctifrons*) and juvenile black sea bass (*Centropristis striata*), which are not typically found in shallow New England waters during the winter months. Fishermen also reported dramatic changes in Jonah crab (*Cancer borealis*) catch during the warm intrusion. Standardized fisheries surveys (NOAA Northeast Fisheries Science Center trawl survey and Northeast Area Monitoring and Assessment Program trawl survey) do not operate in the winter months, and thus are unable to provide further insights into the biological impacts of this mid-winter warm intrusion. Given the scale of the warm intrusion in January 2017, however, it is likely that the event had major, short-term impacts on ecosystem structure and function. Further research is needed to substantiate these specific ecosystem impacts of the ring intrusion.

HOW UNUSUAL ARE THE RING INTRUSIONS?

The Pioneer Array provides important new perspectives on shelf-break exchange, and observations from the array clearly show that onshore intrusions of warm core ring water masses are penetrating farther onshore than previously noted in historical data or the scientific literature. This is consistent with recent studies described earlier that indicate larger-amplitude Gulf Stream meanders and more frequent warm core rings since the year 2000. However, because the Pioneer Array has only been collecting observations since late 2013, it is difficult to quantify how unusual the recent ring intrusion events have been since 2013 using Pioneer Array observations alone.

The NOAA National Marine Fisheries Service's EcoMon program has been collecting CTD profiles over the Middle Atlantic Bight shelf between Hudson Canyon and the eastern end of Long Island, New York, since 1981; these long-term measurements allow us to place recent events in context. EcoMon observations are mapped onto a cross-shelf grid based on distance from the 100 m isobaths. Only observations collected during the months of September from 1981 to 2010 were used to calculate the climatological mean values and standard deviations (Figure 6a,b).

A significant intrusion event was identified in observations collected during the September 2014 EcoMon cruise (Figure 6c,d). The 34.0 isohaline outcropped at the 50 m isobath, 70 km shoreward of the shelf break (Figure 6c). In contrast, the surface outcrop of the 34.0 isohaline was located 20 km seaward of the shelf break in the EcoMon climatology (Figure 6a). Note that the slope of the 34.0 isohaline is in the opposite direction in September 2014 (downward offshore) compared to the climatology (upward offshore in the shelf-break front). The 34.0 isohaline intersected the seafloor at the 60 m isobath in September 2014, 50 km shoreward of the shelf break and roughly 30 km shoreward of its climatological position. This shoreward shift in the isohaline surfaces resulted in the mid-shelf salinity being five standard deviations above the climatological mean value in September 2014.

The shelf waters were also much warmer than average during the same time period, with much of the sub-thermocline water mass ranging from 14°–16°C, compared to climatological averages of 10°–12°C. Thus, the entire shelf was substantially warmer and saltier than average in late summer 2014, consistent with other ring intrusions documented by the OOI Pioneer Array.

LOOKING FORWARD—FUTURE IMPLICATIONS OF OOI PIONEER ARRAY SCIENCE

The OOI Pioneer Array has measured a number of significant shelf-break exchange events from the pre-commissioning deployments in late 2013 to the present. Some of the anomalous water mass properties measured over the continental shelf have rarely been observed in the past. The significant onshore penetration of warm core ring water is particularly likely to have important impacts on the continental shelf ecosystem and the seasonal movements of fish. By combining observations from the Pioneer Array, the CFRF Shelf Research Fleet, and the EcoMon program, we see that extreme or outlier events with warm, salty intrusions onto the shelf are occurring more frequently and penetrating further onshore than data from historical hydrographic archives would suggest.

We have presented primarily data on the thermohaline signatures of the exchange events. The next stage of Pioneer Array data analysis and modeling is processing and quality control of the velocity measurements from moorings and gliders and the computation of cross-shelf fluxes to characterize heat, salt, and buoyancy fluxes from these events. The ultimate goal will be to parameterize these fluxes based on dynamically important parameters such as the Rossby and Burger numbers, the maximum jet velocity in the shelf-break jet, and the maximum azimuthal velocities and spatial scales of warm core rings (e.g., Cenedese et al., 2013).

Observations from the OOI Pioneer Array suggest that coastal ocean dynamics are changing rapidly south of New England, with important implications for commercial fisheries, ecosystems, and future storm intensities from both hurricanes and nor'easters. There is an urgent need for focused numerical modeling studies to investigate the dynamics of shelf-break exchange. It is vital to explore the influence of larger, more frequent, and longer-lived warm core rings on the shelf-break front and on continental shelf circulation and ecosystems. Changes to shelf-break exchange may significantly affect nutrient transport between the deep ocean and the continental shelf, with consequences for higher trophic level productivity, including commercially harvested fish.

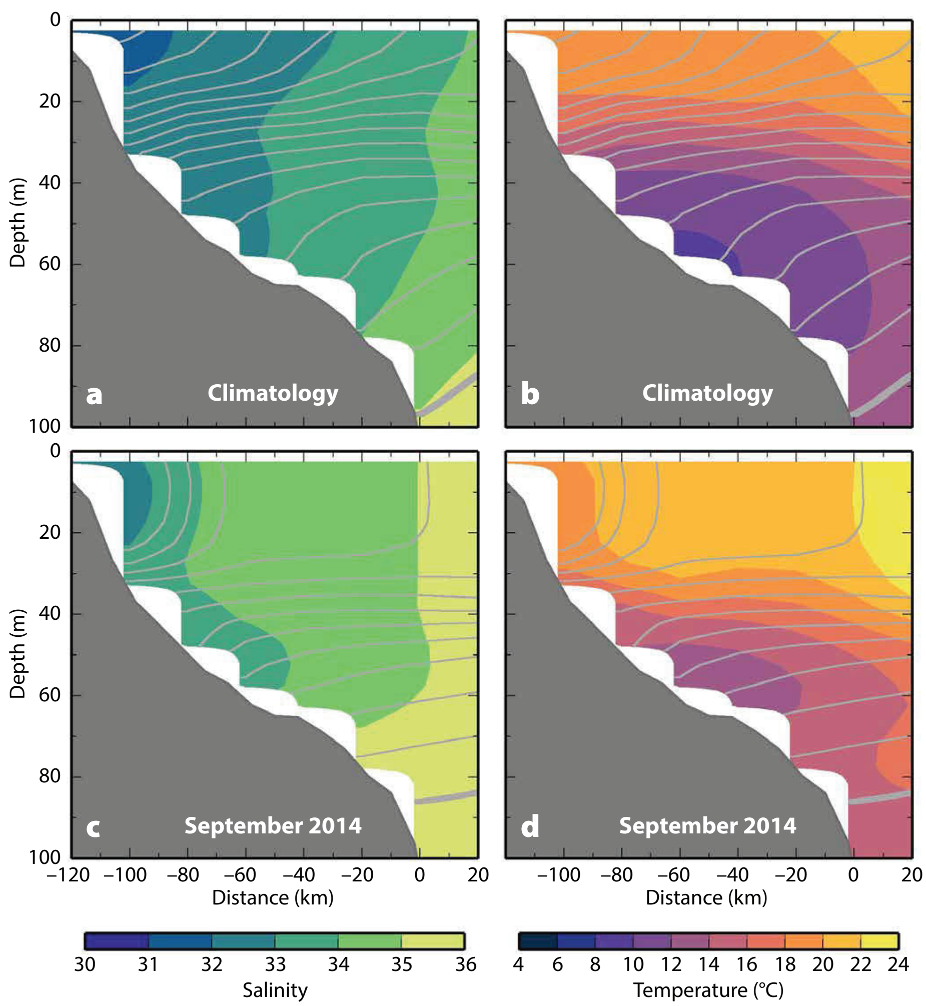

FIGURE 6. Cross-shelf transects of salinity (left panels) and temperature (right panels) from the Ecosystem Monitoring (EcoMon) cruises from NOAA's Northeast Fisheries Science Center. (a–b) Climatological mean fields constructed using observations collected from September cruises from 1981 to 2010. (c–d) Observations collected in September 2014. Gray contours are isopycnals with a contour interval of 0.25 kg m^{-3} and the 26.5 kg m^{-3} isopycnal bold.

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ACKNOWLEDGMENTS

GG, WZ, RT, and MD were supported by the National Science Foundation under grant OCE-1657853. WZ was also supported by grant OCE-1634965. JP is grateful for the support of the Woods Hole Oceanographic Institution Summer Student Fellow Program. AMM was supported by a grant from the MacArthur Foundation. GG and AMM were also supported by a grant from the van Beuren Charitable Foundation for collection and analysis of hydrographic data collected by the CFRF Shelf Research Fleet. Data from the OOI Pioneer Array was obtained from the NSF Ocean Observatories Initiative Data Portal, http://ooinet.oceanobservatories.org, as well as from the OOI raw data archive. AG and MM were partially supported by NOAA Grant No. NA11NOS0120038 for implementation of the Mid-Atlantic Regional Association Coastal Ocean Observing System. AG acknowledges the support of Jenifer Clark for the GS-WCR charts, which enabled the census results reported here. Data collected by the CFRF Shelf Research Fleet is available at http://science.whoi.edu/users/seasoar/cfrfwhoi. PF acknowledges the NOAA scientists and technicians who coordinated the collection and processing of EcoMon data used in this analysis. The authors thank Frank Bahr and Aubrey Ellertson for their efforts in coordinating and processing Shelf Fleet data as well as the fishermen who collect these data while at sea. We also thank the many dedicated scientists, engineers, and administrators who have worked so hard over more than a decade to make the Pioneer Array a reality.

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ARTICLE CITATION

Gawarkiewicz, G., R.E. Todd, W. Zhang, J. Partida, A. Gangopadhyay, M.-U.-H. Monim, P. Fratantoni, A. Malek Mercer, and M. Dent. 2018. The changing nature of shelf-break exchange revealed by the OOI Pioneer Array. *Oceanography* 31(1):60–70, https://doi.org/10.5670/oceanog.2018.110.