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Hydrographic Conditions on the Northeast United States Continental Shelf in 2016 – NAFO Subareas 5 and 6

Paula Fratantoni
NOAA National Marine Fisheries Service
Northeast Fisheries Science Center
166 Water Street, Woods Hole, MA, 02543 USA

Abstract

An overview is presented of the atmospheric and oceanographic conditions on the Northeast U.S. Continental Shelf during 2016. The analysis utilizes hydrographic observations collected by the operational oceanography programs of the Northeast Fisheries Science Center (NEFSC), which represents the most comprehensive consistently sampled ongoing environmental record within the region. Overall, 2016 was characterized by warming and generally more saline conditions across the region. Deep (slope) waters entering the Gulf of Maine were warmer and saltier than average and their temperature and salinity suggest a subtropical source. Mixed layers in the western Gulf of Maine were minimal during the winter of 2016, presumably a consequence of anomalously warm air temperatures that persisted over the northeastern United States during winter and suppressed winter convective overturning in the western Gulf of Maine. By contrast, during late summer, observations indicate that Gulf Stream Warm Core Ring water intruded onto the shelf in the Middle Atlantic Bight and through deep channels into the Gulf of Maine, leading to anomalous warming across the outer shelf off southern New England and in the deep basins of the Gulf of Maine. Such episodic events have the potential to cause significant changes in the ecosystem, including changes in nutrient loading on the shelf, the seasonal elimination of critical habitats such as the cold pool and shelf-slope front, disruption of seasonal migration cues, and an increase in the concentration of offshore larval fish on the shelf.

Introduction

The Northeast United States (NEUS) Continental Shelf extends from the southern tip of Nova Scotia, Canada, southwestward through the Gulf of Maine and the Middle Atlantic Bight, to Cape Hatteras, North Carolina (Fig. 1a). Contrasting water masses from the subtropical and subpolar gyres influence the hydrography in this region. Located at the downstream end of an extensive interconnected coastal boundary current system, the NEUS shelf is the direct recipient of cold/fresh arctic-origin water, accumulated coastal discharge and ice melt that has been advected thousands of kilometers around the boundary of the subpolar North Atlantic. Likewise, subtropical water masses, advected by the Gulf Stream, slope currents and associated eddies, also influence the composition of water masses within the NEUS shelf region. The western boundary currents of the subpolar and subtropical gyres respond to variations in basin-scale forcing through changes in position, volume transport and/or water mass composition and it is partly through these changes that basin-scale climate variability is communicated to the local NEUS shelf.

To first order, hydrographic conditions along the NEUS shelf are determined by the relative proportion of two main sources of water entering the region: cold/fresh arctic-origin water advected by the coastal boundary current from the north and warmer, more saline slope waters residing offshore of the shelf break. The source waters first enter the NEUS shelf region through the Gulf of Maine, a semi-enclosed shelf sea that is partially isolated from the open Northwest Atlantic by two shallow banks, Browns and Georges Banks. Below 100 meters, exchange between the Gulf of Maine and the deeper North Atlantic is restricted to a single deep channel, the Northeast Channel, which bisects the shelf between the two banks. This deep channel interrupts the continued flow of cold, fresh arctic-origin water along the slope, redirecting the majority of this flow into the Gulf of Maine. In the meantime, denser slope waters enter the basin through the same channel at depth, gradually spreading into a network of deep basins within the Gulf of Maine (Fig. 1b). In the upper layers of the Gulf of Maine, the shelf waters circulate counter-clockwise around the basin before continuing southwestward through the Middle-Atlantic Bight (Fig. 1b). The shelf water is progressively modified by atmospheric fluxes of heat and salt and through mixing with both deeper slope waters and the discharge of several local rivers. In this way, the Gulf of Maine represents the gateway to the NEUS shelf region, responsible for setting the initial hydrographic conditions for water masses entering the Middle Atlantic Bight further downstream.

The pronounced seasonal cycle of heating and cooling over the region drives seasonal variations in water mass composition that are typically larger than interannual variations. During fall and winter, intense cooling at the surface removes buoyancy, resulting in overturning and vertical homogenization of a significant portion of the water column. During spring and summer, surface heating re-stratifies the surface layer, isolating a remnant of the previous winter's cold/fresh mixed water at depth. In the Gulf of Maine, this remnant water mass is isolated at intermediate depths, bounded at the surface by the seasonal thermocline and at depth by warmer slope water masses. In the Middle Atlantic Bight where waters are shallower, this remnant water mass is trapped at the bottom, bounded at the surface by the seasonal thermocline. Variations in these seasonal processes (e.g. less cooling in winter or shifts in the timing of springtime warming) can result in interannual variations in the composition and distribution of water masses. In addition, fluctuations in the composition and volume of source waters entering the Gulf of Maine may also drive interannual variations in water properties relative to this seasonal mean picture.

The slope water that enters the Gulf of Maine is a mixture of two water masses: warm, saline, relatively nutrient-rich Warm Slope Water (WSLW) originating in the subtropics and cooler, fresher, relatively nutrient-poor Labrador Slope Water (LSLW) originating in the subpolar region. Seaward of the Gulf of Maine, the relative proportion of these two water masses varies over time. However, in general, the volume of each decreases with increasing along-slope distance from their respective sources; LSLW (WSLW) volume decreases from north to south (south to north). Decadal shifts in the position of the Gulf Stream appear to be closely tied to changes in slope water temperature offshore of the NEUS shelf and to the composition of slope water entering the Gulf of Maine (Davis et al., 2017). Cooling in the slope water offshore is accompanied by a southward shift in the Gulf Stream and a predominance of northern source water (LSLW) in the deep layers of the Northeast Channel.

Data and Methods

The U.S. National Oceanic and Atmospheric Administration's Northeast Fisheries Science Center (NEFSC) conducts multiple shelf-wide surveys every year in support of its mission to monitor the NEUS ecosystem. Monitoring efforts have been ongoing since 1977. Typically, the NEFSC completes six full-shelf hydrographic surveys per year, in addition to several more regionally focused surveys – the minimum required to resolve the dominant seasonal cycle in this region. However, budget cuts and ship maintenance issues led to the elimination and/or truncation of two of these six surveys in 2016 so that overall roughly half as many stations were occupied in 2016 over just three seasons, leading to a critical loss of seasonal resolution.

During 2016, hydrographic data were collected on 8 individual NEFSC cruises, amounting to 1356 profiles of temperature and salinity and 1235 in NAFO subareas 5 and 6 (Table 1). Data were collected aboard the NOAA ships *Henry Bigelow* and *Gordon Gunter,* and the R/V *HR Sharp* using a combination of Seabird Electronics SBE-19+ SEACAT profilers and SBE 9/11 CTD units. All processed hydrographic data, cruise reports and annual hydrographic summaries are accessible at: http://www.nefsc.noaa.gov/epd/ocean/MainPage/index.html.

Absent fixed station observations, time series of surface and bottom temperature and salinity are constructed from area-weighted averages of profile data within five sub-regions spanning the Northeast U.S. Continental Shelf (Fig. 6 for regional delineations). Anomalies are calculated relative to a reference annual cycle, defined by a harmonic fit to regional average temperature and salinity collected between 1981-2010. The reference period corresponds with the standard recommended by the World Meteorological Organization. Anomalies are defined as the difference between the observed 2016 value at an individual station and the expected value for each location and time of year based on the reference annual cycle, while regional anomalies are the area-weighted average of these anomalies within a given subarea. The methods used and an explanation of uncertainties are presented in Holzwarth and Mountain (1990).

Basin-Scale Conditions in 2016

During 2016, surface air temperatures were warmer than average (1981-2010) everywhere but the central basin during winter, summer and fall. During spring, an area of colder air temperatures extended from the central basin over northern North America and the Canadian Archipelago (Fig. 2). Overall, the seasonal range of regional average air temperatures over the northeastern U.S. continent and adjoining shelf was near normal. Sea surface temperature mirrored these patterns, with cooler than average SST in the central basin and Labrador Sea during winter/spring and persistent warming over the NEUS shelf throughout the year (Fig. 3). Annually, the magnitude of the warming was comparable to that observed in the 1950s, however 2016 was characterized by enhanced warming in summer and fall (Fig 4).

It has been suggested that an index measuring the atmospheric sea level pressure difference between Iceland and the Azores is a reliable indicator of atmospheric conditions and oceanic response in the North Atlantic. The so-called North Atlantic Oscillation (NAO) has been related (with lags) to the intensity, frequency and pathway of storms crossing the North Atlantic; the intensity of westerly winds; the depth of convection and amount of sea ice in the Labrador Basin; the temperature and salinity of waters on the Canadian and U.S. continental shelves; and the position of the north wall of the Gulf Stream (e.g. Visbeck *et al.*, 2003; Petrie, 2007). The NAO index was positive for the third consecutive year during the winter of 2016, indicative of a deepening of the Icelandic low and a strengthening of the Azores high (Fig. 5). A positive NAO is typically associated with stronger northwesterly winds over the shelves, warmer bottom waters in the Gulf of Maine, a northward shift in the Gulf Stream, and a predominance of Warm Slope Water in the Northeast Channel (Petrie, 2007; Mountain, 2012; Joyce *et al.*, 2000).

Hydrographic Conditions in 2016

Relative to historical values, regional ocean temperatures across the NEUS shelf were warm during 2016 (Fig. 6). Annually, waters in the upper 30 meters were between 1.0-1.5°C warmer than normal everywhere, with the largest anomalies occurring in the southern Middle Atlantic Bight, Georges Bank and eastern Gulf of Maine. Of the seasons sampled, warming was most pronounced during spring in the southern Middle Atlantic Bight where regional temperature anomalies exceeded 2°C all the way to the bottom (Fig. 7). Extremely warm conditions were also observed near the bottom in the northern Middle Atlantic Bight during spring, with comparatively weaker warming in the upper layers. By contrast, regional temperature anomalies were large throughout the water column during fall in the northern Middle Atlantic Bight (Fig.7) In the Gulf of Maine, temperatures were roughly 1°C warmer than average at both the surface and bottom throughout the year. The details of the seasonal differences are revealed in synoptic maps, showing warmer temperatures across the entire shelf in spring and fall, but with the largest anomalies observed during fall at the shelf edge near the surface and in shallow regions near the bottom (Fig 8).

Annually, surface waters in the upper 30 meters were saltier than normal in 2016, particularly in the Middle Atlantic Bight (Fig. 9). Large anomalies were observed during spring in the southern Middle Atlantic Bight, where anomalies approached 0.7 psu, and during fall in the northern Middle Atlantic Bight where anomalies were at the upper limit of the historical range, reaching 2.0 psu (Fig. 10a). Saline conditions were also observed near the bottom, although the magnitude of the anomalies was modulated compared to upper layers (Fig. 9 and 10b). Synoptically, the large regional salinity anomalies observed at the surface in the Middle Atlantic Bight during fall were strongest near the shelf edge aligned with regions of warming (Fig. 8), although a tongue of saline water extended inshore between Georges Bank and the eastern tip of Long Island, NY (Fig 11). The salinity within this shoreward protrusion was > 34, suggesting that the anomaly was caused by an intrusion of slope waters onto the shelf. Satellite derived observations of sea surface temperature indicate that several large amplitude Gulf Stream meanders and warm core rings were impinging on the shelf during this time (Fig 12).

Deep inflow through the Northeast Channel continues to be dominated by Warm Slope Water (Fig. 13). Springtime temperature-salinity and temperature-depth profiles indicate the presence of a very weaker Cold Intermediate layer in the western Gulf of Maine during spring 2016, a mid-depth water mass formed seasonally as a product of convective mixing driven by winter cooling (Fig. 14 & 15). In fact, the remnant winter water in the Cold Intermediate Layer is over 1.5°C warmer and slightly fresher than average in 2016, suggesting that convective mixing was suppressed in the preceding winter (Fig. 14). Correspondingly, the bottom water observed in Wilkinson Basin is cooler and fresher than average (Fig. 15 & 16). This is not surprising considering the fact that air temperatures over the Northeastern U.S were more than 2°C warmer than normal in winter 2016 (Fig 2). Vertical mixing during winter is an important process in the Western Gulf of Maine. Deeper mixing has greater potential to tap into nutrient rich slope water at depth resulting in a thicker intermediate layer during spring, both potentially having an impact on the timing or intensity of spring phytoplankton blooms.

Impacts

Our observations suggest that the Northeast U.S. Continental Shelf has been warming at a rate of ~.02-.05 °C/year since 1977, with significant interannual variations in temperature and salinity superimposed on this trend. As a result, the habitats of fish and invertebrate species in this region are experiencing change on a variety of temporal and spatial scales, with the potential to impact distribution and abundance. Observations suggest that the Northeast US Continental Shelf is being influenced more frequently by the Gulf Stream and that the increased interactions may be related to changes in the meandering character of the current (Andres, 2016). Extreme diversions and meanders in the Gulf Stream's path (e.g. Gawarkiewicz et al., 2012) and detached Gulf Stream Warm Core Rings (e.g. Zhang and Gawarkiewicz, 2015) directly and indirectly influence the hydrography on the shelf, often leading to intrusions of comparatively warm and salty water onto the shelf. These episodic intrusions have the potential to cause significant changes in the ecosystem, for instance leading to significant changes in nutrient loading on the shelf, the seasonal elimination of critical habitats such as the cold pool and shelf-slope front, disruption of seasonal migration cues, and an increase in the concentration of offshore larval fish on the shelf.

Summary

- Observations indicate that ocean temperatures on the NEUS shelf continue to increase
- An intrusion of Gulf Stream ring water in the Middle Atlantic Bight contributed to enhanced warming and salinification in late-summer/early-fall and probably led to erosion of the Cold Pool
- Anomalously warm winter air temperatures over the Northeastern U.S. suppressed deep convective mixing in the western Gulf of Maine, resulting in a warmer intermediate water mass
- Slope waters entering the Gulf of Maine through the Northeast Channel were anomalously warm and salty, consistent with the properties characteristic of Warm Slope Water derived from subtropical origins

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Table 1. Inventory of hydrographic monitoring on the Northeast U.S. Shelf during 2016

Sub-area	Division(s)	Month(s)	Type[1]	Description	Station count
5	Y,Z	4,5,6	S	Bottom trawl survey	195
5	Y,Z	5,6	S	Ecosystems monitoring survey	158
5	Y,Z	6	O	Sea scallop survey	15
5	Y,Z	6,7,8	O	Marine Mammal (AMAPPS) survey	112
5	Y,Z	8	S	Ecosystems monitoring survey	60
5	Y,Z	9,10,11	S	Bottom trawl survey	219
5	Y,Z	10	S	Ecosystems monitoring survey	10
6	A,B,C	4,5,6	S	Bottom trawl survey	134
6	A,B,C	5,6	S	Ecosystems monitoring survey	83
6	A,B,C	5	O	Sea scallop survey	1
6	A,B,C	6,7	O	Marine Mammal (AMAPPS) survey	54
6	A,B,C	8	S	Ecosystems monitoring survey	53
6	A,B,C	9,10	S	Bottom trawl survey	138
6	A,B,C	10	S	Ecosystems monitoring survey	3

[1] Sampling design: S refers to stratified-random and O to other survey designs.

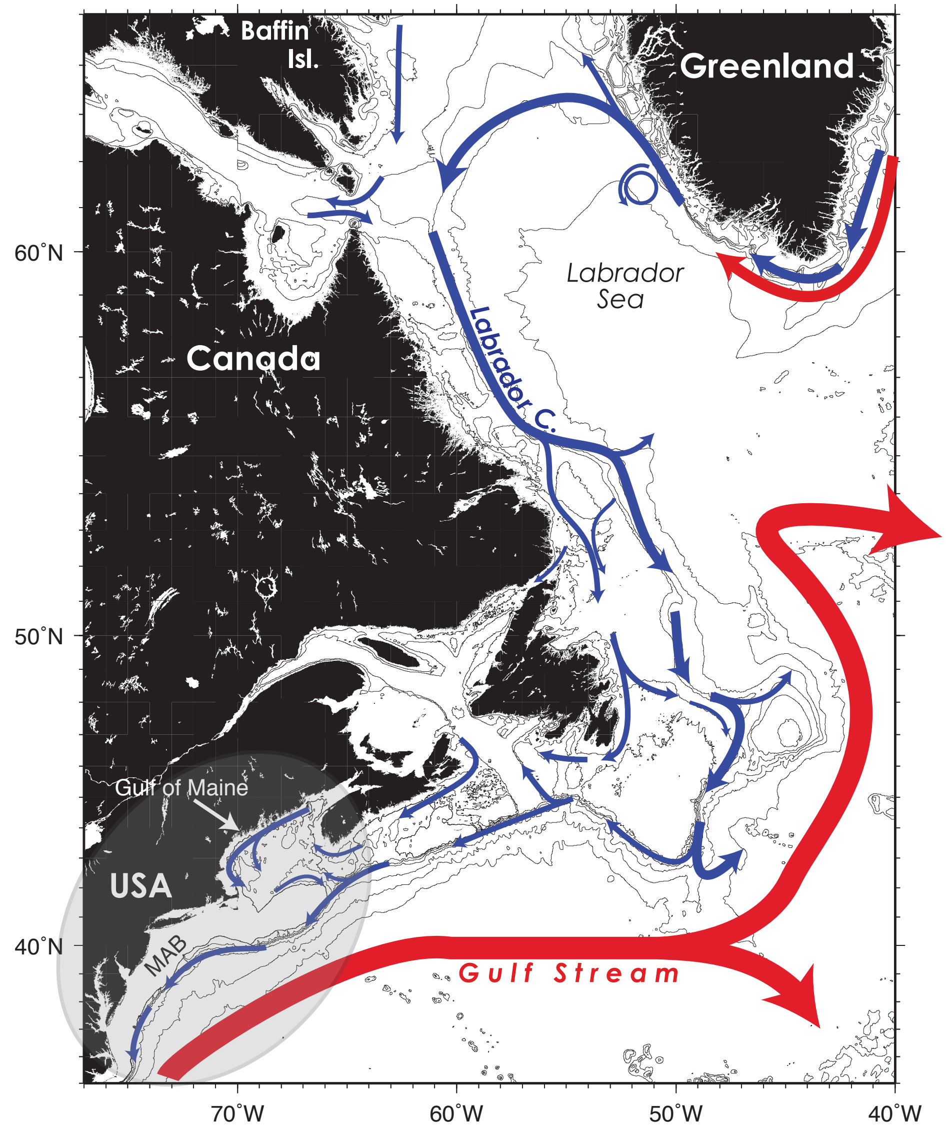


Fig. 1a. Circulation schematic of the western North Atlantic. The Northeast U.S. Shelf region is identified by the shaded oval. The 100, 200, 500, 1000, 2000, 3000 and 4000 meter isobaths are shown.

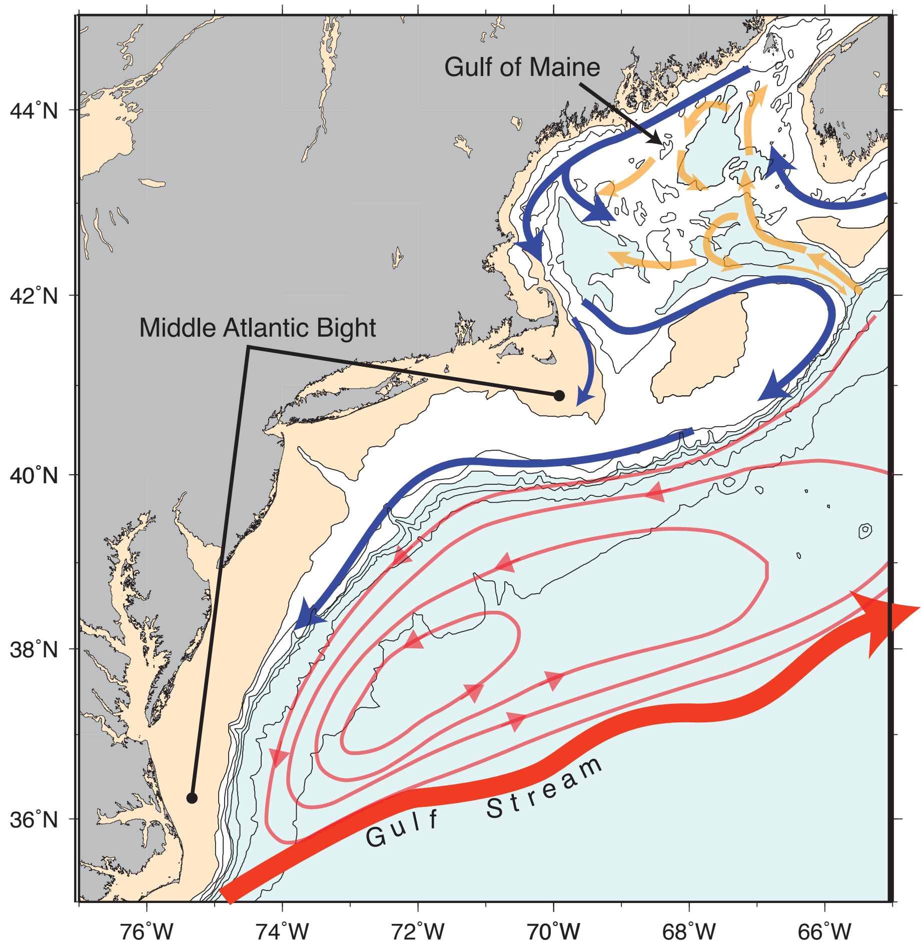


Fig. 1b. Circulation schematic for the Northeast U.S. Shelf region, where blue arrows represent shelf water circulation and orange arrows represent deeper slope water circulation pathways. Water depths deeper than 200 meters are shaded blue. Water depths shallower than 50 meters are shaded tan.

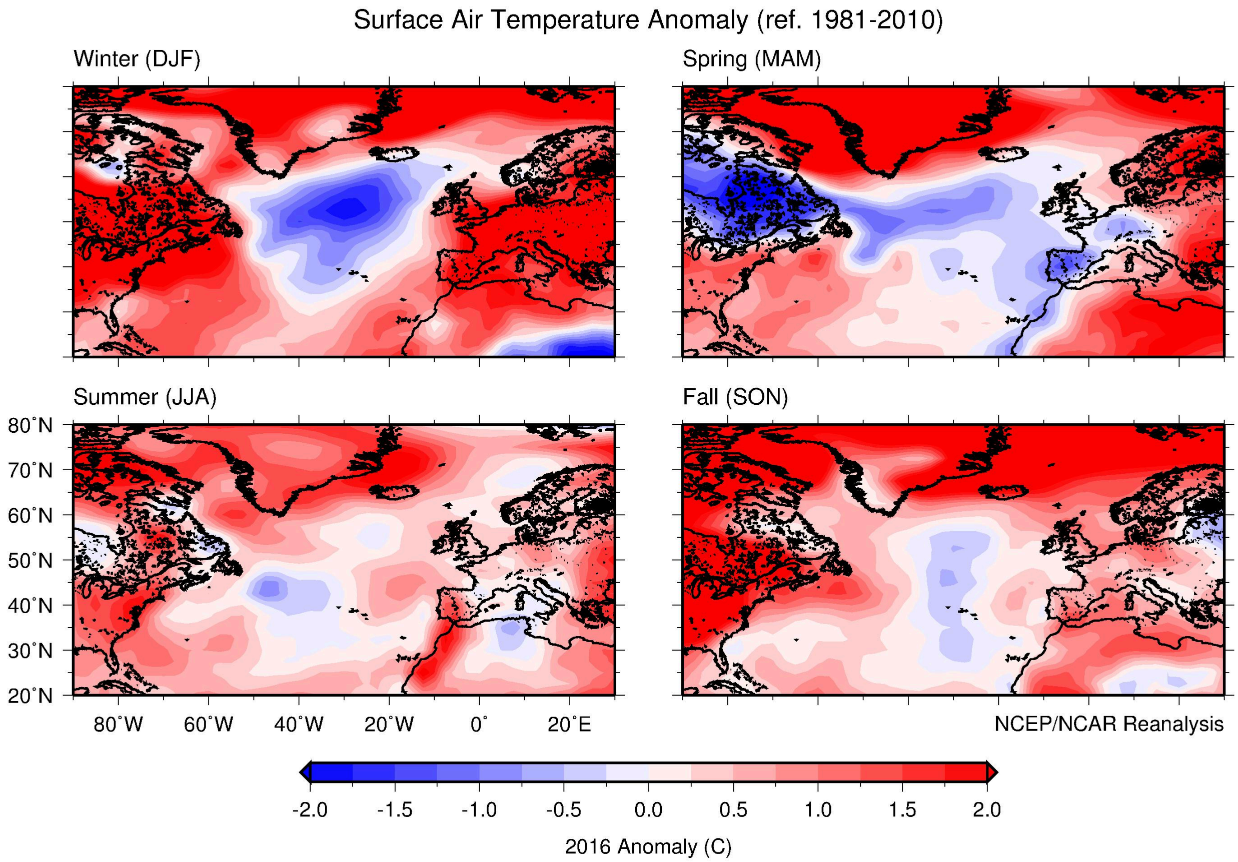


Fig. 2. Surface air temperature anomaly derived from the NCEP/NCAR Reanalysis product (http://www.esrl.noaa.gov/psd/data/composites/day/). Seasons are made up of 3-month periods where winter spans December-February. Positive anomalies correspond to warming in 2016 relative to the reference period (1981-2010).

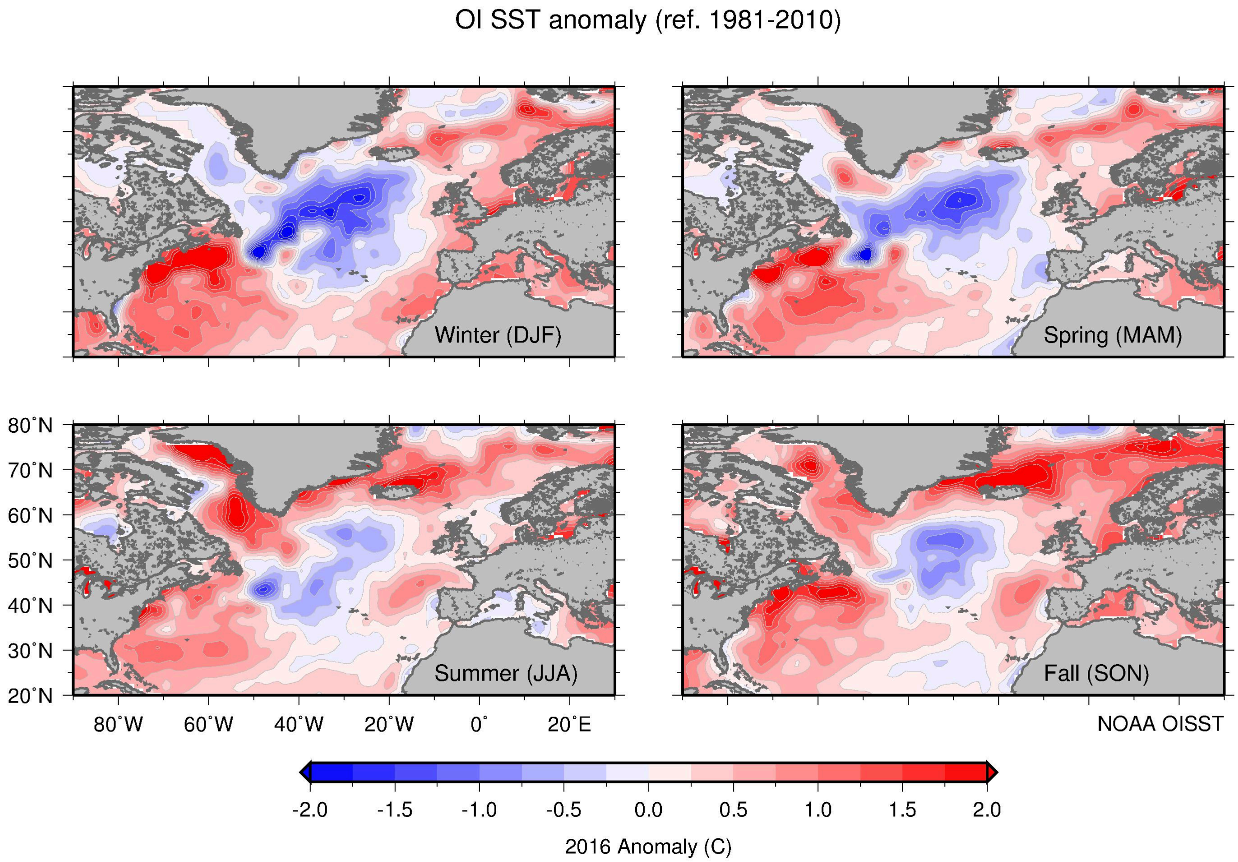
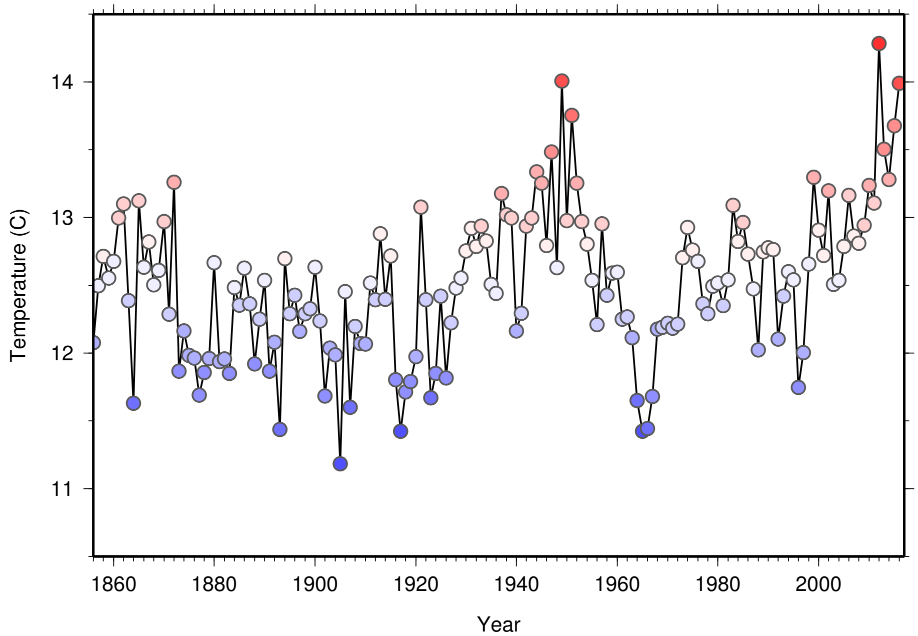


Fig. 3. Sea surface temperature anomaly derived from the NOAA's Optimum Interpolation (OI) SST product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html). Seasons are made up of 3-month periods where winter spans December-February. Positive anomalies correspond to warming in 2016 relative to the reference period (1981-2010).



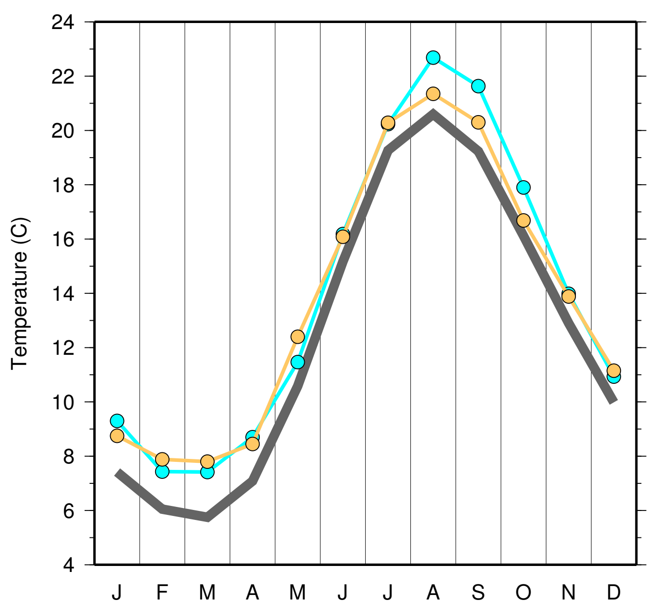


Fig. 4. Top: Regional average annual sea surface temperature for the NEUS shelf region calculated from NOAA's extended reconstructed sea surface temperature product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html). Colors correspond with the anomaly scale in Figure 3. Bottom: Regional average monthly mean SST for the NEUS shelf for 2016 (cyan), 1951 (orange) and 1981-2010 (gray) calculated from the same product.

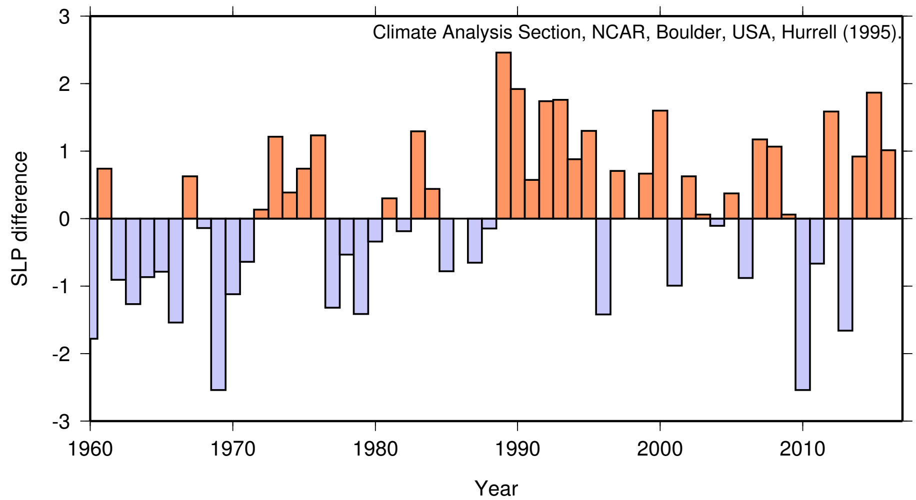


Fig. 5. North Atlantic Oscillation index computed from principal component analysis of sea level pressure in the North Atlantic (see Hurrell, 1995).

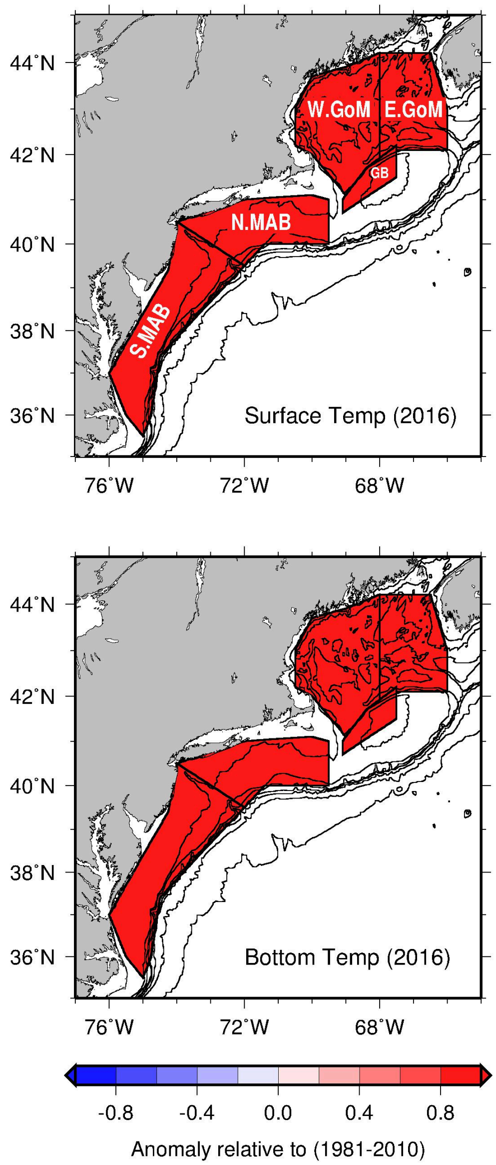


Fig. 6. Surface (upper panel) and bottom (lower panel) regional annual temperature anomaly (°C). Positive anomalies correspond to warming in 2016 relative to the reference period (1981-2010). The region labels correspond to the panels in Figure 7.

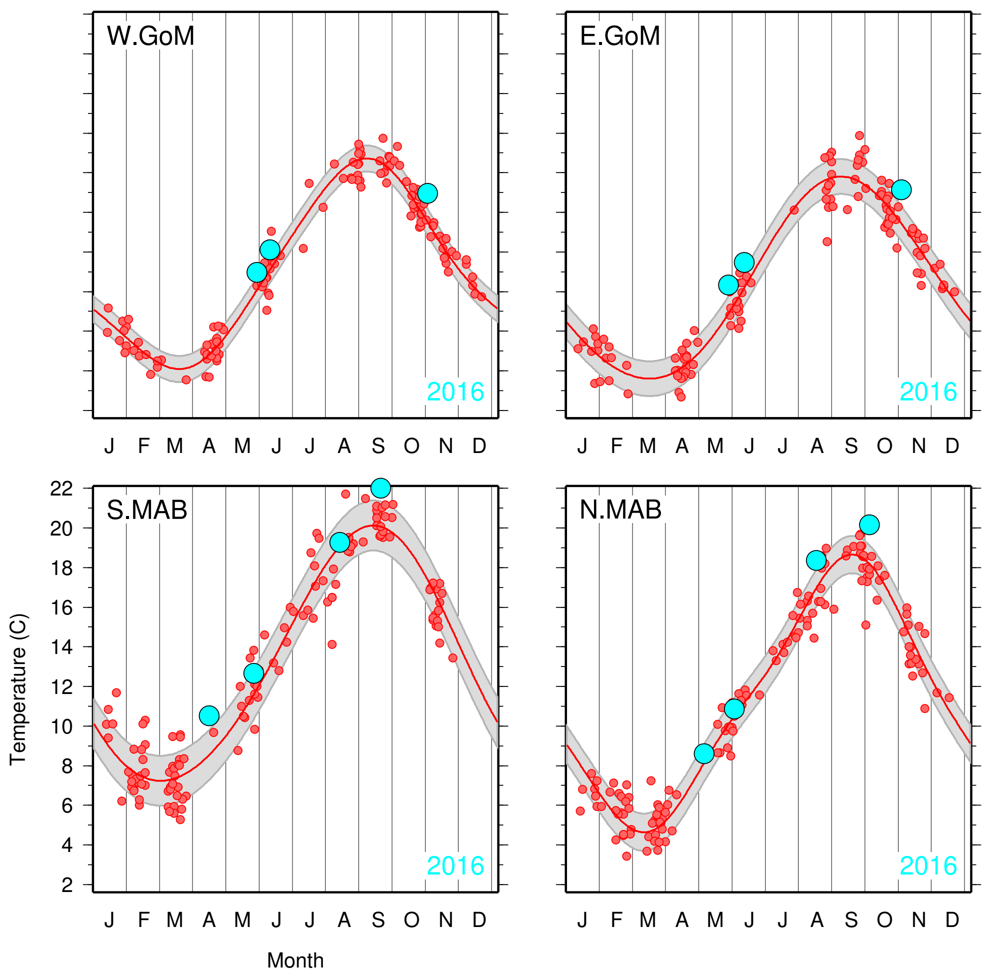


Fig. 7a. Regional average 0-30 meter temperature (°C) as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 6. An annual harmonic fit to the regional average temperatures from 1981-2010 is shown by the red curve with the points contributing to the fit also shown in red. The gray shading depicts one standard deviation around this fit. The regional average temperatures from 2016 surveys are shown in cyan.

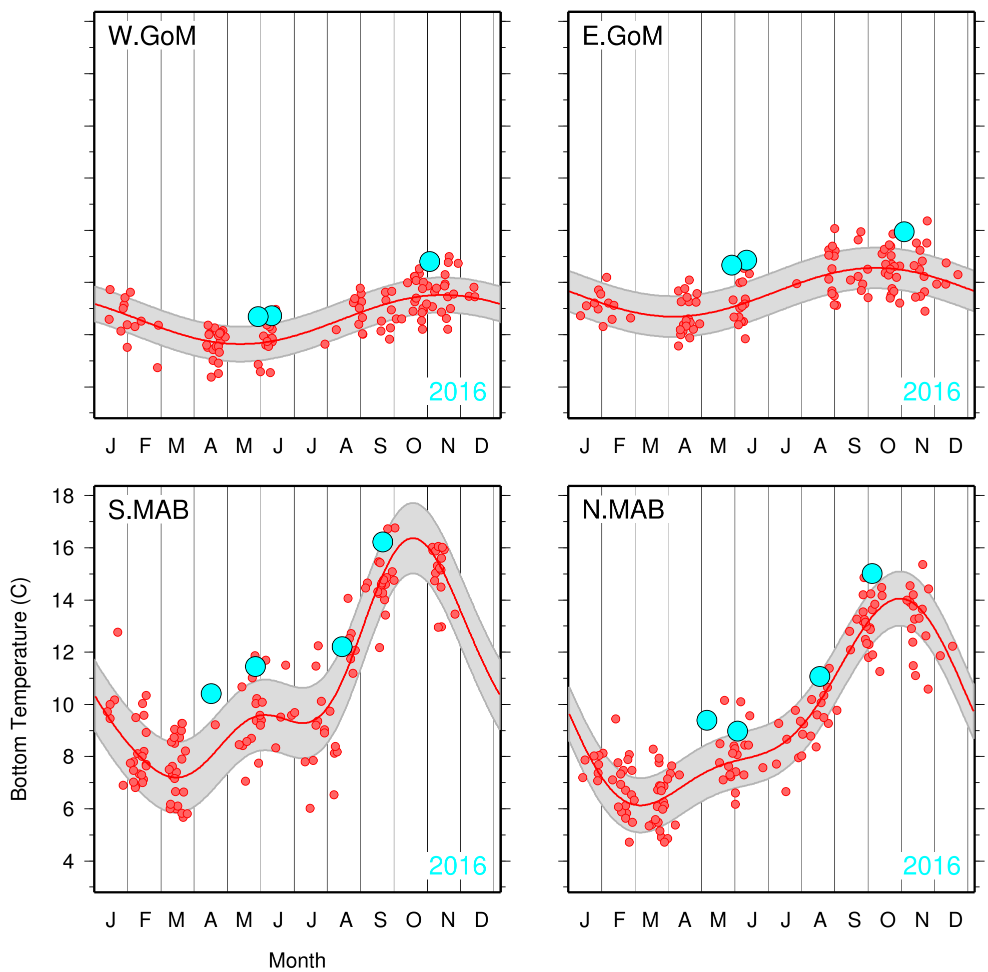


Fig. 7b. As in Fig. 7a, but for bottom temperatures.

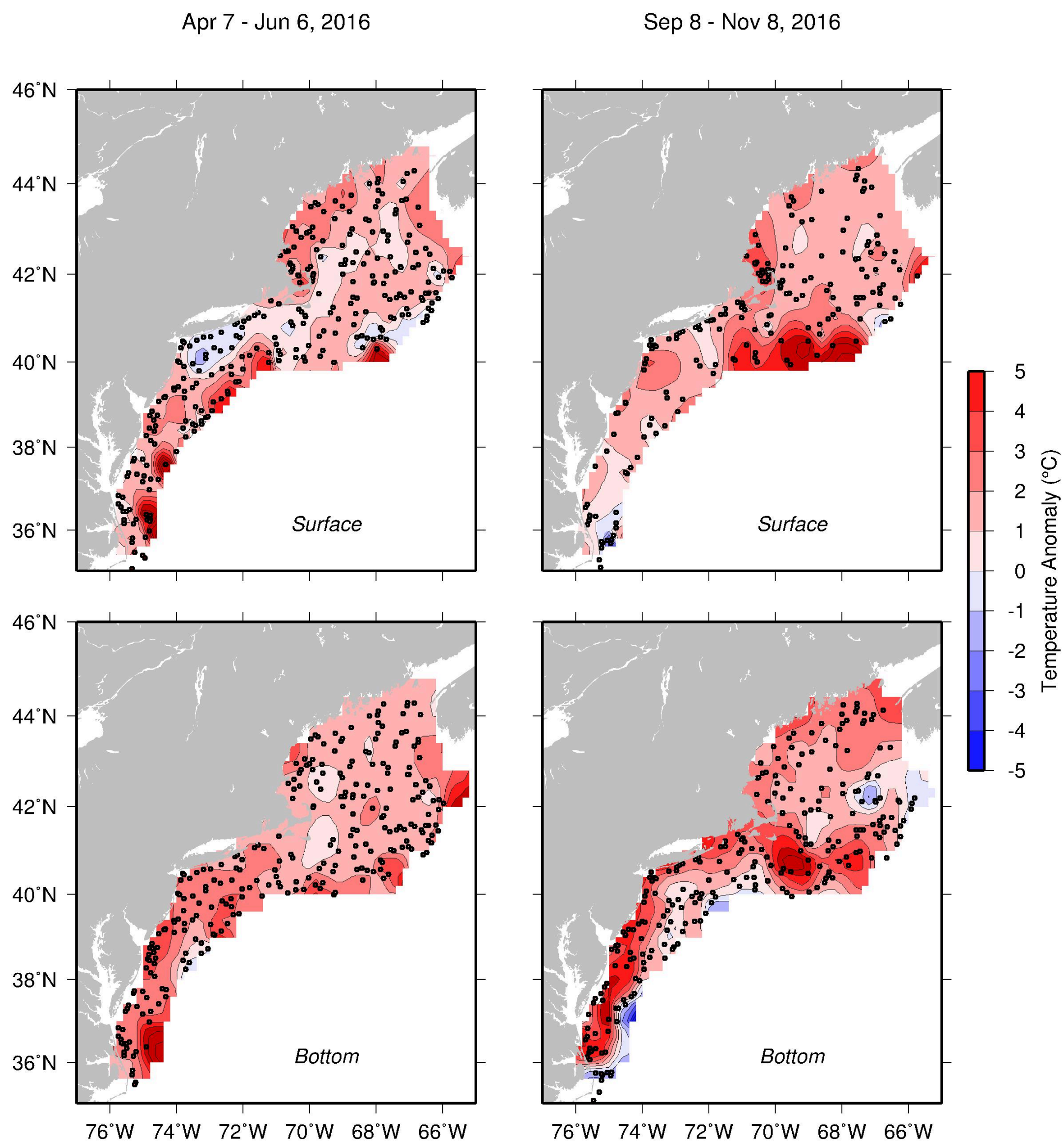


Fig. 8. Surface (upper panels) and bottom (lower panels) temperature anomaly from the spring 2016 (left) and fall 2016 (right) ground fish surveys. Positive anomalies correspond to warming in 2016 relative to the reference period (1977-1987).

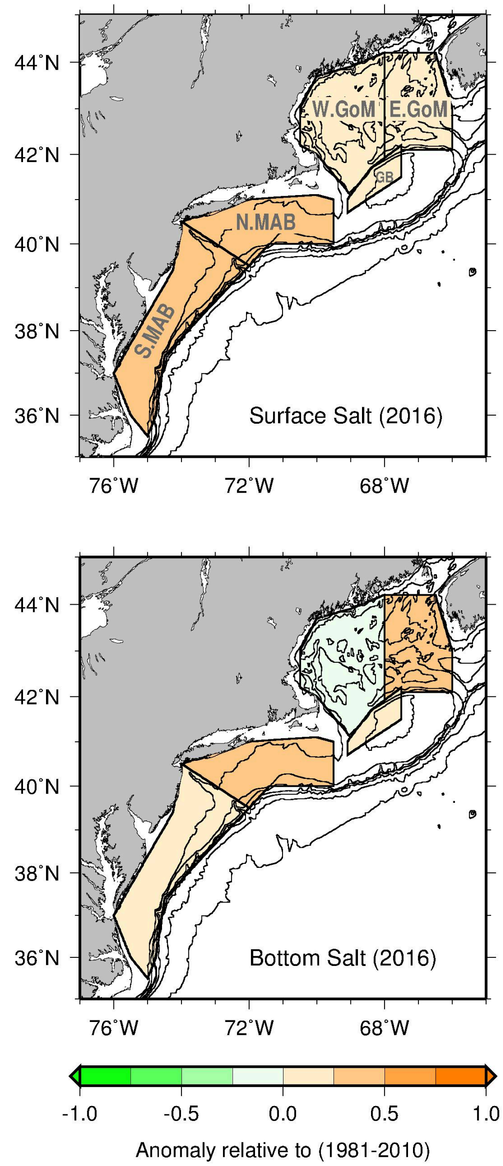


Fig. 9. Surface (upper panel) and bottom (lower panel) regional annual salinity anomaly. Positive anomalies correspond to more saline conditions in 2016 relative to the reference period (1981-2010). The region labels correspond to the panels in Figure 10.

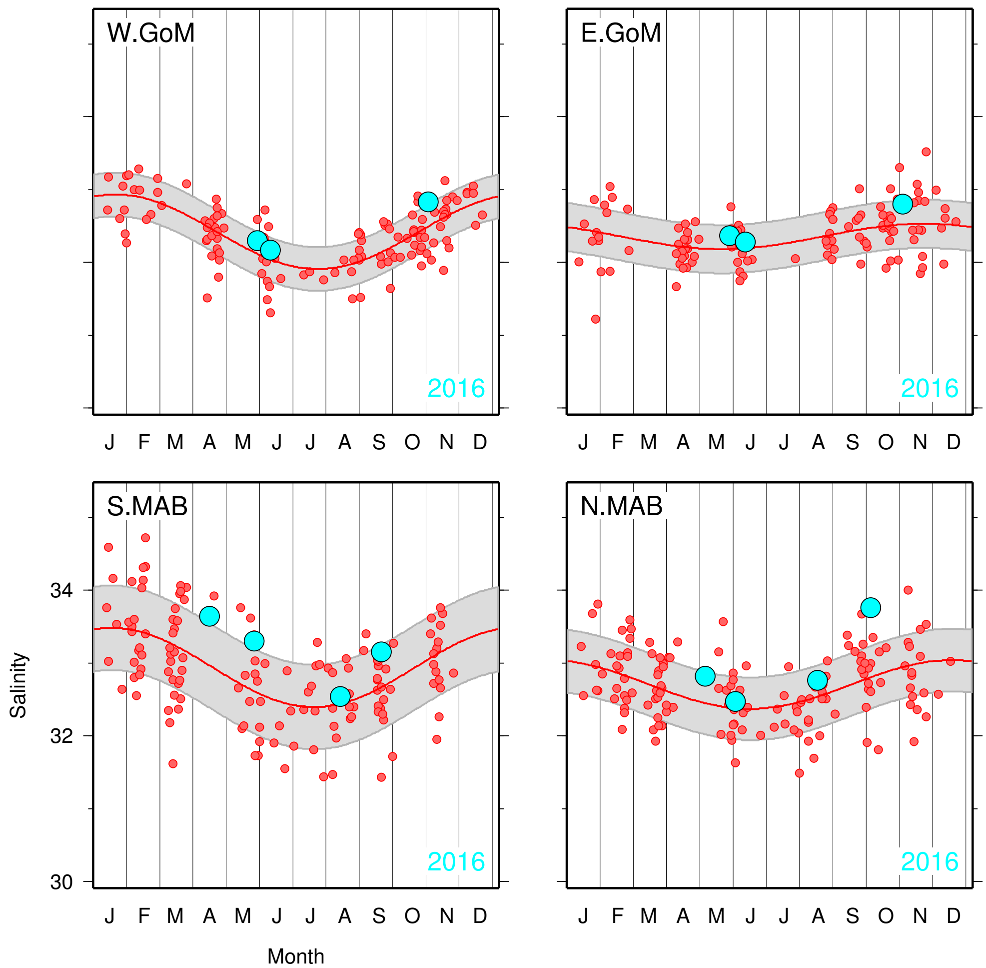


Fig. 10a. Regional average 0-30 meter salinity as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 9. An annual harmonic fit to the regional average salinities from 1981-2010 is shown by the red curve with the points contributing to the fit also shown in red. The gray shading depicts one standard deviation around this fit. The regional average salinities from 2016 surveys are shown in cyan.

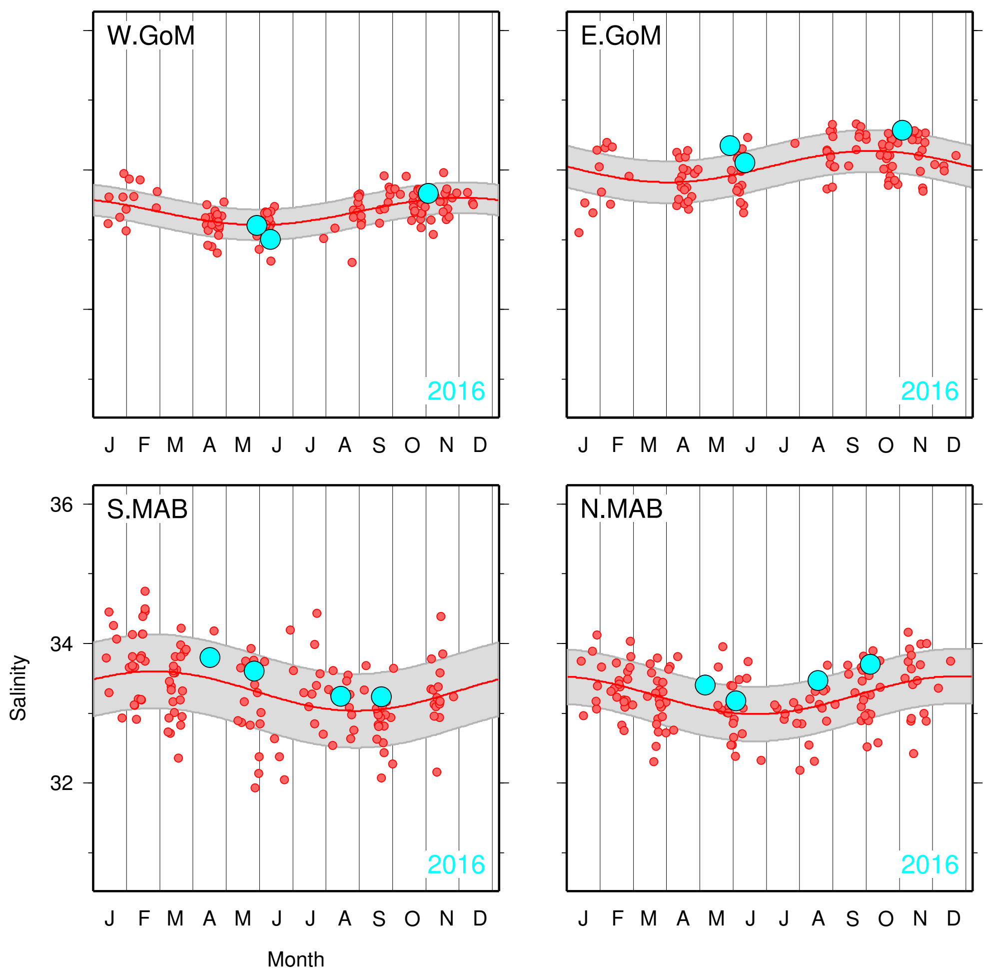


Fig. 10b. As in Fig. 10a, but for bottom salinities.

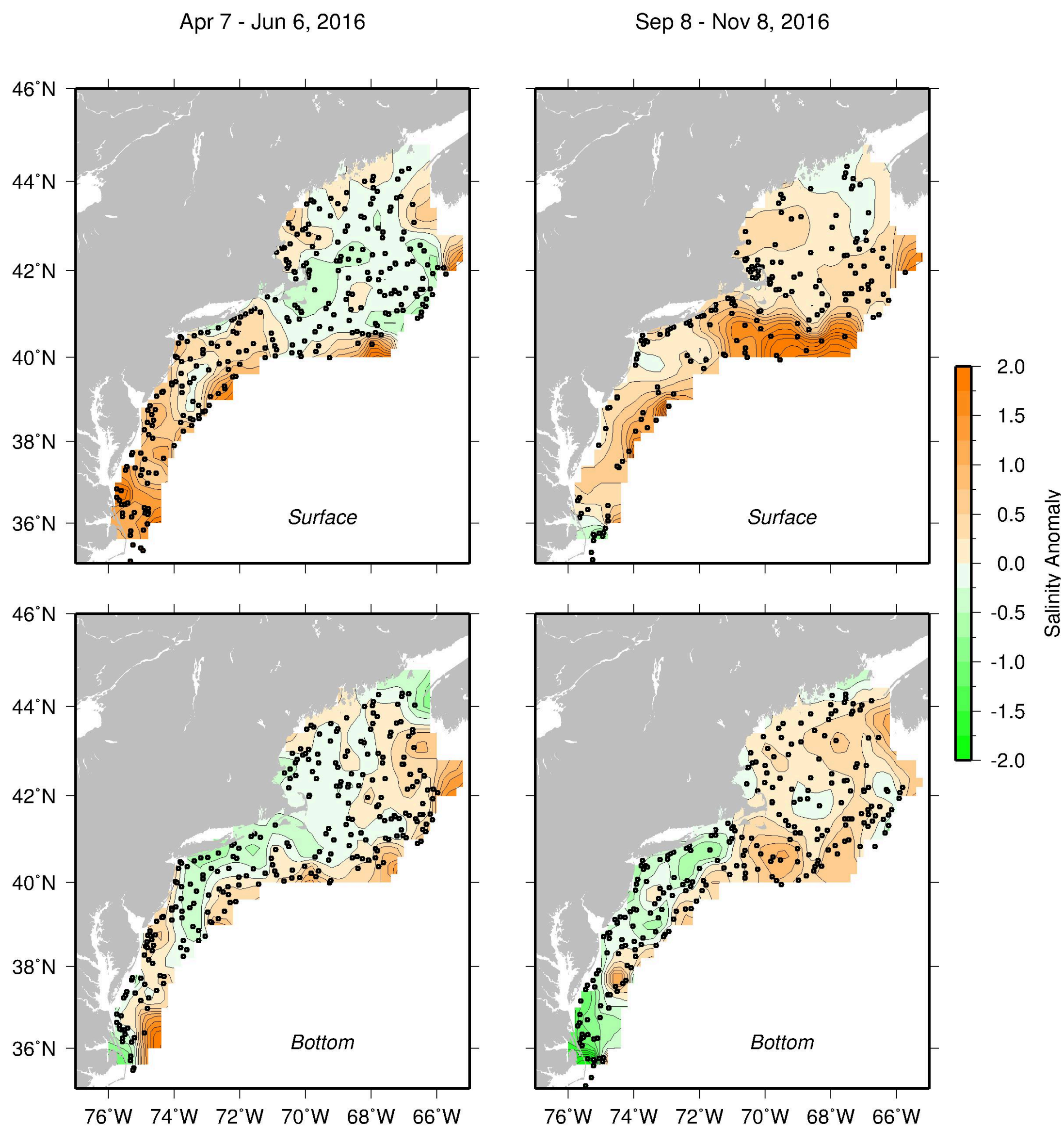


Fig. 11. Surface (upper panels) and bottom (lower panels) salinity anomaly from the spring 2016 (left) and fall 2016 (right) ground fish surveys. Positive anomalies correspond to more saline conditions in 2016 relative to the reference period (1977-1987).

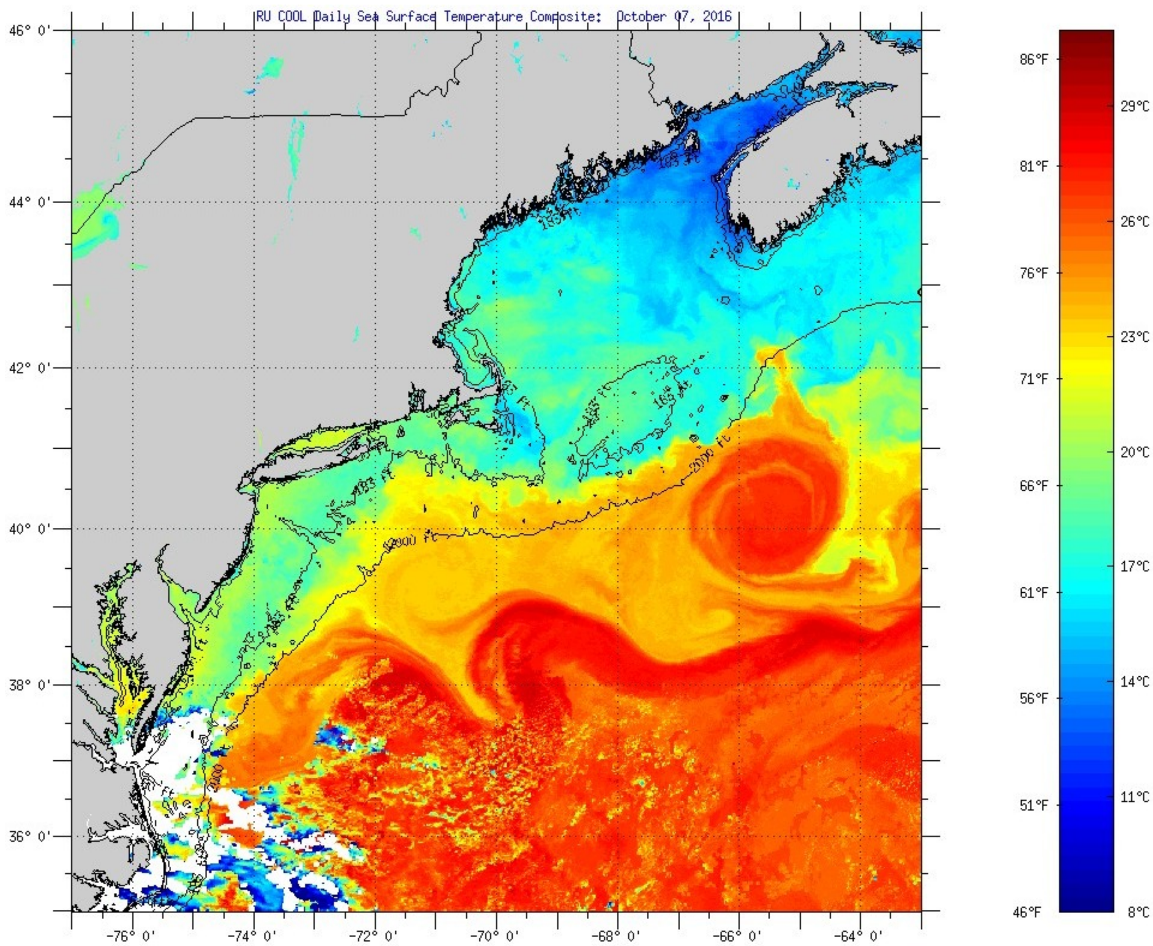


Fig. 12. Daily composite sea surface temperature derived by the Coastal Ocean Observations Lab, Rutgers University, from data collected by the Advanced Very High Resolution Radiometer on October 7, 2016.

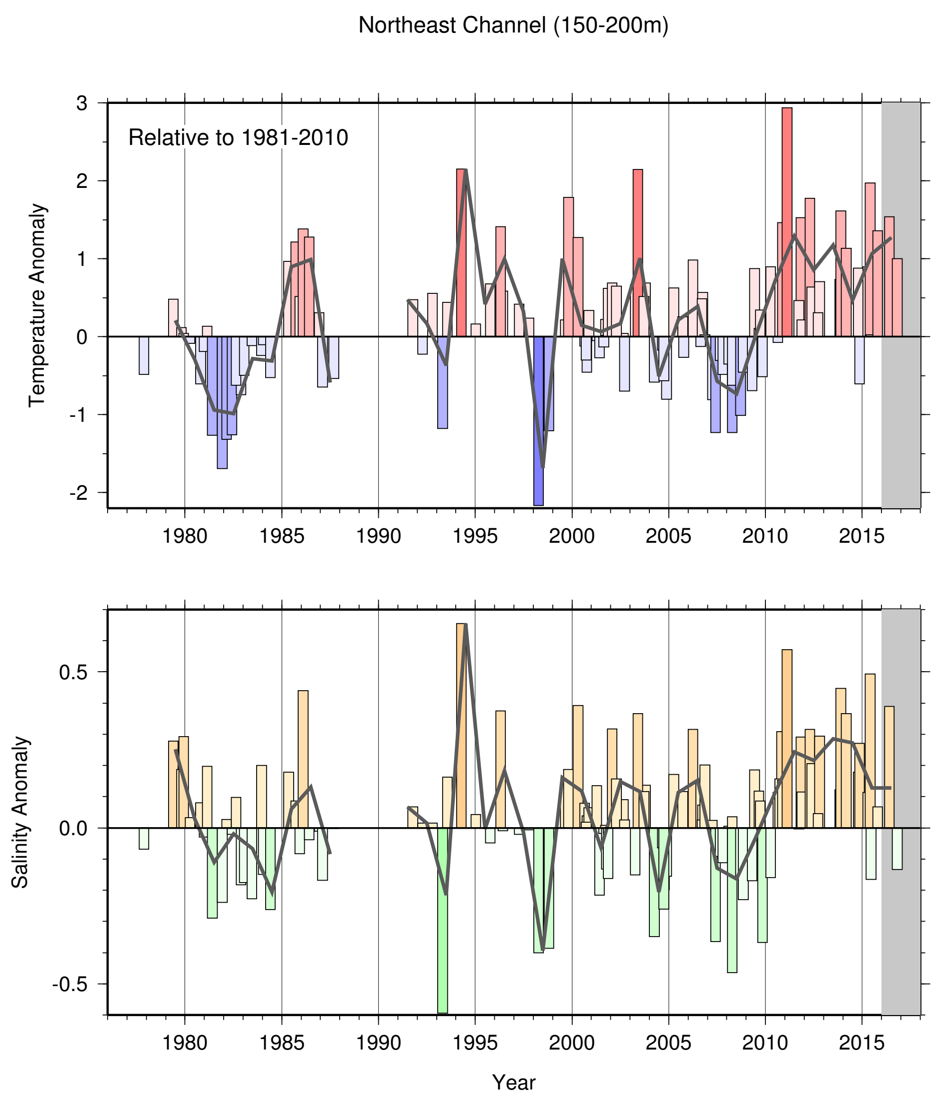


Fig. 13. Time series of temperature and salinity anomaly in the deep Northeast Channel. Each bar represents a volume-weighted average of all observations from a single survey collected between 150-200 meters in the Northeast Channel. The grey curve shows the annual average anomaly time series. Positive values are warmer and saltier than the long-term mean calculated for 1981-2010. The gray shading highlights sampling done in 2016.

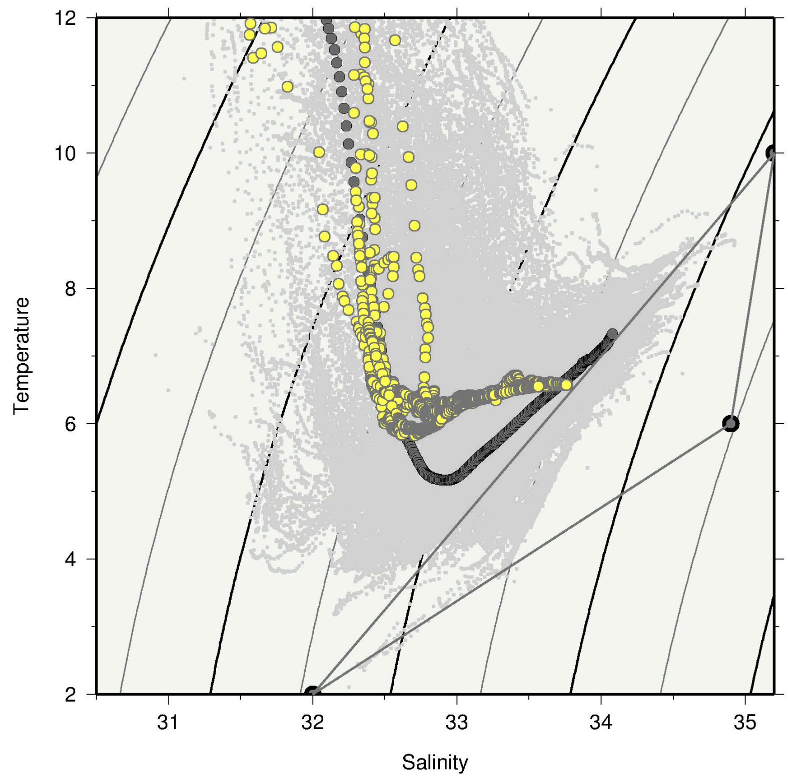


Fig. 14. Temperature-salinity diagram showing water properties in Wilkinson Basin in the western Gulf of Maine. All observations from spring 2016 (yellow) are shown along with the spring climatological average profile (1981-2010, dark gray). The lightest gray dots show the historical range encompassed by observations from the reference period, 1981-2010. Temperature and salinity properties representative of source waters entering the Gulf of Maine are shown by the mixing triangle.

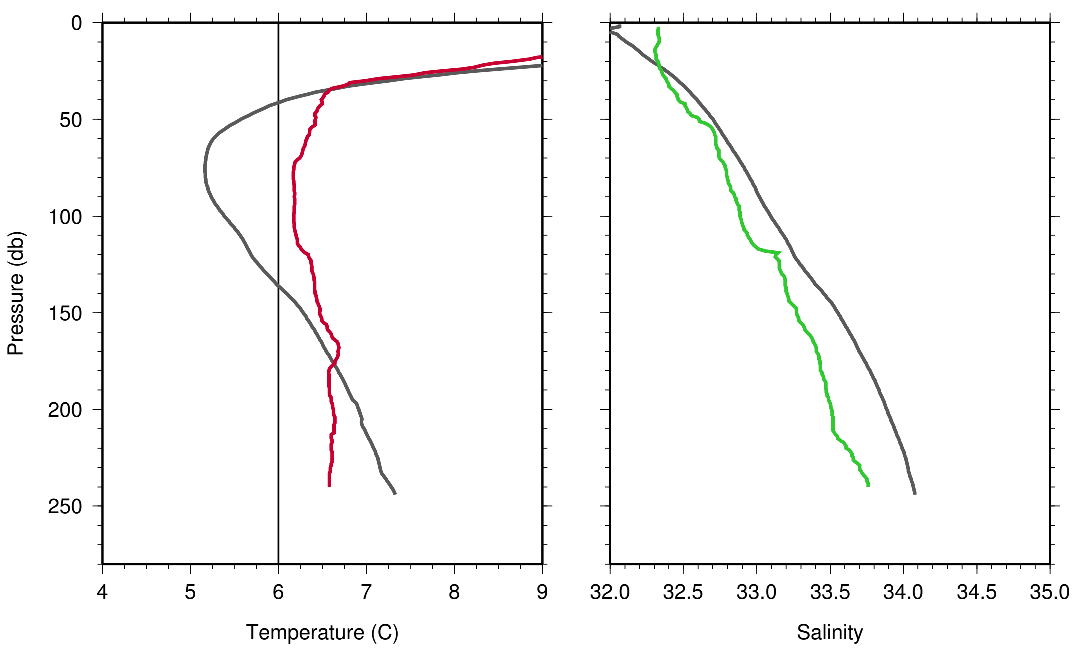


Fig. 15. Average profiles of temperature (left) and salinity (right) from repeated observations collected during June in Wilkinson Basin in the western Gulf of Maine. All observations from June 2016 (red and green) are shown along with the climatological average profile for the same month (1981-2010, dark gray). Waters in the Cold Intermediate Layer in the western Gulf of Maine are typically colder than 6°C, denoted by the vertical line.

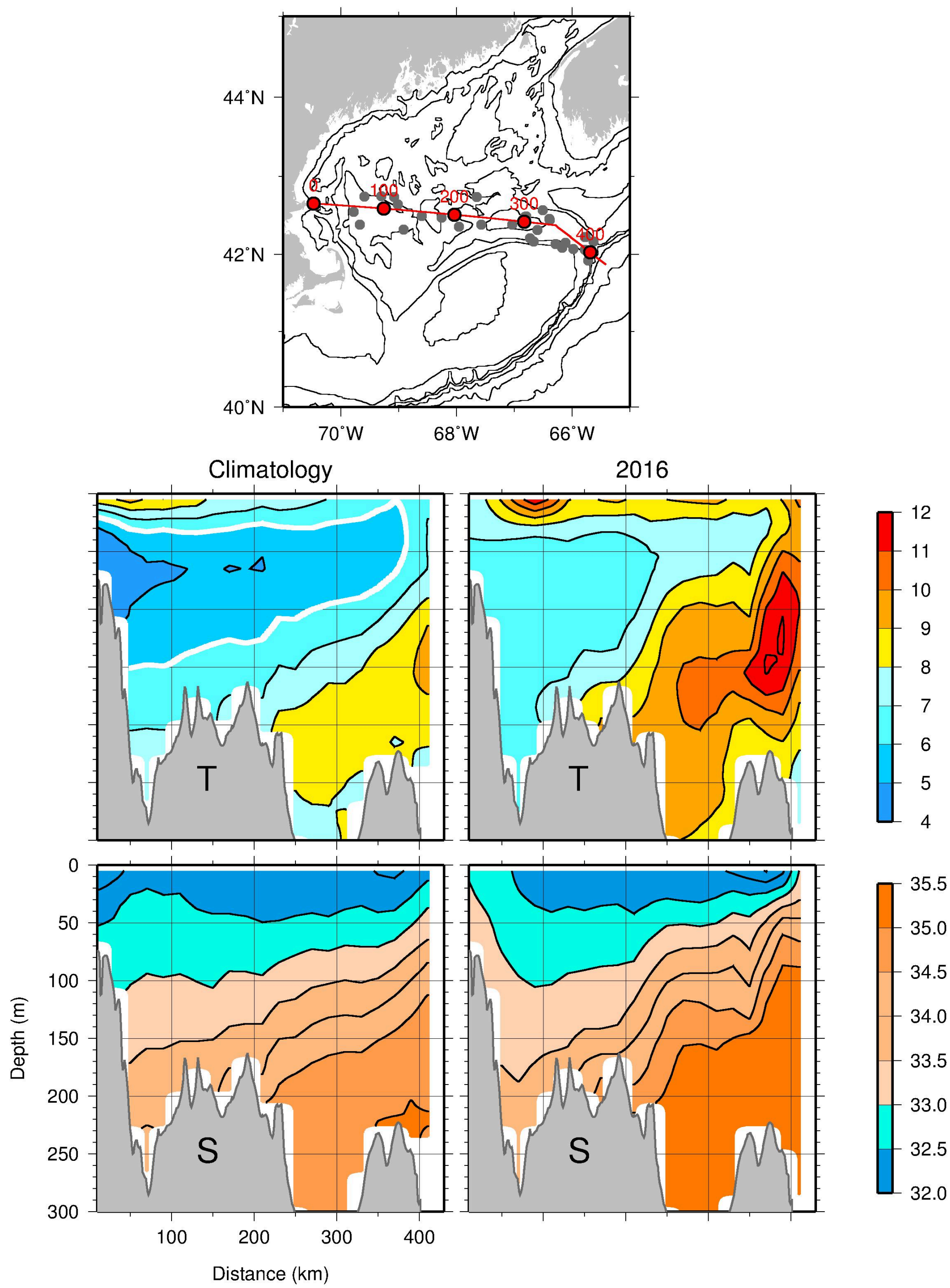


Fig. 16. Vertical sections of temperature (top) and salinity (bottom) crossing the Gulf of Maine along a zonal transect shown in the map. The left panels show the climatological average for May spanning the years 1981-2010. The bottom panels show the synoptic mean section for May 2016. The heavy white contour highlights the 6°C isotherm as an indicator of the boundary of the cold intermediate layer. Along-transect distances and the May 2016 station distribution are shown on the map for reference.