Northwest Atlantic Fisheries Organization

Serial No. N6537 **NAFO SCR Doc. 16/03**

SCIENTIFIC COUNCIL MEETING – JUNE 2016

Hydrographic Conditions on the Northeast United States Continental Shelf in 2015 –

NAFO Subareas 5 and 6

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Abstract

An overview is presented of the atmospheric and oceanographic conditions on the Northeast U.S. Continental Shelf during 2015. 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, 2015 was characterized by warming, an increase in the seasonal range of temperature 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 anomalously deep during the winter of 2015, presumably a consequence of anomalously cold air temperatures that persisted over the northeastern United States during winter. The vigorous mixing led to the formation of an anomalously thick layer of intermediate water extending to the bottom of Wilkinson Basin in the following spring. Finally, observations indicate that Gulf Stream water intruded onto the shelf in the Middle Atlantic Bight during late summer, leading to anomalous warming at the shelfbreak and in the upper 30 meters across the width of the shelf. Pycnocline gradients were enhanced and aligned with a shoreward protruding tongue of saline water. 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 (Pers. Comm. T. Joyce and Y-O. Kwon.) 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 led to the elimination of two of these six surveys in 2015 and ship maintenance issues led to truncation of the remaining surveys so that overall roughly half as many stations were occupied in 2015 over just two seasons.

During 2015, hydrographic data were collected on 8 individual NEFSC cruises, amounting to 1240 profiles of temperature and salinity and 1102 in NAFO subareas 5 and 6 (Table 1). Data were collected aboard the NOAA ships *Henry Bigelow* and *Gordon Gunter,* the charter vessel *Eagle Eye II* 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 2015 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 2015

During 2015, surface air temperatures were colder than average (1981-2010) over the North American continent, Labrador Sea and central North Atlantic during winter and warmer than average during summer and fall suggesting a larger seasonal range in 2015 (Fig. 2). Sea surface temperature mirrored these patterns, with cooler than average SST in the central basin and near shore along the NEUS Shelf during winter/spring and enhanced warming over the NEUS shelf in summer and fall (Fig. 3). On average, the magnitude of the surface warming is comparable to that observed in the 1950s but, unlike the 1950's, 2015 is characterized by an increased seasonal range with enhanced warming in summer and fall (Fig. 4). This is consistent with Friedland and Hare (2007) who demonstrated that the difference between the summer maximum SST and the winter minimum SST on the NEUS shelf has been increasing since 1980.

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 during the winter of 2015, 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). Distinct from earlier periods (prior to 2000), the index continues to fluctuate between strongly negative and strongly positive anomalies on shorter time scales, remaining in one phase for no more than 1-2 years. This undoubtedly complicates the response in the ocean, particularly for those processes that involve the propagation of anomalies or adjustments over multiple years.

Hydrographic Conditions in 2015

Relative to historical values, regional ocean temperatures across the NEUS shelf were warm during 2015 (Fig. 6). Annually, waters in the upper 30 meters were between 0.3-1.4°C warmer than normal everywhere, with the largest anomalies occurring in the Middle Atlantic Bight. Of the seasons sampled, warming was most pronounced during late-summer/early-fall, particularly in the Middle Atlantic Bight where regional temperature anomalies exceeded 2°C all the way to the bottom (Fig. 7). During winter/spring, regional upper ocean temperatures were near normal to slightly colder than normal across the NEUS Shelf. By contrast, bottom waters were warm year round in the eastern Gulf of Maine, and anomalously cold in the western Gulf of Maine, particularly during spring. The details of the seasonal differences are revealed in synoptic maps, which show colder temperatures primarily near the coast during spring and enhanced warming along the shelf edge during fall (Fig. 8).

Annually, surface waters in the upper 30 meters were saltier than normal in 2015, particularly in the Middle Atlantic Bight (Fig. 9). Large anomalies were observed during fall and spring when in the Middle Atlantic Bight, where anomalies exceeded 1 psu (Fig. 10a). By comparison, bottom waters were slightly saltier than normal everywhere except the western Gulf of Maine, where conditions were near normal (Fig. 9). Synoptically, the large regional salinity anomalies observed at the surface in the Middle Atlantic Bight are reflective of enhanced positive anomalies aligned with regions of warming (Fig. 10) extending shoreward from the shelf edge in the northern (southern) Middle Atlantic Bight in fall (spring) (Fig. 11).

The extreme temperature and salinity anomalies observed during summer and fall were presumably caused by a procession of Gulf Stream warm core rings, whose interaction with the topography at the shelf break drove an incursion of Gulf Stream water onto the shelf between spring and fall of this year (e.g., Zhang and Gawarkiewicz, 2015). The conditions are indicative of a significant intrusion with the largest temperature anomalies occurring in the upper 20 m and throughout the water column over the shelfbreak and upper slope. Gradients in the seasonal thermocline are enhanced by the inundation and appear to support the shoreward protrusion of high salinity water (Fig. 12). Salty intrusions are not uncommon in this region, representing an important mechanism for promoting exchange across the shelf-slope front and setting shelf water properties (Lentz, 2003). The impingement of warm, saline Gulf Stream water at the shelfbreak in 2015 also appears to have eroded the cold pool – a seasonal bottom-trapped feature formed when winter-cooled shelf water is isolated from the surface by summer heating (Fig. 12). Both the cold pool and the shelf-slope front serve as critical habitat for fisheries on the NEUS shelf (e.g. Sullivan et al., 2005; Miller et al., 2016).

Deep inflow through the Northeast Channel continues to be dominated by Warm Slope Water (Fig. 13). Springtime temperature-salinity profiles indicate the presence of a pronounced Cold Intermediate Layer in the western Gulf of Maine during 2015, a mid-depth water mass formed seasonally as a product of convective mixing driven by winter cooling (Fig. 14). In fact, the remnant winter water resident in the Cold Intermediate Layer extends to the bottom of Wilkinson Basin in spring 2015, confirming that robust convective mixing took place in the preceding winter (Fig. 15). This is not surprising considering the fact that air temperatures over the Northeastern U.S were more than 2°C colder than normal in 2015 (Fig. 2). Cold/dry winds blowing off the continental land mass will lead to more efficient evaporative cooling in the western Gulf of Maine and deeper convective mixing. In general, deeper vertical mixing has greater potential to tap into nutrient rich slope water at depth and should result in a thicker intermediate layer during spring, both potentially having an impact on the timing or intensity of spring phytoplankton blooms.

Impacts

Episodic events such as the Gulf Stream water intrusion that was observed in fall 2015 have the potential to cause significant changes in the ecosystem. For instance, this event could lead to 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 the seasonal range in ocean temperatures on the NEUS shelf is increasing, mirroring seasonal trends in air temperatures over the region, with greater warming occurring in spring and fall
- 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 warming and erosion of the Cold Pool
- Anomalously cold winter air temperatures over the Northeastern U.S. contributed to deeper mixing and colder, fresher intermediate/bottom waters in the western Gulf of Maine
- 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 2015

Sub-area	Division(s)	Month(s)	Type[1]	Description	Station count
5	Y,Z	4,5	S	Bottom trawl survey	210
5	Y,Z	5,6	S	Ecosystems monitoring survey	97
5	Y,Z	5,6	O	Sea scallop survey	54
5	Y,Z	6,7	O	Marine Mammal (AMAPPS) survey	42
5	Y,Z	9,10,11	S	Bottom trawl survey	212
5	Y,Z	10	S	Ecosystems monitoring survey	80
5	Y,Z	4,5	S	Bottom trawl survey	210
5	Y,Z	5,6	S	Ecosystems monitoring survey	97
6	A,B,C	3,4	S	Bottom trawl survey	144
6	A,B,C	5	S	Ecosystems monitoring survey	56
6	A,B,C	5	O	Apex Predator survey	2
6	A,B,C	8	O	Benthic habitat survey	22
6	A,B,C	9	S	Bottom trawl survey	144
6	A,B,C	10	S	Ecosystems monitoring survey	39

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

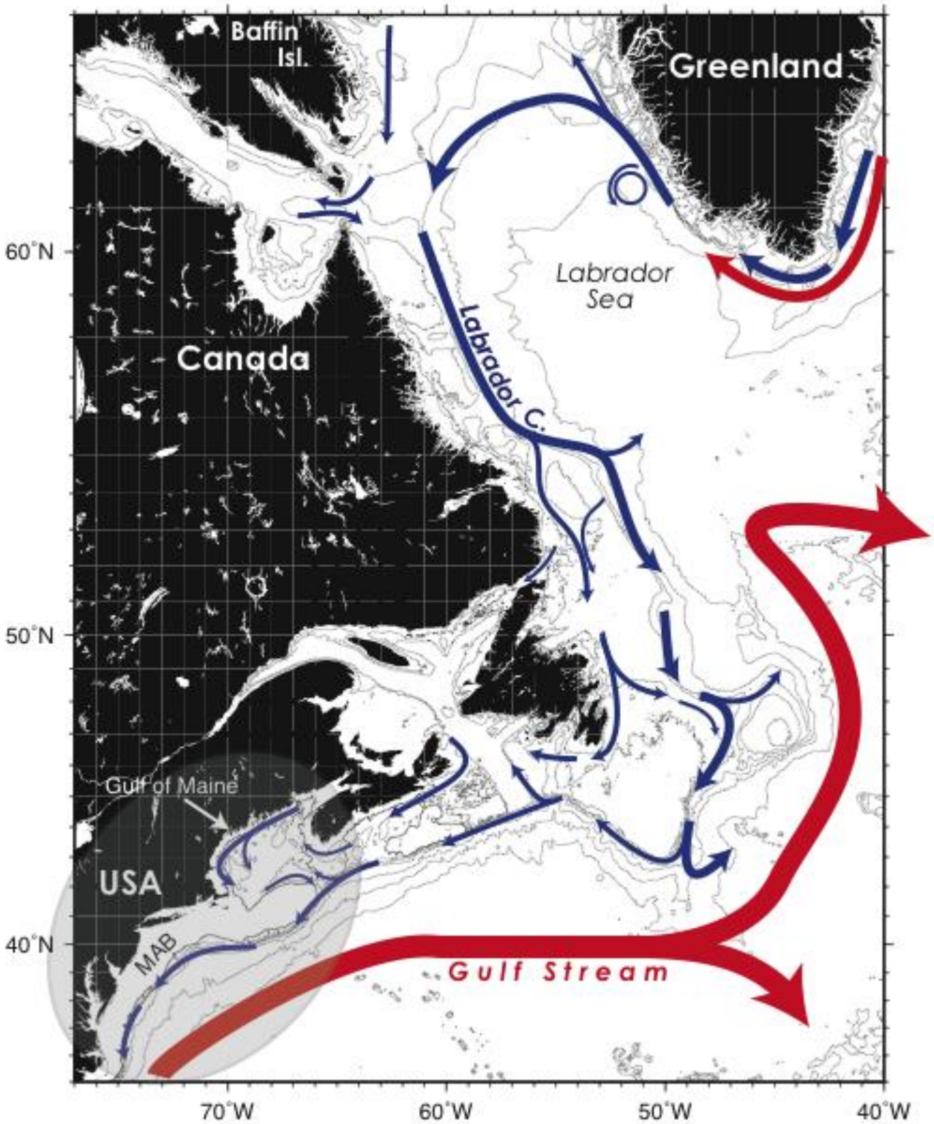


Fig. 1a. Circulation schematic of the western North Atlantic. The Northeast U.S. Shelf region is identified by the shaded oval. The 100, 200, 500, 1000, 2000, 3000 and 4000 meter isobaths are shown.

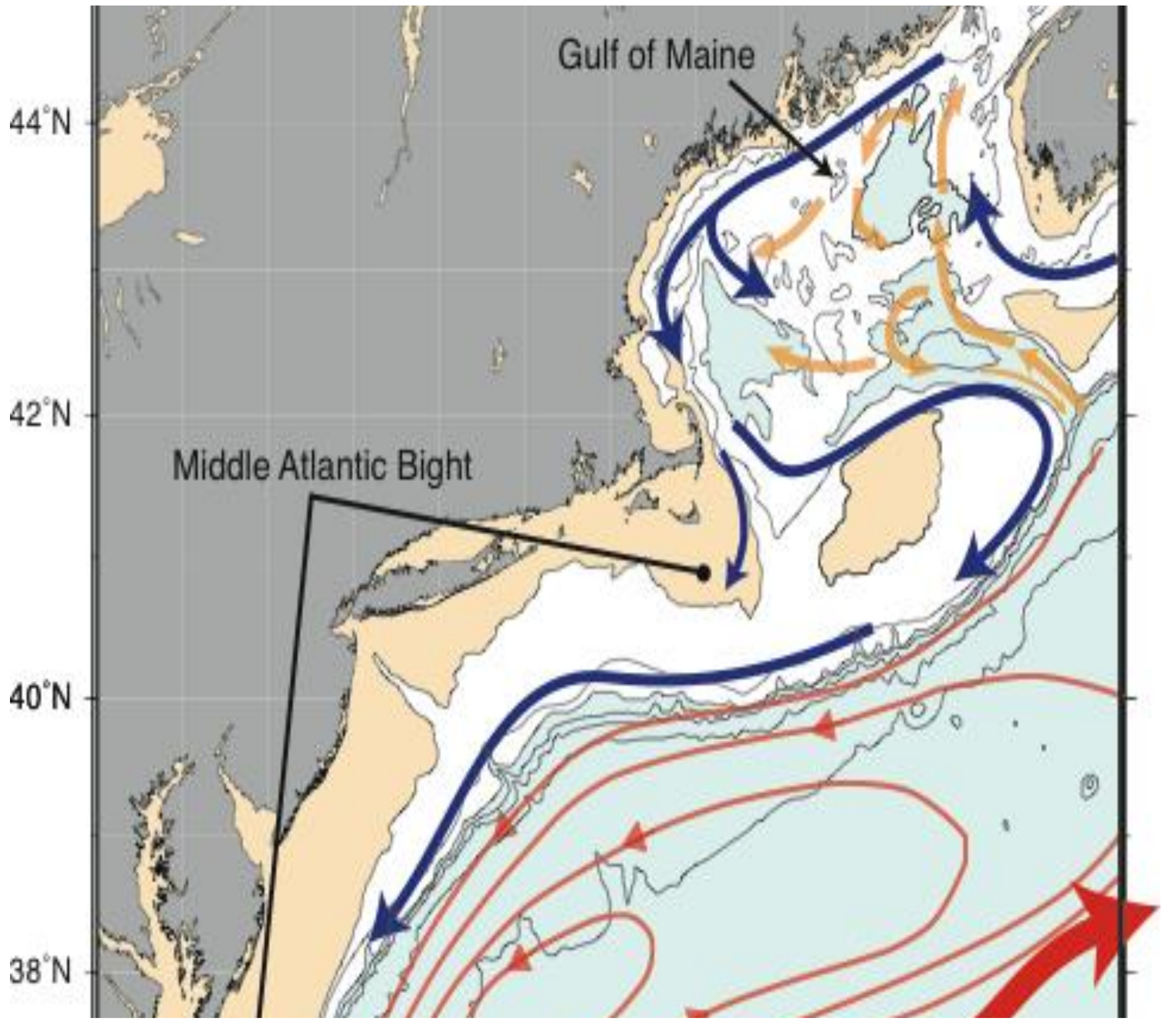


Fig. 1b. Circulation schematic for the Northeast U.S. Shelf region, where blue arrows represent shelf water circulation and orange arrows represent deeper slope water circulation pathways. Water depths deeper than 200 meters are shaded blue. Water depths shallower than 50 meters are shaded tan.

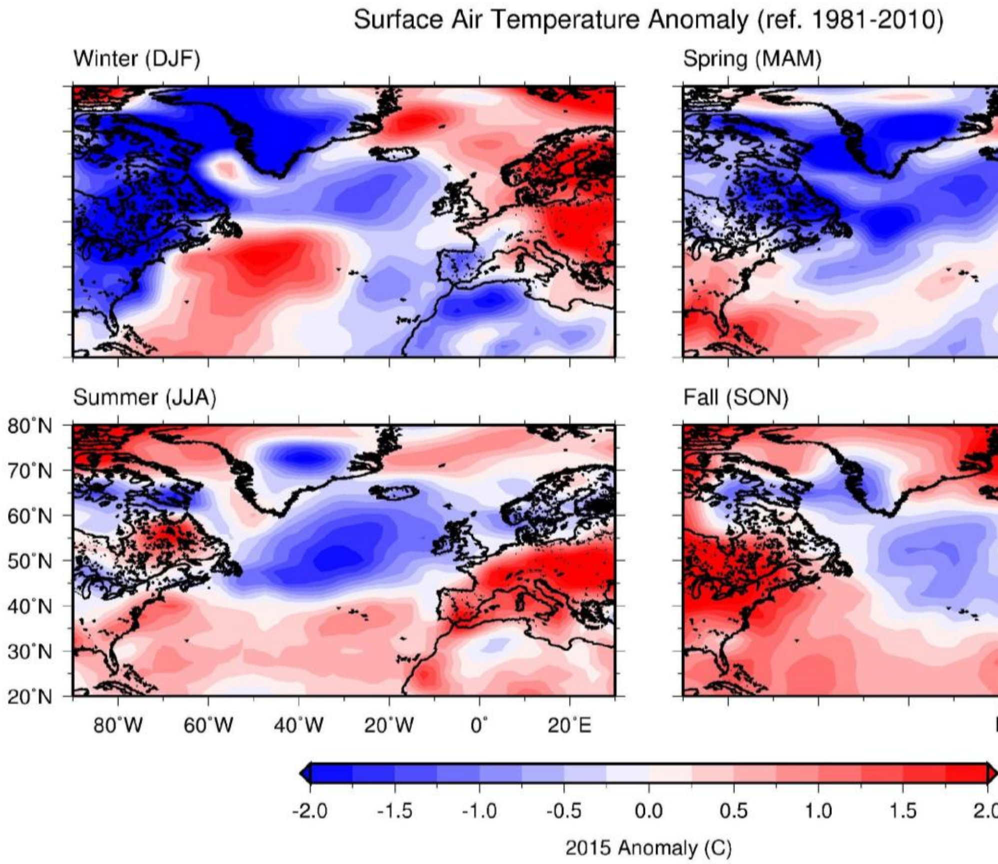


Fig. 2. Surface air temperature anomaly derived from the NCEP/NCAR Reanalysis product (http://www.esrl.noaa.gov/psd/data/composites/day/). Seasons are made up of 3-month periods where winter spans December-February. Positive anomalies correspond to warming in 2015 relative to the reference period (1981-2010)

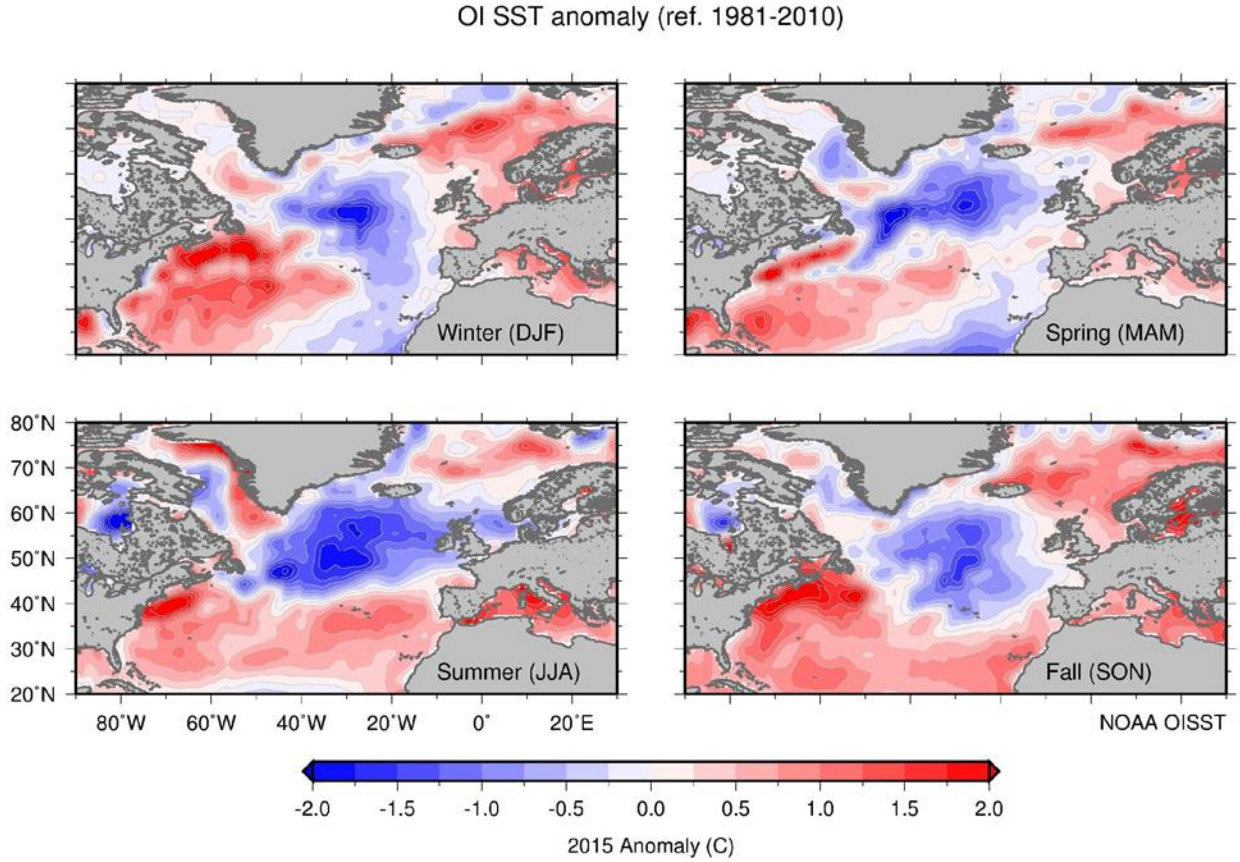
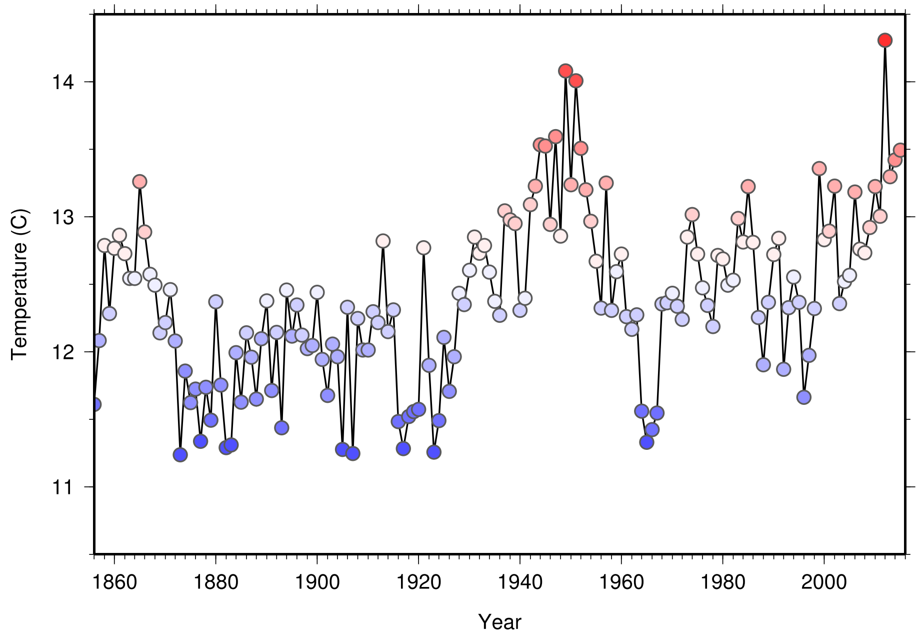


Fig. 3. Sea surface temperature anomaly derived from the NOAA's Optimum Interpolation (OI) SST product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html). Seasons are made up of 3-month periods where winter spans December-February. Positive anomalies correspond to warming in 2015 relative to the reference period (1981-2010).



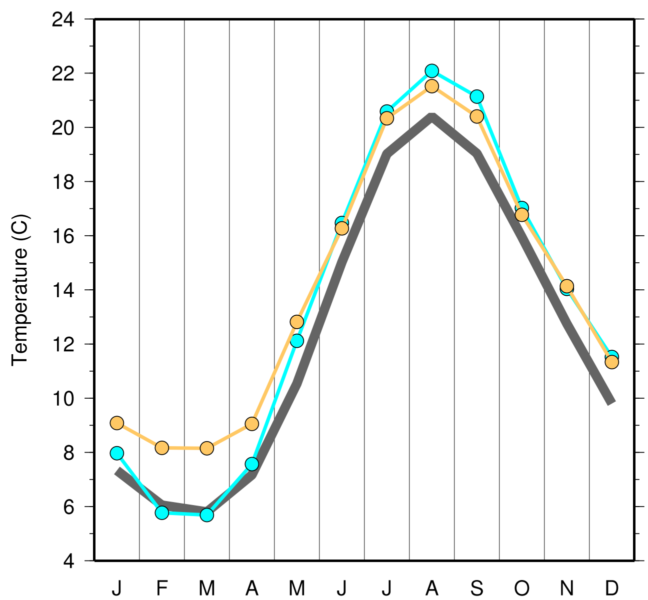


Fig. 4. Top: Regional average annual sea surface temperature for the NEUS shelf region calculated from NOAA's extended reconstructed sea surface temperature product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html). Colors correspond with the anomaly scale in Figure 3. Bottom: Regional average monthly mean SST for the NEUS shelf for 2015 (cyan), 1951 (orange) and 1981-2010 (gray) calculated from the same product.

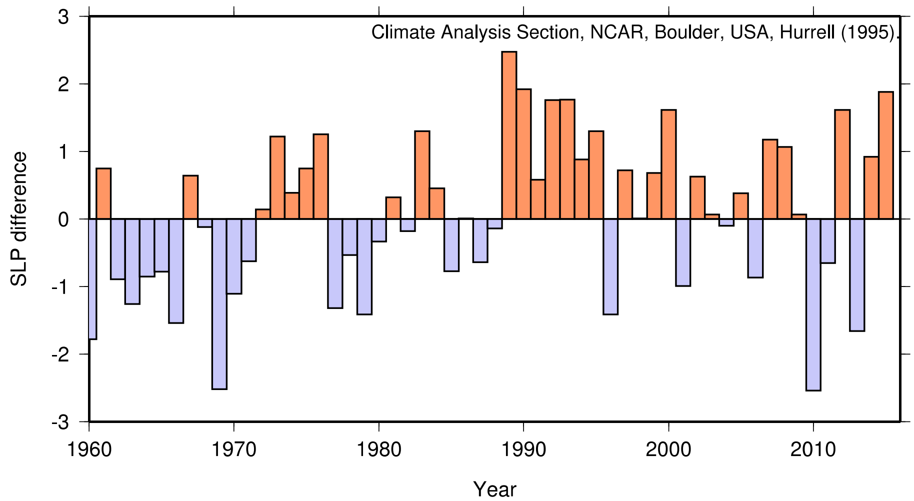


Fig. 5. North Atlantic Oscillation index computed from principal component analysis of sea level pressure in the North Atlantic (see Hurrell, 1995).

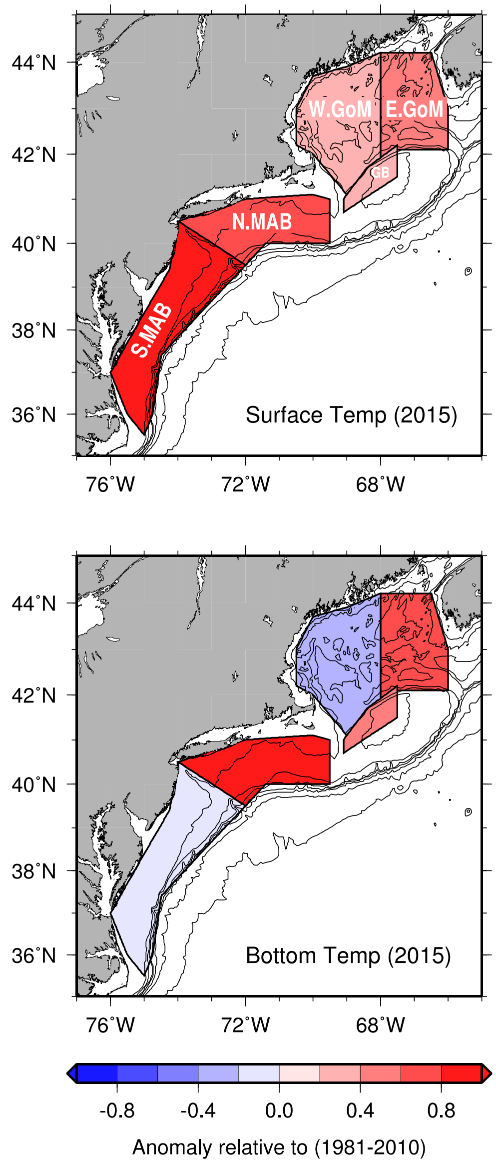


Fig. 6. Surface (upper panel) and bottom (lower panel) regional annual temperature anomaly (°C). Positive anomalies correspond to warming in 2015 relative to the reference period (1981-2010). The region labels correspond to the panels in Fig. 7.

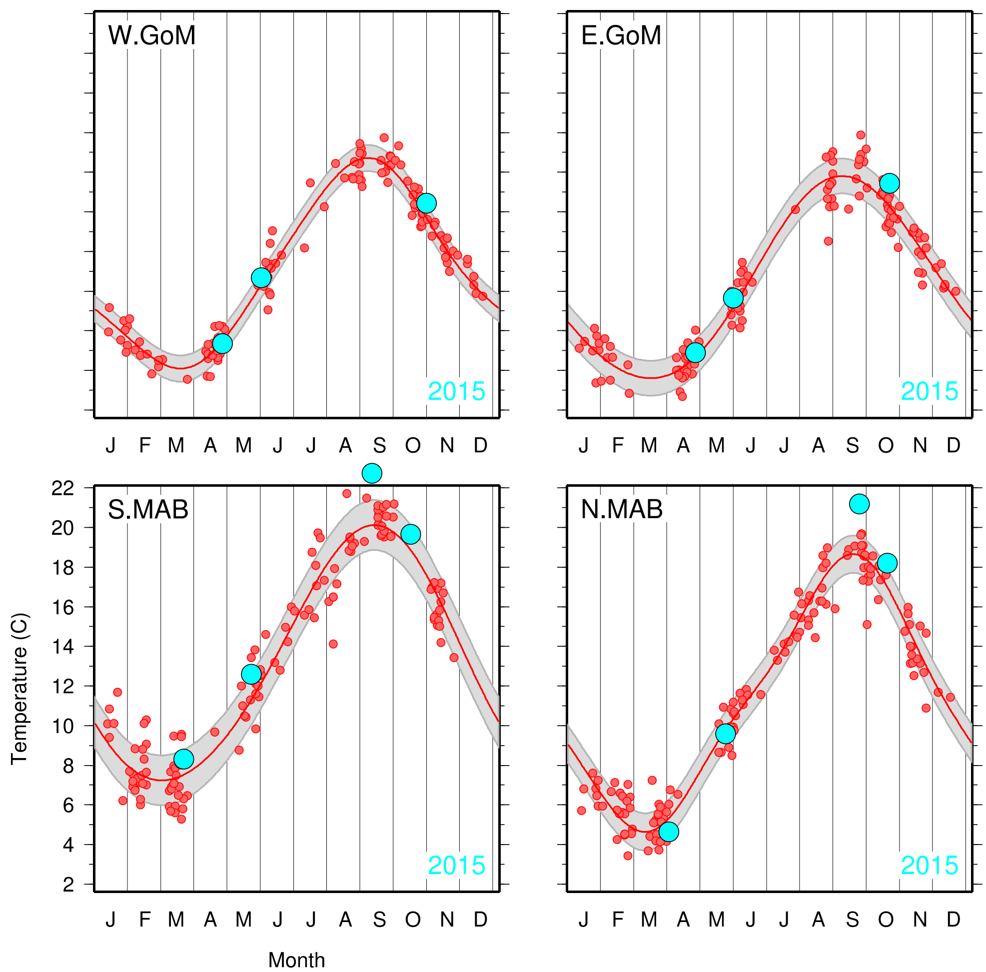


Fig. 7a. Regional average 0-30 meter temperature (°C) as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 6. An annual harmonic fit to the regional average temperatures from 1981-2010 is shown 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 2015 surveys are shown in cyan.

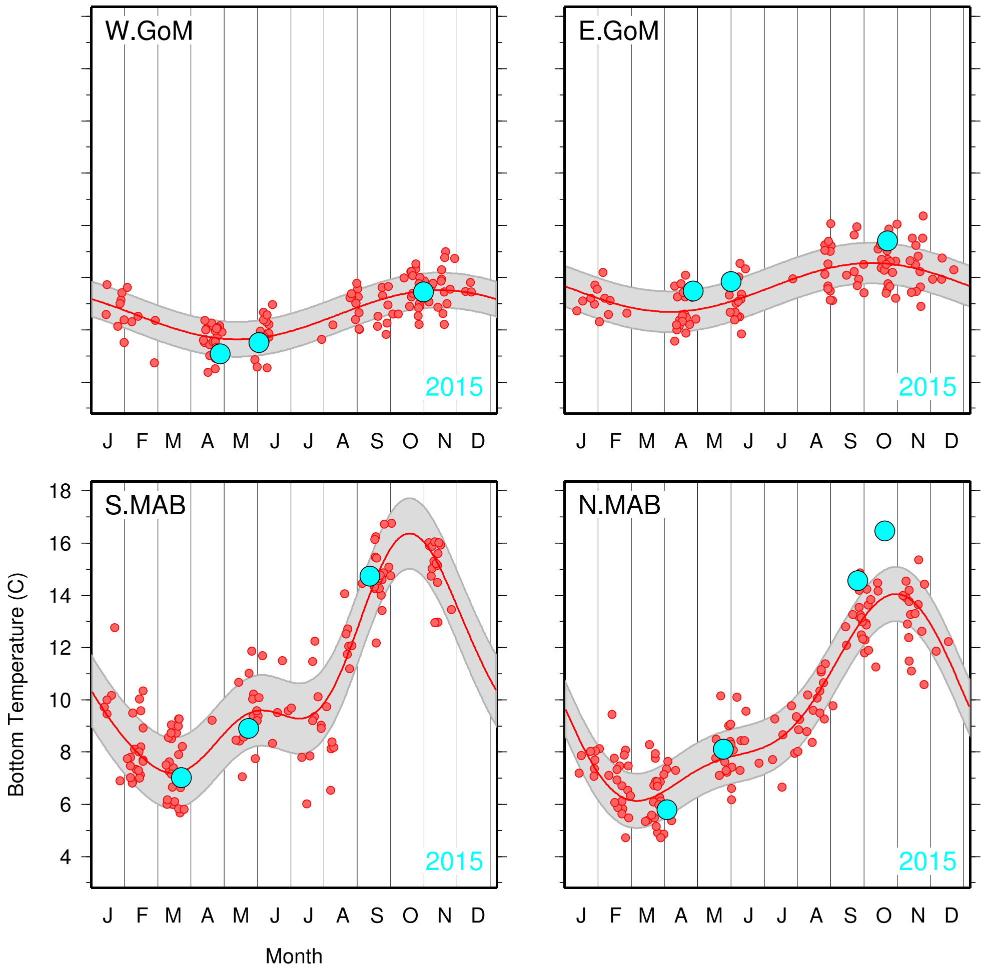


Fig. 7b. As in Fig. 7a, but for bottom temperatures.

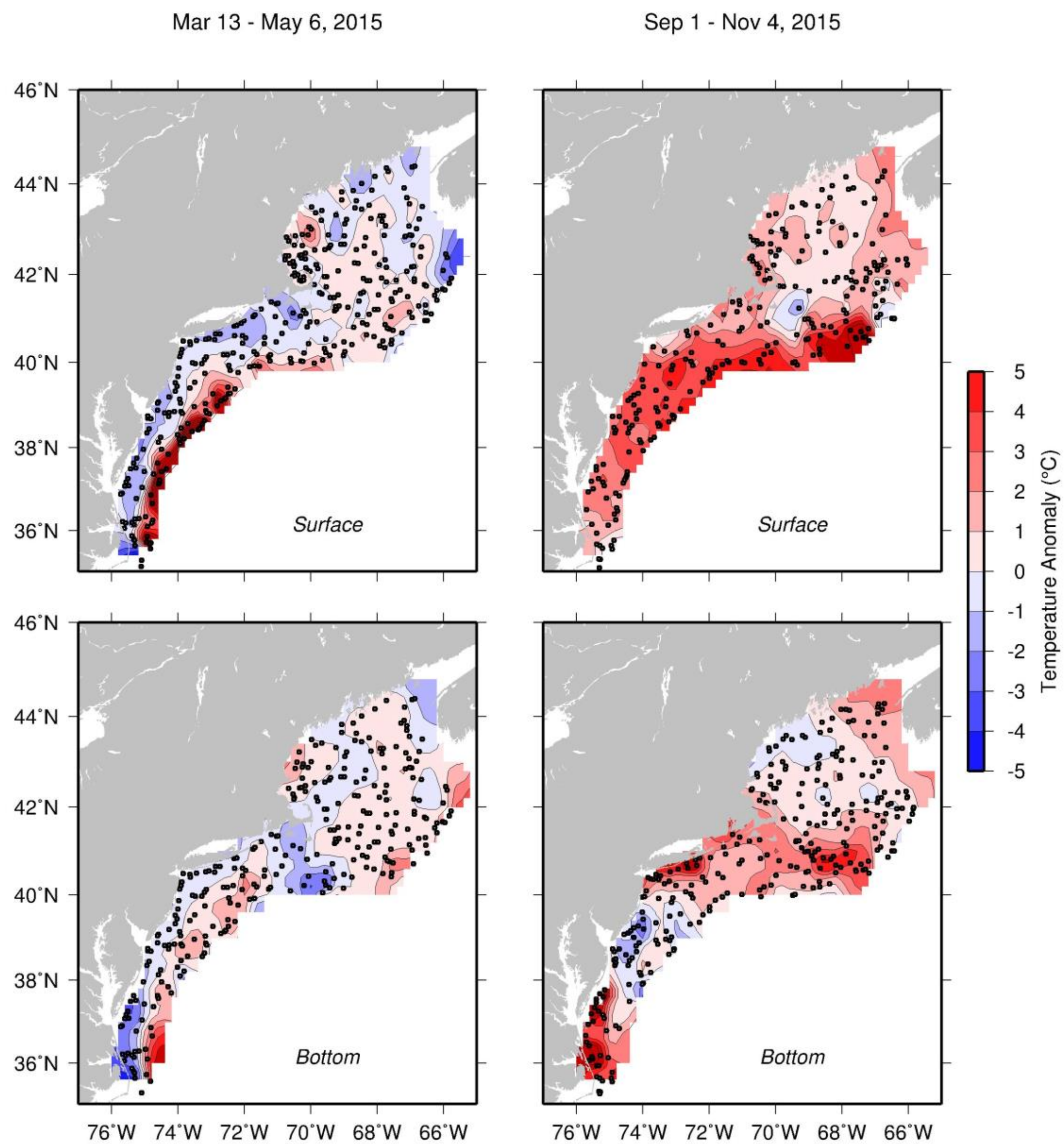


Fig. 8. Surface (upper panels) and bottom (lower panels) temperature anomaly from the spring 2015 (left) and fall 2015 (right) ground fish surveys. Positive anomalies correspond to warming in 2015 relative to the reference period (1977-1987).

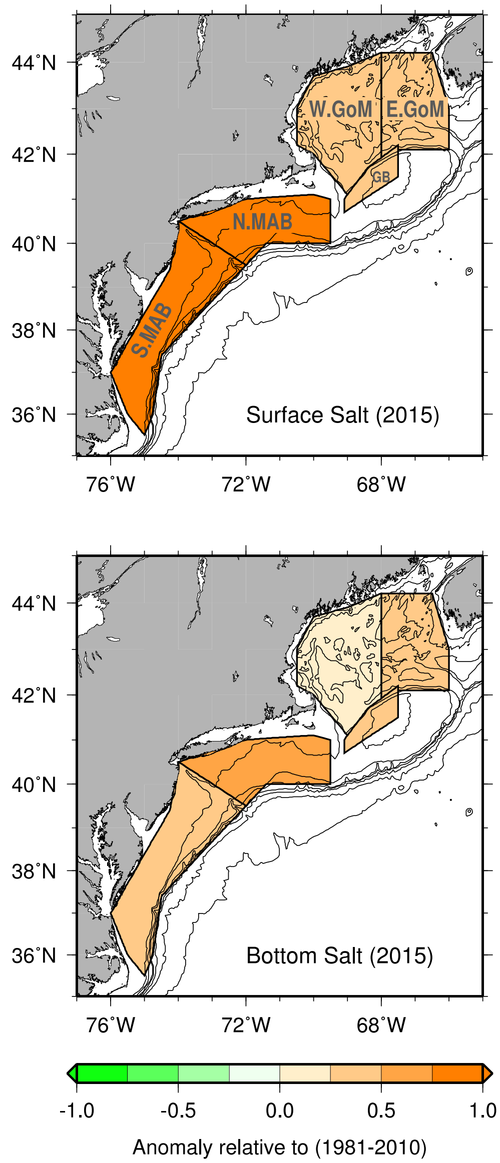


Fig. 9. Surface (upper panel) and bottom (lower panel) regional annual salinity anomaly. Positive anomalies correspond to more saline conditions in 2015 relative to the reference period (1981-2010). The region labels correspond to the panels in Figure 10.

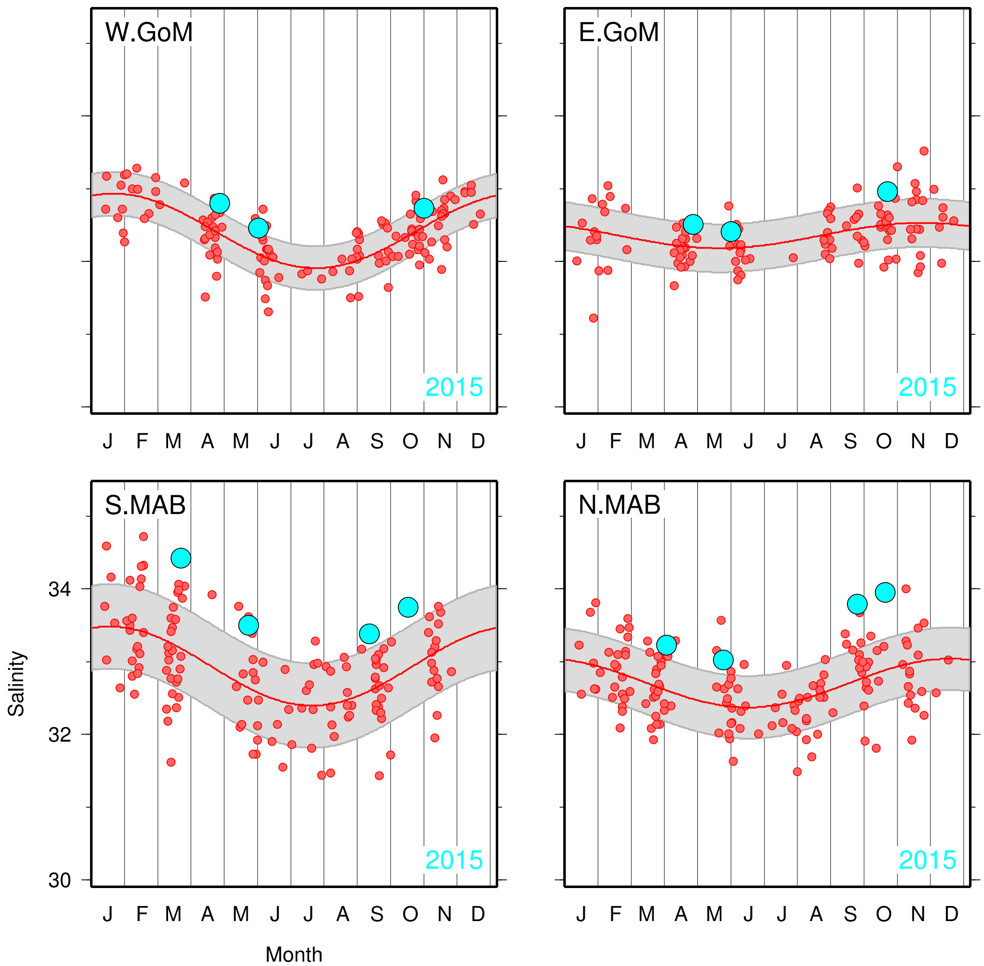


Fig. 10a. Regional average 0-30 meter salinity as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 9. An annual harmonic fit to the regional average salinities from 1981-2010 is shown by the 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 2015 surveys are shown in cyan.

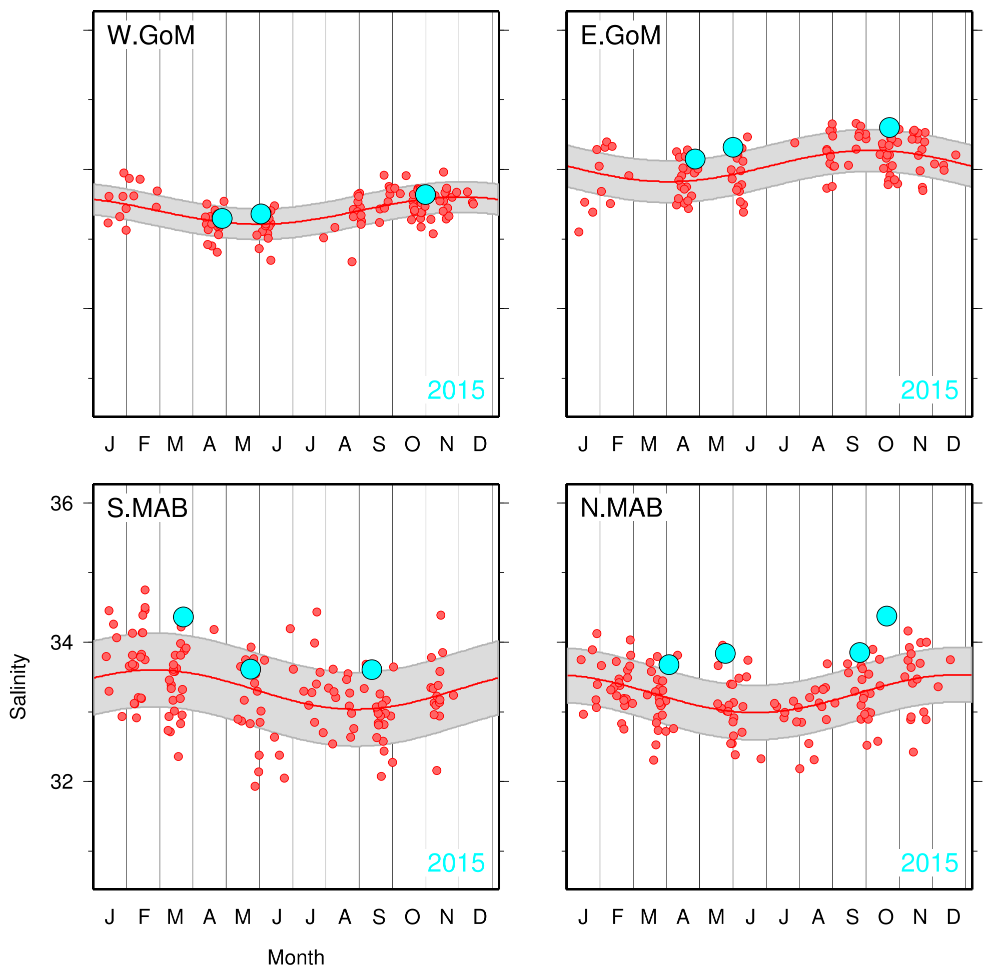


Fig. 10b. As in Fig. 10a, but for bottom salinities.

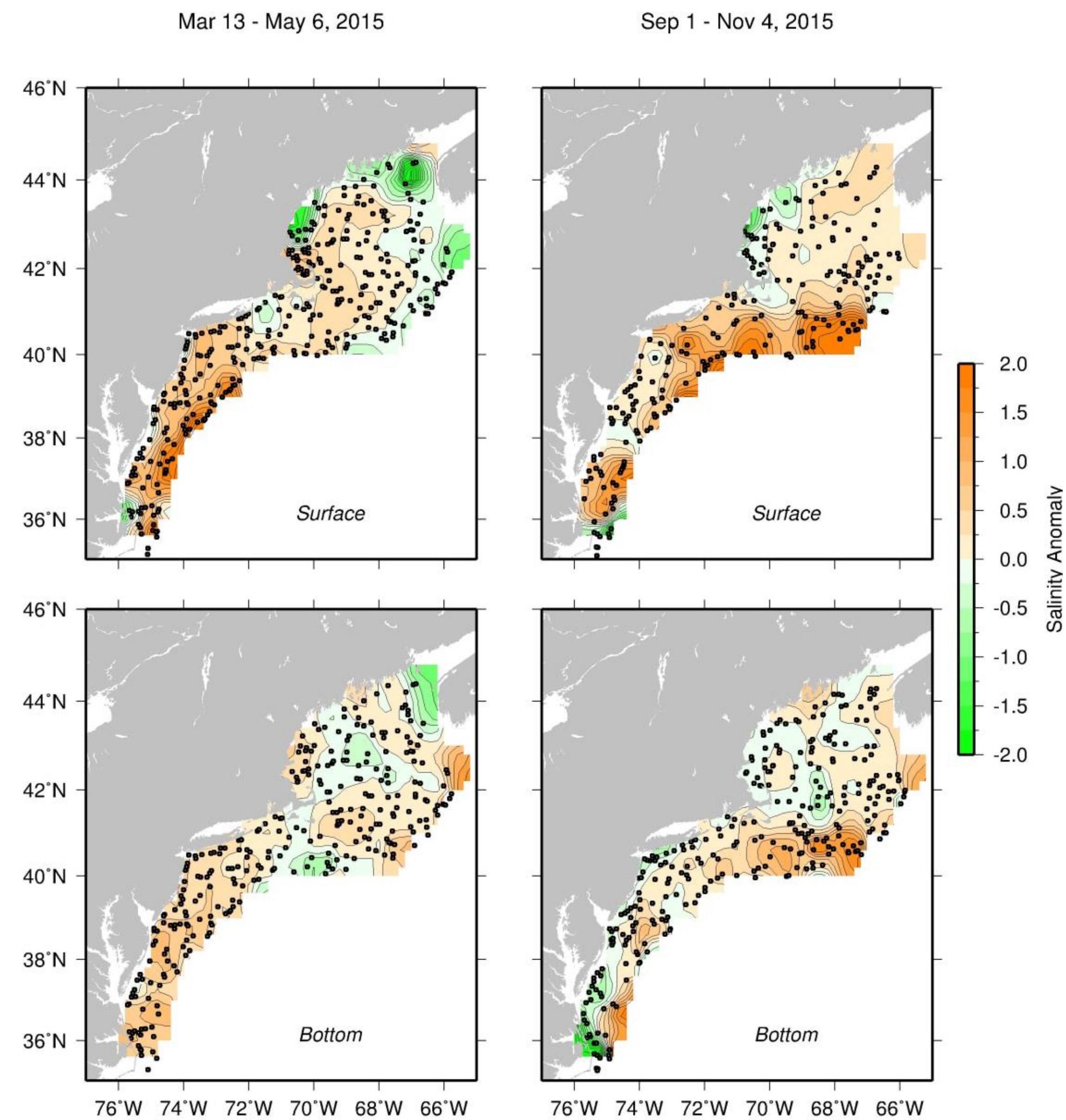


Fig. 11. Surface (upper panels) and bottom (lower panels) salinity anomaly from the spring 2015 (left) and fall 2015 (right) ground fish surveys. Positive anomalies correspond to more saline conditions in 2015 relative to the reference period (1977-1987).

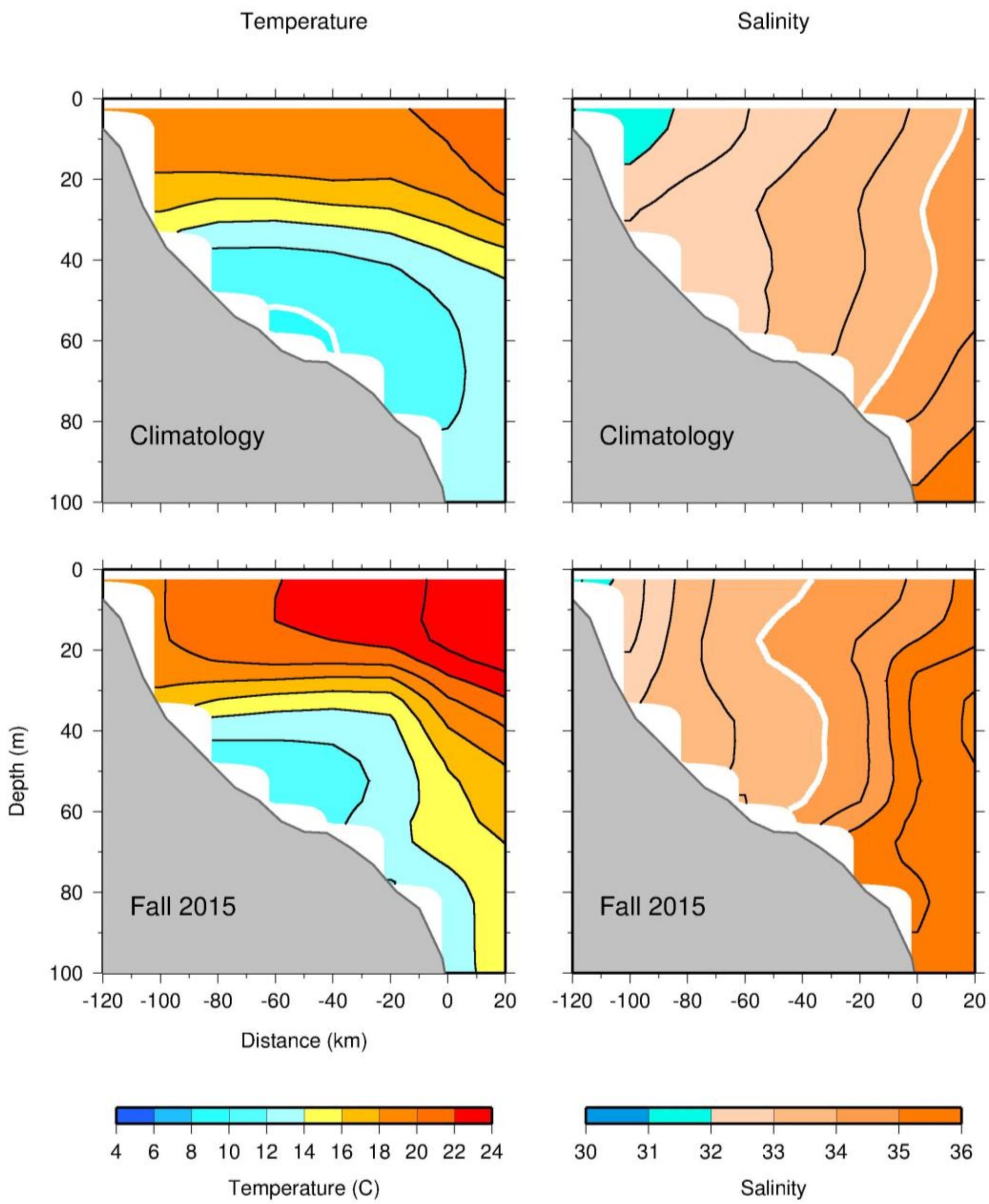


Fig. 12. Vertical sections of temperature (left) and salinity (right) crossing the continental shelf in the Middle Atlantic Bight. The top panels show the climatological average for September spanning the years 1981-2010. The bottom panels show the synoptic mean section for September 2015. The heavy white contour highlights the 10°C isotherm as an indicator of the boundary of the cold pool and the 34 isohaline typically aligned with the shelf-slope front.

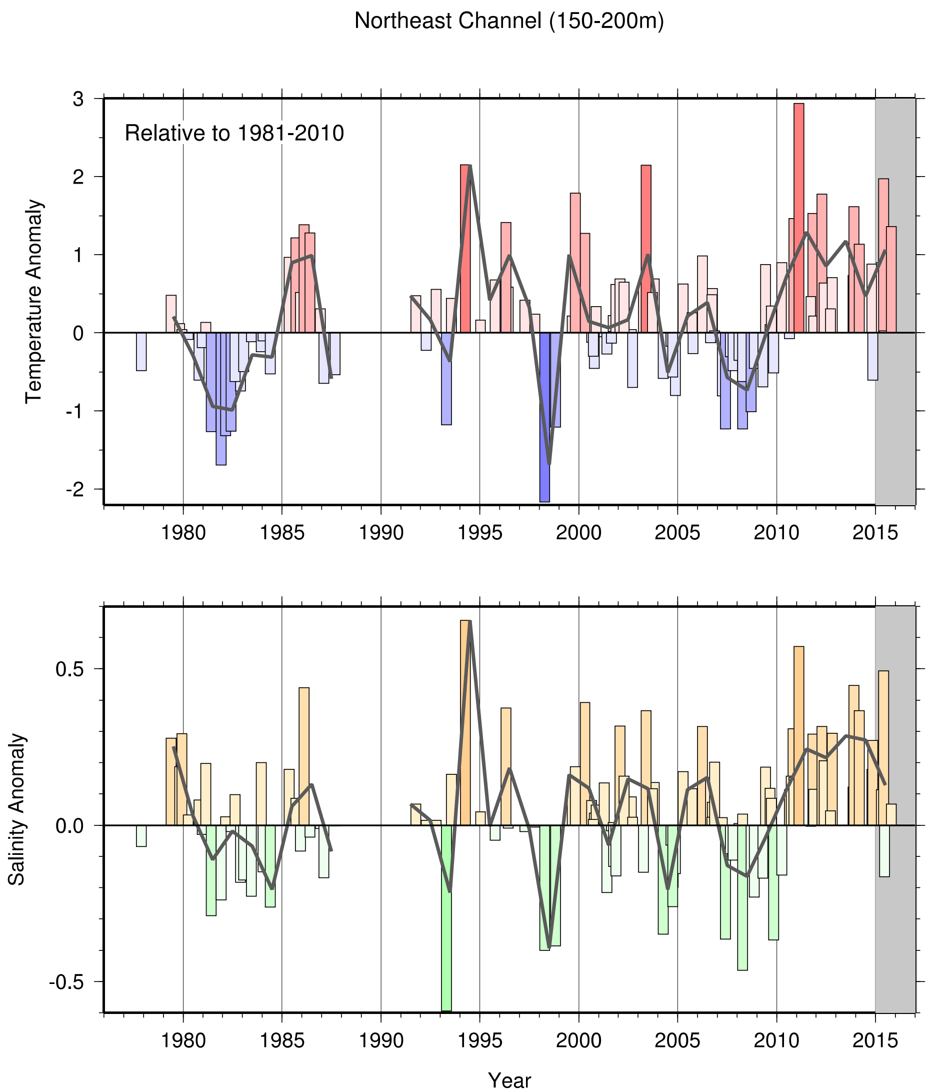


Fig. 13. Time series of temperature and salinity anomaly in the deep Northeast Channel. Each bar represents a volume-weighted average of all observations from a single survey collected between 150-200 meters in the Northeast Channel. The grey curve shows the annual average anomaly time series. Positive values are warmer and saltier than the long-term mean calculated for 1981-2010. The gray shading highlights sampling done in 2015.

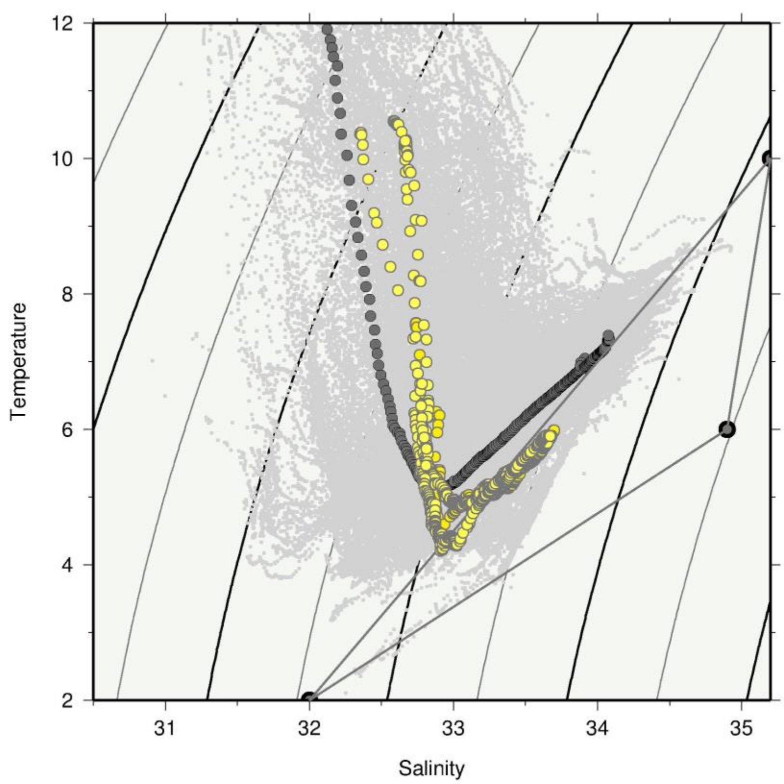


Fig. 14. Temperature-salinity diagram showing water properties in Wilkinson Basin in the western Gulf of Maine. All observations from spring 2015 (yellow) are shown along with the spring climatological average profile (1981-2010, dark gray). The lightest gray dots show the historical range encompassed by observations from the reference period, 1981-2010. Temperature

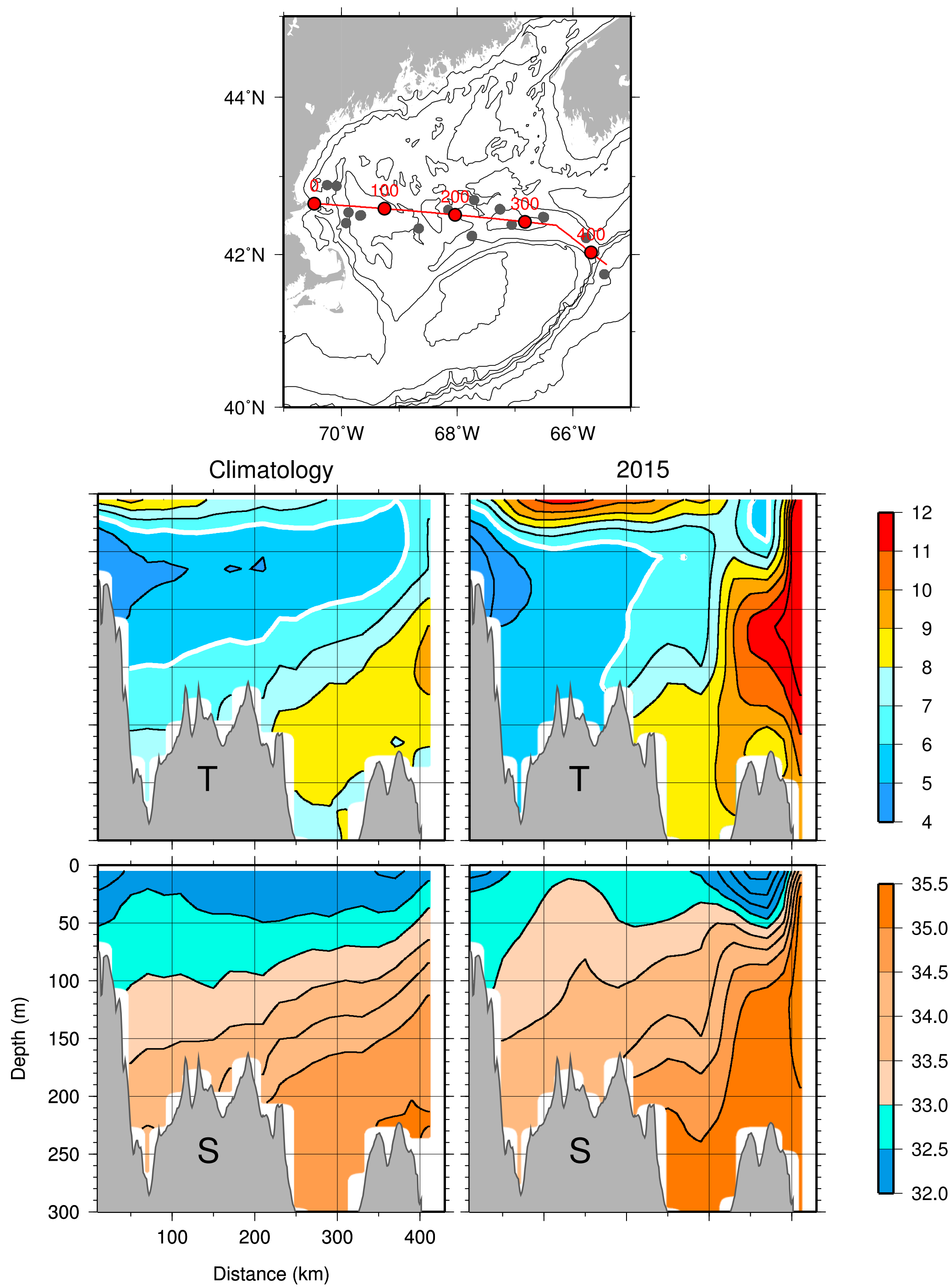


Fig. 15. Vertical sections of temperature (top) and salinity (bottom) crossing the Gulf of Maine along a zonal transect shown in the map. The left panels show the climatological average for May spanning the years 1981-2010. The bottom panels show the synoptic mean section for May 2015. The heavy white contour highlights the 6°C isotherm as an indicator of the boundary of the cold intermediate layer. Along-transect distances and the May 2015 station distribution are shown on the map for reference.