NOT TO BE CITED WITHOUT PRIOR
REFERENCE TO THE AUTHOR(S)

Northwest Atlantic Fisheries Organization

Serial No. N6422 **NAFO SCR Doc. 15/004**

SCIENTIFIC COUNCIL MEETING – JUNE 2015

Hydrographic Conditions on the Northeast United States Continental Shelf in 2014 – 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 2014. 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, 2014 was characterized by continued warming throughout the water column, 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 2014, 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 cold intermediate water in the following spring. Finally, observations reveal a significant intrusion of Gulf Stream water in the Middle Atlantic Bight during late summer. The intrusion encompassed the width of the shelf, leading to profound changes in the water mass distributions. 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. 1). 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 coast, 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 2014 and ship maintenance issues led to truncation of the remaining surveys so that overall roughly half as many stations were occupied in 2014 over just two seasons.

During 2014, hydrographic data were collected on 8 individual NEFSC cruises, amounting to 1201 profiles of temperature and salinity and 1131 in NAFO subareas 5 and 6 (Table 1). Data were collected aboard the NOAA ships *Henry Bigelow, Pisces* 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 2014 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 is presented in Holzwarth and Mountain (1990).

Basin-Scale Conditions in 2014

During 2014, surface air temperatures were generally colder than average (1981-2010) over the North American continent and central North Atlantic, particularly in winter and spring. Conversely, air temperatures were warmer than average over the NEUS continental shelf, with enhanced anomalies in summer and fall suggesting a larger seasonal range in 2014 (Fig. 2). Sea surface temperature (SST) mirrored these patterns, with cooler than average SST in the central basin, warmer than average SST along the NEUS shelf year round 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, 2014 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 2014, 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 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 2014

Relative to historical values, regional ocean temperatures across the NEUS shelf were uniformly warm during 2014 (Fig. 6). Annually, waters in the upper 30 meters were approximately 1°C warmer than normal everywhere. Of the seasons sampled, warming was most pronounced during late-summer/early-fall, with regional temperature anomalies reaching nearly 2°C all the way to the bottom (Fig. 7). Correspondingly, bottom waters were warm over the entire region, with temperatures exceeding historical values year round in the eastern Gulf of Maine. While regionally surface waters were generally warm in both seasons, warming was particularly strong in the fall along the shelf edge at the surface and near shore and over shallow banks at the bottom (Fig 8).

Annually, surface waters in the upper 30 meters were saltier than normal in 2014, particularly in the Middle Atlantic Bight (Fig. 9). The largest regional salinity anomalies were observed during fall when anomalies exceeded 1 psu in the Middle Atlantic Bight (Fig. 10a). By comparison, bottom waters were slightly saltier than normal everywhere (Fig. 9), with the largest regional anomalies occurring in late-summer/early-fall, coincident with the period of enhanced warming (Fig 10b). Synoptically, the large regional salinity anomalies observed in the Middle Atlantic Bight are reflective of a large swath of positive anomalies extending from the shelf edge toward shore between Cape Cod, MA and Cape Hatteras, NC (Fig 11). During this period, nearshore waters just offshore of Long Island, NY were more than 1.5 psu saltier than normal.

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 inner shelf between spring and fall of this year (e.g. Zhang et al., 2015). The conditions are indicative of a significant intrusion that inundated the shelf with the largest anomalies occurring at the surface, ultimately moving the 34 isohaline (typically aligned with the shelf-slope front) 100 km inshore of its climatological position and rendering the shelf-slope front unidentifiable in a composite cross-shelf section (Fig 12a). Salinity over the mid-shelf was more than 5 standard deviations larger than the long-term mean, while temperature was more than 2 standard deviations higher (Fig 12b). Anomalies were largest over the cold pool – a seasonal bottom-trapped feature formed when winter-cooled shelf water is isolated from the surface by summer heating – which was virtually eliminated by the inundation event (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; A. Miller, personal communication).

The influence of Gulf Stream meanders and warm core rings is also evident in the Northeast Channel during fall (Fig. 13-15). Aside from Gulf Stream influences, 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 thicker Cold Intermediate Layer in the western Gulf of Maine during 2014. This is a mid-depth water mass, characterized by its temperature minimum, formed seasonally as a product of convective mixing driven by winter cooling (Fig. 15). A thicker Cold Intermediate Layer suggests that robust convective mixing took place in the preceding winter leading to deep mixed layers. Indeed, winter mixed layers during 2014 were four times as deep and 2°C colder than those observed in 2012 (Fig. 16). The differences are understandable considering the fact that winter air temperatures over the Northeastern U.S were more than 3°C colder in 2014 compared with 2012 (Fig 17). 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

2014 was characterized by continued warming throughout the water column and an increase in the seasonal range of temperature. Recent studies have demonstrated that distributions of fish and shellfish are changing (e.g. Pinsky et al., 2013) and warming trends have been implicated in shifting thermal habitats on the NEUS shelf (NEFSC Ecosystem Advisory, 2014). That said, while observations indicate that the distribution of several southern species is shifting poleward over time, indications are that warming is not necessarily responsible for the shift in every species (Bell et al., 2014). Certainly, episodic events such as the extreme Gulf Stream water intrusion that was observed in fall 2014 have the potential to cause significant changes in the ecosystem. For instance, this event could lead 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

- Despite anomalously cold winter air temperatures over the Northeastern U.S., ocean temperatures continue to be anomalously warm and more saline at the surface and bottom
- Cold and dry winter air temperatures over the Northeastern U.S. contributed to deeper mixed layers and a well-developed thicker cold intermediate layer in the western Gulf of Maine
- Observations indicate that the seasonal range in ocean temperatures on the NEUS shelf is increasing, mirroring the seasonal trends in air temperatures over the region, with greater warming occurring in spring and fall.
- An intrusion of Gulf Stream water in the Middle Atlantic Bight during late-summer/early-fall led to extreme changes in the water mass distributions on the shelf, including the elimination of the Cold Pool and disruption of the shelf-slope front
- 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.

References

Armi, L., and N.A. Bray, 1982. A standard analytic curve of potential temperature versus salinity for the Western North Atlantic. Journal of Physical Oceanography 12, 384–387.

Bell, R., D. Richardson, J. Hare, P. Lynch and P. Fratantoni, 2014. Disentangling the effects of climate, abundance and size on the distribution of marine fish: an example based on four stocks from the Northeast U.S. Shelf. ICES Journal of Marine Science, doi: 10.1093/icesjms/fsu217.

Friedland, K. and J. Hare, 2007: Long-term trends and regime shifts in sea surface temperature on the continental shelf of the northeast United States. *Continental Shelf Research,* 27, 2313-2328.

Holzwarth TJ, Mountain DG. 1990. Surface and Bottom Temperature Distributions from the Northeast Fisheries Center Spring and Fall Bottom Trawl Survey Program, 1963- 1987. NEFSC Reference Document 90-03, 62 pp.

Joyce, T.M., C. Deser, and M.A. Spall, 2000: The relationship between decadal variability of Subtropical Mode Water and the North Atlantic Oscillation. *J. Climate*, 13, 2550-2569.

Mountain, D.M., 2012: Labrador Slope Water entering the Gulf of Maine – Response to the North Atlantic Oscillation, *Continental Shelf Research*, 47, 150-155.

NEFSC Ecosystem Advisory, 2014, http://nefsc.noaa.gov/ecosys/advisory/current/

Petrie, B., 2007: Does the North Atlantic Oscillation Affect Hydrographic Properties on the Canadian Atlantic Continental Shelf? *Atmosphere-Ocean*, 45, 141-151.

Pinsky, M.L., B. Worm, M.J. Fogarty, J.L. Sarmiento, S.A. Levin, 2013: Marine taxa track local climate velocities. *Science*, 341(6151)**:** 1239-1242.

Sullivan, M.C., R.K. Cowen and B.P. Steves, 2005: Evidence for atmosphere-ocean forcing of yellowtail flounder (*Limanda ferruginea*) recruitment in the Middle Atlantic Bight. *Fisheries Oceanography*, 14, 386-399.

Visbeck, M., E.P. Chassignet, R. Curry, T. Delworth, B. Dickson, G. Krahmann, 2003: The Oceans's Response to North Atlantic Osciallation Variability, In: J. Hurrell, Y. Kushner, G. Ottersen and M. Visbeck (Eds.), *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*. Geophysical monograph 134, Washington: American Geophysical Union, pp. 113-145.

Zhang, W. G. and G. G. Gawarkiewicz, 2015: A direct intrusion of Gulf Stream water onto the Mid-Atlantic Bight Continental Shelf, *Nature Geoscience,* submitted.

Table 1: Inventory of hydrographic monitoring on the Northeast U.S. Shelf during 2014

Sub-area	Division(s)	Month(s)	Type[1]	Description	Station count
5	Y,Z	3	S	Ecosystems monitoring survey	60
5	Y,Z	3,4	O	Marine Mammal (AMAPPS) survey	67
5	Y,Z	4,5	S	Bottom trawl survey	212
5	Y,Z	7	O	Sea scallop survey	65
5	Y,Z	7	O	Marine Mammal (AMAPPS) survey	15
5	Y,Z	9	O	Northern Right Whale survey	22
5	Y,Z	9,10,11	S	Bottom trawl survey	197
5	Y,Z	11	S	Ecosystems monitoring survey	99
6	A,B,C	4	S	Bottom trawl survey	74
6	A,B,C	3,4	O	Marine Mammal (AMAPPS) survey	112
6	A,B,C	7	O	Sea scallop survey	5
6	A,B,C	9	O	Northern Right Whale survey	2
6	A,B,C	9,10	S	Bottom trawl survey	145
6	A,B,C	11	S	Ecosystems monitoring survey	56

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

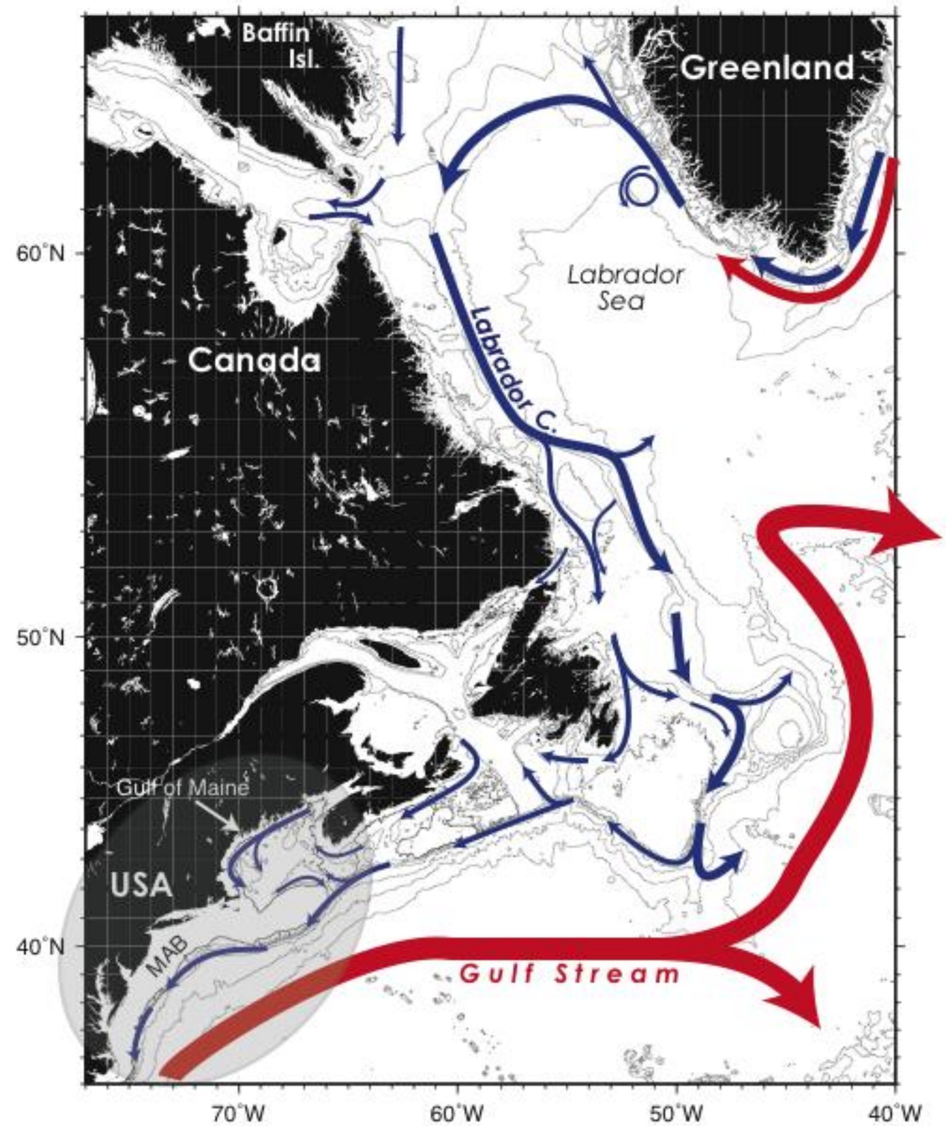


Figure 1a: Circulation schematic of the western North Atlantic. The Northeast U.S. Shelf region is identified by the shaded oval. The 100, 200, 500, 1000, 2000, 3000 and 4000 meter isobaths are shown.

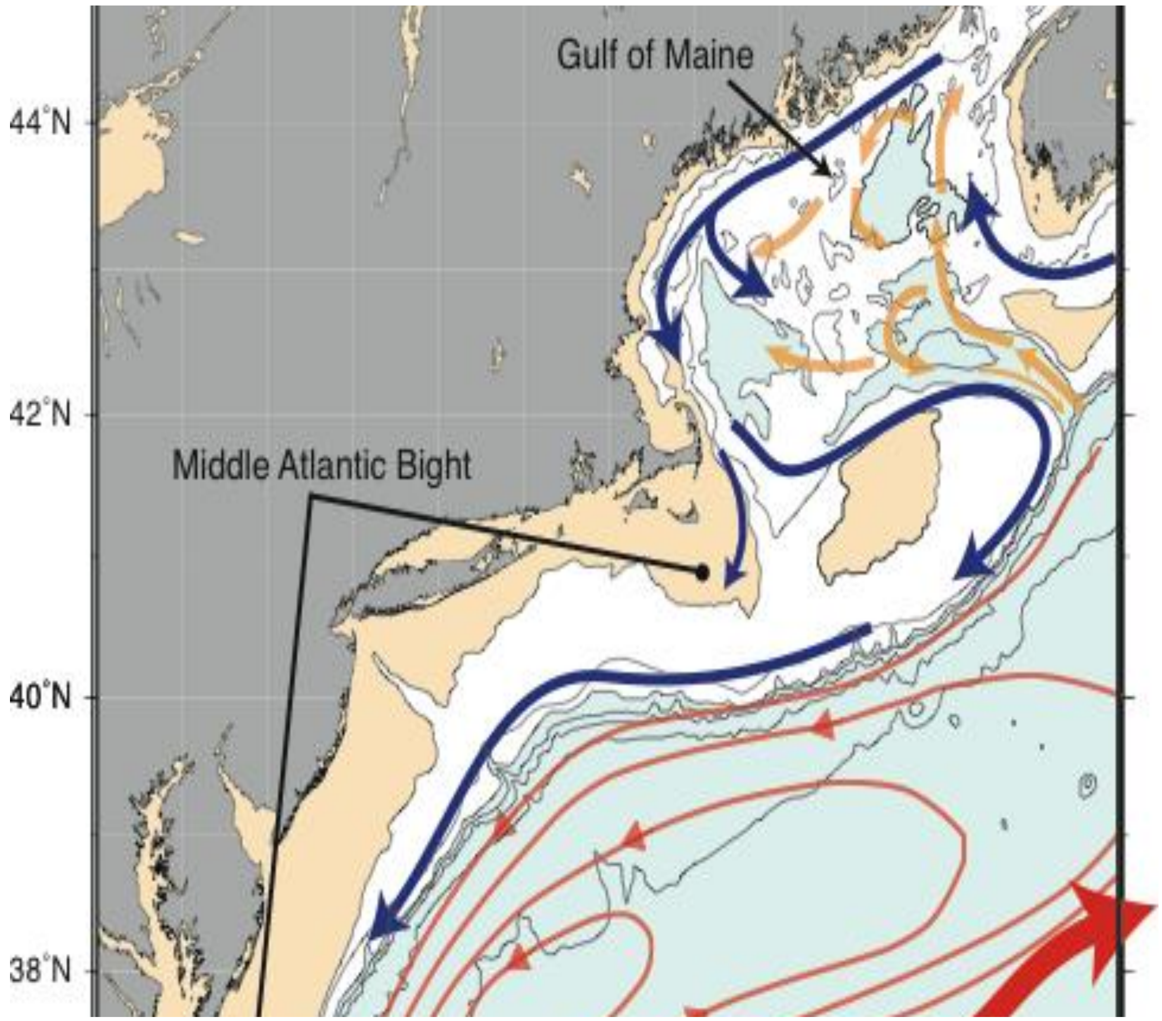


Figure 1b: Circulation schematic for the Northeast U.S. Shelf region, where blue arrows represent shelf water circulation and orange arrows represent deeper slope water circulation pathways. Water depths deeper than 200 meters are shaded blue. Water depths shallower than 50 meters are shaded tan.

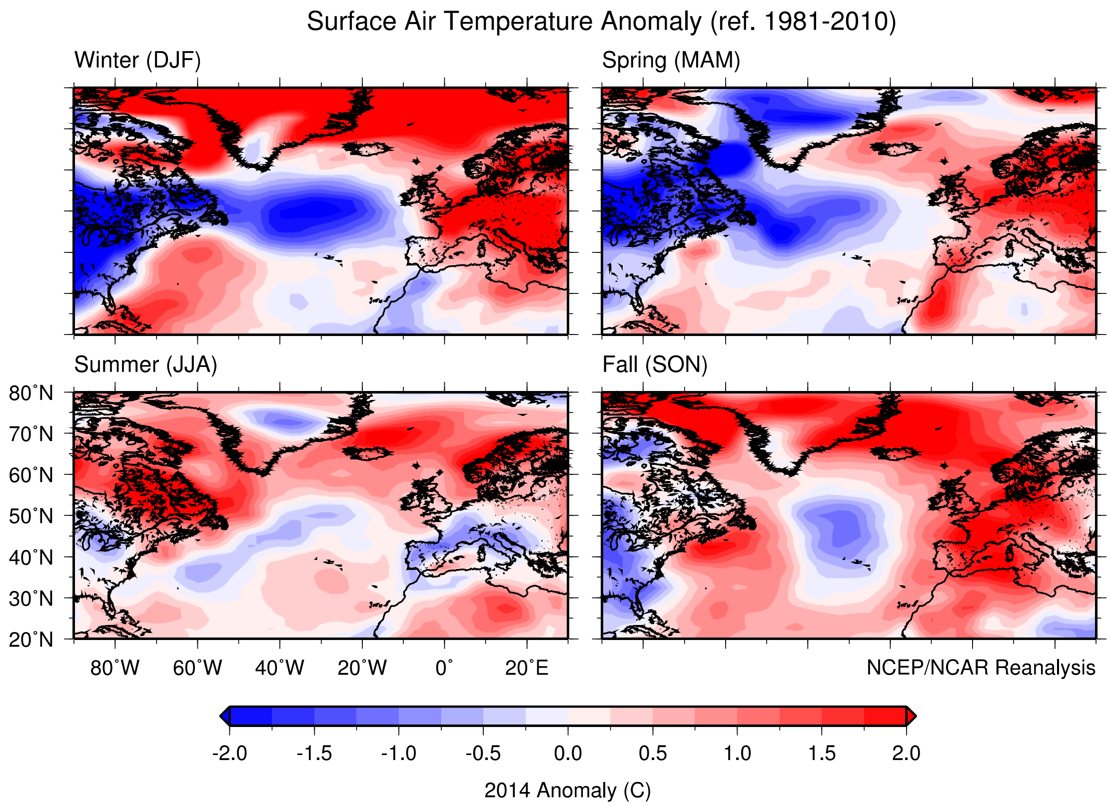


Figure 2: Surface air temperature anomaly derived from the NCEP/NCAR Reanalysis product (http://www.esrl.noaa.gov/psd/data/composites/day/). Seasons are made up of 3-month periods where winter spans December-February. Positive anomalies correspond to warming in 2014 relative to the reference period (1981-2010).

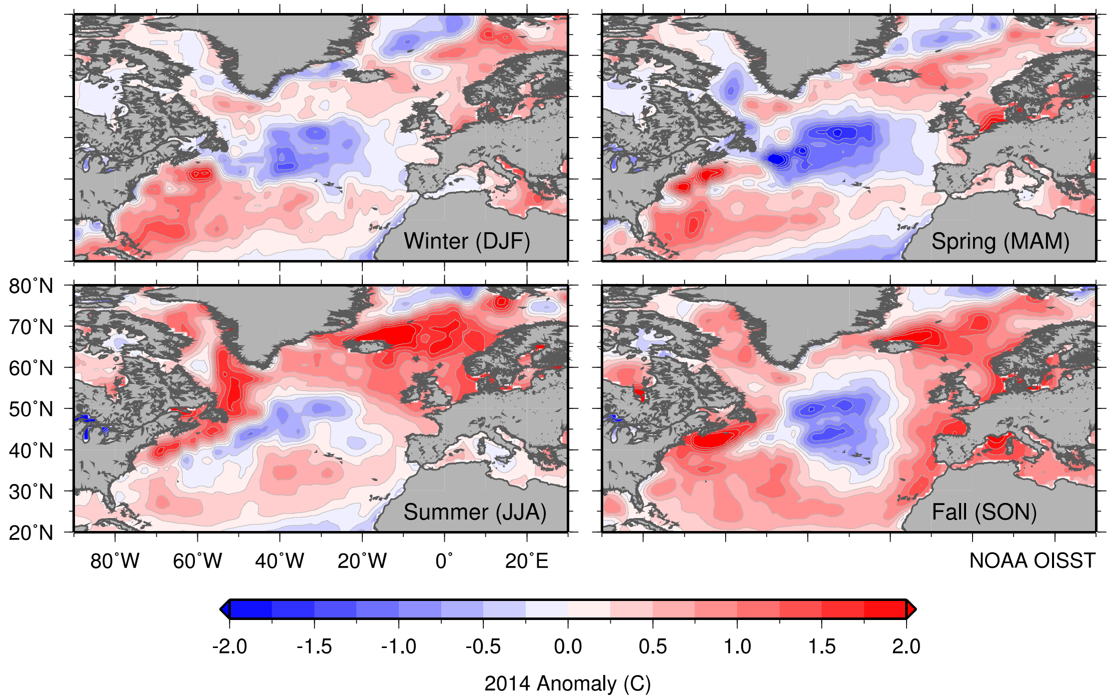
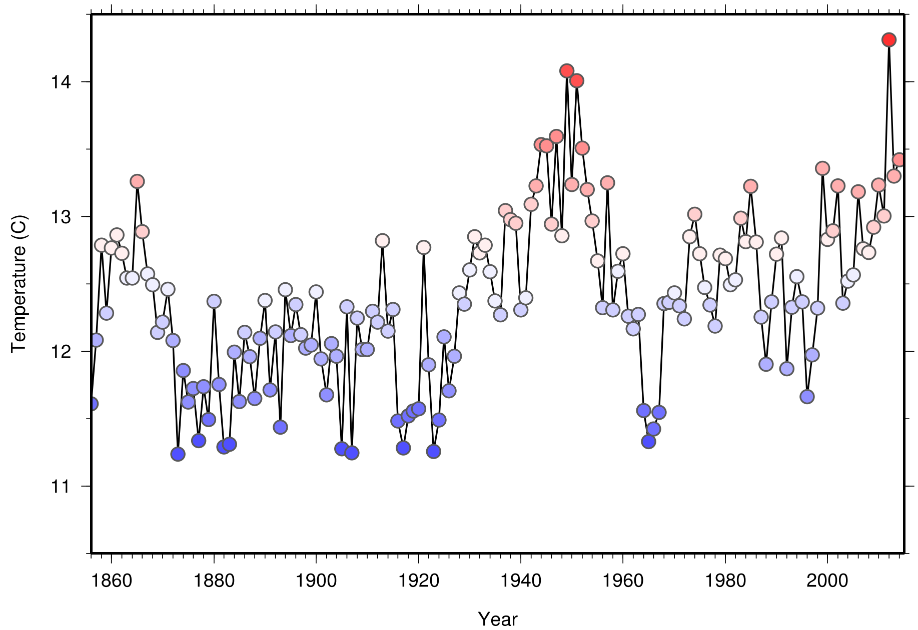


Figure 3: Sea surface temperature anomaly derived from the NOAA's Optimum Interpolation (OI) SST product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html). Seasons are made up of 3-month periods where winter spans December-February. Positive anomalies correspond to warming in 2014 relative to the reference period (1981-2010).



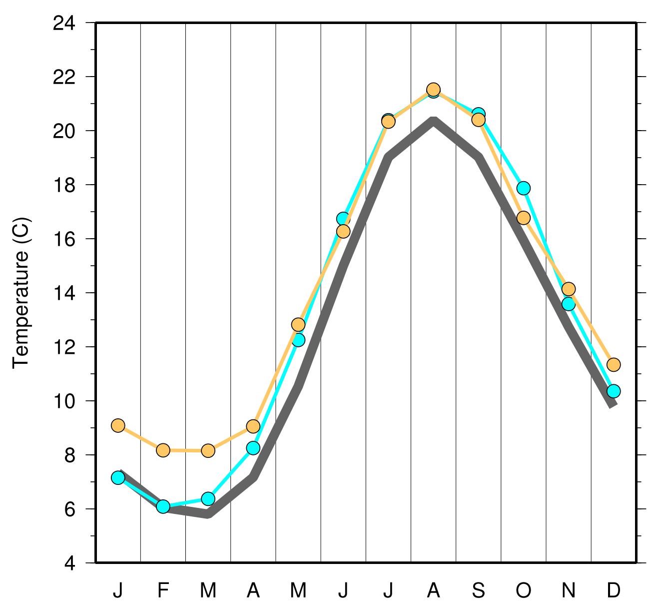


Figure 4: Top: Regional average annual sea surface temperature for the NEUS shelf region calculated from NOAA's extended reconstructed sea surface temperature product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html). Colors correspond with the anomaly scale in Figure 3. Bottom: Regional average monthly mean SST for the NEUS shelf for 2014 (cyan), 1951 (orange) and 1981-2010 (gray) calculated from the same product.

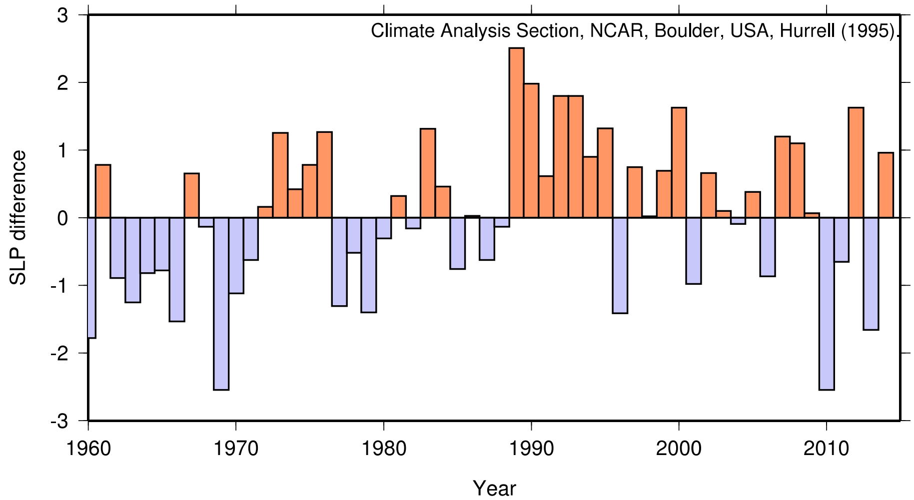


Figure 5: North Atlantic Oscillation index computed from principal component analysis of sea level pressure in the North Atlantic (see Hurrell, 1995).

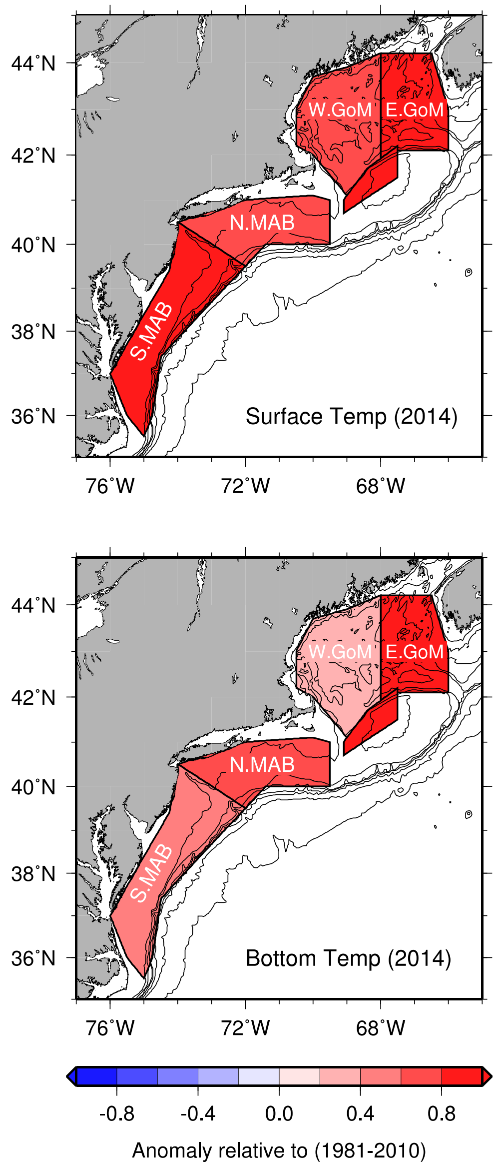


Figure 6: Surface (upper panel) and bottom (lower panel) regional annual temperature anomaly (°C). Positive anomalies correspond to warming in 2014 relative to the reference period (1981-2010). The region labels correspond to the panels in Figure 7.

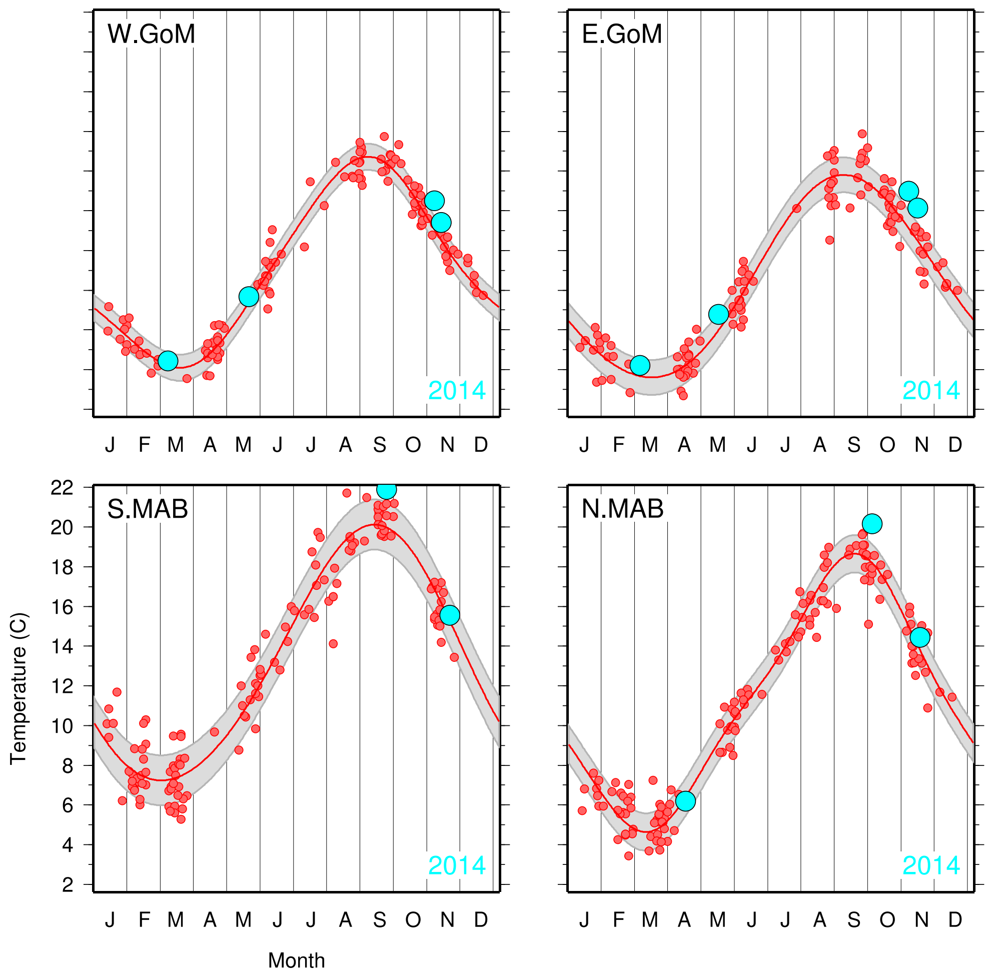


Figure 7a: Regional average 0-30 meter temperature (°C) as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 6. An annual harmonic fit to the regional average temperatures from 1981-2010 is 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 2014 surveys are shown in cyan.

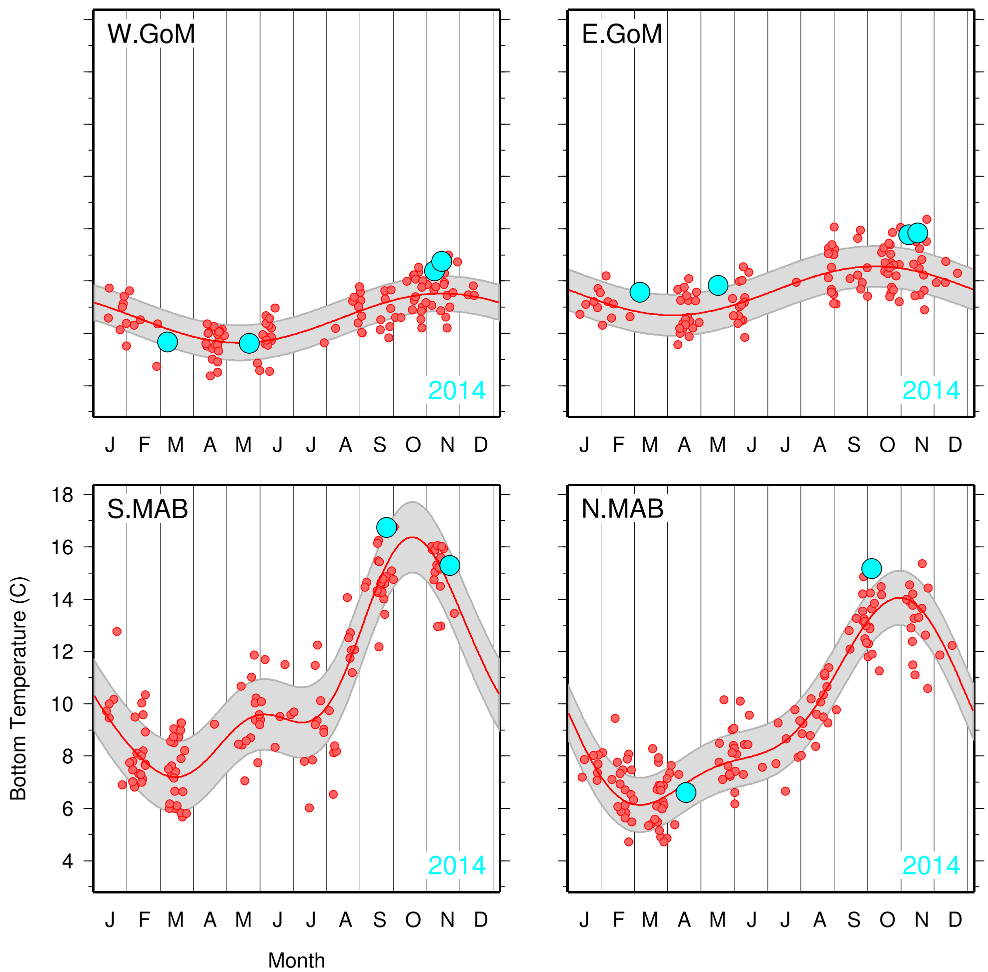


Figure 7b: As in Figure 7a, but for bottom temperatures.

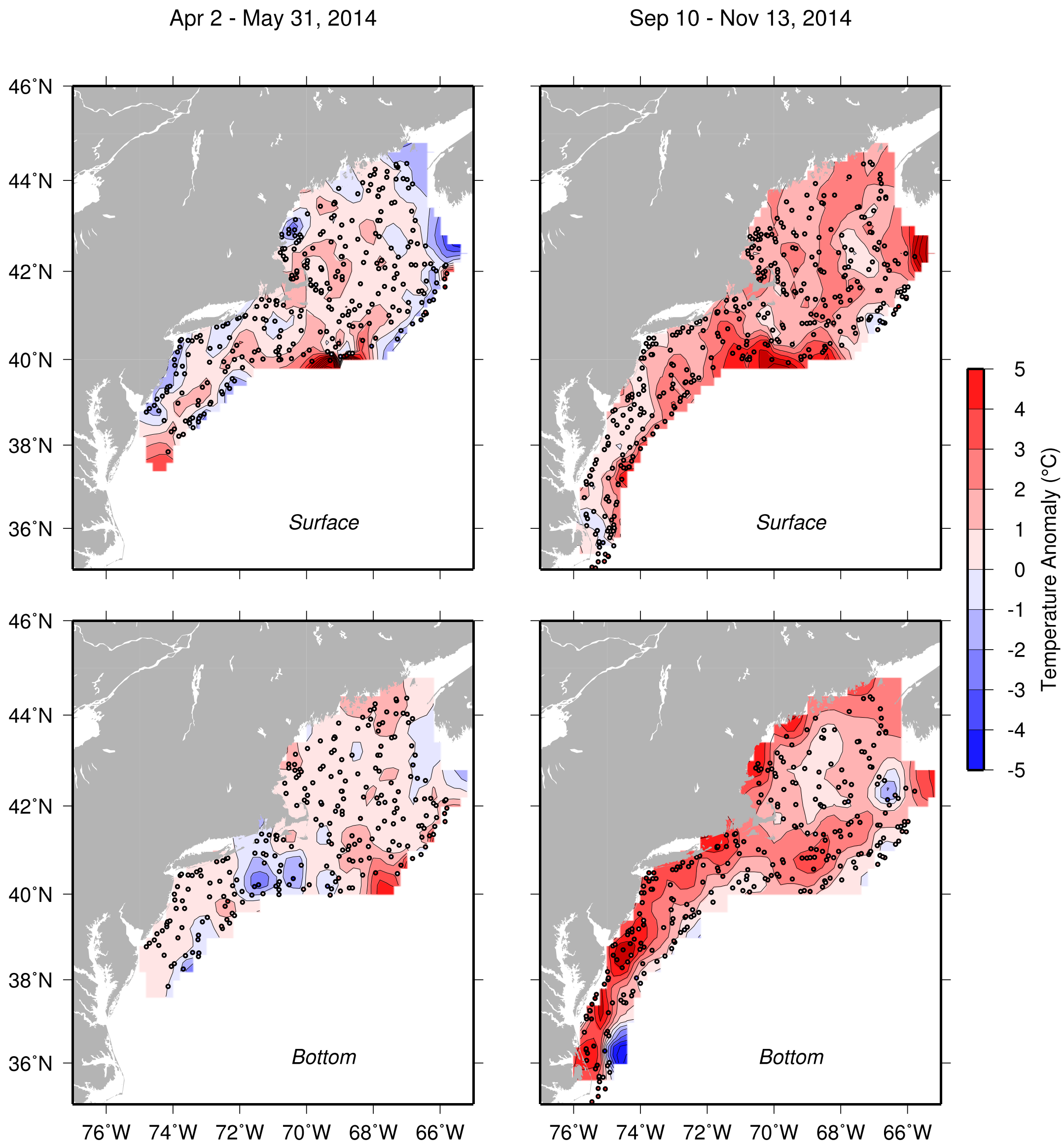


Figure 8: Surface (upper panels) and bottom (lower panels) temperature anomaly from the spring 2014 (left) and fall 2014 (right) ground fish surveys. Positive anomalies correspond to warming in 2014 relative to the reference period (1977-1987).

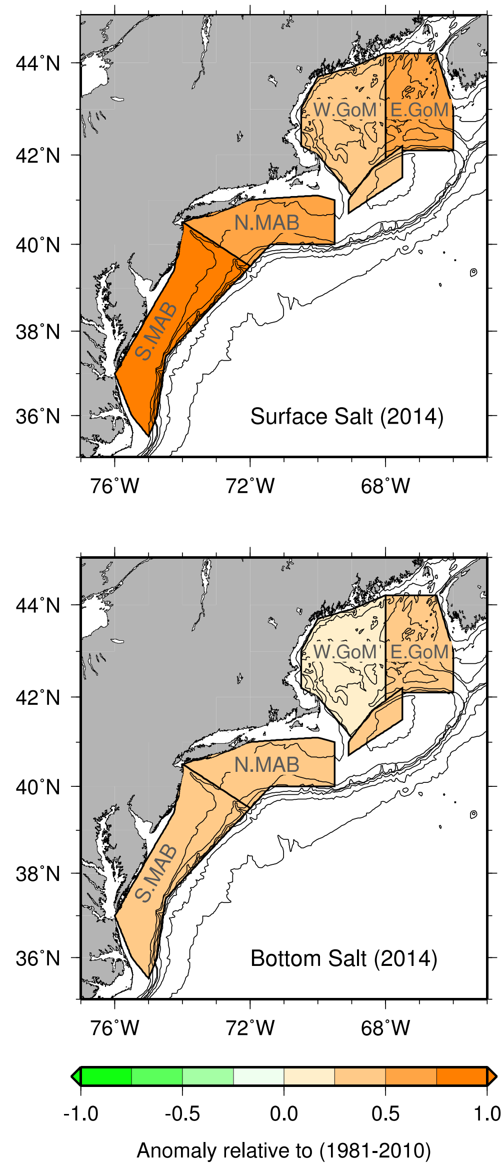


Figure 9: Surface (upper panel) and bottom (lower panel) regional annual salinity anomaly. Positive anomalies correspond to more saline conditions in 2014 relative to the reference period (1981-2010). The region labels correspond to the panels in Figure 10.

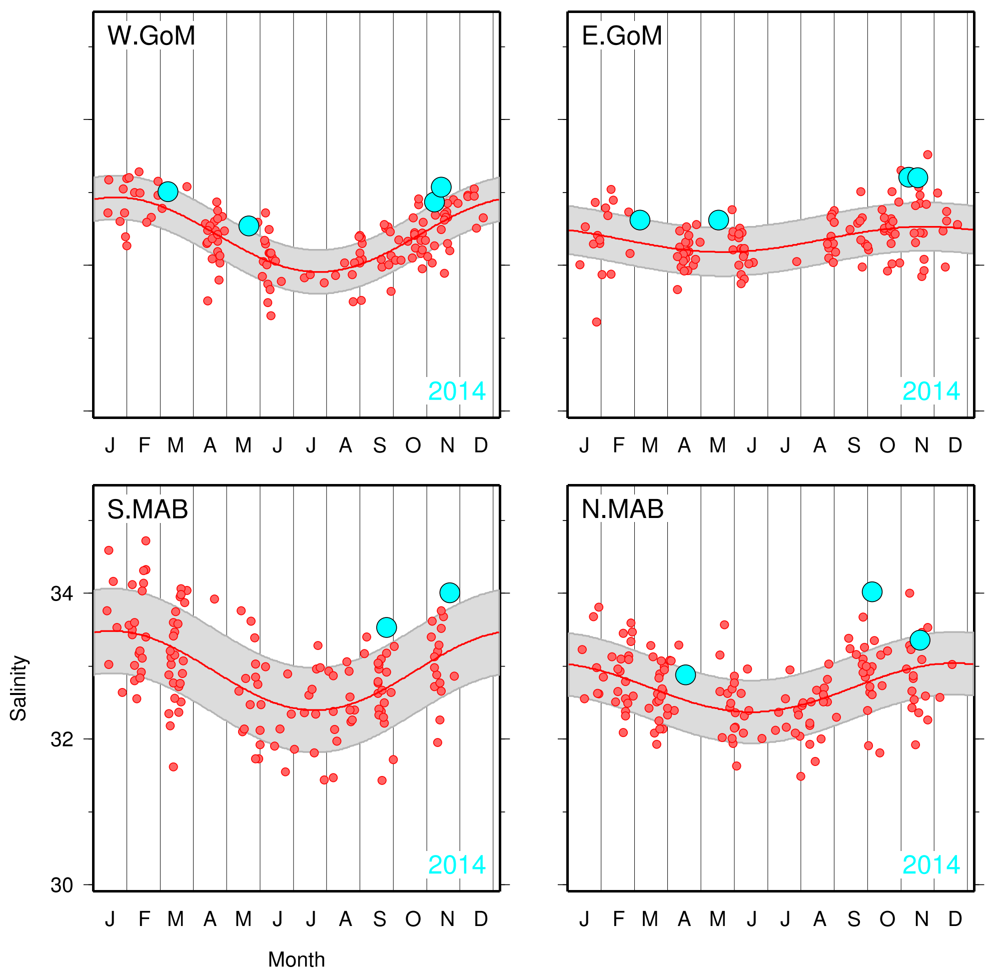


Figure 10a: Regional average 0-30 meter salinity as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 9. An annual harmonic fit to the regional average salinities from 1981-2010 is shown by 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 2014 surveys are shown in cyan.

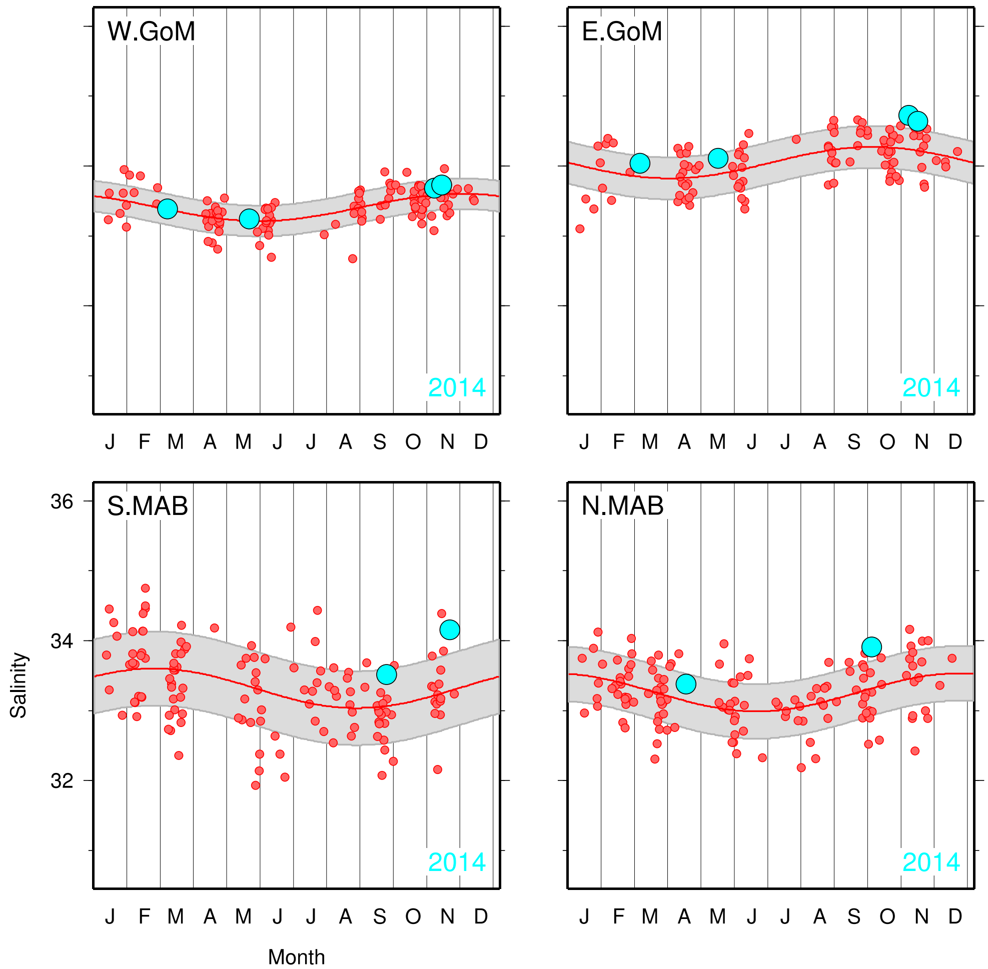


Figure 10b: As in Figure 10a, but for bottom salinities.

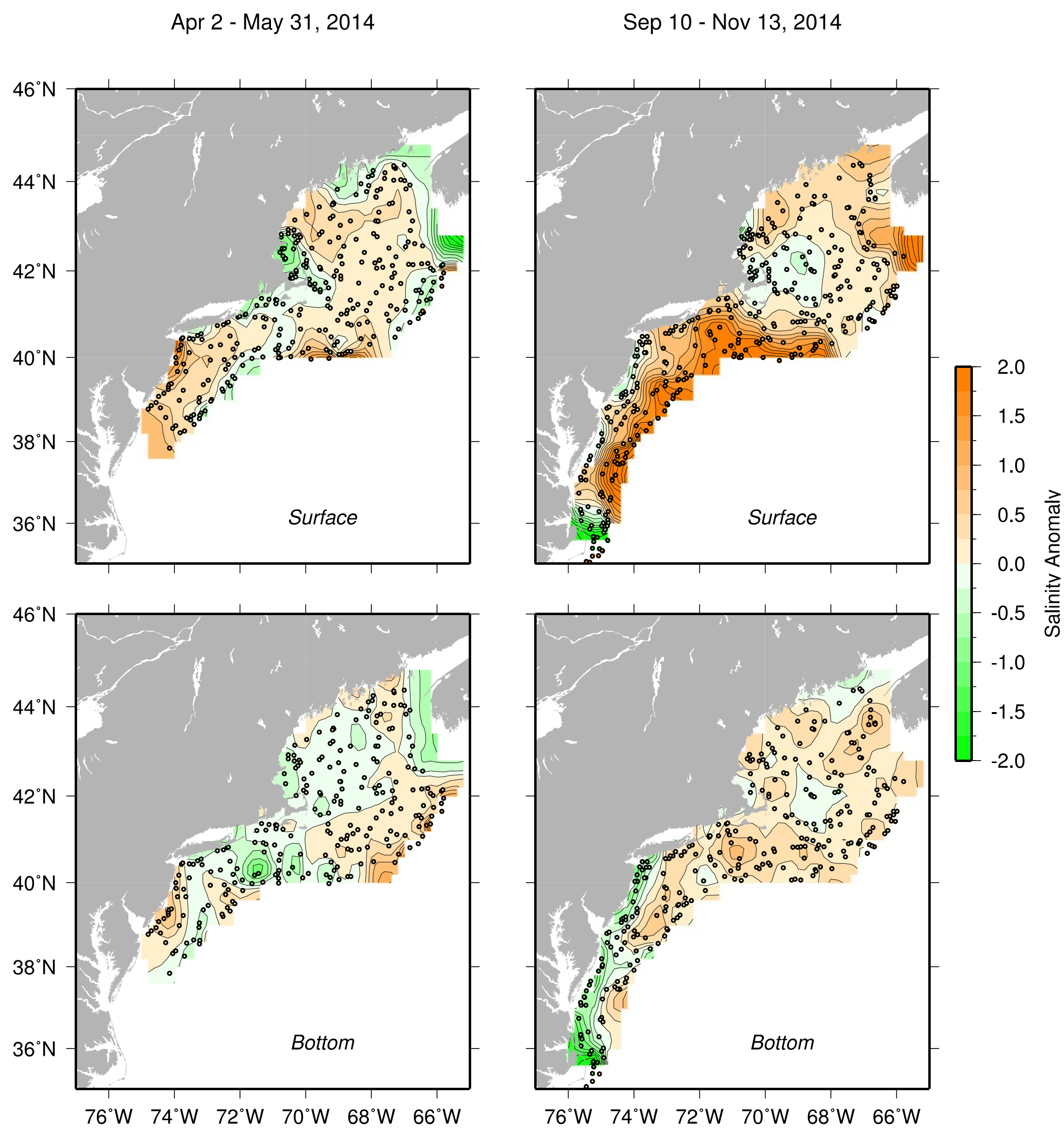


Figure 11: Surface (upper panels) and bottom (lower panels) salinity anomaly from the spring 2014 (left) and fall 2014 (right) ground fish surveys. Positive anomalies correspond to more saline conditions in 2014 relative to the reference period (1977-1987).

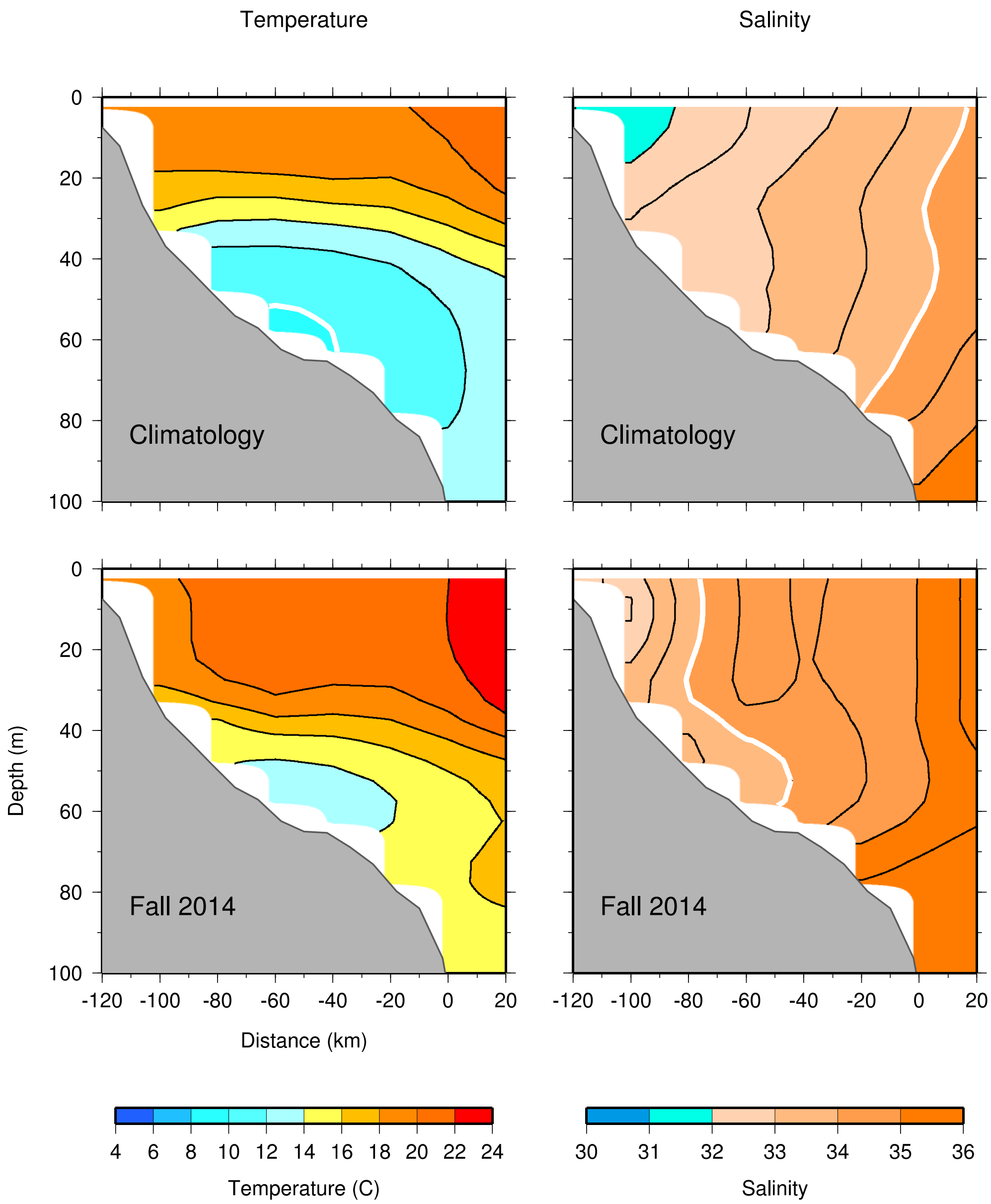


Figure 12a: Vertical sections of temperature (left) and salinity (right) crossing the continental shelf in the Middle Atlantic Bight. The top panels show the climatological average for September spanning the years 1981-2010. The bottom panels show the synoptic mean section for September 2014. The heavy 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.

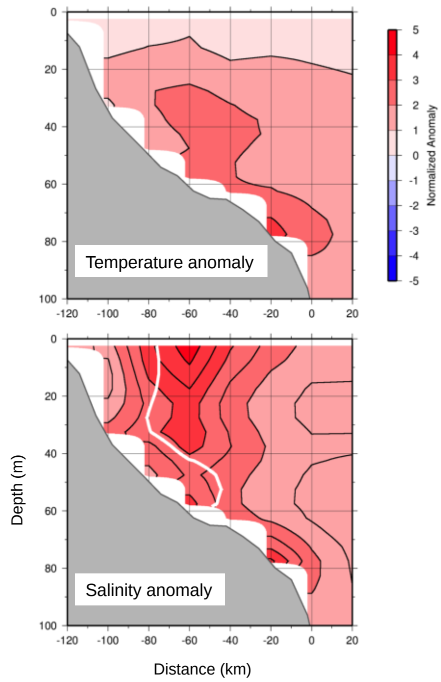


Figure 12b: Temperature (top panel) and salinity (bottom panel) anomalies associated with the vertical sections shown in Fig 12a. Positive anomalies correspond to warmer or more saline conditions in 2014 relative to the reference period (1981-2010). Anomalies have been normalized by the standard deviation of the temperature (salinity) over the reference period.

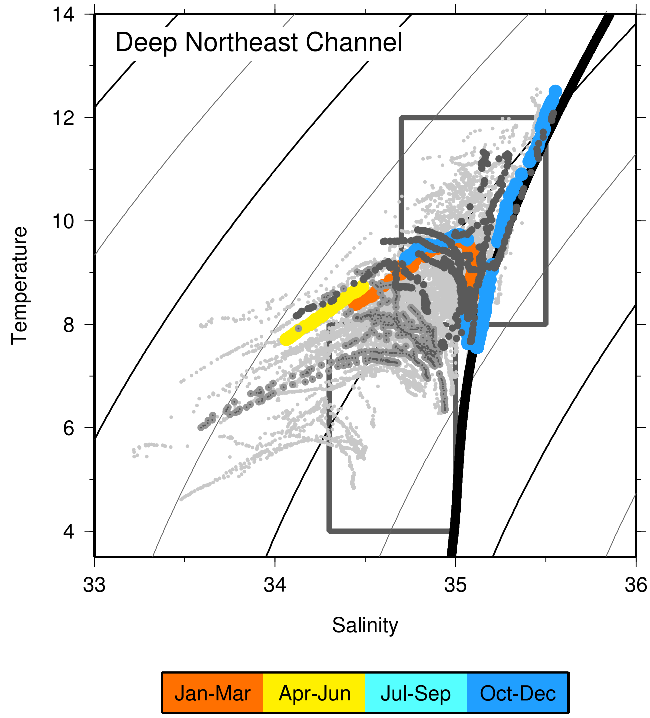


Figure 13: Temperature-salinity diagram showing water properties of the deep inflow to the Gulf of Maine, taken from 150-200 meter depth in the Northeast Channel. Observations from 2014 (colored), 2012 (darkest gray) and 2008 (medium gray) are shown. The lightest gray dots show the historical range encompassing 1981-2010. The heavy black curve is the standard T-S curve constructed by Armi and Bray (1982) for western North Atlantic Central Water, which we take to be representative of Gulf Stream water. The two boxes outline the range of temperature and salinity typically attributed to Warm Slope Water (warmer/saltier) and Labrador Slope Water (colder/fresher).

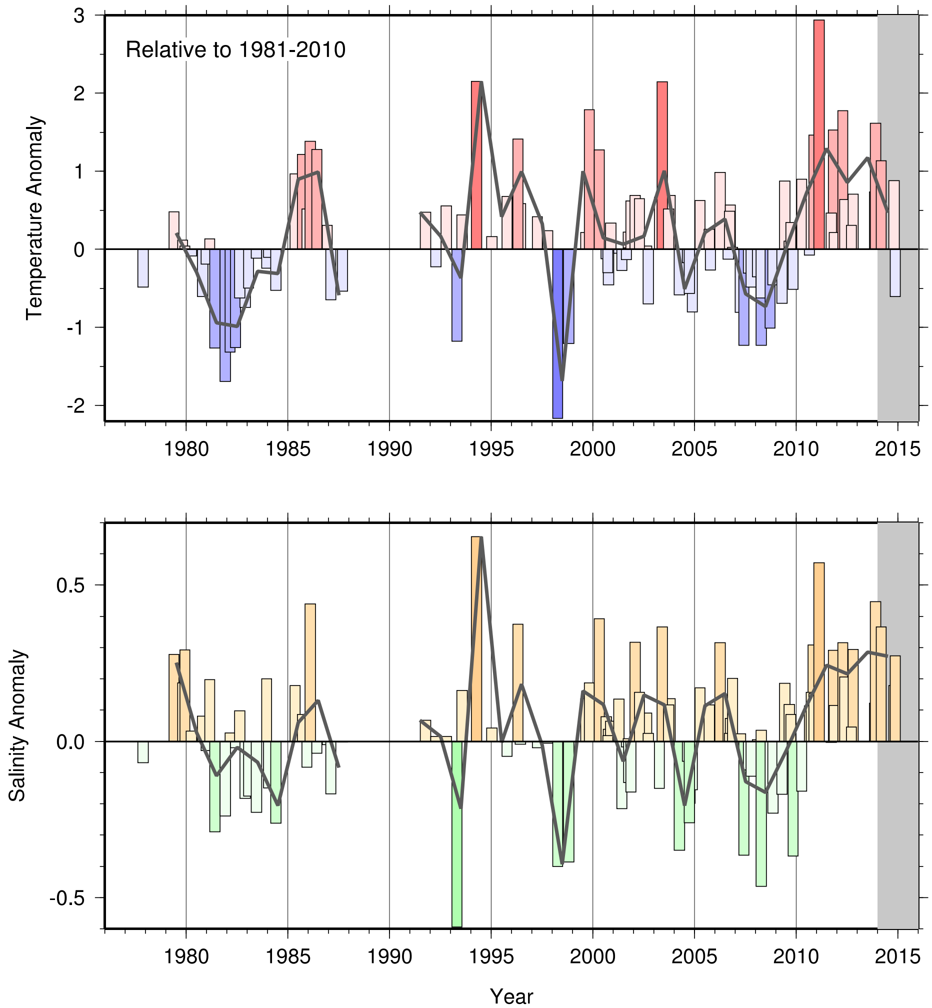


Figure 14: Time series of temperature and salinity anomaly in the deep Northeast Channel. Each bar represents a volume-weighted average of all observations from a single survey collected between 150-200 meters in the Northeast Channel. The grey curve shows the annual average anomaly time series. Positive values are warmer and saltier than the long-term mean calculated for 1981-2010. The gray shading highlights sampling done in 2014.

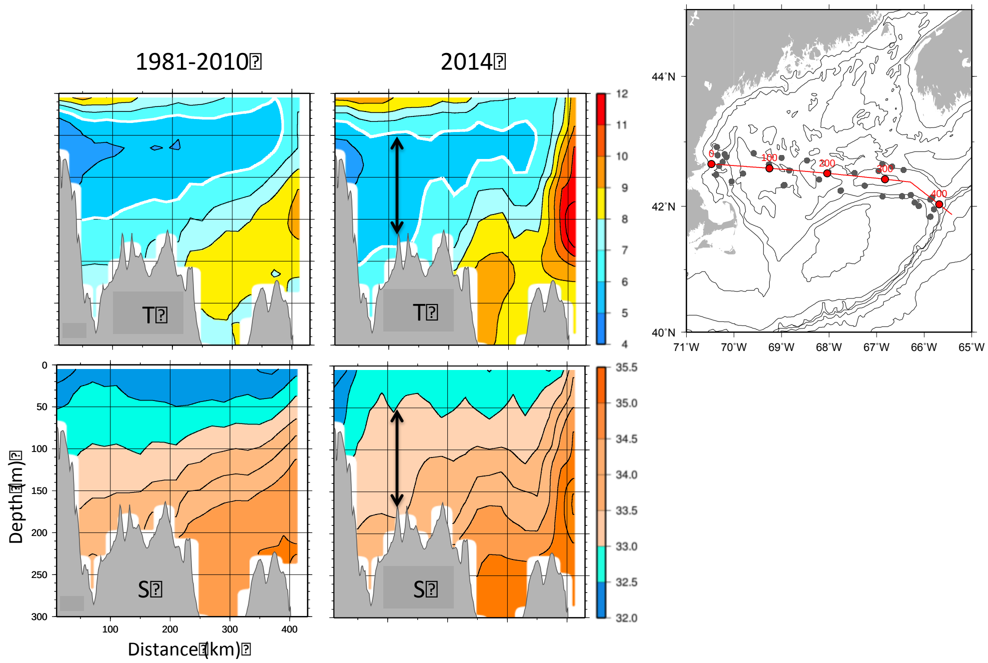


Figure 15: Vertical sections of temperature (top) and salinity (bottom) crossing the Gulf of Maine along a zonal transect shown in the map. The left panels show the climatological average for May spanning the years 1981-2010. The bottom panels show the synoptic mean section for May 2014. The heavy white contour highlights the 6°C isotherm as an indicator of the boundary of the cold intermediate layer. Along-transect distances and the May 2014 station distribution are shown on the map for reference.

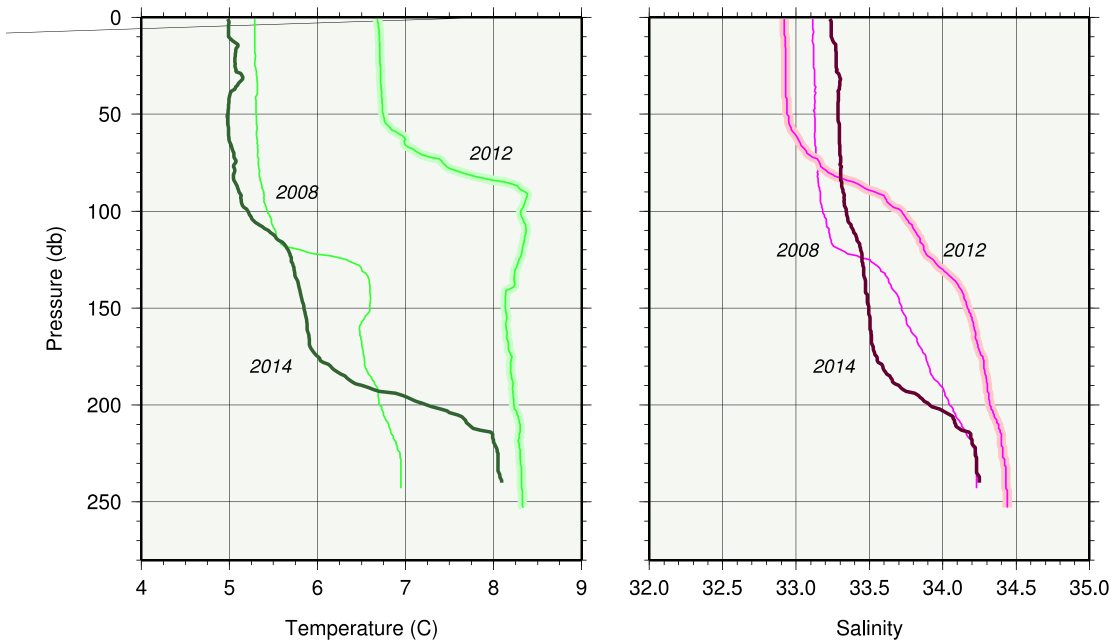


Figure 16: Average vertical profiles of temperature and salinity collected at a fixed station in Wilkinson Basin in the western Gulf of Maine. Profiles are shown from February 2008, 2012 and 2014.

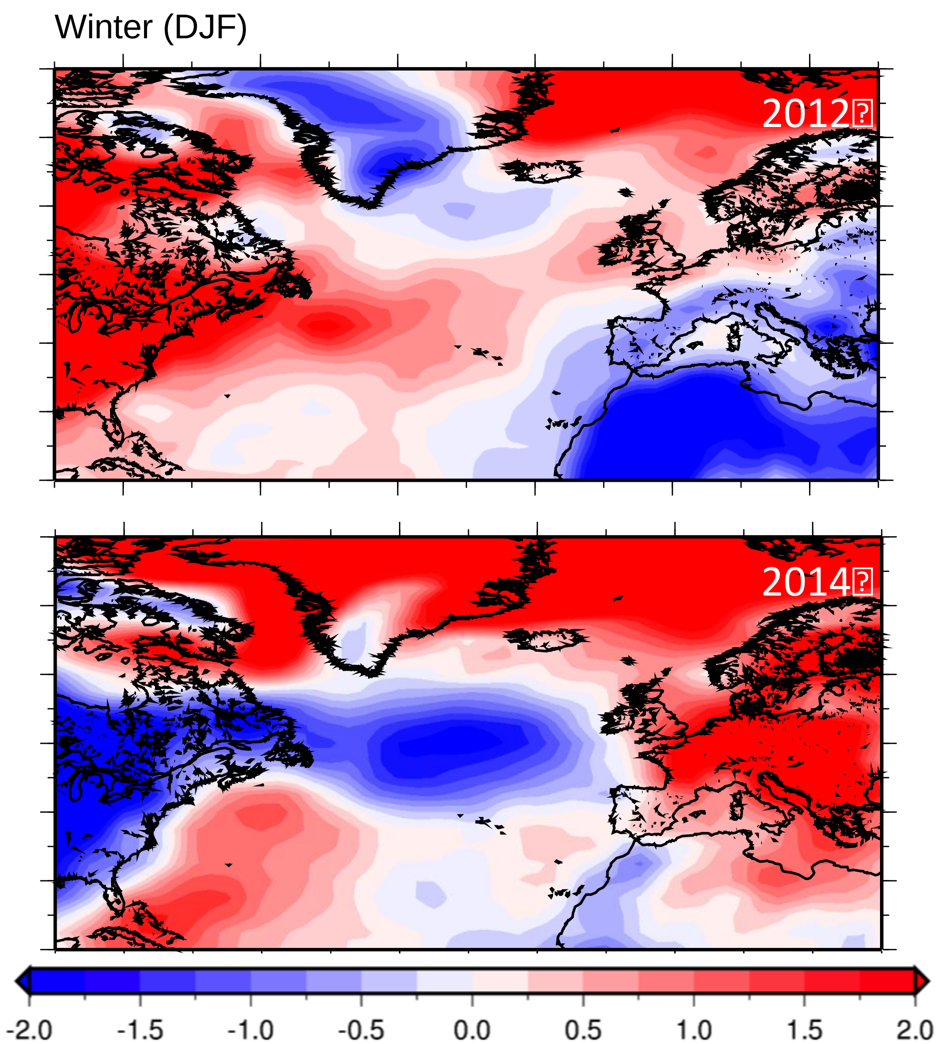


Figure 17: Winter (Dec-Feb) surface air temperature anomaly for 2012 (top) and 2014(bottom) as derived from the NCEP/NCAR Reanalysis product (http://www.esrl.noaa.gov/psd/data/composites/day/). Positive anomalies correspond to warming relative to the reference period (1981-2010).