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Hydrographic Conditions on the Northeast United States Continental Shelf in 2018 – 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 2018. 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, 2018 was characterized by warmer than average water temperatures observed everywhere except in the southern Middle Atlantic Bight. Warming was enhanced toward the north, with the largest positive anomalies observed in the Gulf of Maine. Large fresh anomalies were observed throughout the Middle Atlantic Bight during fall, consistent with the record high precipitation rates observed over this region during 2018. Overall, deep (slope) waters entering the Gulf of Maine were predominantly warmer and saltier than average, and their temperature and salinity suggest a subtropical source. Extremely warm winter air temperatures, followed by late onset storms and extreme cold during April, confined winter mixing to the western shelf and upper slope in the Gulf of Maine, leading to minimal intermediate water formation during 2018.

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, ship scheduling constraints in 2018 led to the elimination of the winter Ecosystem Monitoring (EcoMon) Survey, while mechanical issues, shipyard delays and poor weather contributed to truncation of the fall and spring ground fish surveys. Further, inclement weather and a reduction in sea day allocations led to truncated survey coverage for all 3 remaining EcoMon surveys. Overall less than half as many stations were occupied in 2018, leading to a loss of seasonal resolution particularly in the Gulf of Maine.

During 2018, hydrographic data were collected on 10 individual NEFSC cruises, amounting to 1016 profiles of temperature and salinity and 938 in NAFO subareas 5 and 6 (Table 1). Data were collected aboard the NOAA ship *Henry Bigelow,* NOAA ship *Gordon Gunter,* R/V *HR Sharp and R/V Endeavor* 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 2018 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 2018

Surface air temperatures were predominantly warmer than average (relative to 1980-2010) over the eastern United States and adjoining waters throughout 2018, with February measuring the third warmest on record (Fig 2). The Northeastern United States experienced its third warmest February since 1895. Notable exceptions include January, April and November when cooler air temperatures were observed. Sea surface temperatures were generally warmer than average in the subtropical North Atlantic and cooler than average in the subpolar North Atlantic, with this pattern being most pronounced in the second half of the year (Fig 3). Warm SST was observed along the entire east coast of the United States, except nearshore south of the Hudson River Valley during the first half of the year (Fig 3). Annually, the magnitude of the warming was comparable to that observed in the 1950s (Fig 4). A series of winter storms impacted the east coast of the United States during March, bringing heavy snow, strong winds and coastal flooding. Higher than average rainfall during August, followed by the passage of Hurricane Florence in September, resulted in record high precipitation rates in 2018 over the Mid-Atlantic states.

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 winter NAO index was weekly negative during 2018, ending a period of four consecutive years of strongly positive conditions (Fig. 5). While this is indicative of a weakening of both the subpolar (Icelandic) low and the subtropical (Azores) high, the 2018 distribution of sea level pressure anomalies did not resemble a typical NAO pattern (IROC, 2019). A negative NAO is typically associated with a more zonally oriented atmospheric Jet Stream and North Atlantic storm track, stronger cold-air outbreaks and increased storminess over eastern North America

Hydrographic Conditions in 2018

Relative to historical values, regional ocean temperatures on the NEUS Shelf were generally warmer than normal in the north and slightly cooler than normal in the south during 2018 (Fig. 6). Annually, upper ocean temperatures were between 0.5-1.9°C warmer than normal everywhere except in the southern Middle Atlantic Bight, with the largest anomalies observed in the Gulf of Maine. Annual anomalies are consistent with seasonal conditions in most regions, suggesting that no one season dominates the annual mean. Of the seasons sampled, warming was most pronounced during spring in the Gulf of Maine and during summer on Georges Bank, where regional temperature anomalies exceeded 1 standard deviation (Fig. 7a). The exception was that cold conditions were observed in the southern Middle Atlantic Bight during 2018, with the annual mean being dominated by cold conditions in September. Similar patterns were observed near the bottom, with warm conditions over most of the region except the southern Middle Atlantic Bight (Fig. 7b). During summer, the bottom temperature measured more than one standard deviation above normal in the northern Middle Atlantic Bight, while similarly large anomalies were observed near bottom in the western Gulf of Maine year-round. Cold anomalies were observed during fall near the bottom in the southern Middle Atlantic Bight. The details of the seasonal differences are revealed in synoptic maps compiled from the spring and fall ground fish surveys (Fig 8). The pattern of warm anomalies in the north and cold anomalies in the south was evident in spring, particularly at the surface. Surface temperatures were predominantly warm across the entire shelf in fall while notable warm anomalies were observed nearshore and cold anomalies were observed along the outer shelf south of Chesapeake Bay at the bottom during fall.

Annually, surface waters in the upper 30 meters were slightly saltier than normal in the northern Middle Atlantic Bight and eastern Gulf of Maine and near normal to slightly fresh elsewhere (Fig. 9). Seasonally, large positive anomalies (exceeding one standard deviation) were observed during April/May in the eastern Gulf of Maine. Notably fresh conditions were observed in the southern Middle Atlantic Bight during summer/fall, dominating the annual mean (Fig 10a). These large fresh anomalies are linked to anomalous precipitation: 2018 was the 14th warmest and 3rd wettest year on record for the continental U.S., with four major storms impacting the US east coast during March and one major hurricane delivering record flooding in the southeastern U.S. (NOAA-NCEI, 2019). Bottom waters in the eastern Gulf of Maine were saltier than average during March (the only season sampled), while near normal conditions were observed elsewhere (Fig. 9 and 10b). Bottom water conditions were more seasonally variable in the Middle Atlantic Bight, with slightly fresh conditions in the northern Middle Atlantic Bight reflecting anomalously fresh conditions in November (Fig 10b). Synoptically, saline conditions were pervasive during spring throughout the Gulf of Maine and on Georges Bank, with extremely fresh anomalies concentrated nearshore in the western Gulf of Maine (Fig 11). During fall, notably fresh anomalies were observed throughout the Middle Atlantic Bight near the bottom and at the surface south of Delaware Bay.

Deep inflow through the Northeast Channel continues to be dominated by Warm Slope Water (Fig. 12a,b). During spring, the water crossing the sill in the Northeast Channel was more than 3°C warmer than average conditions (Figure 15). Springtime temperature-salinity and temperature-depth profiles indicate the Cold Intermediate Layer, a mid-depth water mass formed seasonally as a product of convective mixing driven by winter cooling, is confined to the western slope of Wilkinson Basin in the western Gulf of Maine (Fig. 13-15). The Cold Intermediate Layer is collocated with very fresh water over the western shelf and extends 50 meters deeper on the western slope than is seen in the climatological average (Fig. 15). On average, air temperatures were mild over the continent in March. However, there were several significant snow and wind events during four nor'easters that influenced this region during the month and anomalously cold air temperatures were observed over land in April. It is expected that extremely warm air temperatures over the North American continent during February suppressed wintertime convective mixing in the western Gulf of Maine, but that the series of vigorous storms in March and extremely cold conditions in April drove convective mixing on the western shelf (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 ~.03-.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 have experienced change on a variety of temporal and spatial scales, with the potential to drive changes in distribution and abundance. On shorter timescales, observations suggest that the NEUS Continental Shelf is being influenced more frequently by the Gulf Stream (Gawarkiewicz et al., 2018) 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

- Atmospheric conditions in 2018 were very warm and wet
- Waters on the Northeast U.S. Continental Shelf were warmer than average except in the southern Middle Atlantic Bight
- Large fresh anomalies observed in the southern Middle Atlantic Bight are linked to anomalous precipitation
- A deep Cold Intermediate Layer was observed trapped along the western shelf and slope bordering Wilkinson Basin, suggesting that cooling and convective overturn may have been constrained to the continental shelf

- Deep waters entering the Gulf of Maine continue to be warm and salty, suggestive of a southern source

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Table 1. Inventory of hydrographic monitoring on the Northeast U.S. Shelf during 2018

Sub-area	Division(s)	Month(s)	Type[1]	Description	Station count
5	Y,Z	4,5	S	Bottom trawl survey	132
5	Y,Z	5,6	S	Ecosystems monitoring survey	108
5	Y,Z	5,6	O	Sea scallop survey	37
5	Y,Z	6,7	O	ECOA-OAP	16
5	Y,Z	8	S	Ecosystems monitoring survey	42
5	Y,Z	8	O	Mesopelagic/Deep Sea survey	11
5	Y,Z	8,9,10,11	S	Bottom trawl survey	175
5	Y,Z	11	S	Ecosystems monitoring survey	9
6	A,B,C	3,4	S	Bottom trawl survey	128
6	A,B,C	5	S	Ecosystems monitoring survey	28
6	A,B,C	5	O	Sea scallop survey	12
6	A,B,C	7	O	ECOA-OAP	4
6	A,B,C	8	S	Ecosystems monitoring survey	48
6	A,B,C	9	S	Bottom trawl survey	135
6	A,B,C	11	S	Ecosystems monitoring survey	53

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

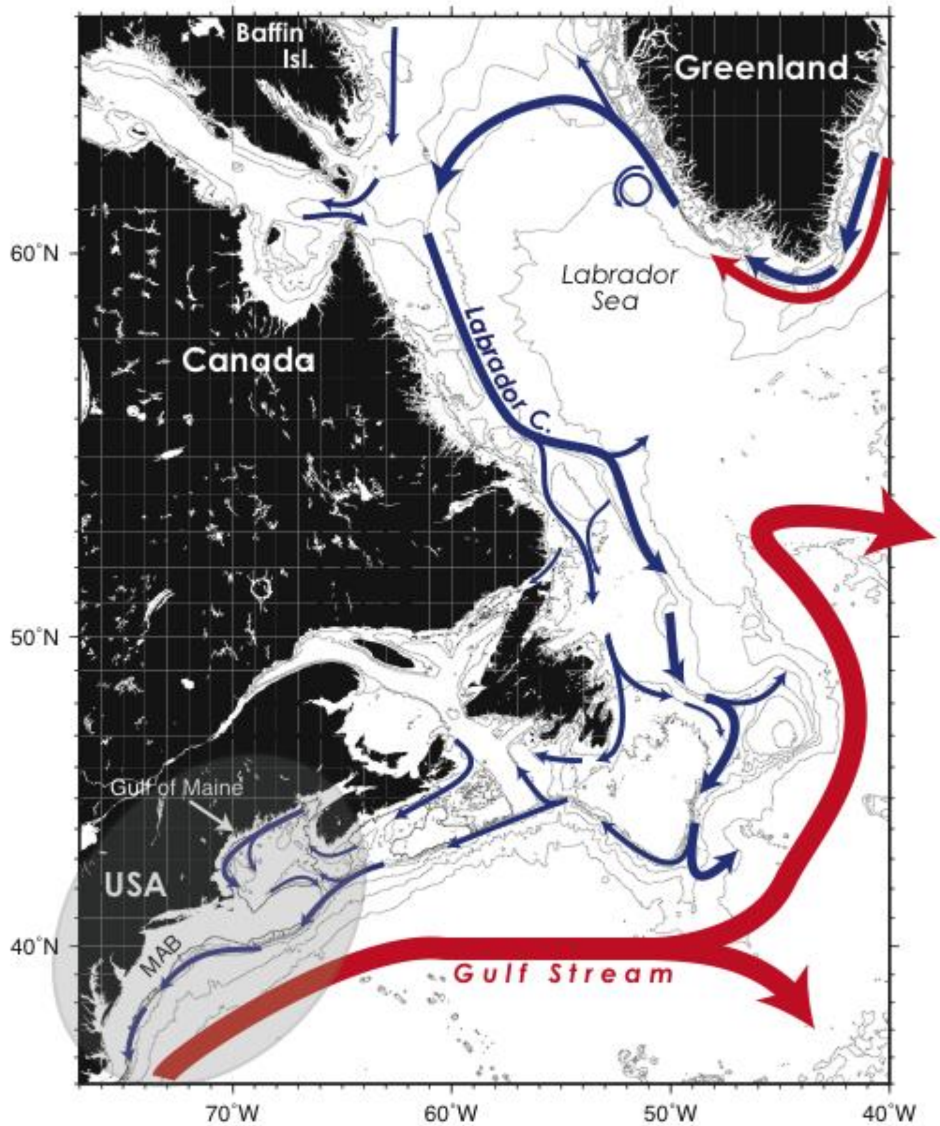

Figure 1a. Circulation schematic of the western North Atlantic. The Northeast U.S. Shelf region is identified by the shaded oval. The 100, 200, 500, 1000, 2000, 3000 and 4000 meter isobaths are shown.

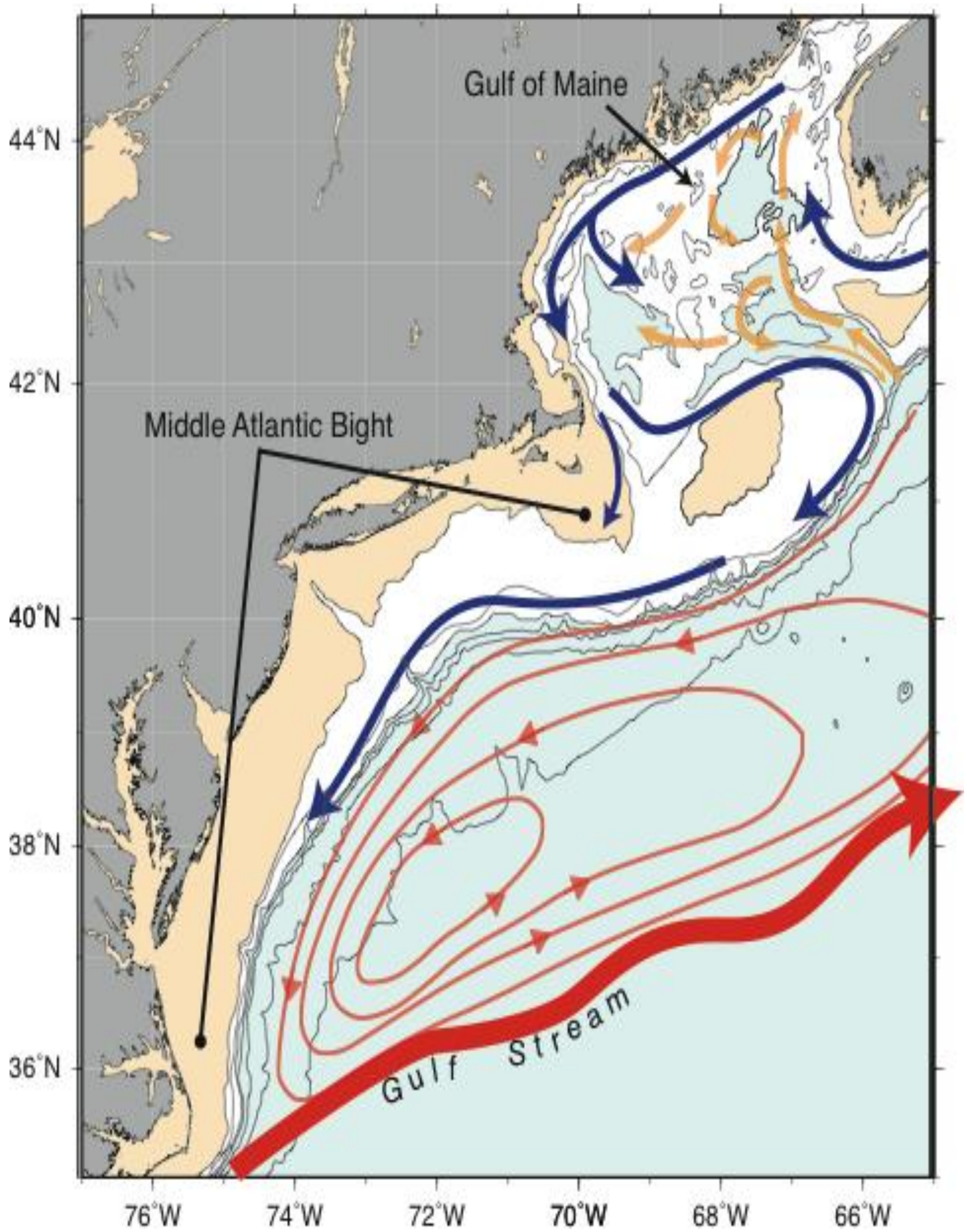

Figure 1b. Circulation schematic for the Northeast U.S. Shelf region, where blue arrows represent shelf water circulation and orange arrows represent deeper slope water circulation pathways. Water depths deeper than 200 meters are shaded blue. Water depths shallower than 50 meters are shaded tan.

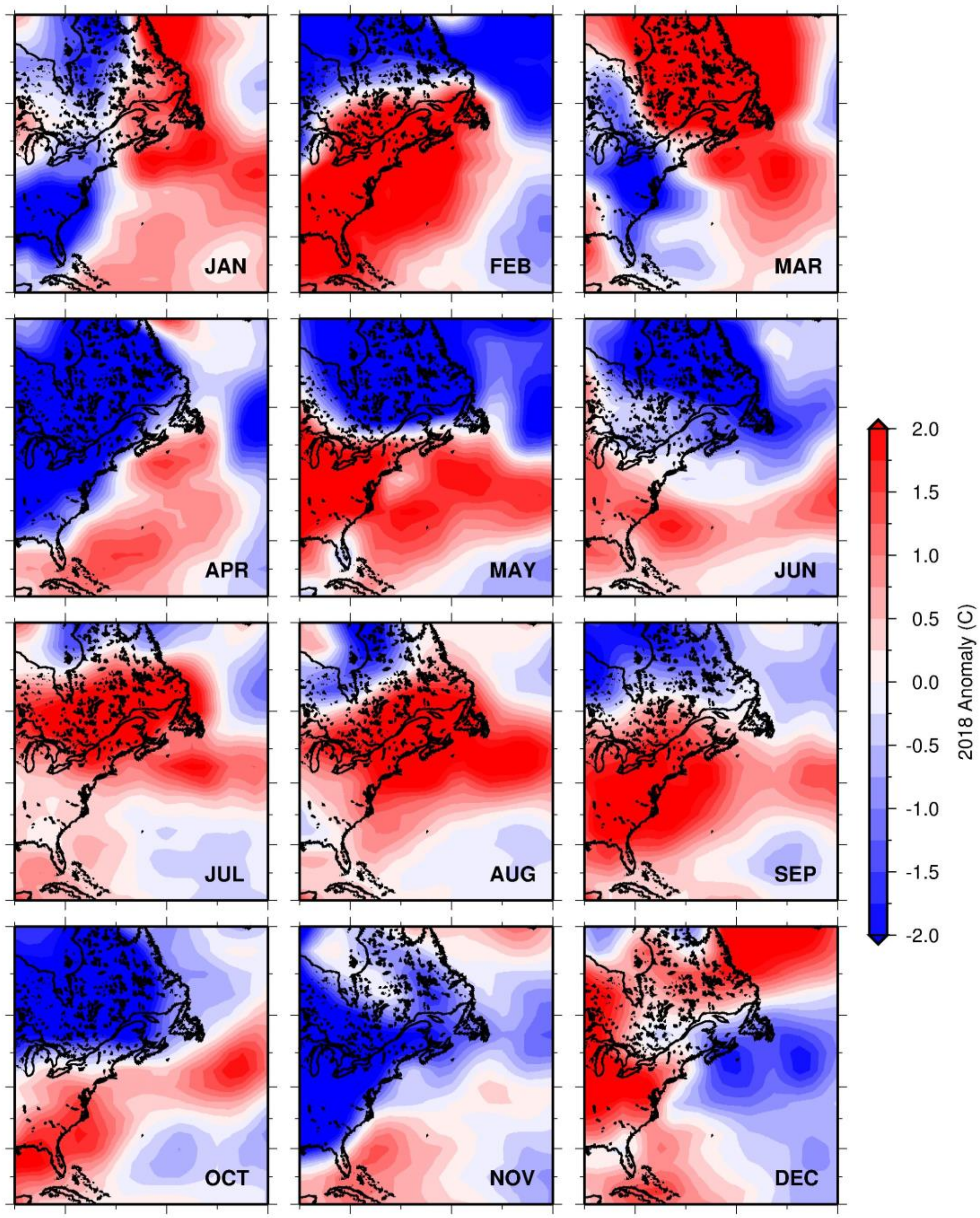

Figure 2. Surface air temperature anomaly derived from the NCEP/NCAR Reanalysis product (http://www.esrl.noaa.gov/psd/data/composites/day/). Positive anomalies correspond to warming in 2018 relative to the reference period (1981-2010).

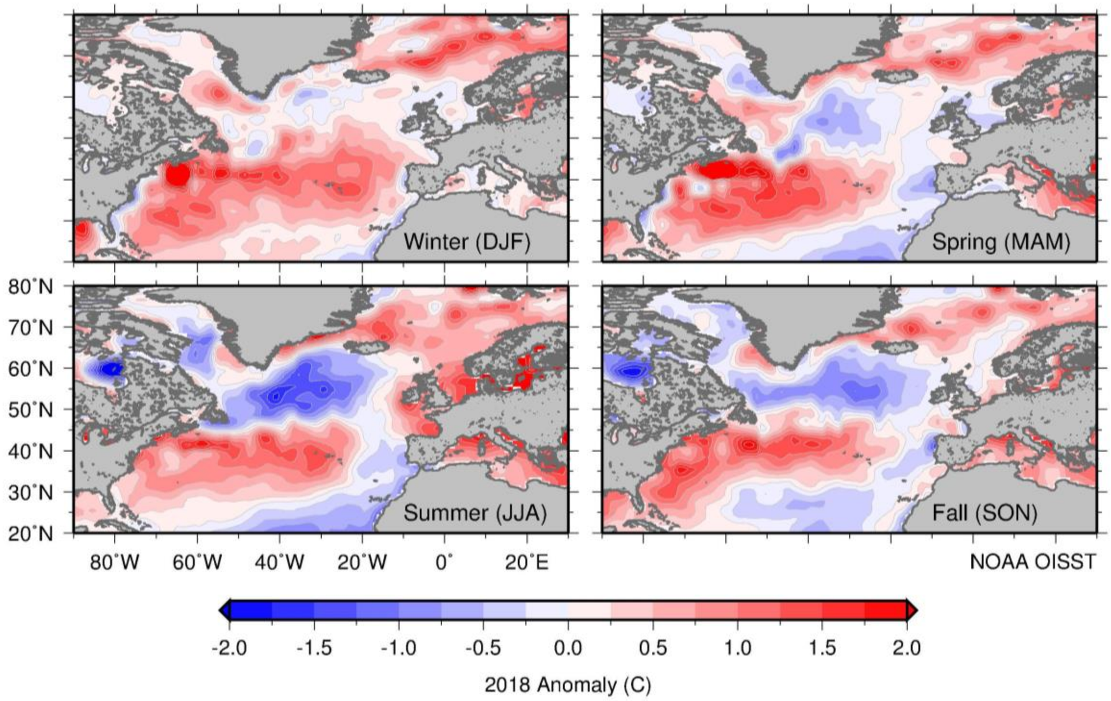

Figure 3. Sea surface temperature anomaly derived from the NOAA's Optimum Interpolation (OI) SST product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html). Seasons are made up of 3-month periods where winter spans December-February. Positive anomalies correspond to warming in 2018 relative to the reference period (1981-2010).

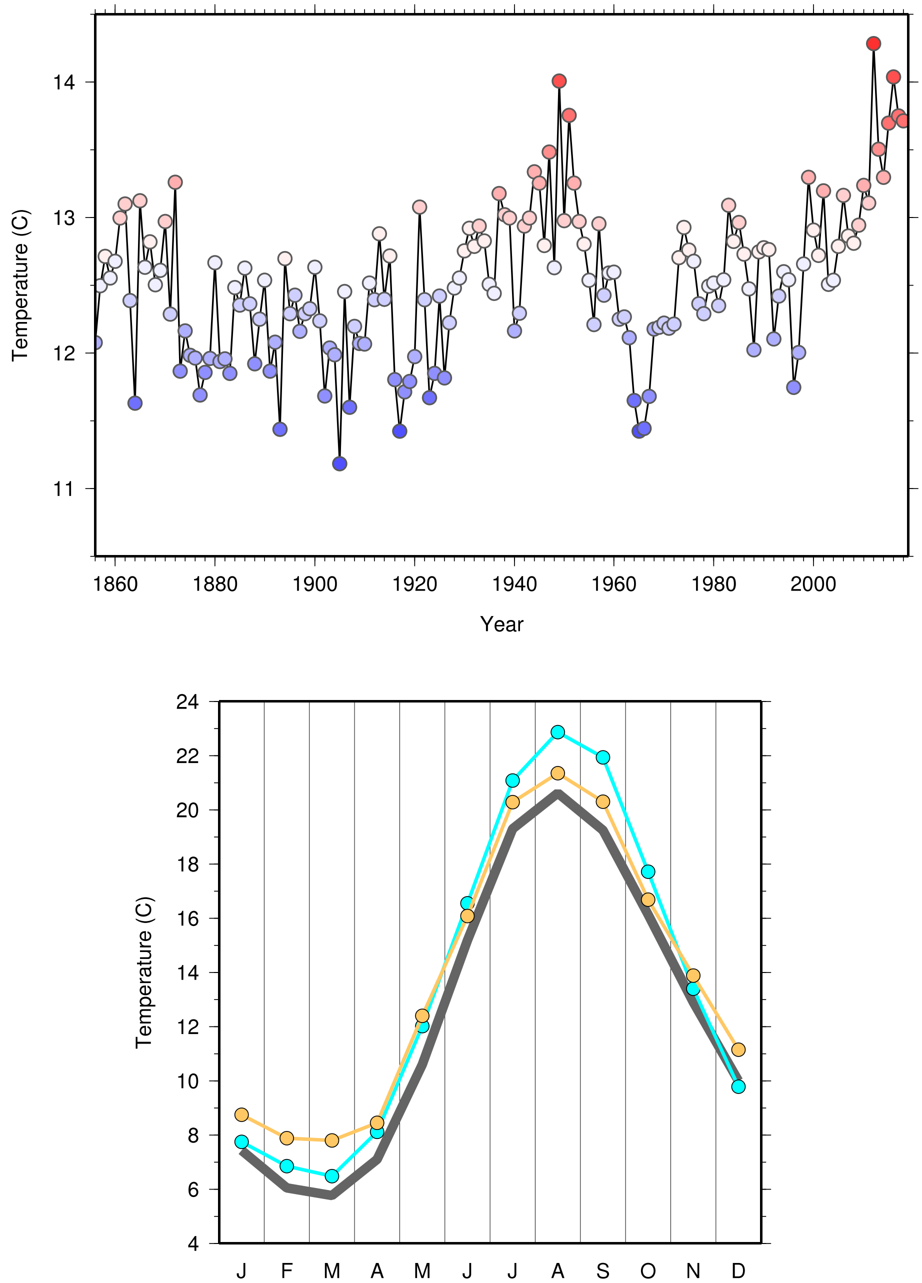

Figure 4. Top: Regional average annual sea surface temperature for the NEUS shelf region calculated from NOAA's extended reconstructed sea surface temperature product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html). Colors correspond with the anomaly scale in Figure 3. Bottom: Regional average monthly mean SST for the NEUS shelf for 2018 (cyan), 1951 (orange) and 1981-2010 (gray) calculated from the same product.

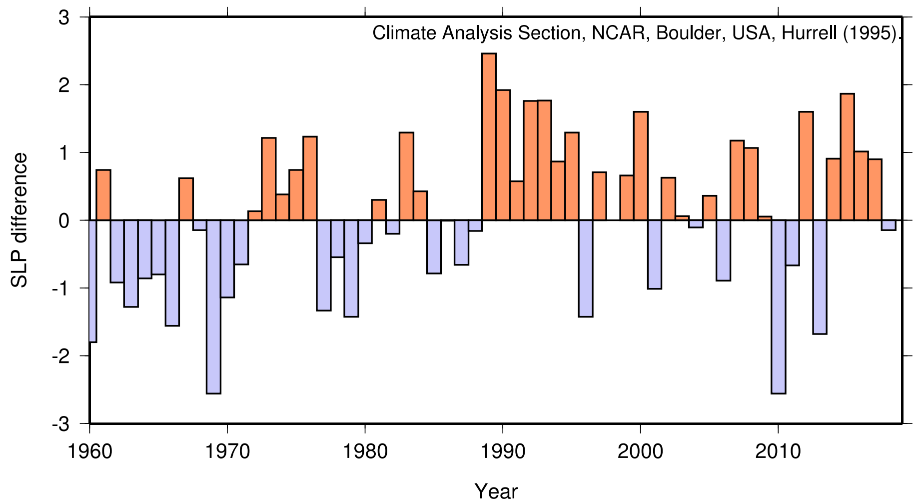

Figure 5. North Atlantic Oscillation index computed from principal component analysis of sea level pressure in the North Atlantic (see Hurrell, 1995).

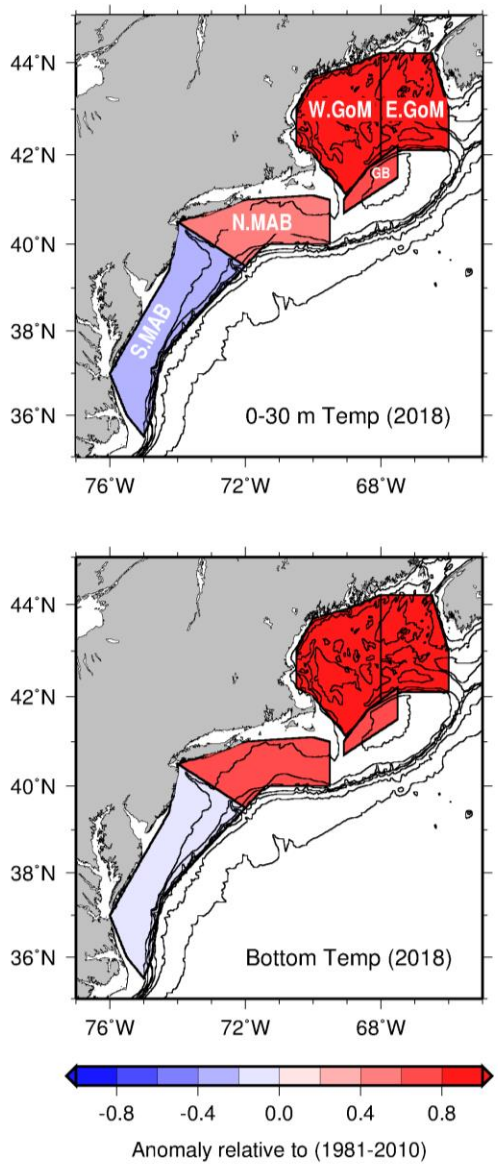

Figure 6. Surface (upper panel) and bottom (lower panel) regional annual temperature anomaly (°C). Positive anomalies correspond to warming in 2018 relative to the reference period (1981-2010). The region labels correspond to the panels in Figure 7.

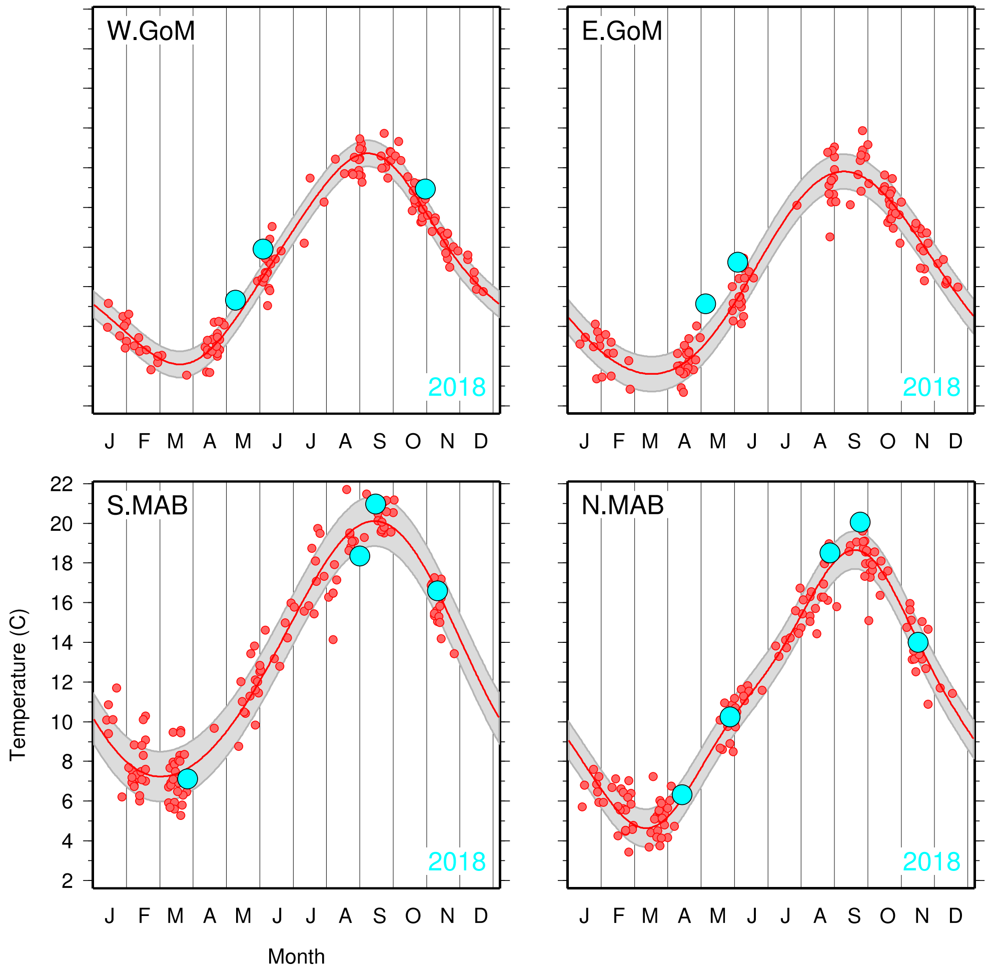

Figure 7a. Regional average 0-30 meter temperature (°C) as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 6. An annual harmonic fit to the regional average temperatures from 1981-2010 is 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 2018 surveys are shown in cyan.

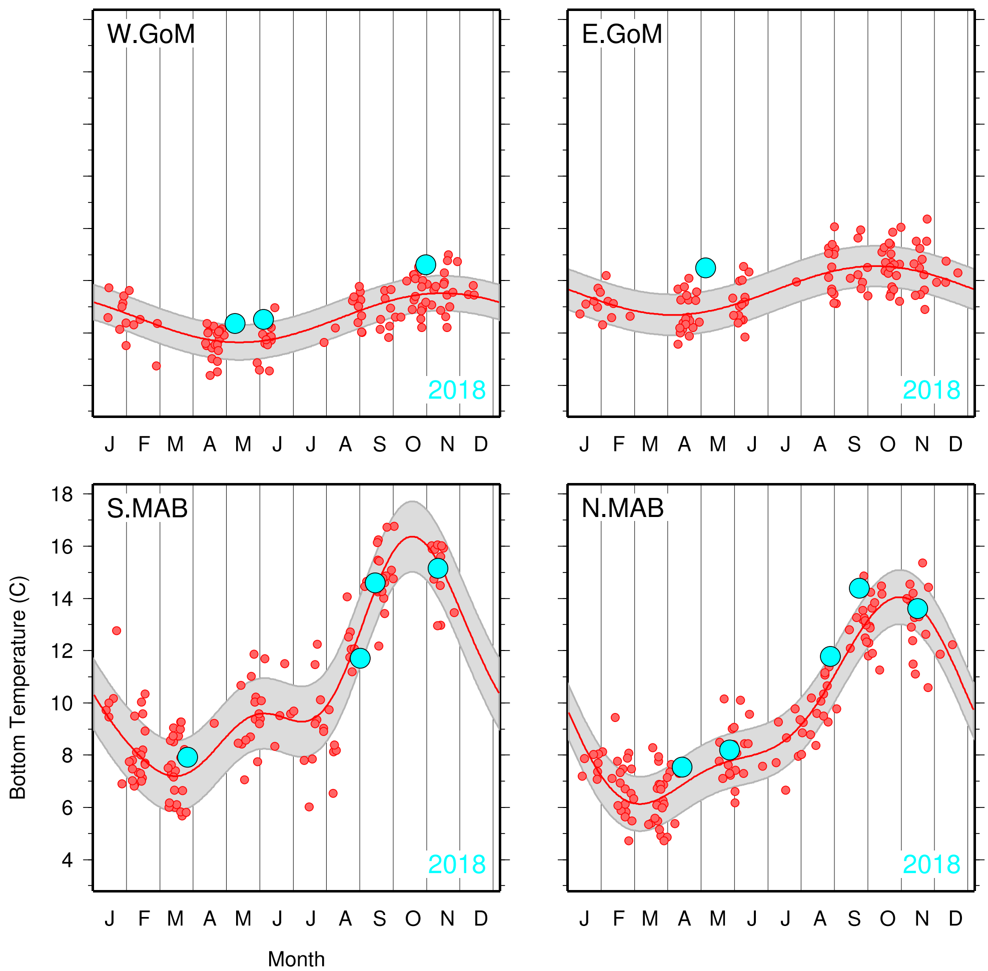

Figure 7b. As in Fig. 7a, but for bottom temperatures.

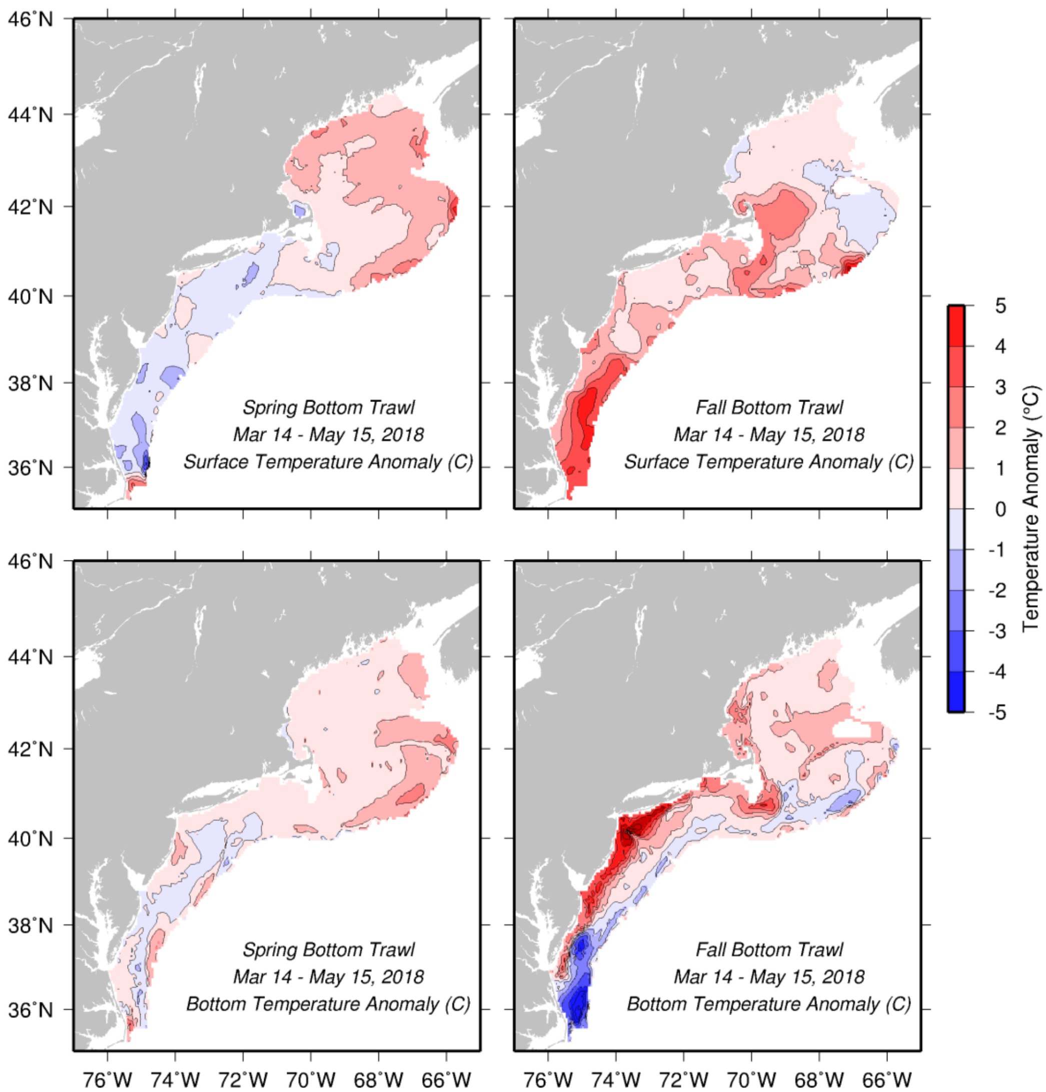

Figure 8. Surface (upper panels) and bottom (lower panels) temperature anomaly from the spring 2018 (left) and fall 2018 (right) ground fish surveys. Positive anomalies correspond to warming in 2018 relative to the reference period (1977-1987).

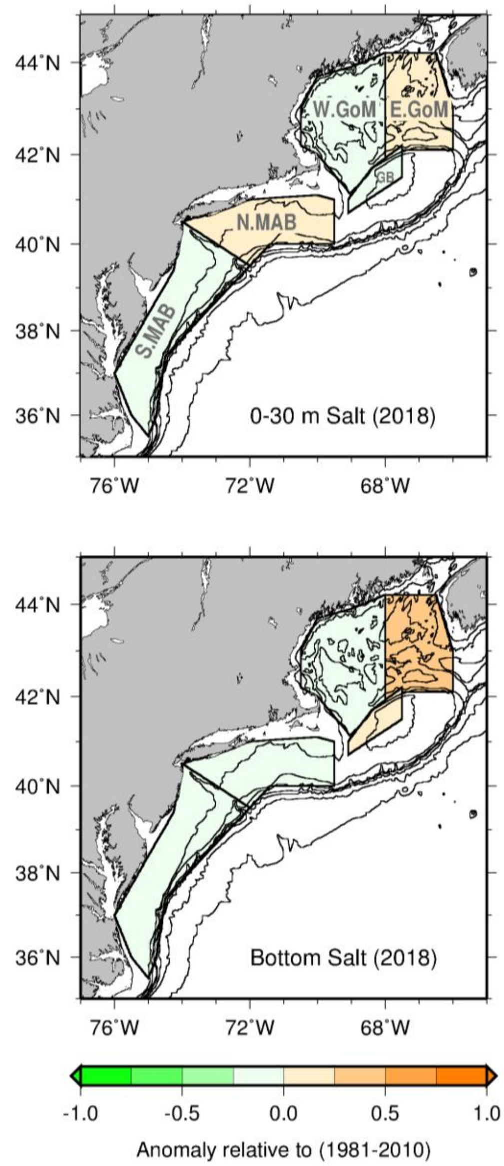

Figure 9. Surface (upper panel) and bottom (lower panel) regional annual salinity anomaly. Positive anomalies correspond to more saline conditions in 2018 relative to the reference period (1981-2010). The region labels correspond to the panels in Figure 11.

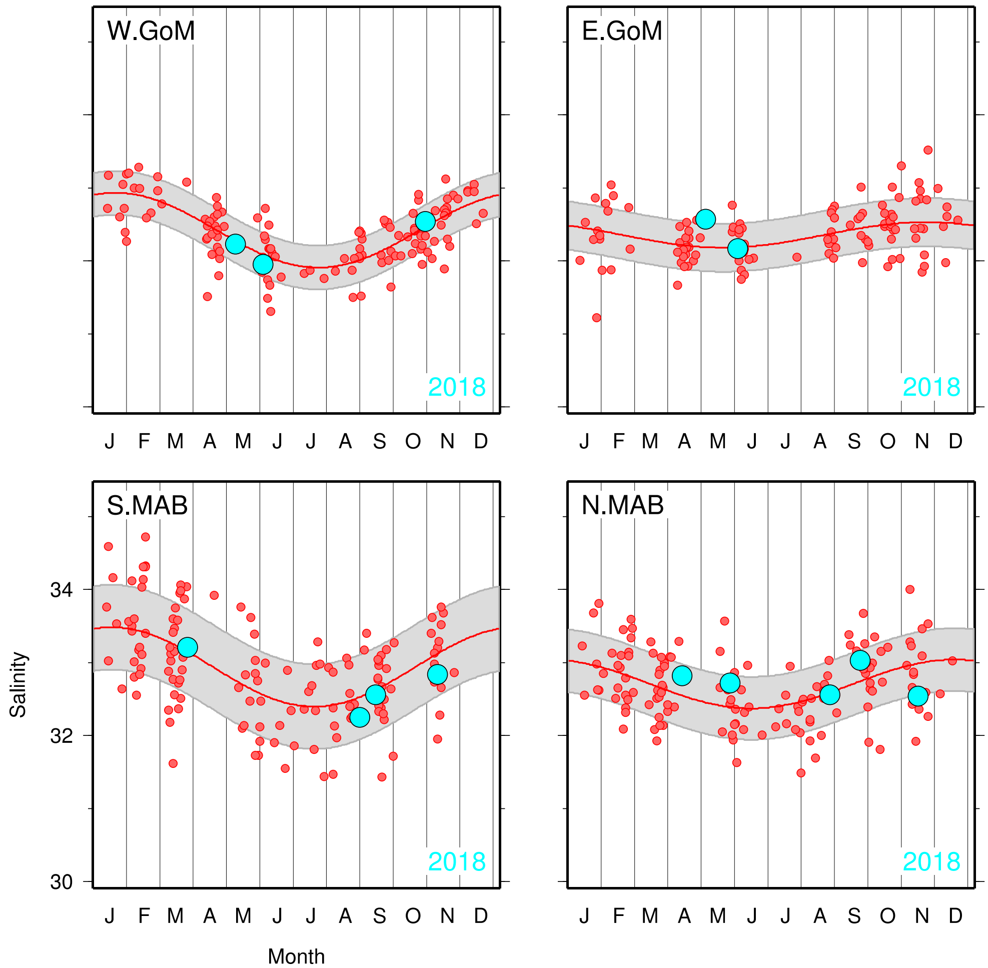

Figure 10a. Regional average 0-30 meter salinity as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 10. An annual harmonic fit to the regional average salinities from 1981-2010 is shown by 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 2018 surveys are shown in cyan.

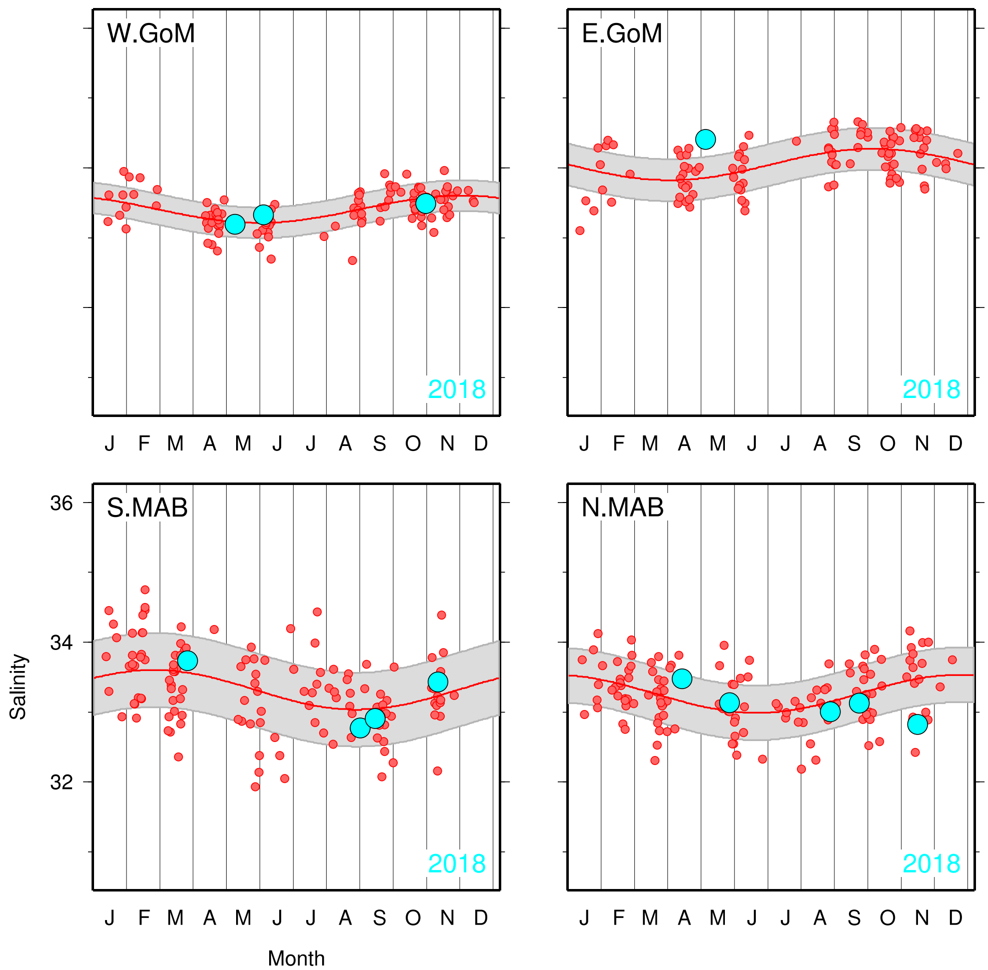

Figure 10b. As in Fig. 11a, but for bottom salinities.

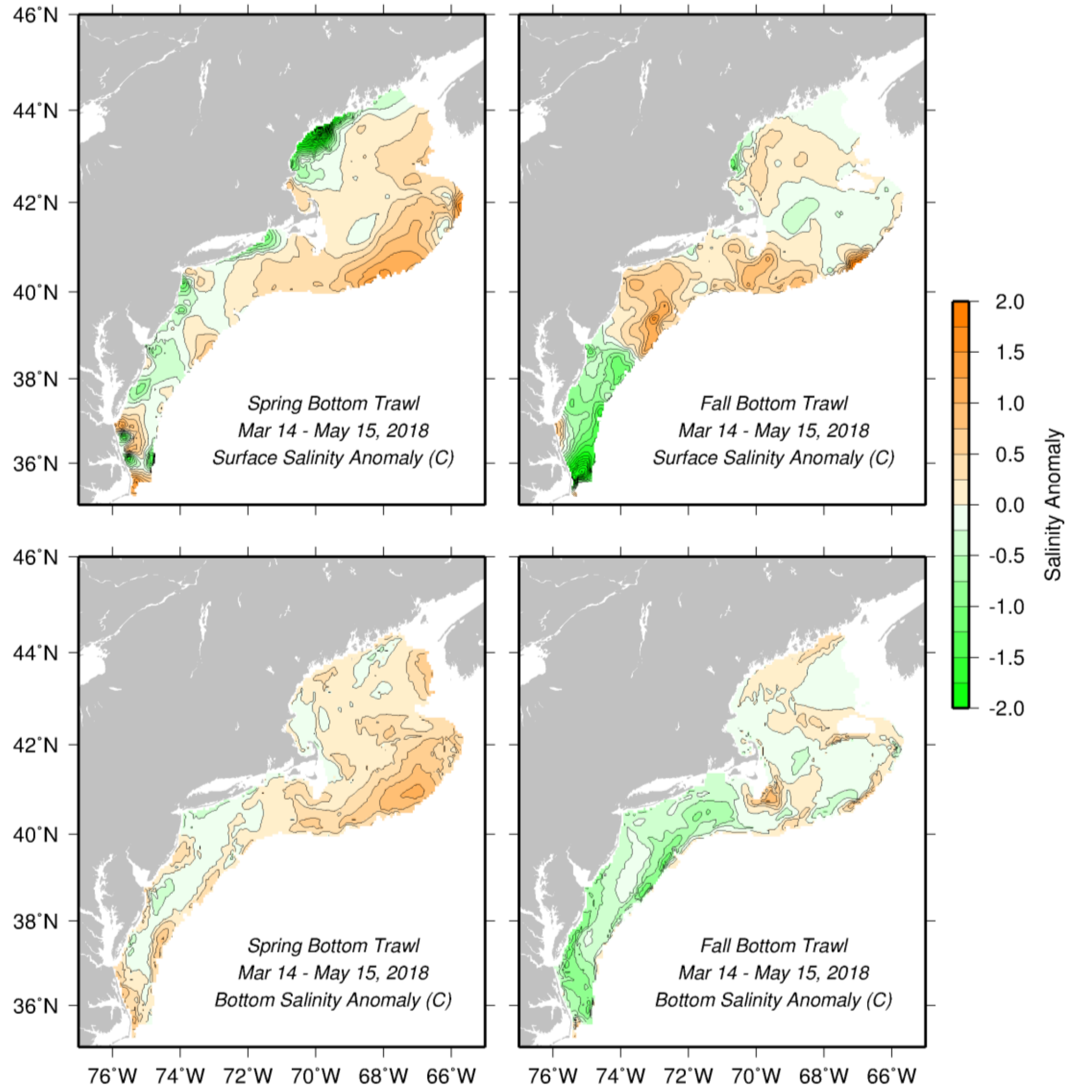

Figure 11. Surface (upper panels) and bottom (lower panels) salinity anomaly from the spring 2018 (left) and fall 2018 (right) ground fish surveys. Positive anomalies correspond to more saline conditions in 2018 relative to the reference period (1977-1987).

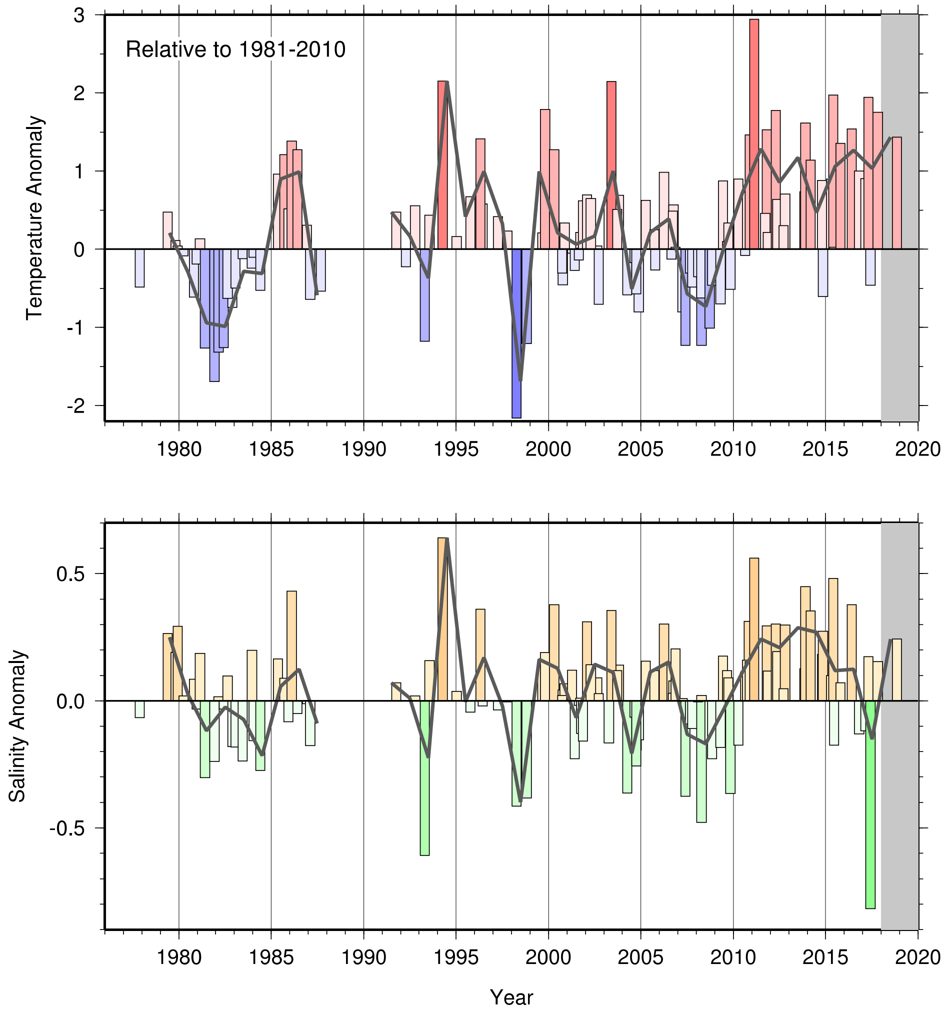

Figure 12a. Time series of temperature and salinity anomaly in the deep Northeast Channel. Each bar represents a volume-weighted average of all observations from a single survey collected between 150-200 meters in the Northeast Channel. The grey curve shows the annual average anomaly time series. Positive values are warmer and saltier than the long-term mean calculated for 1981-2010. The gray shading highlights sampling done in 2018.

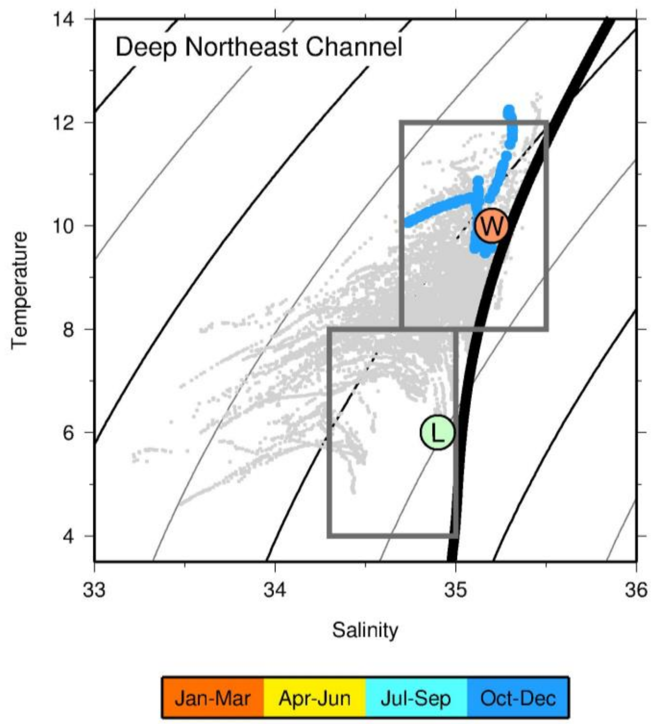

Figure 12b. Temperature-salinity profiles extracted from the deep Northeast Channel (150-250 m). Profiles from 2018 (shown in color, with colors corresponding to time of year) are compared with all profiles observed between 1981-2010 (grey). The boxes delineate the property range typically associated with Labrador Slope Water (L) and Warm Slope Water (W). The heavy black curve is the standard T–S curve constructed by Armi and Bray (1982) for Western North Atlantic Central Water, the saltiest water mass we expect to influence the Northeast U.S. Shelf.

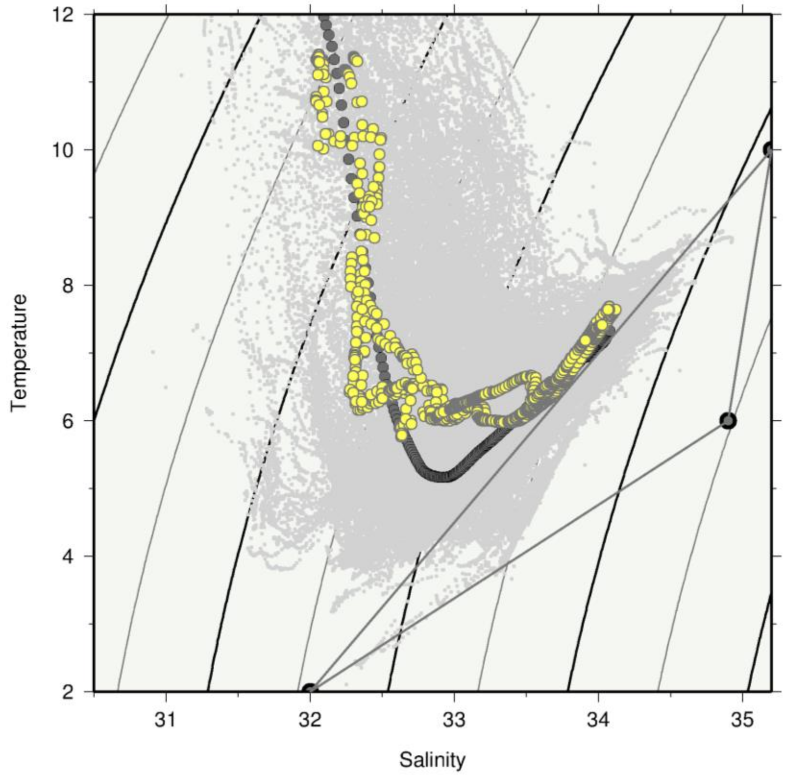

Figure 13. Temperature-salinity diagram showing water properties in Wilkinson Basin in the western Gulf of Maine. All observations from spring 2018 (yellow) are shown along with the spring climatological average profile (1981-2010, dark gray). The lightest gray dots show the historical range encompassed 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.

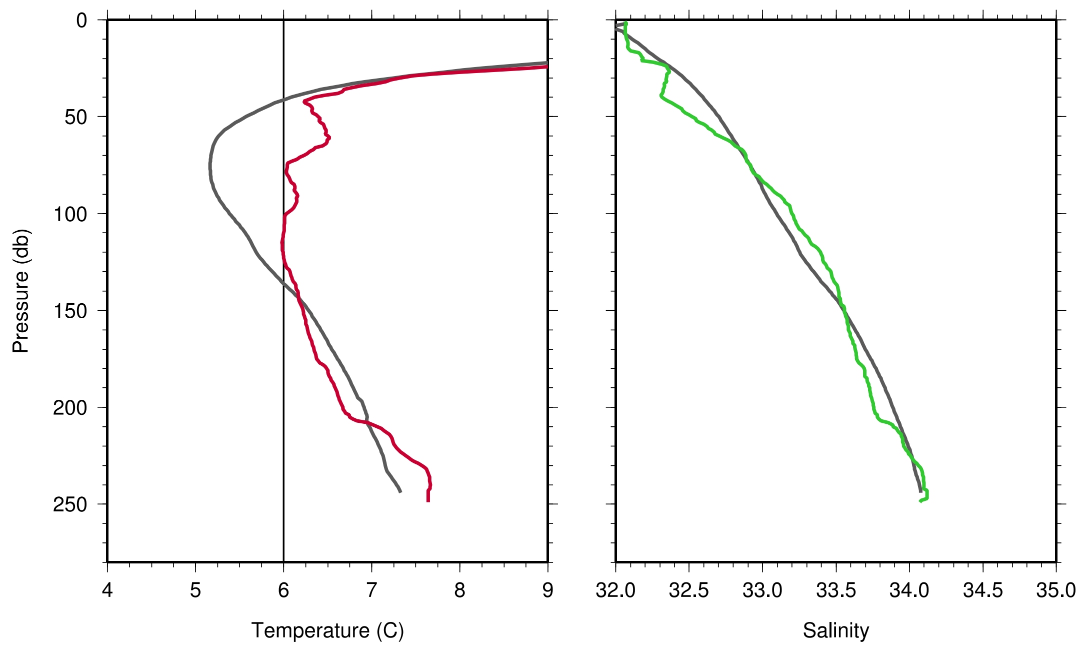

Figure 14. Average profiles of temperature (left) and salinity (right) from repeated observations collected during June in Wilkinson Basin in the western Gulf of Maine. All observations from June 2018 (red and green) are shown along with the climatological average profile for the same month (1981-2010, 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.

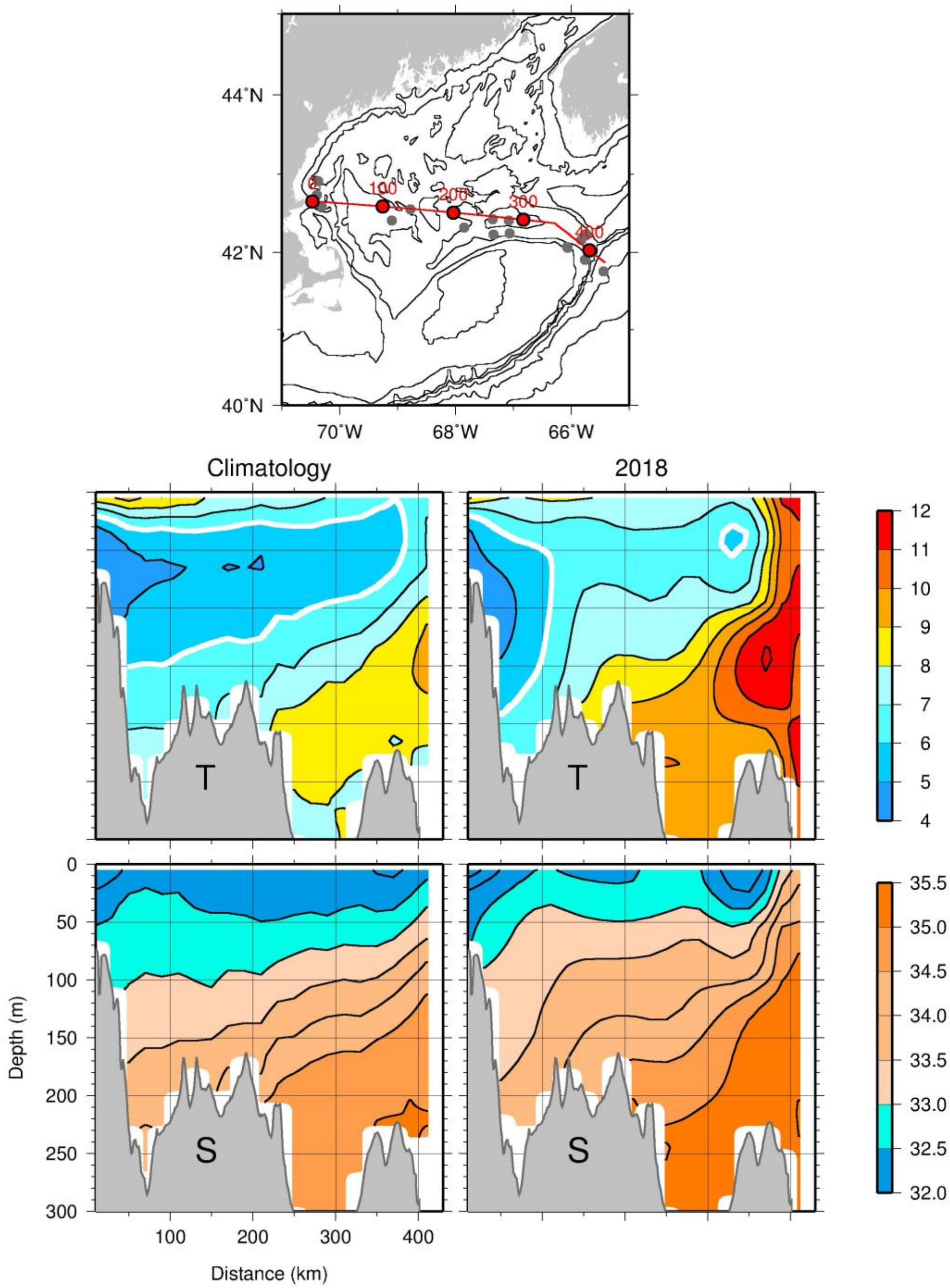

Figure 15. Vertical sections of temperature (top) and salinity (bottom) crossing the Gulf of Maine along a zonal transect shown in the map. The left panels show the climatological average for May spanning the years 1981-2010. The right panels show the synoptic mean section for May 2018. The heavy white contour highlights the 6°C isotherm as an indicator of the boundary of the cold intermediate layer. Along-transect distances and the May 2018 station distribution are shown on the map for reference.