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Hydrographic Conditions on the Northeast United States Continental Shelf in 2019 – 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 2019. 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, 2019 was characterized by warmer than average water temperatures observed across the entire Northeast US Shelf, with enhanced warming observed near the bottom. Extreme warm anomalies observed in the northern Middle Atlantic Bight are linked to warm core Gulf Stream rings and consistent with observations of increased ring formation since 2010. Deep (slope) waters entering the Gulf of Maine continue to be warmer and saltier than average, marking a full decade that southern source waters have dominated the slope water composition in theregion. The Cold Intermediate Layer in the western Gulf of Maine consisted of a narrower band of colder water compared with climatology, while the underlying water mass was warmer and fresher than normal.

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, limited sea day allocations in 2019 led to the elimination of the winter Ecosystem Monitoring (EcoMon) Survey and truncation of the others. Overall, 30-40% of the stations were left unsampled, leaving the far northern (Gulf of Maine) and far southern (southern Middle Atlantic Bight) survey areas under-sampled for the year.

During 2019, hydrographic data were collected on 8 individual NEFSC cruises, amounting to 1288 profiles of temperature and salinity and 1204 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, R/V Connecticut and R/V Endeavor* using a combination of Seabird Electronics SBE-19+ SEACAT profilers and SBE 9/11 CTD units. Cruise reports, and annual hydrographic summaries are accessible at: https://nefsc.noaa.gov/HydroAtlas/. Data are publicly available from the World Ocean Database maintained by NOAA's National Centers for Environmental Information at: http://www.nodc.noaa.gov/OC5/SELECT/dbsearch/dbsearch.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 2019 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 2019

Surface air temperatures over the western North Atlantic basin were organized in a tri-pole pattern, with warmer than average temperatures to the north and south bounding cooler than average conditions in a latitudinal band centered on Newfoundland (Fig. 2). The pattern was most pronounced in Winter and Spring. Notably warm air temperatures blanket the Northeast US Shelf during April and from July to October, while cold anomalies are present in January, March and November. Sea surface temperature mirrored these patterns, although warm anomalies were more prominent in surface waters in the Middle Atlantic Bight (Fig. 3). Annually, sea surface temperatures were not quite as warm as previous years, but magnitudes were still above the long term mean (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 winter NAO index was positive during 2018-19 (Fig. 5). While this is indicative of a deepending of the subpolar (Icelandic) low and a strengthening of the subtropical (Azores) high, the distribution of sea level pressure anomalies was most evident in the eastern region (IROC, 2020). A positive NAO is typically associated with stronger northwesterly winds over the shelves, colder than normal air temperatures over the Newfoundland and Labrador shelves, warmer than normal air temperatures over the Northeast U.S. Shelf, 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). However, in winter 2018-19 wind speeds across the North Atlantic were generally lower than average, particularly east of Newfoundland, and colder than normal air temperatures were limited to eastern Newfoundland (IROC, 2020).

Hydrographic Conditions in 2019

Relative to historical values, regional ocean temperatures across the NEUS shelf were warm during 2019 (Fig. 6). Annually, waters in the upper 30 meters were between 0.5-1.1°C warmer than normal everywhere. Of the seasons sampled, warming was most pronounced during summer in the Middle Atlantic Bight and eastern Gulf of Maine, where regional temperature anomalies approached 2°C (Fig. 7a). Extremely warm conditions were also observed near the bottom across the entire region, with anomalies exceeding those at the surface (Fig. 6). Most notably, anomalies reached 2.7°C during October in the northern Middle Atlantic Bight, well outside the typical envelope of variability (Fig. 7b) Similarly, bottom temperatures measured more than one standard deviation above normal throughout the year in the Gulf of Maine (Fig. 7b). The details of the seasonal differences are revealed in synoptic maps compiled from the spring and fall ground fish surveys (Fig 8). During spring, warm anomalies were pervasive across the entire Northeast Shelf, exclusive of the shelf edge, and enhanced warming was observed in the deep channels and basins of the Gulf of Maine. By contrast, extremely warm anomalies were observed near shore in the Middle Atlantic Bight and along the outer shelf offshore of Georges Bank during September- October (Fig 8). Time series observations of near-surface temperature from NDBC buoy 44008, located south of Nantucket Shoals, observed near normal conditions during late spring (May- July), followed by an extended period of anomalously warm conditions during summer (August- September), returning to near-normal or slightly warm conditions in Fall (Fig. 9). The ocean temperature anomalies reach an impressive 4-5°C during summer, which is suggestive of an oceanic driver.

Annually, in 2019 surface waters in the upper 30 meters were saltier than normal in the northern Middle Atlantic Bight and eastern Gulf of Maine, but near normal elsewhere (Fig. 10).
Seasonally, large positive anomalies were observed during September and October in the northern Middle Atlantic Bight, where anomalies exceeded 1.0 psu (Fig. 11a). Similar patterns were observed near the bottom, with more saline conditions observed in the northern Middle Atlantic Bight and eastern Gulf of Maine (Fig. 10). Seasonally, bottom waters in the eastern Gulf of Maine were saltier than normal throughout the year, whereas bottom waters in the northern Middle Atlantic Bight were anomalously salty in October relative to the rest of the year (Fig.11b). Synoptically, notably fresh conditions were present at the surface during spring particularly in the southern Middle Atlantic Bight and western Gulf of Maine (Fig 12). By contrast, anomalously saline conditions were observed at the surface along the shelf edge during Fall. In addition, anomalously saline conditions were observed at the bottom during fall, coincident with the warm near-bottom anomalies observed south of Georges Bank (Fig 8 and 12). Satellite derived observations of sea surface temperature suggest offshore forcing is likely responsible for the warm, salty anomaly near Georges Bank (Fig 13). Satellite images reveal a large warm core ring impinging on the shelf in the region with filaments of warm slope water protruding onshore (Fig 13).

Deep inflow through the Northeast Channel continues to be dominated by Warm Slope Water, marking a full decade that southern source waters have dominated the slope water composition in the region (Fig. 14). Springtime temperature-salinity and temperature-depth profiles indicate the presence of a Cold Intermediate layer in the western Gulf of Maine, a mid-depth water mass formed seasonally as a product of convective mixing driven by winter cooling (Fig. 15 & 16). The remnant winter water in the Cold Intermediate Layer was slightly colder and fresher than average in 2019, suggesting convective mixing was strong in the preceding winter (Fig. 15). In Wilkinson Basin, the entire water column below 75 meters was warmer than average, with anomalies increasing toward the bottom (Fig. 16 & 17). 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, driving changes in distribution and abundance. 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) and an increase in the frequency of warm core ring formation by the Gulf Stream (Gangopadhyay, et al., 2019). 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

- Waters on the Northeast U.S. Continental Shelf were warmer than average particularly near the bottom
- Extreme warm anomalies observed in the northern Middle Atlantic Bight are linked to the influence of warm core Gulf Stream rings
- The Cold Intermediate Layer in the western Gulf of Maine consisted of a narrower band of colder water compared with climatology
- Deep waters entering the Gulf of Maine continue to be warm and salty, marking a full decade that southern source waters have dominated the slope water composition in the region

References

Andres, M., 2016. On the recent destabilization of the Gulf Stream Path downstream of Cape Hatteras, *Geophysical Research Letters*. 43, doi:10.1002/2016GL069966.

Davis, X., T.M. Joyce, and Y-O. Kwon, 2017. Prediction of silver hake distribution on the Northeast U.S. shelf based on the Gulf Stream path index. *Continental Shelf Research*, 138, 61- 64.

Gangopadhyay, A., G. Gawarkiewicz, E.N.S. Silva, M. Monim and J. Clark, 2019. An observed regime shift in the formation of Warm Core Rings from the Gulf Stream, Scientific Reports, 9, 12319 (2019). https://doi.org/10.1038/s41598-019-48661-9.

Gawarkiewicz, G. G., R. E. Todd, A. J. Plueddemann, M. Andres, and J. P. Manning, 2012. Direct interaction between the Gulf Stream and the shelfbreak south of New England, *Scientific Reports*, 2(553), doi:10.1038/srep00553.

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

Holzwarth TJ and 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.

Hurrell JW. 1995. Decadal trends in the North Atlantic Oscillation and relationships to regional temperature and precipitation. *Science*. 269, 676-679.

ICES Report on Ocean Climate (Highlights), 2020. https://ocean.ices.dk/iroc/#.

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

Visbeck, M., E.P. Chassignet, R. Curry, T. Delworth, B. Dickson and 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. Dynamics of the direct intrusion of Gulf Stream ring water onto the Mid-Atlantic Bight Shelf, *Geophys. Res. Lett.,* 42, 7687-7695, doi:10.1002/2015GL065530.

Table 1. Inventory of hydrographic monitoring on the Northeast U.S. Shelf during 2019

Sub-area	Division(s)	Month(s)	Type[1]	Description	Station count
5	Y,Z	3,4,5	S	Bottom trawl survey	208
5	Y,Z	5	O	North Atlantic Right Whale	30
5	Y,Z	5,6	S	Ecosystems monitoring survey	132
5	Y,Z	5,6	O	Sea scallop survey	34
5	Y,Z	8	S	Ecosystems monitoring survey	97
5	Y,Z	7,8	O	Mesopelagic/Deep Sea survey	17
5	Y,Z	9,10,11	S	Bottom trawl survey	191
5	Y,Z	10,11	S	Ecosystems monitoring survey	73
6	A,B,C	3	S	Bottom trawl survey	143
6	A,B,C	5	S	Ecosystems monitoring survey	37
6	A,B,C	5	O	Sea scallop survey	1
6	A,B,C	8	S	Ecosystems monitoring survey	44
6	A,B,C	8	O	Mesopelagic/Deep Sea survey	1
6	A,B,C	9	S	Bottom trawl survey	142
6	A,B,C	10	S	Ecosystems monitoring survey	54

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

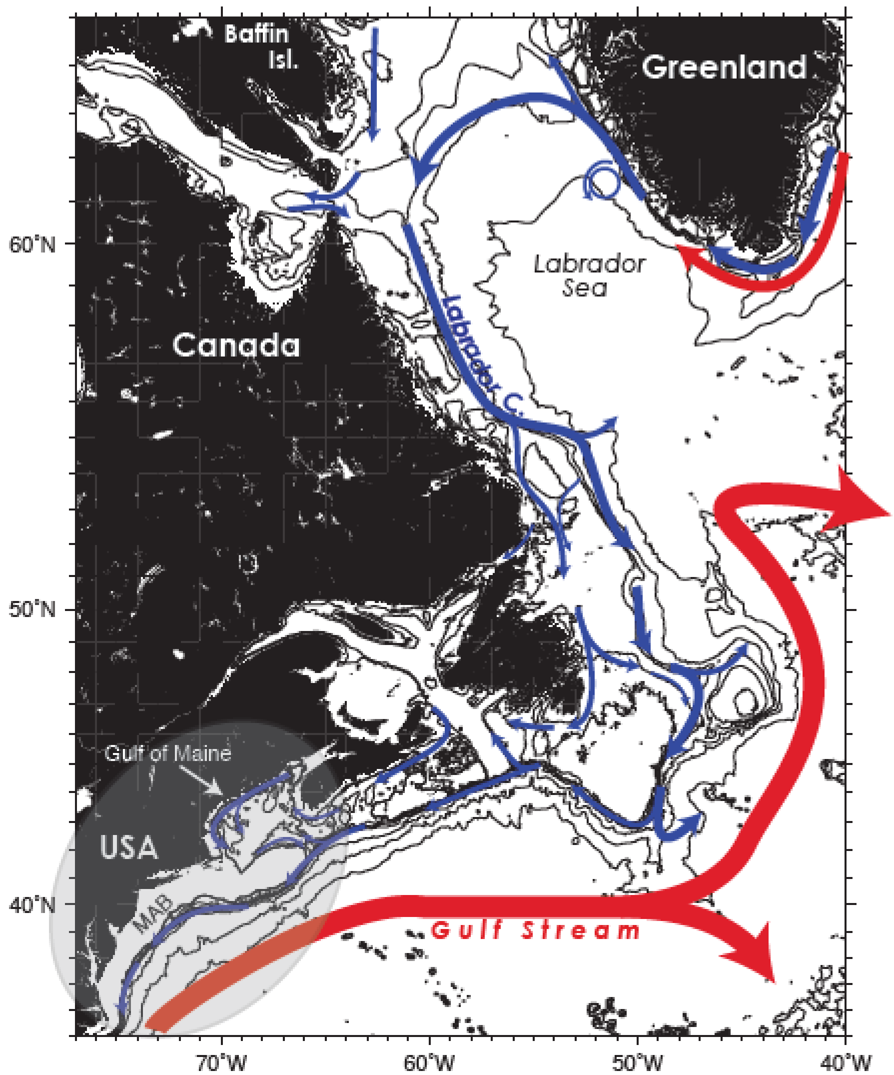

Figure 1a. Circulation schematic of the western North Atlantic. The Northeast U.S. Shelf region is identified by the shaded oval. The 100, 200, 500, 1000, 2000, 3000 and 4000 meter isobaths are shown.

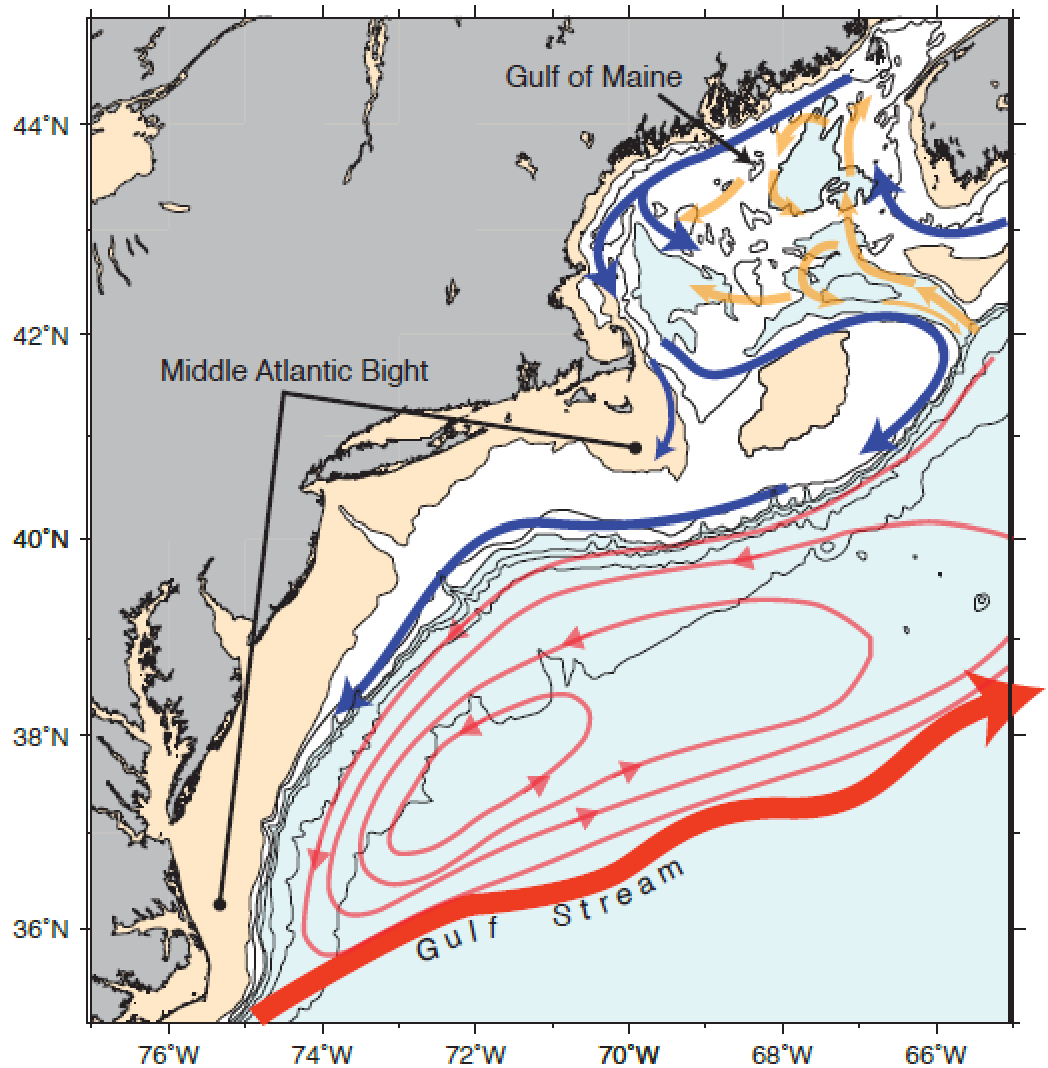

Figure 1b. Circulation schematic for the Northeast U.S. Shelf region, where blue arrows represent shelf water circulation and orange arrows represent deeper slope water circulation pathways. Water depths deeper than 200 meters are shaded blue. Water depths shallower than 50 meters are shaded tan.

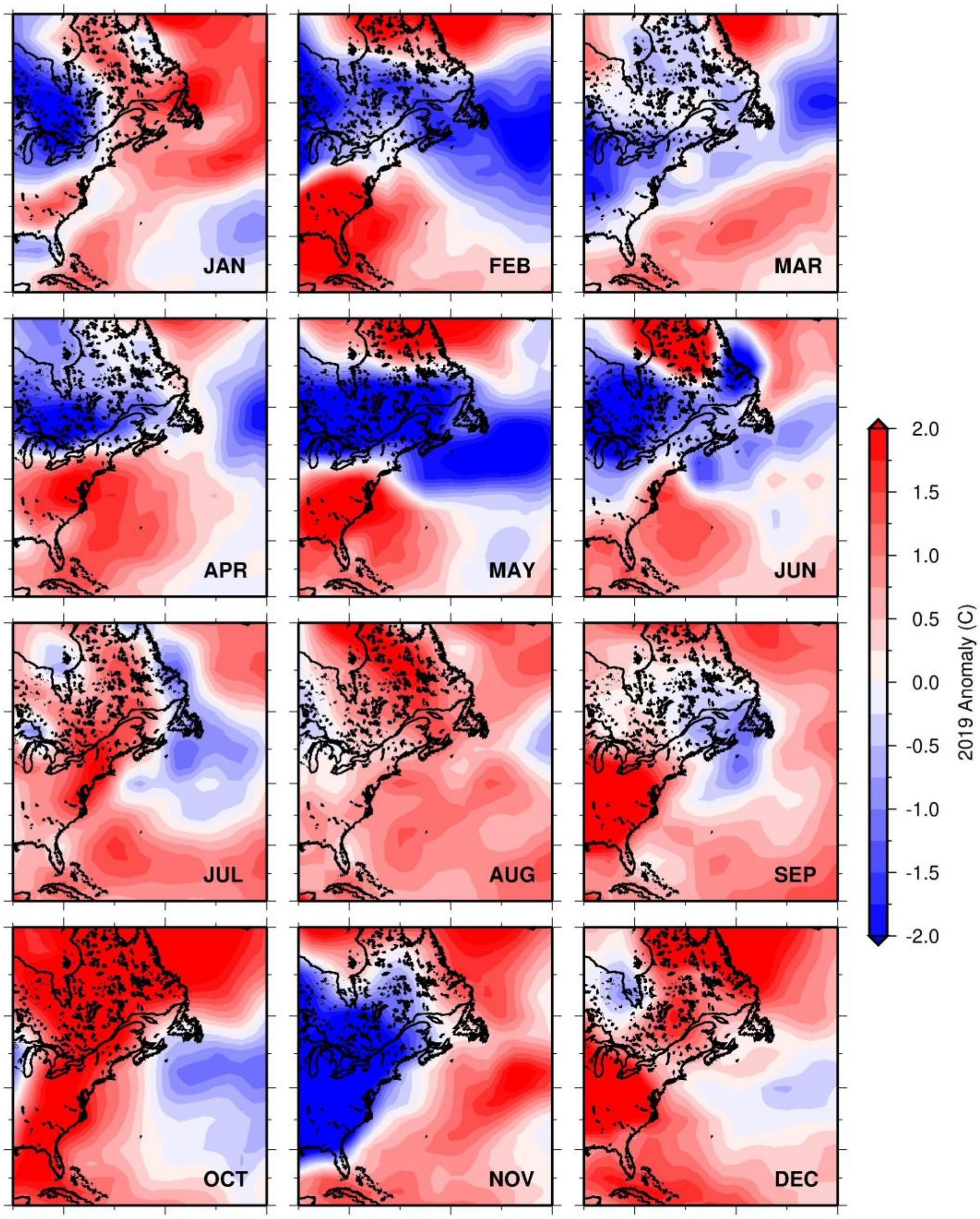

Figure 2. Surface air temperature anomaly derived from the NCEP/NCAR Reanalysis product (http://www.esrl.noaa.gov/psd/data/composites/day/). Positive anomalies correspond to warming in 2019 relative to the reference period (1981-2010).

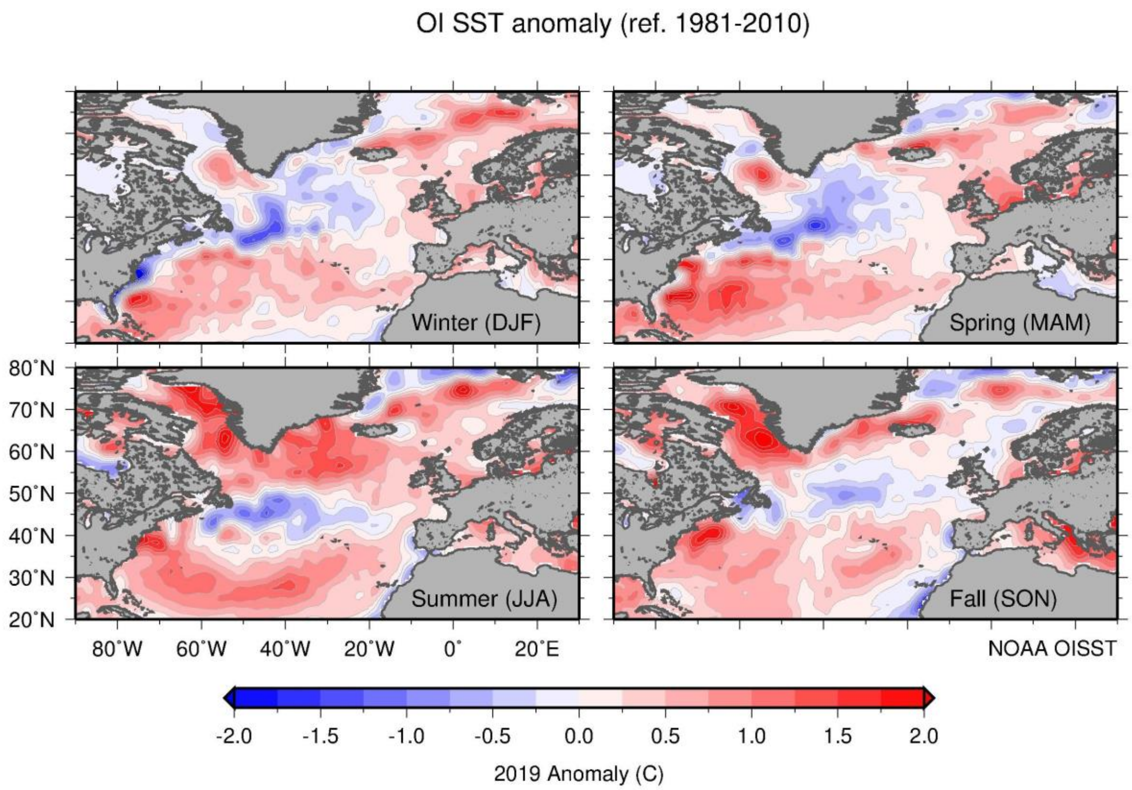

Figure 3. Sea surface temperature anomaly derived from the NOAA's Optimum Interpolation (OI) SST product (http://www.esrl.noaa.gov/psd/data/gridded/ data.noaa.oisst.v2.html). Seasons are made up of 3-month periods where winter spans December-February. Positive anomalies correspond to warming in 2019 relative to the reference period (1981-2010).

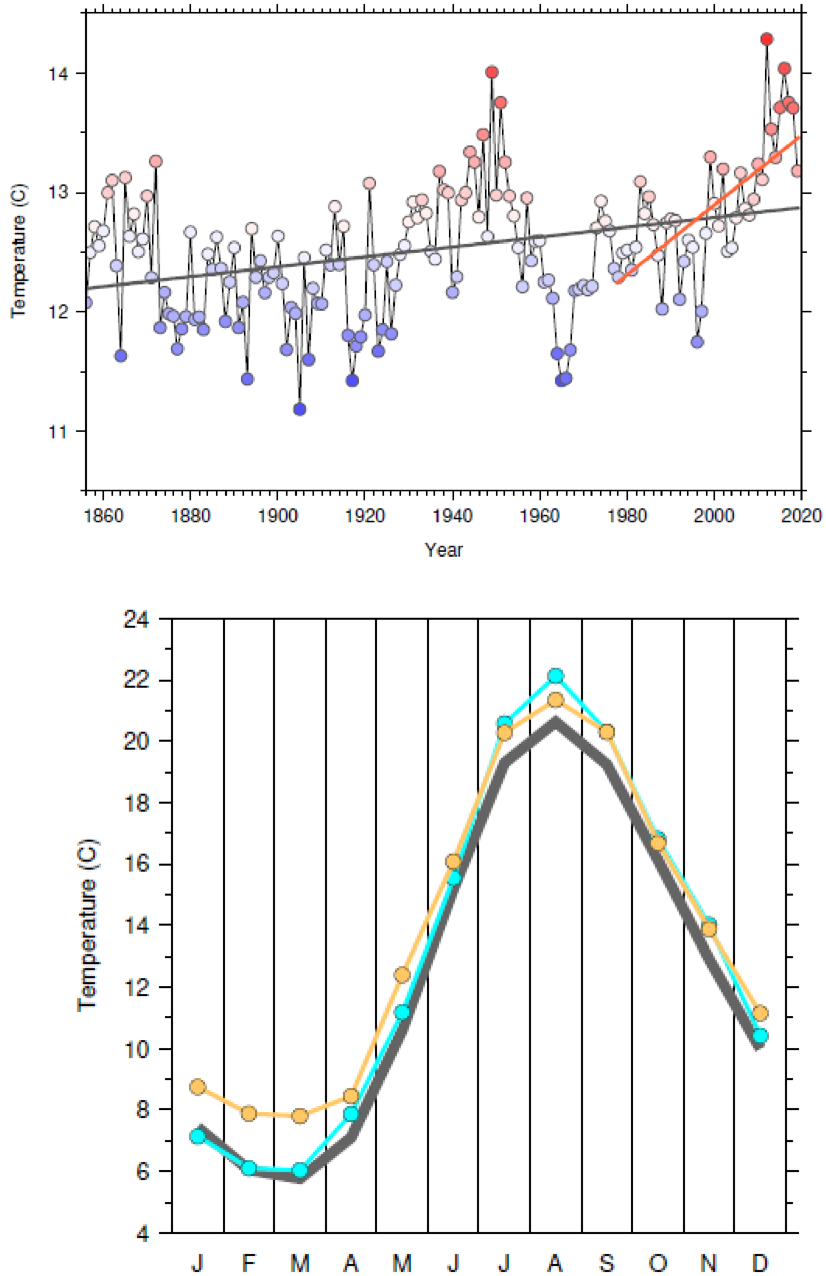

Figure 4. Top: Regional average annual sea surface temperature for the NEUS shelf region calculated from NOAA's extended reconstructed sea surface temperature product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html). Colors correspond with the anomaly scale in Figure 3. Bottom: Regional average monthly mean SST for the NEUS shelf for 2019 (cyan), 1951 (orange) and 1981-2010 (gray) calculated from the same product.

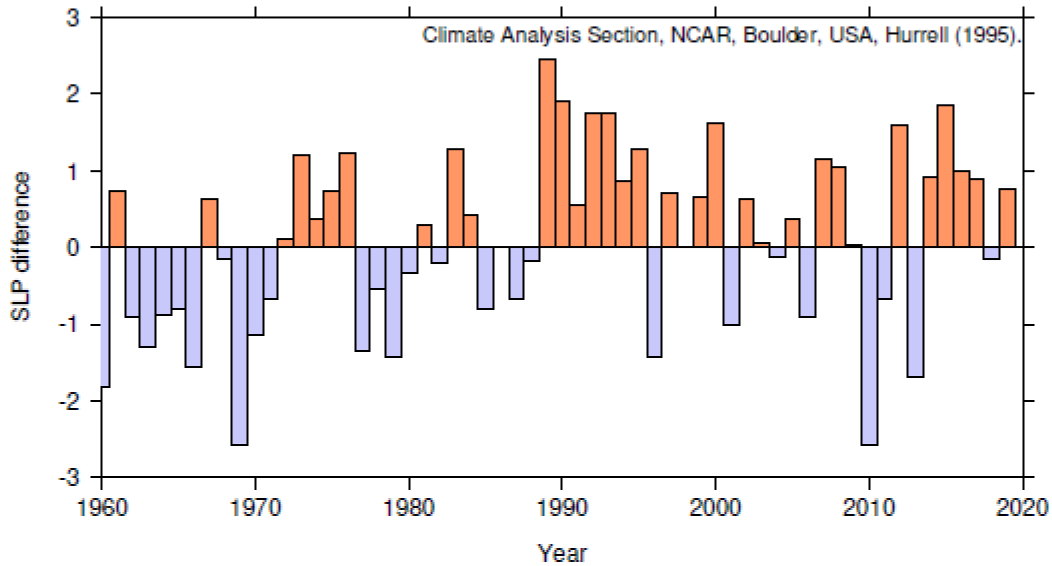

Figure 5. North Atlantic Oscillation index computed from principal component analysis of sea level pressure in the North Atlantic (see Hurrell, 1995).

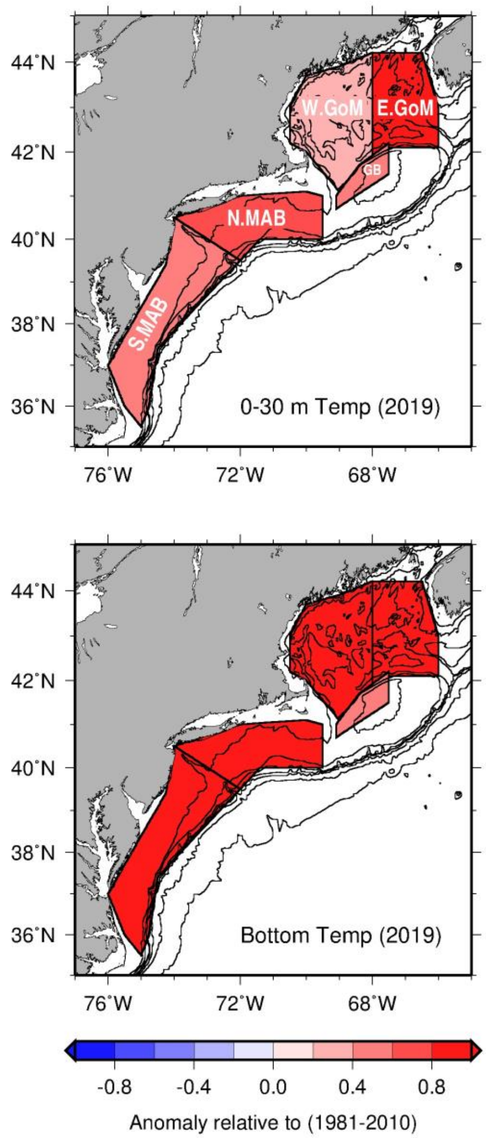

Figure 6. Surface (upper panel) and bottom (lower panel) regional annual temperature anomaly (°C). Positive anomalies correspond to warming in 2019 relative to the reference period (1981- 2010). The region labels correspond to the panels in Figure 7.

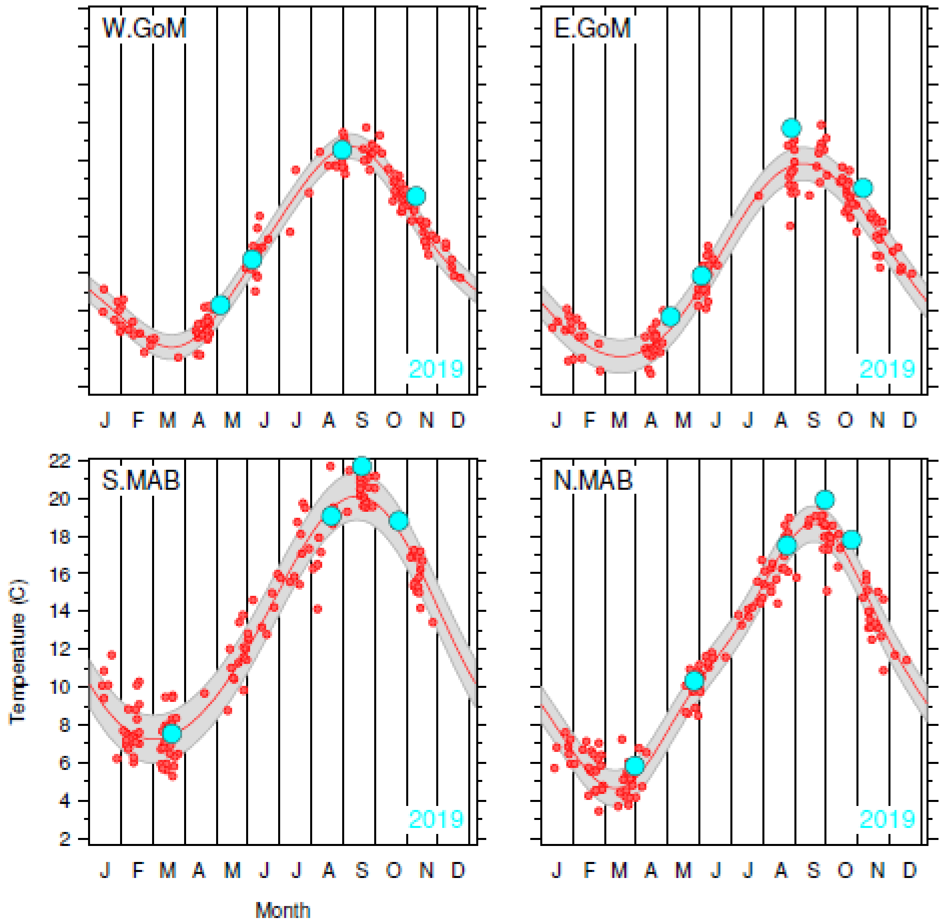

Figure 7a. Regional average 0-30 meter temperature (°C) as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 6. An annual harmonic fit to the regional average temperatures from 1981-2010 is 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 2019 surveys are shown in cyan.

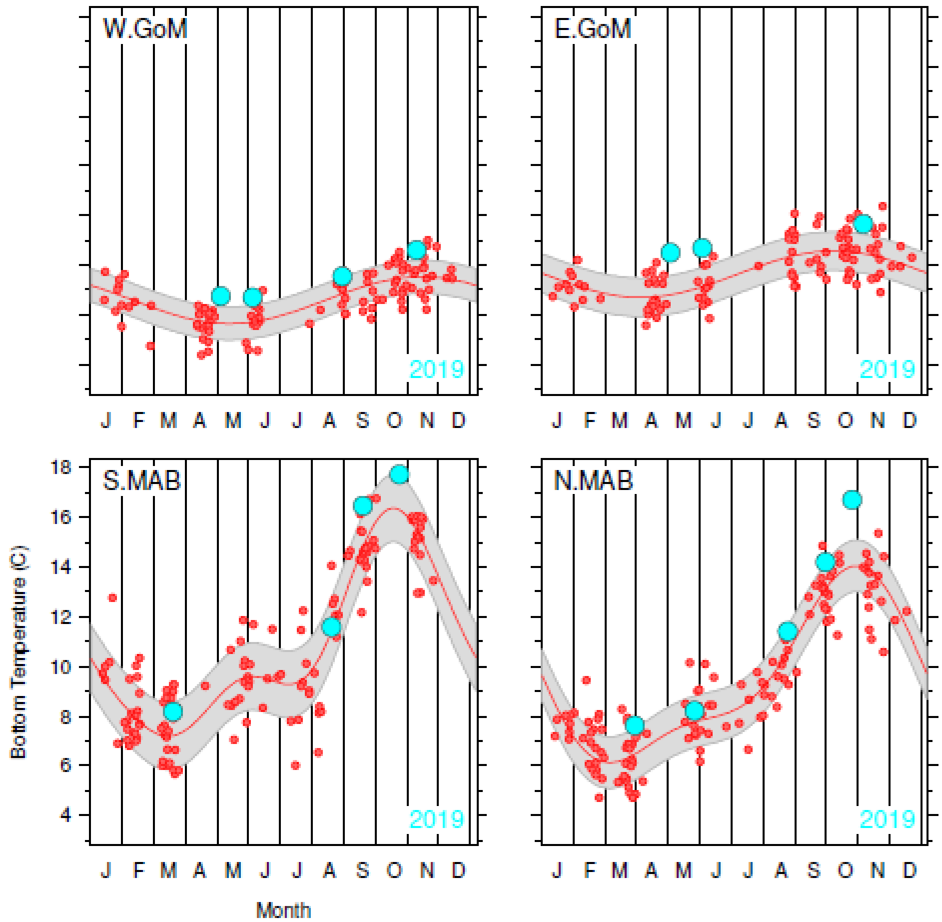

Figure 7b. As in Fig. 7a, but for bottom temperatures.

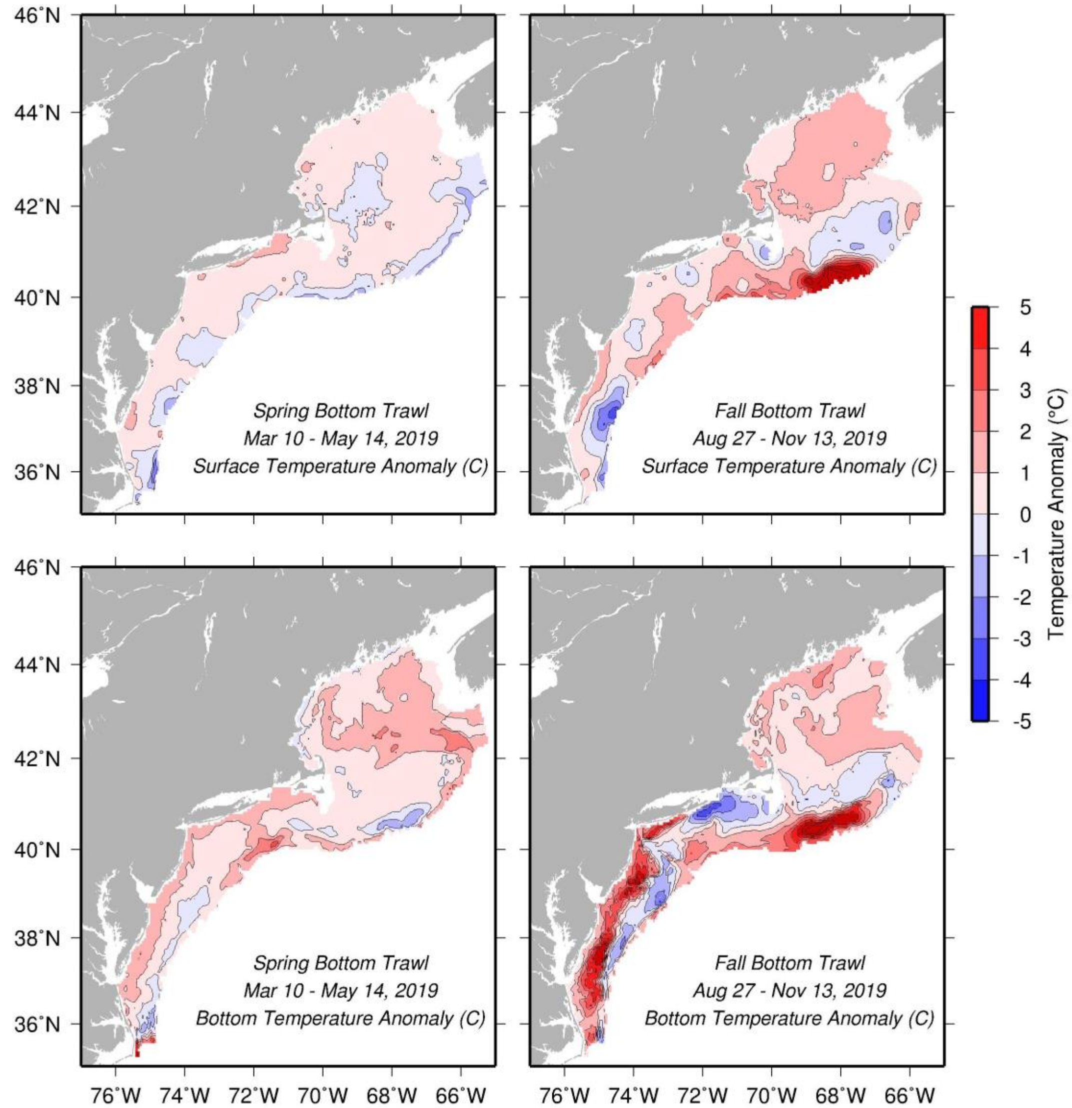

Figure 8. Surface (upper panels) and bottom (lower panels) temperature anomaly from the spring 2019 (left) and fall 2019 (right) ground fish surveys. Positive anomalies correspond to warming in 2019 relative to the reference period (1977-1987).

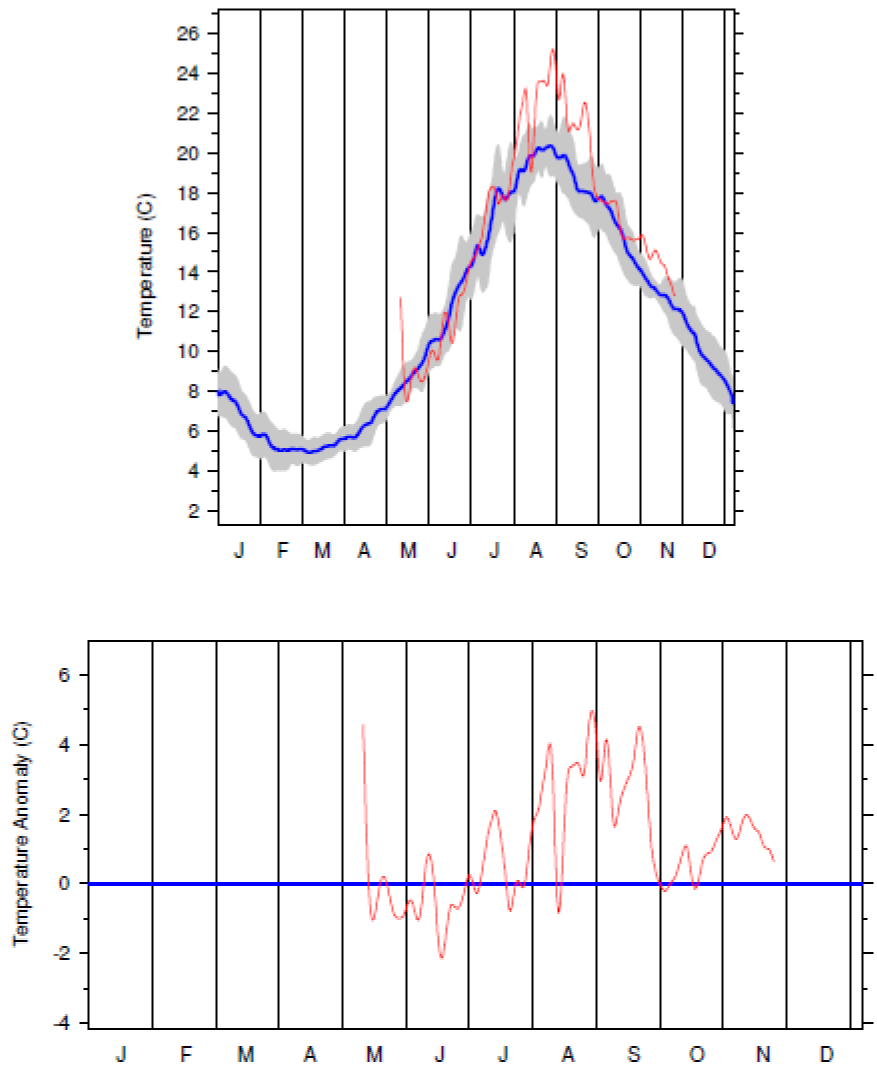

Figure 9. (top) Time series of surface ocean temperature from NDBC buoy 44008 located south of Nantucket Shoals in the northern Middle Atlantic Bight. Temperatures observed in 2019 (red) are compared with average temperatures (2000-2010, blue) in the top panel. The gray shading indicates one standard deviation about the long-term mean. The lower panel shows the difference between 2019 and the long-term mean temperature, where positive values indicate warmer conditions in 2019.

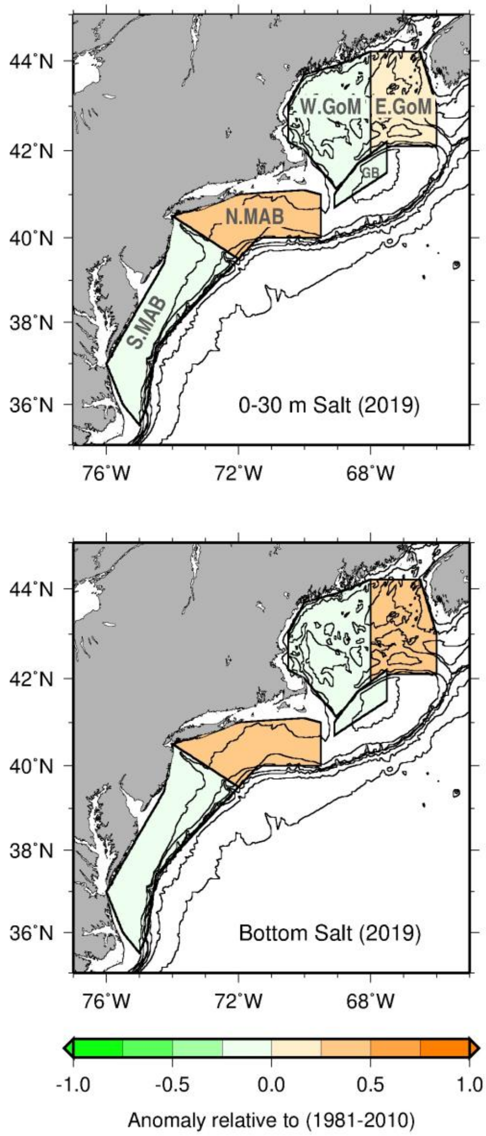

Figure 10. Surface (upper panel) and bottom (lower panel) regional annual salinity anomaly. Positive anomalies correspond to more saline conditions in 2019 relative to the reference period (1981-2010). The region labels correspond to the panels in Figure 11.

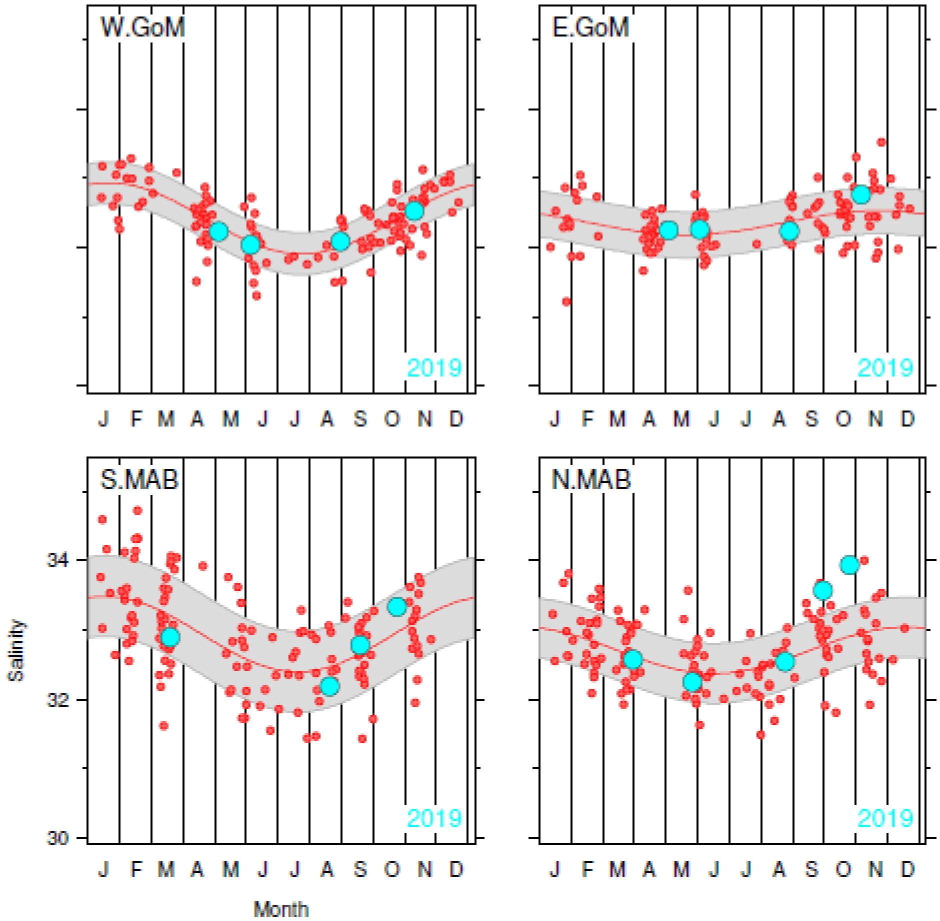

Figure 11a. Regional average 0-30 meter salinity as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 10. An annual harmonic fit to the regional average salinities from 1981- 2010 is shown by 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 2019 surveys are shown in cyan.

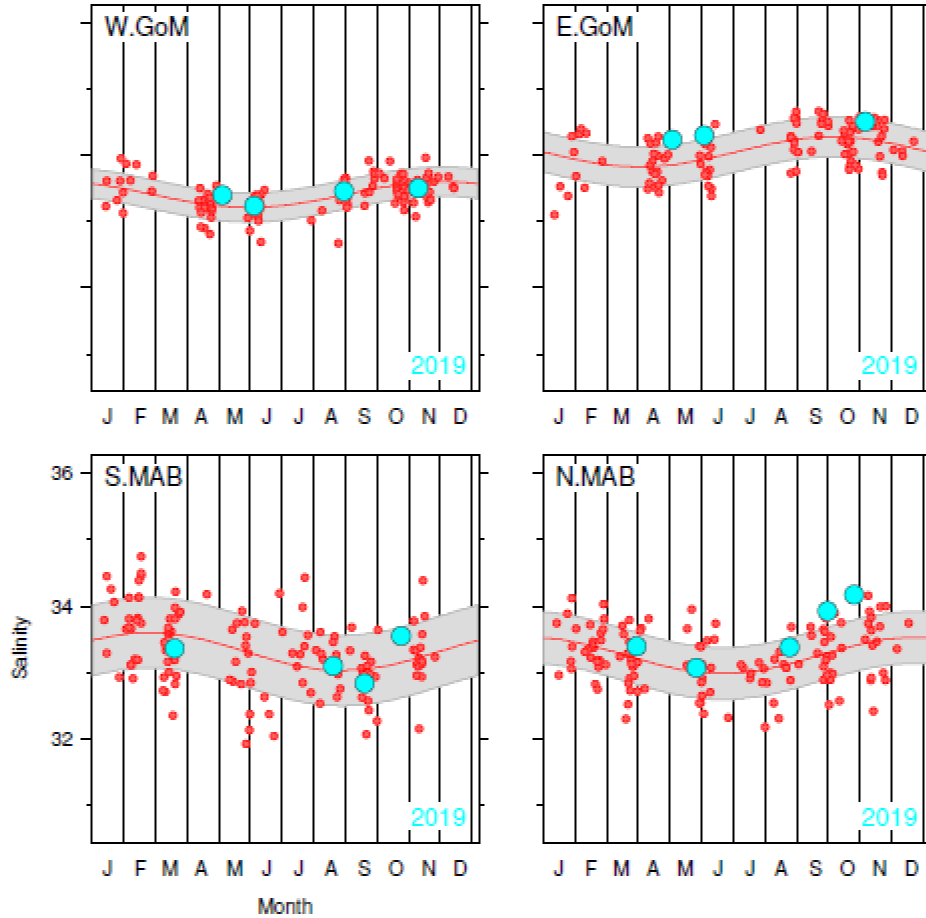

Figure 11b. As in Fig. 11a, but for bottom salinities.

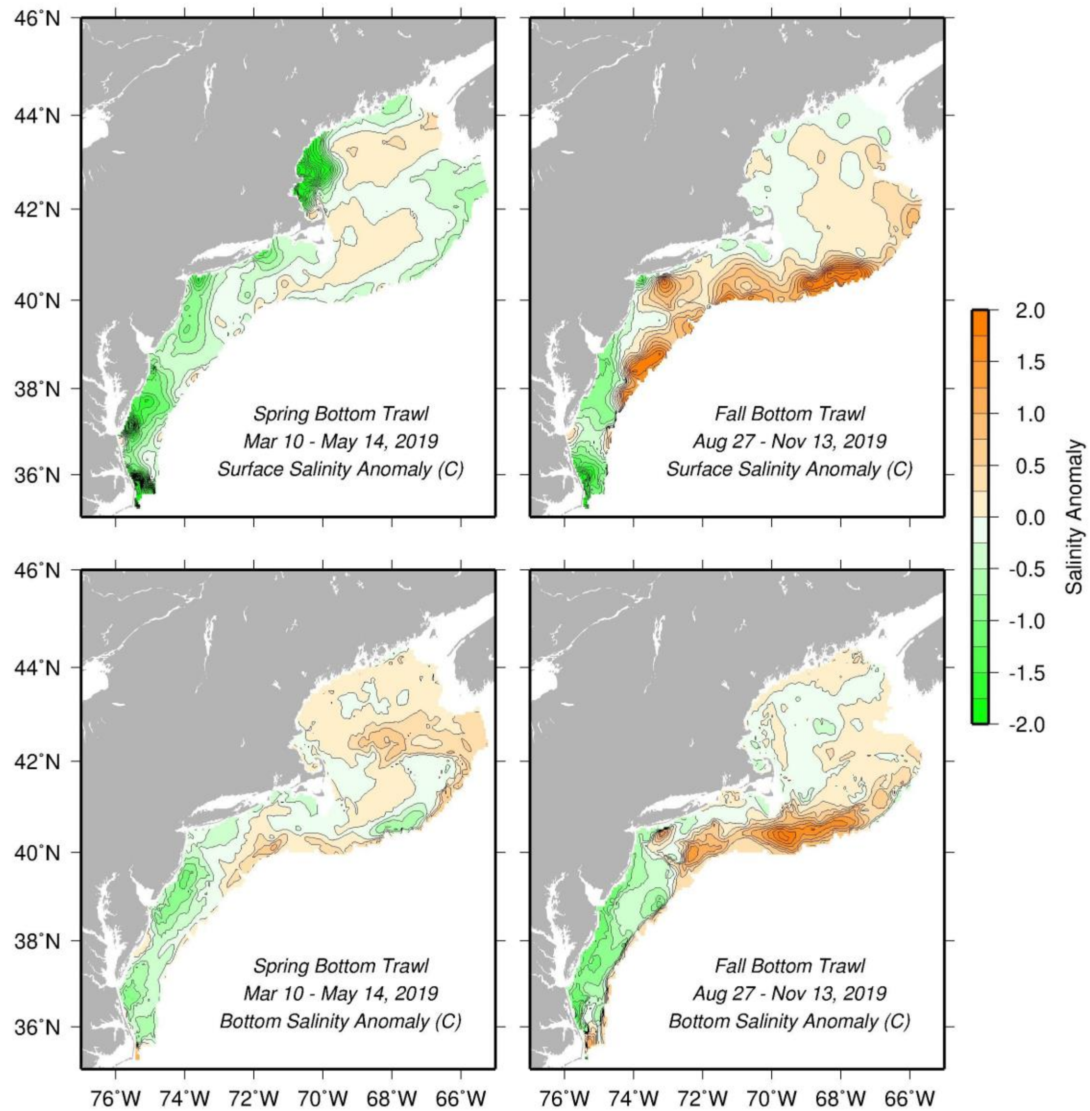

Figure 12. Surface (upper panels) and bottom (lower panels) salinity anomaly from the spring 2019 (left) and fall 2019 (right) ground fish surveys. Positive anomalies correspond to more saline conditions in 2019 relative to the reference period (1977-1987).

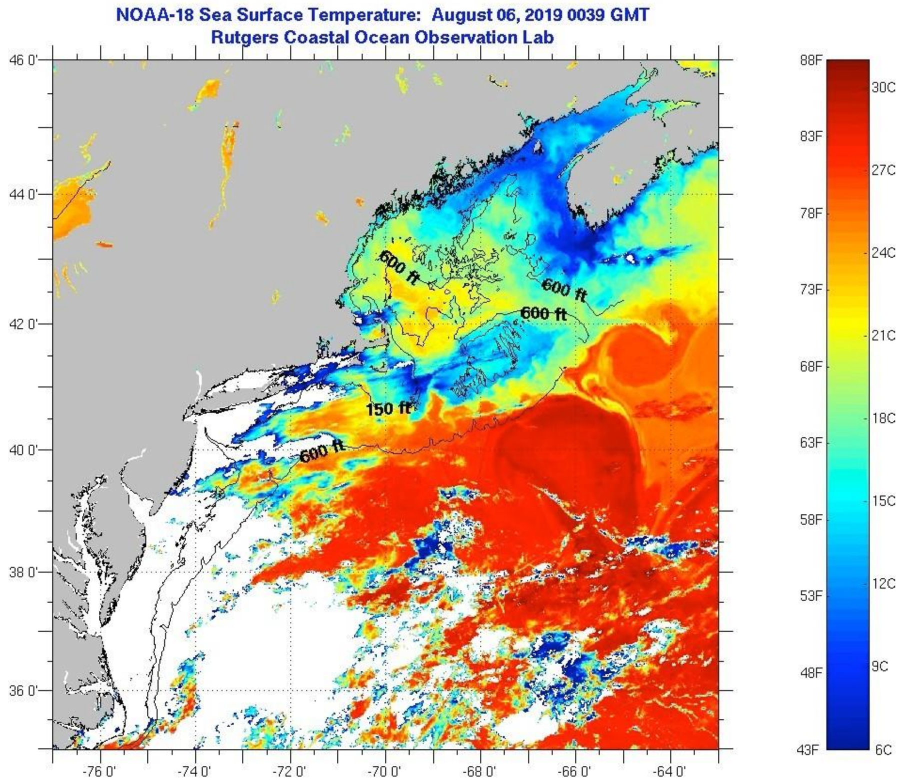

Figure 13. Daily composite sea surface temperature derived by the Coastal Ocean Observations Lab, Rutgers University, from data collected by the Advanced Very High Resolution Radiometer on August 6, 2019.

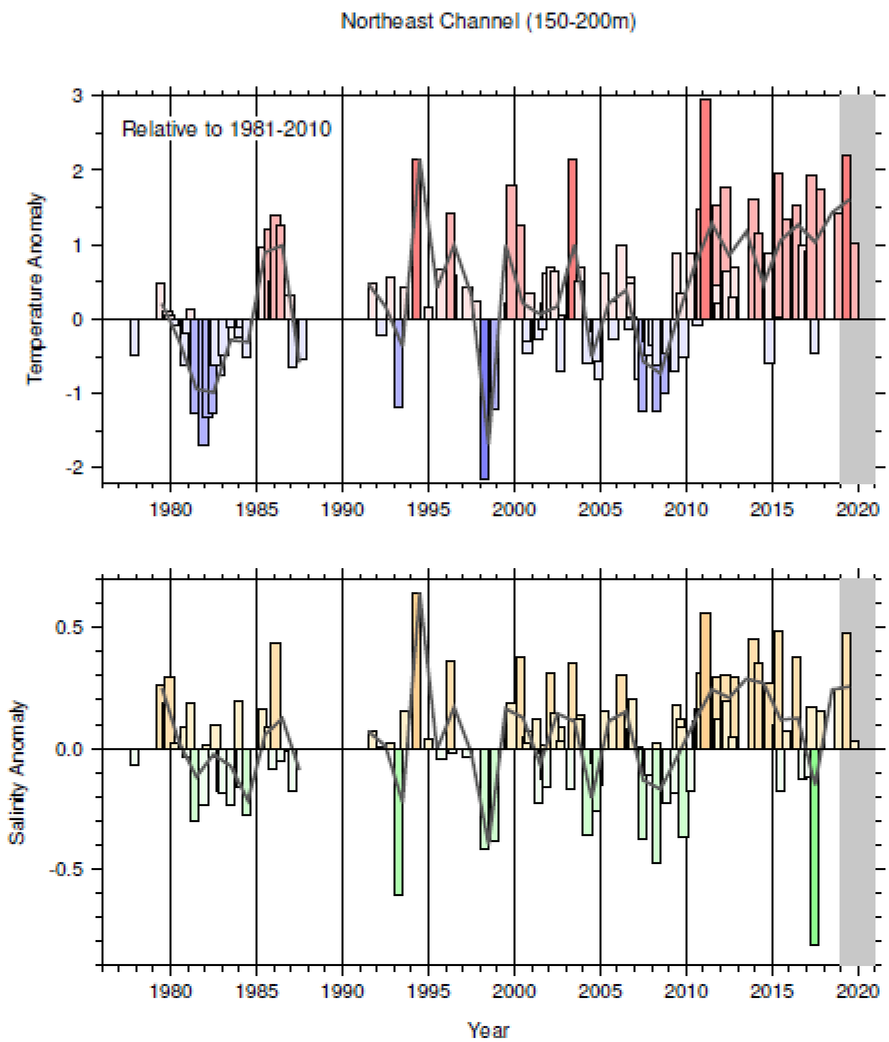

Figure 14. Time series of temperature and salinity anomaly in the deep Northeast Channel. Each bar represents a volume-weighted average of all observations from a single survey collected between 150-200 meters in the Northeast Channel. The grey curve shows the annual average anomaly time series. Positive values are warmer and saltier than the long-term mean calculated for 1981-2010. The gray shading highlights sampling done in 2019.

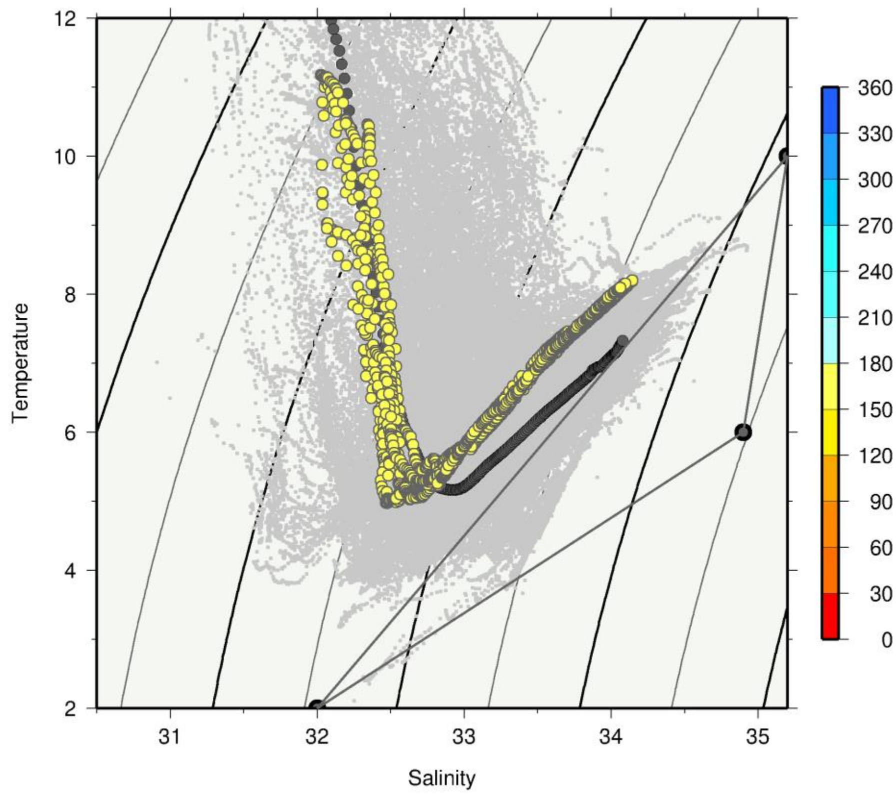

Figure 15. Temperature-salinity diagram showing water properties in Wilkinson Basin in the western Gulf of Maine. All observations from June (yellow) 2019 are shown along with the spring climatological average profile (1981-2010, dark gray). The lightest gray dots show the historical range encompassed 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.

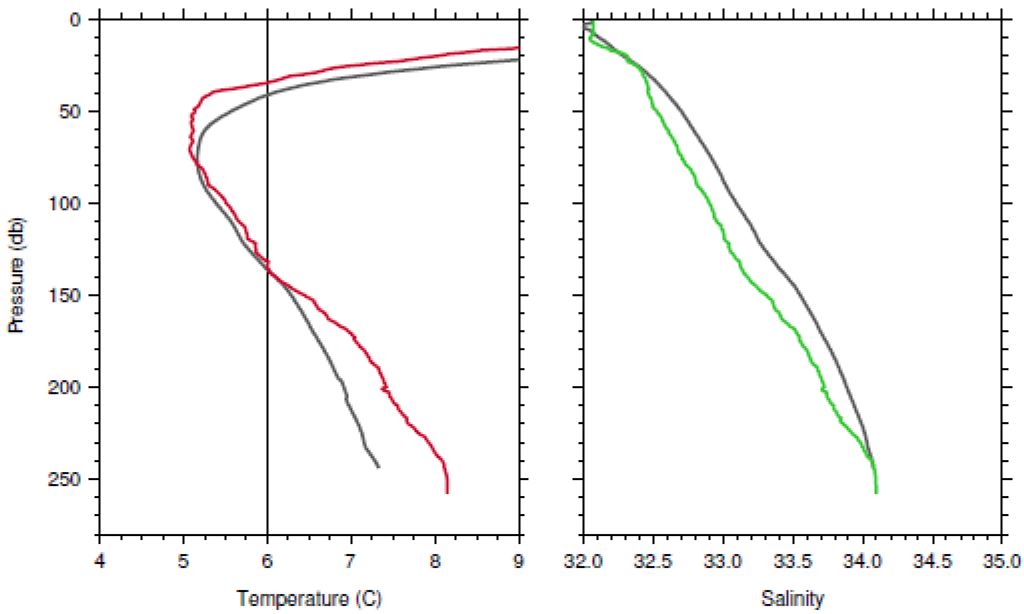

Figure 16. Average profiles of temperature (left) and salinity (right) from repeated observations collected during June in Wilkinson Basin in the western Gulf of Maine. All observations from June 2019 (red and green) are shown along with the climatological average profile for the same month (1981-2010, 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.

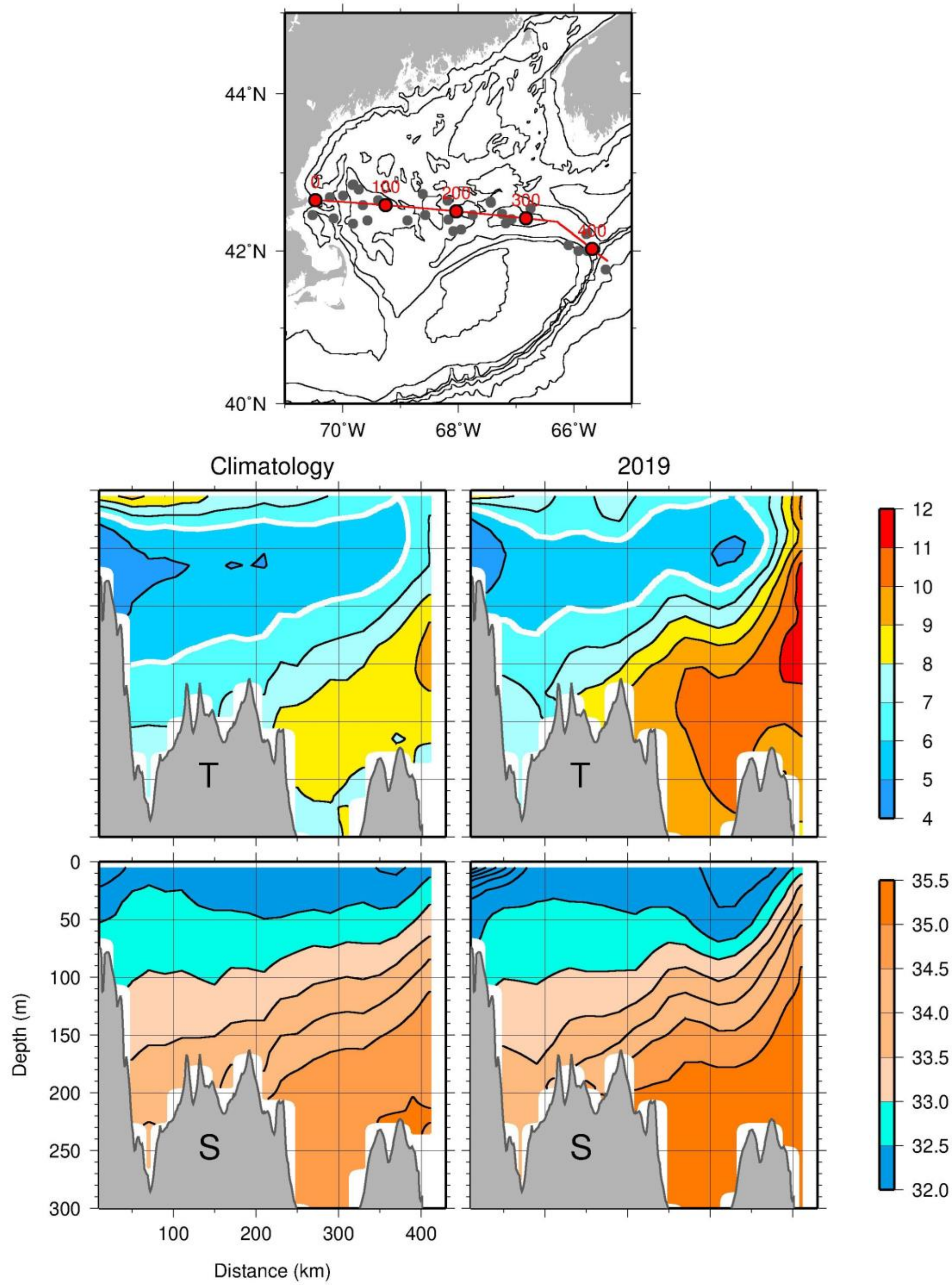

Figure 17. Vertical sections of temperature (top) and salinity (bottom) crossing the Gulf of Maine along a zonal transect shown in the map. The left panels show the climatological average for June spanning the years 1981-2010. The right panels show the synoptic mean section for May 2019. The heavy white contour highlights the 6°C isotherm as an indicator of the boundary of the cold intermediate layer. Along-transect distances and the May 2019 station distribution are shown on the map for reference.