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Hydrographic Conditions on the Northeast United States Continental Shelf in 2020 – NAFO Subareas 5 and 6

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Abstract

A brief overview is presented of the atmospheric and oceanographic conditions on the Northeast U.S. Continental Shelf during 2020. Hydrographic monitoring typically conducted by the operational oceanography programs of the Northeast Fisheries Science Center (NEFSC) were suspended for the entirety of 2020 due to the global pandemic. Time series measurements from a handful of moored buoys in the Gulf of Maine and Southern New England Shelf were examined in their place. All observations point to warmer than average conditions across the region, including in the Cold Intermediate Layer in the eastern Gulf of Maine. Moored measurements in Northeast Channel during fall indicate that warm and salty conditions persist, suggesting that the slope water entering the Gulf of Maine continues to be dominated by southern sources as they have for the past decade.

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, operations were largely suspended in 2020 in response to the global COVID-19 pandemic. In the absence of shipboard observations, timeseries data are examined from several instrumented moorings in the Gulf of Maine and southern New England region (Fig. 9).

During 2020, hydrographic data were collected on 2 NEFSC cruises. Of this total, 130 CTD profiles were obtained within NAFO Subareas 5 and 6 (Table 1). Data were collected at 122 random stratified stations on the shelf south of Hudson Canyon during February-March as part of a truncated spring Groundfish Survey aboard the NOAA ship *Henry Bigelow*. In addition, a limited number of stations were occupied on Nantucket Shoals aboard the NOAA ship *Gloria Michelle* as part of a North Atlantic Right Whale prey study. Data were collected 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://www.fisheries.noaa.gov/resource/data/2010-2019-hydrographic-conditions-northeast-us-continental-shelf-conductivity. 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

Anomaly maps are examined from surface and bottom temperature and salinity in the southern Middle Atlantic Bight – the only subregion that was fully sampled in 2020. 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 2020 value at an individual station and the expected value for each location and time of year based on the reference annual cycle. The methods used and an explanation of uncertainties are presented in Holzwarth and Mountain (1990). In the absence of shipboard measurements, timeseries observations of temperature and salinity are also examined from moored instrumentation maintained in the Gulf of Maine and south of Georges Bank. Hourly time series of water column temperature and salinity measured by Seabird Electronics SBE-37 CTDs are subjected to a 40-hour lowpass filter, while ocean surface temperature observations measured at each of the meteorological buoys are subjected to an 8-day lowpass filter. The resulting timeseries from 2020 are subsequently compared with the average timeseries measured between 2000-2010.

Basin-Scale Conditions in 2020

Surface air temperatures over the western North Atlantic basin were warmer than average throughout most of the year (Fig. 2). Warming was most pronounced over the Northeast U.S. Shelf in Winter and Fall. Colder anomalies were observed over the eastern U.S. extending offshore during spring (April and May). Sea surface temperature mirrored these patterns (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 2019-20 (Fig. 5). 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). Indeed, in winter 2019-20 wind speeds across the North Atlantic were generally higher than average, air temperatures were relatively warm across the northeastern U.S. and the Labrador Sea (IROC, 2021).

Hydrographic Conditions in 2020

Relative to historical values, regional ocean temperatures on the shelf in the southern MAB were warm during spring of 2020 (Fig. 6). On average, waters in the upper 30 meters were near 2°C warmer than normal and even warmer near the bottom, reaching 2.5°C (Fig. 7). Synoptic maps show that the warming was pervasive across the southern MAB at both surface and bottom (Fig 8).

Time series observations of ocean surface temperature collected by NDBC buoys and subsurface measurements from moorings in the Gulf of Maine and south of Georges Bank (Figure 9) provide evidence of warming elsewhere on the Northeast U.S. Shelf. Temperatures in Jordan basin were warmer than average at the surface during summer (June through September) and anomalously warm throughout the year at depth (>=100 m, M01, Fig 10a). Temperatures on the Central Gulf of Maine Shelf (E01) were more than one standard deviation warmer during winter (February-April) and summer (July-August, Fig. 11a). Instruments in the Northeast Channel only recorded during November and December in 2020, but reported temperatures were more than one standard deviation warmer than average at all depths during this time (N01, Fig 12a). Anomalously warm conditions were also recorded at the surface on Cashes Ledge in the northwest Gulf of Maine (NDBC 44005, Fig. 13a), with temperatures ranging from 0.5 to 2.5 C warmer than normal during November when the sensor was recording. Finally, surface water temperatures were warmer than normal during winter south of Georges Bank, with anomalies reaching 2 degrees in March (NDBC 44011, Fig 14a). Most notable in this record was an extreme event recorded in late-June, lasting through mid-July, when temperature anomalies reached 10 C! Satellite derived observations of sea surface temperature reveal a large warm core ring impinging on the shelf in this region with filaments of warm slope water protruding onshore (Fig 15).

On average, surface waters measured slightly saltier than normal in the upper 30 meters of the southern Middle Atlantic Bight when shipboard measurements were conducted during spring (Fig. 16 and 17). Regionally, a mix of positive and negative salinity anomalies were observed across the southern Middle Atlantic Bight, with saline conditions at the shelf edge near the bottom and in the southern portion of the survey area at the surface (Fig. 18). Fresher conditions were observed in the north at both surface and bottom (Fig. 18). Salinity measured by moorings in the Gulf of Maine paint a mixed picture, with fresh conditions observed throughout 2020 in the upper 100 m in Jordan Basin (M01, Fig. 10b), near normal conditions on the central shelf in November (E01, Fig. 11b) and saltier than average conditions at all depths in Northeast Channel during November and December (N01, Fig. 12b).

The warm and salty conditions observed by mooring N01 during November-December are consistent with the persistent warm salty conditions that have been observed by NEFSC shipboard surveys since 2010. This suggests that deep inflow 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. Springtime temperature-salinity profiles from Jordan Basin indicate the presence of a Cold Intermediate layer in the eastern Gulf of Maine, a mid-depth water mass formed seasonally as a product of convective mixing driven by winter cooling (Fig. 19). The remnant winter water in the Cold Intermediate Layer is significantly warmer and slightly fresher than typical in 2020. The temperature of the Cold Intermediate Layer is set by the magnitude of cooling and strength of convective overturn in the winter. During 2020 the upper 50 meters of the water column was fully mixed from February through early May, with evidence that mixing penetrated as deep as 100 m in late March (Fig. 20). However, relative to climatology, surface waters were warmer and fresher than normal in January and did not get as cold in the following months, leading to a warmer intermediate layer. Vertical mixing during winter is an important process in the Gulf of Maine, particularly in the western basin. 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. An example of the effects on shelf temperature are clearly shown in the surface temperature record from NDBC buoy 44011 during July 2020 (Fig. 14).

Summary

- Monitoring activities in 2020 were curtailed by the global COVID-19 pandemic, with shipboard observations limited to the southern Middle Atlantic Bight during early spring
- All observations point to warmer than average conditions across the region
- Moored CTD's in Northeast Channel measured warm and salty conditions at depth during fall, suggesting that slope waters entering the Gulf of Maine continue to be dominated by southern sources.

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Table 1. Inventory of hydrographic monitoring on the Northeast U.S. Shelf during 2020

Sub-area	Division(s)	Month(s)	Type[1]	Description	Station count
5	Y,Z	2,3	O	North Atlantic Right Whale	8
6	A,B,C	3	S	Bottom Trawl Survey	122

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

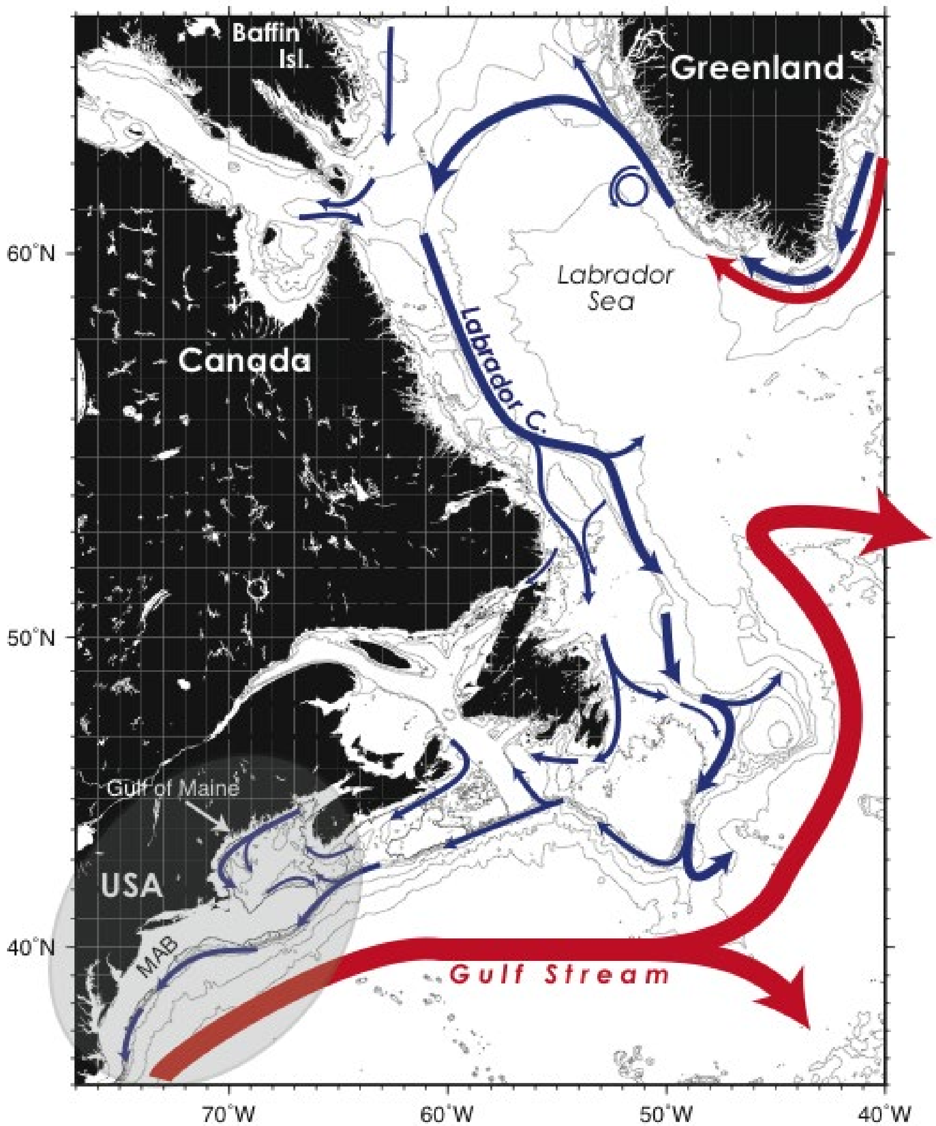


Figure 1a. Circulation schematic of the western North Atlantic. The Northeast U.S. Shelf region is identified by the shaded oval. The 100, 200, 500, 1000, 2000, 3000 and 4000 meter isobaths are shown.

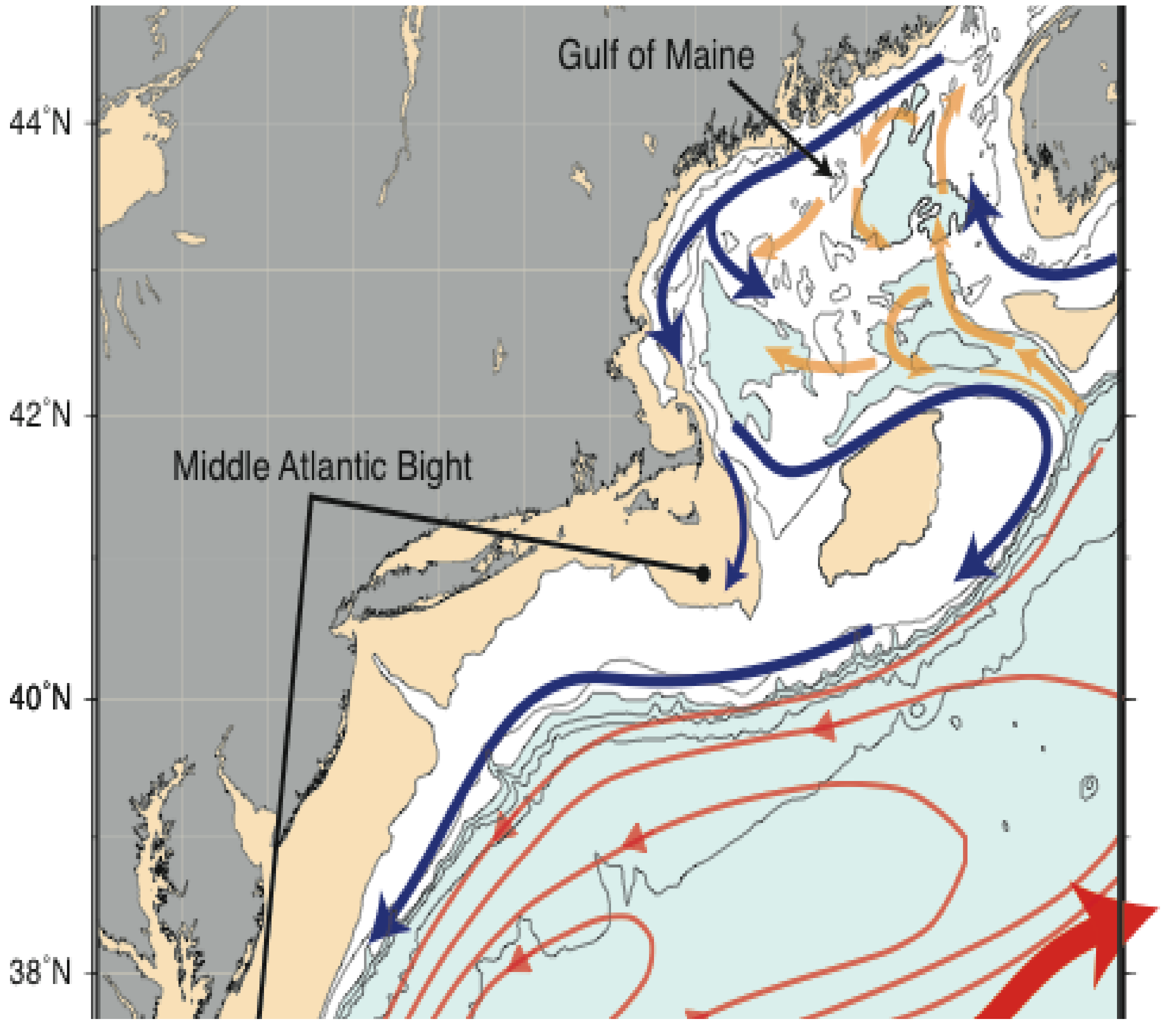


Figure 1b. Circulation schematic for the Northeast U.S. Shelf region, where blue arrows represent shelf water circulation and orange arrows represent deeper slope water circulation pathways. Water depths deeper than 200 meters are shaded blue. Water depths shallower than 50 meters are shaded tan.

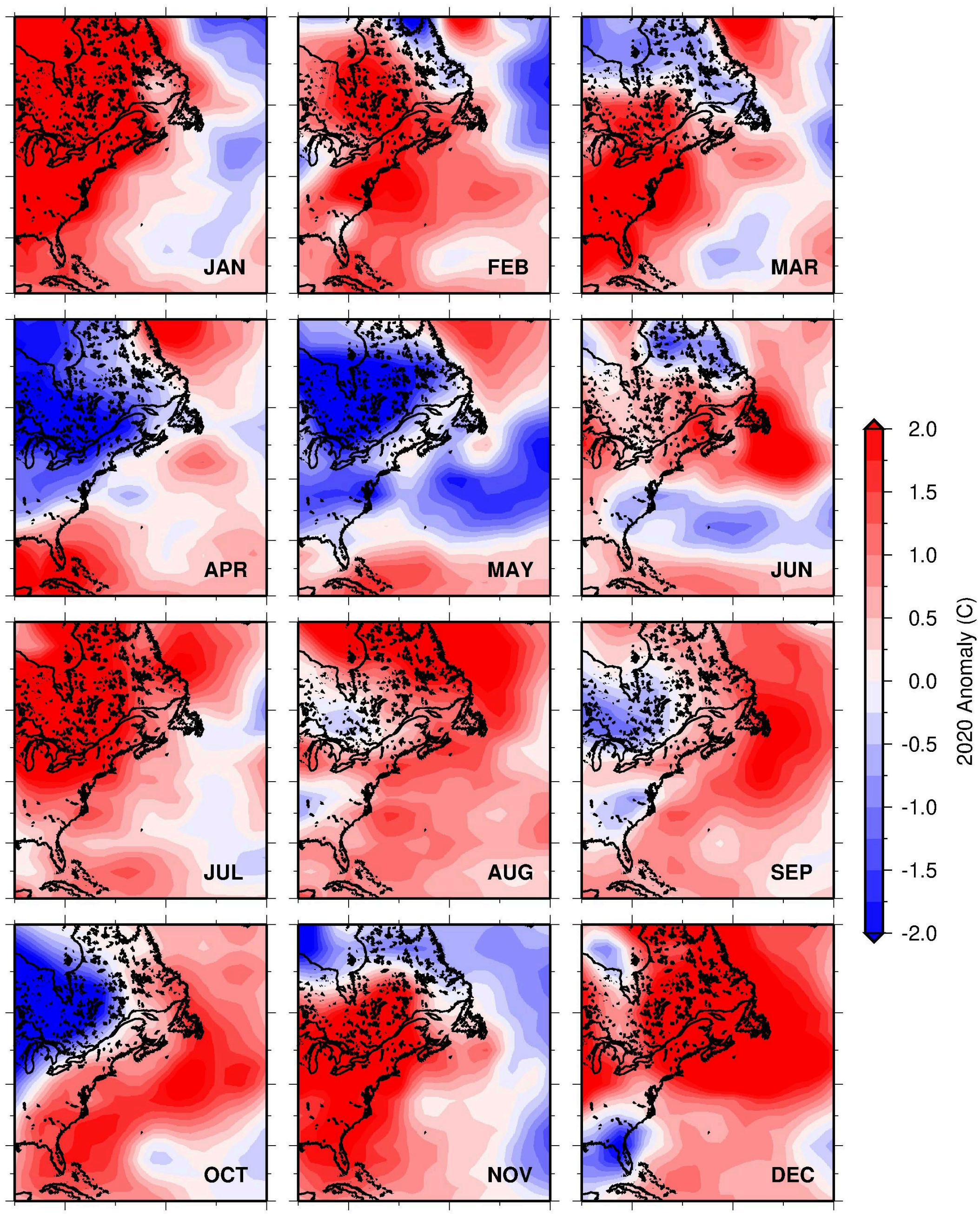


Figure 2. Surface air temperature anomaly derived from the NCEP/NCAR Reanalysis product (http://www.esrl.noaa.gov/psd/data/composites/day/). Positive anomalies correspond to warming in 2020 relative to the reference period (1981-2010).

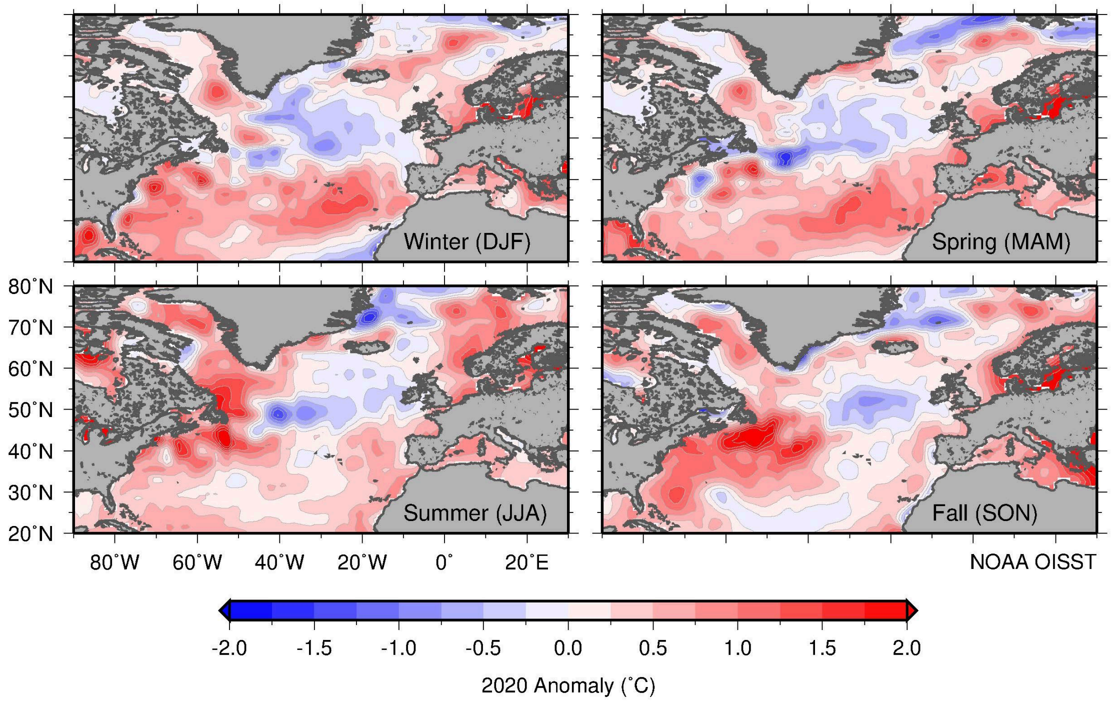


Figure 3. Sea surface temperature anomaly derived from the NOAA's Optimum Interpolation (OI) SST product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html). Seasons are made up of 3-month periods where winter spans December-February. Positive anomalies correspond to warming in 2020 relative to the reference period (1981-2010).

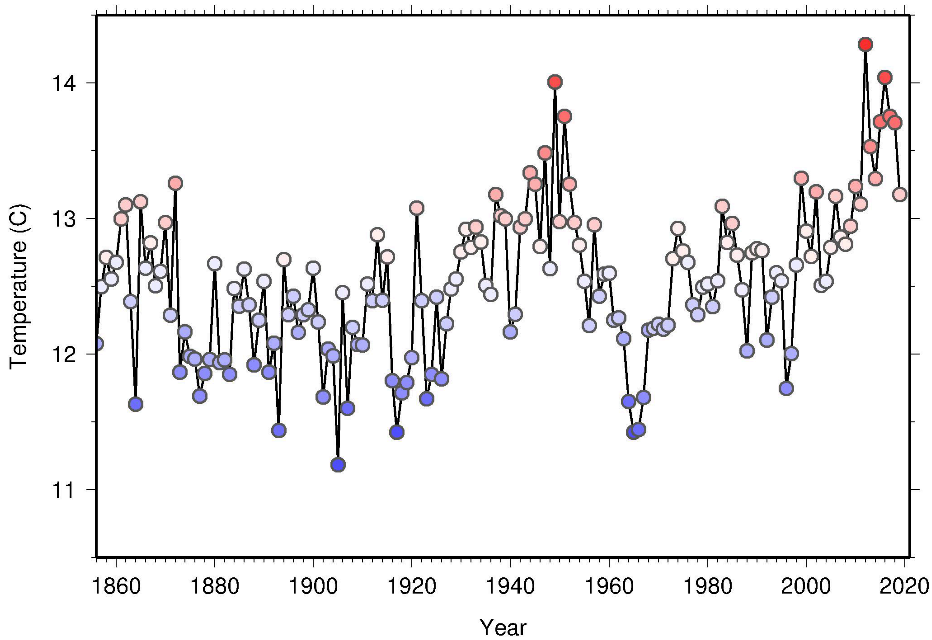


Figure 4. Regional average annual sea surface temperature for the NEUS shelf region calculated from NOAA's extended reconstructed sea surface temperature product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html). Colors correspond with the anomaly scale in Figure 3.

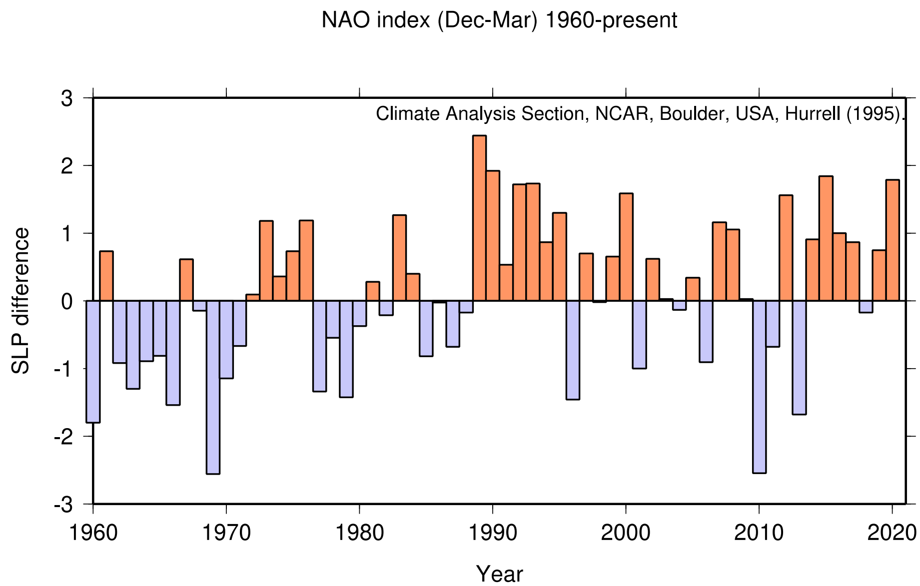


Figure 5. North Atlantic Oscillation index computed from principal component analysis of sea level pressure in the North Atlantic (see Hurrell, 1995).

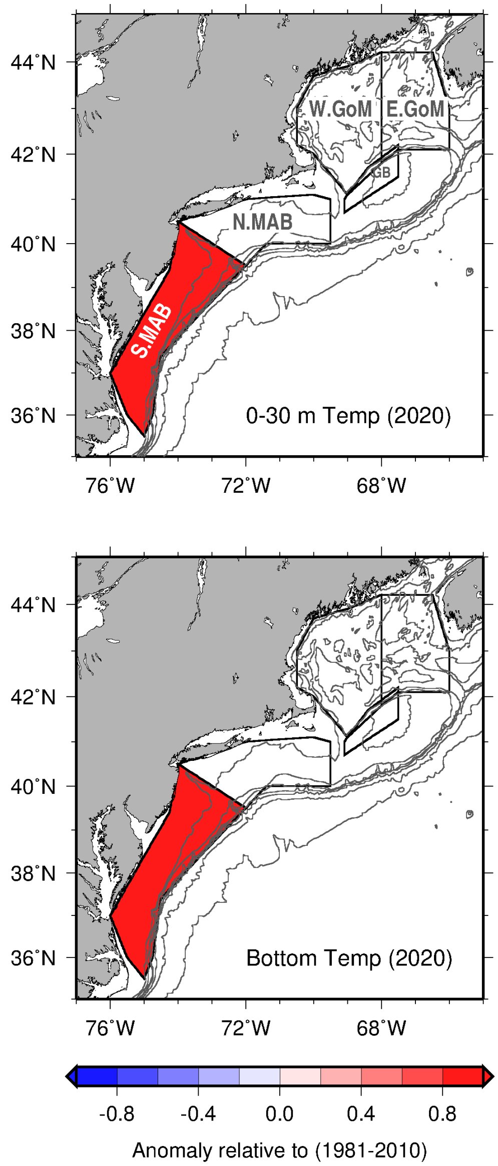


Figure 6. Surface (upper panel) and bottom (lower panel) regional average temperature anomaly (°C). Positive anomalies correspond to warming in 2020 relative to the reference period (1981-2010). The region labels correspond to the panels in Figure 6.

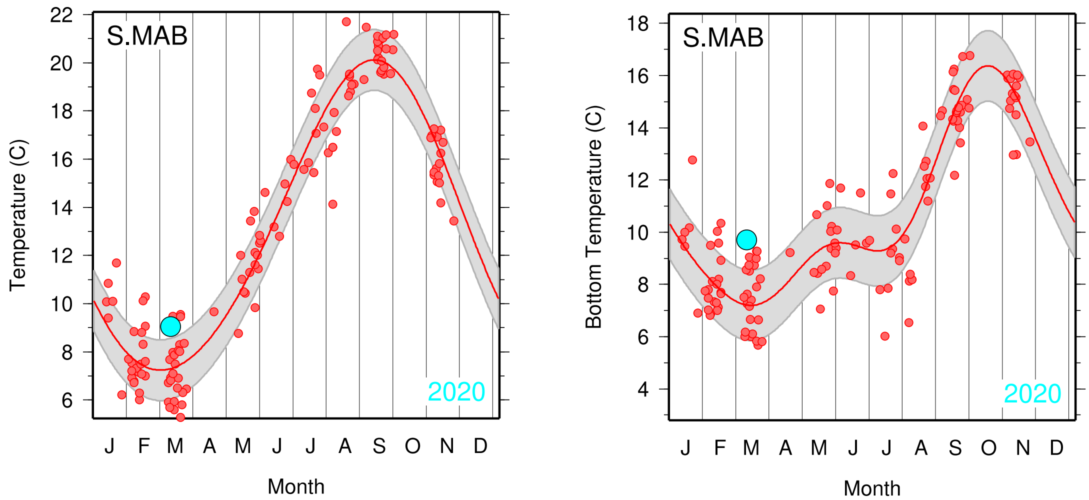


Figure 7. Regional average 0-30 meter temperature (°C) (left) and near bottom (right) as a function of calendar day in the southern MAB. The other regions were not sampled with sufficient spatial coverage to calculate regional averages. Each dot represents a volume-weighted average of all observations 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 2020 surveys are shown in cyan.

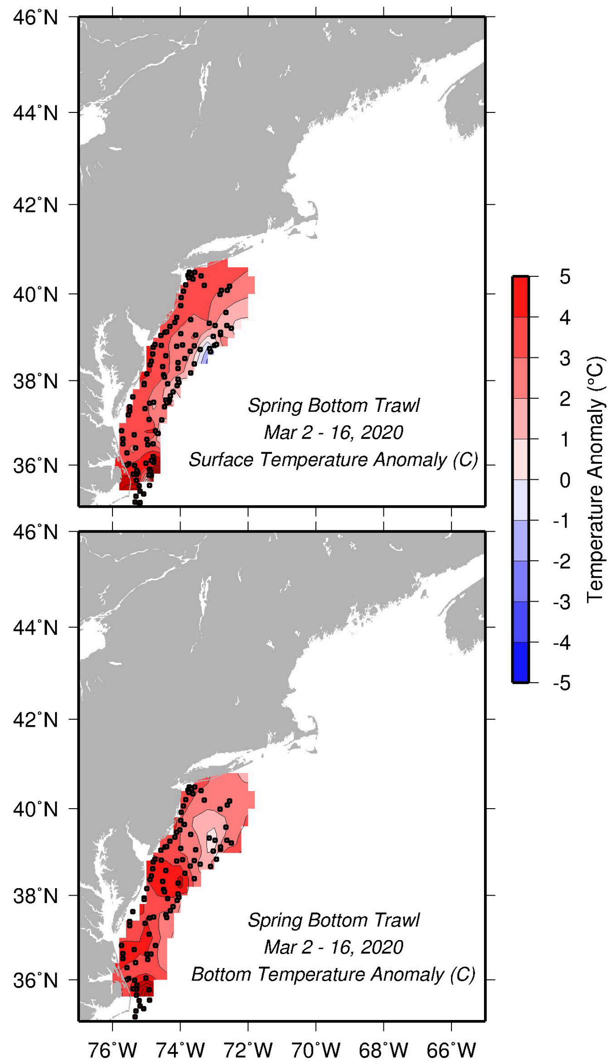


Figure 8. Surface (upper panels) and bottom (lower panels) temperature anomaly from the truncated spring 2020 ground fish survey. Positive anomalies correspond to warmer conditions in 2020 relative to the reference period (1977-1987).

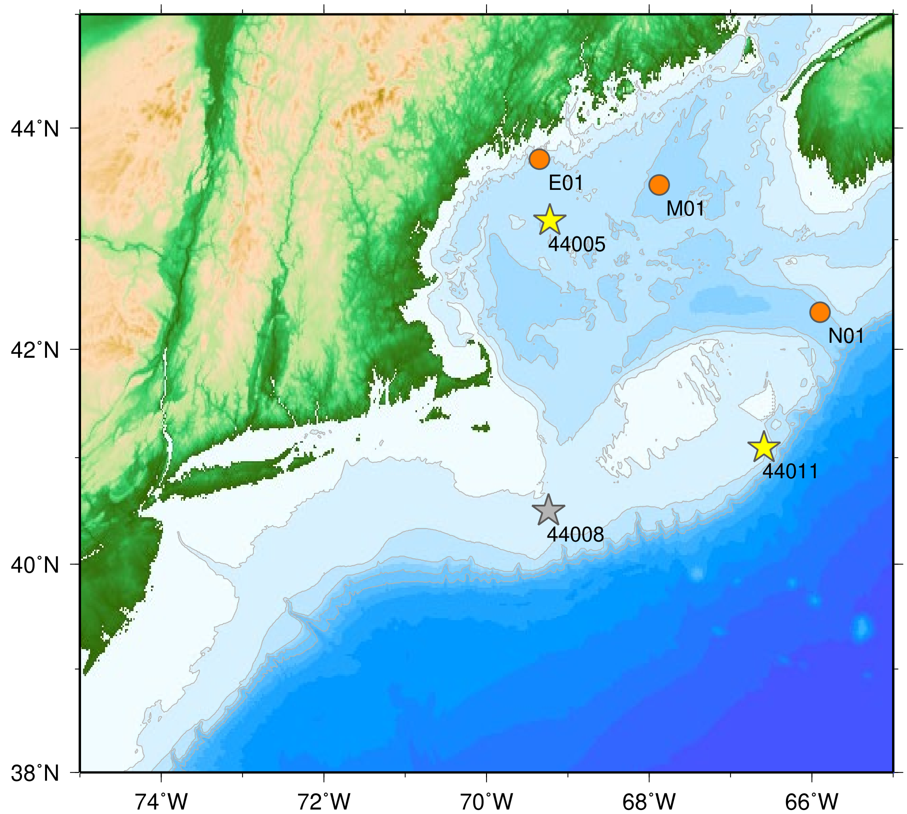


Figure 9. Map of buoy/mooring locations in the Northeast U.S. Shelf region. Stars show the location of three meteorological buoys maintained by the National Data Buoy Center (NOAA) from which observations of ocean surface temperature are analyzed. The grey shading indicates no data was available in 2020. The circles show the location of oceanographic moorings instrumented with Conductivity Temperature Depth (CTD) instruments and maintained by the University of Maine. Observations of temperature and salinity are analyzed from moorings deployed on the Central Gulf of Maine Shelf (E01), in Jordan Basin (M01) and in the Northeast Channel (N01). Contours show the 50m ,100m, 200m, 500m, and 1000m isobaths.

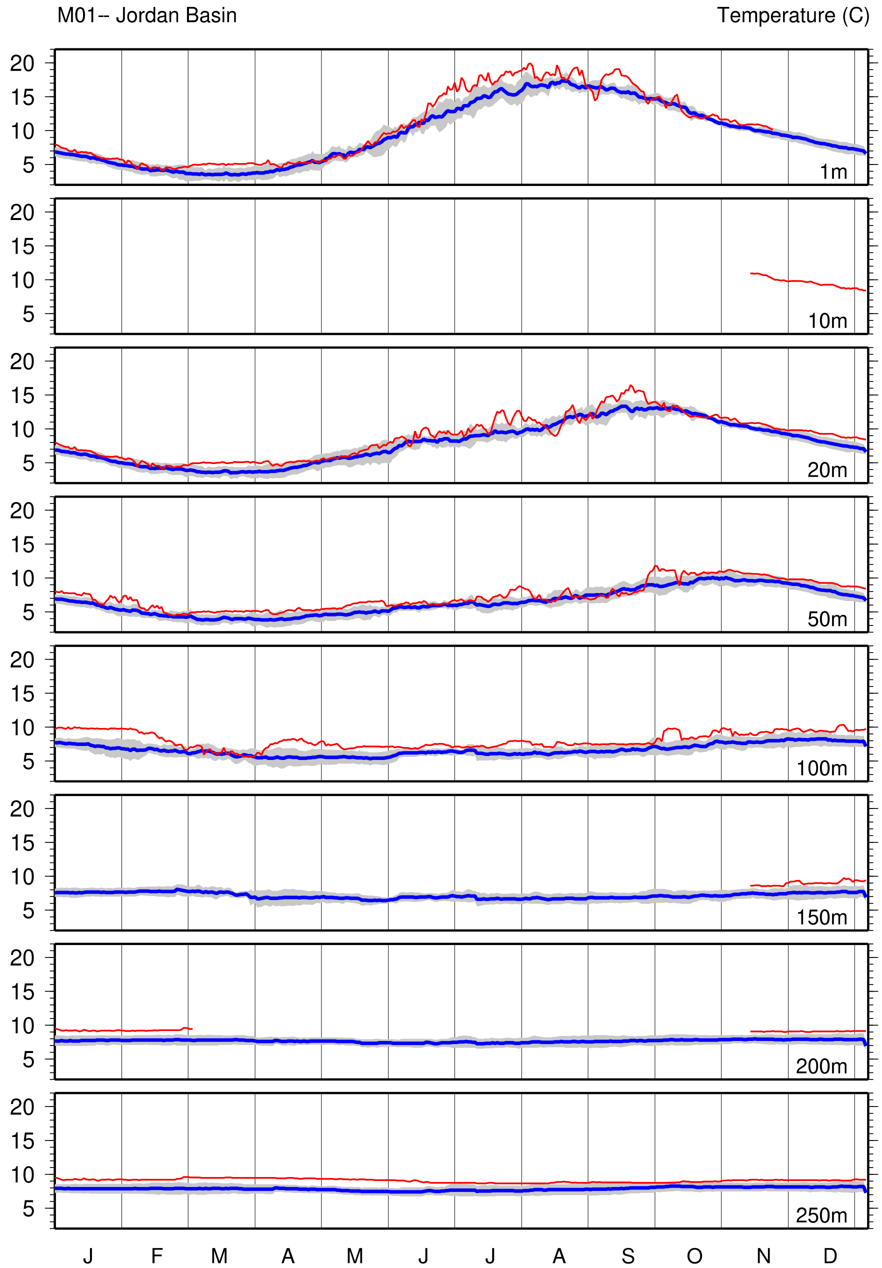


Figure 10a. Time series of temperature measured by CTDs at various depths on mooring M01, located in Jordan Basin (Figure 6). Temperatures observed in 2020 (red) are compared with average temperatures (2000-2010, blue). The gray shading indicates one standard deviation about the long-term mean.

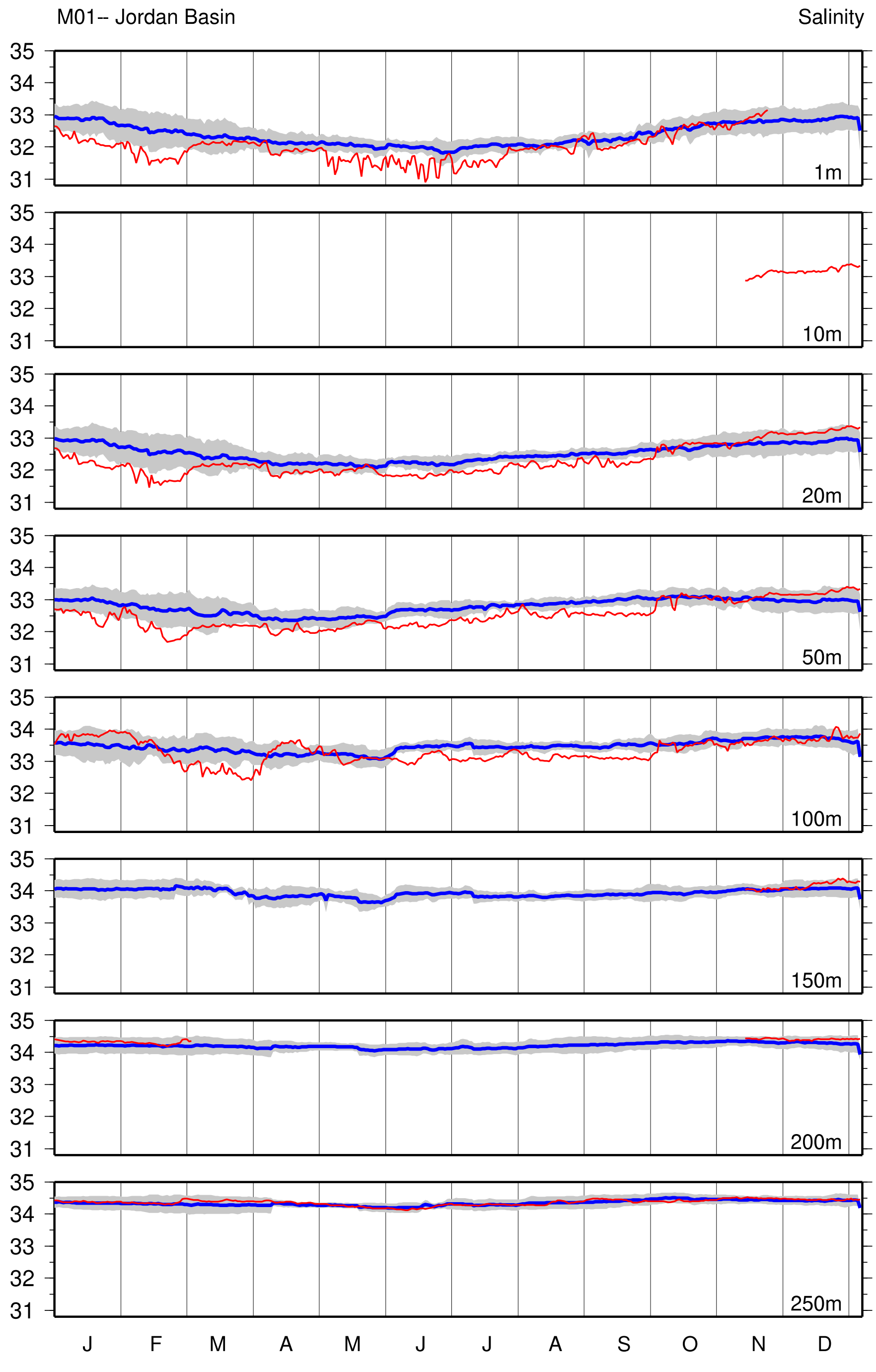


Figure 10b. Time series of salinity measured by CTDs at various depths on mooring M01, located in Jordan Basin (Figure 6). Temperatures observed in 2020 (red) are compared with average temperatures (2000-2010, blue). The gray shading indicates one standard deviation about the long-term mean.

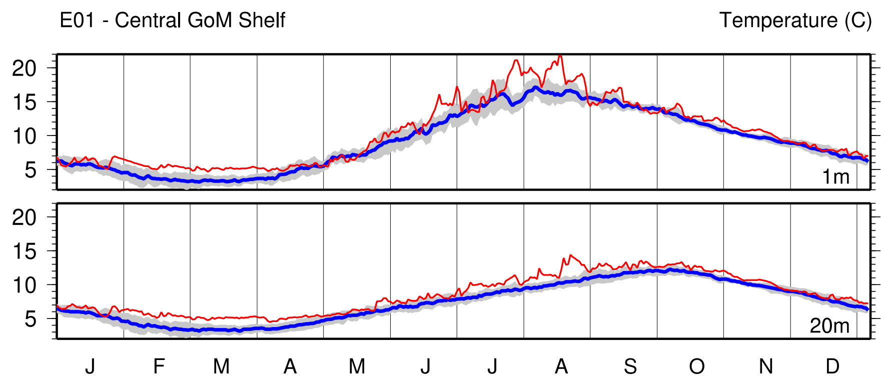


Figure 11a. Time series of temperature measured by CTDs at various depths on mooring E01, located on the Central Gulf of Maine Shelf (Figure 6). Temperatures observed in 2020 (red) are compared with average temperatures (2000-2010, blue). The gray shading indicates one standard deviation about the long-term mean.

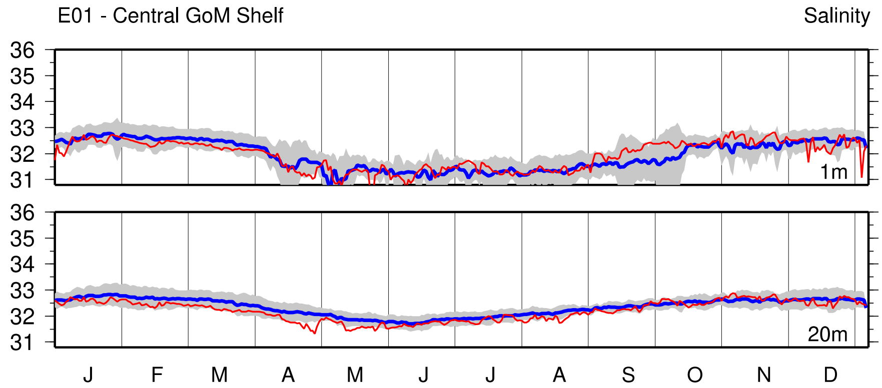


Figure 11b. Time series of salinity measured by CTDs at various depths on mooring E01, located on the Central Gulf of Maine Shelf (Figure 6). Temperatures observed in 2020 (red) are compared with average temperatures (2000-2010, blue). The gray shading indicates one standard deviation about the long-term mean.

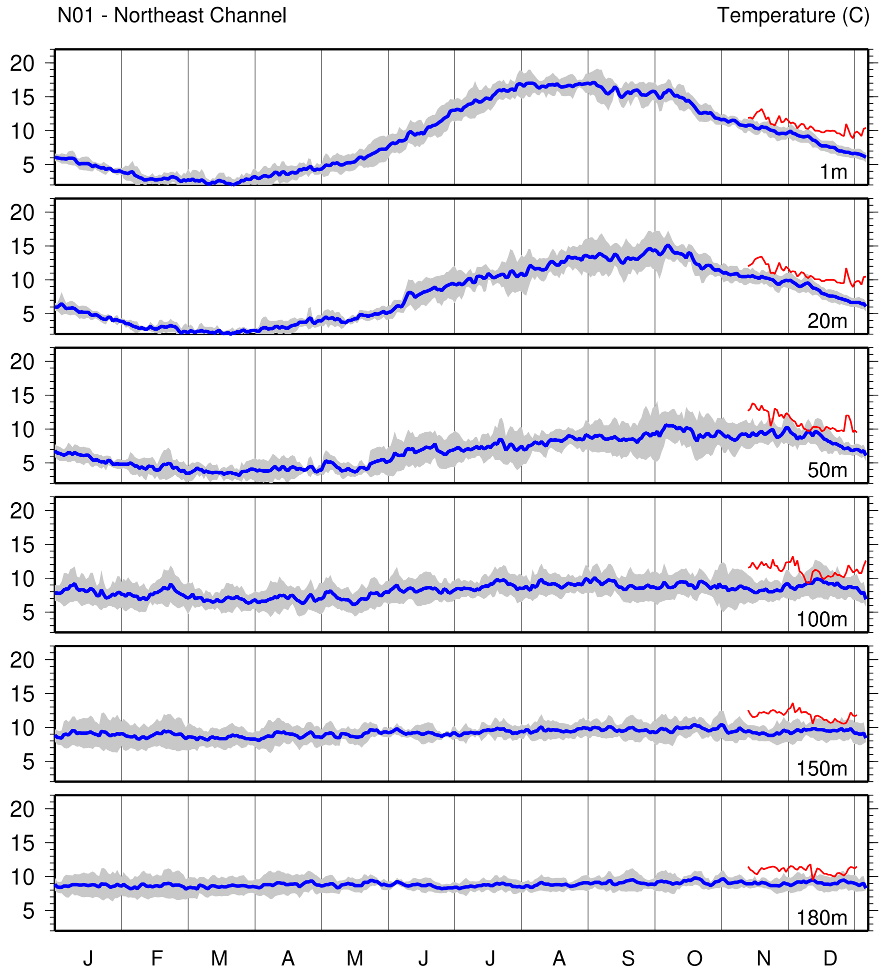


Figure 12a. Time series of temperature measured by CTDs at various depths on mooring N01, located in Northeast Channel (Figure 6). Temperatures observed in 2020 (red) are compared with average temperatures (2000-2010, blue). The gray shading indicates one standard deviation about the long-term mean.

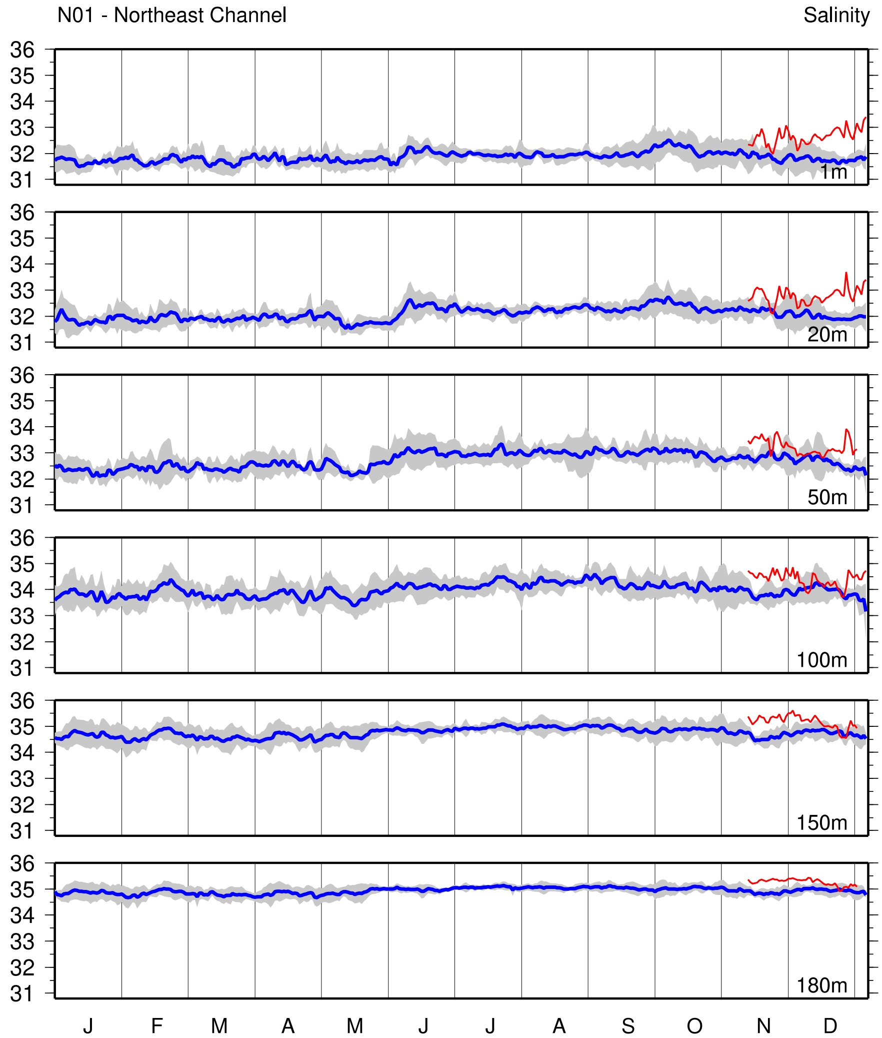
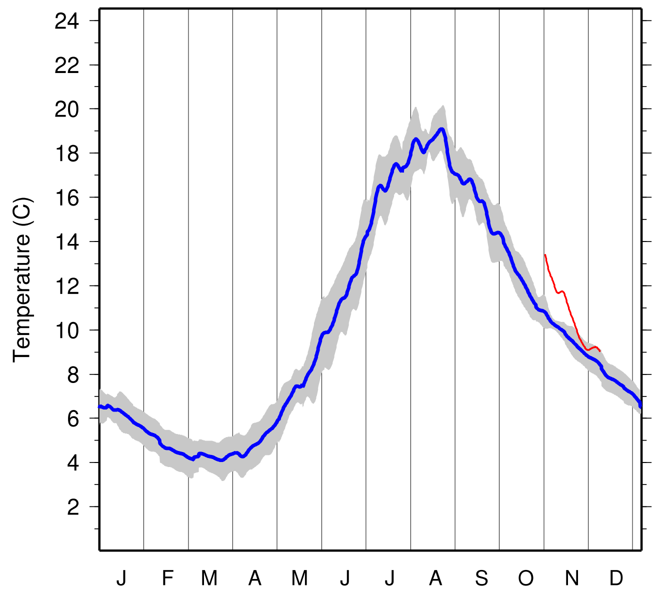


Figure 12b. Time series of salinity measured by CTDs at various depths on mooring N01, located in Northeast Channel (Figure 6). Temperatures observed in 2020 (red) are compared with average temperatures (2000-2010, blue). The gray shading indicates one standard deviation about the long-term mean.



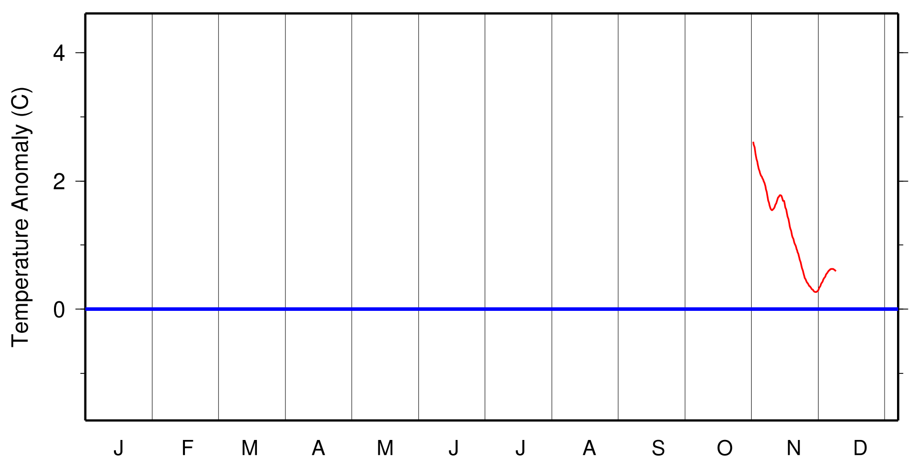


Figure 13. (top) Time series of surface ocean temperature measured by NDBC buoy 44005 located on Cashes Ledge in the northwestern Gulf of Maine (Figure 6). Temperatures observed in 2020 (red) are compared with average temperatures (2000-2010, blue) in the top panel. The gray shading indicates one standard deviation about the long-term mean. The lower panel shows the difference between 2020 and the long-term mean temperature, where positive values indicate warmer conditions in 2020.

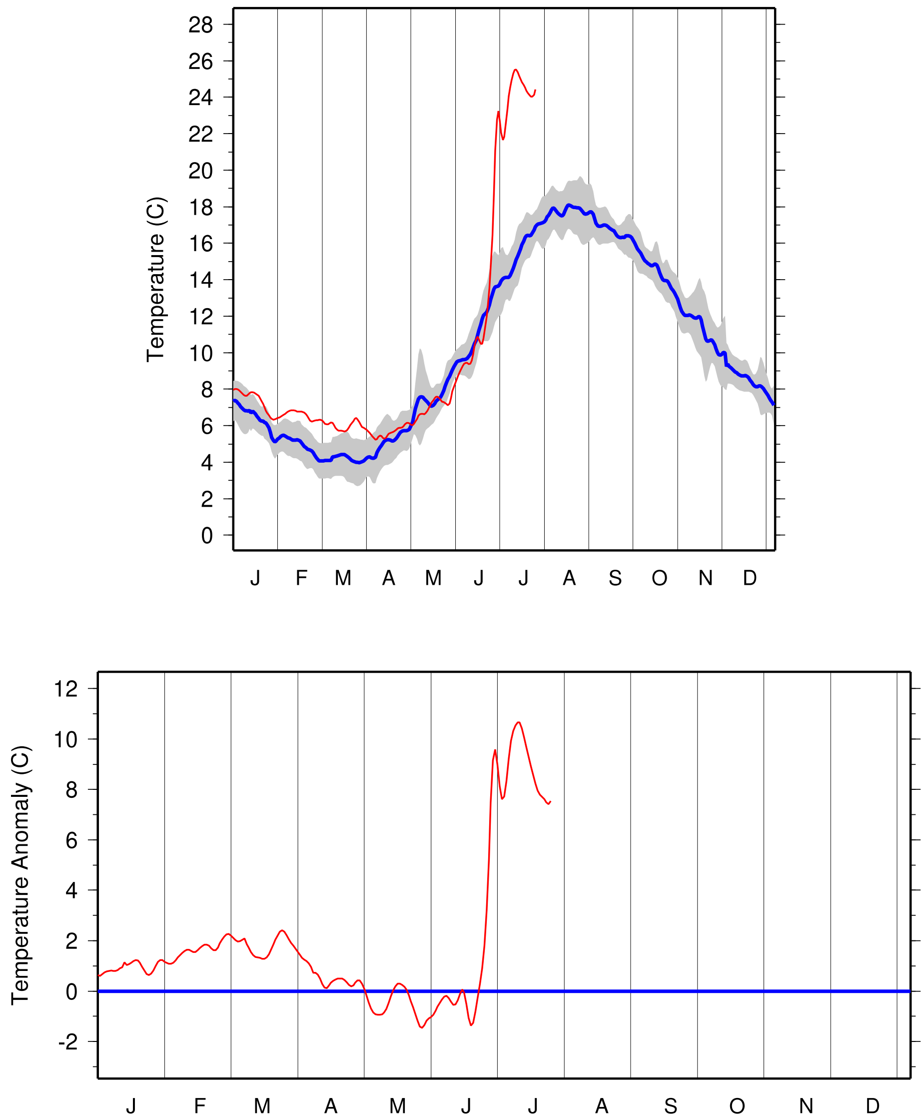


Figure 14. (top) Time series of surface ocean temperature measured by NDBC buoy 44011 located on the shelf south of Georges Bank (Figure 6). Temperatures observed in 2020 (red) are compared with average temperatures (2000-2010, blue) in the top panel. The gray shading indicates one standard deviation about the long-term mean. The lower panel shows the difference between 2020 and the long-term mean temperature, where positive values indicate warmer conditions in 2020.

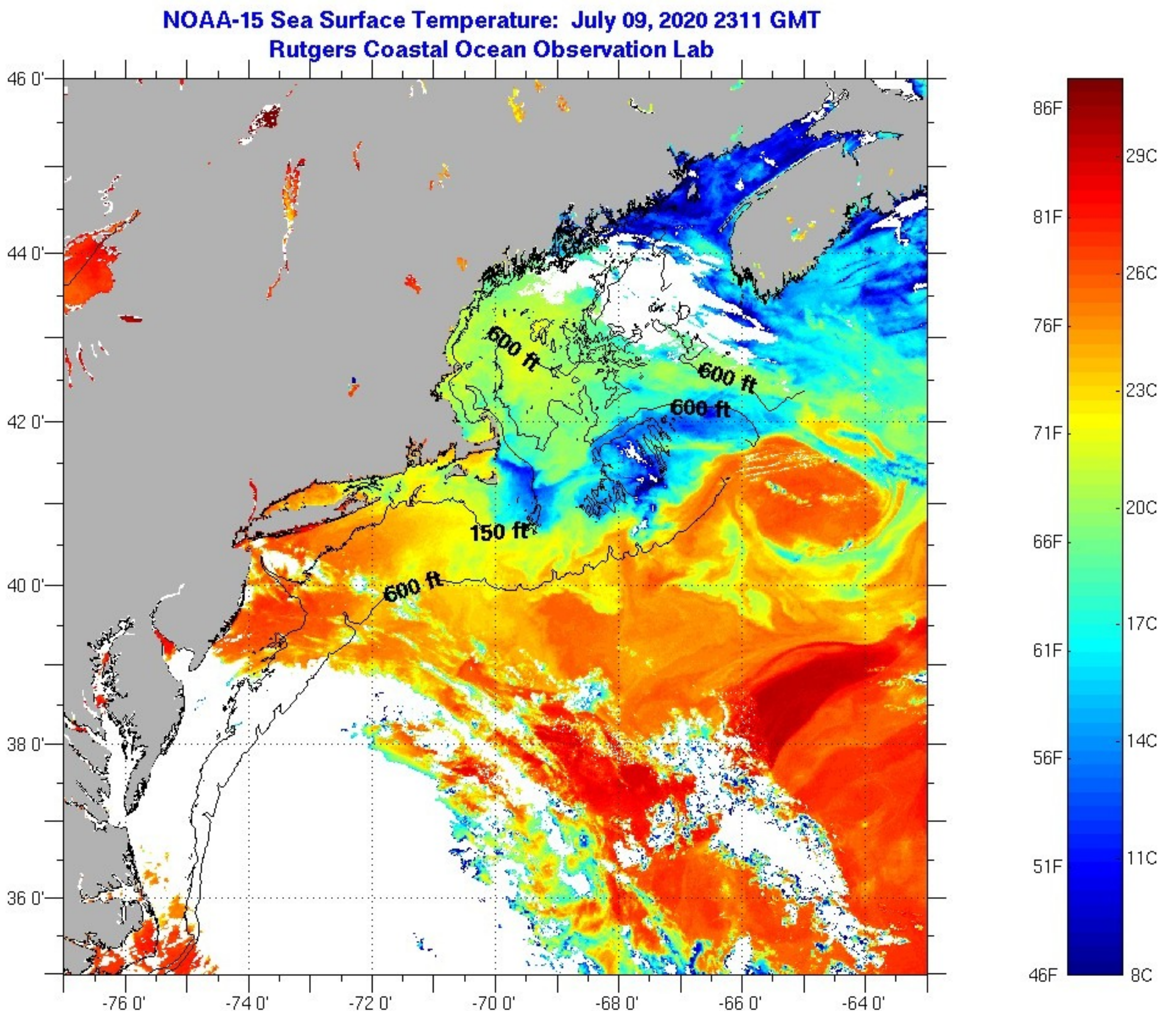


Figure 15. Daily composite sea surface temperature derived by the Coastal Ocean Observations Lab, Rutgers University, from data collected by the Advanced Very High Resolution Radiometer on July 9, 2020.

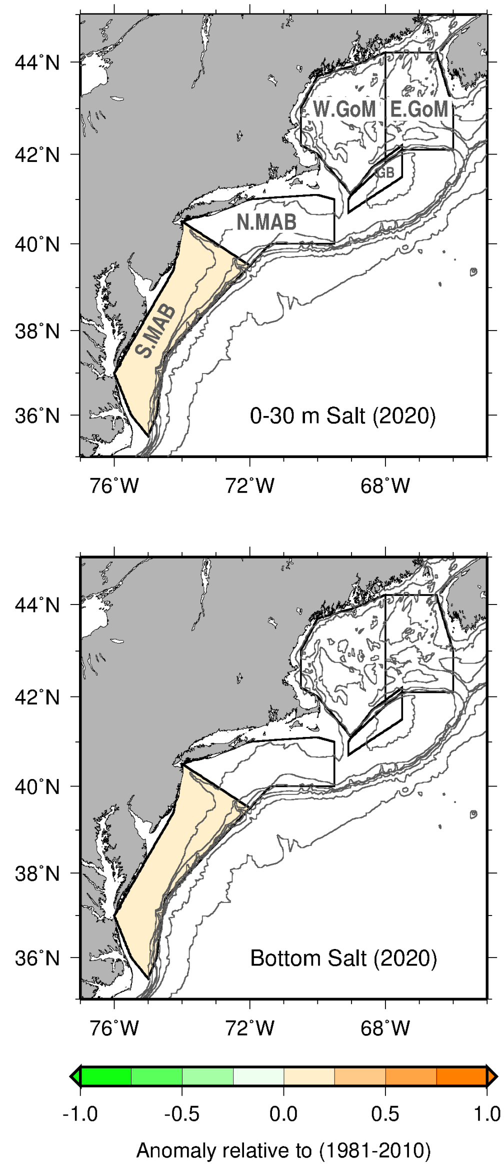


Figure 16. Surface (upper panel) and bottom (lower panel) regional annual salinity anomaly. Positive anomalies correspond to more saline conditions in 2020 relative to the reference period (1981-2010). The region labels correspond to the panels in Figure 17.

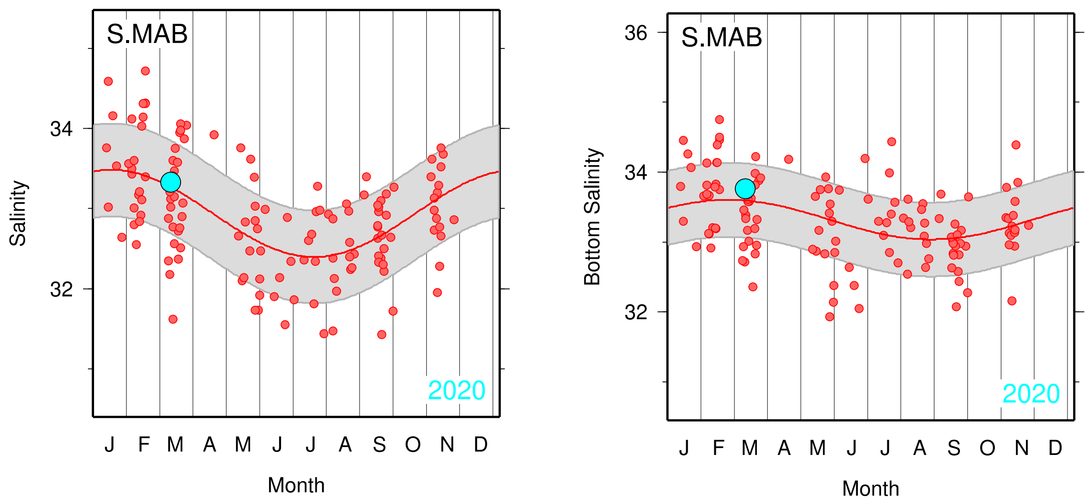


Figure 17. Regional average 0-30 meter salinity (left) and near bottom salinity (right) as a function of calendar day in the southern MAB. The other regions were not sampled with sufficient spatial coverage to calculate regional averages. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 16. 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 salinities from 2020 surveys are shown in cyan.

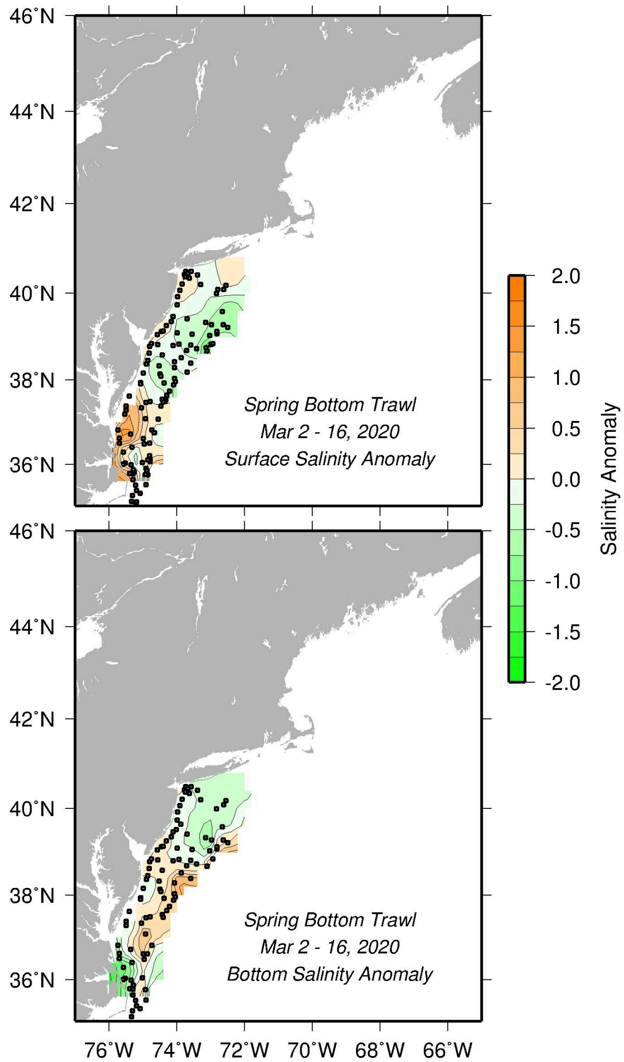


Figure 18. Surface (upper panels) and bottom (lower panels) salinity anomaly from the truncated spring 2020 ground fish survey. Positive anomalies correspond to more saline conditions in 2020 relative to the reference period (1977-1987).

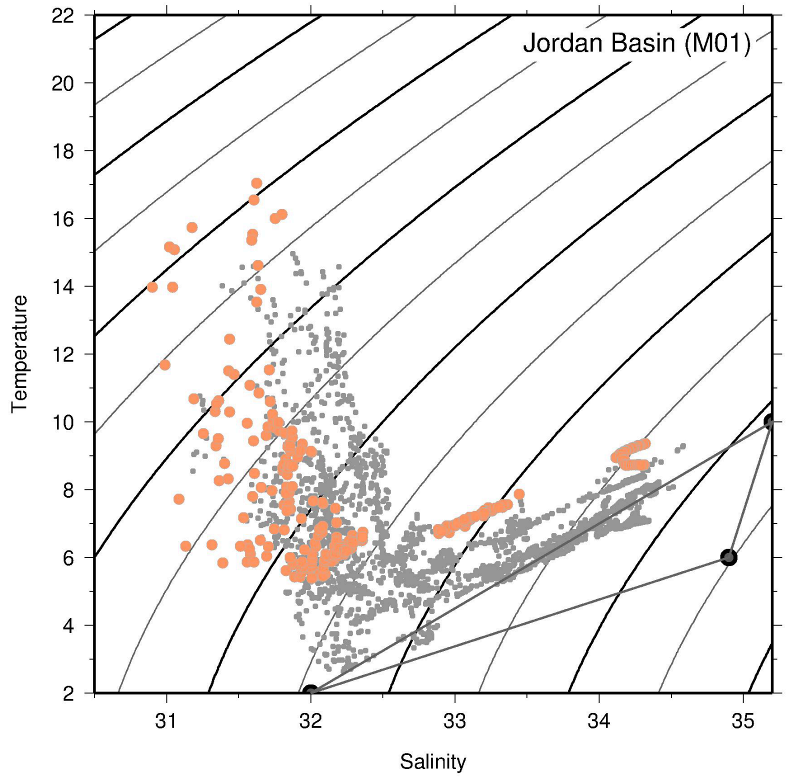


Figure 19. Temperature-salinity diagram showing water properties in Jordan Basin as measured by mooring M01 in the eastern Gulf of Maine (Fig 9). Observations collected April-June 2020 are shown in orange. The gray dots show the historical range encompassed by observations from the reference period, 1981-2010. Temperature and salinity properties representative of source waters entering the Gulf of Maine are shown by the mixing triangle.

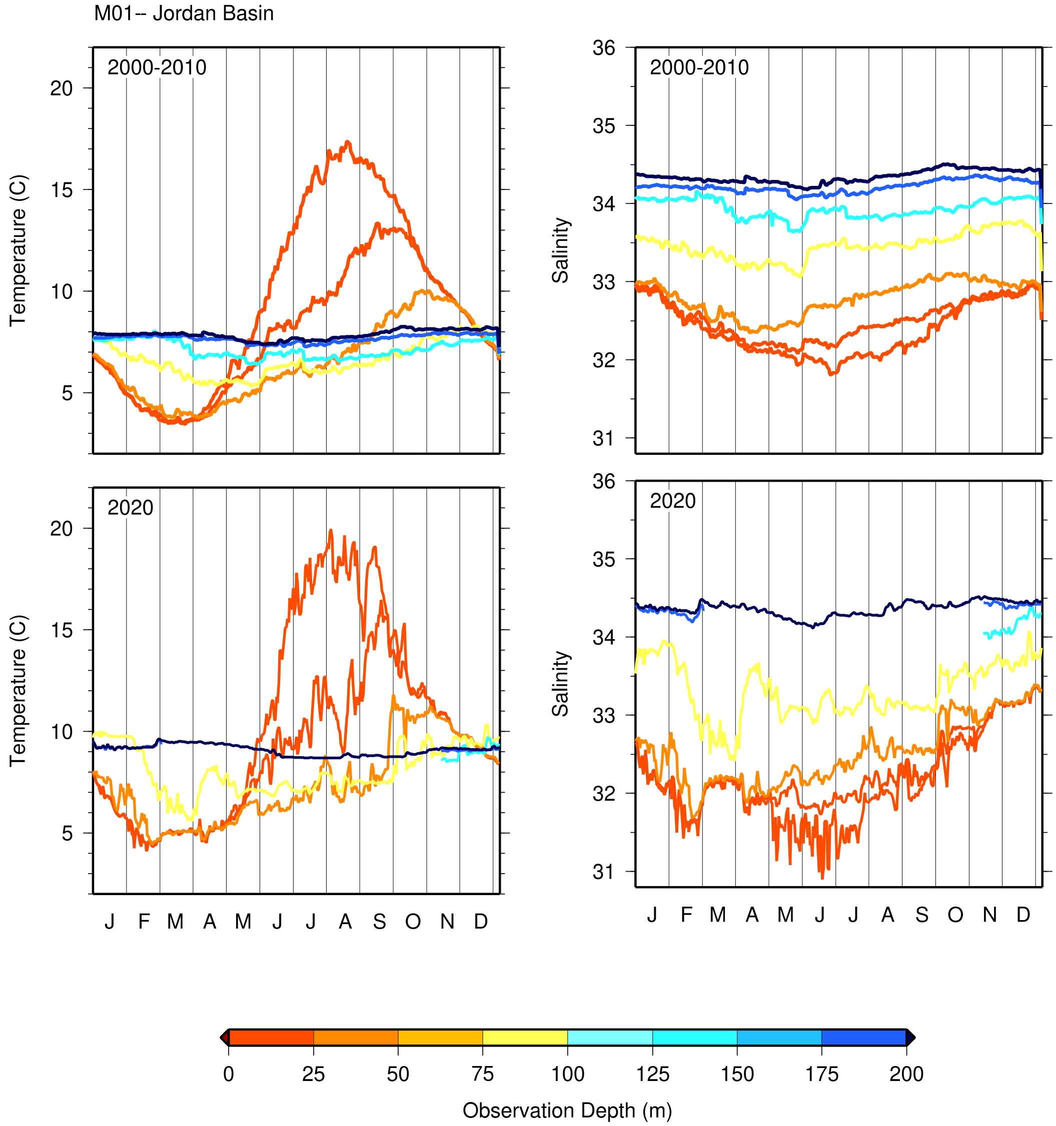


Figure 20. Annual cycle of temperature (left) and salinity (right) measured by CTDs at various depths on mooring M01, located in Jordan Basin (Figure 6). Temperature and salinity observed in 2020 (lower panels) are compared with the average temperature and salinity measured between 2000-2010 in the upper panels.