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Hydrographic Conditions on the Northeast United States Continental Shelf in 2022 – 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 2022. 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. Record warm temperatures were recorded across the entire Northeast U.S. Shelf during 2022. Notable cold anomalies observed in the northern Middle Atlantic Bight during Fall are linked to a Warm Core Ring filament and distortion of the shelf-slope front. Deep (slope) waters entering the Gulf of Maine continue to be warmer and saltier than average, marking more than one full decade that southern source waters have dominated the slope water composition in the region. The Cold Intermediate Layer in the western Gulf of Maine was warmer than normal, while the underlying water mass in Wilkinson Basin was much warmer and slightly saltier 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. The

NEFSC aims to complete 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. Reduced sea day allocations in 2022 eliminated both the winter and summer Ecosystem Monitoring (EcoMon) Surveys, leading to a loss in seasonal resolution. Overall, roughly 30% of planned stations were left unsampled for the year, with notable gaps in the far northern (Gulf of Maine) and far southern (southern Middle Atlantic Bight) survey areas (Fig. 2).

During 2022, hydrographic data were collected on 9 individual NEFSC cruises, amounting to 1123 profiles of temperature and salinity and 1012 in NAFO subareas 5 and 6 (Table 1). Data were collected aboard the NOAA *ships FSV Henry Bigelow, FSV Pisces, R/V Ronald H. Brown, R/V Auk and R/V Gloria Michelle*, in addition to the R/V *HR Sharp, and M/V Warren Jr.* using a combination of Seabird Electronics SBE-19+ SEACAT profilers and SBE 9/11 CTD units. Cruise reports are accessible at: https://www.fisheries.noaa.gov/resource/data/2010-2019-ecosystem-monitoring-northeast-us-continental-shelf-cruise-reports. 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. 7 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 1991-2020. The reference period corresponds with the standard recommended by the World Meteorological Organization (WMO, 2021). Anomalies are defined as the difference between the observed 2022 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 2022

Surface air temperatures over the western North Atlantic basin were very cold in the north and warmer in the south during the first few months of 2022 (Fig. 3). In January, the eastern US and Canada, exclusive of Newfoundland and Nova Scotia, were blanketed by extreme cold anomalies which extended offshore into the Labrador Sea in the north and onto the US continental shelf in the south. Warmer air filled in over the eastern seaboard during February-March, displacing cold anomalies over land and along the shelves from the Grand Banks to Florida. By April, warm anomalies dominated throughout most of the western North Atlantic, inclusive of the Labrador Sea. Very warm temperatures were observed over the Northeast U.S. Shelf and Canadian Shelves from August through November, with extreme anomalies observed in the Labrador Sea during September. Sea surface temperatures were consistently warm in the shelf regions south of Newfoundland throughout 2022, while surface waters were generally colder than normal north of Newfoundland during winter, spring and summer (Fig. 4). Warm anomalies were notably strong during summer and fall over the Grand Banks, Gulf of St. Lawrence and Northeast U.S. Shelf, with anomalies extending offshore into the central basin. Regionally, monthly sea surface temperature anomalies on the Northeast U.S. Shelf exceeded 2C in June, August and November (Fig. 5).

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 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 2021-22 (Fig. 6). The positive index was associated with a typical sea level pressure anomaly pattern, involving a deepening of the subpolar (Icelandic) low and strengthening of the subtropical (Azores) high, although action centers are shifted west of their typical positions (IROC, 2023). In 2022, wind speeds across the North Atlantic were generally higher than average further north, but mildly weaker than expected over mid-latitudes east of the U.S. and Canada (IROC, 2023). The distribution of winter air temperature anomalies observed in 2022 (Fig. 3) was consistent with expected patterns under positive NAO conditions, with cold anomalies to the north and warm anomalies to the south.

Hydrographic Conditions in 2022

Relative to historical values (1991-2020), regional ocean temperatures across the NEUS shelf were warm during 2022 (Fig. 7). Annually, the upper ocean (0-30 m) was between 0.9-2.0 degrees warmer than normal across the region, but anomalies were twice as large in the north. This marks a continuation of the gradual warming that has been reported by others for this region, with trends measuring ~.03-.05 °C/year since 1977 and significant interannual variations superimposed on this trend (Fig. 7). Relative to the annual cycle, warming was observed across all seasons in the Gulf of Maine, while warm anomalies were concentrated in March in the Middle Atlantic Bight with near-normal to even cool conditions observed during summer-fall (Fig. 8a). Surface temperature records from an NDBC buoy located south of Nantucket Shoals, corroborate the cold temperatures observed during fall in the shipboard observations (Fig. 9). In addition, the buoy reports an extended period of anomalously warm conditions with pronounced anomalies during June, July, August and November, when surface temperature anomalies reached an impressive 4-5C. Spatial and temporal patterns were similar near the bottom, with bottom temperatures anomalies roughly matching those at the surface (Fig. 7a). Long-term warming trends were consistent from top to bottom in all regions and variability was coherent, particularly in the Middle Atlantic Bight where water depths are shallower than in the Gulf of Maine (Fig. 7b). Like the upper ocean, very warm anomalies were observed year-round at the bottom of the Gulf of Maine (Fig. 8b). Similarly, warm anomalies were also observed near bottom in the Middle Atlantic Bight, particularly during March and June (Fig. 8b). The spatial distribution of the seasonal differences is revealed in synoptic maps compiled from the spring and fall ground fish surveys (Fig. 10). Warm anomalies were observed at the surface and bottom across the entire Northeast Shelf in spring. Notably cool conditions were observed across the Northern Middle Atlantic Bight during fall, particularly at the surface.

On average, waters in the upper 30 meters were saltier than normal in 2022, particularly in the southern Middle Atlantic Bight (Fig. 11). Large positive anomalies were observed during March and September in the southern Middle Atlantic Bight, where anomalies reached nearly 0.8 psu (Fig. 12a). Similar patterns were observed near the bottom, with more saline conditions observed in the southern Middle Atlantic Bight (Fig. 11). Bottom waters in the Middle Atlantic Bight were saltier than normal throughout the year, except in the northern Middle Atlantic Bight during September, when anomalously fresh conditions were observed

(Fig. 12b). Synoptically, saline conditions were pervasive during spring across the Northeast Shelf (Fig. 13). Fresh anomalies were prevalent in the northern Middle Atlantic Bight during Fall (Fig. 13). These fresh anomalies are coincident with enhanced cold anomalies (Fig. 10) and appear to be associated with a Warm Core Ring filament and associated eddy located directly offshore (Fig. 14). The interaction of this filament with topography at the shelfbreak appears to be driving a so-called Pinocchio's Nose intrusion to the west (Zhang and Gawarkiewicz, 2015) resulting in a contraction of the Cold Pool footprint to the south (Fig. 15). Evidence of the shrinking of the Cold Pool can also be seen in the synoptic maps of bottom temperature anomaly (Fig. 10), wherein isolated positive anomalies observed south of Long Island indicate the absence of the Cold Pool water mass in this region.

Deep inflow through the Northeast Channel continues to be dominated by Warm Slope Water, marking more than one decade that southern source waters have dominated the slope water composition in the region (Fig. 16). Springtime temperature-salinity and temperature-depth profiles indicate the presence of a weak 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. 17 & 18). Remnant winter water in this layer was roughly 2°C warmer than average and capped by very warm surface waters in 2022 (Fig. 19). Deep waters below the Cold Intermediate Layer in Wilkinson Basin were much warmer and slightly more saline than average (Fig. 18 & 19). 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 in situ observations continue to show 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 continue to experience 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). Northward shifts in the Gulf Stream path (NEFSC State of the Ecosystem Report, 2023) and extreme diversions and meanders in its 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, leading to intrusions of comparatively warm and salty water onto the shelf. There is evidence that the frequency of intrusions is increasing in proportion to the increase in Warm Core Rings formed annually (Silver et al., 2023; Gawarkiewicz et al., 2022). 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 in 2022
- Notable cold anomalies were observed in the northern MAB during Fall, likely caused by the influence of a Warm Core Ring filament and distortion of the shelf-slope front
- In the western Gulf of Maine, the Cold Intermediate Layer was warmer than normal, and the underlying water mass in Wilkinson Basin was much warmer and slightly saltier than normal
- Deep waters entering the Gulf of Maine continue to be warm and salty, making more than one full decade that southern source waters have dominated the slope water composition in the region.

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Table 1. Inventory of hydrographic monitoring on the Northeast U.S. Shelf during 2022

Sub-area	Division(s)	Month(s)	Type[1]	Description	Station count
4	X	4,5	S	Bottom trawl survey	12
4	X	6	S	Ecosystems monitoring survey	15
4	X	8	S	East Coast Ocean Acidification survey	7
4	X	11	S	Ecosystems monitoring survey	9
4	X	11	S	Bottom trawl survey	12
5	Y,Z	2,3	S	North Atlantic Right Whale Prey Studies	21
5	Y,Z	3	O	North Atlantic Right Whale	8
5	Y,Z	3,4,5	S	Bottom Trawl Survey	205
5	Y,Z	5,6	O	Sea scallop survey	33
5	Y,Z	5,6	S	North Atlantic Right Whale	29
5	Y,Z	5,6	O	Ecosystems monitoring survey	117
5	Y,Z	8	S	East Coast Ocean Acidification survey	23
5	Y,Z	10,11	S	Bottom Trawl survey	157
5	Y,Z	11	S	Ecosystems monitoring survey	72
6	A,B,C	3	S	Bottom trawl survey	143
6	A,B,C	6	S	Ecosystems monitoring survey	46
6	A,B,C	8,9	O	East Coast Ocean Acidification survey	14
6	A,B,C	9,10	S	Bottom Trawl survey	140
6	A,B,C	11	S	Ecosystems monitoring survey	4

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

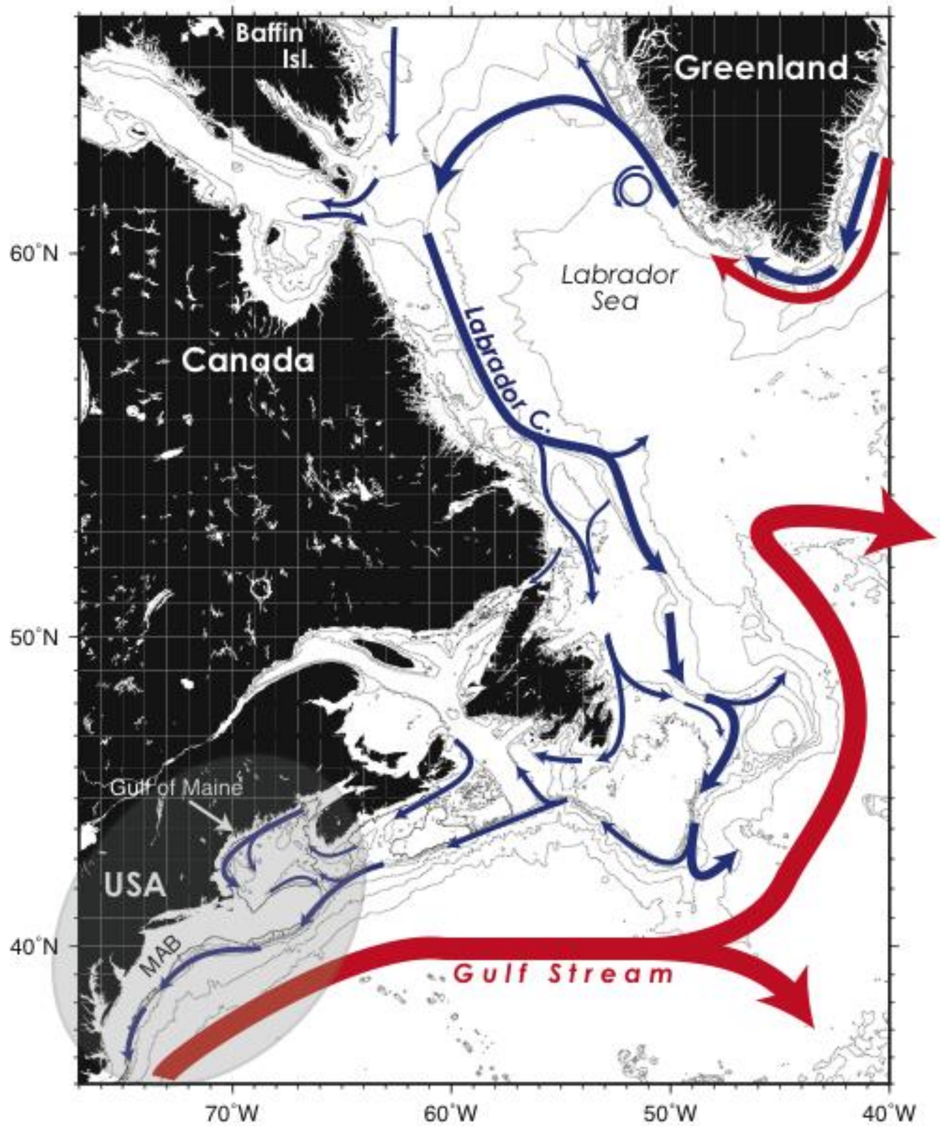


Figure 1a. Circulation schematic of the western North Atlantic. The Northeast U.S. Shelf region is identified by the shaded oval. The 100, 200, 500, 1000, 2000, 3000 and 4000 meter isobaths are shown.

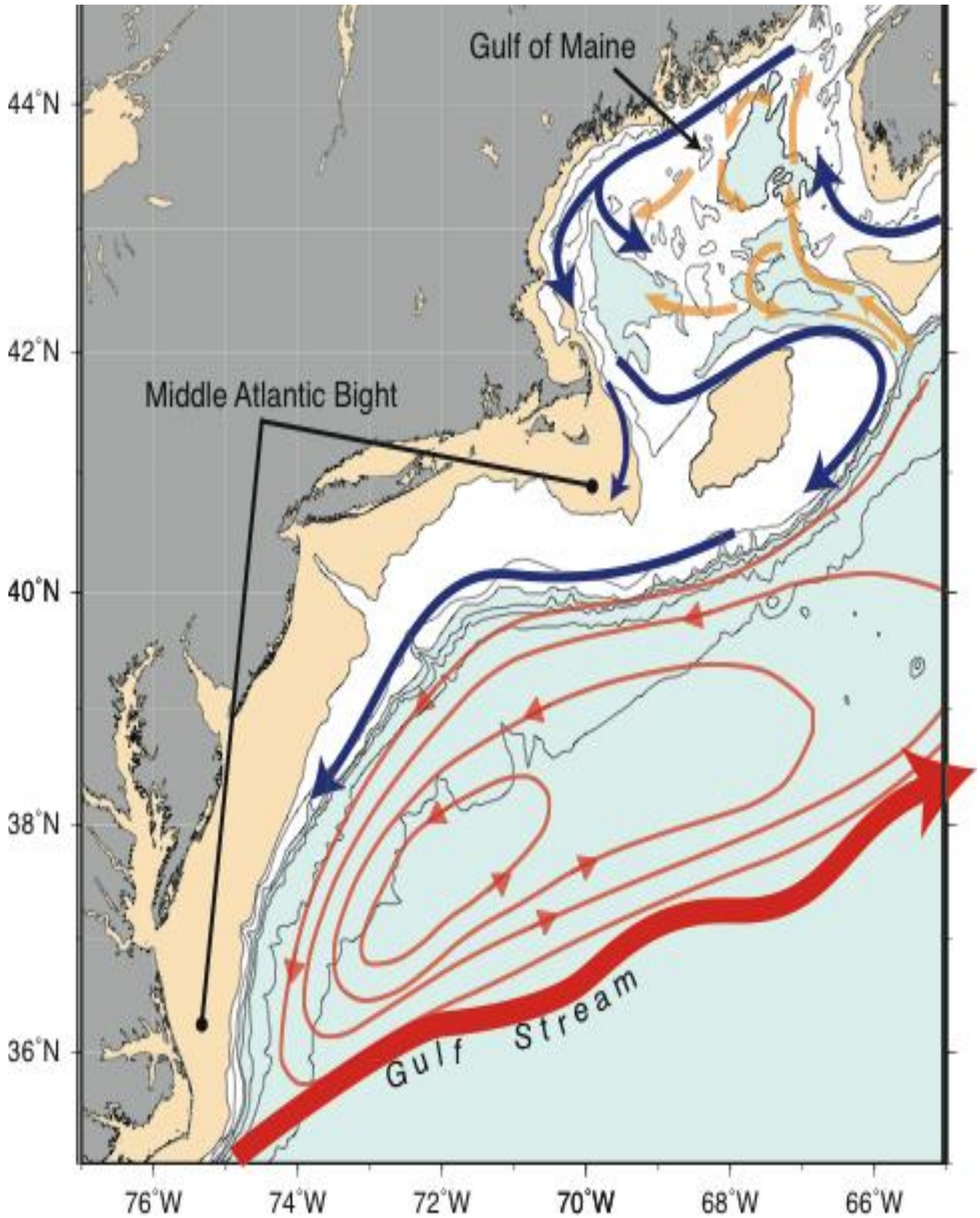


Figure 1b. Circulation schematic for the Northeast U.S. Shelf region, where blue arrows represent shelf water circulation and orange arrows represent deeper slope water circulation pathways. Water depths deeper than 200 meters are shaded blue. Water depths shallower than 50 meters are shaded tan.

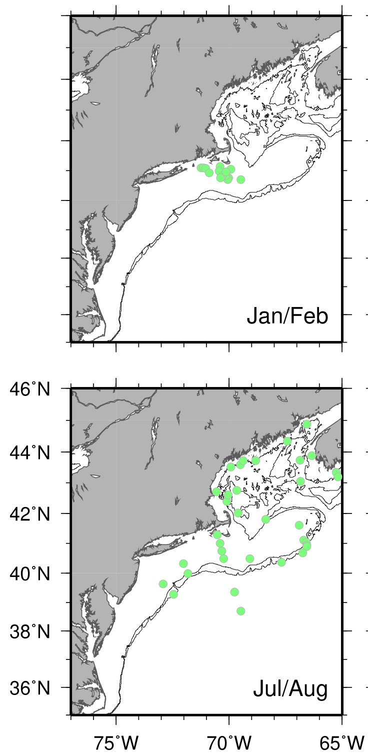


Figure 2. Distribution of hydrographic stations occupied in 2022. Contours show the 100 m and 200 m isobaths.

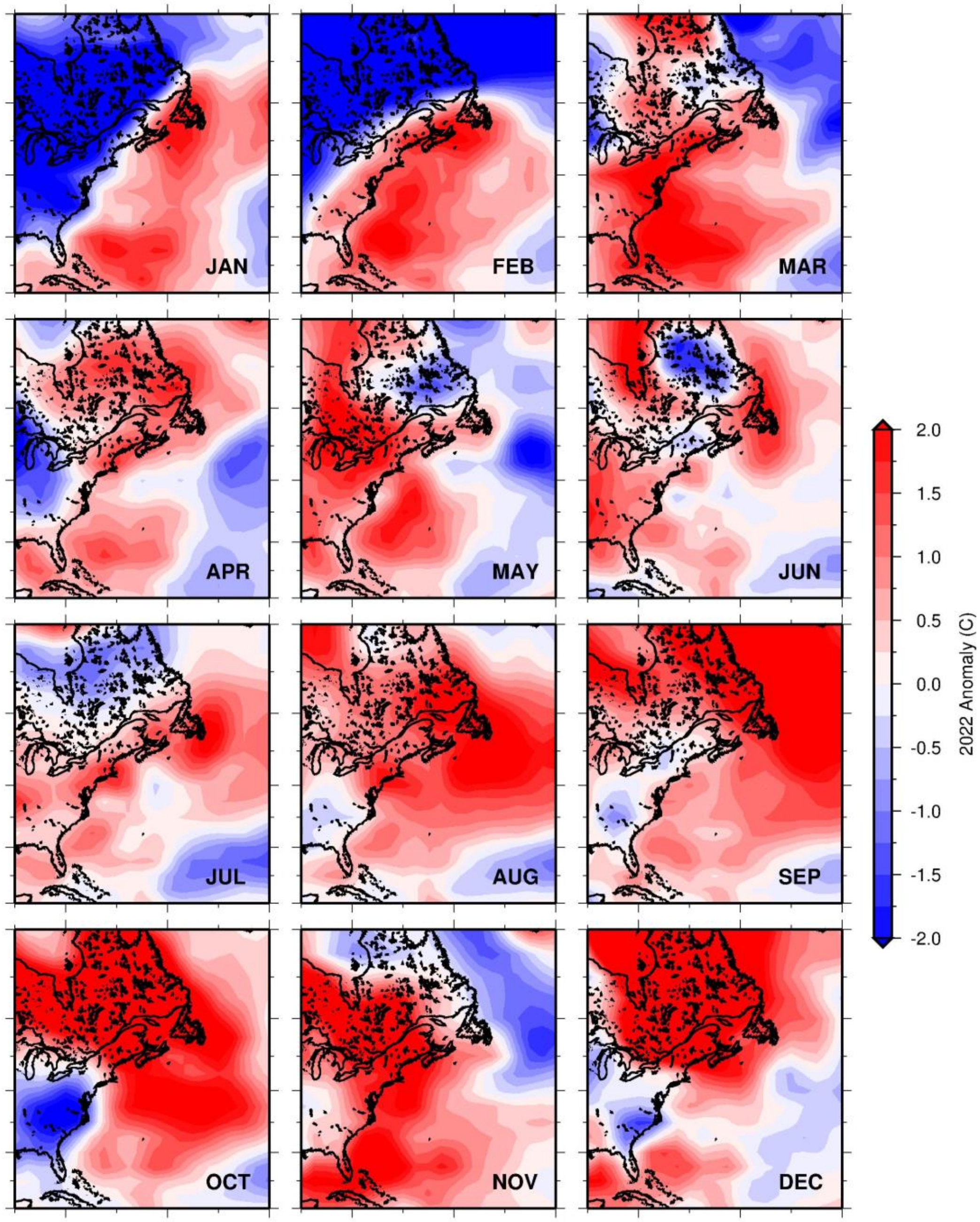


Figure 3. Surface air temperature anomaly derived from the NCEP/NCAR Reanalysis product (http://www.esrl.noaa.gov/psd/data/composites/day/). Positive anomalies correspond to warming in 2022 relative to the reference period (1991-2020).

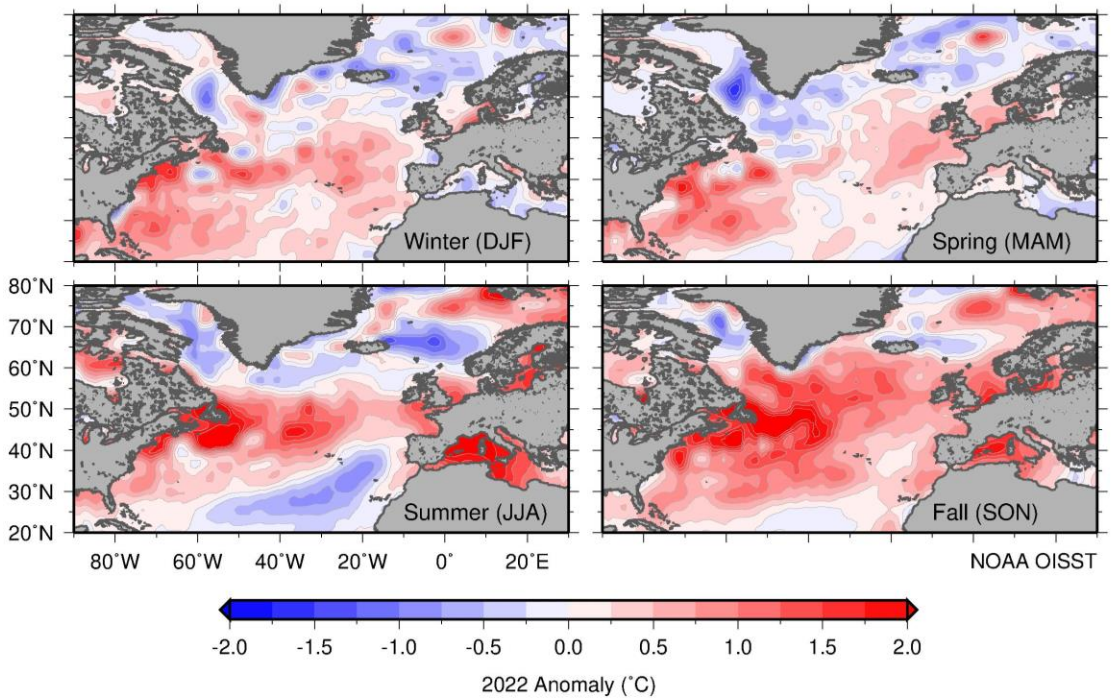
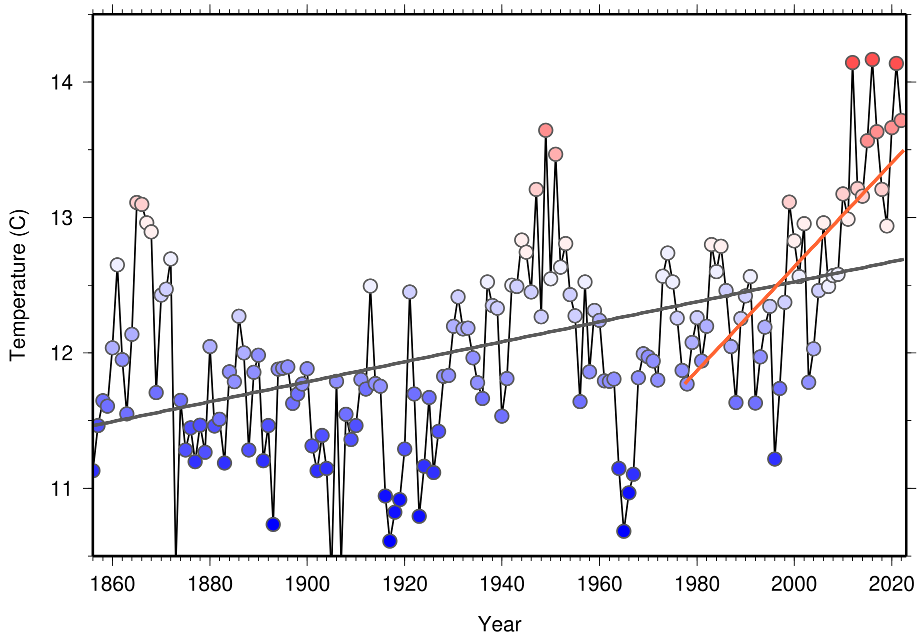


Figure 4. Sea surface temperature anomaly derived from the NOAA's Optimum Interpolation (OI) SST product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html). Seasons are made up of 3-month periods where winter spans December-February. Positive anomalies correspond to warming in 2022 relative to the reference period (1991-2020).



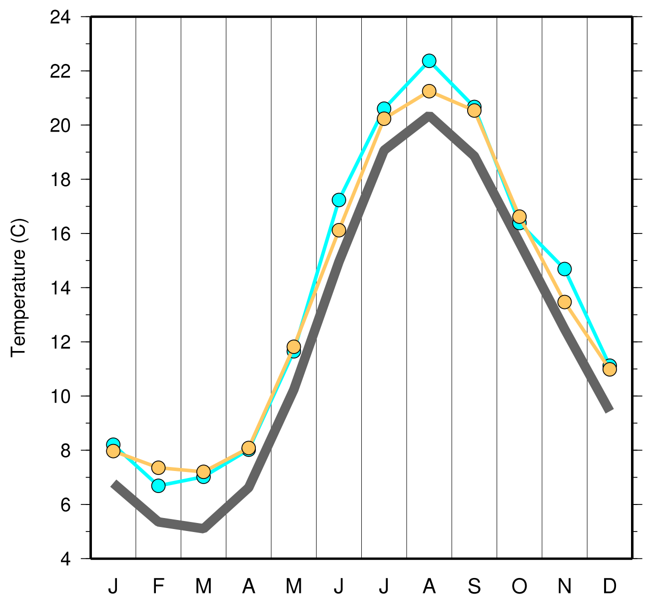


Figure 5. Top: Regional average annual sea surface temperature for the NEUS shelf region calculated from NOAA's extended reconstructed sea surface temperature product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html). Colors correspond with the anomaly scale in Figure 4. Bottom: Regional average monthly mean SST for the NEUS shelf for 2022 (cyan), 1951 (orange) and 1991-2020 (gray) calculated from the same product.

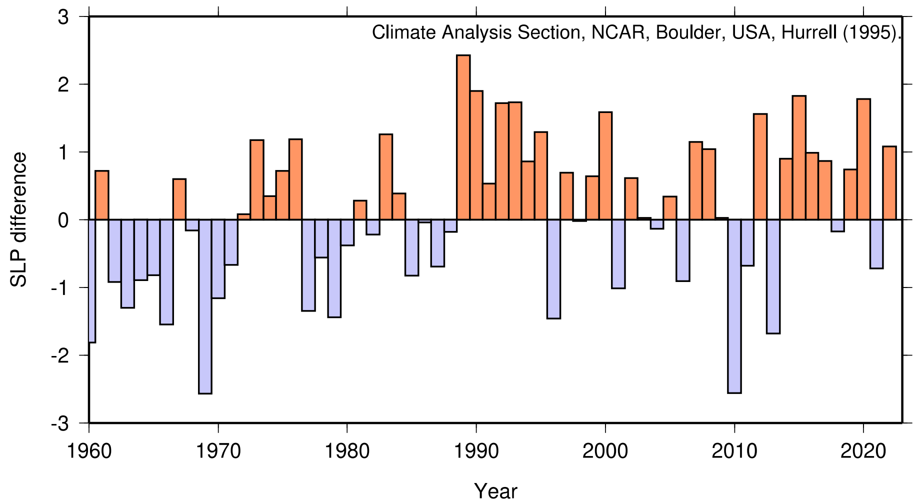


Figure 6. North Atlantic Oscillation index computed from principal component analysis of sea level pressure in the North Atlantic (see Hurrell, 1995).

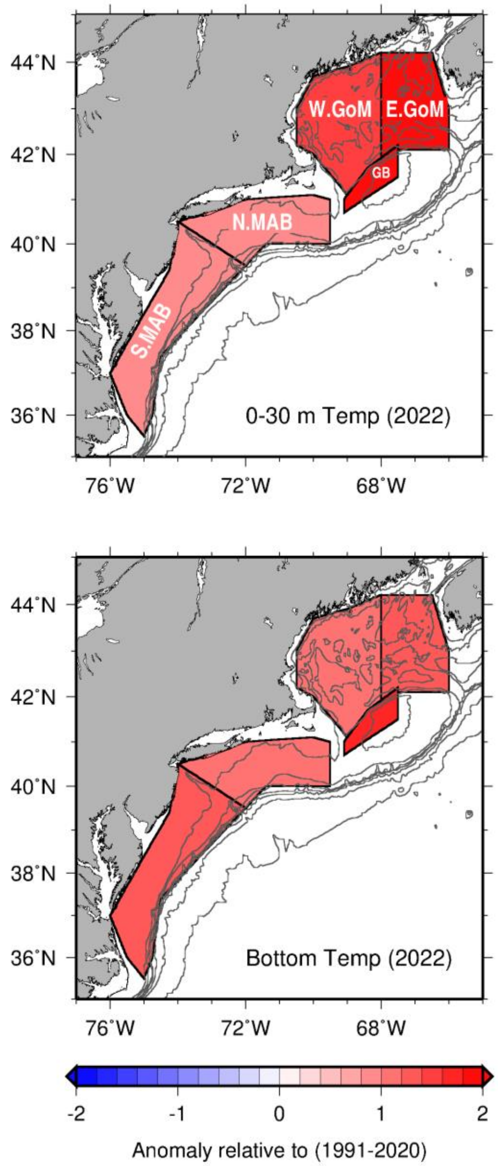


Figure 7a. Surface (upper panel) and bottom (lower panel) regional annual temperature anomaly. Positive anomalies correspond to warmer conditions in 2022 relative to the reference period (1991-2020). The region labels correspond to the panels in Figure 8.

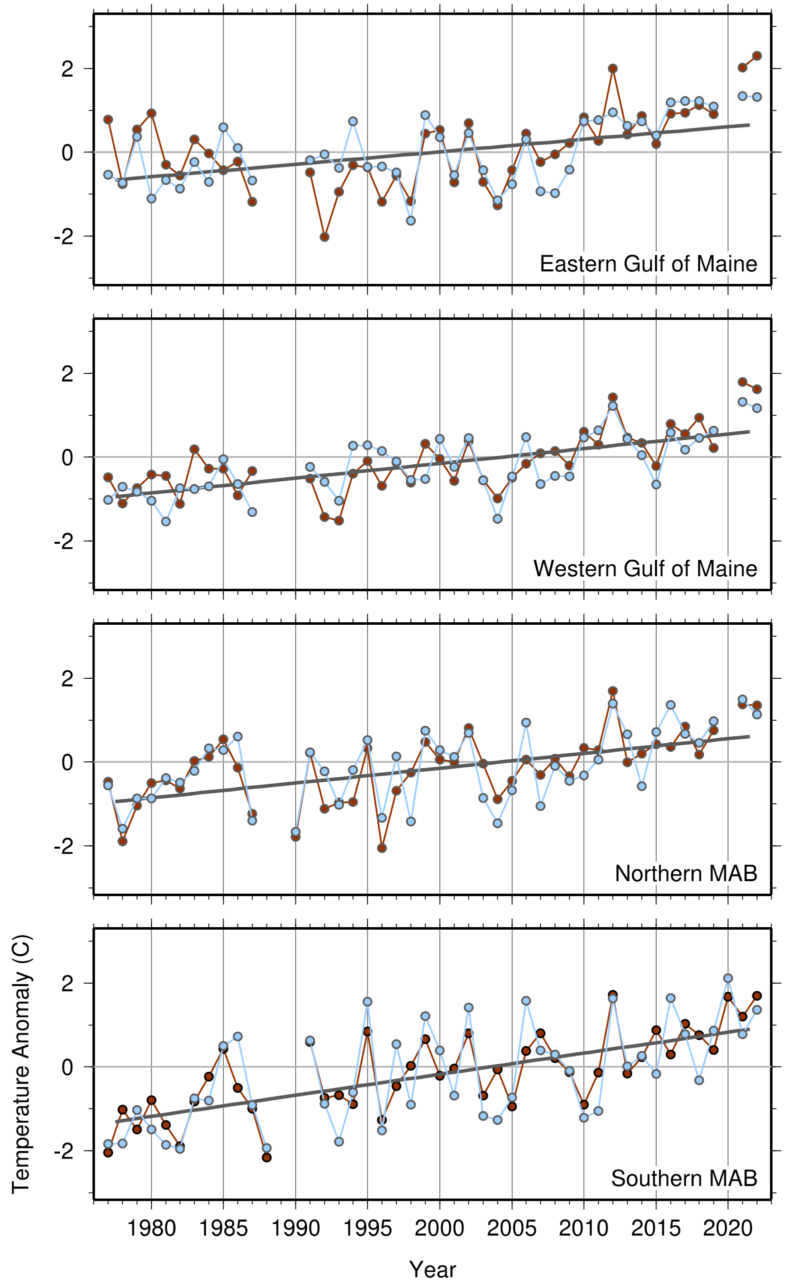


Figure 7b. Time series of surface (red) and bottom (blue) regional annual average temperature anomaly (°C). Positive anomalies correspond to warming in 2022 relative to the reference period (1991-2020). Gray line shows the temporal trend based on linear regression where significance is confirmed based on p-value ≤ 0.05.

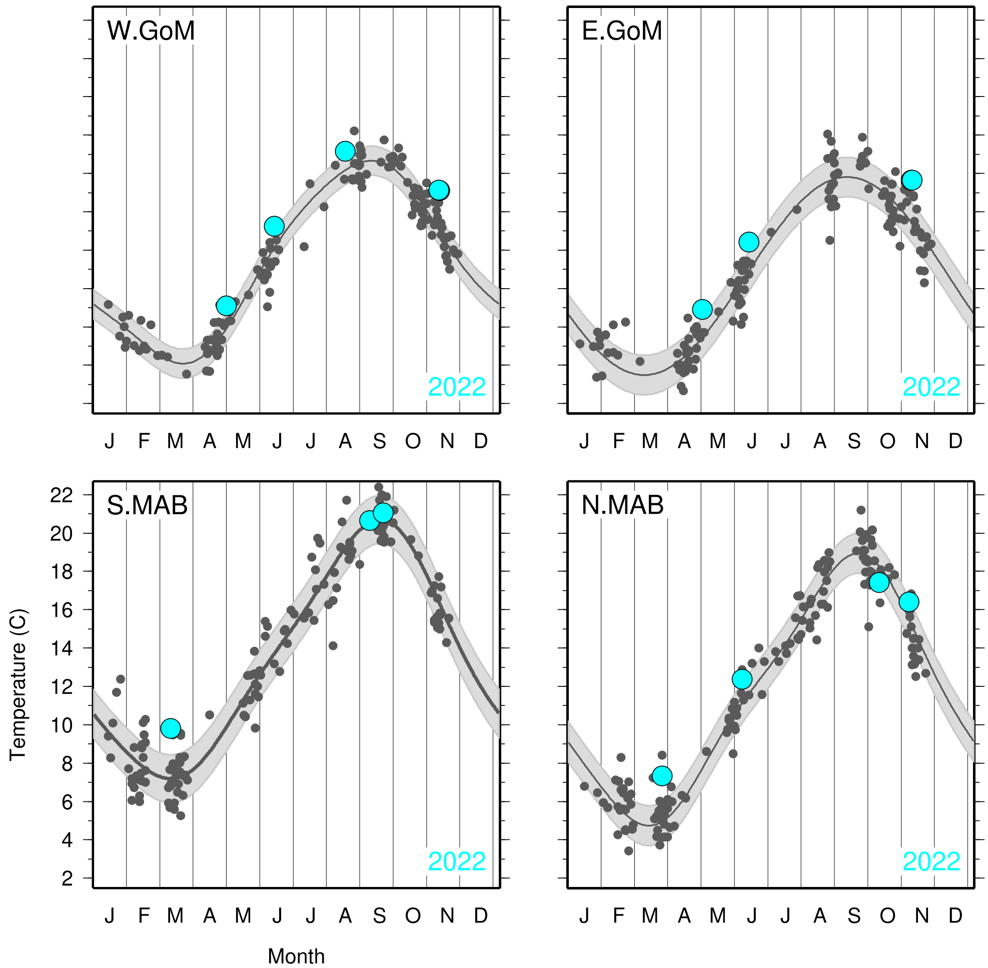


Figure 8a. Regional average 0-30 meter temperature (°C) as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 7. An annual harmonic fit to the regional average temperatures from 1991-2020 is shown by the gray curve with the points contributing to the fit also shown in gray. The shading depicts one standard deviation around this fit. The regional average temperatures from 2022 surveys are shown in cyan.

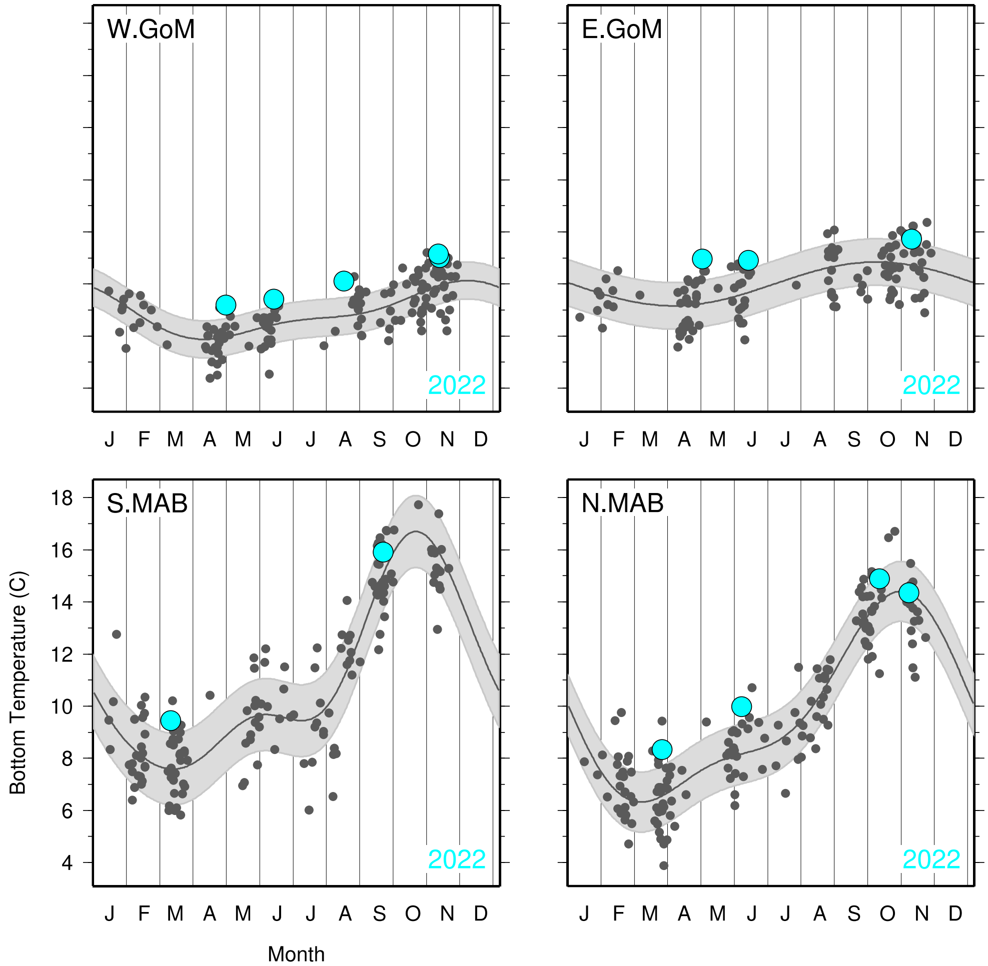


Figure 8b. As in Fig. 8a, but for bottom temperatures.

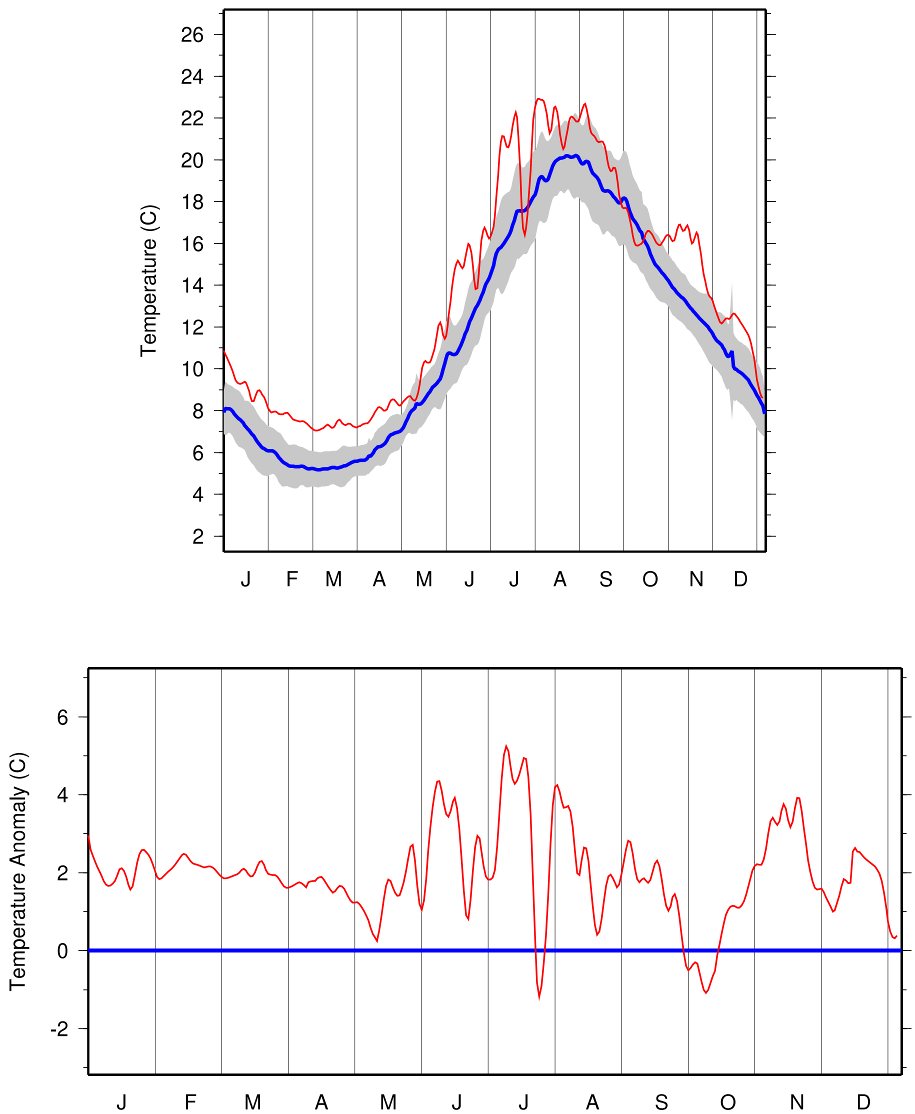


Figure 9. (top) Time series of surface ocean temperature from NDBC buoy 44008 located south of Nantucket Shoals in the northern Middle Atlantic Bight. Temperatures observed in 2022 (red) are compared with average temperatures (1991-2020, blue) in the top panel. The gray shading indicates one standard deviation about the long-term mean. The lower panel shows the difference between 2022 and the long-term mean temperature, where positive values indicate warmer conditions in 2022.

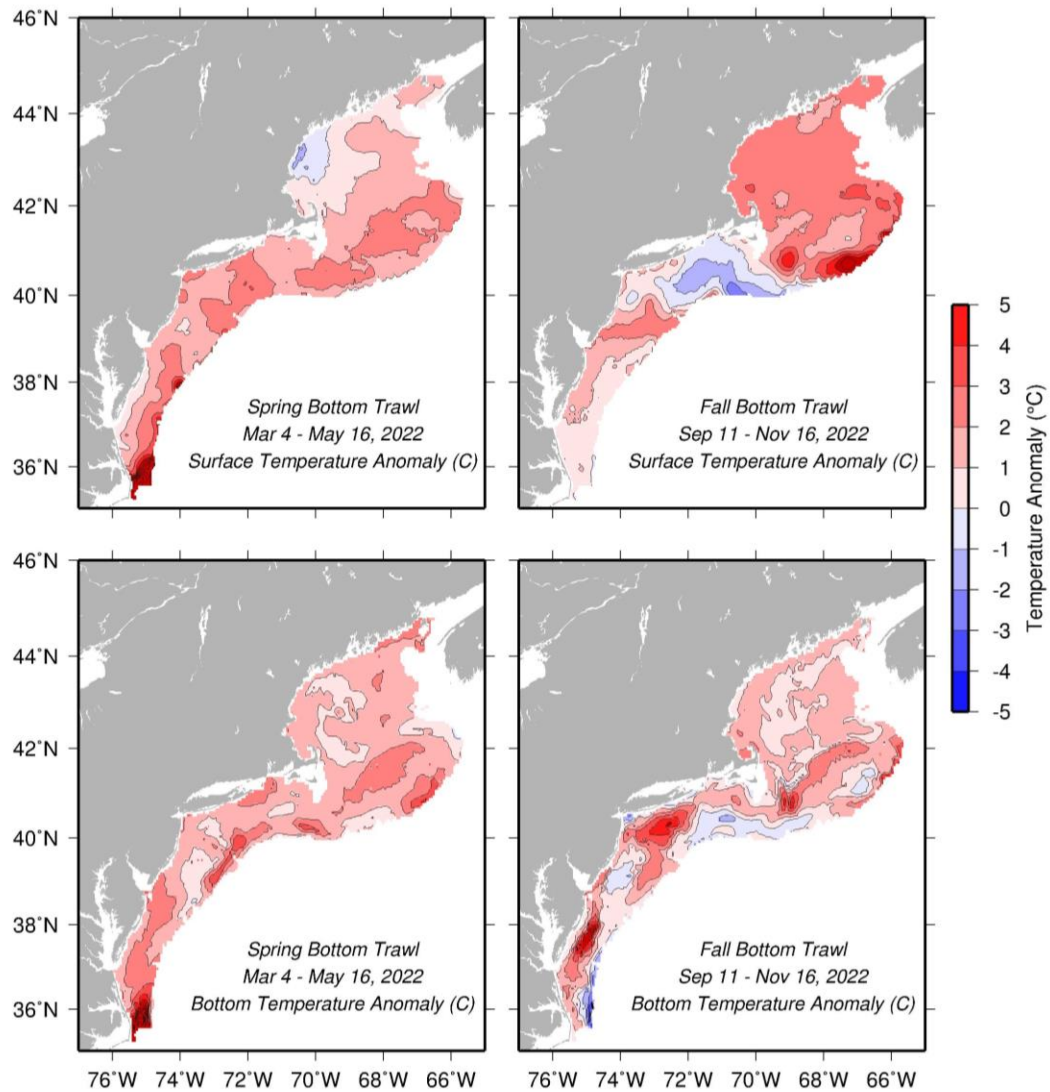


Figure 10. Surface (upper panels) and bottom (lower panels) temperature anomaly from the spring 2022 (left) and fall 2022 (right) ground fish surveys. Positive anomalies correspond to warming in 2022 relative to the reference period (1991-2020).

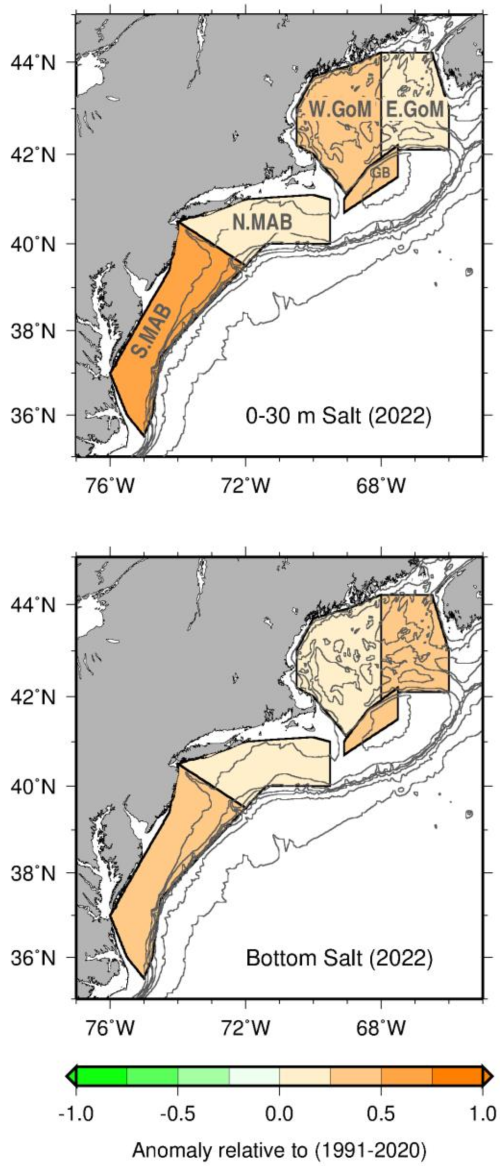


Figure 11. Surface (upper panel) and bottom (lower panel) regional annual salinity anomaly. Positive anomalies correspond to more saline conditions in 2022 relative to the reference period (1991-2020). The region labels correspond to the panels in Figure 12.

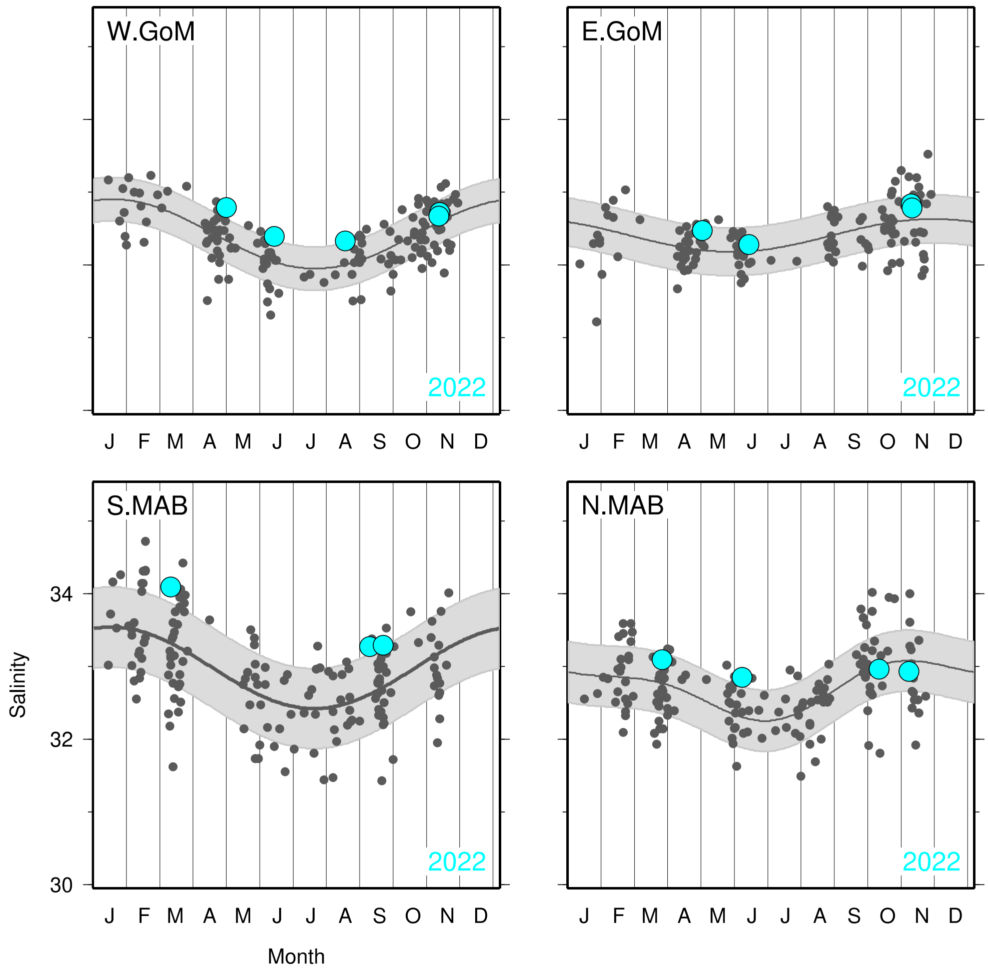


Figure 12a. Regional average 0-30 meter salinity as a function of calendar day. Each dot represents a volume-weighted average of all observations from a single survey falling within the regions delineated in Fig. 11. An annual harmonic fit to the regional average salinities from 1991-2020 is shown by the gray curve with the points contributing to the fit also shown in gray. The shading depicts one standard deviation around this fit. The regional average salinities from 2022 surveys are shown in cyan.

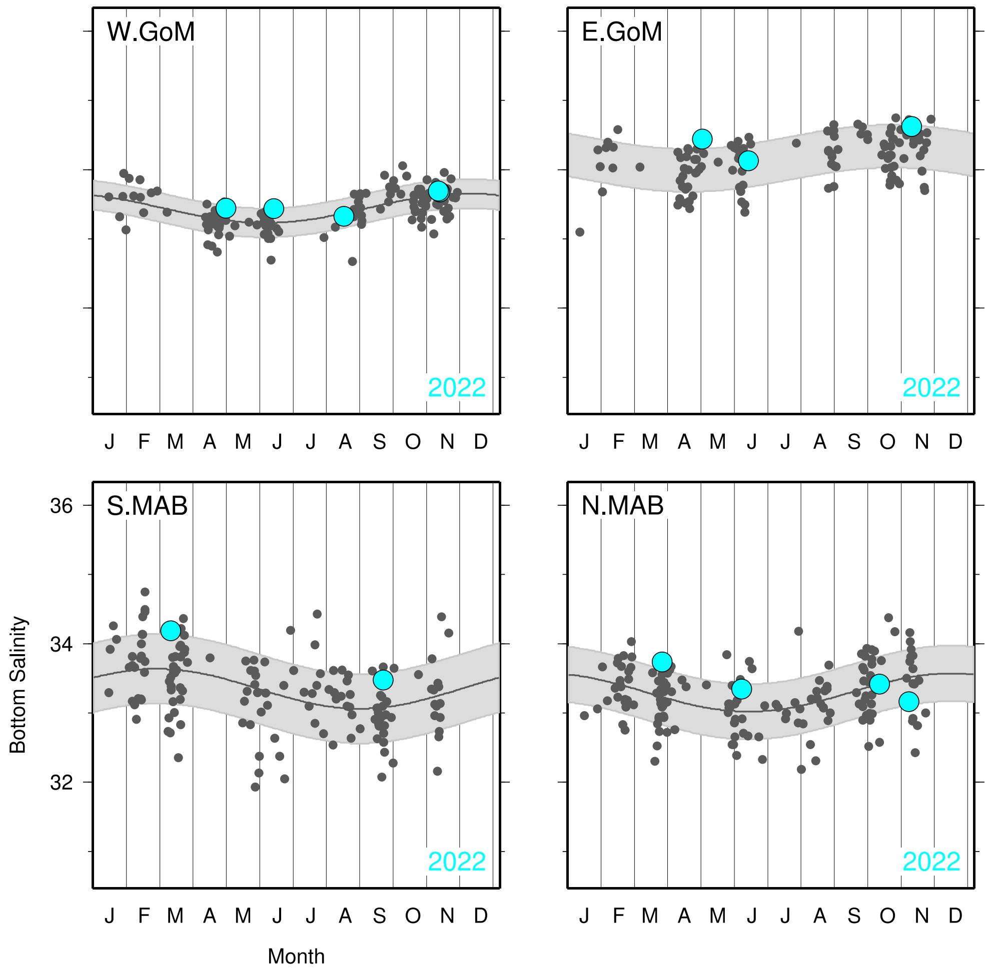


Figure 12b. As in Fig. 12a, but for bottom salinities.

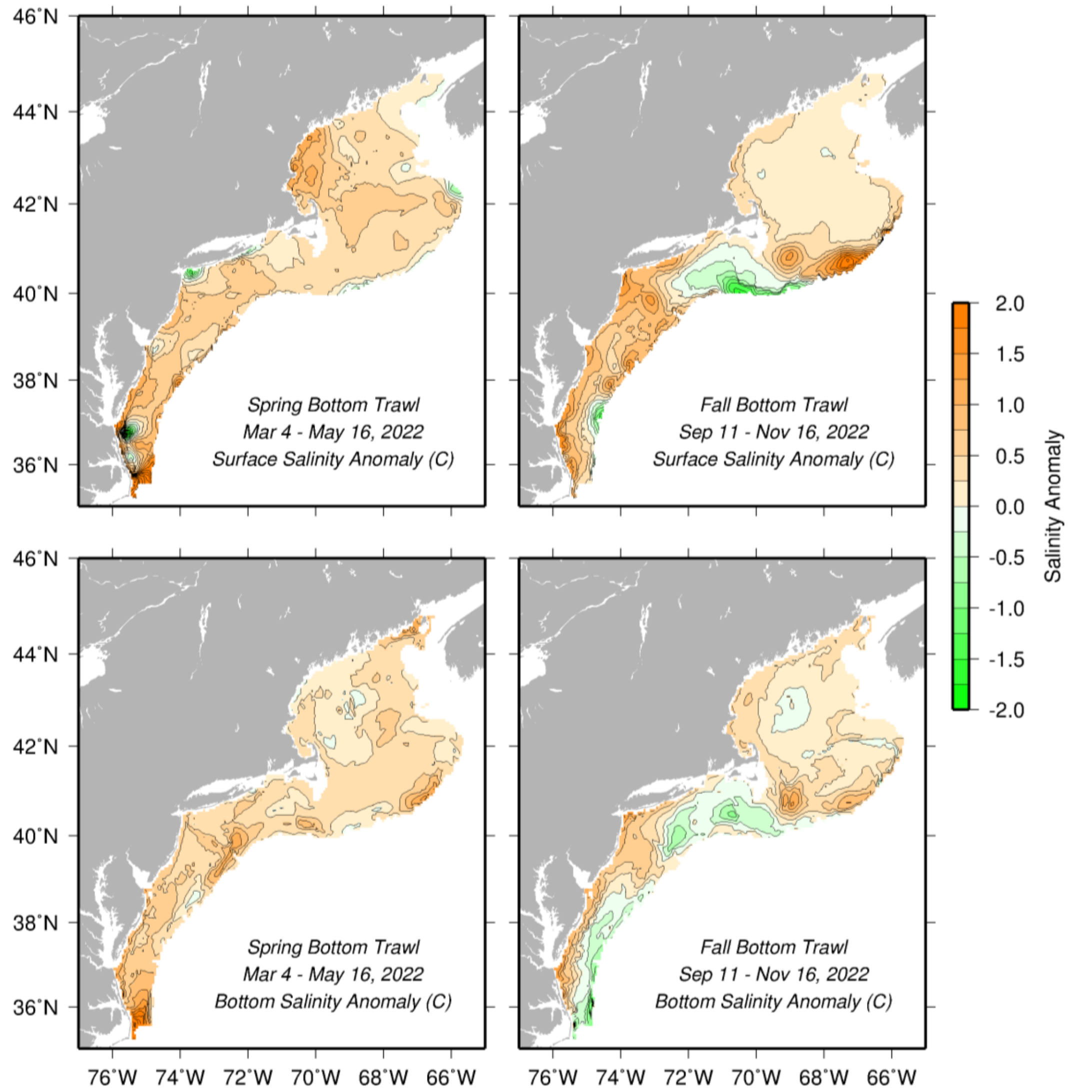


Figure 13. Surface (upper panels) and bottom (lower panels) salinity anomaly from the spring 2022 (left) and fall 2022 (right) ground fish surveys. Positive anomalies correspond to more saline conditions in 2022 relative to the reference period (1991-2020).

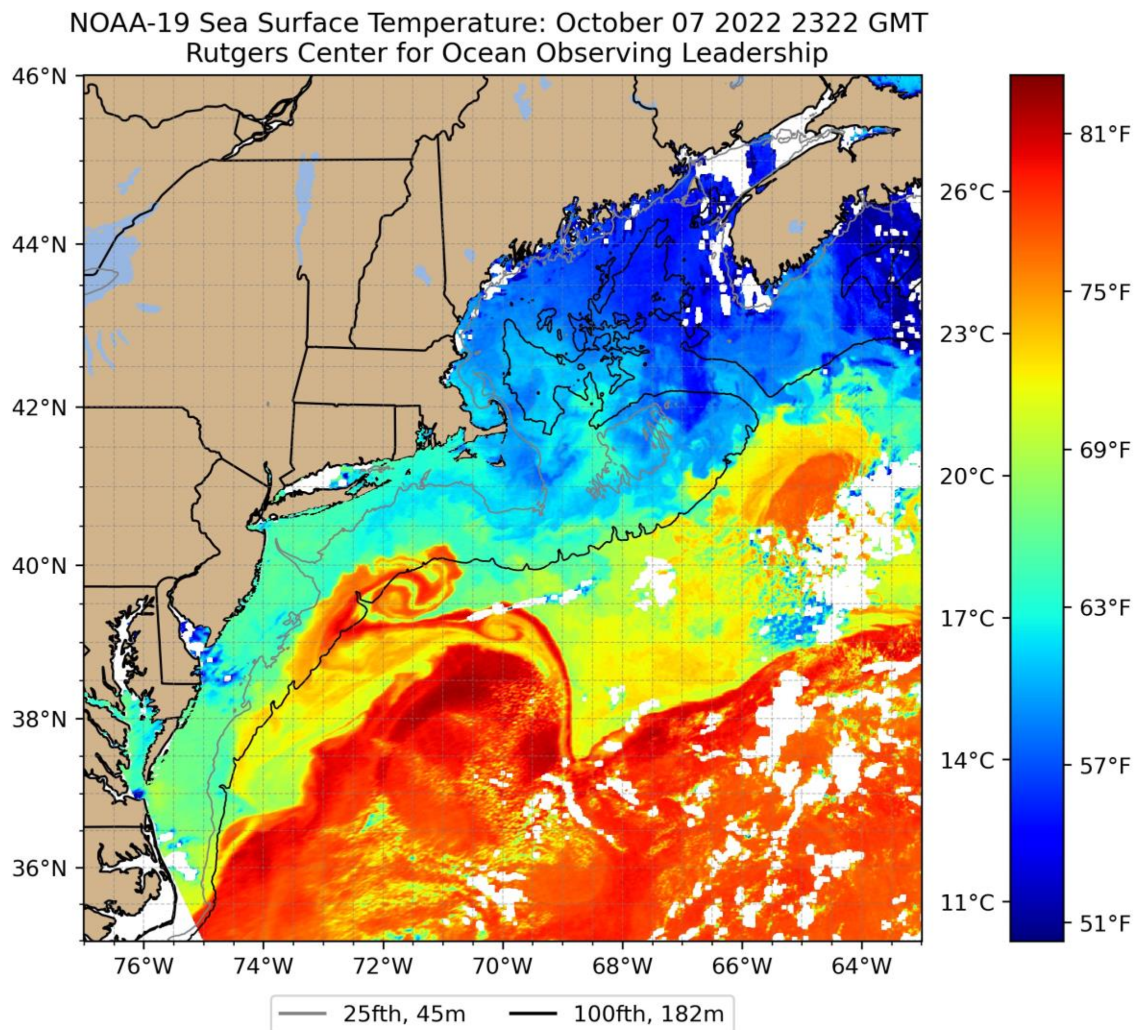


Figure 14. Daily composite sea surface temperature derived by the Coastal Ocean Observations Lab, Rutgers University, from data collected by the Advanced Very High-Resolution Radiometer on October 7, 2022.

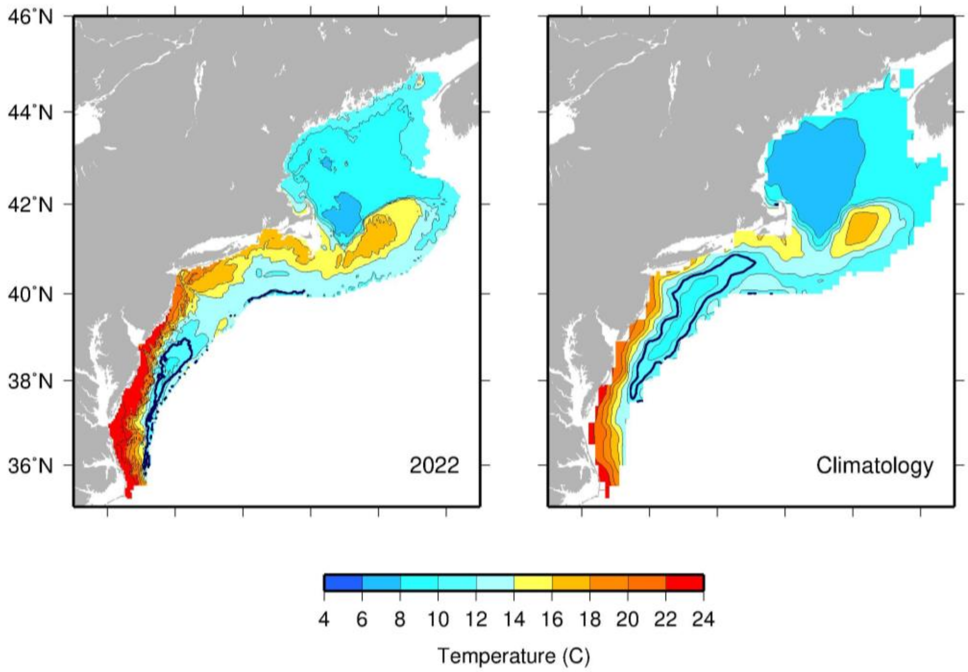


Figure 15. Distribution of bottom temperature as observed in the fall 2022 Ground Fish Survey (left) compared with the climatological average bottom temperature distribution calculated for 1991-2020 (right). The heavy blue contour corresponds with the 10°C isotherm as a proxy for the Cold Pool footprint.

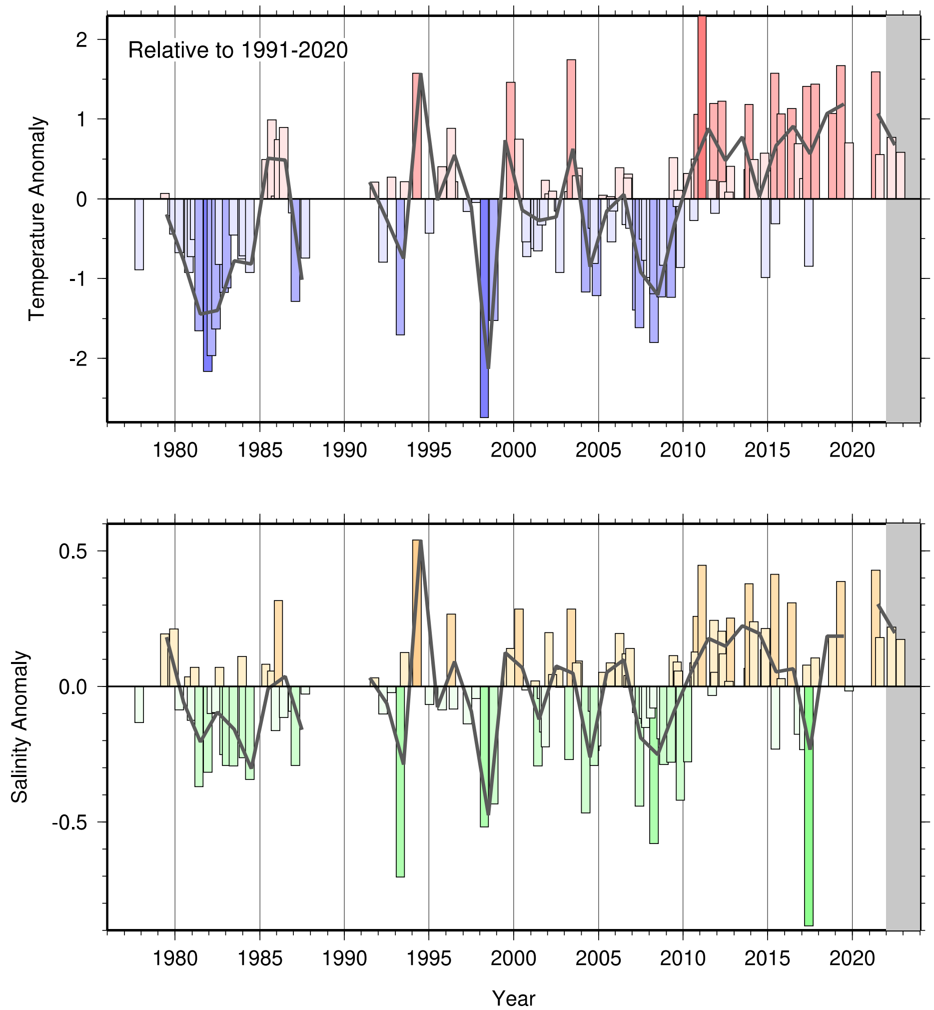


Figure 16. Time series of temperature and salinity anomaly in the deep Northeast Channel. Each bar represents a volume-weighted average of all observations from a single survey collected between 150-200 meters in the Northeast Channel. The grey curve shows the annual average anomaly time series. Positive values are warmer and saltier than the long-term mean calculated for 1991-2020. The gray shading highlights observations from 2022.

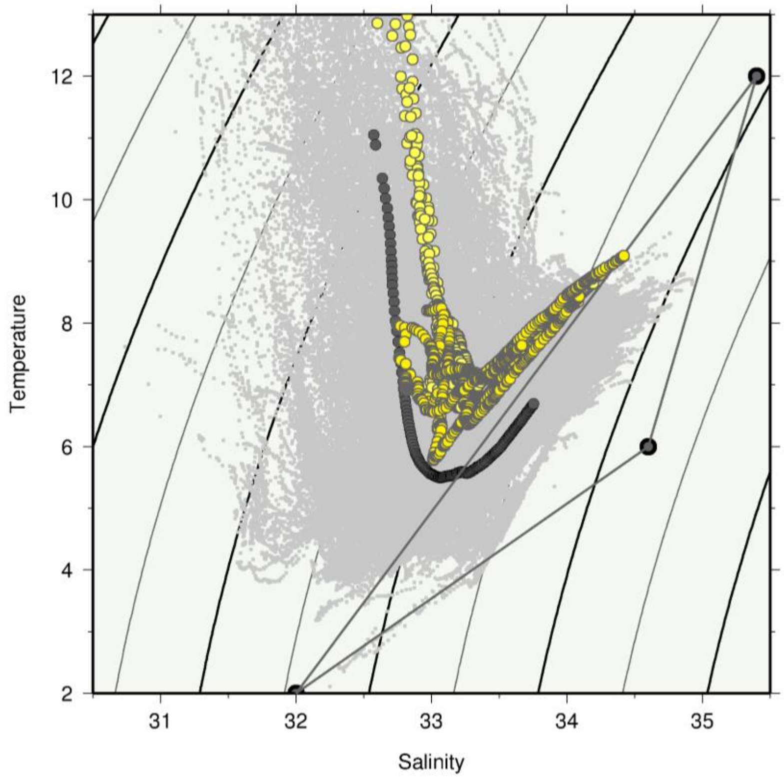


Figure 17. Temperature-salinity diagram showing water properties in Wilkinson Basin in the western Gulf of Maine. All observations from May (yellow) 2022 are shown along with the spring climatological average profile (1991-2020, dark gray). The lightest gray dots show the historical range encompassed by observations from the reference period, 1991-2020. Temperature and salinity properties representative of source waters entering the Gulf of Maine are shown by the mixing triangle.

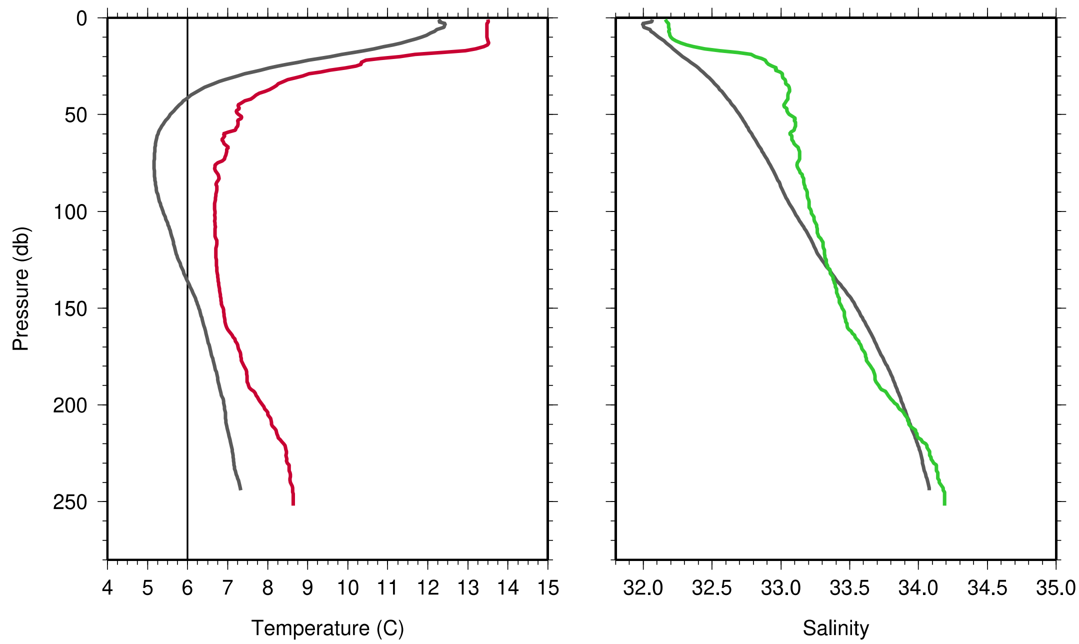


Figure 18. Average profiles of temperature (left) and salinity (right) from repeated observations collected during May in Wilkinson Basin in the western Gulf of Maine. All observations from May 2022 (red and green) are shown along with the climatological average profile for the same month (1991-2020, 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.

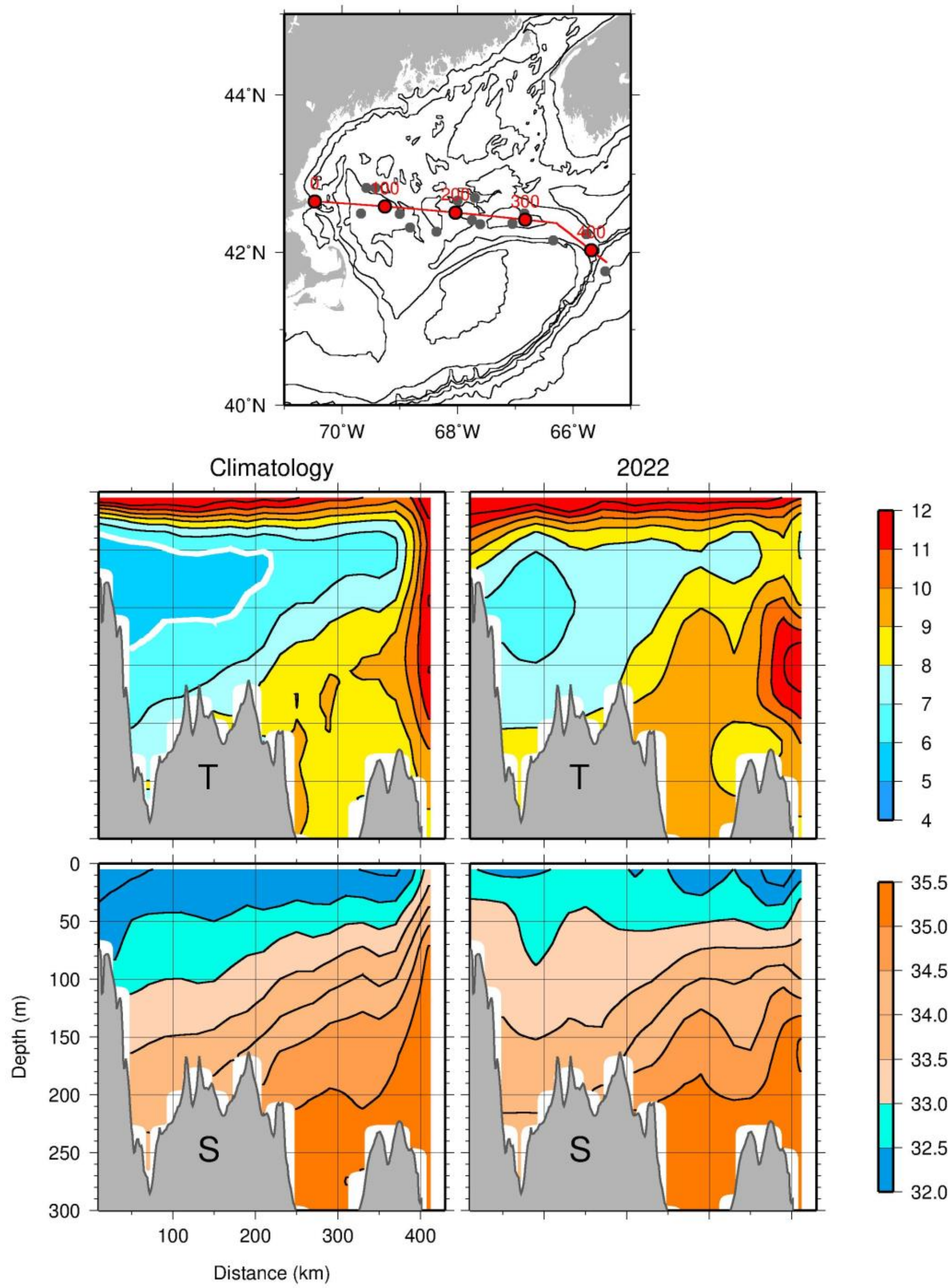


Figure 19. Vertical sections of temperature (top) and salinity (bottom) crossing the Gulf of Maine along a zonal transect shown in the map. The left panels show the climatological average for June spanning the years 1991-2020. The right panels show the synoptic mean section for June 2022. The heavy white contour highlights the 6°C isotherm as an indicator of the boundary of the Cold Intermediate Layer. Along-transect distances and the June 2022 station distribution are shown on the map for reference.