Northeast Fisheries Science Center Reference Document 19-07

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by Paula S Fratantoni, Tamara Holzwarth-Davis, Donald C Melrose, and Maureen H Taylor

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TABLE OF CONTENTS

List of Tables ii
List of Figures ii
Appendix iii
Abstract iv
Introduction 1
Data and Methods 1
Results 3
Summary 5
References Cited 7

LIST OF TABLES

Table 1. Listing of 2016 NOAA Northeast Fisheries Science Center cruises supported by the Oceans and Climate Branch. 8
Table 2. Regional average surface and bottom temperature values computed from CTD data that were sorted into six 2-month time periods for the 5 regions of the Northeast US Continental Shelf. 9
Table 3. Regional average surface and bottom salinity values computed from CTD data that were sorted into six 2-month time periods for the 5 regions of the Northeast US Continental Shelf. ...10

LIST OF FIGURES

Figure 1. Regional designations used in the description of 2015 oceanographic conditions on the Northeast US Continental Shelf. 11
Figure 2a. Bimonthly distribution of hydrographic stations used in the description of 2016 oceanographic conditions on the Northeast US Continental Shelf.. 12
Figure 2b. Histogram of the number of hydrographic stations occupied on Northeast Fisheries Science Center surveys in a given year 13
Figure 3. Time series of the 2016 regional surface and bottom temperatures and anomalies as a function of calendar day 14
Figure 4. Time series of the 2016 regional surface and bottom salinities and anomalies as a function of calendar day 15
Figure 5. Time series of the 2016 regional shelf water temperature, salinity, and volume as a function of calendar day 16
Figure 6a. Near-surface and near-bottom temperature and salinity distributions on the Northeast US Continental Shelf during March-April 2016. 17
Figure 6b. Near-surface and near-bottom temperature anomaly and salinity anomaly distributions on the Northeast US Continental Shelf during March-April 2016.. 18
Figure 7a. Near-surface and near-bottom temperature and salinity distributions on the Northeast US Continental Shelf during May-June 2016. 19
Figure 7b. Near-surface and near-bottom temperature anomaly and salinity anomaly distributions on the Northeast US Continental Shelf during May-June 2016. 20

Figure 8a. Near-surface and near-bottom temperature and salinity distributions on the Northeast US Continental Shelf during July-August 2016.. 21
Figure 8b. Near-surface and near-bottom temperature anomaly and salinity anomaly distributions on the Northeast US Continental Shelf during July-August 2016. 22
Figure 9a. Near-surface and near-bottom temperature and salinity distributions on the Northeast US Continental Shelf during September-October 2016..23
Figure 9b. Near-surface and near-bottom temperature anomaly and salinity anomaly distributions on the Northeast US Continental Shelf during September-October 2016. 24
Figure 10: Daily composite sea surface temperature derived from data collected by the Advanced Very High Resolution Radiometer on October 7, 2016...25
Figure 11. Time series of temperature and salinity anomaly in the deep Northeast Channel.. 26
Figure 12. Vertical sections of temperature and salinity crossing the Gulf of Maine along a zonal transect shown in the map. 27
Figure 13. Temperature-salinity diagram showing water properties in Wilkinson Basin in the western Gulf of Maine. 28
Figure 14. Average profiles of temperature and salinity collected during June in Wilkinson Basin in the western Gulf of Maine. 29
Figure 15. Surface air temperature anomaly derived from the NCEP/NCAR Reanalysis product 30
Figure 16. Sea surface temperature (SST) anomaly derived from NOAA's Optimum Interpolation (OI) SST product...31
Figure 17. Regional average annual sea surface temperature for the NEUS Continental Shelf region calculated from NOAA's extended reconstructed sea surface temperature product..........32
Figure 18. North Atlantic Oscillation index computed from principal component analysis of sea level pressure in the North Atlantic 33

APPENDIX

Table A1. Regional average temperature and salinity calculated from hydrographic observations collected by individual Northeast Fisheries Science Center surveys in the eastern Gulf of Maine. 34
Table A2. Regional average temperature and salinity values calculated from hydrographic observations collected by individual Northeast Fisheries Science Center surveys in the western Gulf of Maine..35
Table A3. Regional average temperature and salinity calculated from hydrographic observations collected by individual Northeast Fisheries Science Center surveys in the Georges Bank area. ..36
Table A4. Regional average temperature and salinity calculated from hydrographic observations collected by individual Northeast Fisheries Science Center surveys in the northern Mid-Atlantic Bight..37
Table A5. Regional average temperature and salinity calculated from hydrographic observations collected by individual Northeast Fisheries Science Center surveys in the southern Mid-Atlantic Bight..38
Table A6. Temperature, salinity, and volume of the shelf water in the Mid-Atlantic Bight during 2016..39

ABSTRACT

Hydrographic observations from 7 surveys spanning the Northeast US Continental Shelf are combined into a descriptive overview of the oceanographic conditions observed during 2016. Temperature and salinity observations are combined into 6 bimonthly time periods to balance both the spatial coverage and temporal resolution of the data during the year. Maps of near-surface and near-bottom property distributions are presented for each bimonthly period, and time series of regional average properties are discussed for 5 geographic regions spanning the shelf: western Gulf of Maine, eastern Gulf of Maine, Georges Bank, and northern and southern Mid-Atlantic Bight. Overall, 2016 was characterized by warmer and more saline conditions than average across the region. Deep (slope) waters entering the Gulf of Maine were warmer and saltier than average, and their temperature and salinity suggest a subtropical source. Mixed layer-depths in the western Gulf of Maine were shallow during the winter of 2016, presumably a consequence of anomalously warm air temperatures that persisted over the northeastern United States during winter and suppressed winter convective overturning in the western Gulf of Maine. By contrast, during late summer, observations indicate that Gulf Stream warm core ring water intruded onto the shelf in the Mid-Atlantic Bight and through deep channels into the Gulf of Maine, leading to anomalous warming across the outer shelf off southern New England and in the deep basins of the Gulf of Maine. Such episodic events have the potential to cause significant changes in the ecosystem, including changes in nutrient availability on the shelf, the seasonal elimination of critical habitats such as the cold pool and shelf-slope front, disruption of seasonal migration cues, and an increase in the concentration of offshore larval fish on the shelf.

INTRODUCTION

The Northeast Fisheries Science Center (NEFSC) conducts multiple surveys on the Northeast US (NEUS) Continental Shelf each year in support of its ongoing mission to monitor the shelf ecosystem and assess how its components influence the distribution, abundance, and productivity of living marine resources. In support of this mission, the NEFSC's Oceans and Climate Branch provides conductivity, temperature, and depth (CTD) instruments to NEFSC cruises for the measurement of water column profiles of temperature and salinity. In addition to providing oceanographic context to specific field programs, these data contribute to a growing database of historical measurements that are used to monitor seasonal and interannual variability in the water properties on the NEUS Continental Shelf.

The NEFSC conducts multiple regionally focused and shelfwide surveys in the NEUS Continental Shelf every year. The shelfwide surveys collect hydrographic measurements at hundreds of randomly stratified stations from Cape Hatteras, North Carolina, to the Gulf of Maine. The NEFSC aims to achieve 6 full-shelf, hydrographic surveys per year – the minimum required to resolve the dominant seasonal cycle in this region. However, ship maintenance issues and reduced sea-day allocations led to the elimination or truncation of 3 of these 6 surveys in 2016. Roughly half the number of stations needed to achieve full coverage were occupied in 2016, and these were restricted to 3 seasons, leading to a critical loss of seasonal and spatial resolution.

Here, we present an annual summary of the 2016 observations, including surface and bottom distributions of temperature and salinity and their anomalies computed relative to a consistent reference period. In addition, regional average values of temperature and salinity and their anomalies are computed for 5 different regions over the 3 bimonthly periods sampled. In the Mid-Atlantic Bight (MAB), the volume and properties of shelf water are specifically examined. Finally, a summary of basin-scale oceanographic and atmospheric conditions provides context to the in situ hydrographic observations.

DATA AND METHODS

The Oceans and Climate Branch provides CTD instrumentation and support to NEFSC programs. Training in instrument maintenance and operation, including deployment, data acquisition, recovery, and preliminary processing, is provided as needed prior to sailing. On NEFSC surveys, CTD instruments are typically deployed in 1 of 2 modes:

(1) During a bongo net tow, an SBE 19plus SeaCAT Profiler[1] CTD instrument is mounted on the conducting wire above the bongo frame and data are collected as a double oblique profile with the ship steaming at approximately 2 knots. The sensors are not soaked at the surface prior to descent during bongo tows, rendering the upper 30 m or more of the downcast unreliable. For this reason, the upcast profile data are processed as the primary data for each station.

(2) During a non-net cast, either an SBE 19plus SeaCAT CTD Profiler is mounted vertically on the wire or an SBE 911plus is deployed with an SBE 32 Carousel Water Sampler and up to 12 Niskin bottles. In the latter configuration, the CTD is oriented so that the intake is exposed to new water as it is lowered and so the downcast profiles

[1] Reference to trade names does not imply endorsement by any collaborating agency or government.

are processed as the primary data for each station. The CTD sensors are soaked for 1 min at the surface prior to descent to allow for sensor equilibration and for the circulation pump to turn on. In SBE 911plus/SBE 32 deployments, water samples are often collected at discrete depths with the Niskin bottles. The water samples are captured on the upcast in order to avoid leakage and sample contamination, which can occur as the pressure increases with depth. Following community protocols, the CTD package is stopped for 30 sec at each sample depth before a bottle is closed in order to allow the package wake to dissipate, the bottles to flush and the surrounding water to equilibrate. The CTD remains stopped for another 10-15 sec after the bottle trip is confirmed to allow time for closure and to collect CTD data for comparison with the water sample data. Water samples are processed ashore for nutrients and carbonate chemistry.

During 2016, hydrographic data were collected on 7 individual NEFSC cruises aboard the NOAA ships *Henry B. Bigelow, Pisces,* and *Gordon Gunter,* and the R/V *HR Sharp* by using a combination of Sea-Bird Electronics SBE 19plus SeaCAT profilers and SBE 911plus CTD units. All raw CTD profile data were processed and quality controlled ashore by using standard Sea-Bird Electronics protocols to produce 1-decibar averaged profiles. Water samples were collected up to twice daily at sea during vertical casts. Following each cruise, these samples were analyzed with a Guildline Autosal Laboratory Salinometer to calibrate the CTD salinity data. Following manufacturer recommended procedures, a slope correction was calculated based on comparisons between the CTD measured conductivity and salinometer results and were applied to the CTD measured conductivity before conversion back to salinity. Vertical density profiles were examined for inversions caused by bad conductivity or temperature readings and/or sensor misalignment. Egregious cases were replaced with a flag value. The processed hydrographic data were loaded into Oracle database tables and made publicly available via anonymous ftp (ftp://ftp.nefsc.noaa.gov/pub/hydro) and in the World Ocean Database archive managed by NOAA's National Centers for Environmental Information. Cruise reports have been prepared for each survey listed in Table 1 and are available online (http://www.nefsc.noaa.gov/epd/oceanography/). Readers are referred to the individual cruise reports for notes, property maps, and aggregate data specific to a particular survey.

Here, we provide an overview of the hydrographic sampling conducted in 2016 and characterize the oceanographic conditions that were observed. The processed CTD data have been sorted into 2-month time bins to balance both the spatial coverage and temporal resolution of the data. Maps of near-surface and near-bottom temperature and salinity have been produced from profile data falling within each bimonthly period. Surface fields include the shallowest observed temperature/salinity at each station that is also in the upper 5 m of the water column, while bottom maps include the deepest observation at each station that also falls within 10 m of the reported water depth. Average values have been computed from the data within 5 regions spanning the NEUS Continental Shelf to examine the spatial and temporal variability over broader areas of the shelf (Figure 1). Regional averages have been computed for the bimonthly-binned fields (Tables 2 - 3) and for individual cruises (Appendix Tables 1-5).

Anomalies were calculated at each station relative to a 1977-1987 reference period to characterize variability that is not related to seasonal forcing. During the reference period the NOAA National Marine Fisheries Service (NMFS) Marine Resources Monitoring and Prediction (MARMAP) program repeatedly occupied stations spanning the entire NEUS Continental Shelf allowing construction of annual cycles for water properties across all regions of the shelf

(Mountain et al. 2004; Mountain and Holzwarth-Davis 1989). The anomalies presented here are defined as the difference between the observed 2016 value at individual stations and the expected value for each location and time of year based on this reference period. Regional anomalies are the area-weighted average of these anomalies within a given domain. The methods used and an explanation of uncertainties are presented in Holzwarth-Davis and Mountain (1990).

The temperature, salinity, and volume of the shelf water in the MAB during 2016 were calculated and compared to the conditions observed during the MARMAP reference period. According to Mountain (2003), the shelf water mass is defined as water within the upper 100 m having salinity less than 34. For each survey in 2016, the area of a subregion was apportioned among its stations by an inverse distance-squared weighting. The shelf water volume at a given station is the thickness of the shelf water at the station multiplied by its apportioned area, and the total shelf water volume within the subregion is the sum of these products for all stations within the region. Similarly, the average temperature and salinity was calculated in the shelf water layer at each station and multiplied by the total shelf water volume for that station. The sum of these products over all stations within a given subregion divided by the total shelf water volume for the region determines the volume-weighted average temperature and salinity. Anomalies in the property and volume of the shelf water mass are calculated relative to like variables derived from MARMAP hydrographic data, as described above. Hence, here regional anomalies are computed as the mathematical difference between regional averages, *not* an average of the anomalies computed for a given subregion.

RESULTS

Hydrographic Conditions in 2016

During 2016, hydrographic data were collected on 7 individual NEFSC cruises, amounting to 1382 profiles of temperature and salinity (Table 1). Despite the bimonthly binning of observations, significant gaps remain in several of the bimonthly periods shown in Figure 2a. This reflects an overall reduction in stations occupied in 2016 relative to previous years (Figure 2b). No sampling occurred in January-February, and only limited sampling occurred in March-April and November-December because of persistent vessel maintenance issues involving multiple vessels and reduced allocation of days at sea. The NOAA Ship *Henry B. Bigelow* remained in port for extended maintenance resulting in the cancellation of the February Ecosystem Monitoring (EcoMon) Survey and a significant delay in the start of the Spring Bottom Trawl survey. Together, this left a significant gap in sampling coverage during winter this year. The shift in the trawl survey schedule necessitated moving the May/June EcoMon Survey from NOAA Ship *Henry B. Bigelow* to NOAA Ship *Gordon Gunter,* resulting in a truncated survey because of limited vessel availability and slower cruising speeds. The October/November EcoMon Survey returned to port after just 1 day of sampling when the NOAA Ship *Pisces* developed serious problems with its main propulsion generator. Combined, 2016 saw a significant reduction in sampling, with only 3 surveys sampling the entire shelf and a critical loss of seasonal resolution. The large gaps in station coverage preclude the calculation of a true area-weighted regional average surface/bottom temperature and salinity in several regions (Tables 2 - 3; Figures 3 - 4).

Relative to historical values, regional ocean temperatures across the NEUS Continental Shelf were warm during 2016 (Figure 3). Annually, waters were between 1.0-1.9°C warmer than normal everywhere, with the largest anomalies occurring in the Mid-Atlantic Bight and Georges Bank (Table 2; Figure 3). Of the seasons sampled, warm anomalies were most pronounced between summer and fall on Georges Bank and in the Mid-Atlantic Bight, where regional temperature anomalies approached 3°C all the way to the bottom. Notable warm anomalies were also observed during spring in the Mid-Atlantic Bight, where near-bottom temperature anomalies exceeded surface values by close to 1°C.

Annually, surface waters were saltier than normal in the Mid-Atlantic Bight and near normal in the Gulf of Maine and on Georges Bank (Figure 4). Notably large positive anomalies in salinity were observed during spring in the southern Mid-Atlantic Bight and during fall in the northern Mid-Atlantic Bight and on Georges Bank (Table 3; Figure 4). Near the bottom, anomalies were modulated compared to upper layers, with near-normal conditions observed annually.

The total volume of shelf water in the Mid-Atlantic Bight, defined as waters having salinity less than 34, was notably reduced during fall in the northern Mid-Atlantic Bight relative to the MARMAP period (Figure 5). While the shelf water mass was warmer than normal, reflective of broader regional conditions, its salinity remained near normal in the northern Mid-Atlantic Bight (Figure 5). This pattern suggests that the anomalously salty conditions observed in the northern Mid-Atlantic Bight during fall (Figure 4) are reflective of a different water mass moving into the region, consistent with a significant shoreward movement of the shelf/slope front. This feature marks the transition between colder/fresher shelf water onshore and warmer/saltier slope water offshore.

Bimonthly surface and bottom property-distribution maps reveal details related to the regional averages in Figures 3 and 4, although temporal continuity suffers from reduced sampling (Figures 6-9). The bimonthly property maps show that regional warm anomalies observed at the surface during September-October (Figure 3) were concentrated near the shelf edge south of Georges Bank and Cape Cod, MA (Figure 9b). Warm anomalies were observed at the bottom, underlying the surface maximums, and enhanced warmth was also observed along the length of the inner shelf into the southern Mid-Atlantic Bight (Figure 9b). Large regional salinity anomalies observed at the surface in the Mid-Atlantic Bight during spring and fall (Figure 4) are reflective of enhanced positive anomalies aligned with regions of warmer water along the shelf edge in the southern Mid-Atlantic Bight during March-April (Figure 6b) and in the northern Mid-Atlantic Bight during September-October (Figure 9b).

Synoptically, while the large regional salinity anomalies observed at the surface in the Mid-Atlantic Bight during fall were strongest near the shelf edge (Figure 9b), a tongue of saline water extended inshore between Georges Bank and the eastern tip of Long Island, NY. The salinity within this shoreward protrusion was > 34, suggesting that the anomaly was caused by an intrusion of slope waters onto the shelf (Figure 9a). Satellite derived observations of sea surface temperature indicate that several large amplitude Gulf Stream meanders and warm core rings impinged on the shelf during this time, with evidence of ring water observed well inshore of the shelf edge (Figure 10). The intrusion of warm, salty, ring water onto the shelf coincides with a notable decrease in the areal extent and an increase in temperature of the Mid-Atlantic Bight Cold Pool (Figure 9a). The Cold Pool, evident in bottom temperature fields in Figure 8a, is formed seasonally when a remnant of cold, winter-mixed water is trapped near the bottom, capped by the warming of surface waters in spring. The feature is typically eroded through a combination of continued atmospheric heating, progressively penetrating the near shore water column, and with the onset of fall storms in November. However, the intrusion of Gulf Stream ring water appears to have led to an accelerated erosion of this important feature.

Deep inflow to the Gulf of Maine through the Northeast Channel continues to be dominated by Warm Slope Water (Figure 11). Correspondingly, observations from the deep basins in the eastern Gulf of Maine are reflective of this pattern, with bottom waters measuring warmer and more saline than normal (Figure 12). The influence of Gulf Stream Warm Core rings was also evident in the Northeast Channel during June, as a tongue of very warm, saline water protruded into the channel at mid-depth (Figure 12). Springtime temperature-salinity and temperature-depth profiles indicate the presence of a weak Cold Intermediate Layer in the western Gulf of Maine during spring 2016, a mid-depth water mass formed seasonally as a product of convective mixing driven by winter cooling (Figures 13 - 14). In fact, the remnant winter water in the Cold Intermediate Layer is over 1.5°C warmer and slightly fresher than average in 2016, suggesting that convective mixing was suppressed in the preceding winter (Figure 13). Correspondingly, the bottom water observed in Wilkinson Basin is cooler and fresher than average (Figures 12 and 14). This finding is not surprising considering the fact that air temperatures over the Northeastern United States were more than 2°C warmer than normal in winter 2016 (Figure 15). 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 and intensity of spring phytoplankton blooms.

Basin-scale Conditions in 2016

During 2016, surface air temperatures were warmer than average (1981-2010) everywhere but the central basin during winter, summer, and fall (Figure 15). During spring, an area of colder air temperatures extended from the central basin over northern North America and the Canadian Arctic Archipelago (Figure 15). Overall, the seasonal range of regional average air temperatures over the northeastern United States and adjoining shelf was near normal. Sea surface temperature mirrored these patterns, with cooler than average sea surface temperature in the central basin and Labrador Sea during winter/spring and persistent warmer than average temperatures over the NEUS Continental Shelf throughout the year (Figure 16). Annually, the magnitude of the warming was comparable to that observed in the 1950s; however, 2016 was characterized by enhanced warming in summer and fall (Figure 17).

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 US Continental Shelves; and the position of the north wall of the Gulf Stream (e.g., Visbeck et al. 2003; Petrie 2007). The NAO index was positive for the third consecutive year during the winter of 2016, indicative of a deepening of the Icelandic low and a strengthening of the Azores' high (Figure 18). A positive NAO is typically associated with stronger northwesterly winds over the shelves, warmer bottom waters in the Gulf of Maine, a northward shift in the Gulf Stream, and a predominance of warm slope water in the Northeast Channel (Petrie 2007; Mountain 2012; Joyce et al. 2000).

SUMMARY

- Observations indicate that ocean temperatures on the NEUS shelf continue to increase relative to the 1977-1987 baseline.

- An intrusion of Gulf Stream ring water in the Mid-Atlantic Bight contributed to enhanced warming and salinification in late-summer/early-fall and probably led to erosion of the Cold Pool.
- Anomalously warm winter air temperatures over the Northeastern United States suppressed deep convective mixing in the western Gulf of Maine, resulting in a warmer intermediate water mass.
- Slope waters entering the Gulf of Maine through the Northeast Channel were anomalously warm and salty, consistent with the properties characteristic of Warm Slope Water derived from subtropical origins.

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Table 1. Listing of 2016 NOAA Northeast Fisheries Science Center cruises supported by the Oceans and Climate Branch, where EcoMon refers to Ecosystem Monitoring Surveys and AMAPPS refers to the Atlantic Marine Assessment Program for Protected Species.

Cruise	Program	Dates	Region(s)[1]	Gear	Casts
HB1601	Spring Bottom Trawl	08 Apr – 07 Jun	Full Shelf	SBE-19,SBE-911+	359
GU1608	EcoMon	21 May - 20 Jun	Full Shelf, Slope Sea	SBE-19+V2,SBE-911+	256
S11601	Scallop Survey	21 May - 23 Jun	GB	SBE-911+	16
HB1603	AMAPPS - Marine Mammal	28 Jun – 24 Aug	MAB, GB offshore	SBE-19+, SBE-911+	239
PC1607	EcoMon	09 - 19 Aug	GB, MAB	SBE-19+V2, SBE-911+	115
HB1604	Fall Bottom Trawl	09 Sep - 09 Nov	Full Shelf	SBE-19+,SBE-911+	384
PC1609	EcoMon	19 - 20 Oct	MAB North	SBE-19+V2,SBE-911+	13

[1] Regional Abbreviation:
GOM = Gulf of Maine
GB = Georges Bank
MAB = Mid-Atlantic Bight

Table 2. Regional average surface and bottom temperature values computed from CTD data that were sorted into six 2-month time periods for the 5 regions of the Northeast US Continental Shelf: Gulf of Maine east (GOME); Gulf of Maine west (GOMW); Georges Bank (GB); Mid-Atlantic Bight north (MABN); and Mid-Atlantic Bight south (MABS).

		SURFACE						BOTTOM					
Region	CD	#obs	Temp	Anomaly	SDV1	SDV2	Flag	#obs	Temp	Anomaly	SDV1	SDV2	Flag
							January-February						
GOME													
GOMW													
GB													
MABN													
MABS													
							March-April						
GOME													
GOMW													
GB													
MABN	108	10	8.41	1.89	1.78	0.47	1	12	9.69	2.82	1.76	1.48	1
MABS	104	75	10.44	1.93	0.22	1.66	0	93	10.41	2.64	0.24	1.09	0
							May-June						
GOME	154	58	9.81	1.29	0.13	0.76	0	59	8.68	1.57	0.16	0.69	0
GOMW	152	88	11.31	1.34	0.12	1.17	0	98	6.72	1.39	0.10	0.62	0
GB	147	85	9.97	1.12	0.15	1.06	0	90	9.30	1.56	0.14	1.11	0
MABN	144	82	11.55	0.43	0.18	0.98	0	83	9.24	1.64	0.20	0.81	0
MABS	145	45	14.11	-0.75	0.27	1.88	0	40	11.40	2.16	0.34	1.31	0
							July-August						
GOME	229	1	19.32	5.02	0.94	nan	1	1	9.29	1.04	0.81	nan	1
GOMW	230	5	21.48	3.21	1.03	0.40	1	4	6.49	1.28	0.63	0.18	1
GB	226	49	18.58	2.33	0.24	1.56	0	40	13.34	1.69	0.21	1.52	0
MABN	221	43	23.16	2.97	0.26	0.95	0	39	11.14	1.34	0.29	1.40	0
MABS	217	50	25.59	1.91	0.26	1.10	0	46	12.19	0.89	0.31	1.84	0
							September-October						
GOME	292	15	14.65	1.46	0.94	0.49	1	17	9.28	0.99	0.30	1.79	0
GOMW	295	21	13.71	1.76	0.26	0.83	0	28	8.69	1.50	0.20	1.04	0
GB	288	44	17.18	2.28	0.23	2.15	0	52	14.92	2.45	0.20	1.76	0
MABN	276	58	20.17	2.37	0.22	1.50	0	64	15.43	2.82	0.26	2.00	0
MABS	259	83	23.13	1.09	0.20	1.19	0	84	16.30	2.67	0.24	2.68	0
							November-December						
GOME	309	15	12.36	1.34	0.22	0.36	0	16	10.24	1.96	0.34	0.66	0
GOMW	309	18	12.39	1.75	0.26	0.41	0	18	8.76	2.05	0.18	0.77	0
GB													
MABN													
MABS													

"Region," the geographic region of the northeast continental shelf
"CD," the calendar mid-date of all the stations within a region for a time period
"#obs," the number of observations included in each average
"Temp," the areal average temperature
"Anomaly," the areal average temperature anomalies
"SDV1," the standard deviation associated with the average temperature anomaly
"SDV2," the standard deviation of the individual anomalies from which the average anomaly was derived
"Flag," a value of "1" indicates that a true areal average could not be calculated because of poor station coverage.
The areal averages listed were derived from a simple average of the observations within the region.

Table 3. Regional average surface and bottom salinity values computed from CTD data that were sorted into six 2-month time periods for the 5 regions of the Northeast US Continental Shelf: Gulf of Maine east (GOME); Gulf of Maine west (GOMW); Georges Bank (GB); Mid-Atlantic Bight north (MABN); and Mid-Atlantic Bight south (MABS).

		SURFACE						BOTTOM					
Region	CD	#obs	Salt	Anomaly	SDV1	SDV2	Flag	#obs	Salt	Anomaly	SDV1	SDV2	Flag
							January-February						
GOME													
GOMW													
GB													
MABN													
MABS													
							March-April						
GOME													
GOMW													
GB													
MABN	108	10	32.91	0.28	1.08	0.35	1	12	33.88	0.05	0.66	0.44	1
MABS	104	75	33.48	0.74	0.13	0.66	0	93	33.82	0.04	0.08	0.43	0
							May-June						
GOME	154	56	32.24	-0.12	0.07	0.32	0	59	34.20	0.17	0.05	0.36	0
GOMW	152	87	32.08	-0.04	0.05	0.38	0	98	33.14	-0.05	0.03	0.27	0
GB	147	85	32.62	-0.27	0.05	0.47	0	90	33.34	0.08	0.05	0.43	0
MABN	144	81	32.38	-0.09	0.08	0.37	0	83	33.27	-0.11	0.07	0.37	0
MABS	145	45	32.96	0.72	0.17	0.81	0	40	33.61	0.09	0.12	0.43	0
							July-August						
GOME	229	1	32.34	-0.24	0.48	nan	1	1	35.05	0.45	0.38	nan	1
GOMW	230	5	32.02	0.22	0.37	0.11	1	4	33.23	-0.14	0.21	0.07	1
GB	226	48	32.62	-0.23	0.08	0.58	0	40	33.33	0.19	0.07	0.53	0
MABN	221	41	32.27	-0.25	0.12	0.43	0	39	33.61	0.01	0.10	0.38	0
MABS	217	50	31.77	-0.07	0.16	0.72	0	46	33.21	-0.10	0.12	0.33	0
							September-October						
GOME	292	15	32.75	0.21	0.40	0.15	1	17	34.60	0.22	0.09	0.32	0
GOMW	295	21	32.83	0.32	0.11	0.12	0	28	33.59	0.09	0.07	0.24	0
GB	288	44	33.51	0.71	0.07	0.93	0	52	33.61	0.34	0.07	0.35	0
MABN	276	58	33.75	0.93	0.10	0.77	0	64	33.84	0.20	0.09	0.70	0
MABS	259	83	32.71	0.36	0.12	0.66	0	84	33.24	-0.35	0.09	0.62	0
							November-December						
GOME	309	15	32.55	-0.17	0.14	0.21	0	16	34.75	0.36	0.09	0.26	0
GOMW	309	18	32.78	0.09	0.10	0.23	0	18	33.75	0.10	0.07	0.22	0
GB													
MABN													
MABS													

"Region," the geographic region of the northeast continental shelf
"CD," the calendar mid-date of all the stations within a region for a time period
"#obs," the number of observations included in each average
"Salt," the areal average salinity: "Anomaly," the areal average salinity anomalies
"SDV1," the standard deviation associated with the average salinity anomaly
"SDV2," the standard deviation of the individual anomalies from which the average anomaly was derived
"Flag," a value of "1" indicates that a true areal average could not be calculated because of poor station coverage.
The areal averages listed were derived from a simple average of the observations within the region.

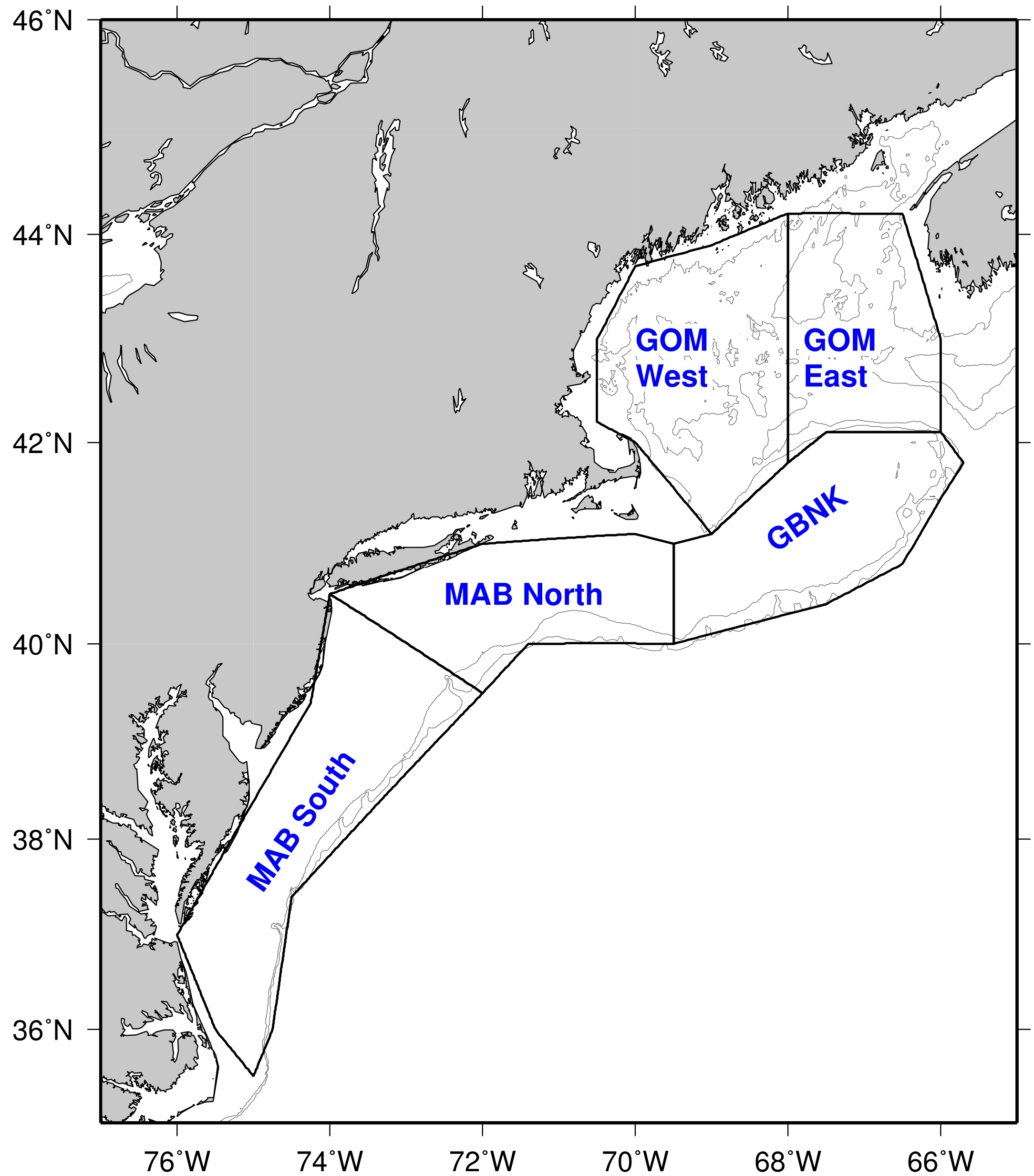

Figure 1. Regional designations used in the description of 2015 oceanographic conditions on the Northeast US Continental Shelf. The 100 m and 200 m isobaths are also shown. MAB = Mid-Atlantic Bight; GBNK = Georges Bank; GOM = Gulf of Maine.

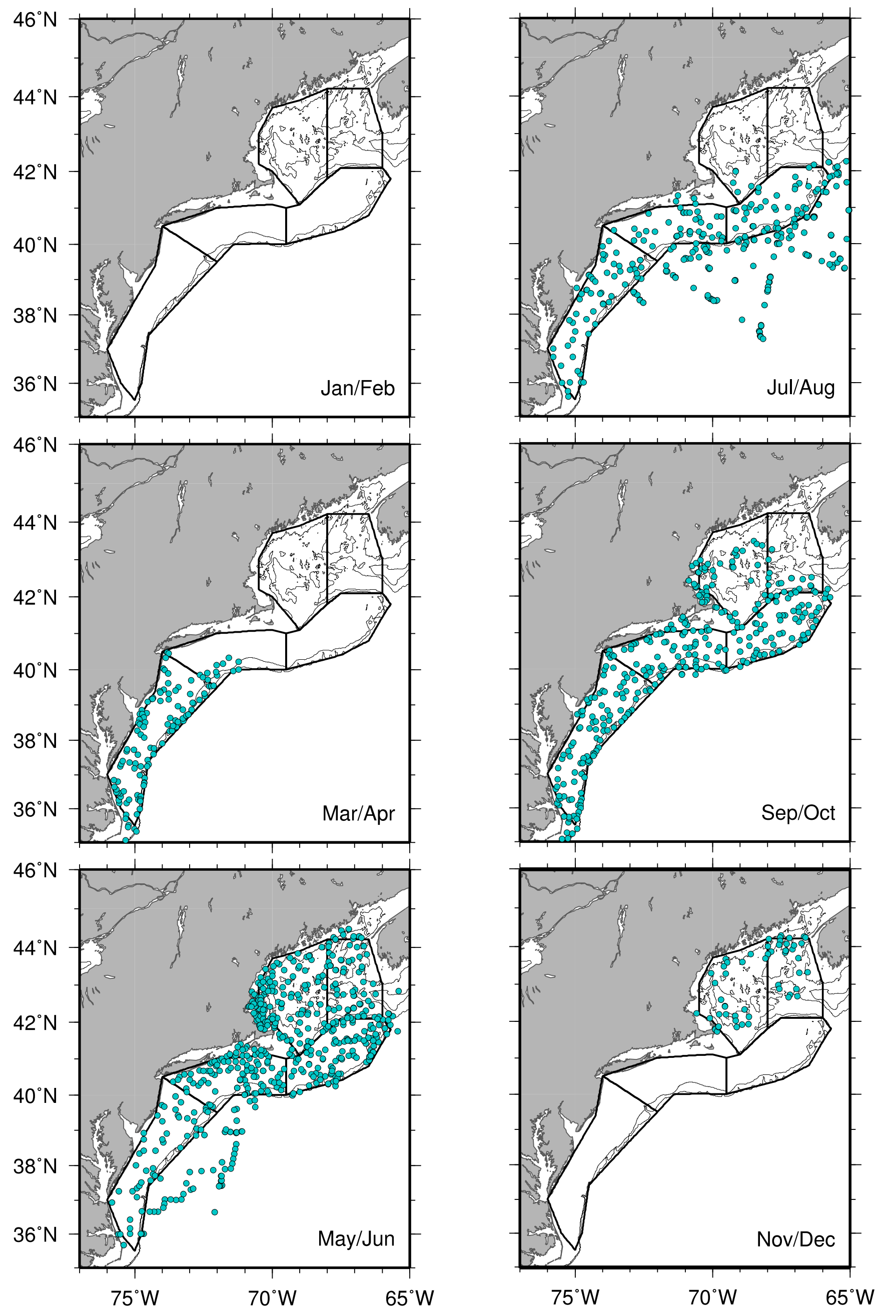

Figure 2a. Bimonthly distribution of hydrographic stations used in the description of 2016 oceanographic conditions on the Northeast US Continental Shelf. Regional boundaries used in the analysis are also shown. Contours correspond with the 100- and 200-m isobaths.

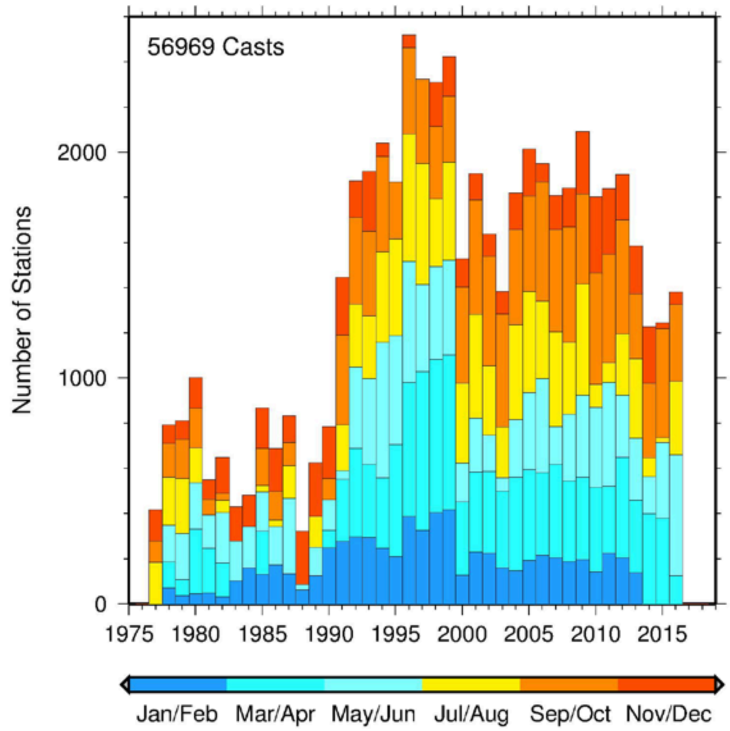

Figure 2b. Histogram of the number of hydrographic stations occupied on Northeast Fisheries Science Center surveys in a given year, color-coded by bimonthly period.

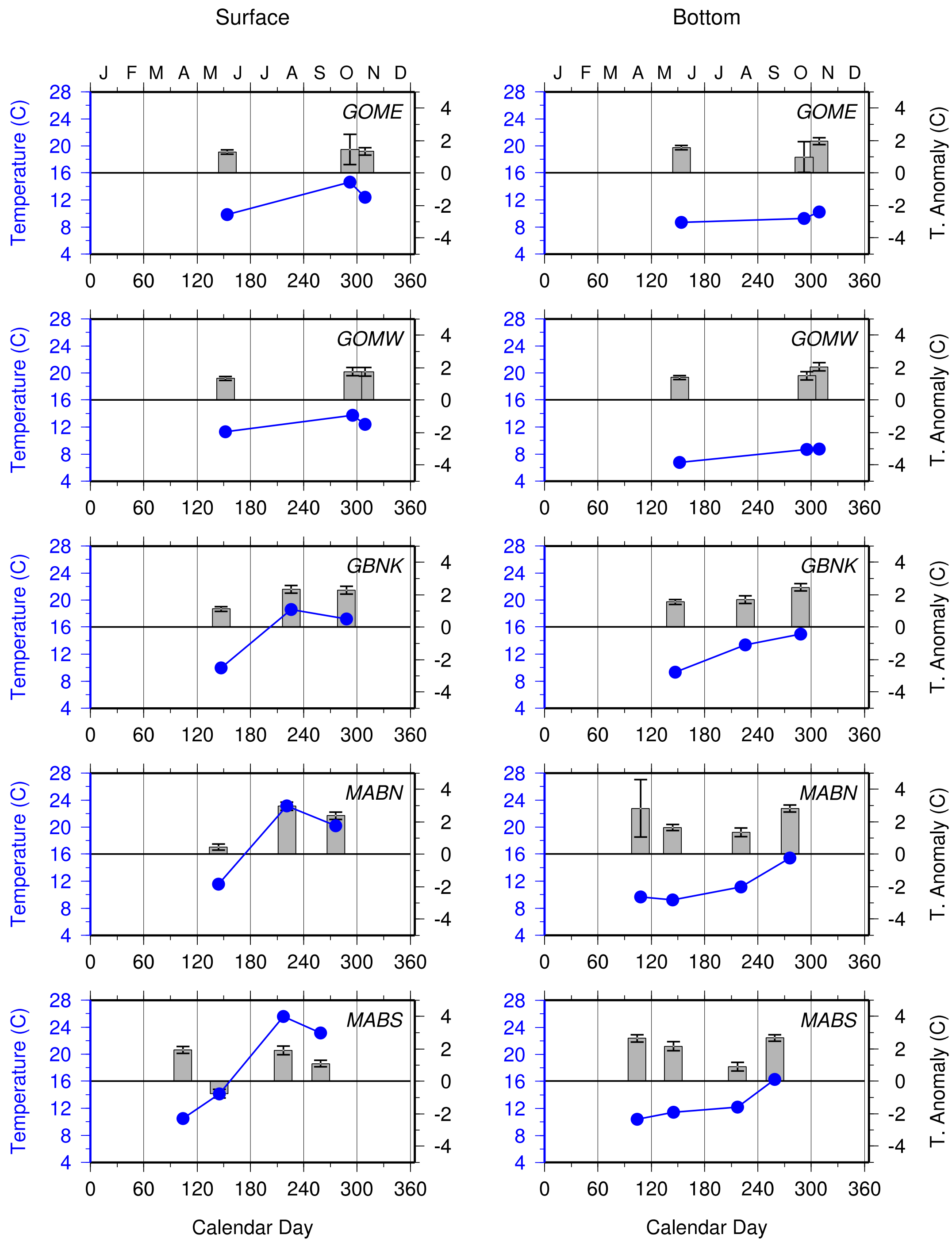

Figure 3. Time series of the 2016 regional surface (left) and bottom (right) temperatures (blue) and anomalies (bars) as a function of calendar day. Error bars are indicated for the anomaly estimates. GOME = Gulf of Maine east; GOMW = Gulf of Maine west; GBNK = Georges Bank; MABN = Mid-Atlantic Bight north; MABS = Mid-Atlantic Bight south.

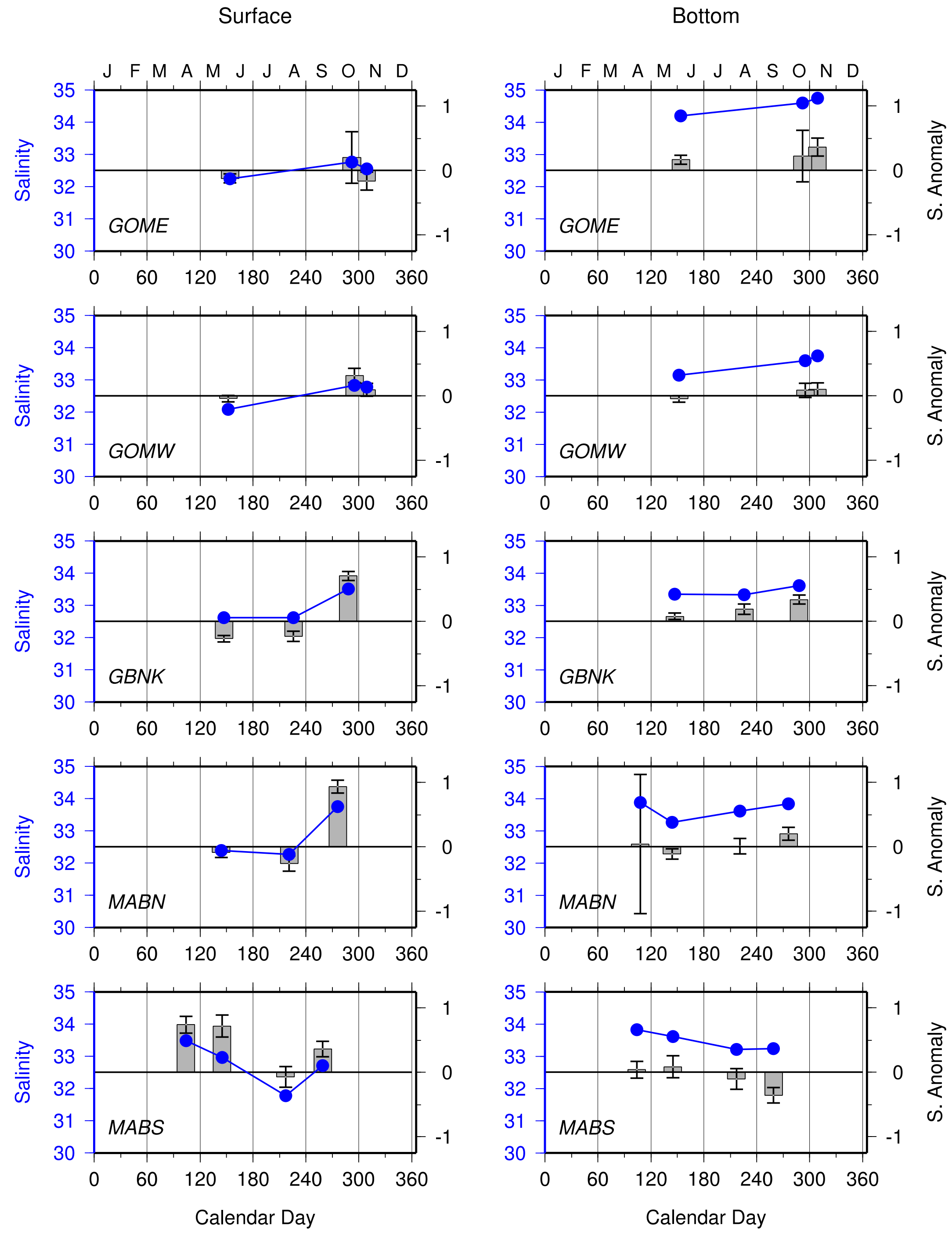

Figure 4. Time series of the 2016 regional surface (left) and bottom (right) salinities (blue) and anomalies (bars) as a function of calendar day. Error bars are indicated for the anomaly estimates. GOME = Gulf of Maine east; GOMW = Gulf of Maine west; GBNK = Georges Bank; MABN = Mid-Atlantic Bight north; MABS = Mid-Atlantic Bight south.

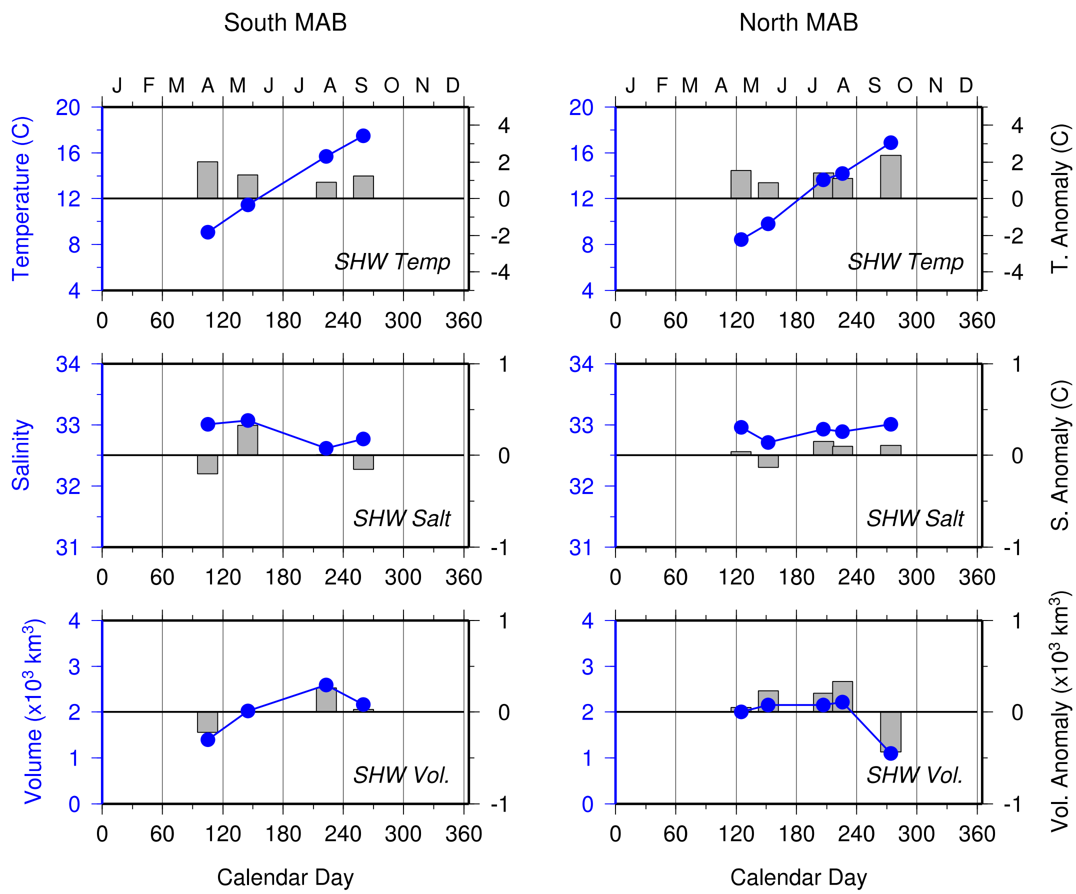

Figure 5. Time series of the 2016 regional shelf water (SHW) temperature, salinity, and volume as a function of calendar day shown in blue for the southern (left) and northern (right) Mid-Atlantic Bight (MAB). The vertical bars show the corresponding shelf water anomalies.

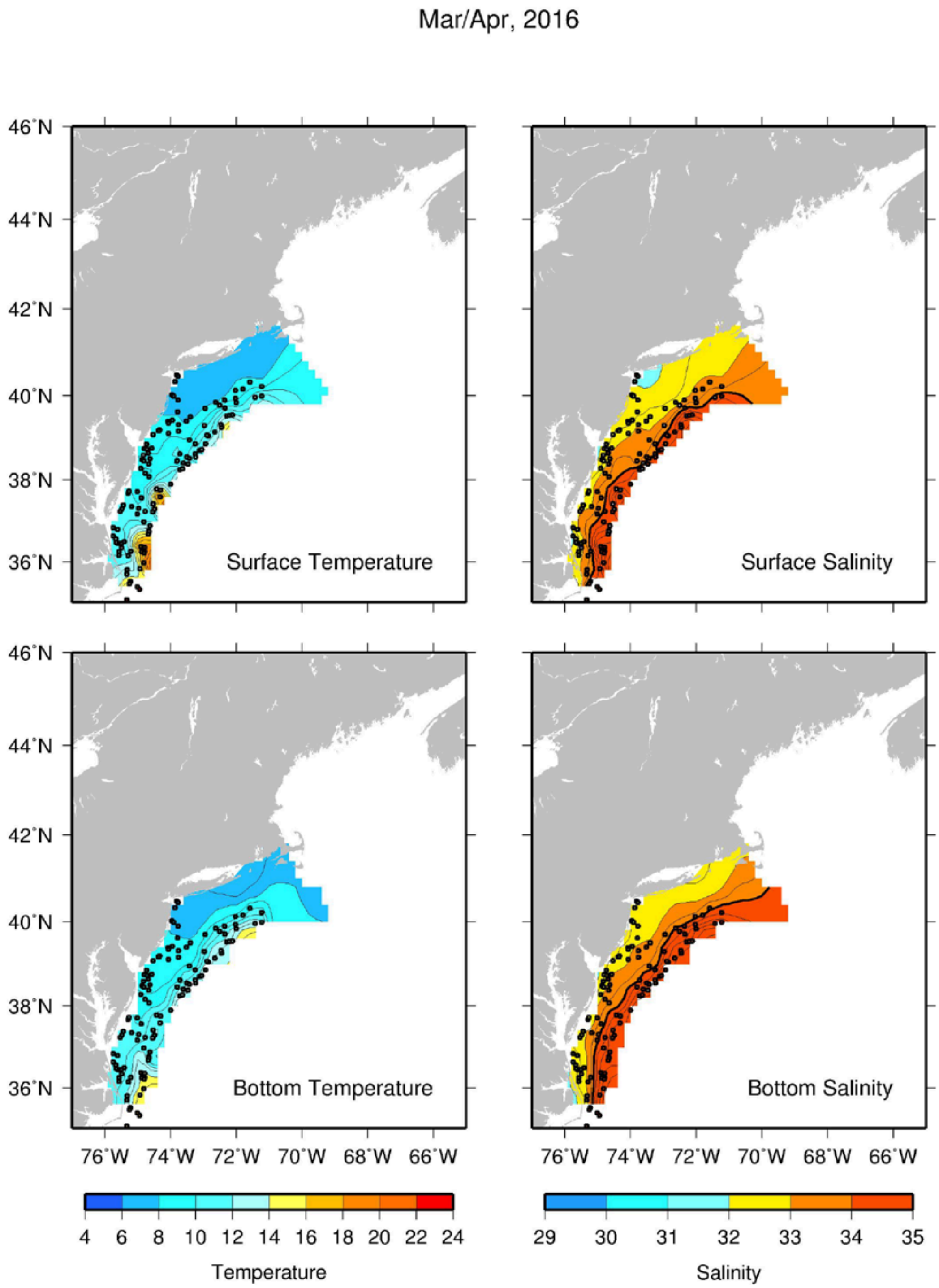

Figure 6a. Near-surface (top) and near-bottom (bottom) temperature (left) and salinity (right) distributions on the Northeast US Continental Shelf during March-April 2016. Temperature and salinity are contoured in increments of 1ºC and 0.5, respectively. The 34 isohaline is denoted by the heavier contour.

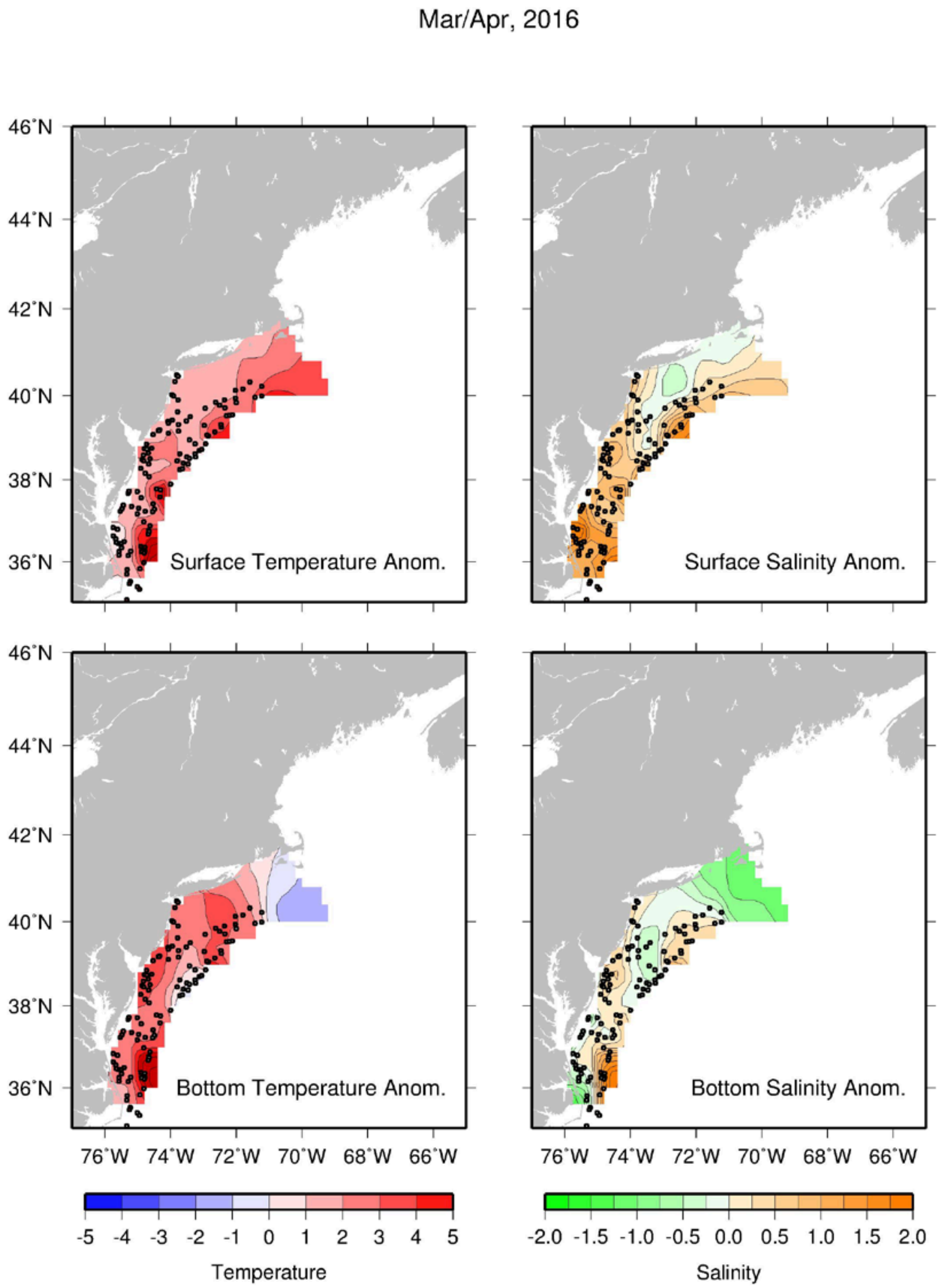

Figure 6b. Near-surface and near-bottom temperature anomaly (left) and salinity anomaly (right) distributions on the Northeast US Continental Shelf during March-April 2016. Temperature and salinity anomaly are contoured in increments of 1ºC and 0.5, respectively.

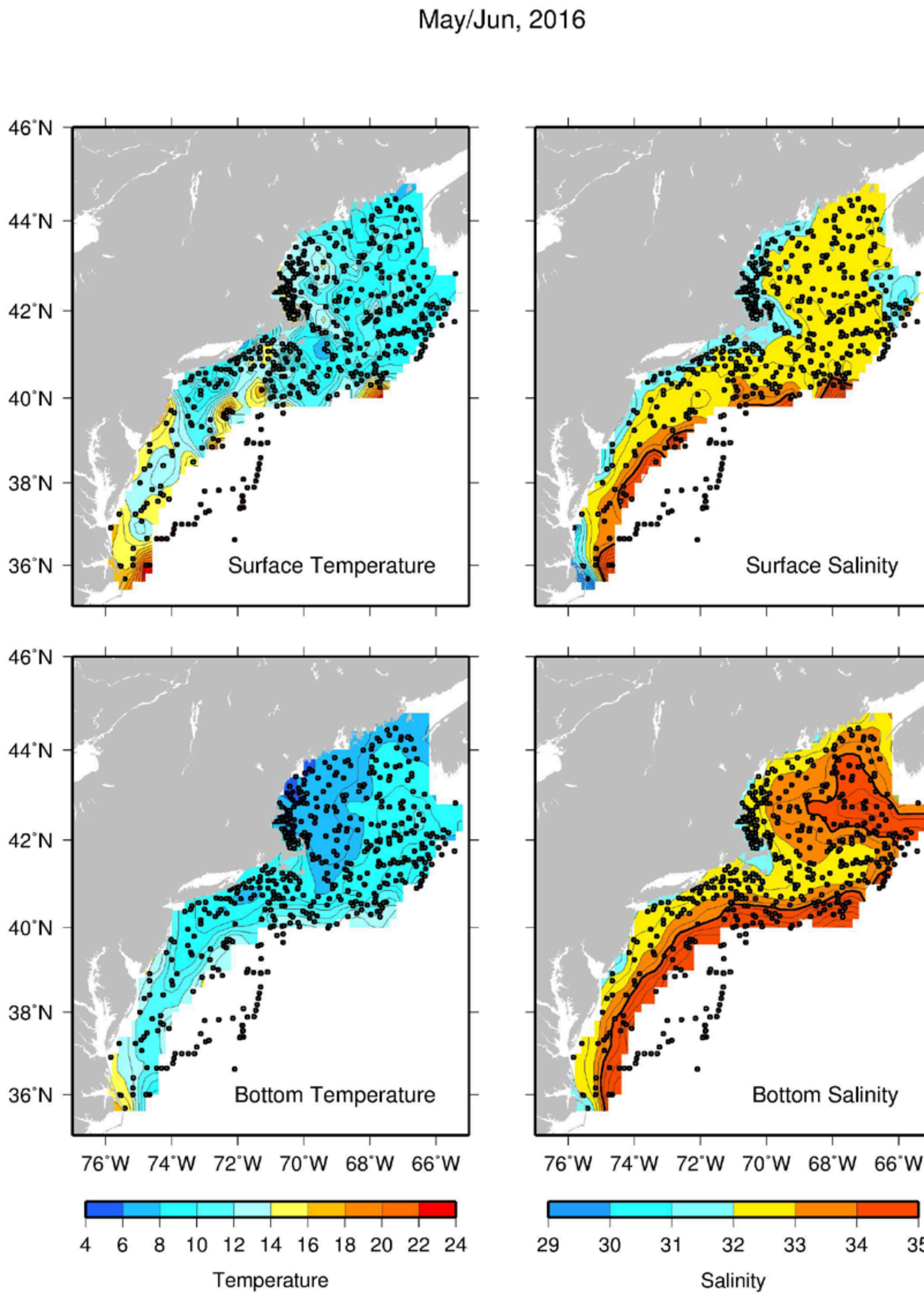

Figure 7a. Near-surface (top) and near-bottom (bottom) temperature (left) and salinity (right) distributions on the Northeast US Continental Shelf during May-June 2016. Temperature and salinity are contoured in increments of 1ºC and 0.5, respectively. The 34 isohaline is denoted by the heavier contour.

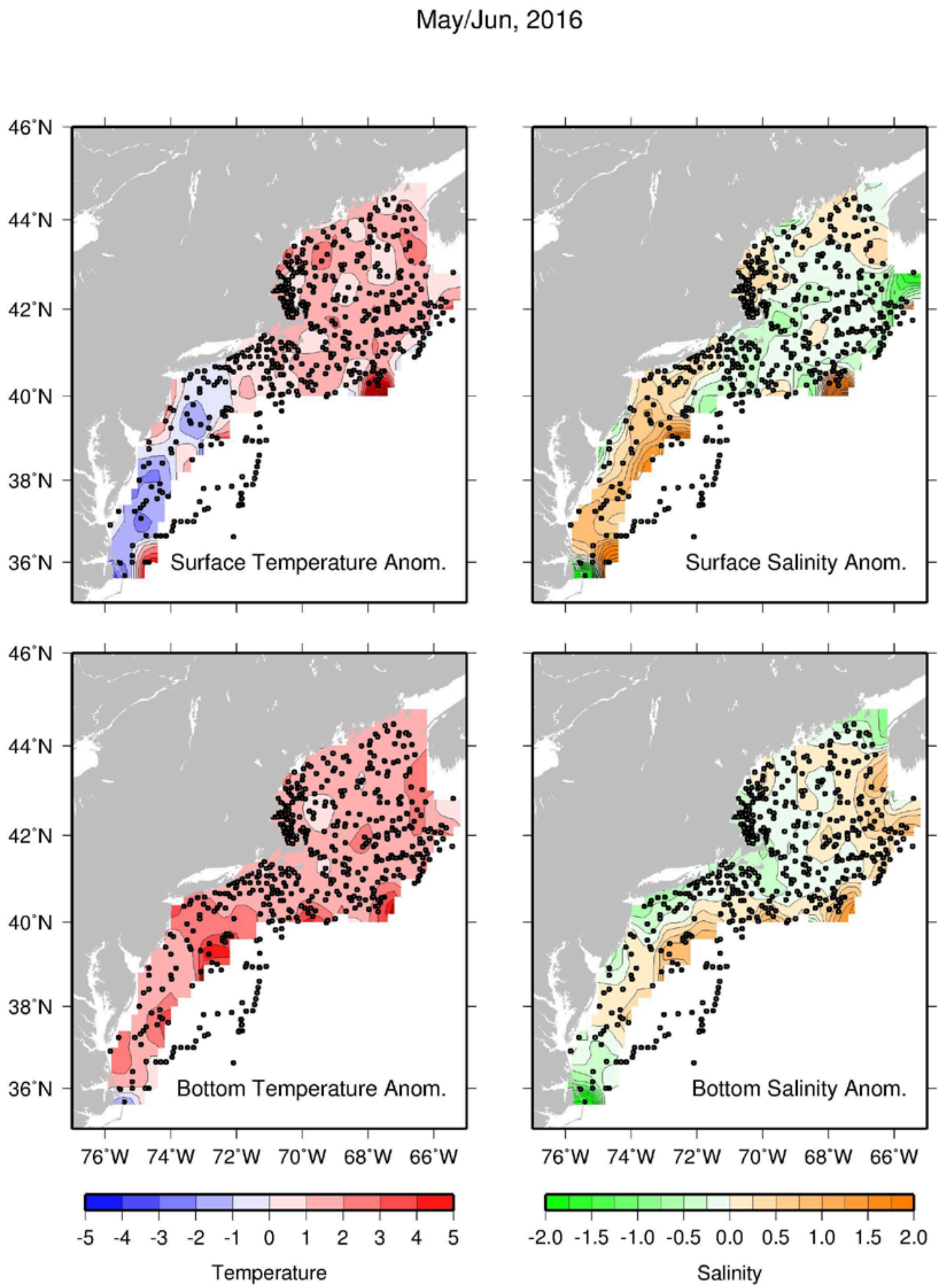

Figure 7b. Near-surface and near-bottom temperature anomaly (left) and salinity anomaly (right) distributions on the Northeast US Continental Shelf during May-June 2016. Temperature and salinity anomaly are contoured in increments of 1ºC and 0.5, respectively.

Jul/Aug, 2016

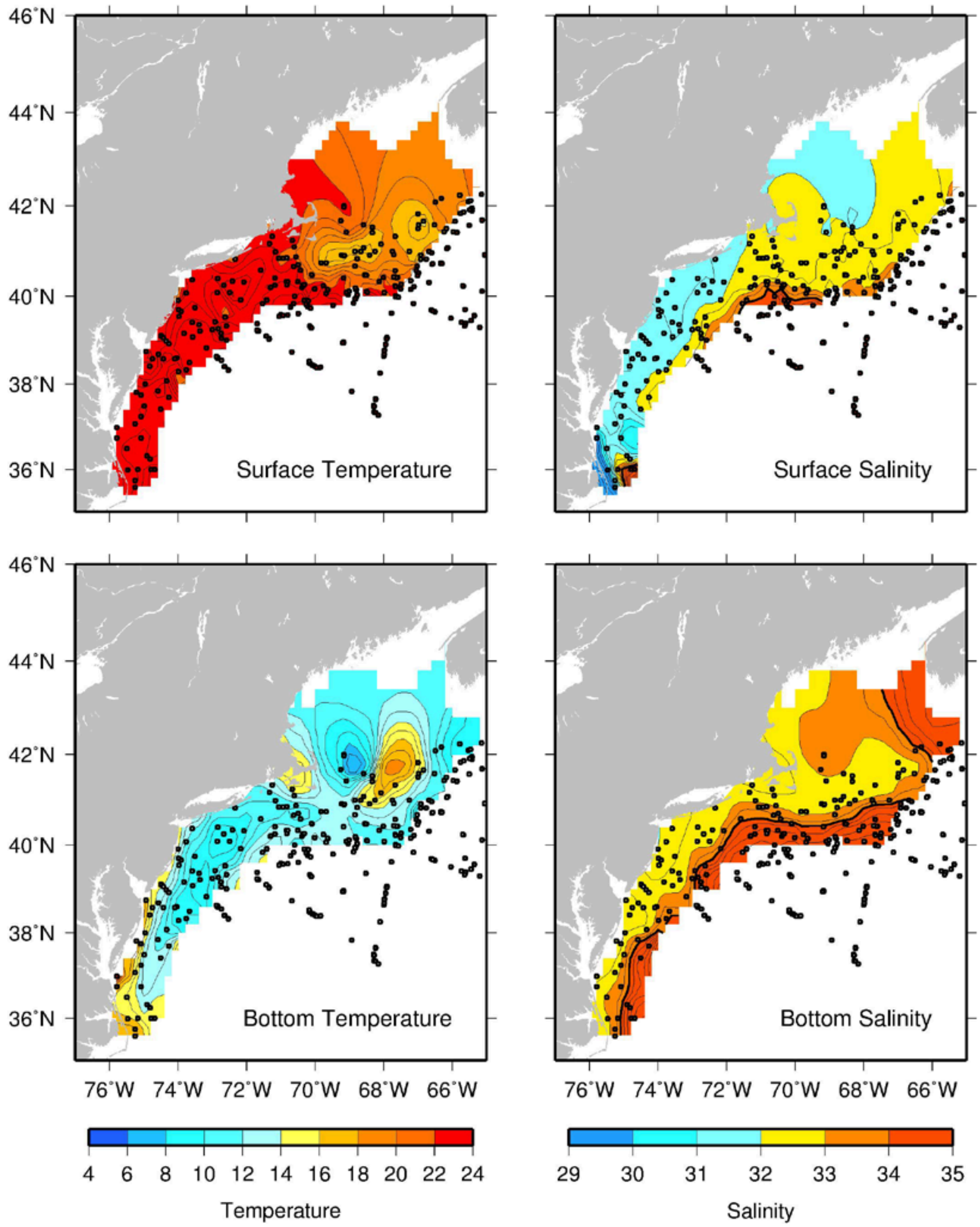

Figure 8a. Near-surface (top) and near-bottom (bottom) temperature (left) and salinity (right) distributions on the Northeast US Continental Shelf during July-August 2016. Temperature and salinity are contoured in increments of 1ºC and 0.5, respectively. The 34 isohaline is denoted by the heavier contour.

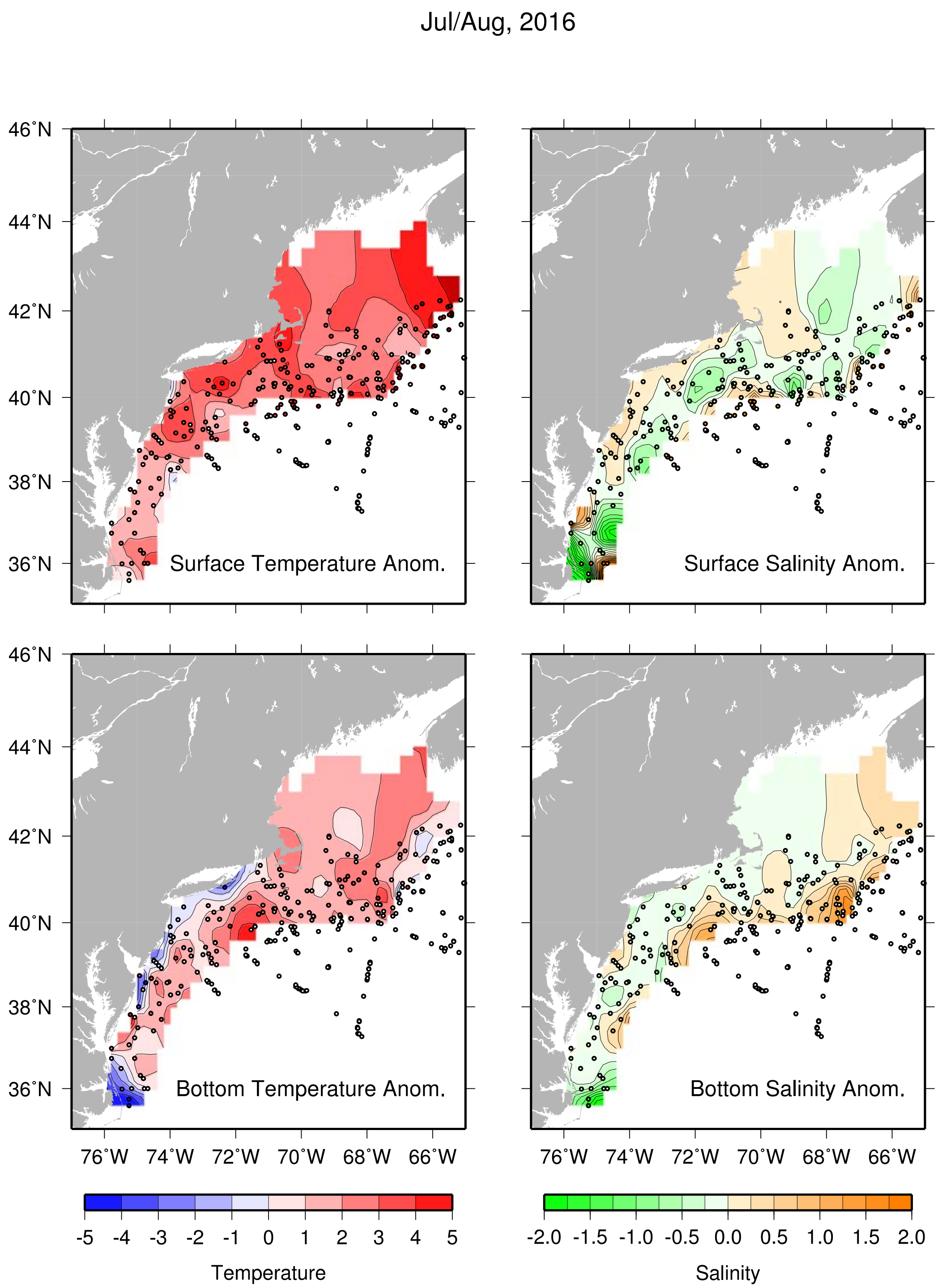

Figure 8b. Near-surface and near-bottom temperature anomaly (left) and salinity anomaly (right) distributions on the Northeast US Continental Shelf during July-August 2016. Temperature and salinity anomaly are contoured in increments of 1ºC and 0.5, respectively.

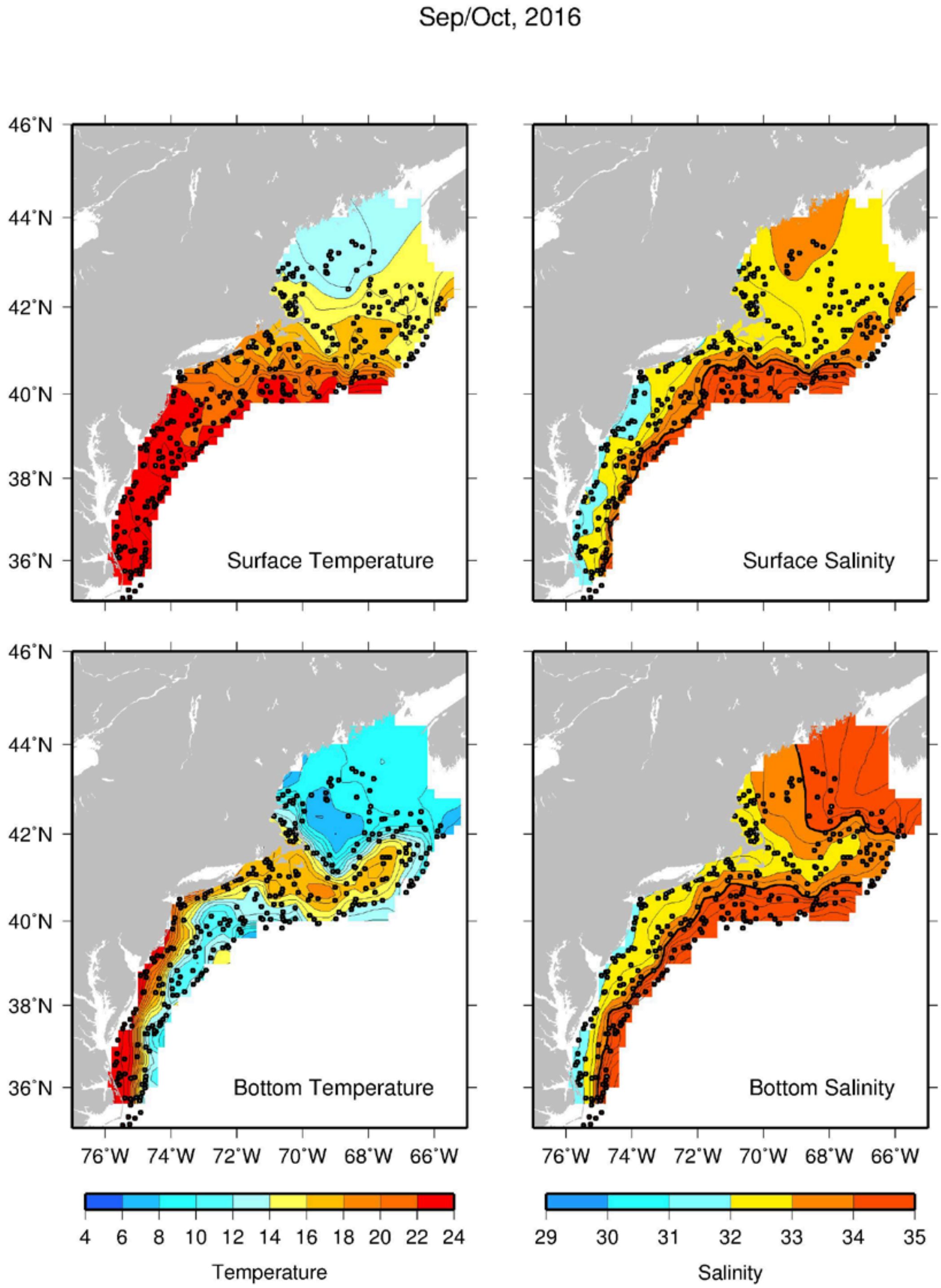

Figure 9a. Near-surface (top) and near-bottom (bottom) temperature (left) and salinity (right) distributions on the Northeast US Continental Shelf during September-October 2016. Temperature and salinity are contoured in increments of 1ºC and 0.5, respectively. The 34 isohaline is denoted by the heavier contour.

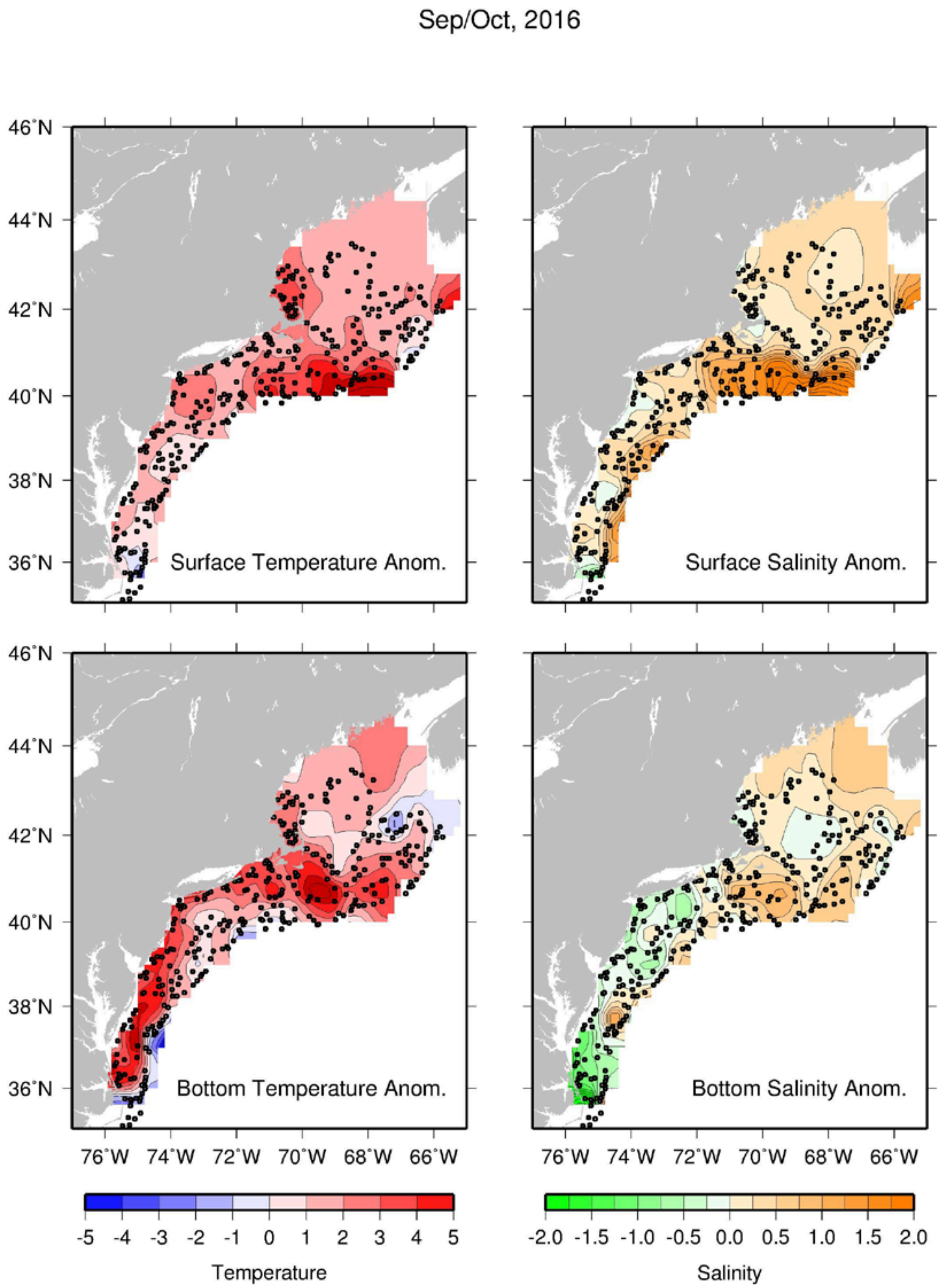

Figure 9b. Near-surface and near-bottom temperature anomaly (left) and salinity anomaly (right) distributions on the Northeast US Continental Shelf during September-October 2016. Temperature and salinity anomaly are contoured in increments of 1ºC and 0.5, respectively.

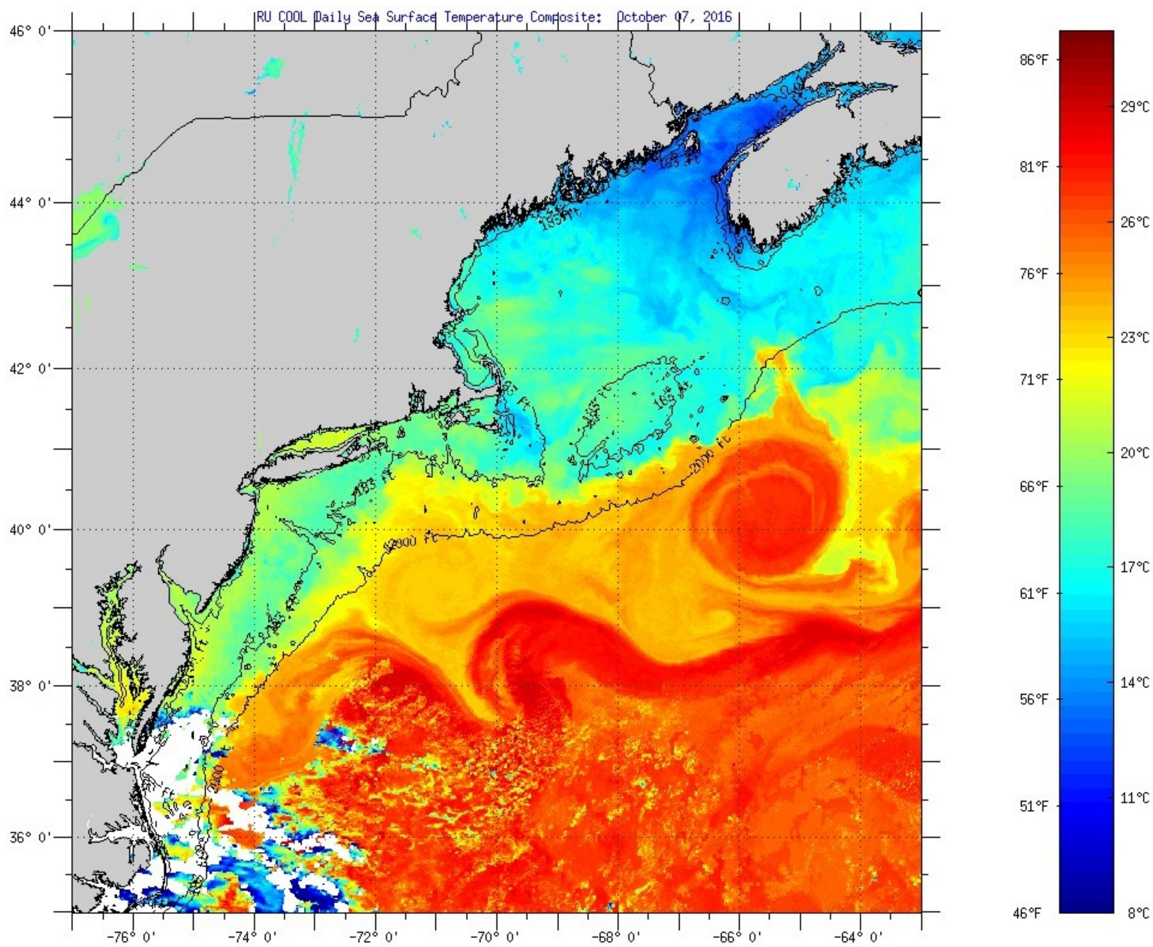

Figure 10: Daily composite sea surface temperature derived by the Coastal Ocean Observation Lab, Rutgers University, from data collected by the Advanced Very High Resolution Radiometer on October 7, 2016.

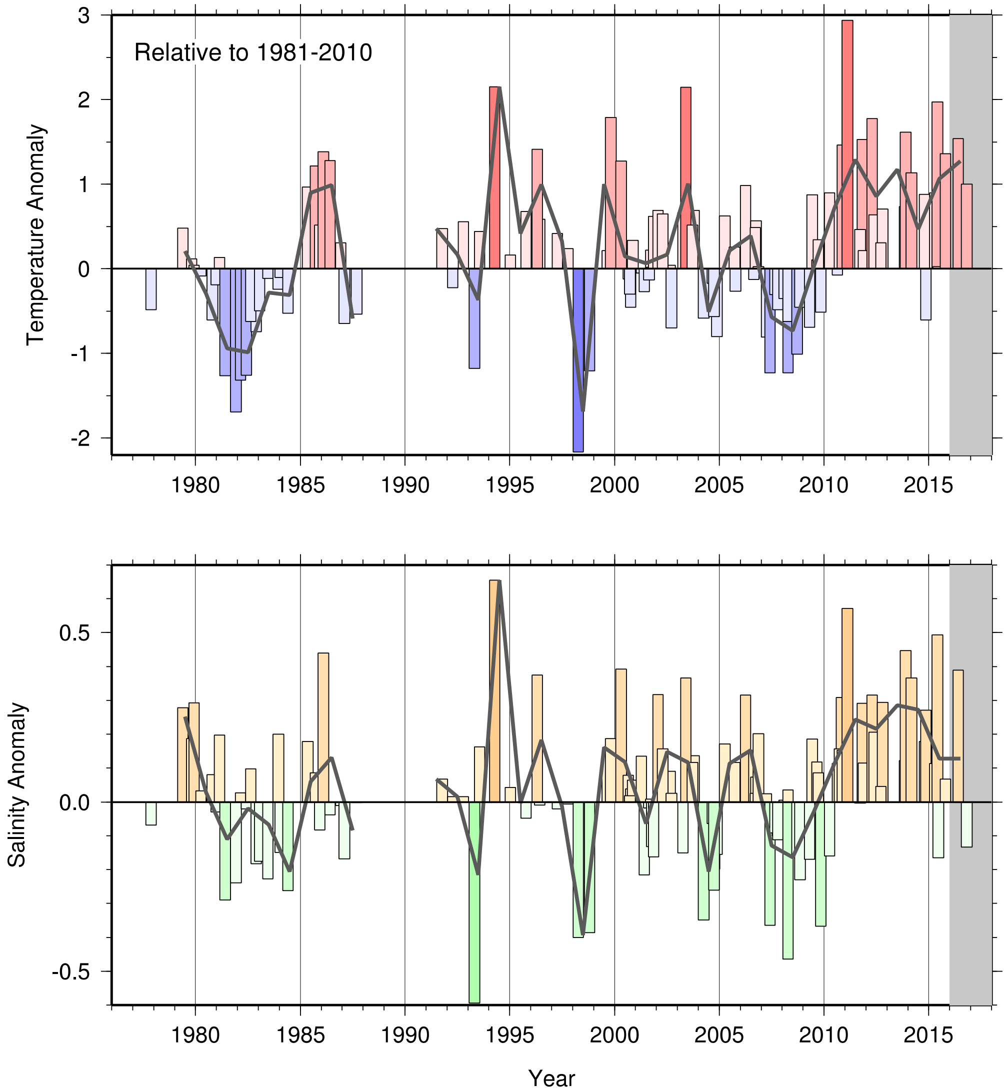

Figure 11. Time series of temperature and salinity anomaly in the deep Northeast Channel. Each bar represents a volume-weighted average of all observations from a single survey collected between 150-200 meters in the Northeast Channel. The gray curve shows the annual average anomaly time series. Positive values are warmer and saltier than the long-term mean calculated for 1981-2010. The gray shading highlights sampling done in 2016.

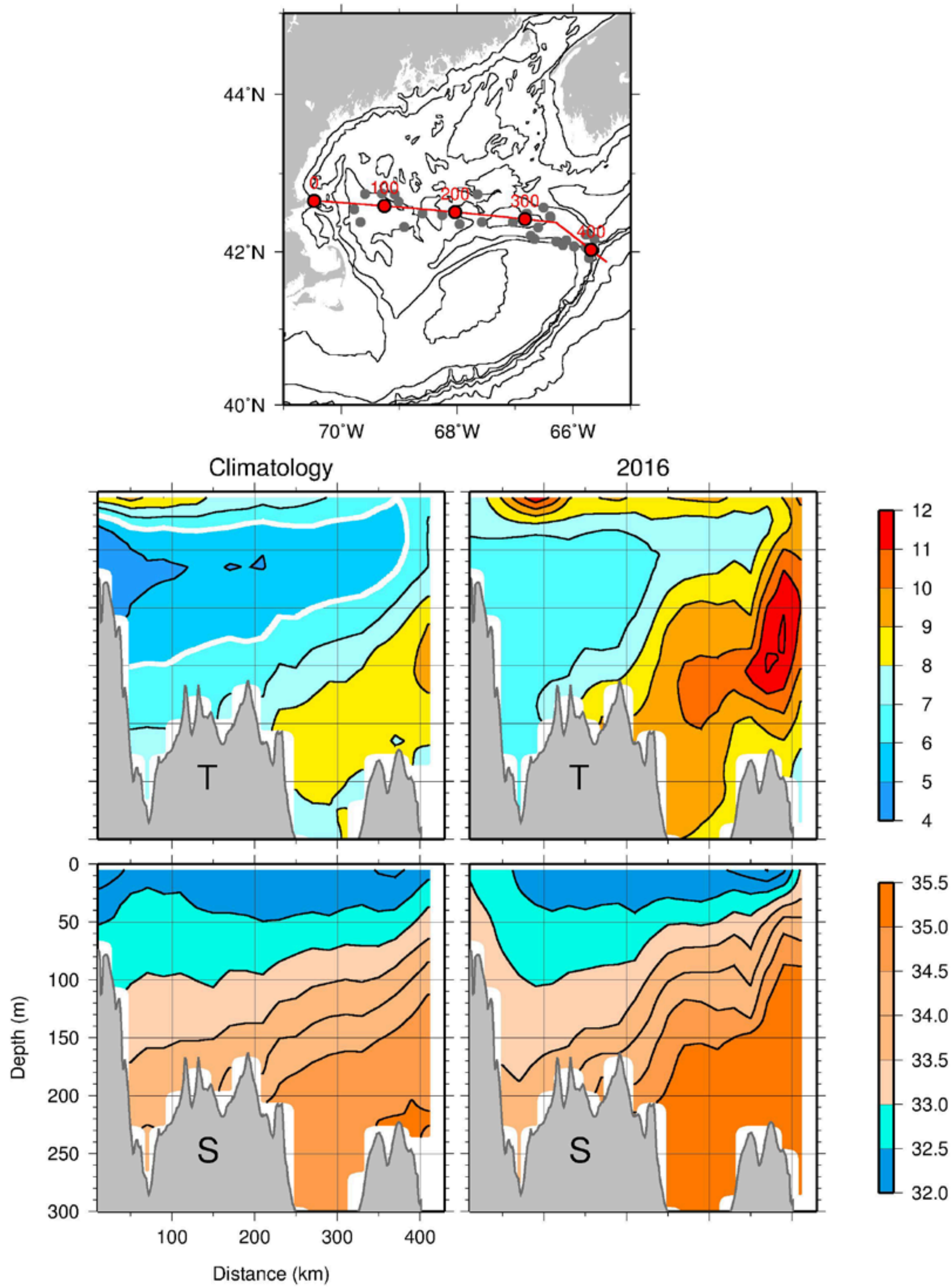

Figure 12. Vertical sections of temperature (top) and salinity (bottom) crossing the Gulf of Maine along a zonal transect shown in the map. The left panels show the climatological average for May spanning the years 1981-2010. The right panels show the synoptic mean section for May 2016. The heavy white contour highlights the 6°C isotherm as an indicator of the boundary of the Cold Intermediate Layer. Along-transect distances and the May 2016 station distribution are shown on the map for reference.

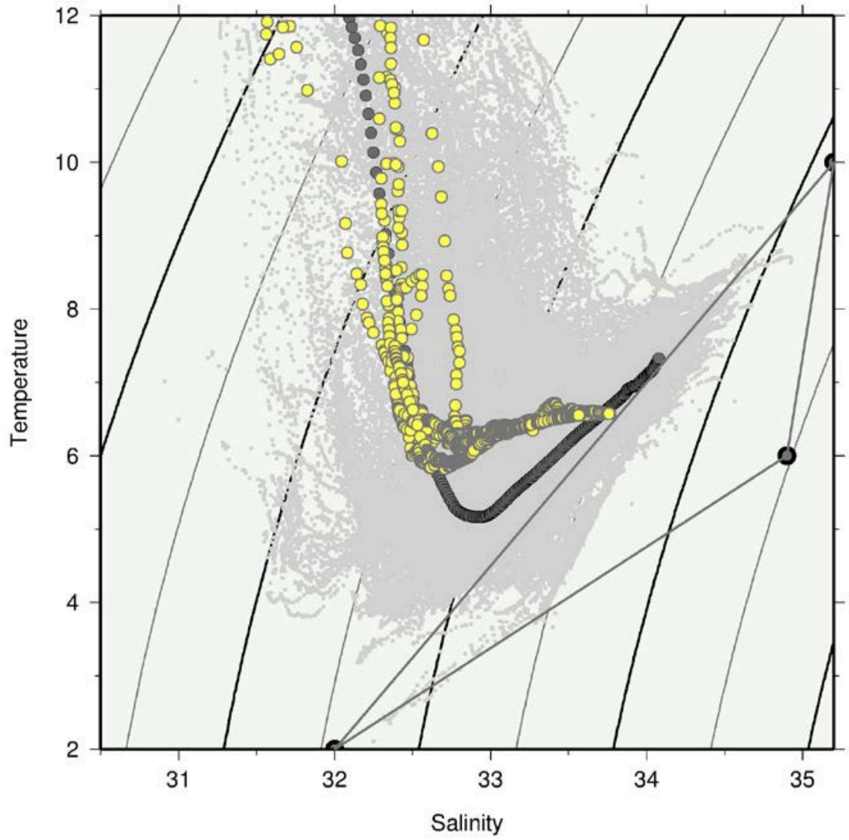

Figure 13. Temperature-salinity diagram showing water properties in Wilkinson Basin in the western Gulf of Maine. All observations from spring 2016 (yellow) are shown along with the spring climatological average profile (1981-2010, dark gray). The lightest gray dots show the historical range encompassed by observations from the reference period, 1981-2010.

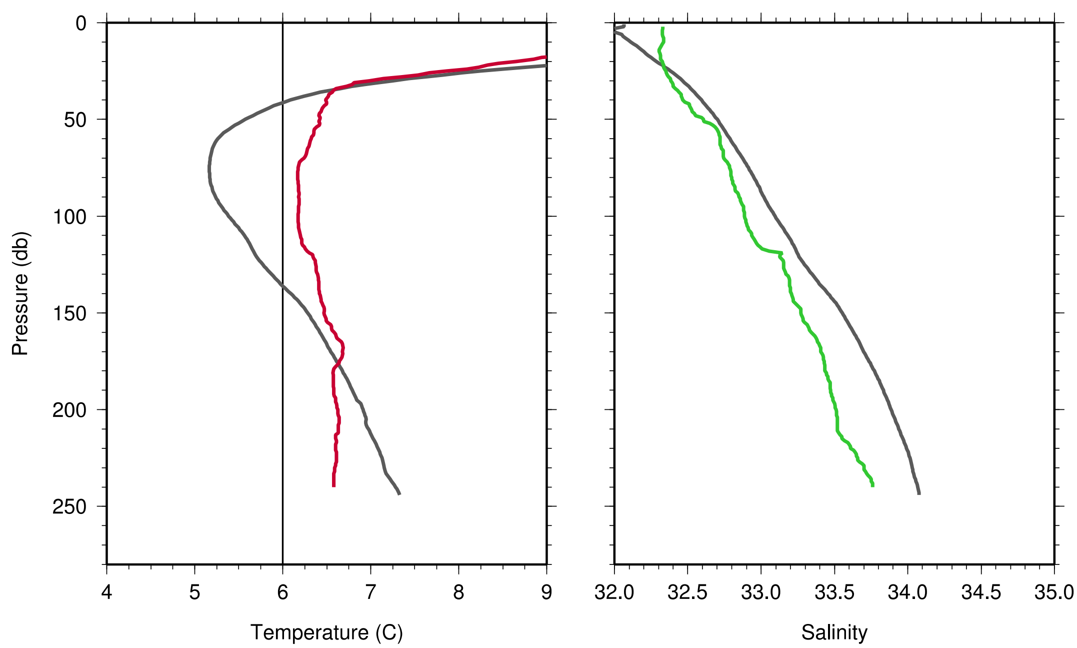

Figure 14. Average profiles of temperature (left) and salinity (right) from repeated observations collected during June in Wilkinson Basin in the western Gulf of Maine. All observations from June 2016 (red and green) are shown along with the climatological average profile for the same month (1981-2010, dark gray). Waters in the Cold Intermediate Layer in the western Gulf of Maine are typically colder than 6°C, denoted by the vertical line.

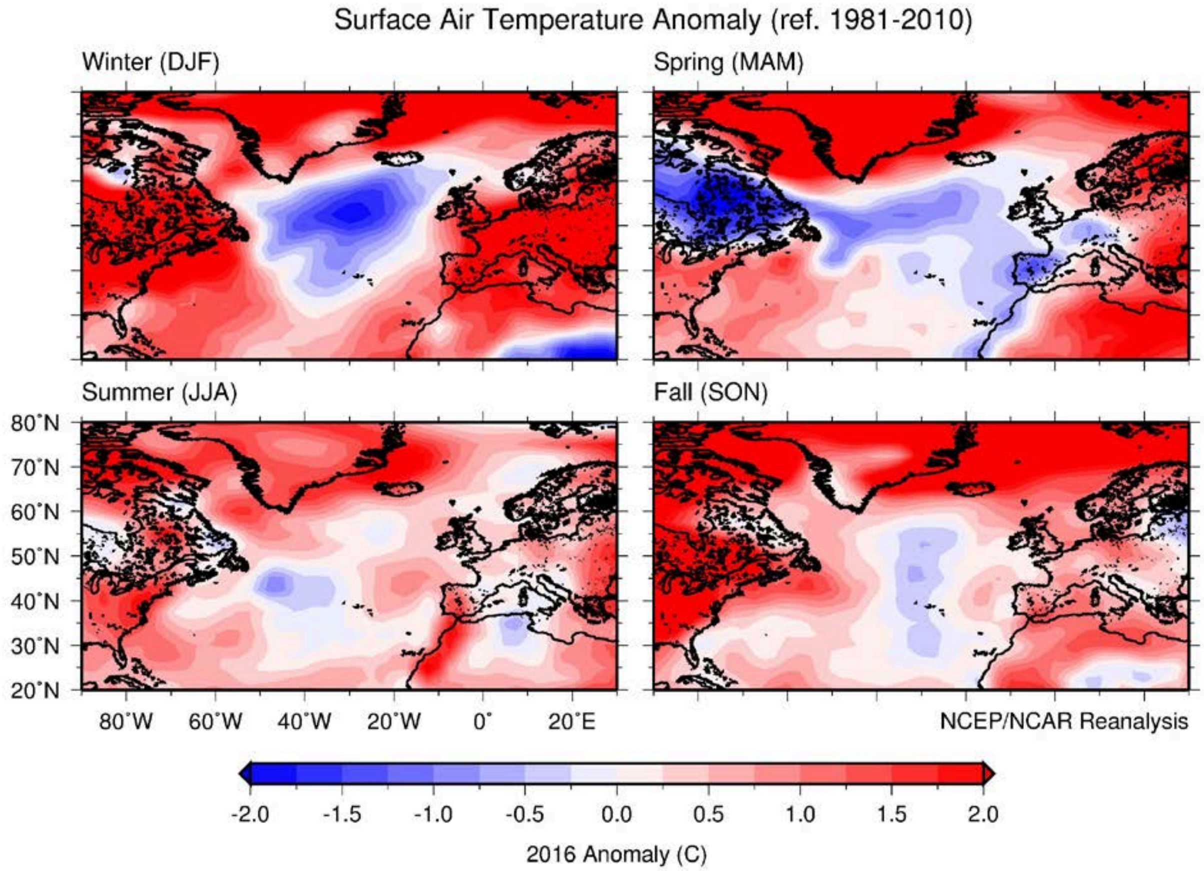

Figure 15. Surface air temperature anomaly on the Northeast US Continental Shelf derived from the National Centers for Atmospheric Prediction (NCEP)/ National Center for Atmospheric Research (NCAR) Reanalysis product (http://www.esrl.noaa.gov/psd/data/composites/day/). Seasons are made up of 3-month periods: winter (Dec, Jan, Feb), spring (Mar, Apr, May), summer (Jun, Jul, Aug), and fall (Sep, Oct, Nov). Positive anomalies correspond to warming in 2016 relative to the reference period (1981-2010).

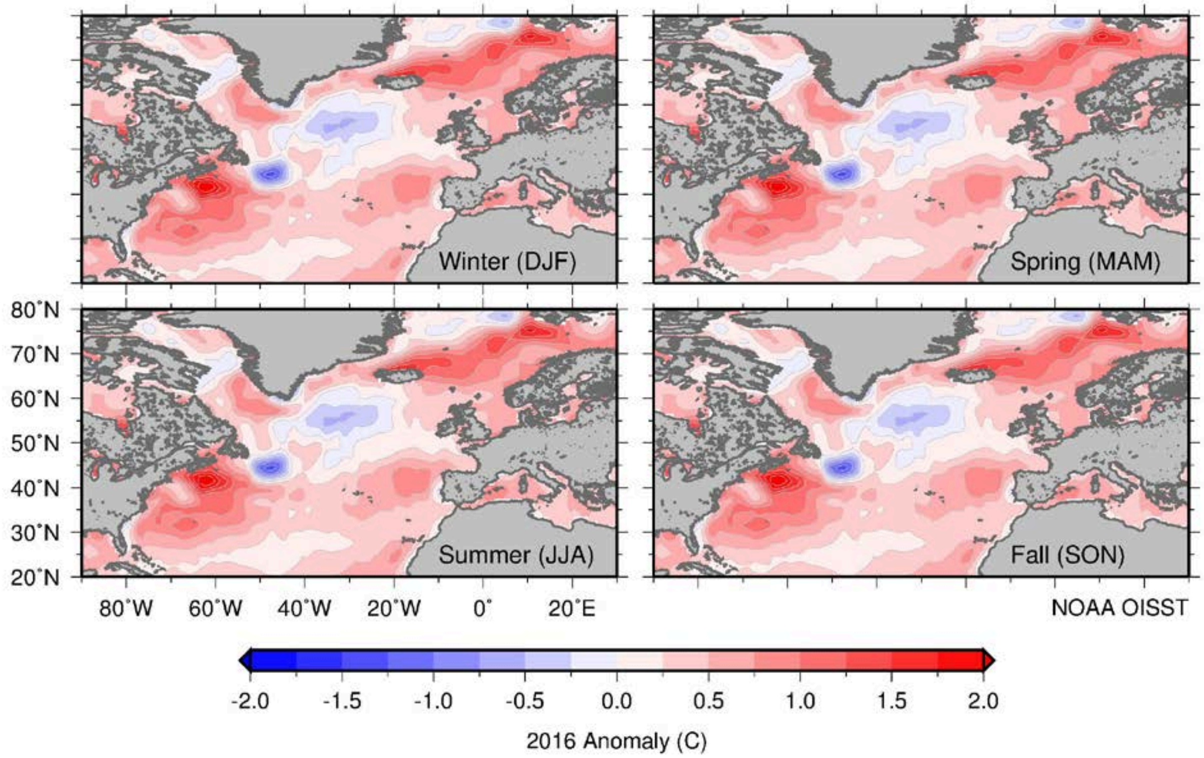

Figure 16. Sea surface temperature (SST) anomaly on the Northeast US Continental Shelf. derived from NOAA's Optimum Interpolation (OI) SST product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html). Seasons are made up of 3-month periods: winter (Dec-Feb), spring (Mar-May), summer (Jun-Aug), and fall (Sep-Nov). Positive anomalies correspond to warming in 2016 relative to the reference period (1981-2010).

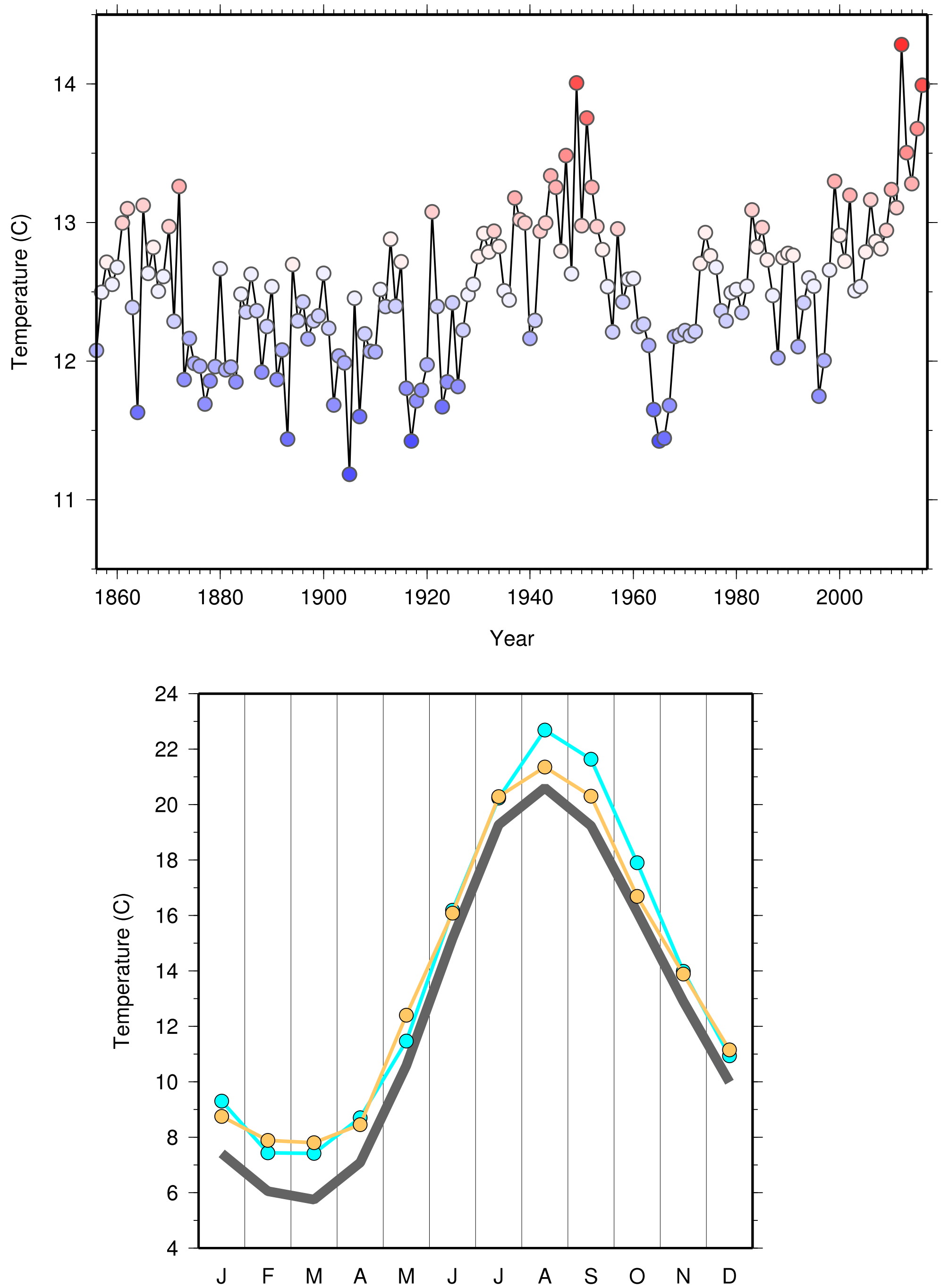

Figure 17. (top) Regional average annual sea surface temperature for the Northeast US (NEUS) Continental Shelf region calculated from NOAA's extended reconstructed sea surface temperature product (http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html). Regional average monthly mean SST for the NEUS shelf for 2016 (cyan), 1951 (orange) and 1981-2010 (gray) calculated from the same product.

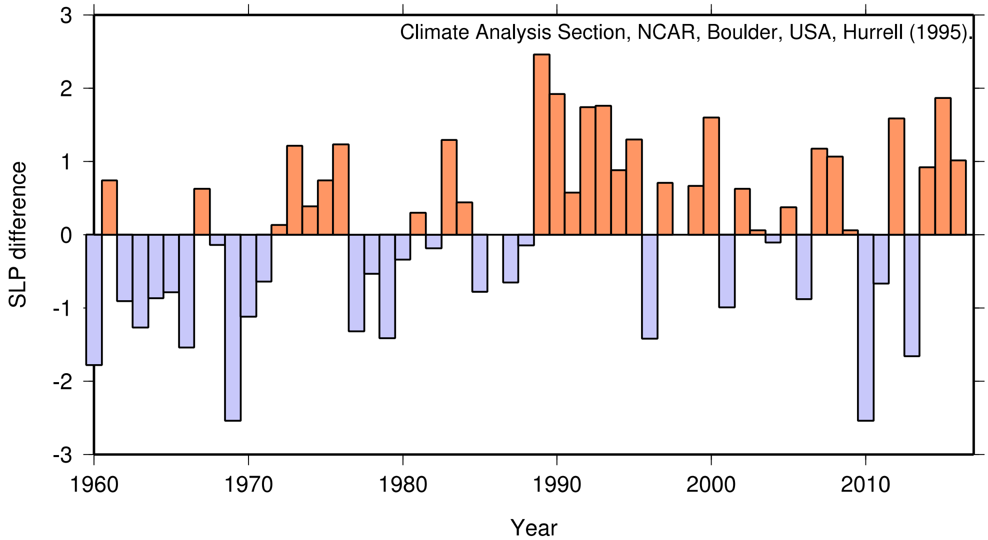

Figure 18. North Atlantic Oscillation index computed from principal component analysis of sea level pressure in the North Atlantic (see Hurrell 1995).

Table A1. Regional average temperature and salinity calculated from hydrographic observations collected by individual Northeast Fisheries Science Center surveys in the eastern Gulf of Maine (boundary defined in Figure 1). Average values incorporating fewer than 10 observations are shown in gray. Average values are not reported for regions containing fewer than 5 observations.

Gulf of Maine East

Cruise	CD	#obs	Surface Temp	Anomaly	SDV1	SDV2	Flag	#obs	Bottom Temp	Anomaly	SDV1	SDV2	Flag
HB1603													
PC1609													
HB1601	148	36	9.14	1.29	0.16	0.75	0	36	8.67	1.47	0.20	0.72	0
GU1608	161	25	10.22	0.99	0.19	0.66	0	20	8.85	1.75	0.28	0.60	0
S11601	171	3	13.57	2.18	0.83	1.04	1	3	7.68				1
PC1607	230	1	19.33	5.00	0.94		1	1	9.29	1.03	0.81		1
HB1604	303	42	13.23	1.55	0.14	0.41	0	34	9.95	1.51	0.20	1.55	0

Cruise	CD	#obs	Surface Salinity	Anomaly	SDV1	SDV2	Flag	#obs	Bottom Salinity	Anomaly	SDV1	SDV2	Flag
HB1603													
PC1609													
HB1601	148	36	32.25	-0.12	0.08	0.37	0	36	34.35	0.19	0.05	0.36	0
GU1608	161	25	32.19	-0.15	0.10	0.36	0	20	34.10	0.14	0.09	0.37	0
S11601	171	3	32.41	-0.20	0.32	0.08	1	3	32.85				1
PC1607	230	1	32.34	-0.24	0.48		1	1	35.05	0.45	0.38		1
HB1604	303	42	32.69	0.04	0.08	0.29	0	34	34.57	0.29	0.06	0.30	0

"Cruise," the code name for a cruise
"CD," the calendar mid-date of all the stations within a region for that cruise
"#obs," the number of observations included in each average
"Temp," the areal average temperature
"Salinty," the areal average salinity
"Anomaly," the areal average temperature or salinity anomaly
"SDV1," the standard deviation associated with the average temperature or salinity anomaly
"SDV2," the standard deviation of the individual anomalies from which the average anomaly was derived
"Flag," a value of "1" indicates that a true areal average could not be calculated due to poor station coverage
The areal averages listed were derived from a simple average of the observations within the region

Table A2. Regional average temperature and salinity values calculated from hydrographic observations collected by individual Northeast Fisheries Science Center surveys in the western Gulf of Maine (boundary defined in Figure 1). Average values incorporating fewer than 10 observations are shown in gray. Average values are not reported for regions containing fewer than 5 observations.

Gulf of Maine West

Cruise	CD	#obs	Surface Temp	Anomaly	SDV1	SDV2	Flag	#obs	Bottom Temp	Anomaly	SDV1	SDV2	Flag
HB1603													
PC1609													
HB1601	148	56	10.80	1.35	0.15	0.92	0	57	6.70	1.40	0.13	0.63	0
GU1608	160	39	12.26	1.02	0.19	1.28	0	38	6.73	1.31	0.16	0.62	0
S11601	162	2	13.59	2.35	1.04	NaN	1	3	6.42	1.03	1.10	0.22	1
PC1607	231	5	21.47	3.21	1.03	0.38	1	4	6.49	1.27	0.63	0.18	1
HB1604	302	53	13.09	1.85	0.15	0.67	0	48	8.80	1.78	0.13	0.94	0

Cruise	CD	#obs	Surface Salinity	Anomaly	SDV1	SDV2	Flag	#obs	Bottom Salinity	Anomaly	SDV1	SDV2	Flag
HB1603													
PC1609													
HB1601	148	56	32.16	-0.05	0.06	0.31	0	57	33.20	-0.05	0.04	0.29	0
GU1608	160	39	31.96	0.05	0.08	0.40	0	38	33.01	-0.05	0.05	0.26	0
S11601	162	2	31.36	-0.68	0.44	NaN	1	3	32.71	-0.20	0.33	0.23	1
PC1607	231	5	32.03	0.22	0.37	0.11	1	4	33.23	-0.14	0.21	0.07	1
HB1604	302	53	32.81	0.20	0.06	0.25	0	48	33.66	0.10	0.04	0.24	0
HB1603													

"Cruise," the code name for a cruise
"CD," the calendar mid-date of all the stations within a region for that cruise
"#obs," the number of observations included in each average
"Temp," the areal average temperature
"Salinity," the areal average salinity
"Anomaly," the areal average temperature or salinity anomaly
"SDV1," the standard deviation associated with the average temperature or salinity anomaly
"SDV2," the standard deviation of the individual anomalies from which the average anomaly was derived
"Flag," a value of "1" indicates that a true areal average could not be calculated due to poor station coverage
The areal averages listed were derived from a simple average of the observations within the region

Table A3. Regional average temperature and salinity calculated from hydrographic observations collected by individual Northeast Fisheries Science Center surveys in the Georges Bank area (boundary defined in Figure 1). Average values incorporating fewer than 10 observations are shown in gray. Average values are not reported for regions containing fewer than 5 observations.

Georges Bank

Cruise	CD	#obs	Surface Temp	Anomaly	SDV1	SDV2	Flag	#obs	Bottom Temp	Anomaly	SDV1	SDV2	Flag
PC1609													
HB1601	142	54	9.30	0.76	0.19	1.06	0	53	9.03	1.51	0.18	1.08	0
GU1608	152	35	10.44	1.18	0.21	1.04	0	34	9.68	1.61	0.22	1.21	0
S11601	165	4	11.52	1.24	1.09	1.04	1	4	9.74	0.97	1.12	0.38	1
HB1603	219	16	19.82	2.42	0.62	1.82	0	8	11.24	2.22	0.56	0.69	0
PC1607	229	33	18.23	2.18	0.27	1.41	0	33	13.63	1.62	0.22	1.64	0
HB1604	289	58	17.09	2.30	0.20	2.01	0	54	14.91	2.43	0.19	1.71	0

Cruise	CD	#obs	Surface Salinity	Anomaly	SDV1	SDV2	Flag	#obs	Bottom Salinity	Anomaly	SDV1	SDV2	Flag
PC1609													
HB1601	142	54	32.71	-0.21	0.06	0.43	0	53	33.38	0.08	0.06	0.38	0
GU1608	152	35	32.55	-0.32	0.08	0.50	0	34	33.34	0.11	0.08	0.49	0
S11601	165	4	32.51	-0.13	0.32	0.14	1	4	32.67	-0.24	0.34	0.09	1
HB1603	219	16	32.87	-0.28	0.20	0.92	0	8	34.30	0.92	0.19	0.60	0
PC1607	229	33	32.56	-0.20	0.09	0.34	0	33	33.22	0.12	0.08	0.52	0
HB1604	289	58	33.50	0.70	0.06	0.87	0	54	33.62	0.33	0.07	0.35	0

"Cruise," the code name for a cruise
"CD," the calendar mid-date of all the stations within a region for that cruise
"#obs," the number of observations included in each average
"Temp," the areal average temperature
"Salinity," the areal average salinity
"Anomaly," the areal average temperature or salinity anomaly
"SDV1," the standard deviation associated with the average temperature or salinity anomaly
"SDV2," the standard deviation of the individual anomalies from which the average anomaly was derived
"Flag," a value of "1" indicates that a true areal average could not be calculated due to poor station coverage
The areal averages listed were derived from a simple average of the observations within the region

Table A4. Regional average temperature and salinity calculated from hydrographic observations collected by individual Northeast Fisheries Science Center surveys in the northern Mid-Atlantic Bight (boundary defined in Figure 1). Average values incorporating fewer than 10 observations are shown in gray. Average values are not reported for regions containing fewer than 5 observations.

Northern Mid-Atlantic Bight

Cruise	CD	#obs	Surface Temp	Anomaly	SDV1	SDV2	Flag	#obs	Bottom Temp	Anomaly	SDV1	SDV2	Flag
HB1601	126	51	8.76	0.47	0.23	1.06	0	51	9.38	1.98	0.28	1.11	0
GU1608	153	41	12.89	0.49	0.26	1.02	0	40	8.97	1.43	0.26	0.71	0
S11601	154	1	13.66	2.74	1.58		1	1	8.73	1.06	2.11		1
HB1603	207	27	21.68	2.01	0.33	1.24	0	21	11.49	1.65	0.41	0.94	0
PC1607	227	19	23.37	3.10	0.36	1.09	0	21	11.08	1.23	0.39	1.69	0
HB1604	274	59	20.33	2.40	0.22	1.51	0	57	14.96	2.44	0.27	1.83	0
PC1609	293	8	19.22	3.06	1.67	0.81	1	8	17.69	4.37	1.69	2.23	1

Cruise	CD	#obs	Surface Salinity	Anomaly	SDV1	SDV2	Flag	#obs	Bottom Salinity	Anomaly	SDV1	SDV2	Flag
HB1601	126	51	32.68	0.08	0.10	0.39	0	51	33.40	-0.12	0.10	0.46	0
GU1608	153	41	32.21	-0.18	0.11	0.35	0	40	33.18	-0.07	0.09	0.28	0
S11601	154	1	32.60	-0.14	0.43		1	1	32.87	-0.51	0.72		1
HB1603	207	27	32.48	-0.26	0.14	0.38	0	21	34.18	0.07	0.13	0.36	0
PC1607	227	19	32.15	-0.29	0.16	0.43	0	21	33.47	-0.02	0.14	0.38	0
HB1604	274	59	33.67	0.90	0.10	0.81	0	57	33.72	0.05	0.09	0.61	0
PC1609	293	8	34.36	1.23	0.70	0.41	1	8	34.90	1.02	0.58	0.62	1

"Cruise," the code name for a cruise
"CD," the calendar mid-date of all the stations within a region for that cruise
"#obs," the number of observations included in each average
"Temp," the areal average temperature
"Salinity," the areal average salinity
"Anomaly," the areal average temperature or salinity anomaly
"SDV1," the standard deviation associated with the average temperature or salinity anomaly
"SDV2," the standard deviation of the individual anomalies from which the average anomaly was derived
"Flag," a value of "1" indicates that a true areal average could not be calculated due to poor station coverage
The areal averages listed were derived from a simple average of the observations within the region

Table A5. Regional average temperature and salinity calculated from hydrographic observations collected by individual Northeast Fisheries Science Center surveys in the southern Mid-Atlantic Bight (boundary defined in Figure 1). Average values incorporating fewer than 10 observations are shown in gray. Average values are not reported for regions containing fewer than 5 observations.

Southern Mid-Atlantic Bight

Cruise	CD	#obs	Surface Temp	Anomaly	SDV1	SDV2	Flag	#obs	Bottom Temp	Anomaly	SDV1	SDV2	Flag
PC1609													
HB1601	106	96	10.42	1.67	0.19	1.58	0	95	10.42	2.59	0.23	1.06	0
S11601	142	1	12.57	-0.70	1.51		1	1	9.72	1.69	1.54		1
GU1608	146	40	13.95	-1.08	0.28	2.05	0	38	11.48	2.12	0.35	1.35	0
HB1603	190	16	21.89	0.81	1.64	1.59	1	8	11.33	1.99	1.89	1.16	1
PC1607	224	39	26.21	2.12	0.29	0.91	0	38	12.21	0.61	0.34	1.89	0
HB1604	260	90	23.13	1.20	0.19	1.18	0	86	16.21	2.63	0.24	2.67	0

Cruise	CD	#obs	Surface Salinity	Anomaly	SDV1	SDV2	Flag	#obs	Bottom Salinity	Anomaly	SDV1	SDV2	Flag
PC1609													
HB1601	106	96	33.48	0.73	0.11	0.64	0	95	33.80	0.03	0.08	0.44	0
S11601	142	1	33.11	0.38	0.74		1	1	33.60	0.24	0.54		1
GU1608	146	40	33.00	0.80	0.18	0.78	0	38	33.64	0.12	0.12	0.43	0
HB1603	190	16	32.09	-0.03	0.83	0.30	1	8	32.97	0.03	0.65	0.25	1
PC1607	224	39	31.82	-0.03	0.17	0.82	0	38	33.24	-0.13	0.12	0.34	0
HB1604	260	90	32.68	0.33	0.11	0.63	0	86	33.25	-0.36	0.09	0.61	0

"Cruise," the code name for a cruise
"CD," the calendar mid-date of all the stations within a region for that cruise
"#obs," the number of observations included in each average
"Temp," the areal average temperature
"Salt," the areal average salinity
"Anomaly," the areal average temperature or salinity anomaly
"SDV1," the standard deviation associated with the average temperature or salinity anomaly
"SDV2," the standard deviation of the individual anomalies from which the average anomaly was derived
"Flag," a value of "1" indicates that a true areal average could not be calculated due to poor station coverage
The areal averages listed were derived from a simple average of the observations within the region

Table A6. Temperature, salinity, and volume of the shelf water in the Mid-Atlantic Bight during 2016. The shelf water is defined as water within the upper 100 meters having salinity less than 34. MABN = Mid-Atlantic Bight north; MABS = Mid-Atlantic Bight south.

CD	Temp	Temp. Anomaly	Salt	Salt Anomaly	SHW Temp	SHW T. Anom	SHW Salt	SHW S. Anom	SHW Volume	SHW Vol. Anomaly
					MABN					
125	9.17	1.46	33.36	0.13	8.44	1.54	32.96	0.04	2001.48	51.13
152	10.19	0.59	33.01	-0.21	9.80	0.86	32.71	-0.13	2154.62	234.50
207	13.38	0.68	33.48	0.13	13.63	1.40	32.93	0.15	2150.70	205.96
226	14.34	0.80	33.23	-0.20	14.21	1.11	32.89	0.10	2215.87	330.76
274	17.55	2.60	34.16	0.53	16.88	2.36	33.01	0.11	1102.51	-432.07
					MABS					
105	11.46	3.00	34.24	0.55	9.09	2.01	33.01	-0.20	1402.52	-220.42
145	12.58	1.95	33.89	0.52	11.47	1.28	33.07	0.33	2029.68	9.77
223	15.82	0.13	33.13	-0.13	15.69	0.90	32.62	0.01	2591.95	262.03
260	17.70	1.27	33.62	0.12	17.50	1.24	32.77	-0.15	2164.00	29.79

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