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Meteorological, Sea Ice and Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine During 2017

D. Hebert, R. Pettipas, and D. Brickman

Fisheries and Oceans Canada
Ocean and Ecosystem Sciences Division
Bedford Institute of Oceanography
P.O. Box 1006, 1 Challenger Drive
Dartmouth, Nova Scotia B2Y 4A2

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

In 2017, the North Atlantic Oscillation index was nearly normal when compared to the 1981 to 2010 mean (+2.7 mb, +0.3 SD [standard deviation]) but significantly much smaller than in 2015 which had the largest value in the 122 year record. Mean annual air temperature anomalies were positive at all sites examined with values ranging from +0.5°C (+0.8 SD) to +1.0°C (+1.4 SD) above the climatology. Positive satellite-based Sea Surface Temperature (SST) annual anomalies prevailed throughout the region with values ranging from +0.7°C (+1.2 SD) at Cabot Strait to +1.9°C (+3.0 SD) for the Western Scotian Shelf. After above-average conditions in 2015, sea ice in 2016 and 2017 returned to similar conditions found in the 2010–2013 period that had extremely low coverage and volume. Long-term coastal monitoring sites at St. Andrews (New Brunswick) and Halifax (Nova Scotia) recorded annual SST anomalies of +0.8°C (+1.5 SD) and +0.7°C (+1.0 SD), respectively, in 2017. At other selected sites across the region, annual water temperature anomalies were positive in 2017: +1.1°C (+3.3 SD) for Cabot Strait at 200–300 m depth range (the second largest anomaly; 2016 was the largest); +0.4°C (+0.7 SD) for Misaine Bank at 100 m; +1.5°C (+1.8 SD) for Emerald Basin at 250 m (the second largest anomaly where 2016 was a record high) and +1.6°C (+3.0 SD) for Georges Basin at 200 m (a record high surpassing 2016). Bottom temperature anomalies in Northwest Atlantic Fisheries Organization (NAFO) Divisions 4VWX were all positive in 2017 ranging from +0.7°C (+1.6 SD) in Division 4Vn to +1.6°C (+2.2 SD) in Division 4X. Stratification on the Scotian Shelf was nearly the same as in 2016 where surface freshening was offset by surface cooling. Since 1948, the stratification has slowly been increasing on the Scotian Shelf due mainly to half freshening and half warming of the surface waters. A composite index, consisting of 18 ocean temperature time series from surface to bottom across the region, indicated that 2017 was the third warmest of 48 years (2012 was the warmest) of observations, with an averaged normalized anomaly of +1.7 SD relative to the 1981–2010 period.

INTRODUCTION

This document discusses air temperature trends, ice cover, sea surface temperatures (SST) and physical oceanographic variability during 2017 on the Scotian Shelf, Bay of Fundy and the Gulf of Maine (Figure 1), from observations and model results. It complements similar reviews of the conditions in the Gulf of St. Lawrence and the Newfoundland-Labrador regions for the Atlantic Zone Monitoring Program (AZMP) (see: Colbourne et al. 2017; Galbraith et al. 2017), which together serve as a basis for a zonal Science Advisory Report (DFO 2018). Environmental conditions are compared with the long-term monthly and annual means. These comparisons are often expressed as anomalies, which are the deviations from the long-term means, or as standardized anomalies, that is, the anomaly divided by the standard deviation (SD). If the data permit, the long-term means and SDs are calculated for the 30-year base period of 1981–2010. The use of standardized anomalies and the same base period allow direct comparison of anomalies among sites and variables.

Temperature and salinity conditions on the Scotian Shelf, in the Bay of Fundy and Gulf of Maine regions are determined by many processes: heat transfer between the ocean and atmosphere; inflow from the Gulf of St. Lawrence supplemented by flow from the Newfoundland Shelf; exchange with offshore slope waters; local mixing; freshwater runoff; direct precipitation; and melting of sea-ice. The Nova Scotia Current is the dominant inflow, originating in the Gulf of St. Lawrence and entering the region through Cabot Strait (Figure 1). This current, whose path is strongly affected by topography, has a general southwestward drift over the Scotian Shelf and continues into the Gulf of Maine where it contributes to the counter-clockwise mean circulation. Mixing with offshore waters from the continental slope also modifies the water mass properties of shelf waters. These offshore waters are generally of two types: Warm Slope Water, with temperatures in the range of 8°C–12°C and salinities from 34.7–35.5; and Labrador Slope Water, with temperatures from 4°C–8°C and salinities from 34.3–35 (Gatien 1976). Shelf water properties have large seasonal cycles, along- and across-shelf gradients, and vary with depth (Petrie et al. 1996).

METEOROLOGICAL OBSERVATIONS

NORTH ATLANTIC OSCILLATION INDEX

The North Atlantic Oscillation (NAO) index used here is the difference in winter (December, January and February) sea level atmospheric pressures between the Azores and Iceland (Rogers 1984), and is a measure of the strength of the winter westerly winds over the Northwest Atlantic. It represents the dominant, large scale meteorological forcing over the North Atlantic Ocean. Specifically, the index was calculated using observed monthly sea level pressures at Ponta Delgada (up to 1997, 2009–2015), Santa Maria (1998–2005), and Lajes (2006–2008) in the Azores, and at Akureyri in Iceland. A small number of missing data early in the time series were filled using pressures from nearby stations.

A high NAO index corresponds to an intensification of the pressure difference between the Icelandic Low and the Azores High. Strong northwest winds, cold air and sea temperatures, and heavy ice in the Labrador Sea and on the Newfoundland shelf areas are usually associated with a high positive NAO index (Colbourne et al. 1994; Drinkwater 1996). The opposite response occurs during years with a negative NAO index.

The NAO has been shown to strongly affect bottom temperature distributions throughout the region from the Labrador Shelf to the Gulf of Maine (Petrie 2007). The response is bimodal, the product of direct and advective effects, with positive (negative) NAO generally corresponding to colder (warmer) than normal bottom temperatures over the Labrador-Newfoundland Shelf, the Gulf of St. Lawrence, and the Eastern Scotian Shelf, and warmer (colder) than normal conditions on the Central and Western Scotian Shelf and in the Gulf of Maine.

In 2017, the winter NAO index was near normal, +2.7 mb (+0.3 SD) above the 1981–2010 mean, but much smaller than 2015, which had the largest positive value in the 122 year record (Figure 2, upper panel). The lower panels of Figure 2 show the sea level atmospheric pressure conditions during the winter of 2017 compared to the 1981–2010 mean. The Icelandic low was slightly lower than the long-term average whereas the Azores high was normal. The centers were almost directly over the NAO index sites.

AIR TEMPERATURES

Surface air temperature anomalies maps relative to the 1981–2010 means for the North Atlantic region are available from the U.S. National Oceanic and Atmospheric Administration's (NOAA 2018) interactive website [accessed November 2018]. In 2017, the annual anomalies were above normal over the Scotian Shelf and the Gulf of Maine (Figure 3). The seasonal anomaly of these regions was above normal during the winter, summer and fall of 2017 for the Scotian Shelf and the Gulf of Maine. For spring, the air temperatures were near normal (Figure 4).

Monthly air temperature anomalies for 2016 and 2017 relative to their 1981–2010 means at six sites in the Scotian Shelf-Gulf of Maine region are shown in Figure 5. Monthly mean temperature data for Canadian sites are from Environment Canada's Adjusted Homogenized Canadian Climate Data (AHCCD) [accessed November 2018] where available (Vincent et al. 2012). In cases where no data were available, observed monthly mean values from the Canadian Climate Summaries (CCS) at the Environment Canada website [accessed November 2018] were used, and anomalies are relative to the CCS long-term means. This is the case for 2009–2011 and 2014–2016 at Sable Island. Monthly means from the Monthly Climatic Data for the World [accessed November 2018] (NOAA 2018) were used for Boston. In general, all sites show that 2017 had slightly above normal temperatures in winter (except for March) and fall, and near- or below-normal temperatures in summer and December (Figure 5). The observed and normalized annual anomalies for these stations are listed in Table 1.

In 2017, the mean annual air temperature anomalies were positive at all sites with anomalies ranging from 0.8 to 1.4 standard deviations above the climatology. The time series of annual anomalies indicates that all sites feature increasing temperatures over the long-term with decadal-scale variability superimposed (Figure 6). Over decadal and shorter periods, there are times when there is no trend or a decreasing trend in the temperature. Linear trends from 1900 to present for Sydney, Sable Island, Shearwater, Yarmouth, Saint John, and Boston correspond to changes (and 95% confidence limits) per century of +0.4°C (0.0°C, +0.8°C), +1.3°C (+1.0°C, +1.7°C), +1.2°C (+0.9°C, +1.5°C), +1.1°C (+0.8°C, +1.4°C), +0.7°C (+0.3°C, +1.1°C), and +1.8°C (+1.4°C, +2.1°C), respectively (Figure 6).

The air-temperature anomalies for the six Scotian Shelf-Gulf of Maine sites are summarized in Figure 7 as a composite sum that illustrates two points. First, for most years the anomalies have the same sign, that is, the stacked bars coincide. Since 1900, when all sites were operating, 95 of the 118 years had five or more stations with the annual anomalies having the same signs; for 66 years, all six stations had anomalies with the same sign. This indicates that the spatial scale of the air-temperature patterns is greater than the largest spacing between sites. Previous analyses yielded an e-folding scale of 1800 km (Petrie et al. 2009). Second, the time scale of the dominant variability has been changing from longer periods for the first half of the record to shorter periods for the second half. The average annual anomaly in 2017 was +0.7°C, the ninth warmest year in 118 years (with 2012 being the warmest).

REMOTELY-SENSED SEA SURFACE TEMPERATURE (SST)

The 4 km resolution Pathfinder 5.2 (Casey et al. 2010) Sea Surface Temperature (SST) database Pathfinder dataset runs from November 1981 to December 2012; recent data were taken from the 1 km resolution Advanced Very High Resolution Radiometer (AVHRR) SST data downloaded from the NOAA and European Organization for the Exploration of Meteorological Satellites (EUMETSAT) satellites by the operational remote sensing group at the Bedford Institute of Oceanography (BIO) [accessed November 2018]. A least-square fit of the Pathfinder and NOAA/EUMETSAT temperatures during the September 1981–December 2012 time period for several regions led to a conversion equation SST(Pathfinder) = 0.988*SST(BIO)-0.02 with an r^2=0.98. Using this regression, the NOAA/EUMETSAT data were converted to be consistent with the longer Pathfinder series. Anomalies were based on 1981–2010 averages.

Monthly temperature anomalies for eight subareas in the Scotian Shelf-Gulf of Maine region (Figure 8) were above normal at the start of 2017 followed by a period of near- or below-normal temperatures and then above normal for the fall (Figure 9). Annual anomalies were calculated from monthly averaged temperatures for the eight subareas (Table 2 and Figure 10). The annual anomalies during 2017 ranged from +0.7°C (+1.2 SD) in Cabot Strait to +1.9°C (+3.0 SD) in Western Scotian Shelf. Over the lengths of the records, all areas show increasing temperature trends, based on a linear least squares fit, ranging from the lowest value +0.3°C/decade (Cabot Strait) to a highest value of +0.6°C/decade (Eastern Scotian Shelf, Central Scotian Shelf and Bay of Fundy). A similar trend in SST from AVHRR measurements was found in the Gulf of St. Lawrence (Galbraith et al. 2012) and on the Newfoundland and Labrador Shelf (Colbourne et al. 2017). The large increase in the observed SST over this period has likely been enhanced by the cold air temperature period at the beginning of the data series (Figure 6) and a rapid SST increase from 1997 (Figure 10).

The overall coherent variability of the annual SST temperature anomalies in the eight regions suggested that a Principal Component Analysis (PCA) might be revealing. The leading mode, PCA1, captured 83% of the variance, all loadings had similar amplitudes, meaning roughly equal contributions from each series, and all had the same sign, indicating in-phase heating or cooling in the eight regions for this mode. Thus, the annual surface temperature variability is dominated by large scale heating. PCA2 accounted for an additional 6% of the variance, with positive loadings in the eastern half of the region, changing to negative values roughly to the west of the Central Scotian Shelf (Figure 11). Since principal component analysis generates orthogonal modes, it is not surprising that the second mode consists of the eastern and western Scotian Shelf varying out of phase. This mode accounts for a small amount of the observed variability.

SEA ICE OBSERVATIONS

Ice areas, volumes, and extents were computed using the Canadian Ice Service (CIS) of Environment Canada weekly composite GIS formatted charts, available from the CIS website [accessed November 2018] for the period 1962–2017. Ice concentration of greater than or equal to (≥) one-tenth was obtained for a grid with 0.1 degree latitude and 0.1 degree longitude intervals from these ice charts. Climatologies (1981–2010) of first and last appearance and duration were generated for each grid point where there was at least five years of ice (Figure 12) and were subtracted from the values determined for 2017 to generate anomaly maps. Grid points, for which the climatology had less than five years with data, or where the duration was less than ten days, were excluded from further analysis. The duration of sea ice is from the number of weeks that ice, with a minimum concentration of 10%, is present. It is not simply the date of the first presence minus the last presence because the ice may disappear from an area for a time and then reappear.

Ice cover and volume indices provide insight on different physical and biological processes. For example, the ice cover index can be related to the initiation and maintenance of the spring phytoplankton bloom. On the other hand, identical ice cover but differing thickness, leading to different ice volumes, could distinguish a winter with above or below normal heat losses. The CIS does not generally compute ice volume estimates for Canadian waters. Nevertheless, we estimated ice volumes for the region by assigning characteristic thicknesses to particular ice types using estimates of ice thickness by stage of development provided by the Canadian Ice Service [accessed November 2018].

ATLANTIC REGION

Ice appeared on the Labrador Shelf near the coast during January and on the northern Newfoundland Shelf during mid-January to mid-February. During February, ice formed on the Newfoundland Shelf and the western and northern portions of the Gulf of St. Lawrence (Figure 13); over much of this region, the day of first appearance of ice on the eastern Newfoundland and Labrador shelves was approximately near normal, whereas, in the western Gulf of St. Lawrence, it was about 15–30 days later than normal. In the western Gulf of St. Lawrence, ice was found during March but none in the eastern Gulf of St. Lawrence off the coast of Newfoundland or southern Newfoundland during this time. Ice appeared about one and a half months later than normal for east of the Avalon Peninsula. The day of last appearance of ice was normal for western Gulf of St. Lawrence and off eastern Newfoundland away from the coast and Labrador (Figure 14). Ice remained less than 10 days in western Cabot Strait and no significant ice was present in eastern Gulf of St. Lawrence where normally ice is present for about a month (Figure 15). Ice duration in eastern coastal Newfoundland was about a half-month longer than normal and normal offshore.

SCOTIAN SHELF

The greater part of sea ice on the Scotian Shelf originates in the Gulf of St. Lawrence, and it is transported through Cabot Strait by northwesterly winds and ocean currents. Sydney Bight and the northeastern coast of Cape Breton are typically the only areas heavily affected by ice in the region. In 2017, ice was not present at most of these locations whereas ice is normally present for about a month based on the climatological values (Figure 12). There had been very little ice on the Scotian Shelf and Cabot Strait from April 2009 until 2015 (Figure 16) where ice coverage was above normal.

The ice areas and volumes for 2017 are compiled in Table 3. All months had significantly lower than normal (e.g., climatological) values. The December 2016 to April 2017 ice coverage (volume) on the Scotian Shelf were the 12th (9th) lowest value in the 56 (52) years long record, the previous year was the 2nd (3rd) lowest levels. After above normal values in 2015, ice conditions returned to conditions found in the 2010–2013 period which had extremely low coverage and volume.

COASTAL TEMPERATURES AND SALINITIES

Coastal near surface temperatures have been collected at Halifax (Nova Scotia) and St. Andrews (New Brunswick) since the 1920s (Figure 17). In 2017, the SST anomalies were +0.7°C (+1.0 SD) for Halifax, a decrease of 0.3°C from 2016 and +0.8°C (+1.5 SD) for St. Andrews, a decrease of 0.6°C from 2016.

Temperature and salinity measurements through the water column have been sampled monthly for the most part since 1924 at Prince 5, at the entrance to the Bay of Fundy (Figure 1). It is the longest continuously operating hydrographic monitoring site in eastern Canada. Its waters are generally well-mixed from the surface to the bottom (90 m), except in the spring. The depth-averaged (0–90 m) temperature, salinity and density time series are shown in Figure 17. In 2017, the annual temperature anomaly was +0.8°C (+1.4 SD) and the salinity anomaly was -0.1 (-0.6 SD). These represent changes of -0.9°C and -0.3 from the 2016 values. The negative density anomaly is accounted for by the positive temperature anomaly and negative salinity anomaly.

The 2017 annual cycle at Prince 5 shows warmer than normal temperatures at the beginning and end of the year with largest positive anomalies (>+2.0°C) at the end of the year, with not much depth dependence in the anomaly (Figure 18). The minimum in salinity observed at Prince 5 is due to the arrival of a large amount of fresh water in the upper ocean from the Saint John River, a nearby source.

The 2017 annual temperature, salinity, and density cycles at Halifax 2 are shown in Figure 19. The observed positive temperature anomaly is due to a warm fall and offshore waters advected there, especially at depth. The deeper variability of the salinity occurs in conjunction with temperature and is indicative of warmer saltier slope water intruding onto the shelf.

STANDARD SECTIONS

The sections across the Louisbourg, Halifax, and Browns Bank Lines were sampled during the spring and late fall of 2017 (Figure 20). Since our fall survey was approximately two months later than the normal time, no anomaly plots are presented. The Cabot Strait section showed average May temperatures, except at the deep temperature maximum found between 200 m and 300 m where it was above average. Late fall temperature was above the September average at depths of 150 m to 300 m and at the pycnocline on the western half of the strait (Figure 21). In the spring, there was anomalously warm, salty water on the offshore along the Louisbourg section, evidence of the intrusion of Slope Water, while the water was cold and fresh between 50 m and 100 m in the same region during late fall (Figure 22). The Halifax section occupations show anomalously warm deep temperatures in Emerald Basin during the spring and on the slope (Figure 23). Similarly, warm, salty water is still present in Emerald Basin during the late fall. On the slope, the water is much warmer and saltier. Comparing to the Louisbourg sections, the data is consistent with an anomalous warm water on slope propagating along the shelf-break. During the spring of 2017, the Browns Bank section showed anomalous cold, fresh water over the outer-shelf and intruding at mid-depth farther on the shelf (Figure 24). During the late fall, anomalous warm, salty water was found on the outer half of the shelf at depth. This may be more evidence of warm, salty water propagating along Scotian Shelf slope and intruding onto the shelf.

SCOTIAN SHELF AND GULF OF MAINE TEMPERATURES

Drinkwater and Trites (1987) tabulated monthly mean temperatures and salinities from available bottle data for 35 areas on the Scotian Shelf and in the eastern Gulf of Maine that generally corresponded to topographic features such as banks and basins. Petrie et al. (1996) updated their report using these same areas and all available hydrographic data. An updated time series of annual mean and filtered (five-year running means) temperature anomalies at selected depths for five areas (Figure 25) is presented (Figure 26). The Cabot Strait temperatures represent a mix of Labrador Current Water and Warm Slope Water entering the Gulf of St. Lawrence along the Laurentian Channel (e.g., Gilbert et al. 2005); the Misaine Bank series characterizes the colder near-bottom temperatures on the Eastern Scotian Shelf, mainly influenced by Labrador Slope Water; the deep Emerald Basin temperature anomalies represent the warmer Slope Water intrusions onto the Shelf that are subsequently trapped in the inner deep basins (note the large anomaly “events” in Figure 26C); the Lurcher Shoals observations define the ocean climate in the southwest Scotian Shelf and the shallow waters entering the Gulf of Maine via the Nova Scotia Current; last, the Georges Basin series represents the slope waters entering the Gulf of Maine through the Northeast Channel. Annual anomalies are based on the averages of monthly anomalies; however, observations may not be available for all months in each area. For Cabot Strait, Misaine Bank, Emerald Basin and Georges Basin, the 2017 annual anomalies are based on observations from five, five, three, and eight months, respectively. There were no observations on Lurcher Shoals for 2017.

In 2017, the annual anomalies were +1.1°C (+3.3 SD) for Cabot Strait at 200–300 m (the second largest anomaly; the largest, third, fourth and fifth largest anomalies were in 2016, 2012, 2014 and 2015, respectively), +0.4°C (+0.7 SD) for Misaine Bank at 100 m, +1.5°C (+1.8 SD) for Emerald Basin at 250 m (the second highest, 2016 was a record high) and +1.5°C (+2.9 SD) for Georges Basin at 200 m (a record high with 2016 and 2014 as the second and third warmest years). These values correspond to changes of -0.2°C, -0.8°C, +0.1°C, and +0.2°C, respectively, from the 2016 values. The 2010 and 2011 NAO anomalies were well below normal and based on similar atmospheric forcing in the past, notably in the mid-1960s, cooler deep-water temperatures might have been expected in this region for 2012 (Petrie2007). Anomalies were highly positive for that year and started to return to normal in 2013, but increased to record or near-record values in 2014 and continued to remain high in 2017. Deep-temperatures warm anomalies continued to increase due to intrusions from offshore slope water.

TEMPERATURES DURING THE ECOSYSTEM TRAWL SURVEYS

In the Maritimes Region, Fisheries and Oceans Canada (DFO), conducts two Research Vessel (RV) trawl surveys each year. During winter, the survey covers Georges Bank, the Bay of Fundy and the western Scotian Shelf. The deep water boundary of the survey is marked roughly by the 200 m isobaths. The broadest spatial temperature and salinity coverage of the Scotian Shelf is obtained during the summer trawl survey, which covers the Scotian Shelf from Cabot Strait to the Bay of Fundy. The deep water boundary of this survey is also marked roughly by the 200 m isobath along the shelf break.

The temperatures from the survey were combined and interpolated onto a 0.2°-by-0.2° latitude-longitude grid using an objective analysis procedure known as optimal estimation (for details see: Petrie et al. 1996). The interpolation method uses the 15 "nearest neighbours" with a horizontal length scale of 30 km and a vertical length scale of 15 m in the upper 40 m and 25 m at deeper depths. Data near the interpolation grid point are weighted proportionately more than those farther away. Temperatures were optimally estimated at the standard depths (e.g., 0 m, 10 m, 20 m, etc.) and for near the bottom. Only the near-bottom temperatures are presented here.

WINTER SURVEY

The winter survey took place between March 2nd and 30th. A total of 48 Conductivity-Temperature-Depth (CTD) stations were sampled during the 2017 survey (Figure 27). The near-bottom temperatures are the coldest on Georges Bank due to the high mixing rates that result in the near-bottom temperature representative of the cold winter surface temperatures (Figure 28). Except for the southwestern portion of Georges Bank, this region shows anomalously warm bottom temperatures with anomalies reaching >+2°C in the Northeast Channel region of the survey.

SUMMER SURVEY

The 2017 summer survey took place between June 28th and August 5th. A total of 201 Conductivity-Temperature-Depth (CTD) stations were sampled (Figure 29). While there is spatial variability in the near-bottom temperature, with the colder waters on the Eastern Scotian Shelf, the near-bottom temperature anomalies for 2017 were positive for most of the shelf (Figure 30). Bottom temperatures ranged from an average of 4.6°C in the Northwest Atlantic Fisheries Organization (NAFO) Division 4Vs to 8.8°C in Division 4X during 2017, illustrating the substantial difference in the environmental conditions across the shelf. The anomalies were positive for these NAFO Divisions in 2017: +0.7°C (+1.6 SD) in 4Vn; +1.3°C (+1.9 SD) in 4Vs; +0.8°C (+1.1 SD) in 4W; and +1.6°C (+2.2 SD) in 4X (Figure 31A-D). Compared to the 2014 record-warm year for 4Vn and 4W, 4Vn had its 8th warmest year, 0.5°C lower than the record and 4W had its 12th warmest year, 1.2°C lower than the record. 2017 was the 5th warmest year in 4Vs; 2015 was the 2nd warmest. Division 4X had its 4th warmest year, 0.6°C lower than the 2012 record temperature. Except for 4X, the bottom temperatures in the other division show above-normal temperatures from the mid-1970s to mid-1980s, followed by a period of below-normal temperatures until around 2000 (Figure 31). All regions, including 4X, show a steadily increasing temperature from approximately 2010.

The volume of the Cold Intermediate Layer (CIL), defined as waters with temperatures less than 4°C, was estimated from the full depth CTD profiles for the region from Cabot Strait to Cape Sable (Panel E of Figure 31). For the period 1970 to 1989, the number of CTD profiles per year was limited; therefore, five-year blocks of data, for example 1970–1974, centre date 1972, were used as input for the procedure to map the irregularly spaced data onto a regular grid. The data were then incremented by one year and a new set of estimates made (i.e., 1970–1974, 1971–1975, etc.). This procedure is similar to filtering (five-year running mean) the data for the 1970–1989 period, effectively reducing the variance. Thus, the long-term mean and particularly the SD (based on the 1981–2010 data in Figure 31E) could be affected. It is expected that the true SD is higher than the one derived here. There is considerable variation in the volume of the CIL from 1998 until 2009 (Figure 31E). In 2017, the observed volume of 4600 km^3 was 0.8 SD less than the 1981–2010 mean value of 5500 km^3 and was the 21st lowest volume in the 44 years of surveys. The smallest volume was in 2012.

DENSITY STRATIFICATION

Stratification of the near surface layer influences physical and biological processes in the ocean such as the extent of vertical mixing, the ocean's response to wind forcing, the timing of the spring bloom, vertical nutrient fluxes and plankton distribution. Under increased stratification, there is a tendency for more primary production to be recycled within the upper mixed layer and hence less available for the deeper layers. The variability in stratification was examined by calculating the density (sigma-t) difference between the near-surface and 50 m water depth. The density differences were based on monthly mean density profiles calculated for areas 4–23 on the Scotian Shelf, as defined by Petrie et al. (1996) (see: Figure 17 in Hebert et al. (2014) for map; also Figure 34). The long-term monthly mean density gradients for 1981–2010 were estimated; these were subtracted from the individual monthly values to obtain monthly anomalies. Annual anomalies for each area were estimated by averaging all available monthly anomalies within a calendar year. These estimates could be biased if, in a particular year, most data were collected in months when stratification was weak, while in another year sampling was in months when stratification was strong. However, initial results using normalized monthly anomalies obtained by dividing the anomalies by their monthly SDs were qualitatively similar to the plots presented here. The Scotian Shelf-wide average annual anomalies and their five-year running means were then calculated for an area-weighted combination of subareas 4–23 on the Scotian Shelf. A stratification of 0.01 (kg m^{-3})/m represents a difference of 0.5 kg m^{-3} over 50 m.

The dominant feature is the period from about 1950 to 1990 with generally below average stratification in contrast to the past 25 years that are characterized by above normal values (Figure 32). Since 1948, there has been an increase in the mean stratification on the Scotian Shelf, resulting in a change in the 0–50 m density difference of 0.36 kg m^{-3} over 50 years. This change in mean stratification is due mainly to a decrease in the surface density, composed of equally of warming and freshening (Figure 33). Stratification in 2017 was nearly the same as in 2016 where surface freshening (a salinity decrease of 0.1) was offset by surface cooling (a temperature decrease of 0.3°C). Examining the 2017 stratification anomaly for areas 4–23 on the Scotian Shelf shows that the overall positive anomaly for the Scotian Shelf (Figure 32) is due to positive anomalies on inner half of eastern Scotian Shelf and outer half of the western Scotian Shelf (Figure 34). This is also evident in the individual transects which is a subset of the data used.

SEA LEVEL

Sea level is a primary variable in the Global Ocean Observing System. Relative sea level is measured with respect to a fixed reference point on land. Consequently, relative sea level consists of two major components: one due to true changes of sea level and a second caused by sinking or rising of the land. In Atlantic Canada, Post-Glacial Rebound (PGR) is causing the area roughly south (north) of the north shore of the Gulf of St. Lawrence to sink (rise) in response to glacial retreat; this results in an apparent rise (fall) of sea level. The PGR rates for Yarmouth, Halifax, and North Sydney have been obtained from Natural Resource Canada's gridded GPS-based vertical velocities (Phillip MacAulay, DFO, pers. comm. 2012; Craymer et al. 2011).

Relative sea level at Yarmouth (1967–2016), Halifax[1] (1920–2016) and North Sydney (1970–2016) are plotted as monthly means and as a filtered series using a five-year running-mean filter (Figure 35). The linear trend of the monthly mean data has a positive slope of 36.3 cm/century (Yarmouth), 33.0 cm/century (Halifax), and 38.1 cm/century (North Sydney). Barnett (1984) found a slightly higher sea level rise for Halifax (36.7 cm/century) for the period 1897–1980. This is due to the decrease in sea-level rise after 1980 as discussed below. With the removal of the PGR for Yarmouth (-10.3 cm/century), Halifax (-14.7 cm/century) and North Sydney (-16.8 cm/ century), sea-level rise is +26.0 cm/century, +18.3 cm/century and +21.3 cm/century, respectively. In 2017, the annual relative sea level relative to the 1981–2010 sea-level-rise trend at Yarmouth, Halifax and North Sydney decreased slightly from 2016 that had an increase after several years of decrease (Figure 36). An interesting feature of the data is the long-term variation that has occurred since the 1920s. It is apparent that from the 1920s to the early 1970s, the sea-level-rise trend at Halifax was greater than the 1981–2010 trends. The residual sea-level data for the common period 1970–2017 shows that the variability has a large spatial structure given the coherence between the three sites. Several potential causes of this decadal scale variability have been examined; however, the cause of these changes is still not

[1] The historical station in Halifax failed in early-2014. The nearby tidal station at Bedford Institute of Oceanography in Dartmouth, Nova Scotia, was used for 2014. For the common operating period, there was no significant difference in the two tide gauges.

understood. Further south, near Delaware, USA, variations in the wind stress in the subtropical gyre appears to be responsible for the low frequency variation in sea level (Hong et al. 2000); yet, 20 years of observed Gulf Stream transport does not show a significant decrease (Rossby et al. 2014).

RESULTS FROM NUMERICAL SIMULATION MODEL

Currents and transports are derived from a numerical model of the North Atlantic Ocean (Brickman et al. 2015). The model has a spatial resolution of 1/12° with 50 z-levels in the vertical (22 in the top 100 m), and partial cells in the bottom layer to adapt to the bathymetry. The model is prognostic, that is, it allows for evolving temperature and salinity fields. Atmospheric forcing is derived from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis forcing (Kalnay et al. 1996). The model is run in various configurations. The analyses reported on here come from a version of the model that has been used to study various phenomena in the Atlantic monitoring zone (Wang et al. 2016; Brickman et al. 2018). This version has a simple representation of the major river systems in the Atlantic region and no tidal forcing. The simulation runs from 1990 to the present, with the latest year updated annually when the surface forcing is available. The model domain is shown in Figure 37.

Some calculations intended to help interpret data collected by the AZMP are presented. Results are presented in terms of standardized anomalies to facilitate comparison to other AZMP analyses. The reader is cautioned that the results outlined below are not measurements, and simulations and improvements in the model may lead to changes in them.

VARIATION IN TRANSPORTS IN THE SCOTIAN SHELF/GULF OF MAINE REGION

The general circulation on the shelf seas of the Maritimes Region of Canada can be characterized as a general northeast-to-southwest flow from the Strait of Belle Isle, through Cabot Strait, and along the Scotian Shelf toward the Gulf of Maine (Figure 38). Part of the water that flows out of the Gulf of St. Lawrence through the western side of Cabot Strait follows the Nova Scotia coastline as the Nova Scotia Current, which ultimately flows into the Gulf of Maine. Another part follows the shelf break and contributes to the Gulf of Maine inflow at the Northeast Channel. Variations in these currents may influence the distribution of various fish and invertebrate larvae from the southern Gulf of St. Lawrence westward to the Gulf of Maine. As well, the currents that stream past Cape Sable Island and through Northeast Channel bring on-shelf and off-shelf water properties into the Gulf of Maine, and the partitioning of the transports is potentially important to processes occurring in the Gulf of Maine.

Monthly mean transports for the 1999–2017 period were extracted from the model simulation for four Maritime sections: Cabot Strait (CS), Halifax (HFX), Cape Sable Island/Browns Bank (CSI) and Northeast Channel (NEC) (Figure 38). From these data, standardized anomaly plots were constructed to illustrate transport variability. The results for the nearshore regions at CS, HFX, and CSI (where nearshore is taken as the subsection between the 100 m isobath and the coastline), the shelf break at HFX, and the inflow at NEC are displayed in Figure 39. From the inflows through the CSI and NEC sections the Gulf of Maine (GoM) inflow ratio CSI/(CSI + NEC) was computed (see below). Note that for all sections except NEC, positive transport denotes a flow direction through CS towards the GoM. For NEC, positive transport denotes flow into the Gulf of Maine.

Transport variability on the Scotian Shelf shows a fairly coherent pattern of annual anomalies for CS, HFX (nearshore and shelf break) and CSI (Figure 40). On a monthly basis, on average, the nearshore series (CS, HFX nearshore, and CSI) and the transport into the GoM at NEC exhibit a seasonal cycle with mid-to-late year transport minima, while the shelf break transport along the Halifax section shows no clear seasonality (Figure 39, although note interannual variability).

For comparison with the numerical model transport estimates, the monthly transport of the Nova Scotia Current off Halifax was calculated using bottom mounted Acoustic Doppler Current Profilers (ADCP). Three upward looking ADCPs had been deployed for six month periods from July 2008 to April 2015 on the 100 m (T1), 170 m (T2), and 180 m (T3) isobaths to monitor the velocity field associated with the Nova Scotia Current along the Halifax Line. Located 12 km east of station 2 is T2 (Figure 1). T1 and T3 are approximately 15 km to the northwest and southeast to T2, respectively. The observations start from 5 m above the bottom to approximately 10 m below the surface, with a 4 m vertical resolution. The horizontal spacing between ADCPs is about 16 km, with T2 located close to the current maximum. The velocity components are rotated by 58° relative to True North to obtain the velocity field with the maximum variance along the major axis. Daily averages of the alongshore velocity were gridded using linear interpolation and multiplied by the cross-sectional area between T1 and T3 to provide monthly estimates of the Nova Scotia Current transport in 10^6 m^3 s^{-1}. Periods where data are available from all three stations are used to establish a linear relationship between the transport estimated using all stations and the transport estimated using only one or two ADCP stations. These relationships have been used to extrapolate the transport estimations to periods where one of the ADCP has failed during the deployment. Starting in May 2015, only the mooring at T2 has been deployed. Work by Dever (2017) showed a high correlation (r^2=0.87) between the depth-integrated current at T2 and the total transport. A negative transport means a southwestward transport toward the Gulf of Maine. The data indicate a period of negative anomalies (stronger southwestward flow) starting in mid-2010 and extending to mid-2011, followed by average or weaker flow that persists until near the end of 2014 where flow is average or above average until Spring 2015 (Figure 41). This was followed by a period of near-normal or below-normal until July 2016. For the fall of 2016 and winter of 2017, the flow was above normal. These trends are well simulated by the model particularly the last 15 months of the record (see HFX nearshore panel of Figure 39).

The fraction of transport into the Gulf of Maine through the Cable Sable Island section (GoM inflow ratio - Figure 42) exhibits a seasonal cycle with a minimum during the summer months. On average, the model predicts that about one half of the transport into the Gulf of Maine enters through the CSI section. Interannually, (Figure 40) the GoM inflow ratio was near neutral from 1999–2007 (with only 2001 and 2004 above normal) and mostly negative from 2008–2017. From the model simulation, the general warming trend over the last decade seen in many data series is evident as increased transport into the GoM at NEC and a reduced GoM inflow ratio.

An overall annual-composite transport index was computed (Figure 43) by summing the standardized anomalies (Figures 39 and 40) for five of the six transport variables (the inflow through NEC was omitted as this metric is not independent of the GoM inflow ratio). If one considers this summation as a measure of the on-shelf flow-through in the system from the southern Gulf of St. Lawrence to the Gulf of Maine, it is found that the model hindcasts strong negative anomalies in 1999–2000, generally weak positive anomalies from 2001 to 2007, followed by alternating stronger negative and positive anomalies thereafter.

SUMMARY

In 2017, the NAO index remained positive (+2.7 mb, +0.3 SD from the 1981–2010 mean) but much lower than in 2015, which had the largest value in the 122-year record. Mean annual air temperature anomalies were positive at all sites. There had been very little ice on the Scotian Shelf and Cabot Strait from April 2009 until 2014. After above-normal values in 2015, ice cover has since been well below normal. In 2016 and 2017, ice was barely present at locations (Cabot Strait, Sydney Bight, and northeastern Cape Breton) where ice is normally present for at least one month based on the climatological values. The analysis of satellite data indicates that SST anomalies were above normal at the start of the year followed by a period of near- or below-normal temperatures and then above normal for the fall.

A graphical summary of selected time series already shown indicates that the periods 1987–1993 and 2003–2004 were predominantly colder than normal, and 1999–2000 and 2010–2017 were warmer than normal (Figure 44). The period 1979–1986 also tended to be warmer than normal. It is apparent that 2012 was an exceptional year based on these series with 14 values above 2 SD. In 2017, all 20 series shown had positive anomalies; 18 variables were more than 1 SD above their normal values. Of these, 6 were more than 2 SD above normal and one more than 3 SD (deep Cabot Strait). In 2017, the average (median) normalized anomaly was 1.7 (1.7) SD, the third highest in the 48-year series. These statistics indicate that 2017 was an extremely warm year with a fairly uniform distribution of positive anomalies throughout the region.

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TABLES

Table 1. The 2017 annual mean air temperature anomaly in degrees and normalized anomaly (relative to the 1981–2010 climatology) and SD of the monthly anomalies for Scotian Shelf and Gulf of Maine.

Site	Annual Anomaly		1981–2010 Climatology	
	Observed (°C)	Normalized (SD)	Mean (°C)	SD (°C)
Sydney	+0.72	+0.89	5.87	0.81
Sable Island	+0.71	+1.04	7.88	0.68
Shearwater (Halifax)	+0.53	+0.79	6.99	0.74
Yarmouth	+0.86	+1.43	7.16	0.62
Saint John	+0.96	+1.12	5.19	0.74
Boston	+0.51	+0.85	10.91	0.60

Table 2. 2017 SST anomalies and long-term SST statistics including 1982–2017 temperature change based on the linear trend.

Site	2017 SST Anomaly (ºC)	2017 SST Anomaly Normalized	1981–2010 Mean Annual SST (ºC)	1981–2010 Annual SST Anomaly Std. Dev. (ºC)	1982–2017 Temperature Trend (ºC/decade)
Cabot Strait	+0.7	+1.2	5.9	0.6	0.3
Eastern Scotian Shelf	+1.3	+1.9	7.1	0.7	0.5
Central Scotian Shelf	+1.6	+2.3	8.5	0.7	0.6
Western Bank	+1.4	+1.6	8.9	0.8	0.6
Western Scotian Shelf	+1.9	+3.0	8.1	0.6	0.5
Lurcher Shoal	+1.3	+1.9	7.2	0.7	0.4
Bay of Fundy	+1.6	+2.5	7.2	0.6	0.6
Georges Bank	+1.1	+2.1	10.0	0.5	0.4

Table 3. Ice area and volume statistics for the Scotian Shelf.

Month	2017 Ice Area (km^2)	2017 Area Anomaly (km^2)	2017 Normalized Area Anomaly	2017 Ice Volume (km^3)	2017 Volume Anomaly (km^3)	2017 Normalized Volume Anomaly
January	11	-1220	-0.6	0.00	-0.19	-0.5
February	190	-11100	-1.0	0.02	-2.78	-1.0
March	5110	-10600	-0.7	0.69	-6.19	-0.9
April	365	-4220	-0.9	0.15	-2.87	-0.9

FIGURES

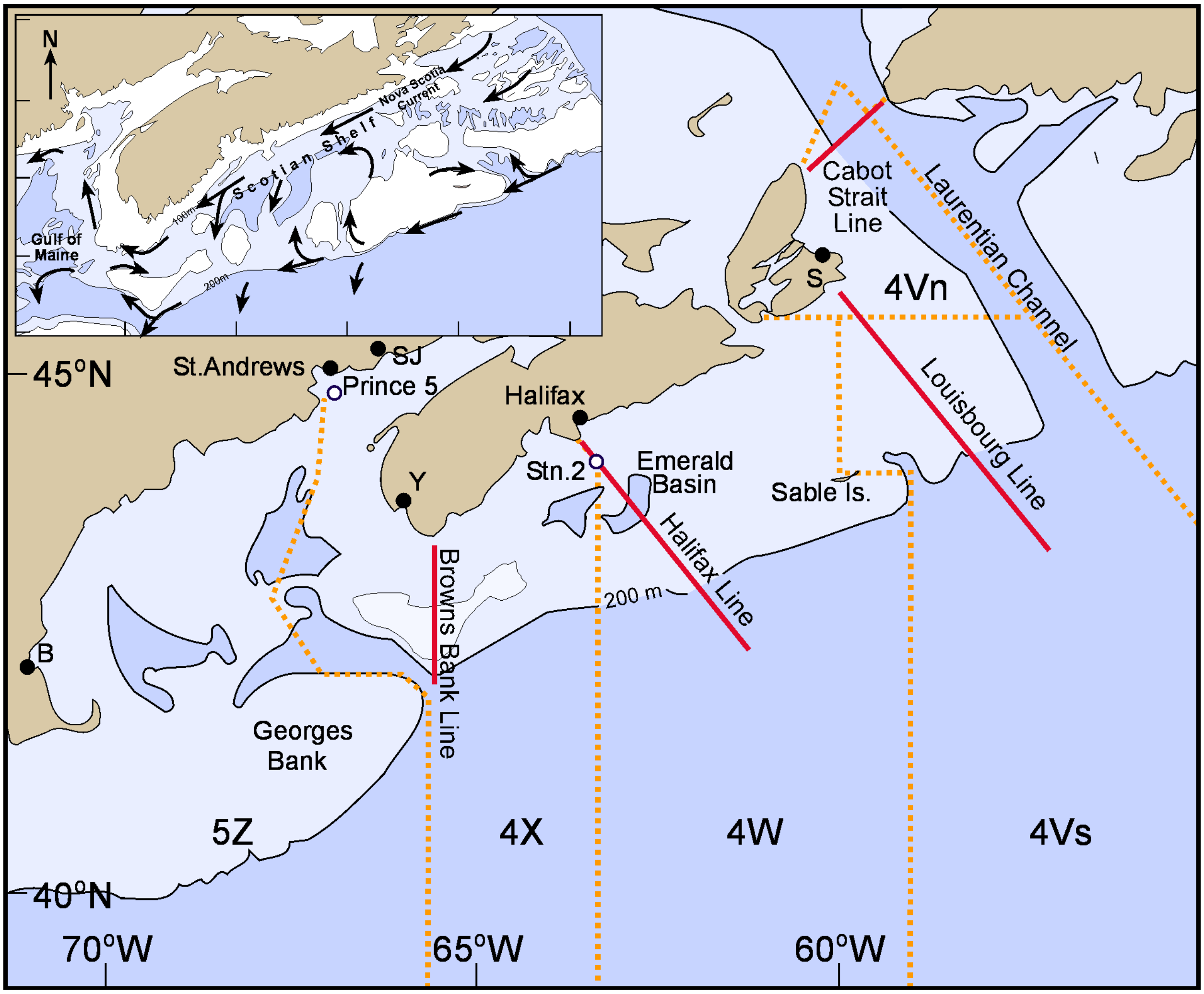

Figure 1. Map of the Scotian Shelf and the Gulf of Maine showing hydrographic stations (white circles), standard sections (red lines) and topographic features. The dotted lines indicate the boundaries of the Northwest Atlantic Fisheries Organization Divisions. Inset depicts major circulation features. Air temperature stations at Sydney (S), Yarmouth (Y), Saint John (SJ), and Boston (B) are designated by a letter.

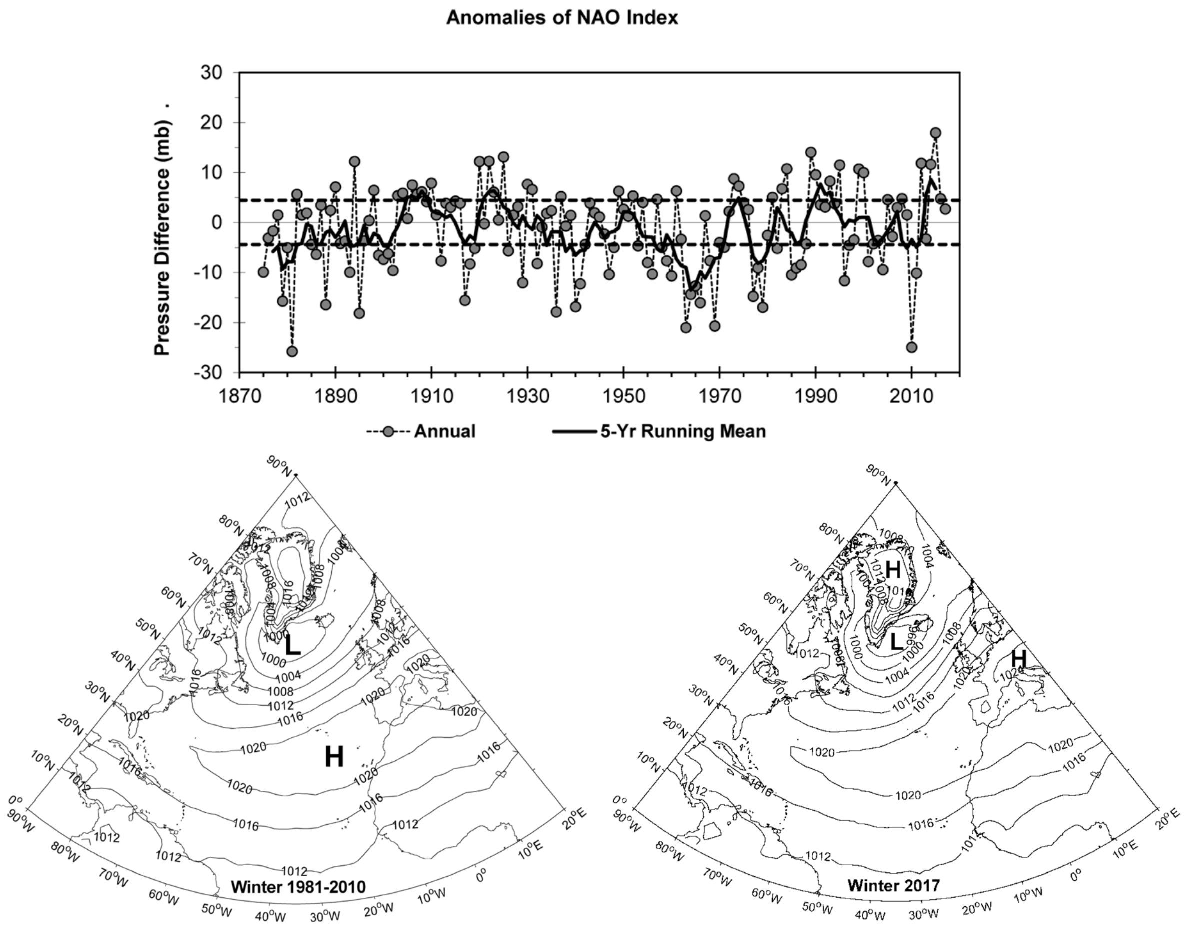

Figure 2. Anomalies of the North Atlantic Oscillation (NAO) index, defined as the winter (December, January, February) sea level pressure difference between the Azores and Iceland, relative to the 1981–2010 mean. Dashed lines (upper penel) are ±0.5 standard deviation (SD). The lower panels show the 1981–2010 December–February mean (bottom left panel) and December 2016–February 2017 mean (bottom right panel) sea level atmospheric pressure over the North Atlantic (Images provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site.)

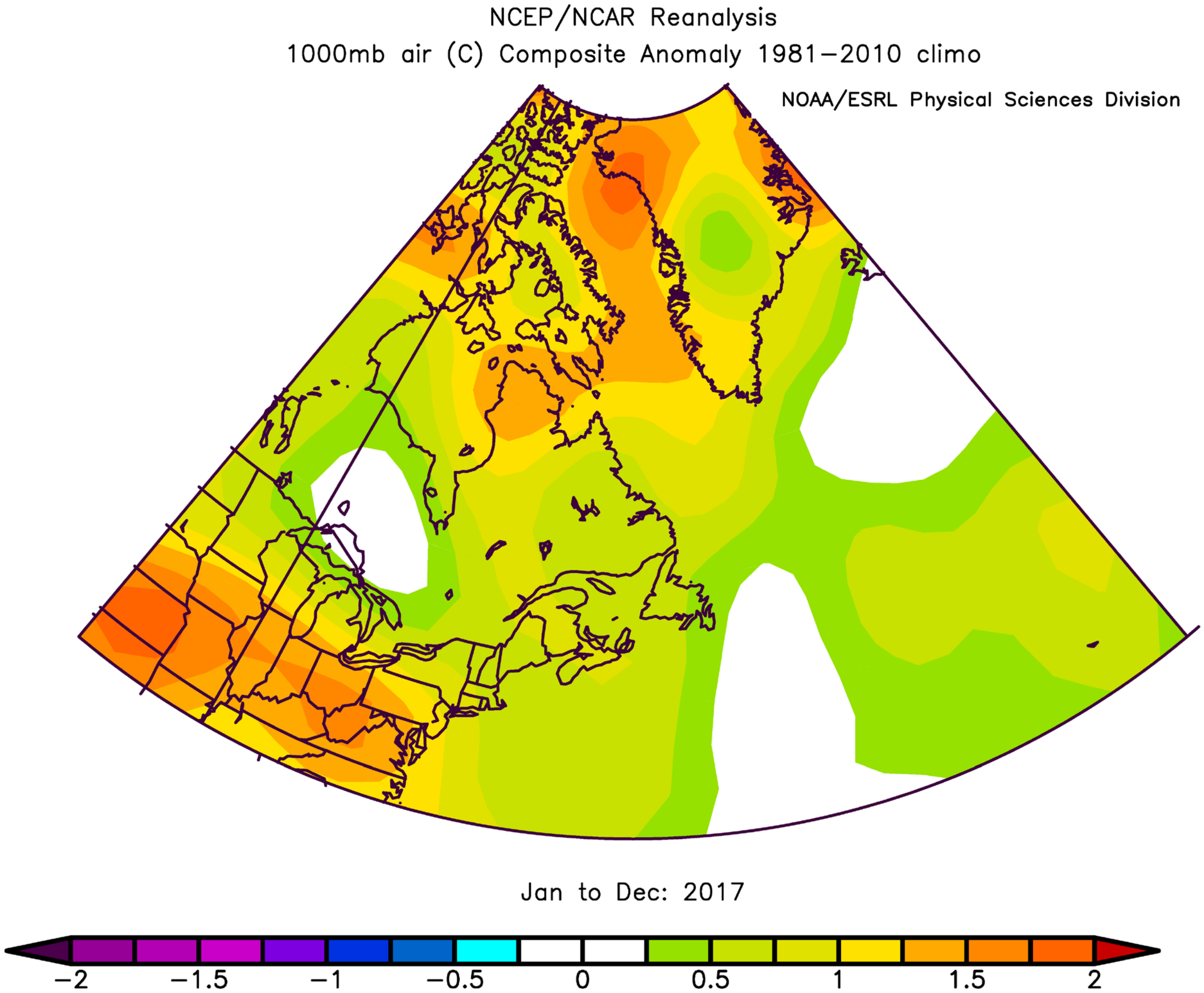

Figure 3. Annual air temperature anomalies (ºC) over the Northwest Atlantic relative to the 1981–2010 means; data were obtained from NOAA Internet site (accessed November 2018). (Images provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site.)

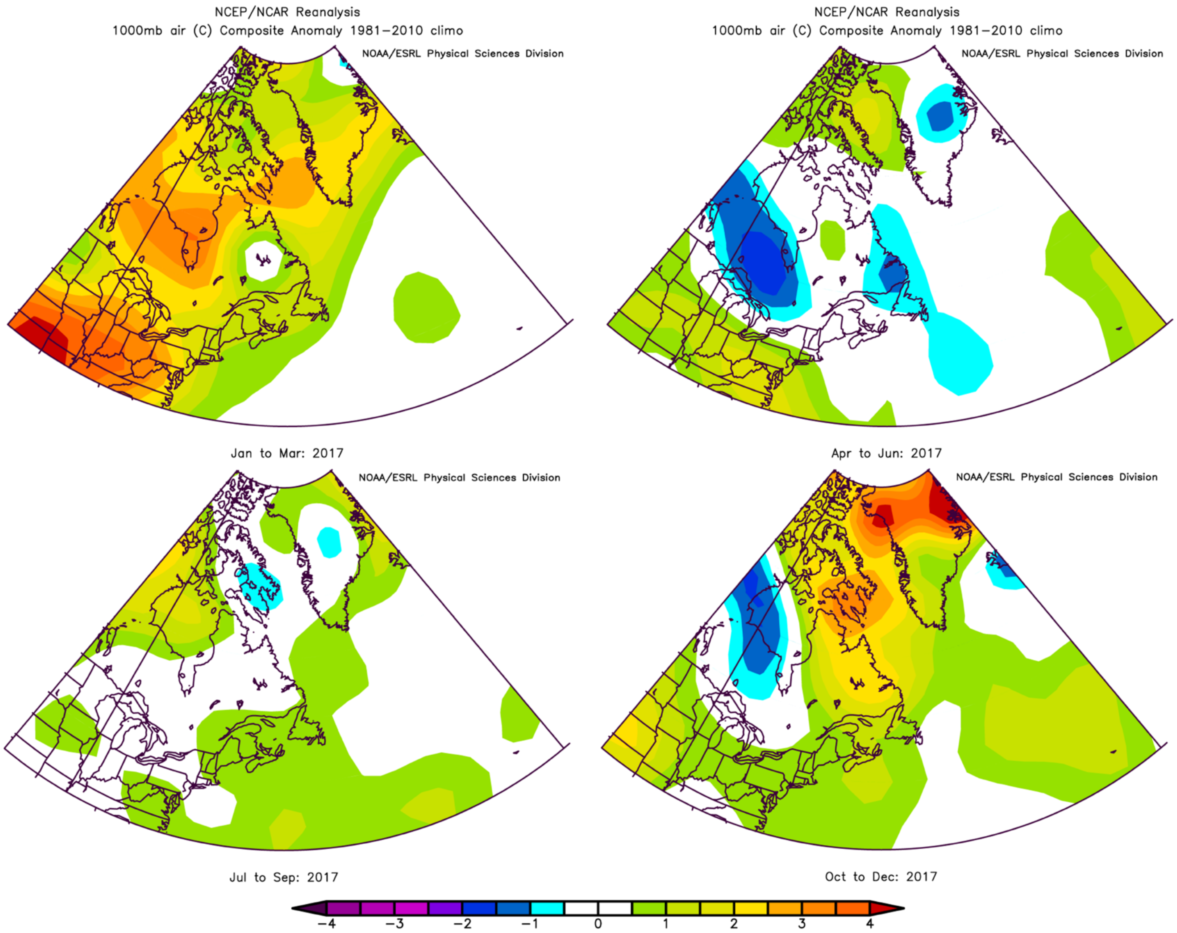

Figure 4. Seasonal air temperature anomalies (ºC) over the Northwest Atlantic relative to the 1981–2010 means; data were obtained from NOAA Internet site (accessed 10 January 2018). (Images provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site).

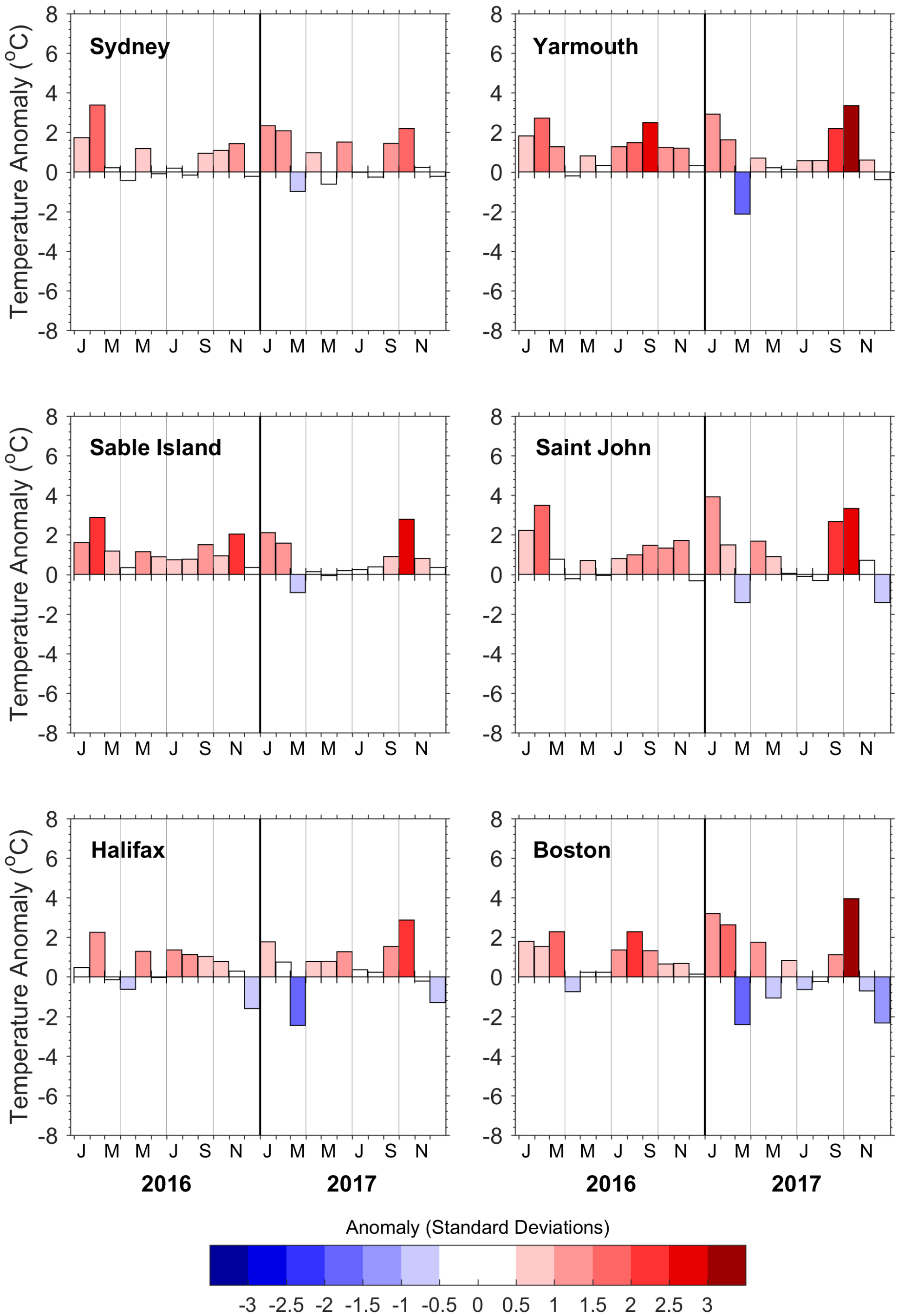

Figure 5. Monthly air temperature anomalies (°C) for 2016 and 2017 (JMMJSN on x-axis represent January, March, May, June, September and November) at coastal sites in Scotian Shelf-Gulf of Maine region (see Figure 1 for locations). Anomalies are colour coded in terms of the numbers of SD above or below normal relative to monthly statistics.

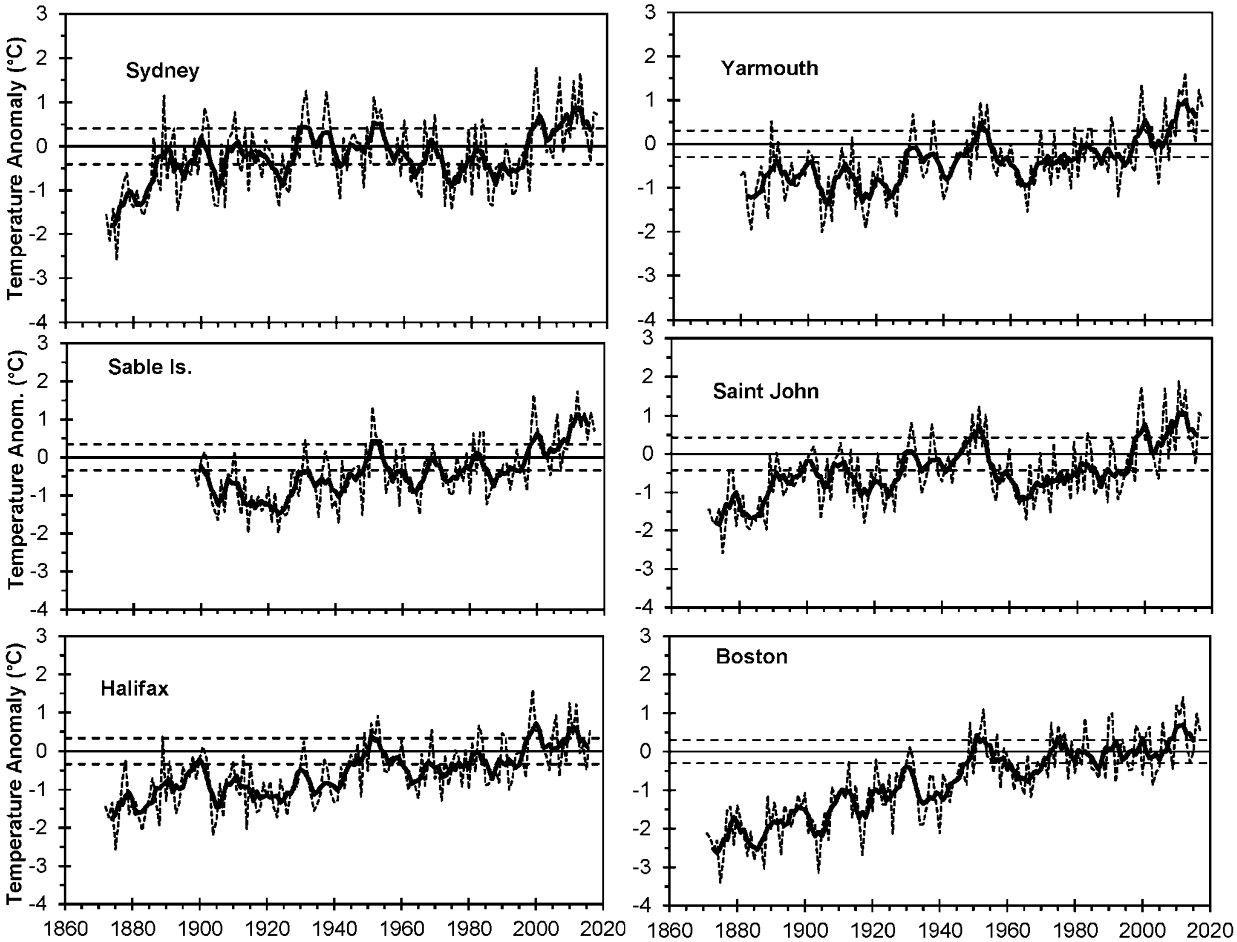

Figure 6. Annual air temperature anomalies in °C (dashed line) and five-year running means (solid line) at selected sites (Sydney, Sable Island, Shearwater, Yarmouth, Saint John, and Boston) in Scotian Shelf-Gulf of Maine region (years 1860 to 2017). Horizontal dashed lines represent plus or minus 0.5 SD for the 1981–2010 period.

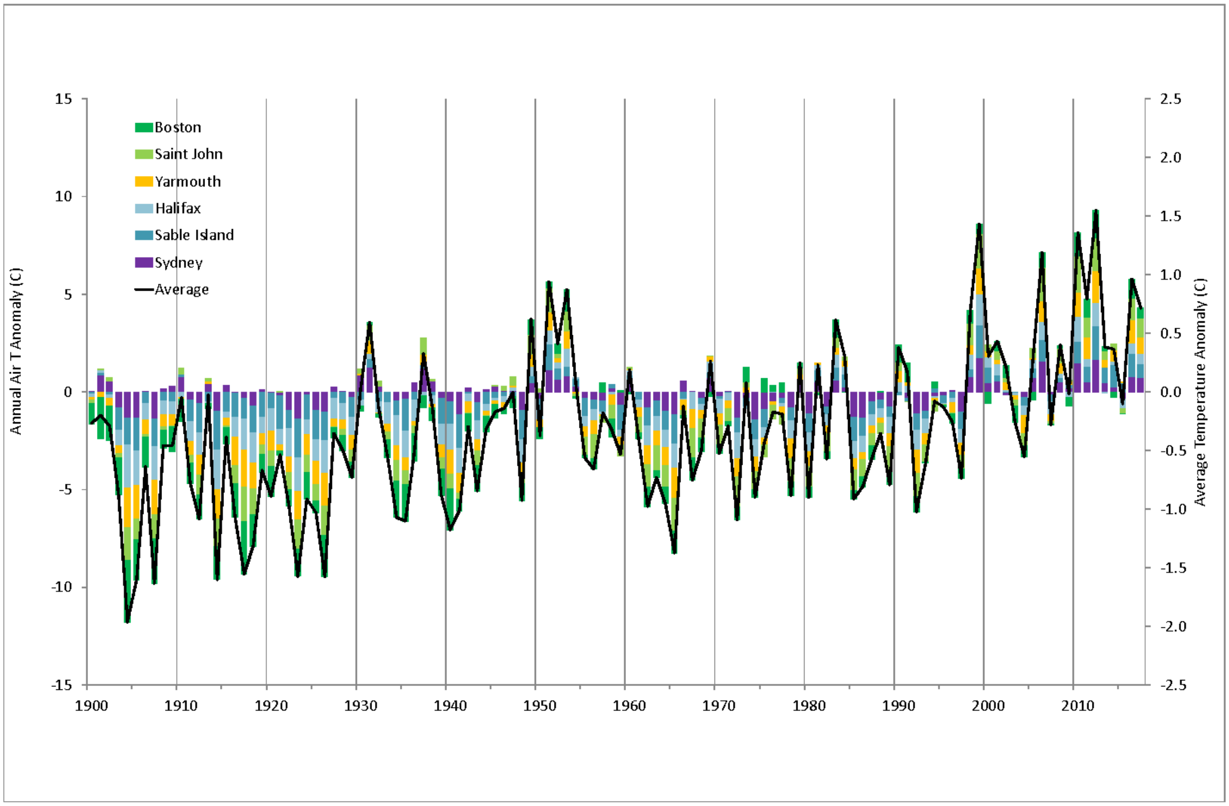

Figure 7. The contributions of each of the annual air temperature anomalies for six Scotian Shelf-Gulf of Maine sites (Boston, Saint John, Yarmouth, Shearwater, Sable Island and Sydney) are shown as a stacked bar chart and the average anomaly as a line. Anomalies referenced to 1981–2010.

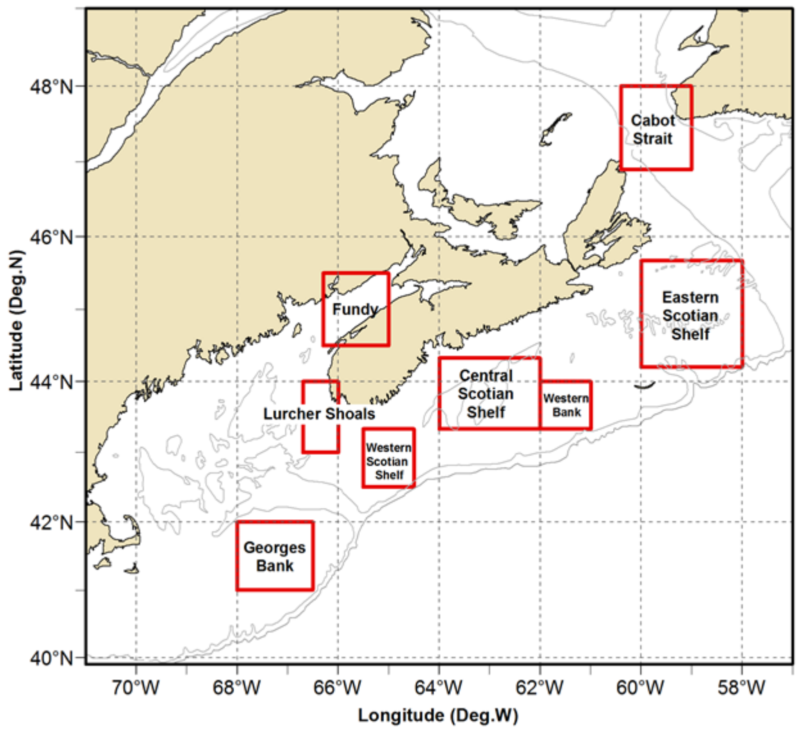

Figure 8. Scotian Shelf-Gulf of Maine areas (Cabot Strait, Eastern Scotian Shelf (ESS), Western Bank, Central Scotian Shelf (CSS), Western Scotian Shelf (WSS), Georges Bank, Lurcher Shoals and Bay of Fundy) used for extraction of sea surface temperature.

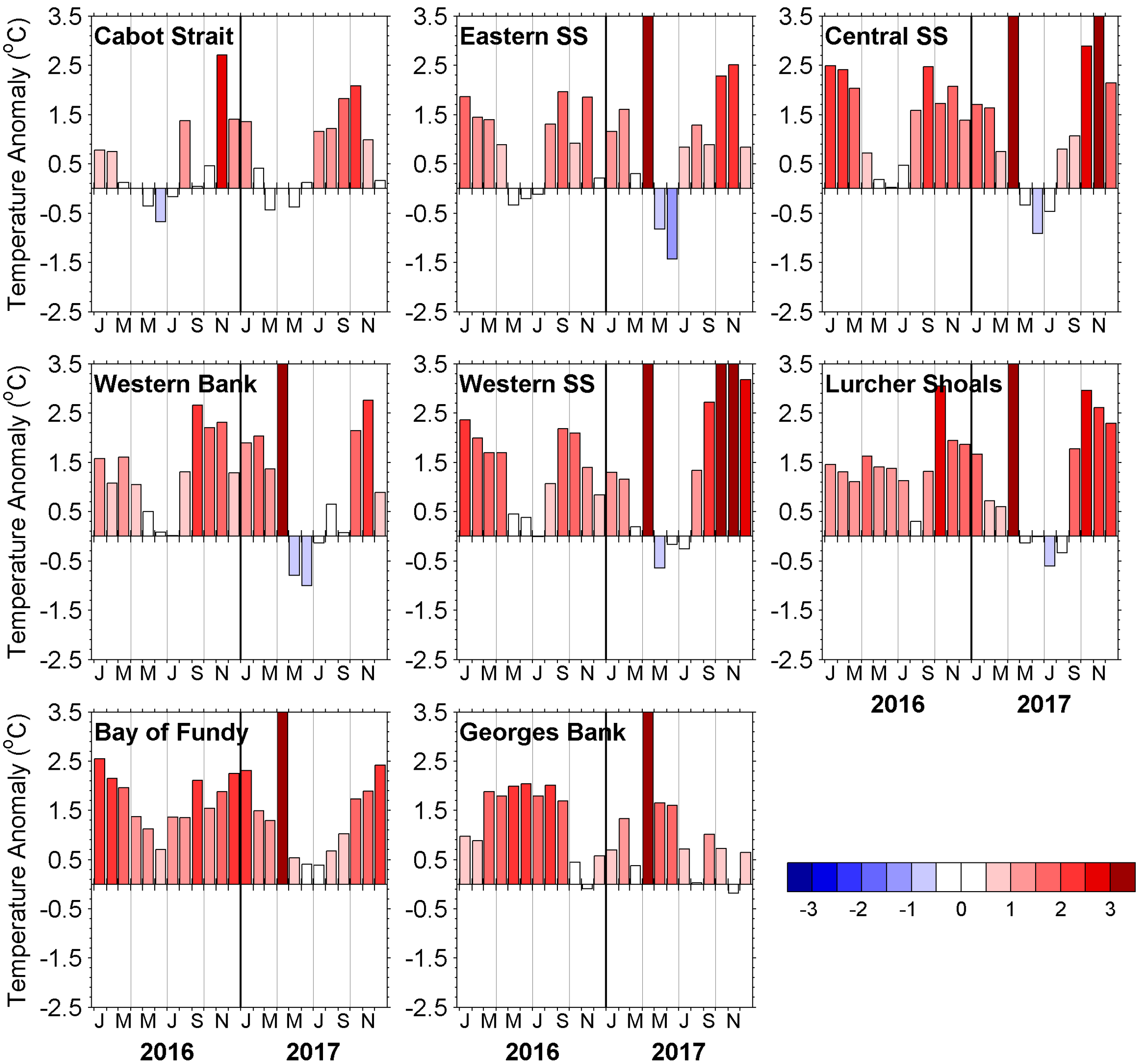

Figure 9. Monthly surface temperature anomalies for 2016 and 2017 for the regions shown in Figure 8. The colours of the bars are the normalized anomalies.

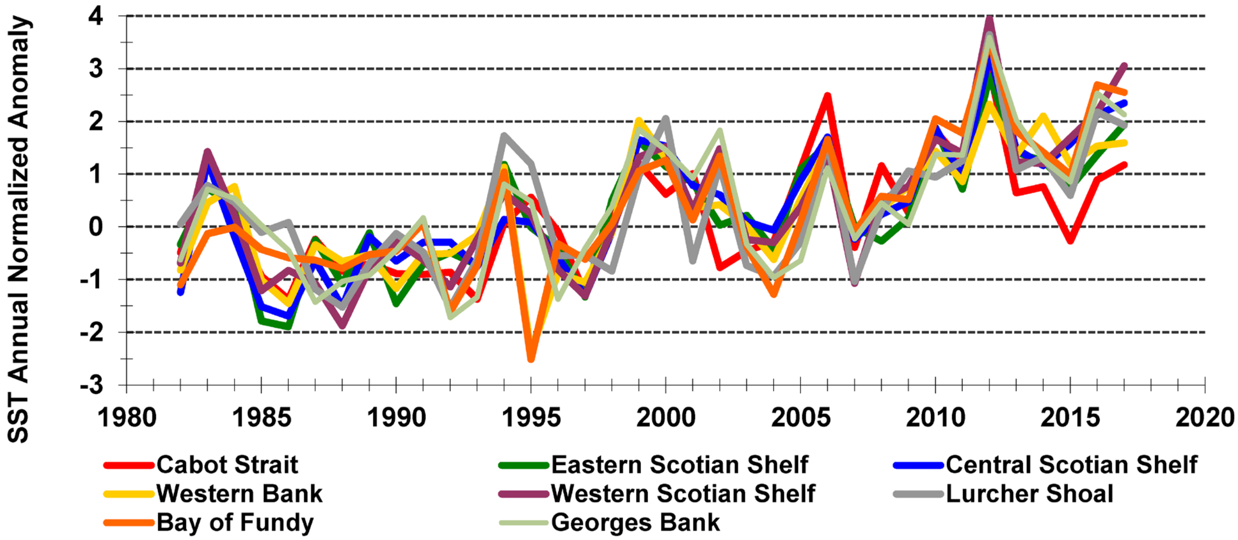

Figure 10. The annual sea surface temperature anomalies derived from satellite imagery compared to their long-term monthly means (eight Scotian Shelf and Gulf of Maine regions - Cabot Strait, Eastern Scotian Shelf, Central Scotian Shelf, Western Bank, Western Scotian Shelf, Lurcher Shoals, Bay of Fundy, and Georges Bank – Figure 8).

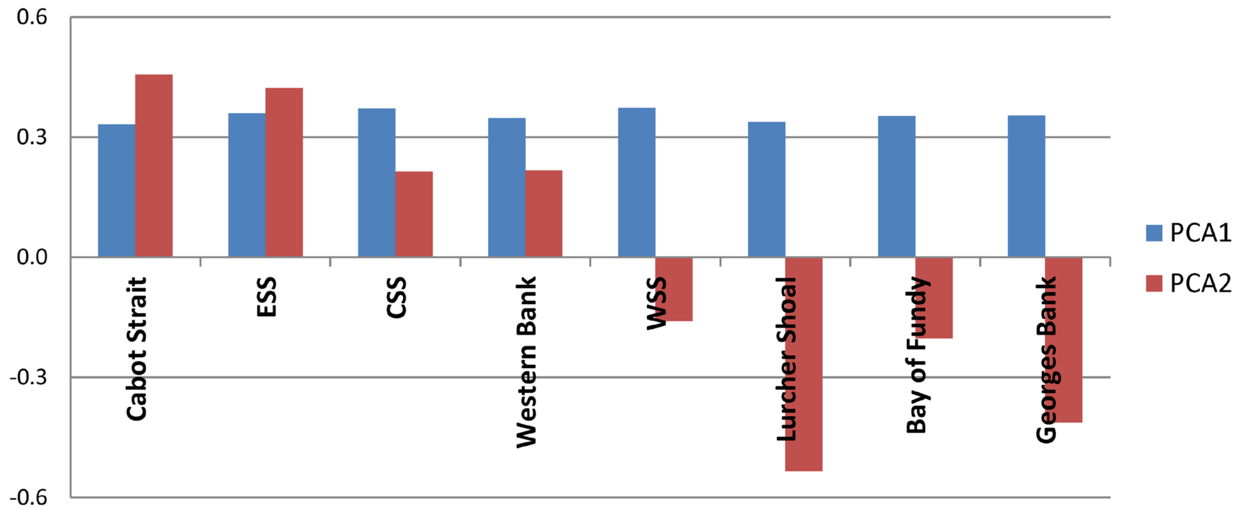

Figure 11. First (PCA1: 83% of the variance) and second (PCA2: 6% of the variance) loadings from a principal components analysis of the annual mean temperature anomalies (Figure 14 for the eight Scotian Shelf and Gulf of Maine regions (Cabot Strait, Eastern Scotian Shelf, Western Bank, Central Scotian Shelf, Western Scotian Shelf, Georges Bank, Lurcher Shoals and Bay of Fundy - Figure 8.

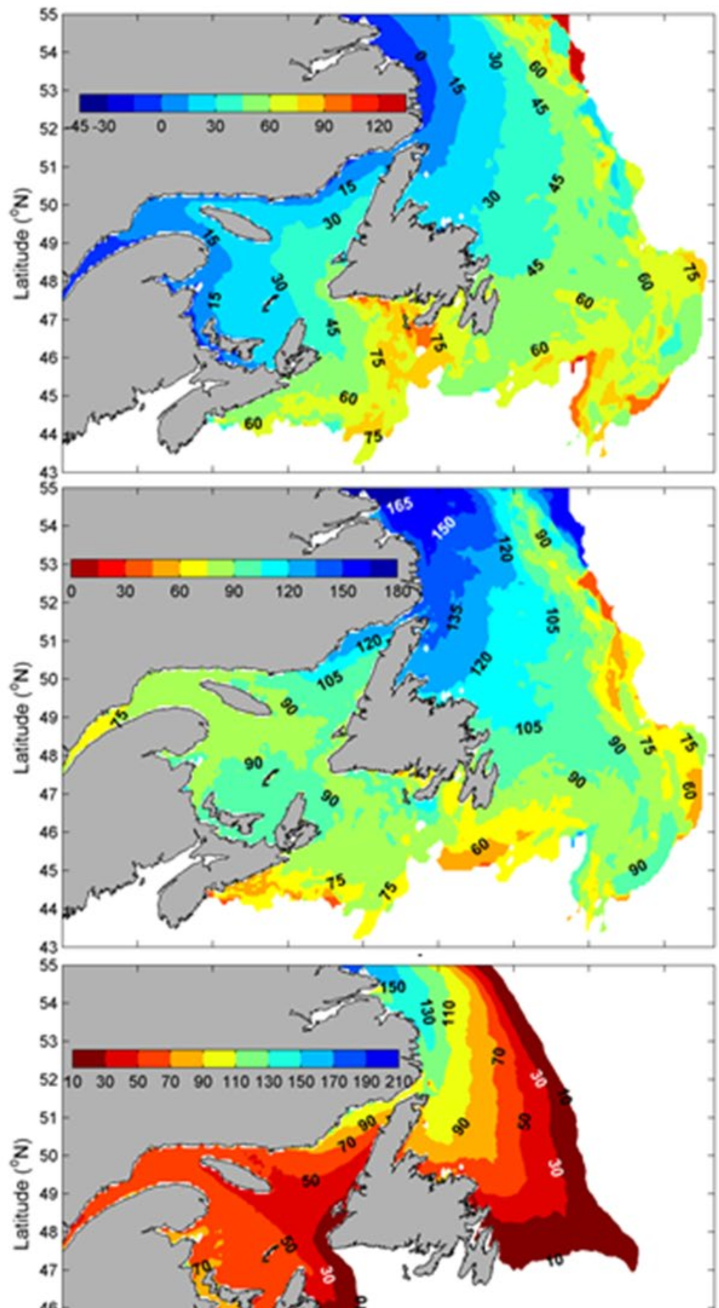

Figure 12. The 1981–2010 mean time when ice in the Gulf of St. Lawrence, Scotian, Newfoundland and Labrador shelves first appeared in days from the beginning of the year (top panel), the time when ice was last seen (middle panel) and the duration of ice (only regions where duration was 10 days or longer is shown; bottom panel). Longitude in degrees on the x-axis (negative values are West) and Latitude in degrees (positive values are North) on the y-axis.

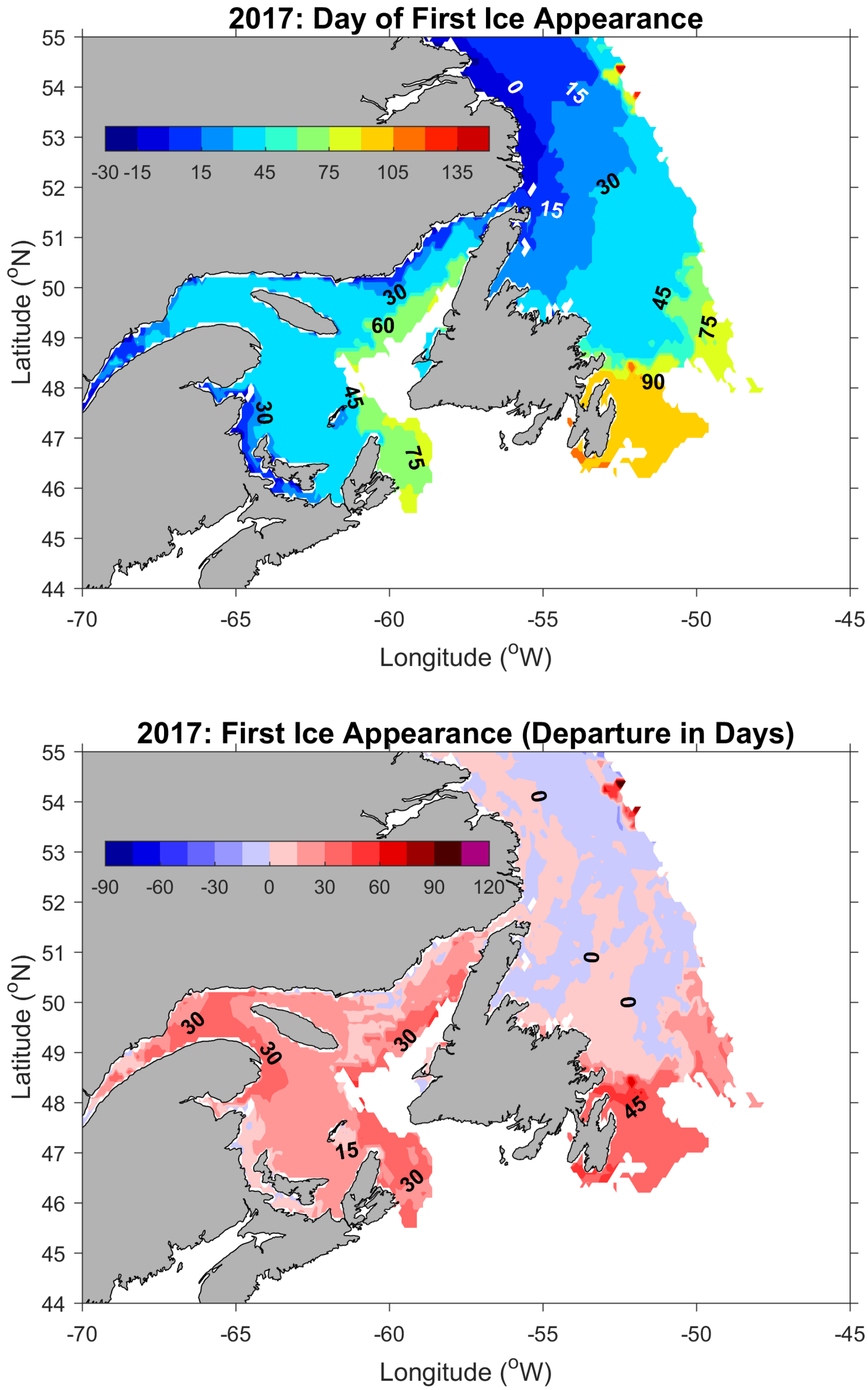

Figure 13. The time when ice in the Gulf of St. Lawrence, Scotian, Newfoundland and Labrador shelves first appeared during 2017 in days from the beginning of the year (top panel) and its anomaly from the 1981–2010 mean in days (bottom panel). Negative (positive) anomalies in blue (red) indicate earlier (later) than normal appearance. Longitude in degrees on the x-axis (negative values are West) and Latitude in degrees (positive values are North) on the y-axis.

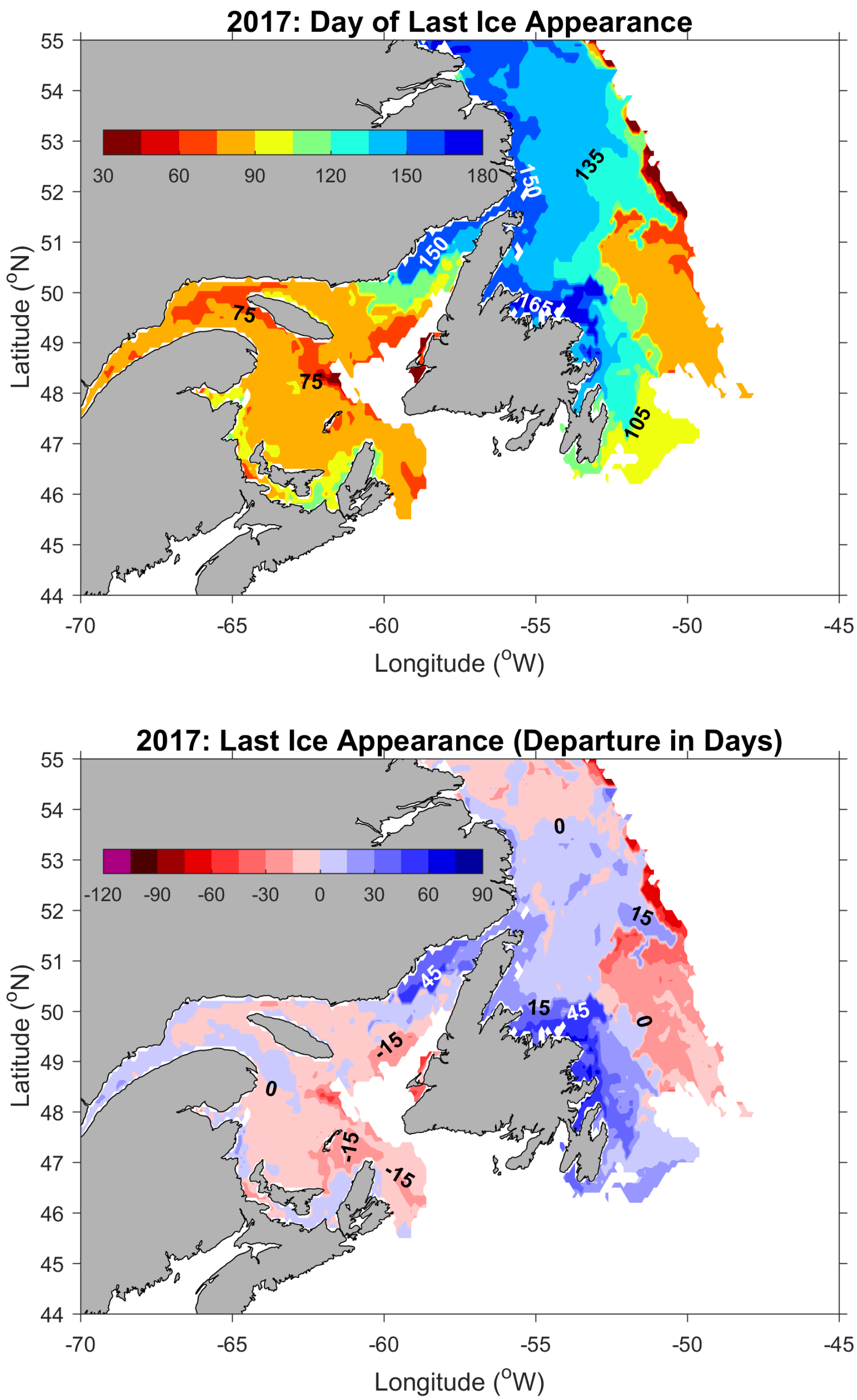

Figure 14. The time when ice in the Gulf of St. Lawrence, Scotian, Newfoundland and Labrador shelves was last seen in 2017 in days from the beginning of the year (top panel) and its anomaly from the 1981–2010 mean in days (bottom panel). Negative (positive) anomalies in red (blue) indicate earlier (later) than normal disappearance. Longitude in degrees on the x-axis (negative values are West) and Latitude in degrees (positive values are North) on the y-axis.

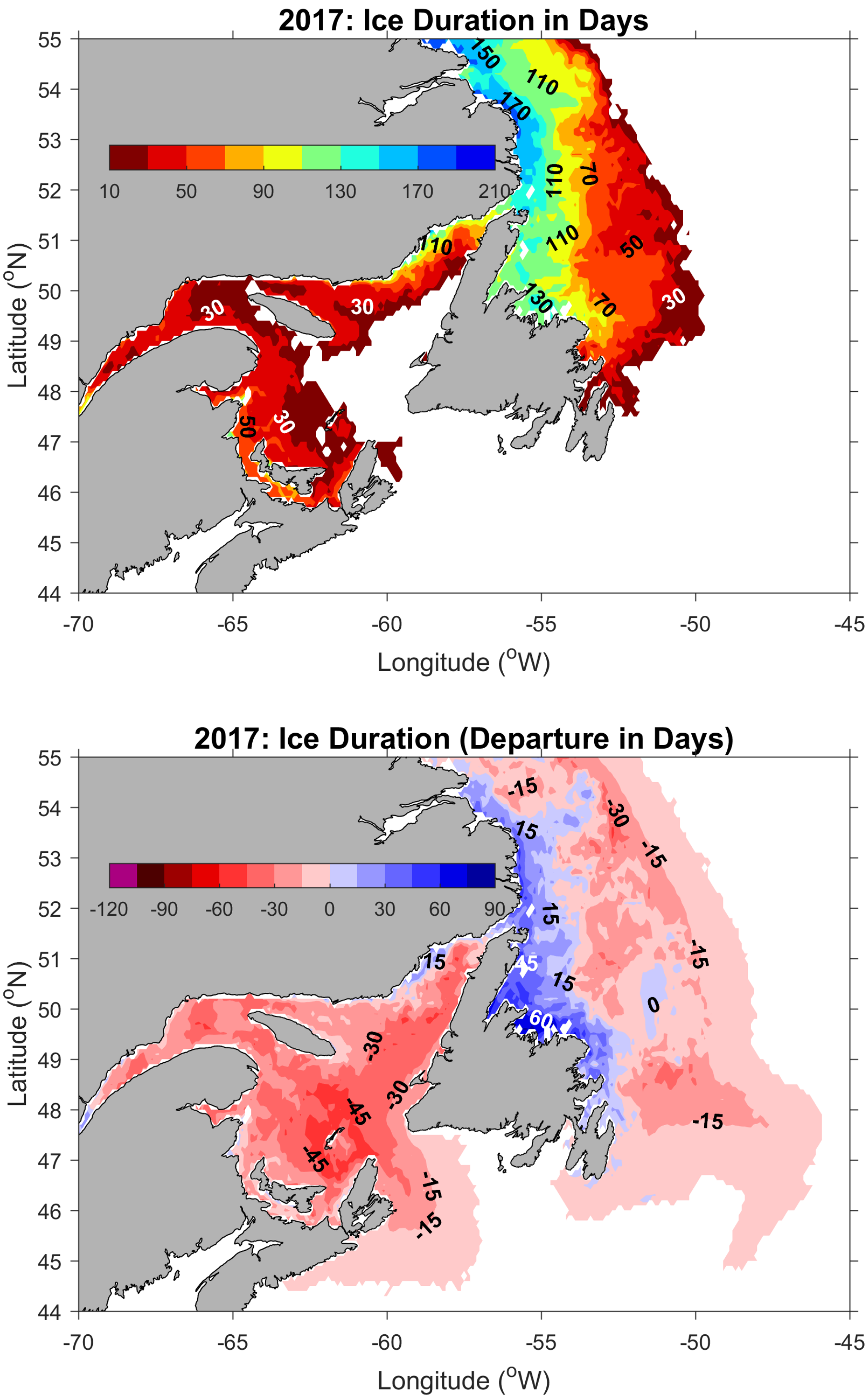

Figure 15. The duration of ice in the Gulf of St. Lawrence, Scotian, Newfoundland and Labrador shelves in days (top panel) during 2017 and the anomalies from the 1981–2010 mean in days (bottom panel). Positive (negative) anomalies in blue (red) indicate durations longer (shorter) than the mean. Note that areas of duration approximately ten days are not displayed. The anomaly panel shows the climatological extent of ice. Longitude in degrees on the x-axis (negative values are West) and Latitude in degrees (positive values are North) on the y-axis.

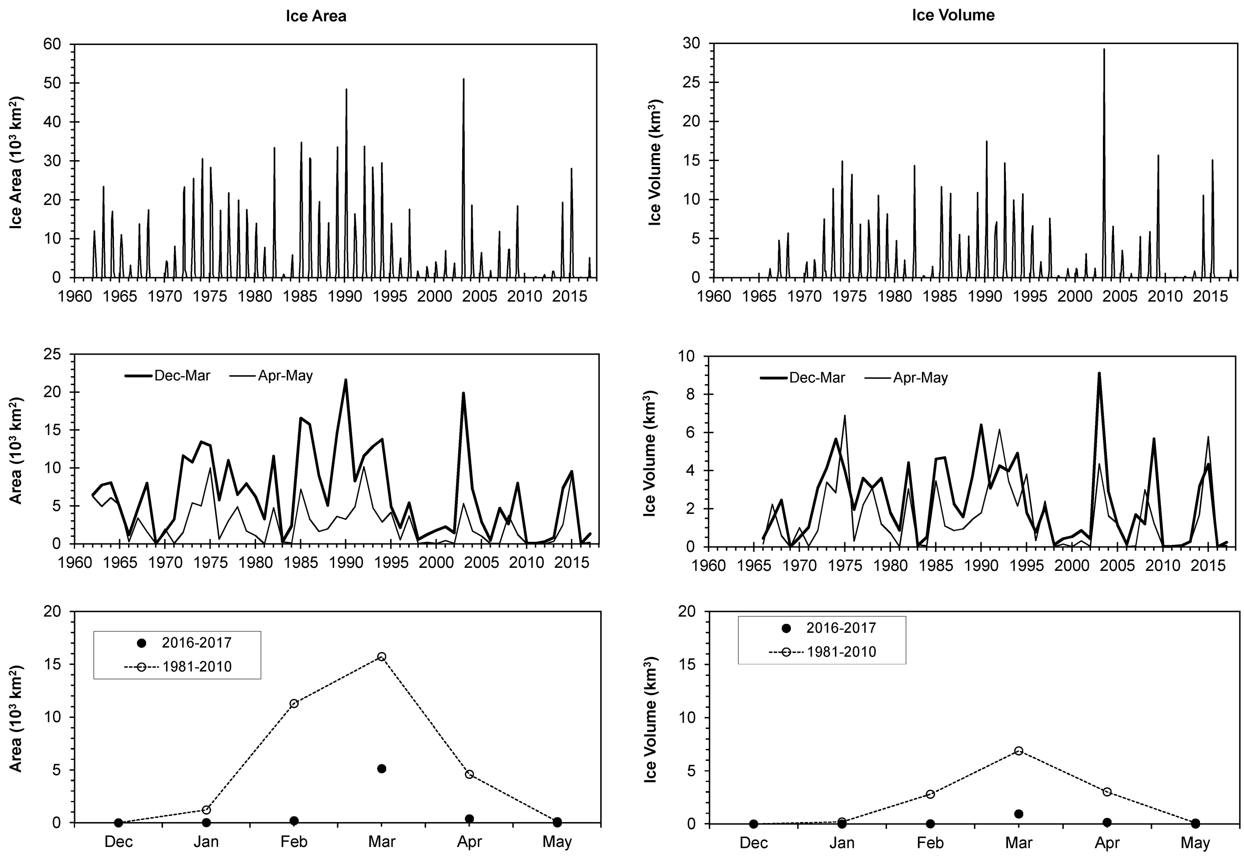

Figure 16. Time series of the monthly mean ice area and volume for the Scotian Shelf (top panels), the average ice area and volume during the usual periods of advancement (January–March) and retreat (April–May) (middle panels), and the comparison of the 2016–2017 monthly areas and volumes to the 1981–2010 means (bottom panels). Note that the 2010–2013 and 2016 ice area and volume is basically zero.

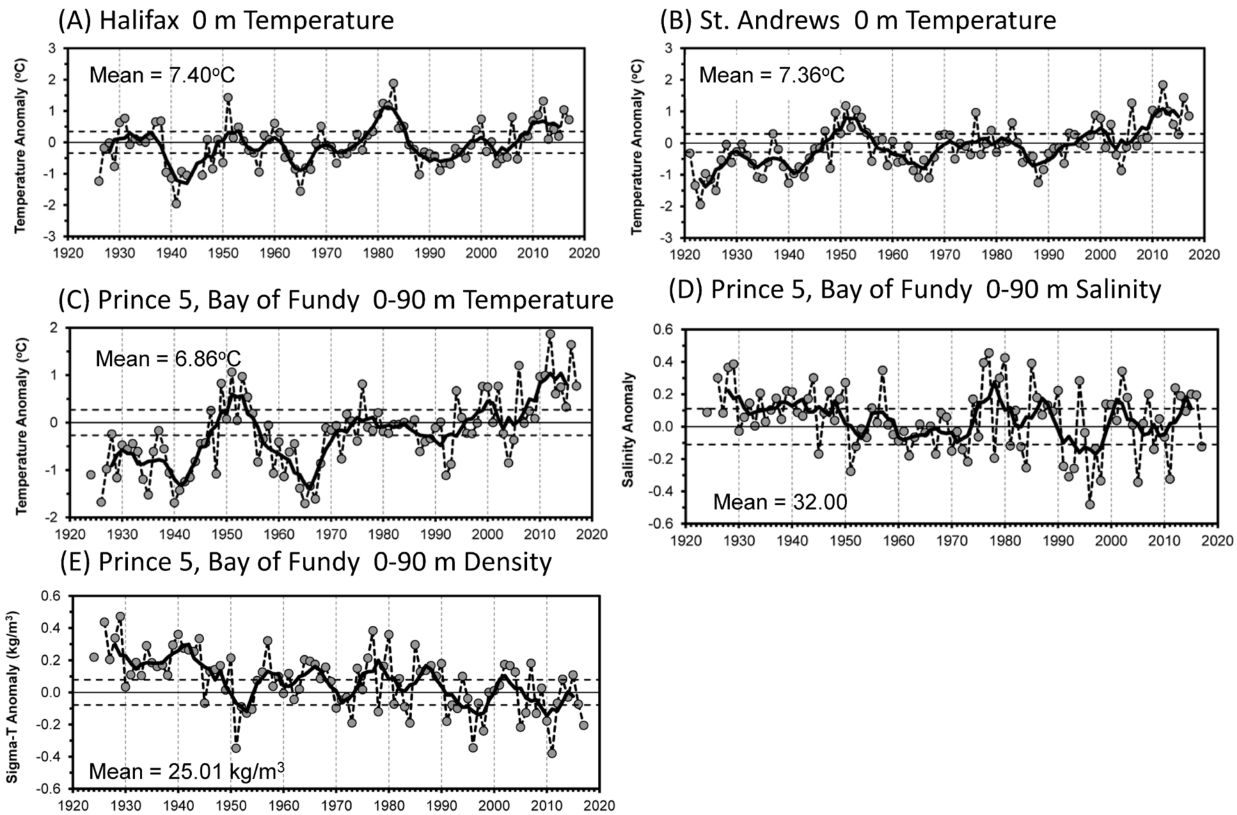

Figure 17. The annual surface temperature anomalies (dotted line with circles) and their five-year running means (heavy black line) for: (A) Halifax Harbour and (B) St. Andrews annual depth-averaged (0–90 m), (C) temperature, (D) salinity, and (E) density anomalies for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Horizontal dashed lines are mean plus and minus 0.5 SD.

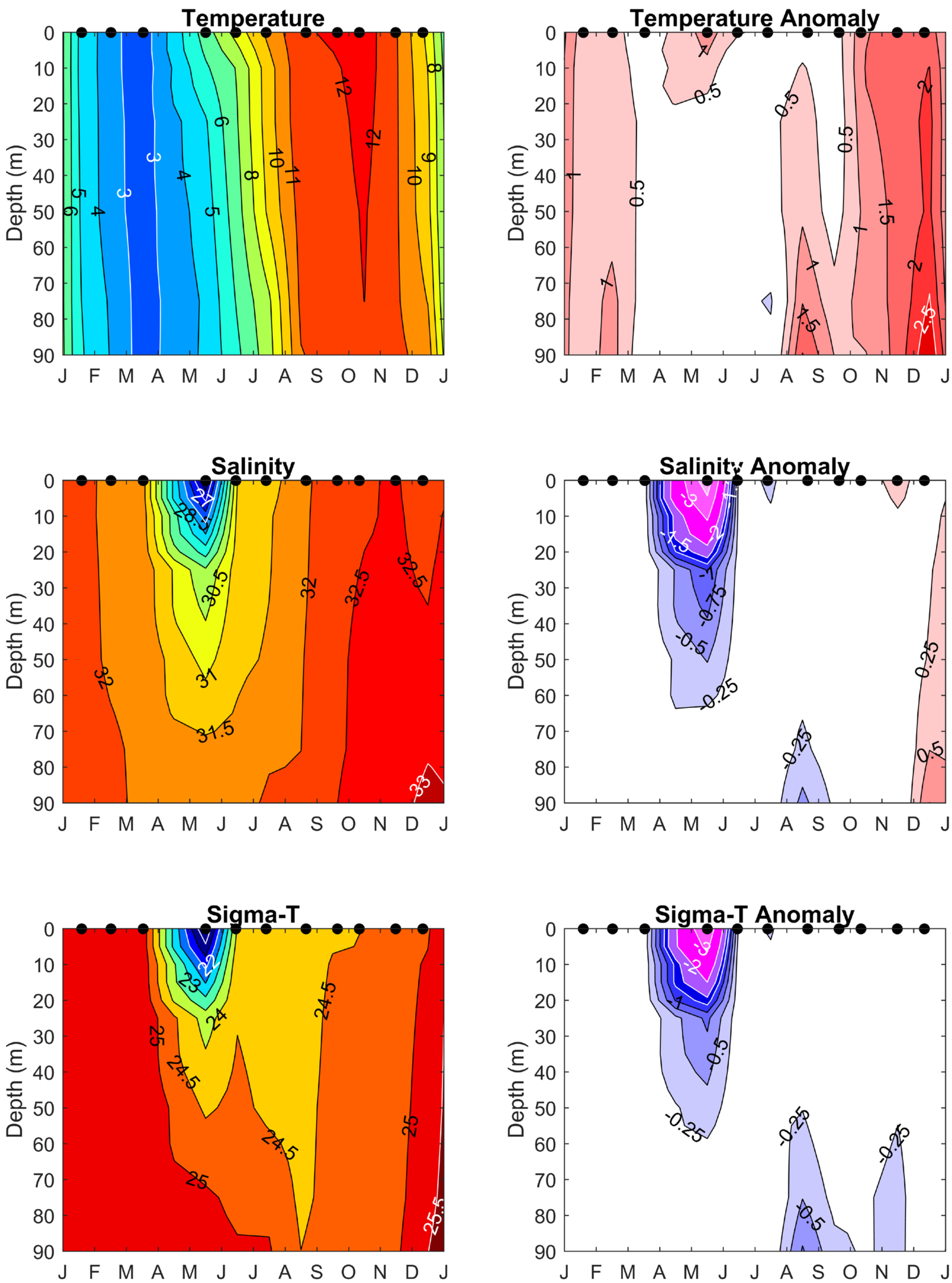

Figure 18. The 2017 annual cycle of temperature (top panel), salinity (middle panel) and density (lower panel) and their anomalies with respect to 1981–2010 monthly means (right panels) for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Bullets indicate periods of sampling.

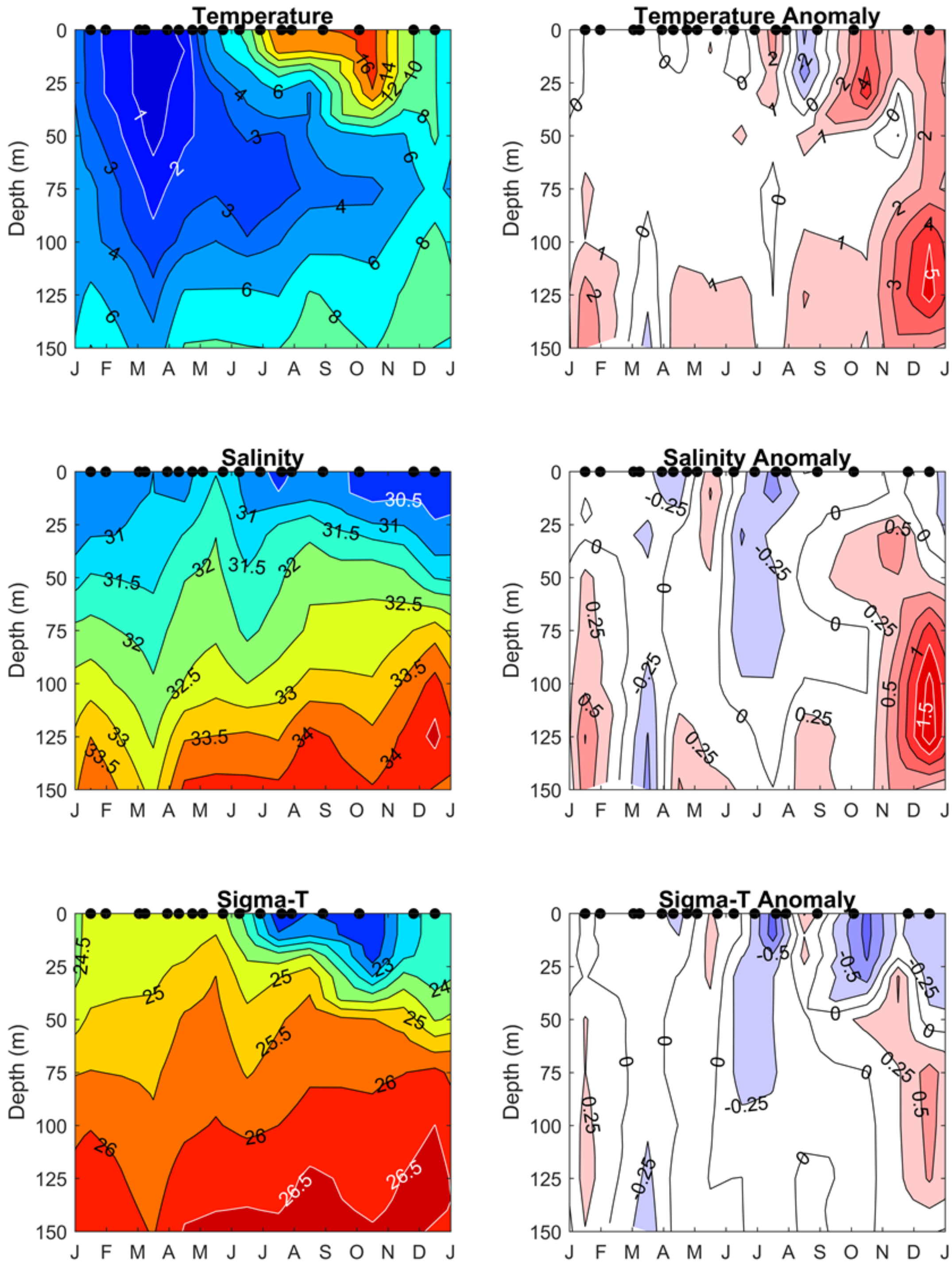

Figure 19. The 2017 annual cycle of temperature (top panel), salinity (middle panel) and density (lower panel) and their anomalies with respect to 1981–2010 monthly means (right panels) for Halifax station 2. Bullets indicate periods of sampling.

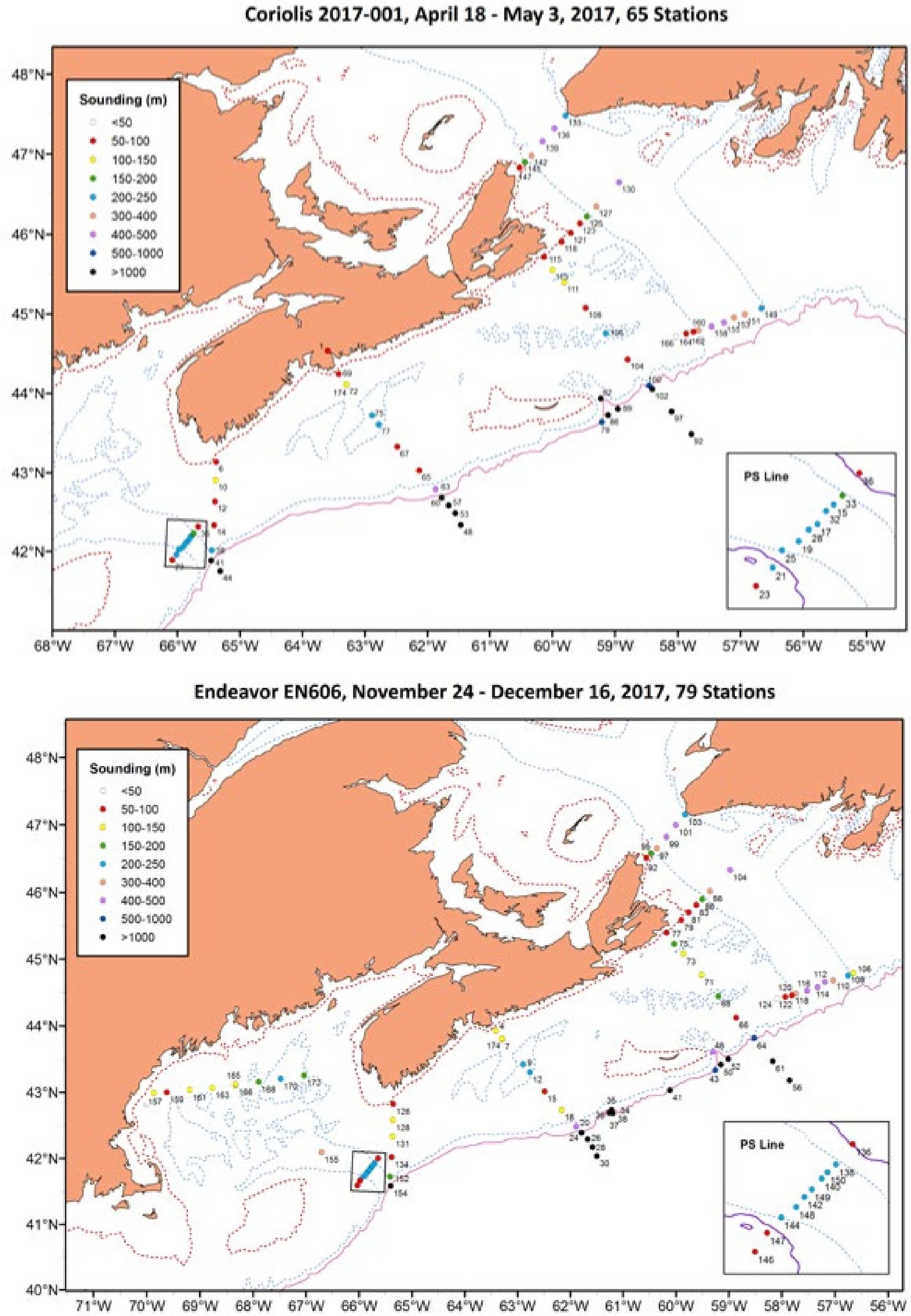

Figure 20. The 2017 sampling of the Scotian Shelf/Gulf of Maine for Spring (top panel) and Fall (bottom panel) surveys.

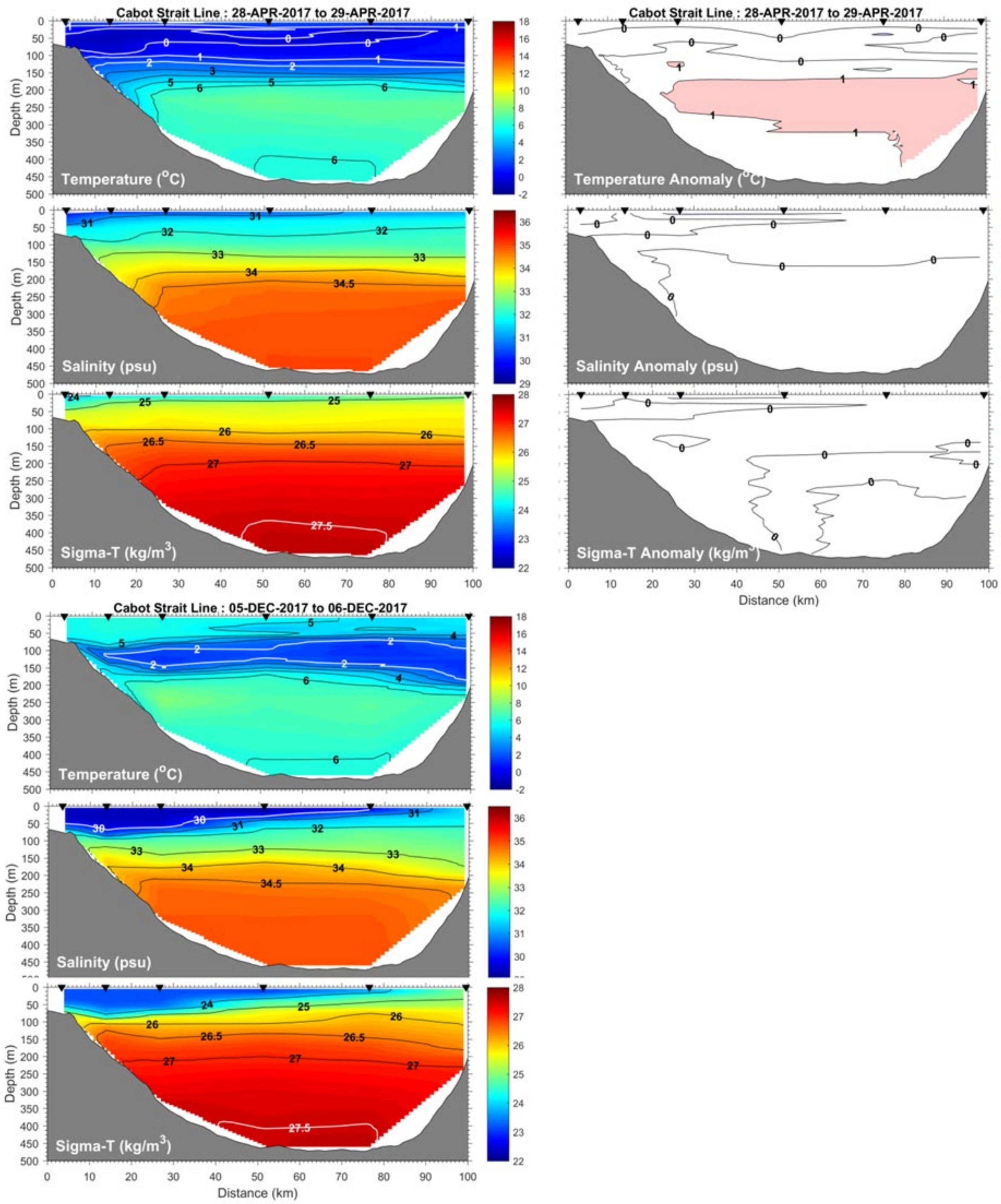

Figure 21. The 2017 sampling of the Cabot Strait Line for Spring (top three panels) and Fall (bottom three panels). Temperature (top panel in each group), salinity (middle panel in each group) and density (lower panel in each group) and their anomalies with respect to 1981–2010 monthly means (right panels). Since the Fall survey was much later than normal, it was not possible to determine the anomalies. Bullets indicate periods of sampling.

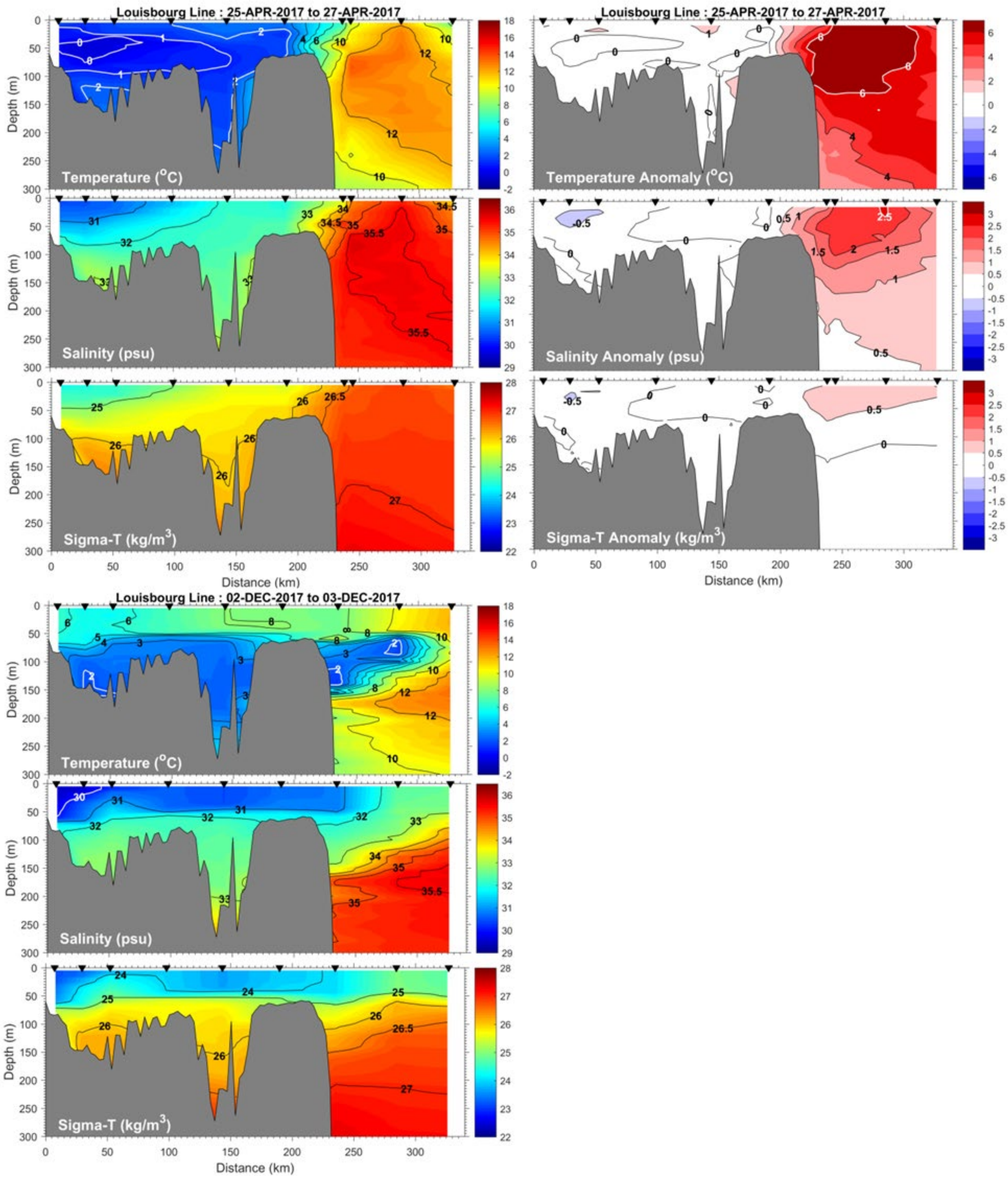

Figure 22. The 2017 sampling of the Louisbourg Line for Spring (top three panels) and Fall (bottom three panels). Temperature (top panel in each group), salinity (middle panel in each group) and density (lower panel in each group) and their anomalies with respect to 1981–2010 monthly means (right panels). Since the Fall survey was much later than normal, it was not possible to determine the anomalies. Bullets indicate periods of sampling.

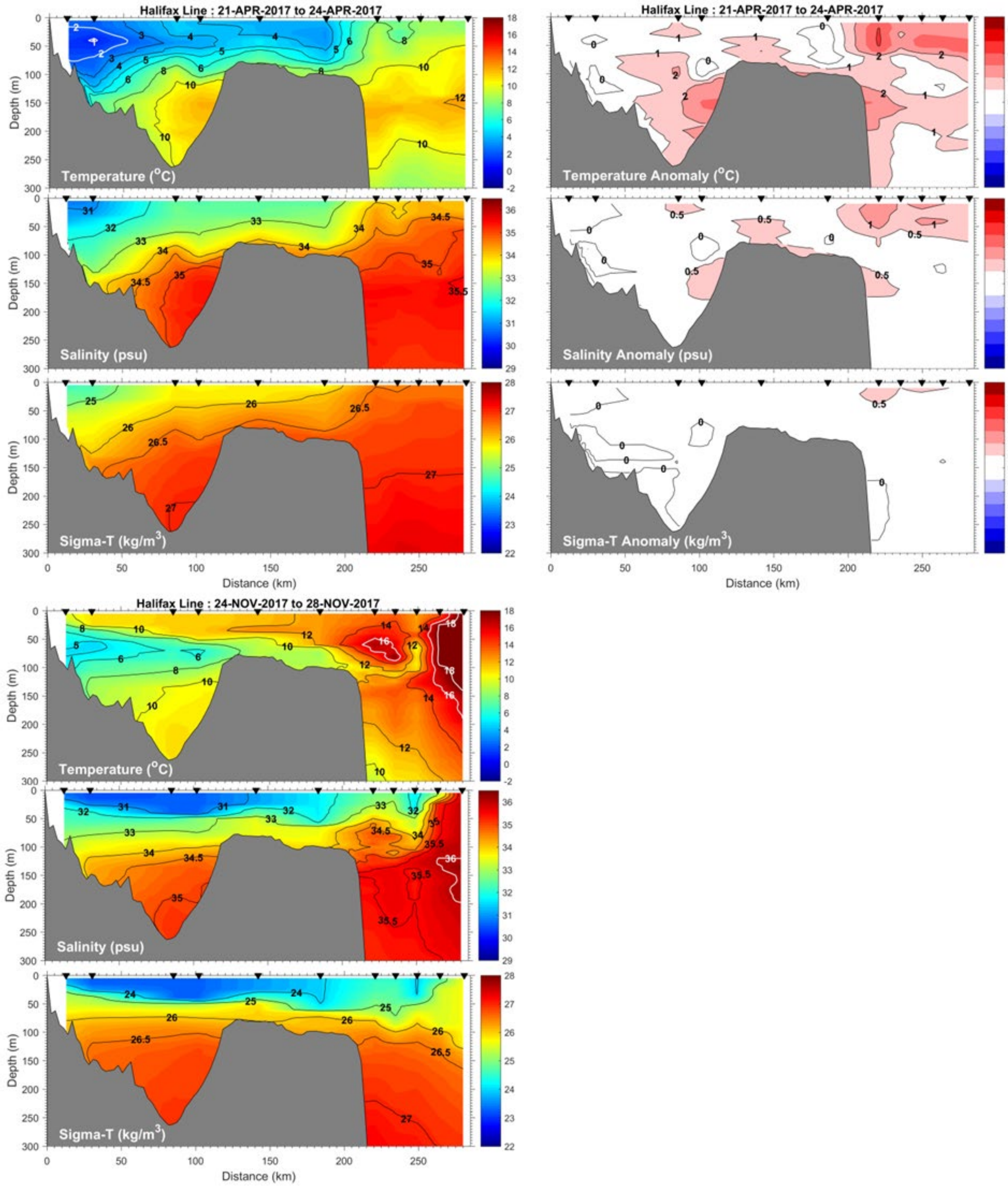

Figure 23. The 2017 sampling of the Halifax Line for Spring (top three panels) and Fall (bottom three panels). Temperature (top panel in each group), salinity (middle panel in each group) and density (lower panel in each group) and their anomalies with respect to 1981–2010 monthly means (right panels). Since the Fall survey was much later than normal, it was not possible to determine the anomalies. Bullets indicate periods of sampling.

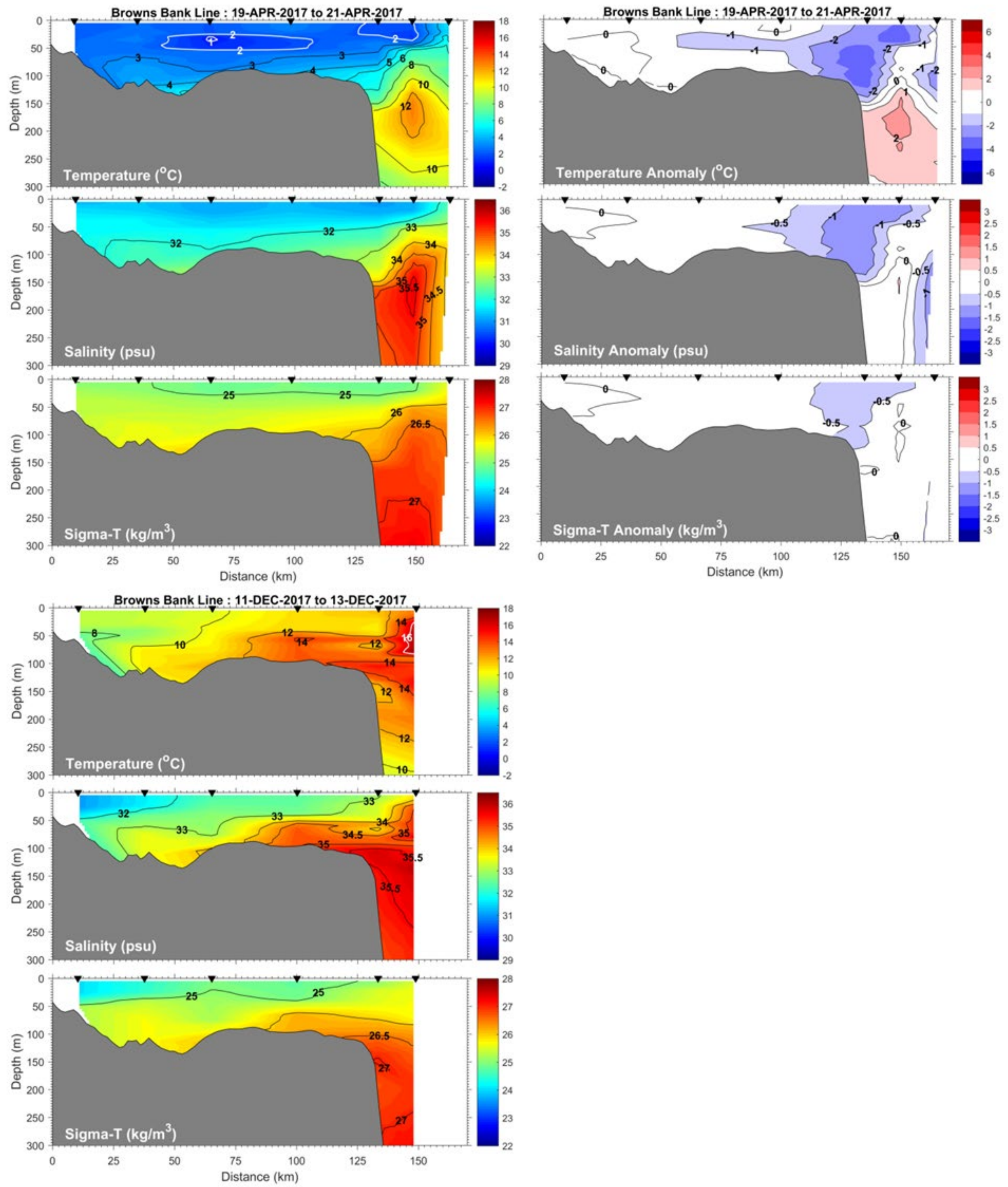

Figure 24. The 2017 sampling of the Browns Bank Line for Spring (top three panels) and Fall (bottom three panels). Temperature (top panel in each group), salinity (middle panel in each group) and density (lower panel in each group) and their anomalies with respect to 1981–2010 monthly means (right panels). Since the Fall survey was much later than normal, it was not possible to determine the anomalies. Bullets indicate periods of sampling.

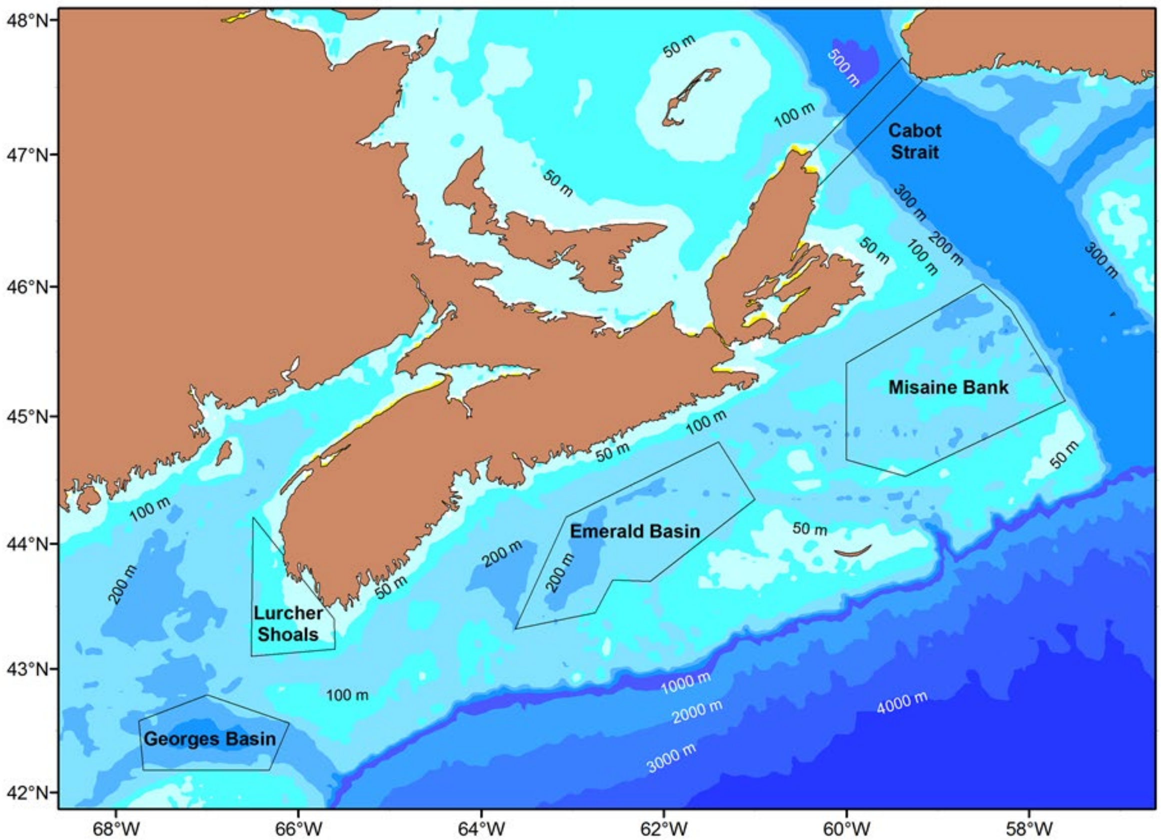

Figure 25. Areas on the Scotian Shelf and eastern Gulf of Maine depicting the different water masses: Cabot Strait; Misaine Bank; Emerald Basin; Lurcher Shoals; and Georges Basin.

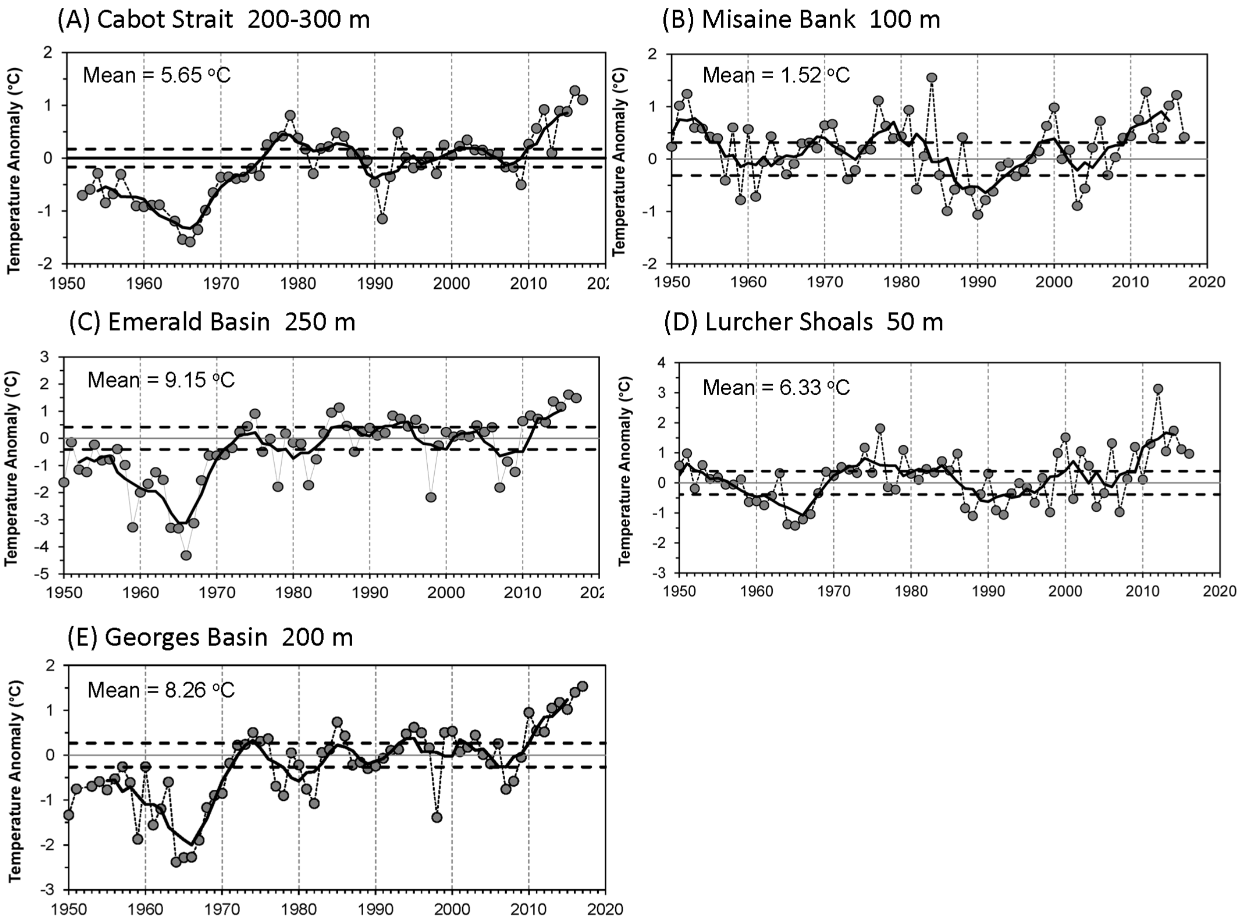

Figure 26. The annual mean temperature anomaly time series (dotted line with circles) and the five-year running mean filtered anomalies (heavy solid line) on the Scotian Shelf and in the Gulf of Maine at: (A) Cabot Strait at 200–300 m, (B) Misaine Bank at 100 m, (C) Emerald Basin at 250 m, (D) Lurcher Shoals at 50 m, and Georges Basin at 200 m (see Figure 25 for locations of regions). Horizontal dashed lines are mean plus and minus 0.5 SD.

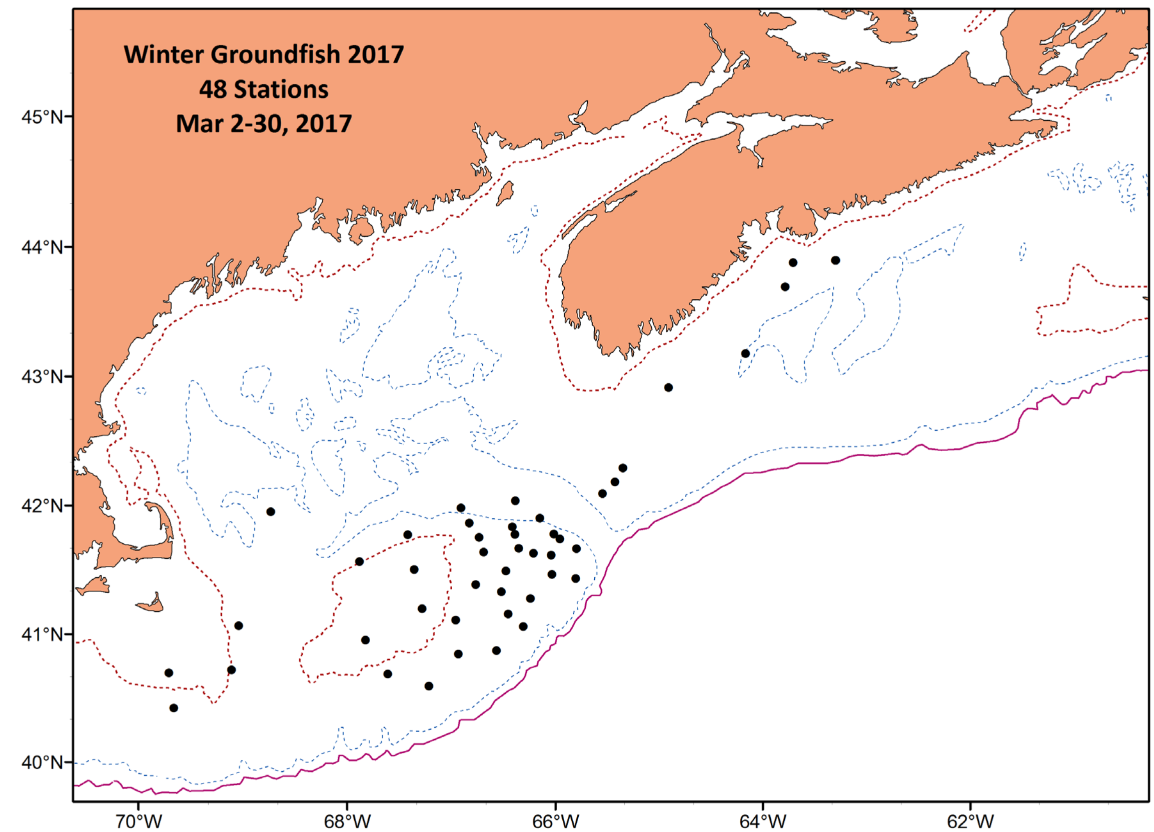

Figure 27. Locations of CTD sampling during the survey.

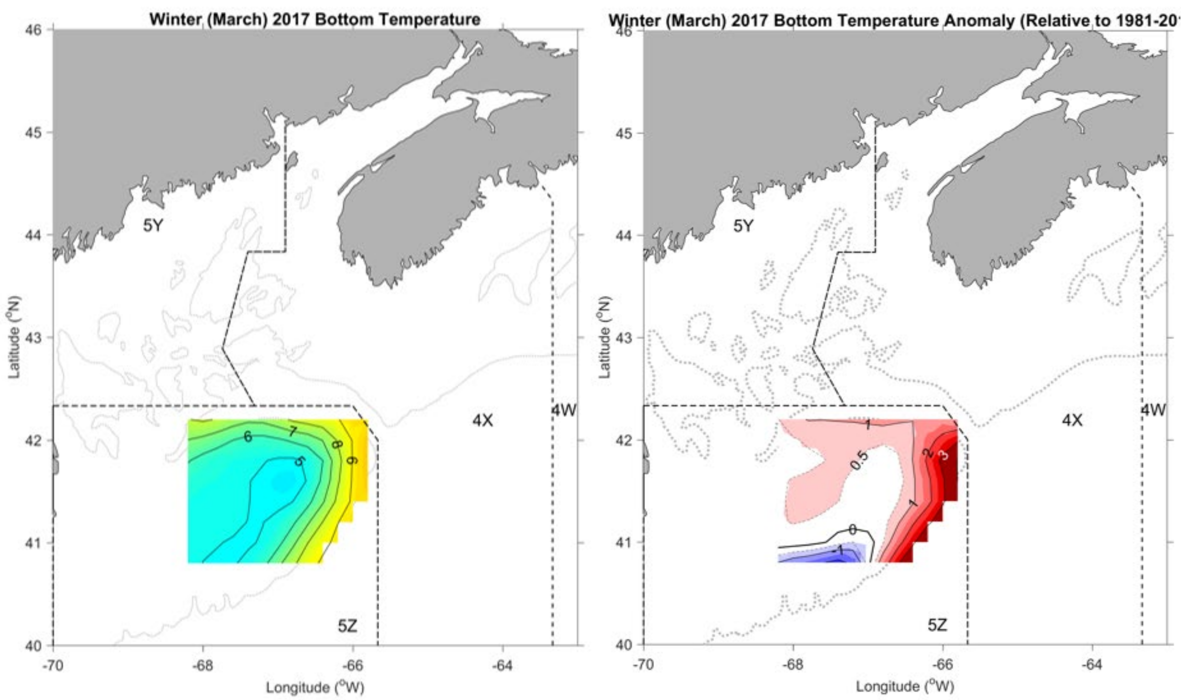

Figure 28. Winter bottom temperature (left panel) and anomaly (right panel; relative to 1981–2010) maps for 2017. NAFO Divisions 4W, 4X, 5Y and 5Z are shown.

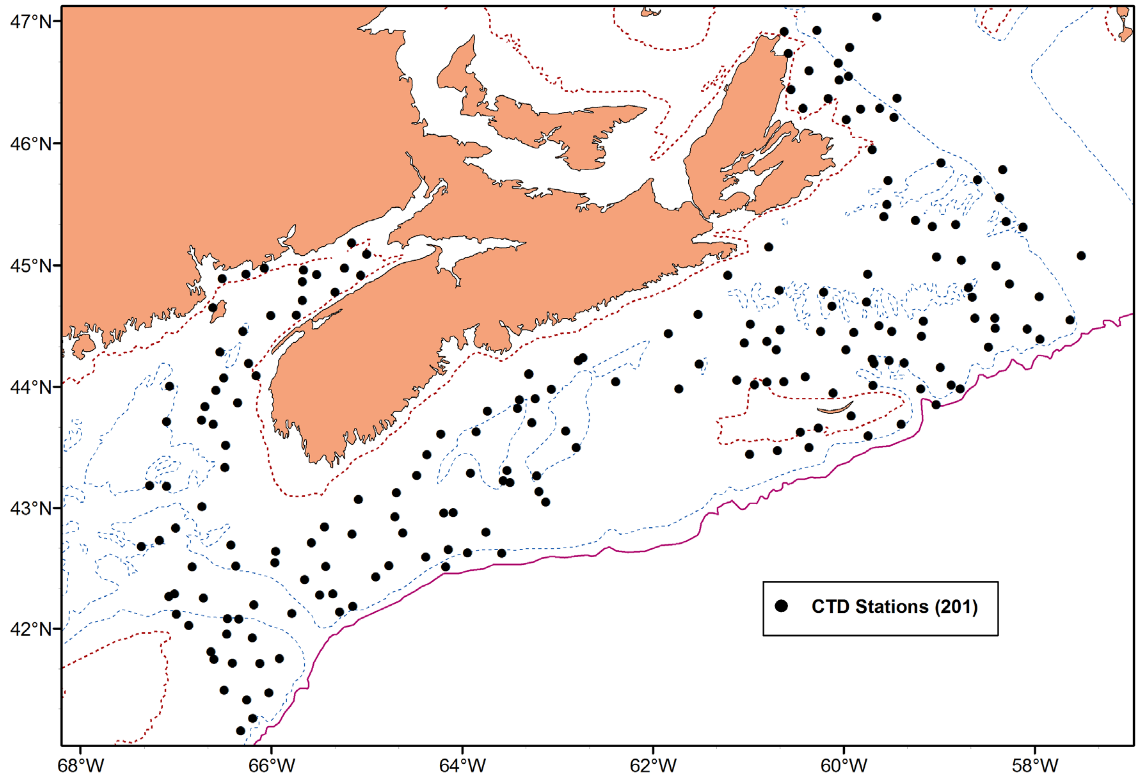

Figure 29. Locations of CTD sampling during the survey.

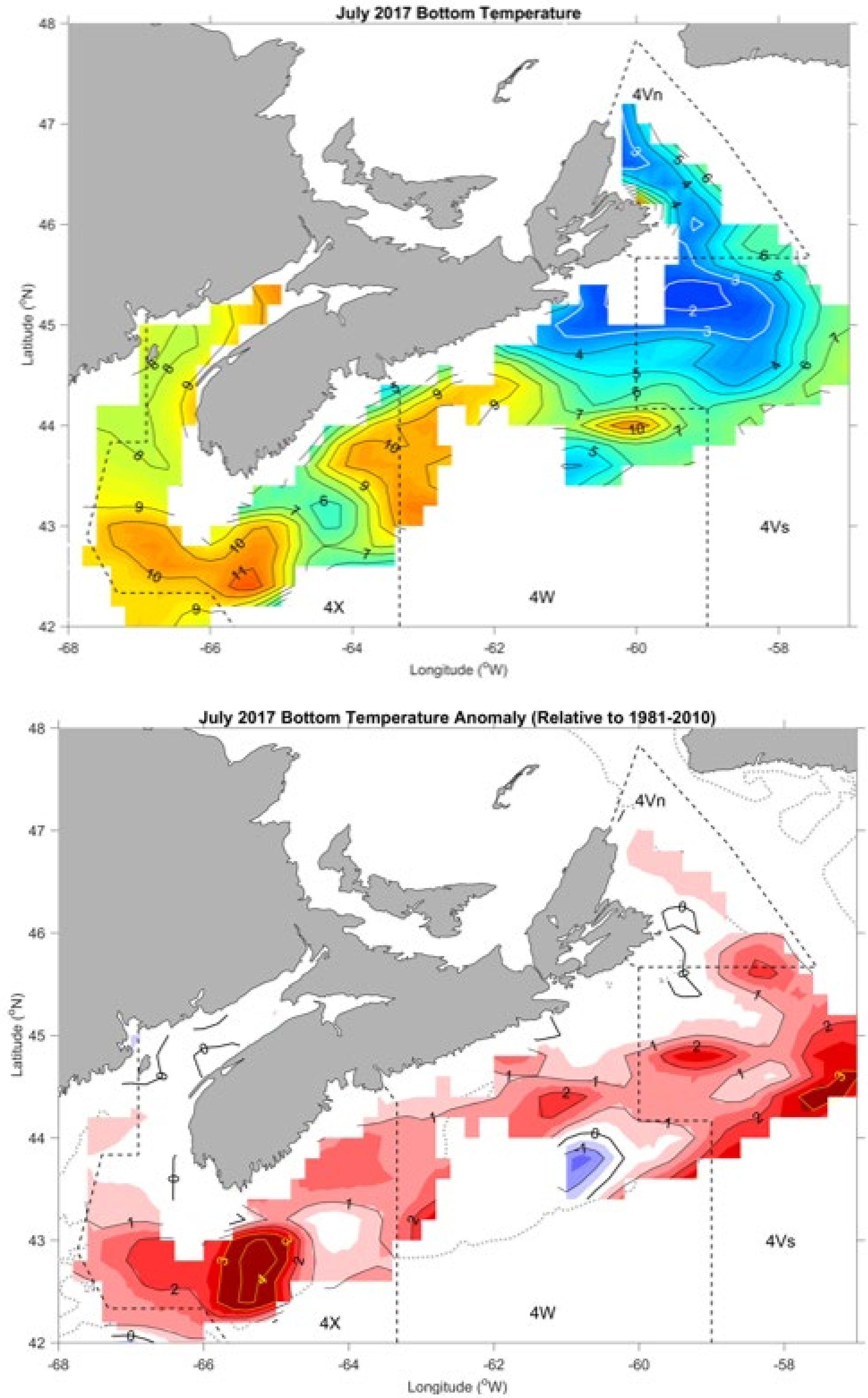

Figure 30. July bottom temperature (upper panel) and anomaly (lower panel; relative to 1981–2010) maps for 2017. NAFO Divisions 4Vn, 4Vs, 4X and 4W are shown.

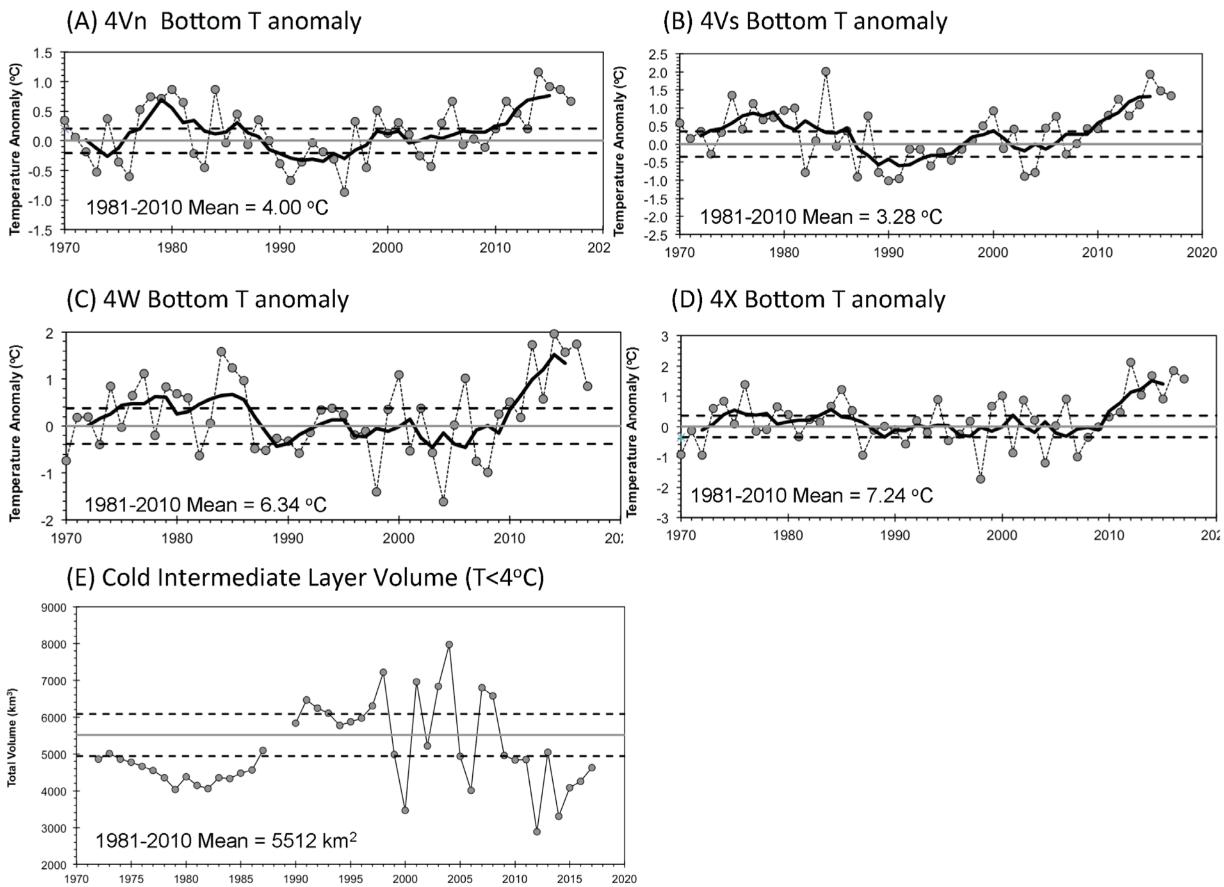

Figure 31. Time series of July bottom temperature anomalies (thin lines with circles) and five-year running mean filtered series (heavy line) for NAFO Divisions: (A) 4Vn, (B) 4Vs, (C) 4W, and (D) 4X. (E) Time series of the Cold Intermediate Layer (CIL; defined as waters with temperature <4°C) volume on the Scotian Shelf based on the DFO RV summer trawl survey. The solid horizontal line is the 1981–2010 mean CIL volume and dashed lines represent ±0.5 SD.

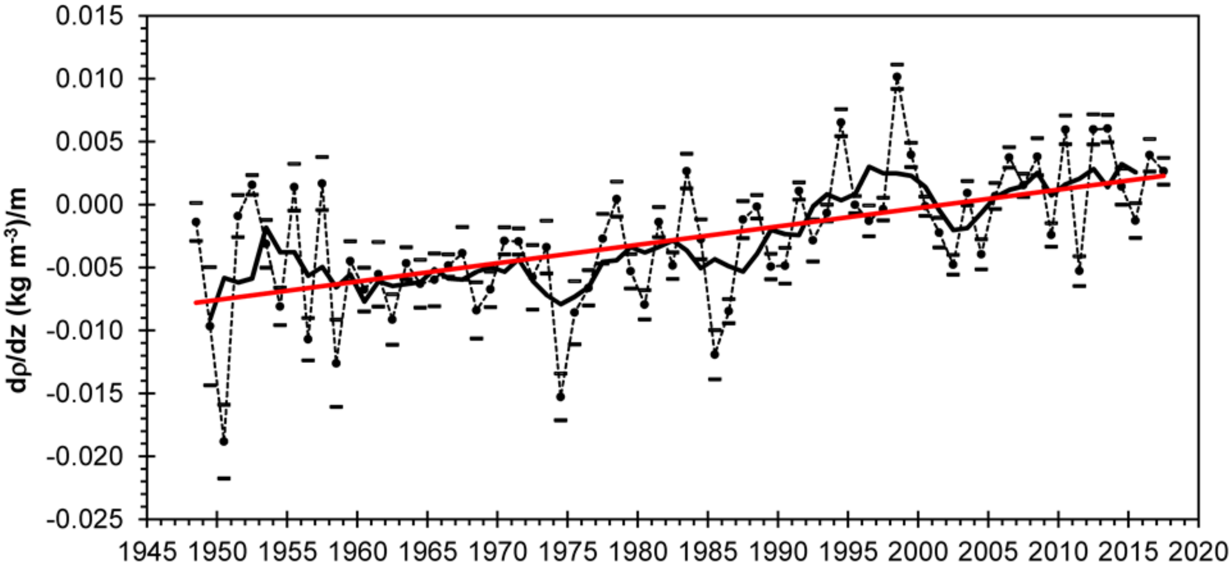

Figure 32. Stratification index (0–50 m density gradient) mean annual anomaly (black dashed line with circles) and five-year running mean (black heavy solid line) averaged over the Scotian Shelf. Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a change in the 0–50 m density difference of 0.36 kg m^{-3} over 50 years.

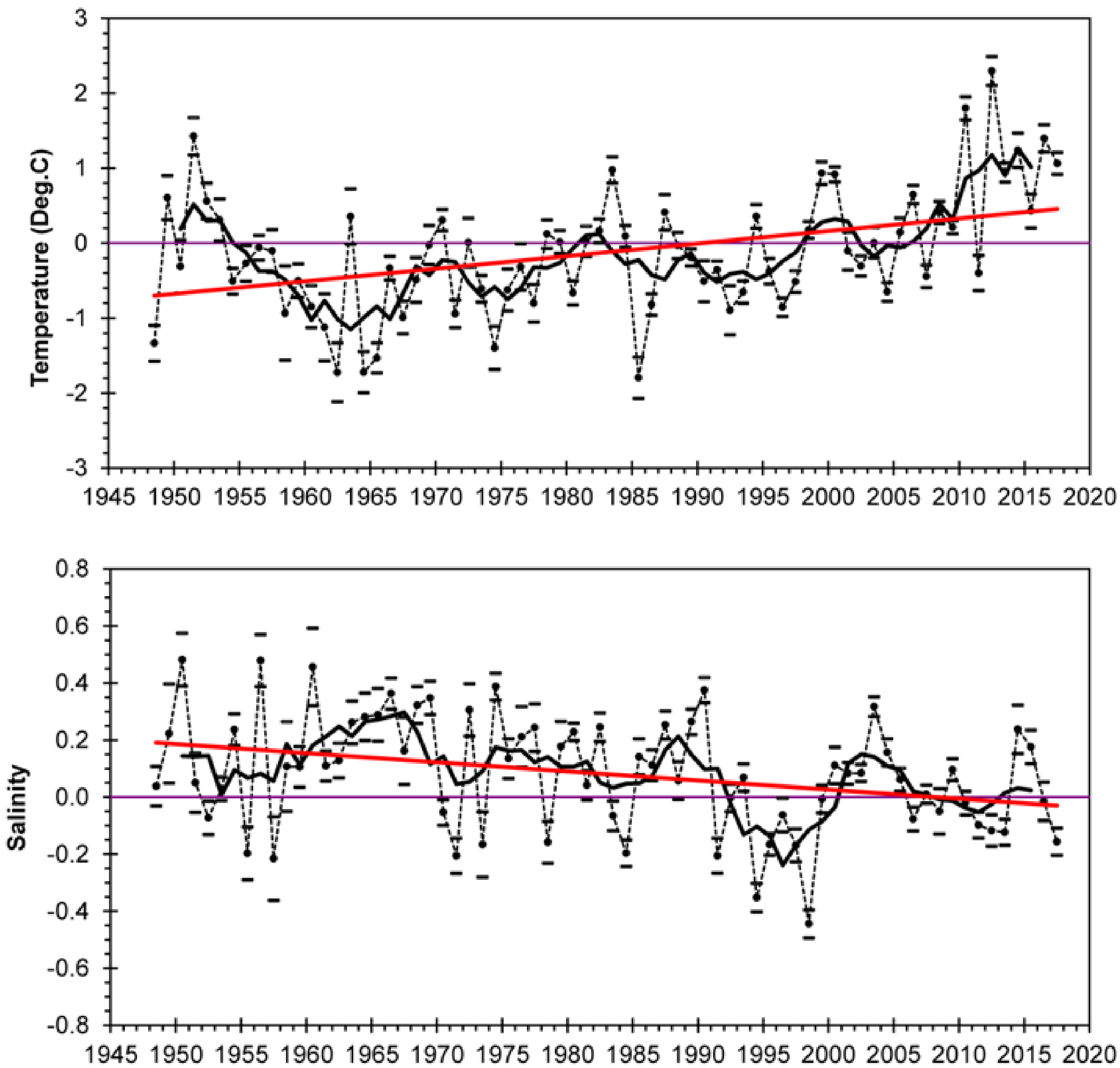

Figure 33. The mean annual surface temperature (top panel) and salinity (lower panel) anomalies (black dashed line with circles) and five-year running mean (black heavy solid line) averaged over the Scotian Shelf. Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a warming of 0.84°C and a freshening of 0.16 over a 50 year period.

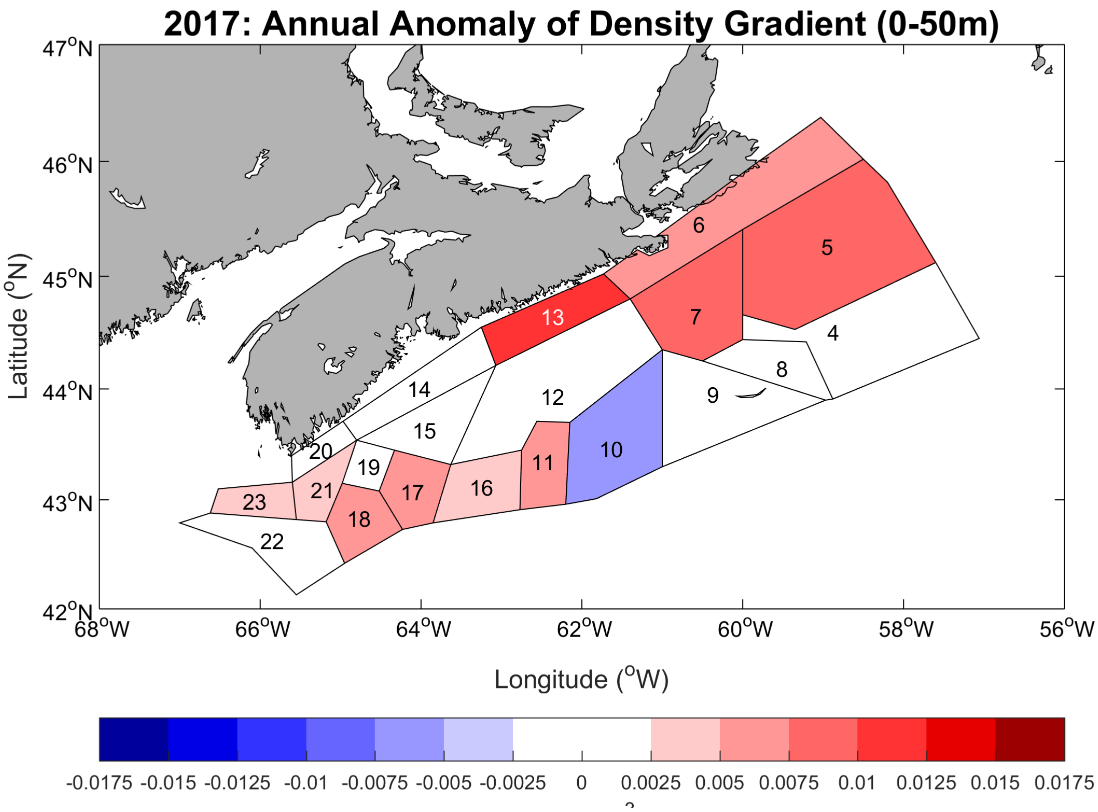

Figure 34. Stratification index (0–50 m density gradient) mean 2017 annual anomaly over the Scotian Shelf.

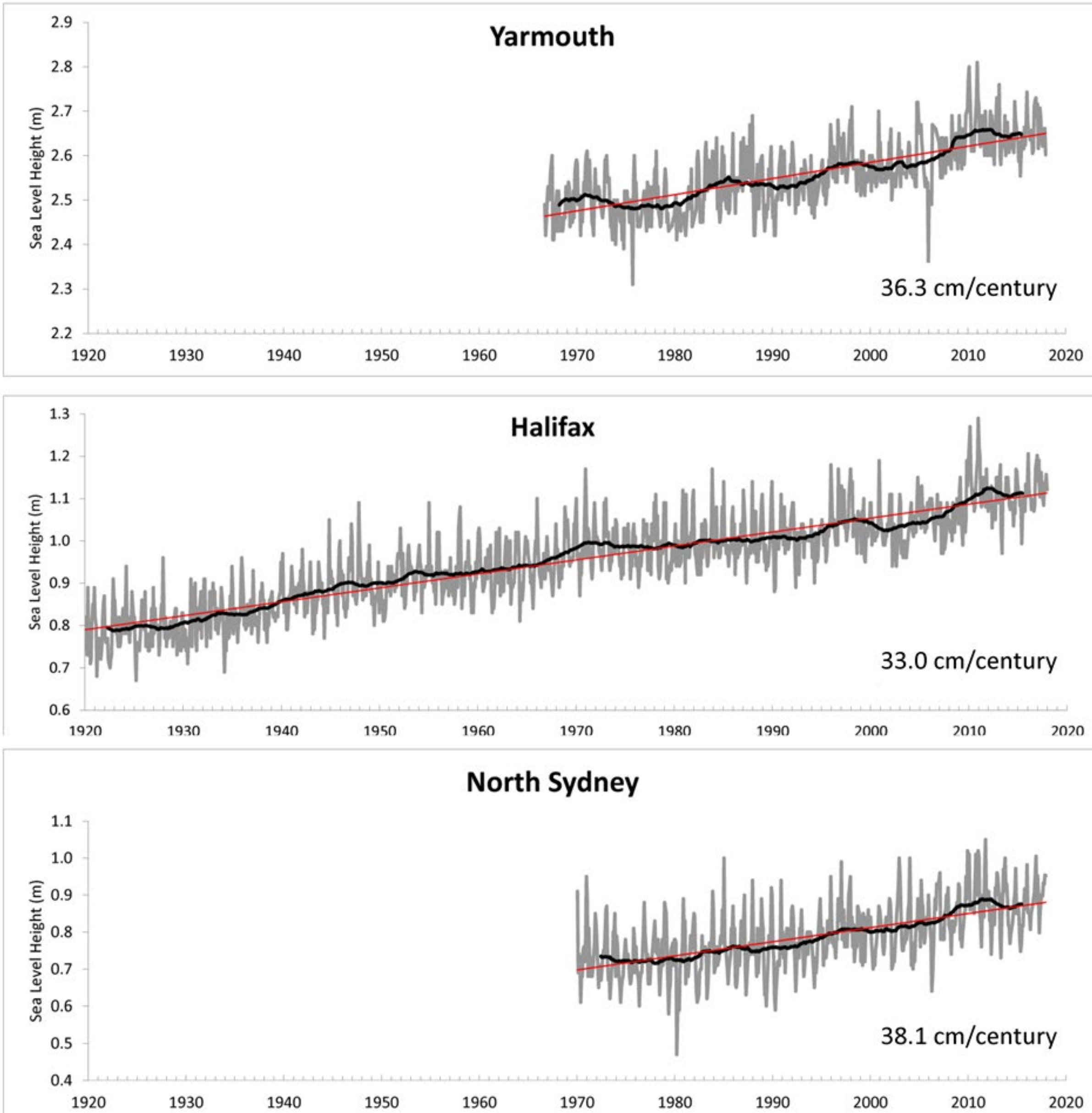

Figure 35. The time series of the monthly means (grey line) and a five-year running mean (black line) of the relative sea level elevations at Yarmouth (top panel), Halifax (middle panel) and North Sydney (bottom panel), along with the linear trend (red line) over the observation period.

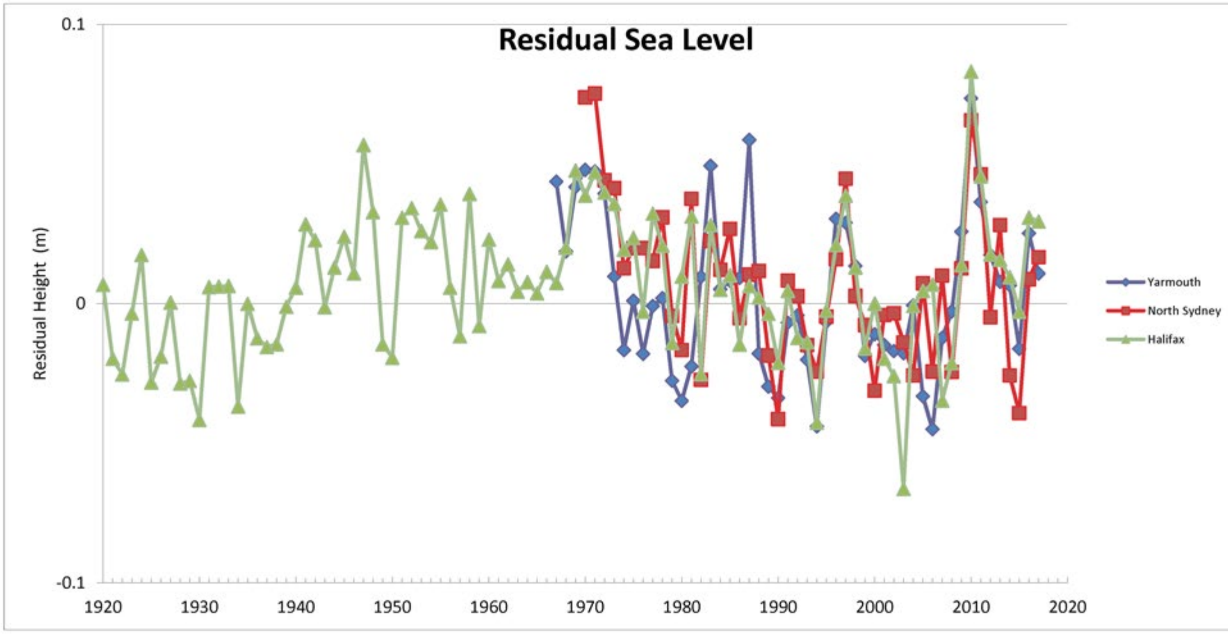

Figure 36. Residual relative sea level (monthly observed values – (1981–2010) linear trend, averaged to annual estimate for Yarmouth (blue line with diamonds), Halifax (green line with triangles) and North Sydney (red line with squares).

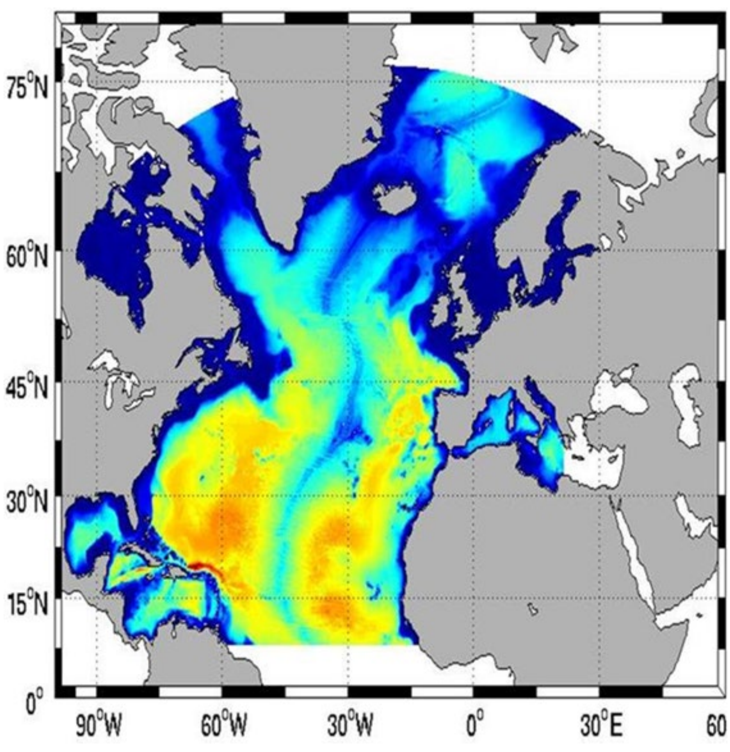

Figure 37. The BIO North Atlantic Model (BNAM) domain Bathymetry coloured from red (deep) to blue (shallow).

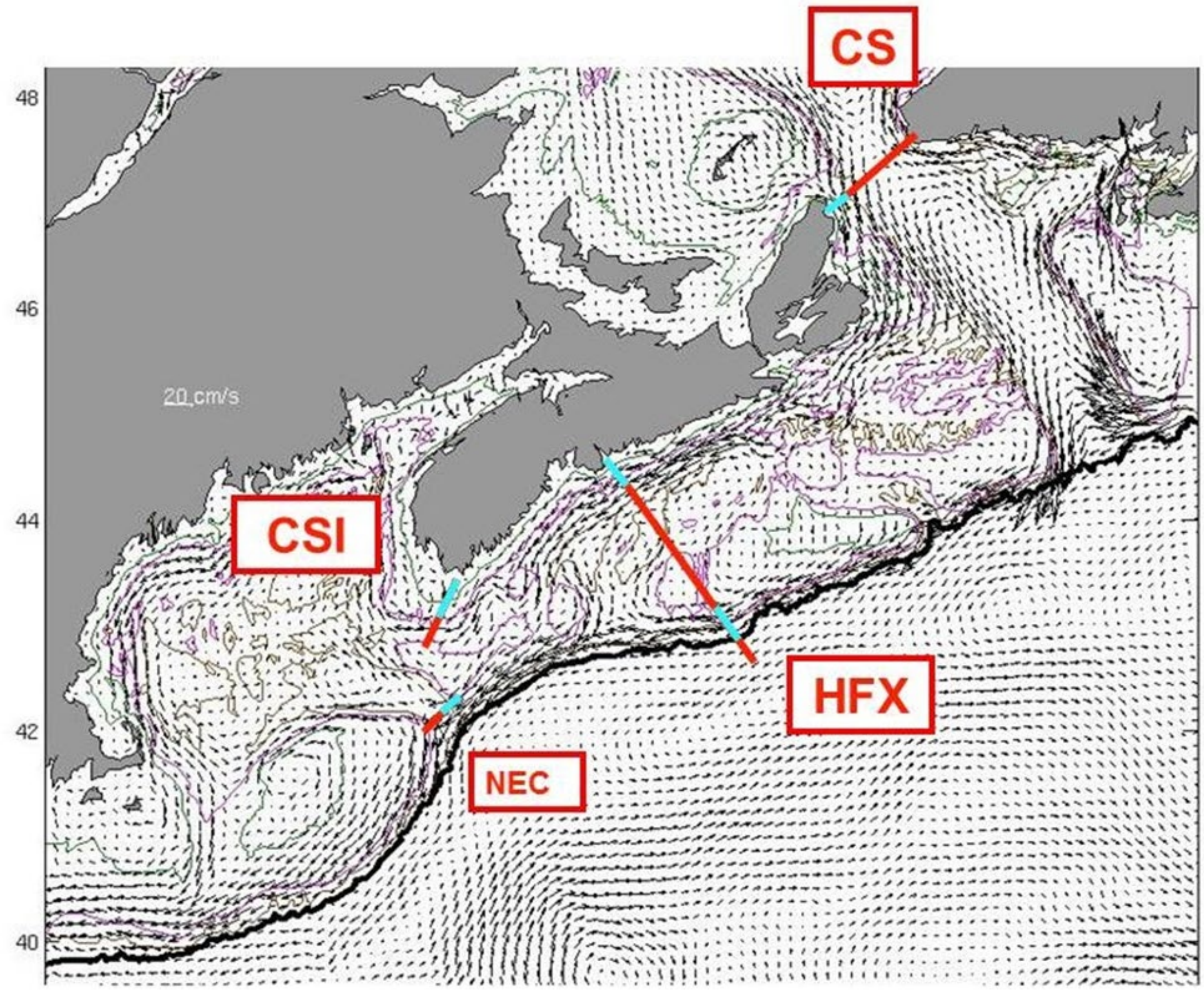

Figure 38. Annual average depth-averaged circulation illustrating the principal flow pathways from the southern Gulf of St. Lawrence to the Gulf of Maine and the subsections where transport calculations were made (cyan). CS = Cabot Strait; HFX = Halifax; CSI = Cape Sable Island/Browns Bank; NEC = Northeast Channel.

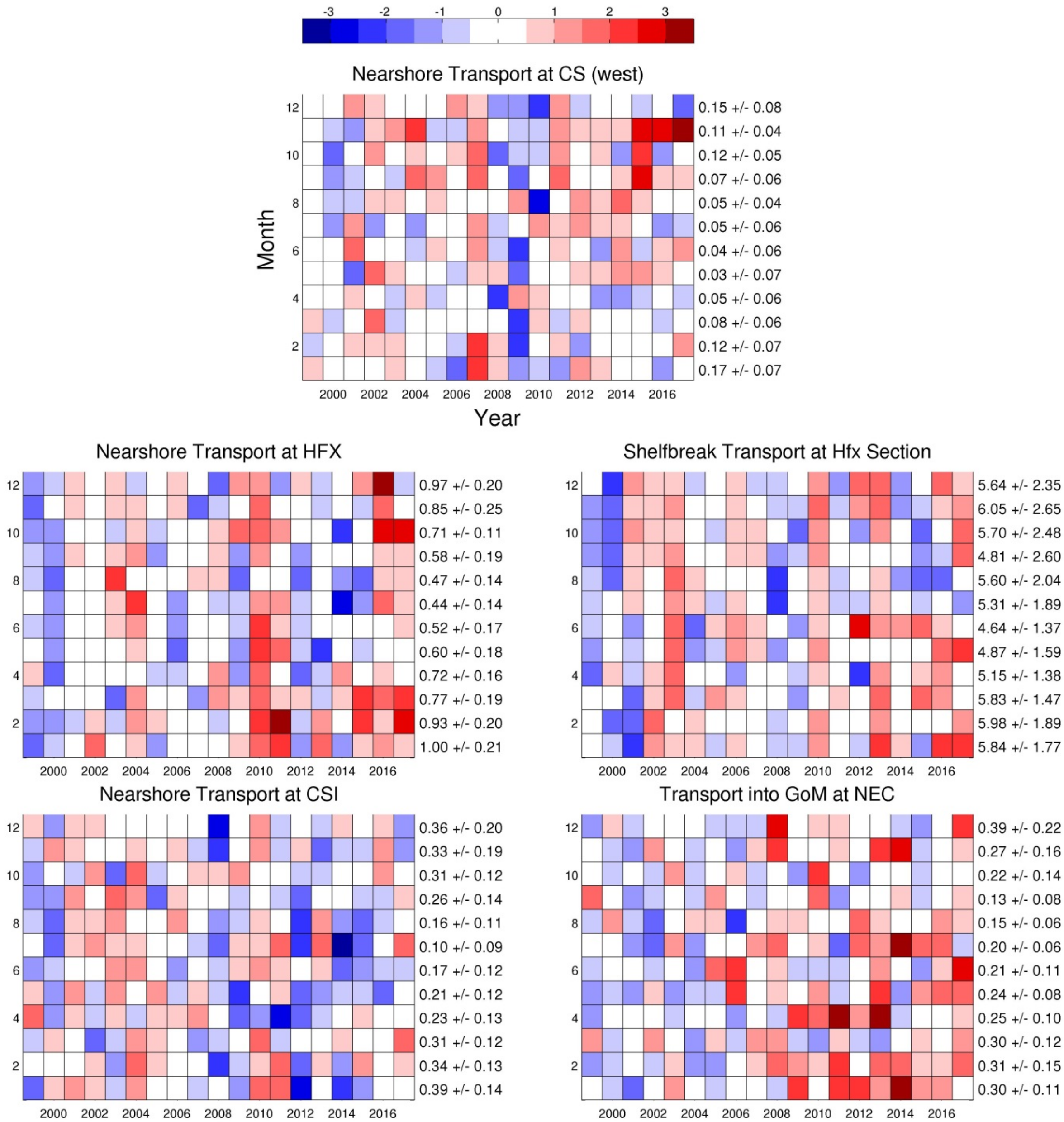

Figure 39. Standardized anomalies of the monthly transport for years 1999–2017 for four Maritime sections: (top) Cabot Strait (CS) west nearshore; (middle) Halifax (HFX) nearshore and shelf break; (bottom) Cape Sable Island (CSI) nearshore and the Northeast Channel (NEC). Numbers to the right are monthly means and standard deviations.

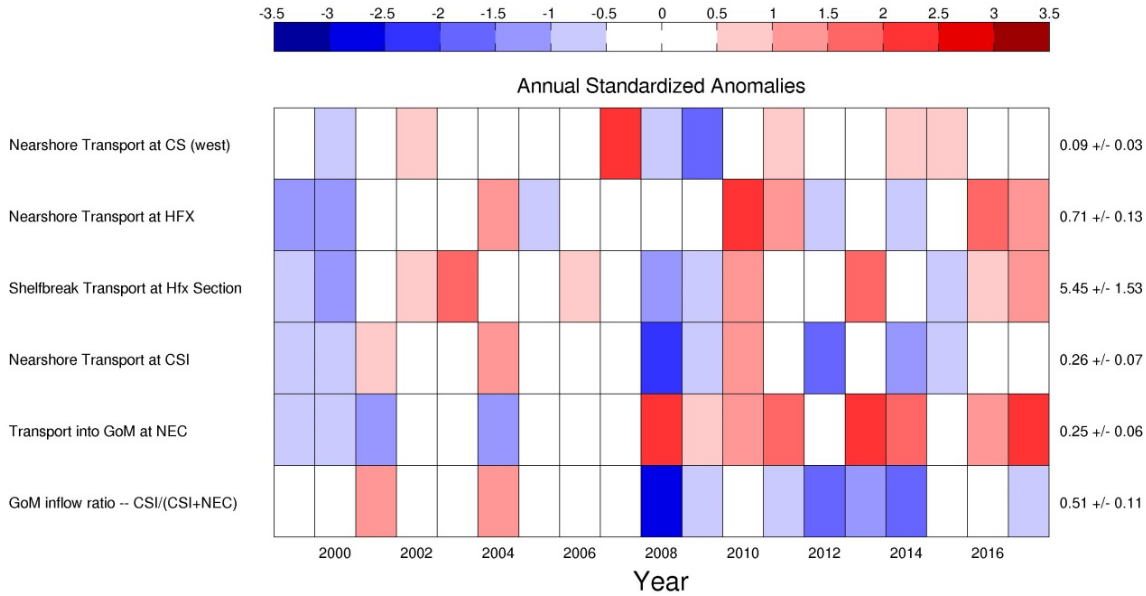

Figure 40. Annual transport anomalies scaled by the standard deviation for the variables in Figures 38 and 41 for years 1999–2017 (top panel). Numbers to the right are annual means and standard deviations. Note: the inflow at the Northeast Channel (NEC) was omitted, as it is not independent. CS = Cabot Strait; HFX = Halifax; CSI = Cape Sable Island; NEC = Northeast Channel.

Transport (SV)											
Month / Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Grand Total
12	-0.46	-0.59	-0.58	-0.33	-0.50	-0.83	-0.42	-0.53	-0.82		-0.56
11	-0.22	-0.34	-0.52	-0.49	-0.43	-0.30	-0.50	-0.38	-0.57	-0.20	-0.39
10	-0.22	-0.51	-0.36	-0.30	-0.32	-0.22	-0.21	-0.17	-0.40	-0.33	-0.30
9	-0.43	-0.21	-0.30	-0.12	-0.14	-0.03	-0.17	-0.13	-0.20	-0.28	-0.20
8	-0.40	-0.26	-0.32	-0.23	-0.13	-0.08	-0.12	-0.18	-0.27	-0.05	-0.20
7	-0.04	-0.29	-0.39	-0.37	-0.11	-0.15	-0.07	-0.22	-0.31	-0.23	-0.22
6		-0.31	-0.54	-0.40	-0.09	-0.16	-0.28	-0.35	0.05	-0.28	-0.26
5		-0.33	-0.52	-0.43	-0.22	-0.12	-0.26	0.04	-0.23	-0.35	-0.27
4		-0.34	-0.33	-0.48	-0.23	-0.37	-0.39	-0.32	-0.31	-0.33	-0.34
3		-0.48	-0.47	-0.55	-0.64		-0.53	-0.63	-0.40	-0.79	-0.56
2		-0.66	-0.68	-0.85	-0.59	-0.64	-0.44	-0.62	-0.46	-0.88	-0.65
1		-0.80	-0.65	-0.67	-0.38	-0.60	-0.45	-0.74	-0.60	-0.71	-0.62
Grand Total	-0.30	-0.43	-0.47	-0.43	-0.32	-0.32	-0.32	-0.35	-0.38	-0.40	-0.38

Figure 41. Monthly transport (1 Sv = 10^6 m^3 s^{-1}) for years 2008–2017 for the Nova Scotia Current south of Halifax from ADCP measurements. Negative transports are to the southwest. The monthly transports are colour-coded for whether they are above, less southwestward (blue), or below, stronger southwestward (red), than the monthly average by observed for the observation period (numbers to the right) by more than one-half standard deviation.

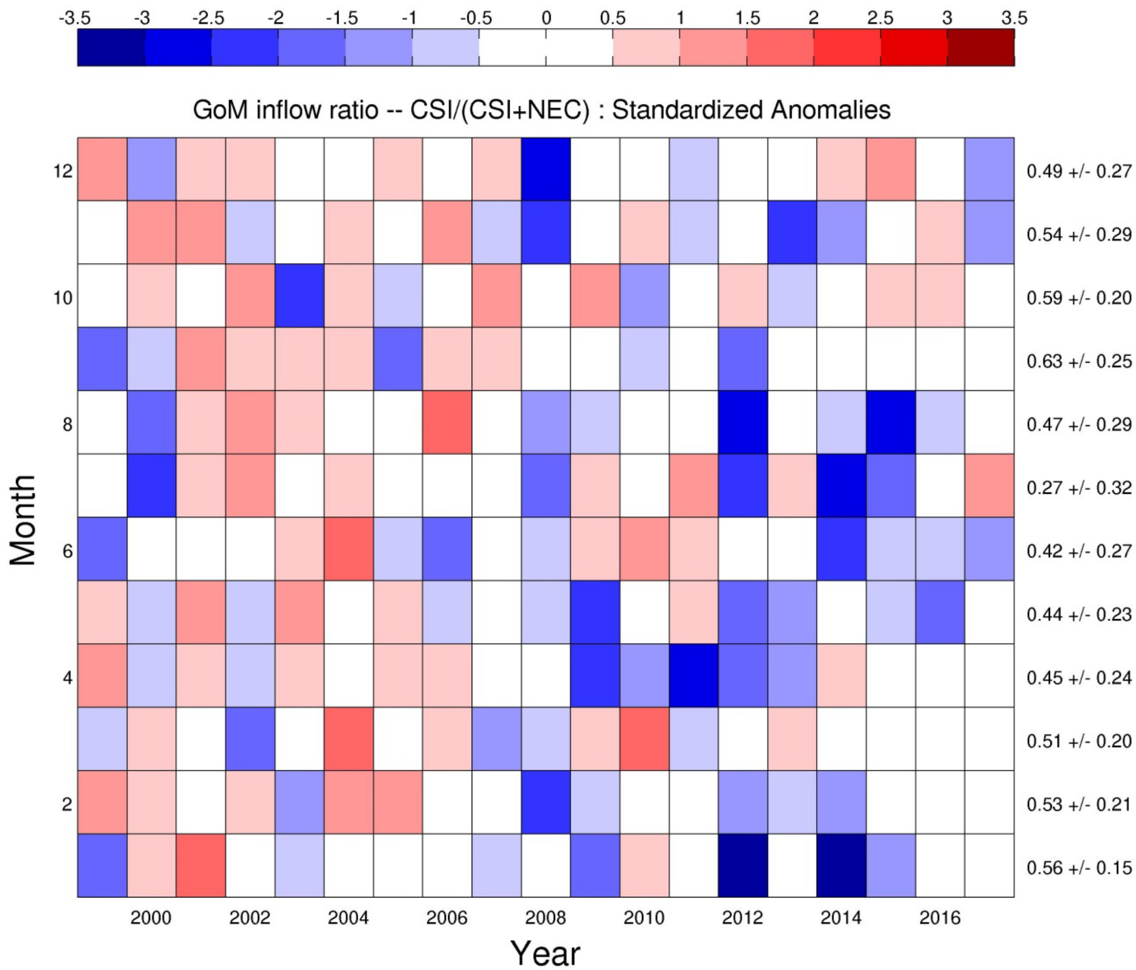

Figure 42. Standardized anomalies of the Gulf of Maine (GoM) inflow ratio for years 1999–2017. Numbers to the right are monthly means and standard deviations. CSI = Cape Sable Island; NEC = Northeast Channel.

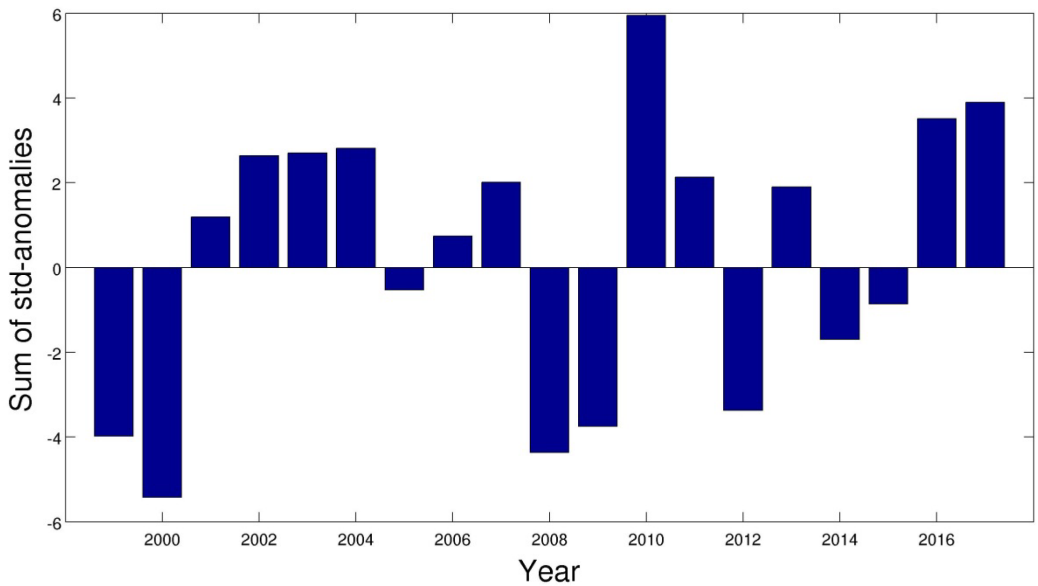

Figure 43. Sum of standardized anomalies for 1999–2017, for the variables in Figures 38 and 39.

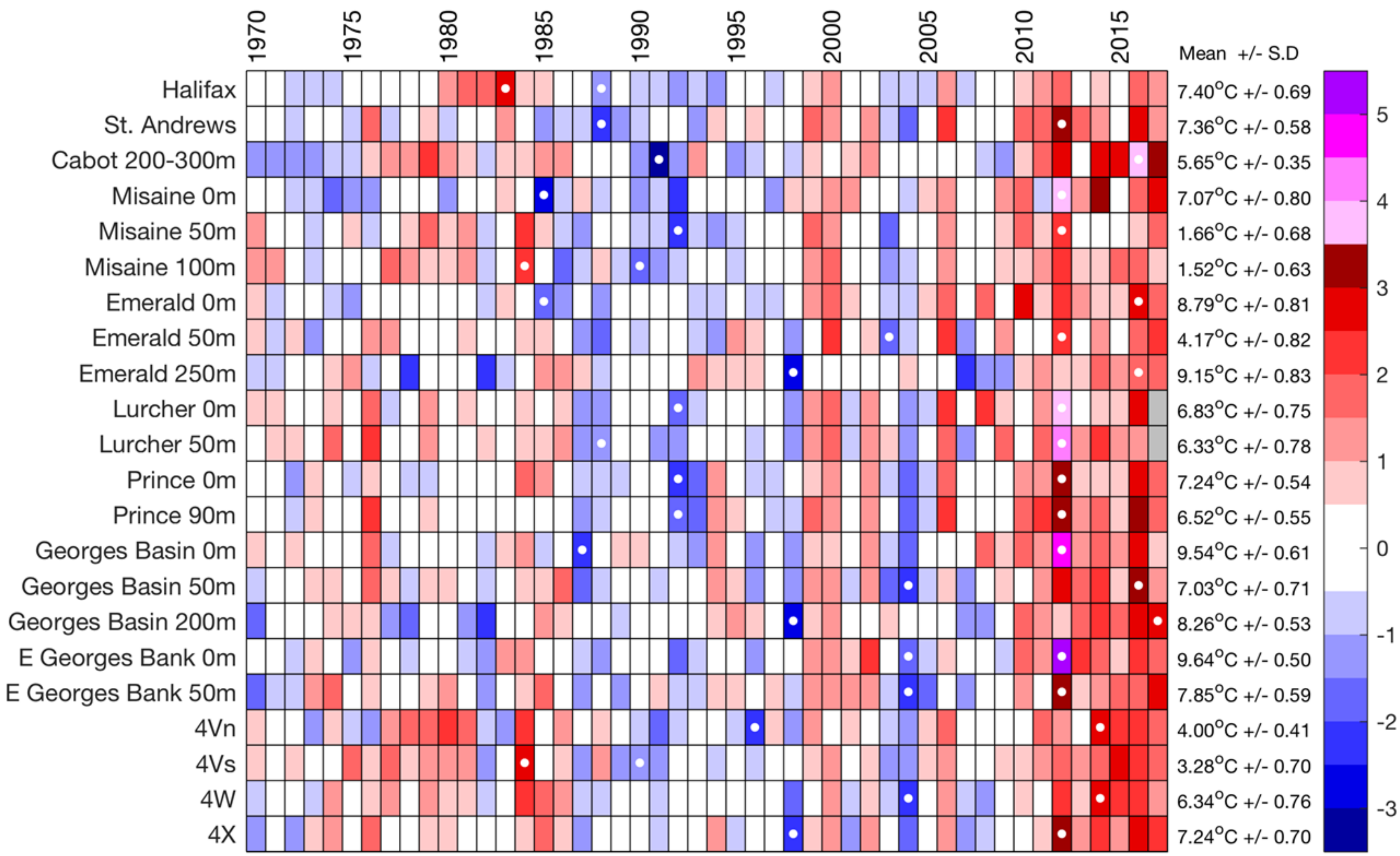

Figure 44. Normalized annual anomalies of temperatures at the bottom and discrete depths for the Scotian Shelf-Gulf of Maine region. These anomalies are based on the 1981–2010 means divided by the standard deviation. Blue colours indicate below normal anomalies, red and purple (for 2012, the colour scale had to be increased above +3.5°SD and is shaded in purple) colours above normal anomalies. White dots represent record minimum and maximum years for each parameter. Gray represents lack of data.