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Meteorological, Sea Ice and Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2015

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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 2015, the North Atlantic Oscillation index was above the 1981-2010 mean (+17.8 mb, +2.0 SD [standard deviation]) and was the largest value in the 121 year record. Mean annual air temperature anomalies were negative at all sites except Sable Island at +0.5^{o}C (+0.7 SD) and slightly positive at Yarmouth, with values ranging elsewhere from slightly negative at Boston to -0.5^{o}C (-0.7 SD) at Halifax. Positive satellite-based sea surface temperature (SST) annual anomalies prevailed throughout the region except at Cabot Strait at -0.1^{o}C (-0.1 SD), with values ranging from +0.4 to +1.1^{o}C (+0.4 to +1.0 SD) above the 1981-2010 mean values. Sea ice coverage on the Scotian Shelf in 2015 was above the 1981-2010 average unlike 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 +0.3^{o}C (+0.3 SD) and +0.0^{o}C (+0.0 SD), respectively, in 2015. At selected sites across the region, annual water temperature anomalies were positive in 2015: +0.9^{o}C (+2.6 SD) for Cabot Strait at 200-300 m depth range (the third largest anomaly; 2012 was the largest); +0.9^{o}C (+1.4 SD) for Misaine Bank at 100 m; +1.2^{o}C (+1.3 SD) for Emerald Basin at 250 m; +1.1^{o}C (+1.4 SD) for Lurcher Shoals at 50 m; and +1.0^{o}C (+1.2 SD) for Georges Basin at 200 m (the warmest year was 2013). Bottom temperature anomalies in Northwest Atlantic Fisheries Organization (NAFO) Divisions 4VWX were all positive in 2015 ranging from +0.9^{o}C (+1.3 SD) in NAFO Division 4X to +1.9^{o}C (+2.8 SD) in NAFO Division 4Vs. Average stratification on the Scotian Shelf continue to weakened from 2013 and was less than the 1981-2010 mean value. Since 1948, the stratification has slowly been increasing on the Scotian Shelf due mainly to one-third freshening and two-thirds warming of the surface waters. A composite index, consisting of 18 ocean temperature time series from surface to bottom across the region, indicated that 2015 was the fifth warmest of 46 years (2012 was the warmest), with an averaged normalized anomaly of +1.2 SD relative to the 1981-2010 period.

Conditions météorologiques, océanographiques physiques et de la glace de mer sur le plateau néo-écossais et dans le golfe du Maine en 2015

RÉSUMÉ

En 2015, l'indice d'oscillation nord-atlantique se situait au-dessus de la moyenne de 1981 à 2010 (+ 17,8 mb, + 2,0 ÉT [écart type]), la valeur la plus élevée de la série longue de 121 ans. Les anomalies moyennes annuelles de la température de l'air étaient négatives à toutes les stations, à l'exception d'Île de Sable avec + 0,5 °C (+ 0,7 ÉT) et Yarmouth où elle était légèrement positive. Les valeurs variaient ailleurs entre légèrement négatives à Boston jusqu'à - 0,5 °C (- 0,7 ÉT) à Halifax. Les anomalies annuelles de température de la surface de la mer étaient positives dans toute la région sauf au détroit de Cabot où elle était de - 0,1 °C (- 0,1 ÉT), avec des valeurs allant de + 0,4 à 1,1 °C (+ 0,4 à + 1,0 ÉT) au-dessus des valeurs moyennes de 1981 à 2010. La couverture de glace de mer sur le plateau néo-écossais en 2015 était au-dessus de la moyenne de 1981 à 2010, contrairement à la période de 2010-2013 qui avait enregistré une couverture et un volume extrêmement faibles. Aux stations de thermographes côtiers à long terme de Saint Andrews (Nouveau-Brunswick) et de Halifax (Nouvelle-Écosse), les anomalies annuelles de la température de la surface étaient respectivement de + 0,3 °C (+ 0,3 ÉT) et de + 0,0 °C (+ 0,0 ÉT) en 2015. À certains endroits de la région, les anomalies annuelles de température de l'eau étaient positives en 2015 : elles étaient de + 0,9 °C (+ 2,6ÉT) dans le détroit de Cabot à des profondeurs entre 200 et 300 m (troisième plus grande anomalie après celles de 2012 et 2014), de + 0,9 °C (+ 1,4 ÉT) sur le banc de Misaine à 100 m de profondeur, de + 1,2 °C (+1,3 ÉT) dans le bassin d'Émeraude à 250 m de profondeur, de + 1,1 °C (+ 1,4 ÉT) dans le haut-fond Lurcher à 50 m de profondeur et de + 1,0 °C (+ 1,2 ÉT) dans le bassin de Georges à 200 m de profondeur (l'année la plus chaude était 2013). Les anomalies de température au fond dans les divisions 4VWX de l'Organisation des pêches de l'Atlantique nord-ouest (OPANO) étaient toutes positives en 2015 et allaient de + 0,9 °C (+ 1,3 ÉT) dans la division 4X de l'OPANO à + 1,9 °C (+ 2,8 ÉT) dans la division 4Vs de l'OPANO. Par rapport à 2013, la stratification moyenne sur le plateau néo-écossais a diminué pour se rendre sous la valeur moyenne de 1981 à 2010. Depuis 1948, la stratification a lentement augmenté sur le Plateau néo-écossais, principalement en raison de la baisse de la salinité (deux tiers du changement) et du réchauffement (un tiers) des eaux de surface. Un indice composite de 18 séries chronologiques des températures de la mer de la surface jusqu'au fond à l'échelle de la région révèle que 2015 était la cinquième année la plus chaude en 46 ans (2012 était la plus chaude), avec une anomalie normalisée moyenne de + 1,2 ÉT par rapport à la période allant de 1981 à 2010.

INTRODUCTION

This document discusses air temperature trends, ice cover, sea surface temperatures (SST) and physical oceanographic variability during 2015 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., 2016; Galbraith et al., 2016). 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. The water mass properties of shelf waters are modified by mixing with offshore waters from the continental slope. These offshore waters are generally of two types: Warm Slope Water, with temperatures in the range of 8-12^{o}C and salinities from 34.7-35.5; and Labrador Slope Water, with temperatures from 4^{o}C-8^{o}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 (NAO) 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 Icelandic Low and the Azores High. Strong northwest winds, cold air and sea temperatures, and heavy ice in the Labrador Sea area 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 2015, the winter NAO index was positive, +17.8 mb (+2.0 SD) above the 1981-2010 mean, which was the largest positive value in the 121 year record (Figure 2, upper panel). The lower panels of Figure 2 show the sea level pressure conditions during the winter of 2015 compared to the 1981-2010 mean. The Icelandic low and Azores high were more intense than the long-term average but with a smaller spatial scale. The Icelandic low was weaker (but farther north) than in 2014, the mid-Atlantic high was stronger and shifted to the northeast. 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, 2015) interactive website. In 2015, the annual anomalies were normal over the Scotian Shelf and above normal for most of the Gulf of Maine (Figure 3). The seasonal anomaly of these regions is below normal during the first half of the year for the Scotian Shelf and the Gulf of Maine with larger anomalies during the winter. For the second half of the year, the air temperatures were above normal except the most eastern part of the Scotian Shelf (Figure 4).

Monthly air temperature anomalies for 2014 and 2015 relative to their 1981-2010 means at six sites in the Scotian Shelf-Gulf of Maine region are shown in Figure 5. Monthly data for the Canadian sites were obtained from the Canadian Climate Summaries (CCS) at the Environment Canada website and from the Monthly Climatic Data for the World (NOAA, 2015) for Boston. In 2012, several stations were transferred from Environment Canada to NAV Canada, changing sensors and reporting tools. After the switchover, there were several months with missing days of data. If a month in the CCS had three or more missing days (no record of minimum or maximum temperature), the daily data report was checked to determine which days were missing. For those days, the daily (0300-0200 local standard time) minimum and maximum temperatures were determined if possible. There were many instances of hourly data available but not daily values. From these temperatures, the daily and monthly averages were determined. In general, all sites show that the winter of 2015 had below normal temperatures and above normal temperatures for the second half of the year (Figure 5). The observed and normalized annual anomalies for these stations are listed in Table 1.

Table 1. The 2015 annual mean air temperature anomaly in degrees and standardize 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	Mean (°C)	SD (°C)
Sydney	-0.4	-0.4	5.87	0.81
Sable Island	+0.5	+0.7	7.88	0.68
Shearwater (Halifax)	-0.5	-0.7	6.99	0.74
Yarmouth	<+0.1	<+0.1	7.16	0.62
Saint John	-0.3	-0.4	5.19	0.74
Boston	>-0.1	>-0.1	10.91	0.60

In 2015, the mean annual air temperature anomalies were negative at all sites except Sable Island at +0.5°C (+0.7 SD) and slightly positive at Yarmouth with values ranging slightly negative at Boston to -0.5°C (-0.7 SD) at Halifax. The time series of annual anomalies indicates that all sites feature increasing temperatures over the long-term with decadal scale variability superimposed (Figure 6). Monthly mean temperature data for Canadian sites are from

Environment Canada's Adjusted Homogenized Canadian Climate Data (AHCCD) where available (Vincent et al., 2012). In cases where no data were available, observed (CSS) monthly mean values were used, and anomalies are relative to the CCS long-term means. This is the case for 2009-2011 and 2014-2015 at Sable Island. The AHCCD time series generally is not updated for a given year until late the following year. Also, the updating of the AHCCD series stopped when they were converted to NAV Canada reporting. Over shorter periods, there are periods 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 +0.3°C (-0.1°C, +0.7°C), +1.3°C (+0.9°C, +1.6°C), +1.2°C (+0.9°C, +1.6°C), +1.0°C (+0.7°C, +1.4°C), +0.6°C (+0.2°C, +1.0°C), and +1.7°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, 93 of the 116 years had five or more stations with the annual anomalies having the same signs; for 64 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 2015 was -0.1°C, the 35th warmest year in 116 years (with 2012 being the warmest), but the first near-normal anomaly since 2010.

REMOTELY-SENSED SEA SURFACE TEMPERATURE (SST)

A 4 km resolution Pathfinder 5.2 (Casey et al., 2010) SST database is maintained at the Bedford Institute of Oceanography (BIO; Dartmouth, Nova Scotia). The 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). A least-square fit of the Pathfinder and NOAA temperatures during the 1981-2010 time period for several regions led to a conversion equation SST(Pathfinder) = 0.989*SST(BIO)-0.02 with an r^2=0.98. Using this regression, the BIO 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 the year followed by a period of near- or below normal temperatures and then above normal from August to December (Figure 9).

Annual anomalies were calculated from monthly averaged temperatures for the eight subareas (Table 2; Figure 10). The annual anomalies during 2015 ranged from -0.1°C (-0.1 SD) in Cabot Strait to +1.1°C (+1.0 SD) on Central Scotian Shelf. Seven of the eight areas had positive anomalies; of those, five were equal or greater than +0.7 SD. 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, Lurcher Shoal and Georges Bank) to a highest value of +0.5°C/decade (Central Scotian Shelf and Western Bank). 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., 2016). 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).

Table 2. 2015 SST anomalies and long-term SST statistics including 1982-2015 temperature change based on the linear trend.

Site	2015 SST Anomaly (°C)	2015 SST Anomaly Normalized	1981-2010 Mean Annual SST (°C)	1981-2010 Annual SST Anomaly Std. Dev. (°C)	1982-2015 Temperature Trend (°C/decade)
Cabot Strait	-0.1	-0.1	5.9	1.0	0.3
Eastern Scotian Shelf	+0.6	+0.5	7.1	1.1	0.4
Central Scotian Shelf	+1.1	+1.0	8.5	1.1	0.5
Western Bank	+1.0	+0.9	8.9	1.2	0.5
Western Scotian Shelf	+1.0	+1.0	8.1	1.1	0.4
Lurcher Shoal	+0.4	+0.4	7.2	1.1	0.3
Bay of Fundy	+0.6	+0.8	7.2	0.8	0.5
Georges Bank	+0.7	+0.7	10.0	1.0	0.3

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. PCA2 accounted for an additional 8% 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 for the period 1962-2015. 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 (Figure 12) and were subtracted from the values determined for 2015 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. They give two main reasons for this (S. McCourt, Environment Canada, pers. comm.):

1. *Ice types are reported in terms of "stage of development", which have an associated range of thickness. For example, "first-year ice" has an associated range of thickness of 30 cm to 120 cm. It is, therefore, difficult to assign a "typical" thickness and in the case of first-year ice, the value assigned will vary from area to area (i.e. first-year ice in the Gulf would have a different thickness than first-year ice in the Arctic).*

2. *Old ice in particular is extremely difficult to estimate thickness and subsequent volume; however, for the Gulf of St. Lawrence this should not be a limiting factor.*

Since observations of ice thickness are not available, ice volumes have been estimated for the region by assigning characteristic thicknesses to particular ice types using estimates of ice thickness by stage of development provided by Canadian Ice Service. While this is not an ideal way to estimate ice volumes, it does provide a basic assessment that can be used as an additional climate index and a reference point for testing ice models.

ATLANTIC REGION

Ice appeared on the Labrador near the coast before the start of the year and on the Labrador shelf, northern Newfoundland Shelf and western Gulf of St. Lawrence and St. Lawrence Estuary during January 2015. During February, ice formed on the Newfoundland Shelf and most of the rest of the Gulf of St. Lawrence (Figure 13); over much of this region, the day of first appearance of ice was approximately near normal to 15-30 days later than normal. The day of last appearance of ice was earlier than normal for northern half of the Gulf of St. Lawrence and off Labrador and later than normal by more than 15 days for the southern part of the Gulf of St. Lawrence and in Cabot Strait. Near the coast of central Newfoundland and off shore, the last day was later than normal and earlier than normal in southeast Newfoundland (Figure 14). Ice duration was much longer than normal by 15 days to over a month in Cabot Strait (Figure 15). No significant ice formed on the southern Newfoundland.

SCOTIAN SHELF

The greater part of sea ice on the Scotian Shelf originates in the Gulf of St. Lawrence, and 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 2015, ice was present at these locations for much longer than the climatological values (Figure 15). There had been very little ice on the Scotian Shelf and Cabot Strait from April 2009 until 2014 (Figure 16).

The ice areas and volumes for 2015 are compiled in Table 3. February had near normal coverage and volume while January was below normal and March and April were well above normal. The December 2014 to April 2015 ice coverage and volume on the Scotian Shelf were above the 1981-2010 average at 0.8 SD and 1.4 SD, respectively, unlike the 2010-2013 period which had extremely low coverage and volume in the 54 year long record.

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

Month	2015 Ice Area (km^2)	2015 Area Anomaly (km^2)	2015 Normalized Area Anomaly	2015 Ice Volume (km^3)	2015 Volume Anomaly (km^3)	2015 Normalized Volume Anomaly
January	60	-1170	-0.5	0.00	-0.2	-0.5
February	10020	-1270	-0.1	2.28	-0.5	-0.2
March	28090	+12370	+0.8	15.07	+8.2	+1.2
April	17620	+13040	+2.7	11.04	+8.0	+2.6

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 2015, the SST anomalies were +0.0°C (+0.0 SD) for Halifax, a decrease of 0.2°C from 2014 and +0.3°C (+0.3 SD) for St.

Andrews, a decrease of 0.3°C from 2014. Interestingly, the SST at Halifax, located in the harbour, had no significant change from 1981 to 2015, due to a warmer early 1980s (Figure 17), whereas the satellite-based SST showed an increase over the same period (Table 2; Figure 10). Slight changes in timing of warming and cooling events can affect estimates of trends over short periods.

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 2015, the annual temperature anomaly was +0.3°C (+0.6 SD) and the salinity anomaly was +0.2 (+1.1 SD). These represent changes of -0.4°C and +0.1 from the 2014 values. The positive density anomaly is accounted for by the positive salinity anomaly but was reduced slightly by the partial density anomaly due to the increase in the temperature.

The 2015 annual cycle at Prince 5 shows warmer than normal temperatures at the beginning and end the year, with the largest positive anomalies (+1.5°C) at the end of the year, with no real depth dependence in the anomaly (Figure 18). The largest temperature anomaly occurred in late 2015, a result of the warm fall air temperatures (Figure 5) and of the cooling of the water that did not penetrate fully to the bottom. The negative temperature anomaly is the result of the colder than normal winter. The minimum of salinity observed at Prince 5 is due to the arrival of fresh water in the upper ocean from the Saint John River; a nearby source. For 2015, the positive salinity anomaly in April is probably the result of a less-than-normal amount of fresh water arriving there due to the cold winter and spring.

The 2015 annual cycle at Halifax 2 follows the standard seasonal temperature cycle (Figure 19). The observed temperature anomaly is due to variability of the depth of the summer mixed layer and the warmer water observed in the late summer due to the warm fall air temperatures and the delay in surface cooling. There is a negative salinity anomaly in the upper ocean in the fall due to the lower than normal salinity of the Nova Scotia Current. The deeper variability of the salinity occurs in conjunction with temperature, and is indicative of warmer saltier slope water intruding onto the shelf.

STANDARD LINES

The Louisbourg, Halifax, and Browns Bank Lines were sampled during the spring and fall of 2015 (Figure 20). The Cabot Strait Line was only sampled during the fall due to ice in the strait in April. For the spring of 2015, the line conducted by Galbraith in March (Galbraith et al., 2016) was included. The Cabot Strait Line showed above average March temperatures and above average fall temperature and salinities at depths of 100 to 200 m (Figure 21). In the fall, the surface temperature near Nova Scotia was very warm and the Louisbourg Line shows anomalously warm water at the surface with a cold anomaly below, probably due the stratification and weak winds to mix the surface heat down (Figure 22). There was anomalously warm, salty water just off the shelf along the Louisbourg Line. Warmer, saltier water was observed at depth over the Halifax Line during both the spring and fall of 2015 (Figure 23). Like for the Louisbourg Line, the surface water on the Halifax Line was anomalously warm during the fall. During the spring of 2015, the Browns Bank Line showed anomalous cold, fresh water at the shelf break (Figure 24). Like the other lines, the surface temperature was above normal during the fall.

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 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, Lurcher Shoals and Georges Basin, the 2015 annual anomalies are based on observations from four, three, ten, two, and seven months, respectively.

In 2015, the annual anomalies were +0.9^{o}C (+2.6 SD) for Cabot Strait at 200-300 m (the third largest anomaly; the record was in 2012 and the second largest anomaly was in 2014), +0.9^{o}C (+1.4 SD) for Misaine Bank at 100 m, +1.2^{o}C (+1.3 SD) for Emerald Basin at 250 m, +1.1^{o}C (+1.4 SD) for Lurcher Shoals at 50 m, and +1.0^{o}C (+1.2 SD) for Georges Basin at 200 m (2014 was the warmest year). These values correspond to changes of -0.0^{o}C, +0.3^{o}C, -0.2^{o}C, -0.6^{o}C and -0.2^{o}C, respectively, from the 2014 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 (Petrie, 2007). 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 2015.

TEMPERATURES DURING THE SUMMER GROUNDFISH SURVEYS

The broadest spatial temperature and salinity coverage of the Scotian Shelf is obtained during the annual Fisheries and Oceans Canada (DFO) research vessel (RV) summer trawl survey, which covers the Scotian Shelf from Cabot Strait to the Bay of Fundy. The deep water boundary of the survey is marked roughly by the 200 m isobath along the shelf break at the Laurentian Channel, at the outer Scotian Shelf, and at the NEC into the Gulf of Maine towards the Bay of Fundy. A total of 216 Conductivity-Temperature-Depth (CTD) stations were sampled during the 2015 survey. The groundfish survey normally takes one month to complete with the area west of Halifax sampled first and the area east of Halifax sampled last. In 2015, it took 1.5 months with a 0.5 month gap in about the middle due to ship-related issues.

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. 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 2015 were positive everywhere (Figure 27).

Bottom temperatures ranged from an average of 4.9°C in NAFO Division 4Vs to 8.2°C in NAFO Division 4X during 2015, illustrating the substantial difference in the environmental conditions across the shelf. The anomalies were positive for these NAFO Divisions in 2015: +0.9°C (+2.2 SD) in 4Vn; +1.9°C (+2.8 SD) in 4Vs; +1.6°C (+2.1 SD) in 4W; and +0.9°C (+1.3 SD) in 4X (Figure 28A-D). Compared to 2012, the year when record or near record warm bottom temperatures were observed, bottom temperatures were different by -0.4°C, +0.7°C, -0.2°C and -1.3°C in NAFO Divisions 4Vn, 4Vs, 4W and 4X, respectively. NAFO Divisions 4Vs was the second highest on record, only 0.1°C lower than the record high in 1984.

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 28). 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 28E) 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 28E). In 2015, the observed volume of 4100 km^3 was 1.2 SD less than the 1981-2010 mean value of 5500 km^3 and was the 7th lowest volume in the 42 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). 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 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 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 value 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 20 years which are characterized by above normal values (Figure 29). Stratification on the Scotian Shelf in 2015 continued to weaken from 2013 and was less than the 1981-2010 mean value. 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 (84% of the total density change), composed of two-thirds warming and one-third freshening (Figure 30). The remainder of the density change occurs at 50 m, mainly due to an increase in salinity. There was a decrease in stratification from 2014 to 2015 due to an increase in surface density as a result of a cooler temperature, a decrease of 0.8°C.

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 (1967-2015), Halifax[1] (1920-2015) and North Sydney (1970-2015) are plotted as monthly means and as a filtered series using a five year running-mean filter (Figure 31). The linear trend of the monthly mean data has a positive slope of 35.7 cm/century (Yarmouth), 32.8 cm/century (Halifax), and 37.0 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 +25.4 cm/century, +18.1 cm/century and +20.2 cm/century, respectively. In 2015, the annual relative sea level at Halifax continued to decrease from the peak in 2010, while Yarmouth decreased from the 2014 level and North Sydney continued to decrease from the peak in 2013 (Figure 31). An interesting feature of the data is the long-term variation that has occurred since the 1920s. In Figure 32, the differences of the annual sea level from the 1981-2010 sea level rise trend are shown. 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 1970-2015 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 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).

CALCULATIONS 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

[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.

vertical (22 in the top 100m), 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 NCEP/NCAR reanalysis forcing (Kalnay et al., 1996).

Other forcing includes the five principal tidal constituents and monthly mean freshwater inputs for the 45 highest discharge rivers from Hudson Bay to the Gulf of Maine. Data for Hudson Bay rivers were provided by Stephen J. Déry (via personal communication), converted to model input by B. DeTracey (BIO), and is available as monthly time series up to 2012, after which time a climatology derived from the data is used. Runoff for the other rivers is obtained from observed data (for the St. Lawrence estuary) and a hydrological model (for details see: Galbraith et al., 2014). The model domain and river locations are shown in Figure 33. A simulation was produced for the entire AZMP period (1999-2015).

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 34). 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 1999-2015 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 34). 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 35. 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 36). On a monthly basis (Figure 35), the inshore series (CS, HFX inshore, and CSI) exhibit a seasonal cycle with mid-year transport minima, while the shelf break transport along the Halifax section and the transport into the GoM at NEC show no clear seasonality.

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 have been deployed for six month periods since 2008 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. T2 is located 12 km east of station 2 (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 are 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 quadratic relationship between the transport estimated using all stations and the transport estimated using only 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 (T3 failed from April 2010 to October 2010, T2 failed from October 2010 to April 2011 and from October 2012 to April 2013 and T1 failed from August 2012 to October 2012, from February to April 2013 and June to October 2013). 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 37). These trends are well simulated by the model (see HFX nearshore panel of Figure 35).

The fraction of transport into the Gulf of Maine through CSI (GoM inflow ratio - Figure 38) exhibits a seasonal cycle with a minimum during the summer months. Interannually (Figure 36) this ratio was near neutral from 1999-2003, positive in 2004 and alternated between positive and negative anomalies from 2005-2009. The 2012 and 2014 warm events (high NAO) are characterized by anomalously low ratios (proportionally more transport via NEC, although this did not hold for 2015) while 2010 (low NAO) is characterized by an anomalously high ratio. On average, the model predicts that about one quarter of the transport into the Gulf of Maine enters through the CSI section, varying between almost none in July to half from January through April.

An overall annual scorecard was computed (Figure 39) by summing the standardized anomalies 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 generally weak and variable anomalies from 1999-2007, followed by alternating stronger negative and positive anomalies thereafter. There is a general negative correlation with the NAO, with the three recent strong positive NAO years (2012, 2014, and 2015) characterized by the strongest negative anomalies in the transport series, and the strongest positive anomalies in the transport series associated with strong negative NAO years (2010, 2011).

SUMMARY

In 2015, the NAO index was positive (+17.8 mb, +2.0 SD from the 1981-2010 mean), which was the largest value in the 121 year record. Mean annual air temperature anomalies were negative at all sites except Sable Island at 0.5°C (0.7 SD) and slightly positive at Yarmouth. In 2015, ice coverage on the Scotian Shelf was above the 1981-2010 average unlike 2010-2013 period, which had extremely low coverage and volume in the 54 year record. The analysis of satellite data indicates that SST anomalies were above normal at the start of the 2015 followed by a period of near- or below normal temperatures and then above normal from August to December.

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 2010-2015 were warmer than normal (Figure 40). 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 2015, 20 of 22 series shown had positive anomalies; 10 variables were more than 1 SD above their normal values. Of these, four were more than 2 SD above normal (the three eastern NAFO-divisions bottom temperature and deep Cabot Strait). In 2015, the average (median) normalized anomaly was 1.1 (1.0), the fifth highest in the 46 year series. The SD of the normalized anomalies was +0.8. These statistics indicate that 2015 was a warm year with a fairly uniform distribution of positive anomalies throughout the region.

Eighteen selected variables of the mosaic plot are summarized as a combination bar plot in Figure 41. This plot represents an overall climate index for the area. These include selected time series for the eastern (Misaine), central (Emerald) and western (Lurcher) Scotian Shelf, the Bay of Fundy (Prince 5) and Georges Bank. In addition, the spatially comprehensive but temporally limited DFO RV summer trawl survey bottom temperatures (NAFO Divisions 4Vn, 4Vs, 4W and 4X) and surface temperatures for Halifax, Nova Scotia, and St. Andrews, New Brunswick, are included because of their long-term nature. The bar components are colour coded so that for any year the contribution of each variable can be determined and systematic spatial patterns seen. The height of each variable's contribution to the bar depends on its magnitude. The positive components are stacked on the positive side, the negative components on the negative side. The composite index indicated that 2015 was the fifth warmest of 46 years, with an averaged normalized anomaly of +1.2 SD relative to the 1981-2010 period. The anomalies did not show a strong spatial distribution in 2015. The leading mode of a principal component analysis of the 18 series captured 51% of the variance with all loadings having the same sign. The loadings of 17 of the 18 variables were strong (0.17 to 0.29) with weak contributions only from the Emerald Basin 250 m series (0.08).

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FIGURES

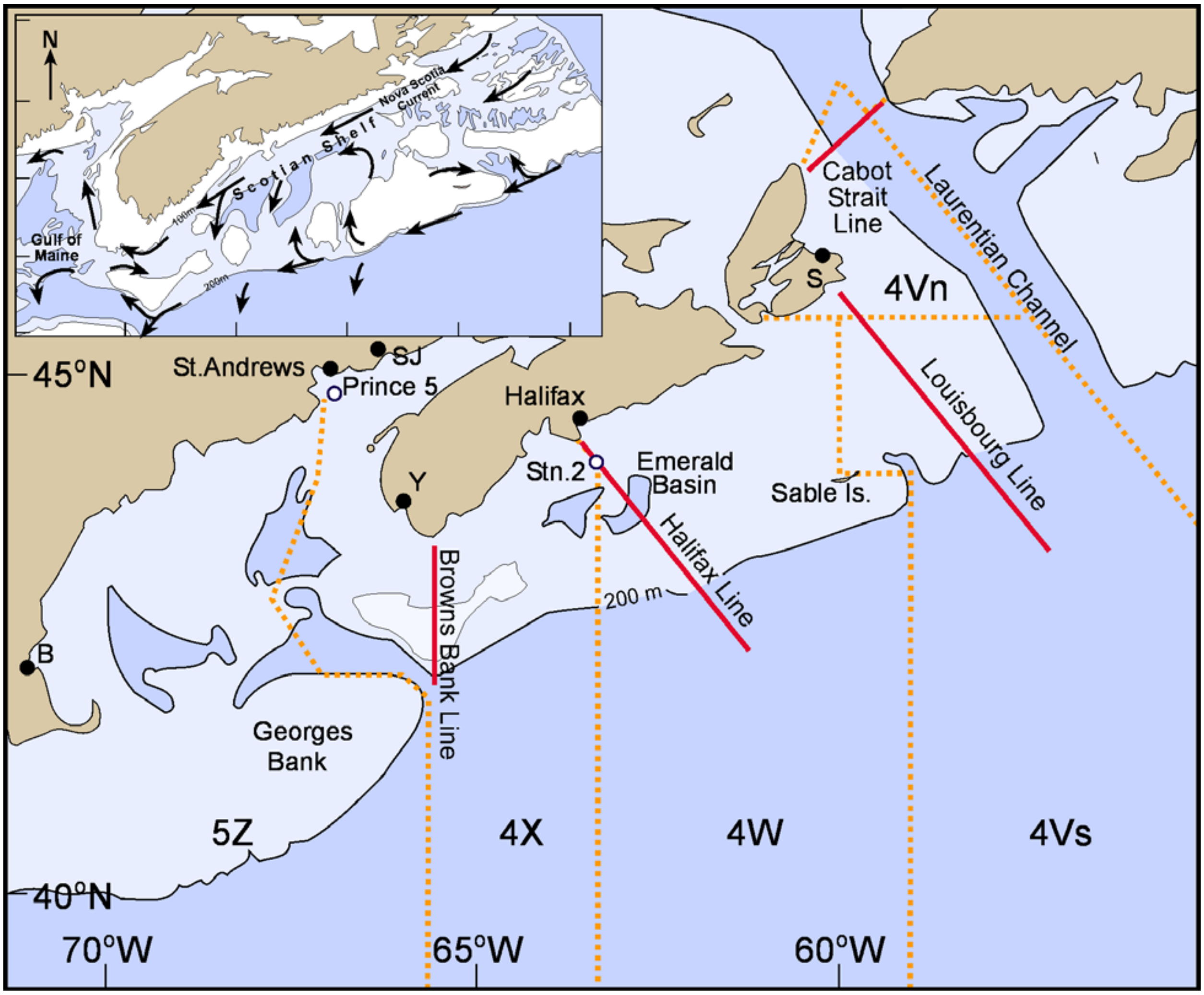

Figure 1. Map of the Scotian Shelf and the Gulf of Maine showing hydrographic stations (white circles), standard sections (red lines) and topographic features. The dotted lines indicate the boundaries of the Northwest Atlantic Fisheries Organization Divisions. Inset depicts major circulation features.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

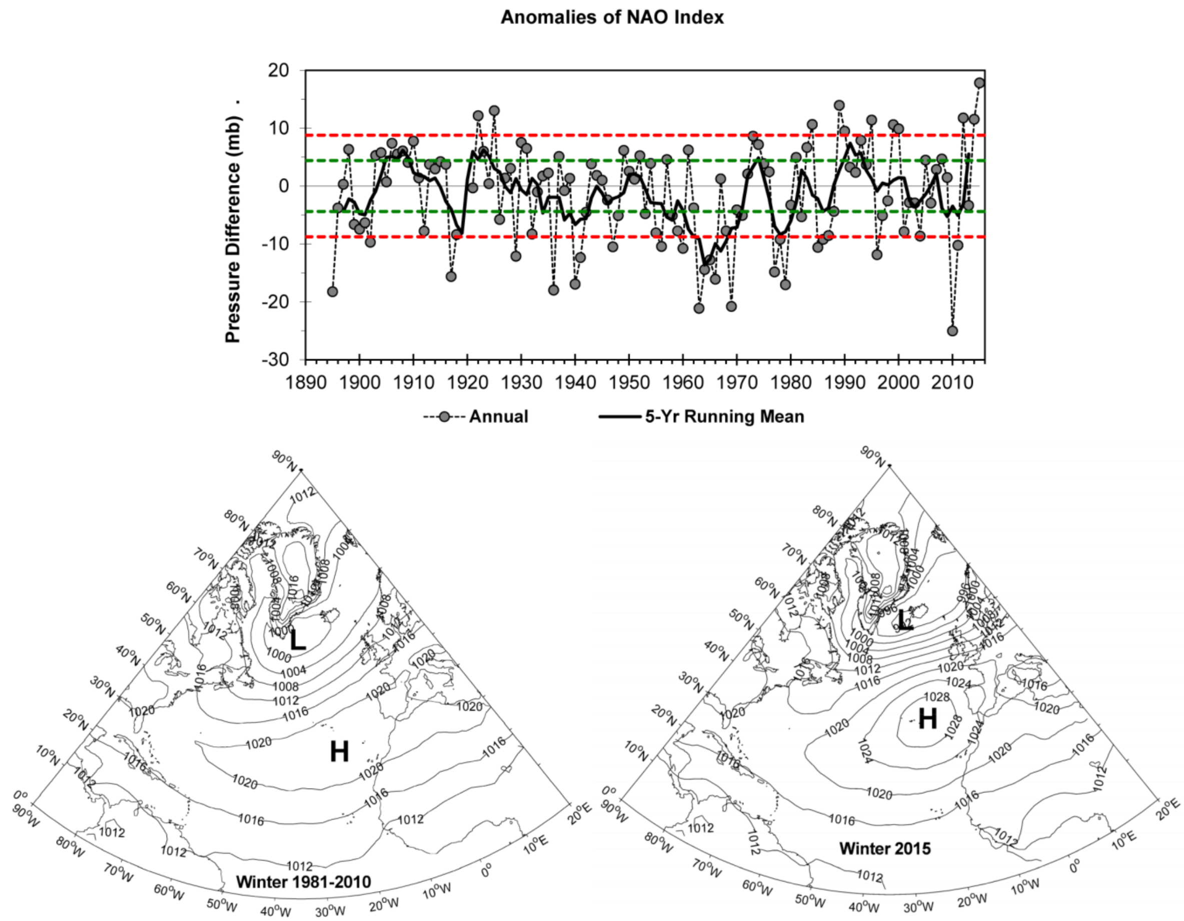

Figure 2. Anomalies of the North Atlantic Oscillation (NAO) index, defined as the winter (December, January, February) sea level pressure difference between the Azores and Iceland, relative to the 1981-2010 mean. The 0.5 (green broken lines) and 1.0 (red broken lines) standard deviations (SDs) are shown (upper panel). The lower panels show the 1981-2010 December-February mean (bottom left panel) and December 2013-February 2014 mean (bottom right panel) sea level pressure over the North Atlantic.

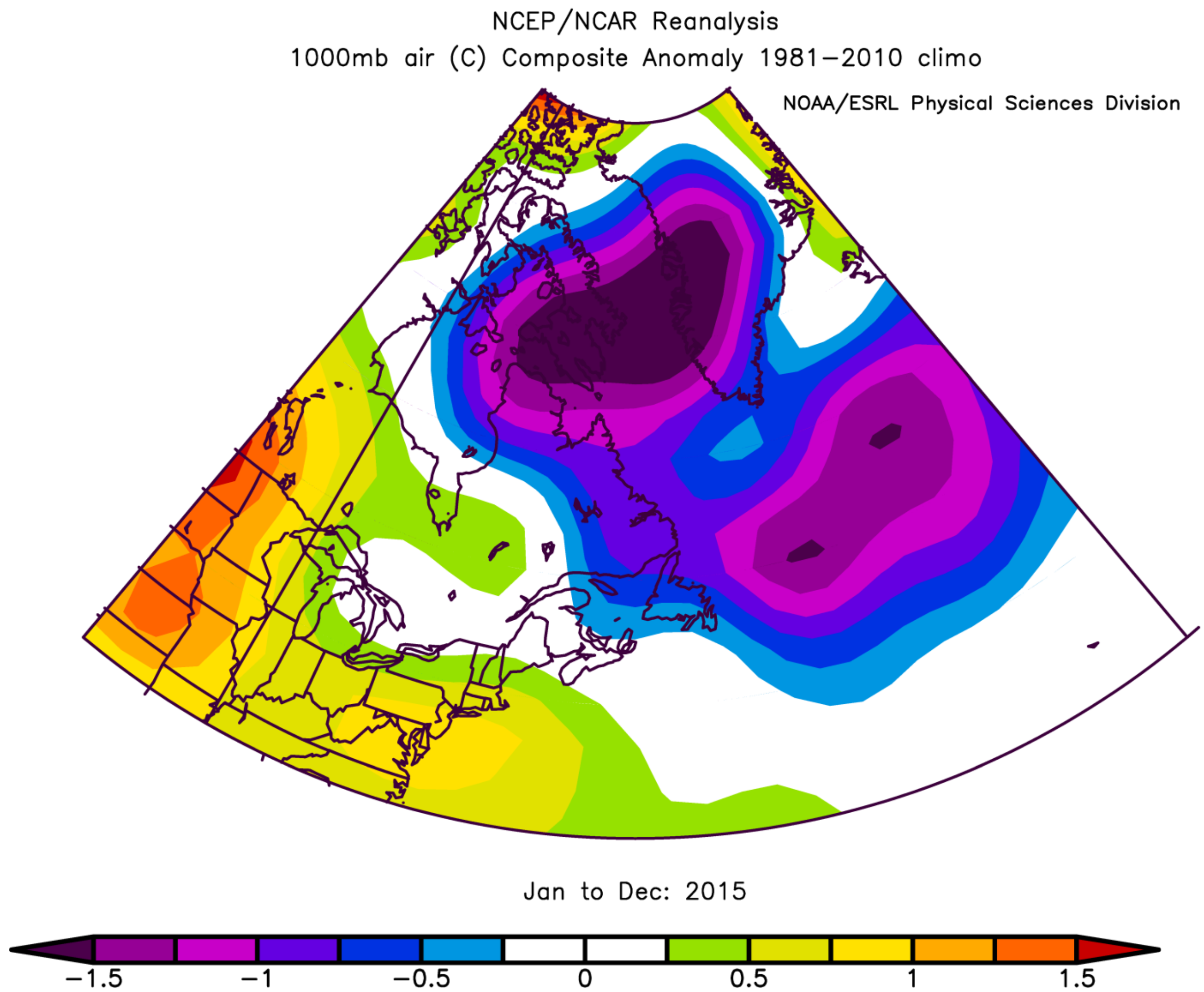

Figure 3. Annual air temperature anomalies (ºC) over the Northwest Atlantic relative to the 1981-2010 means; data were obtained from NOAA Internet site (accessed 4 January 2016).

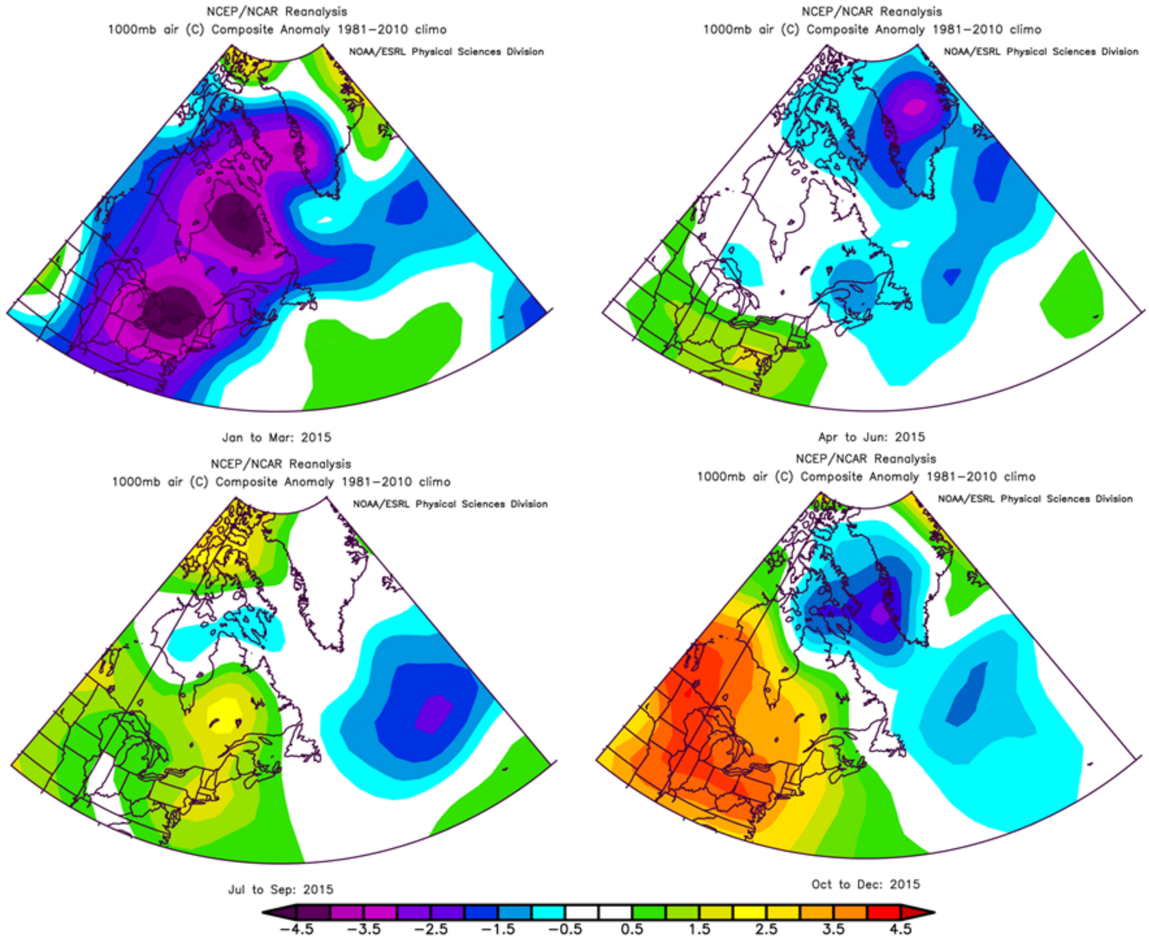

Figure 4. Seasonal air temperature anomalies (ºC) over the Northwest Atlantic relative to the 1981-2010 means; data were obtained from [NOAA Internet site](#) (accessed 4 January 2016).

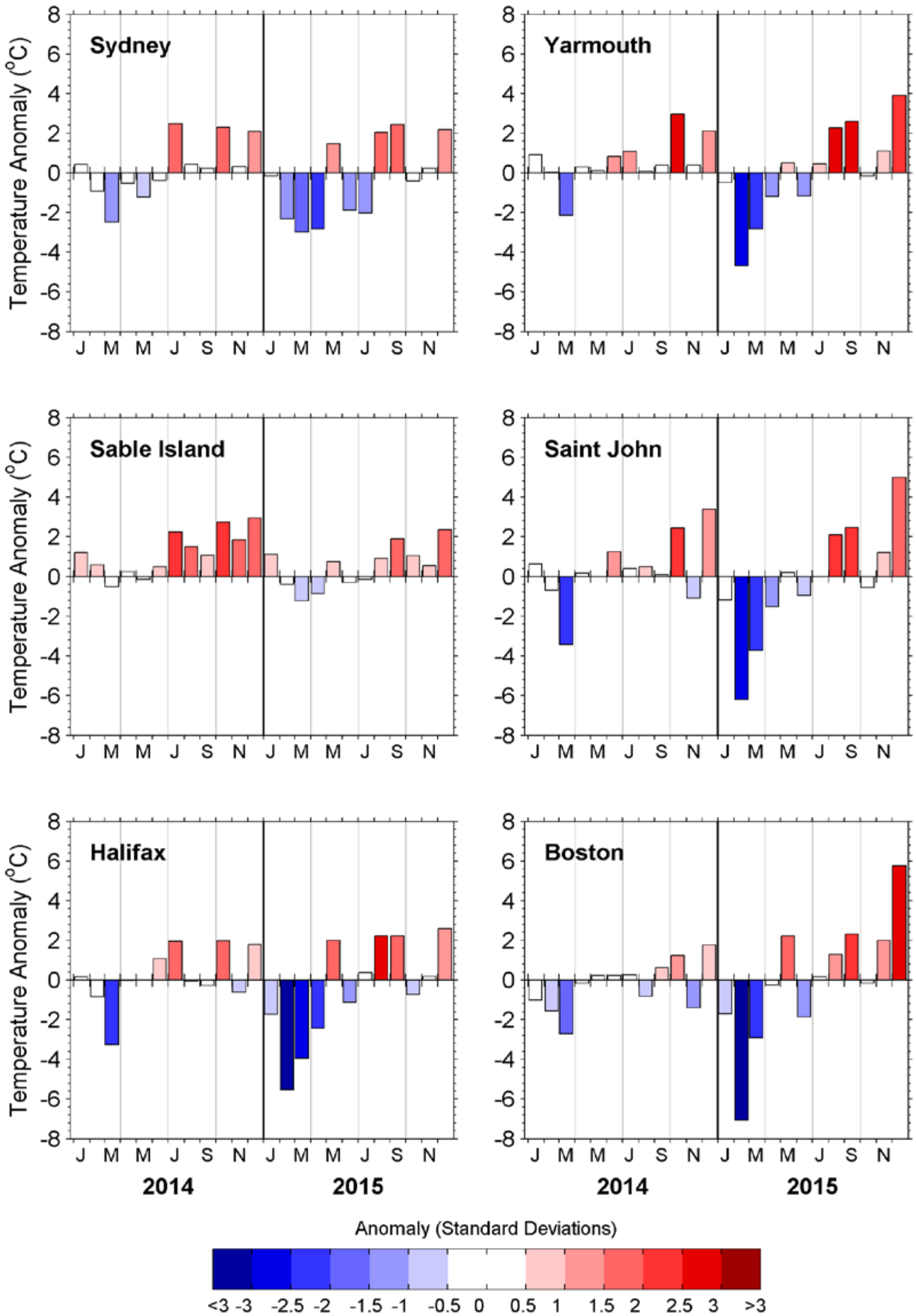

Figure 5. Monthly air temperature anomalies (^oC) for 2014 and 2015 (JMMJSN on x-axis represent January, March, May, June, September and November) at coastal sites in Scotian Shelf-Gulf of Maine region (see Figure 1 for locations). Anomalies are colour coded in terms of the numbers of SD above or below normal relative to monthly statistics.

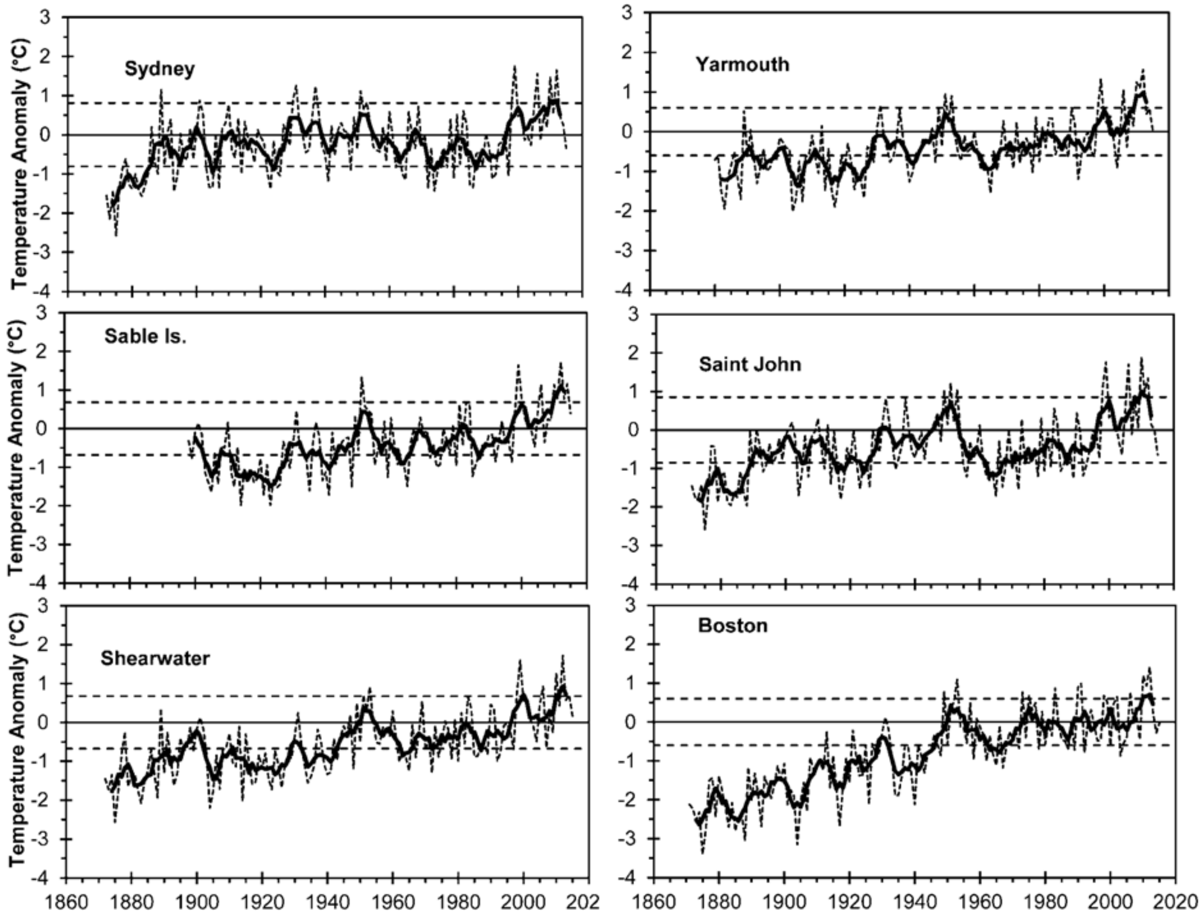

Figure 6. Annual air temperature anomalies in ^{o}C (dashed line) and five year running means (solid line) at selected sites (Sydney, Sable Island, Shearwater, Yarmouth, Saint John, and Boston) in Scotian Shelf-Gulf of Maine region (years 1860 to 2015). Horizontal dashed lines represent plus or minus SD for the 1981-2010 period.

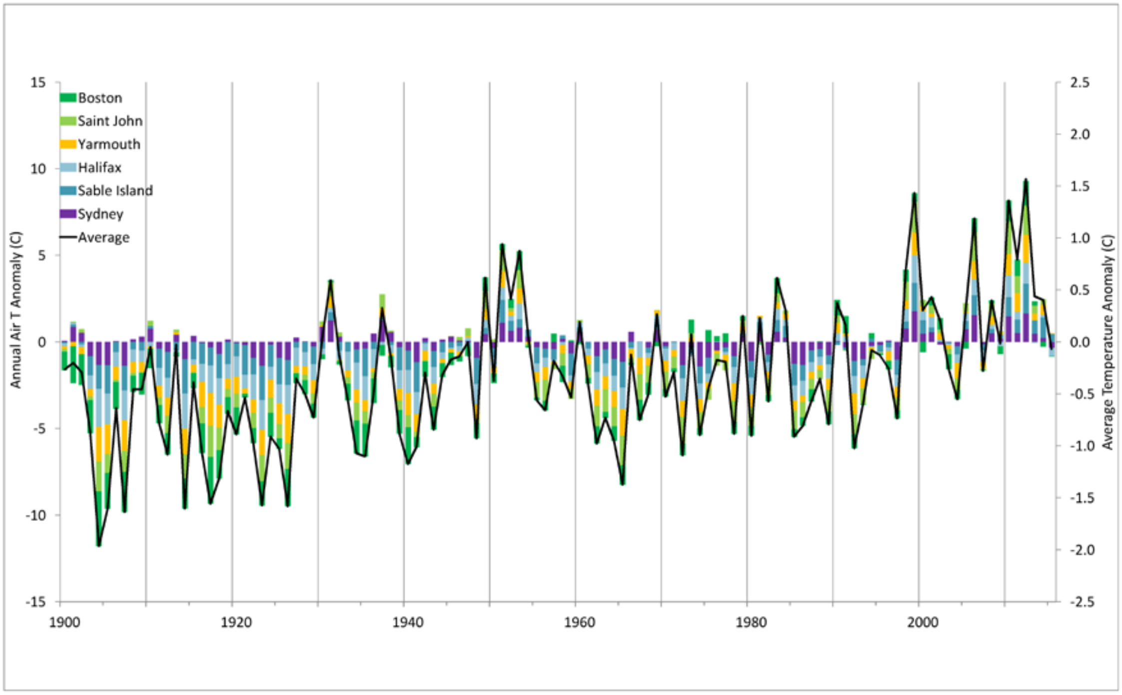

Figure 7. The contributions of each of the annual air temperature anomalies for six Scotian Shelf-Gulf of Maine sites (Boston, Saint John, Yarmouth, Shearwater, Sable Island and Sydney) are shown as a stacked bar chart and the average anomaly as a line. Anomalies referenced to 1981-2010.

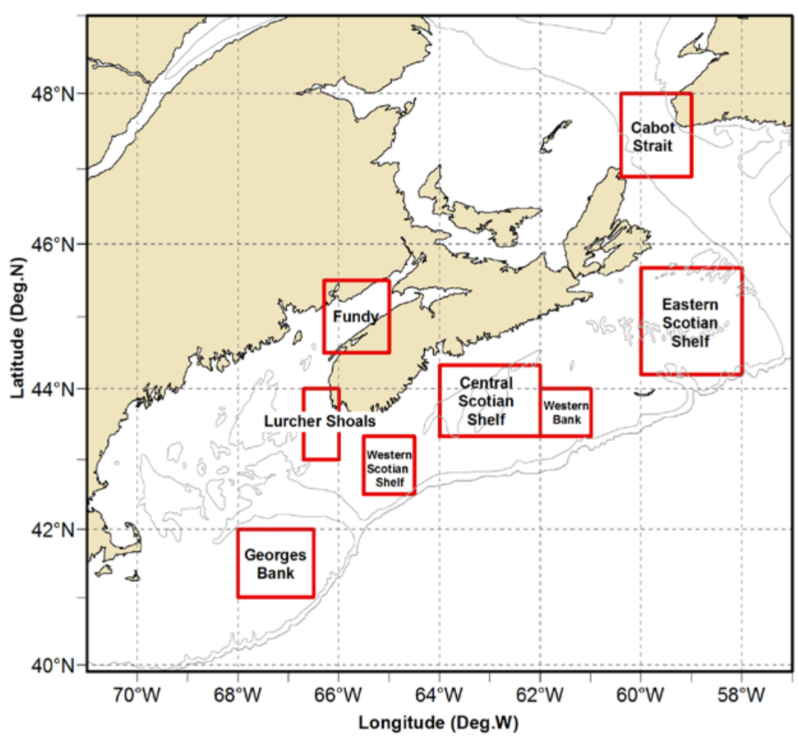

Figure 8. Scotian Shelf-Gulf of Maine areas (Cabot Strait, Eastern Scotian Shelf (ESS), Western Bank, Central Scotian Shelf (CSS), Western Scotian Shelf (WSS), Georges Bank, Lurcher Shoals and Bay of Fundy) used for extraction of sea surface temperature.

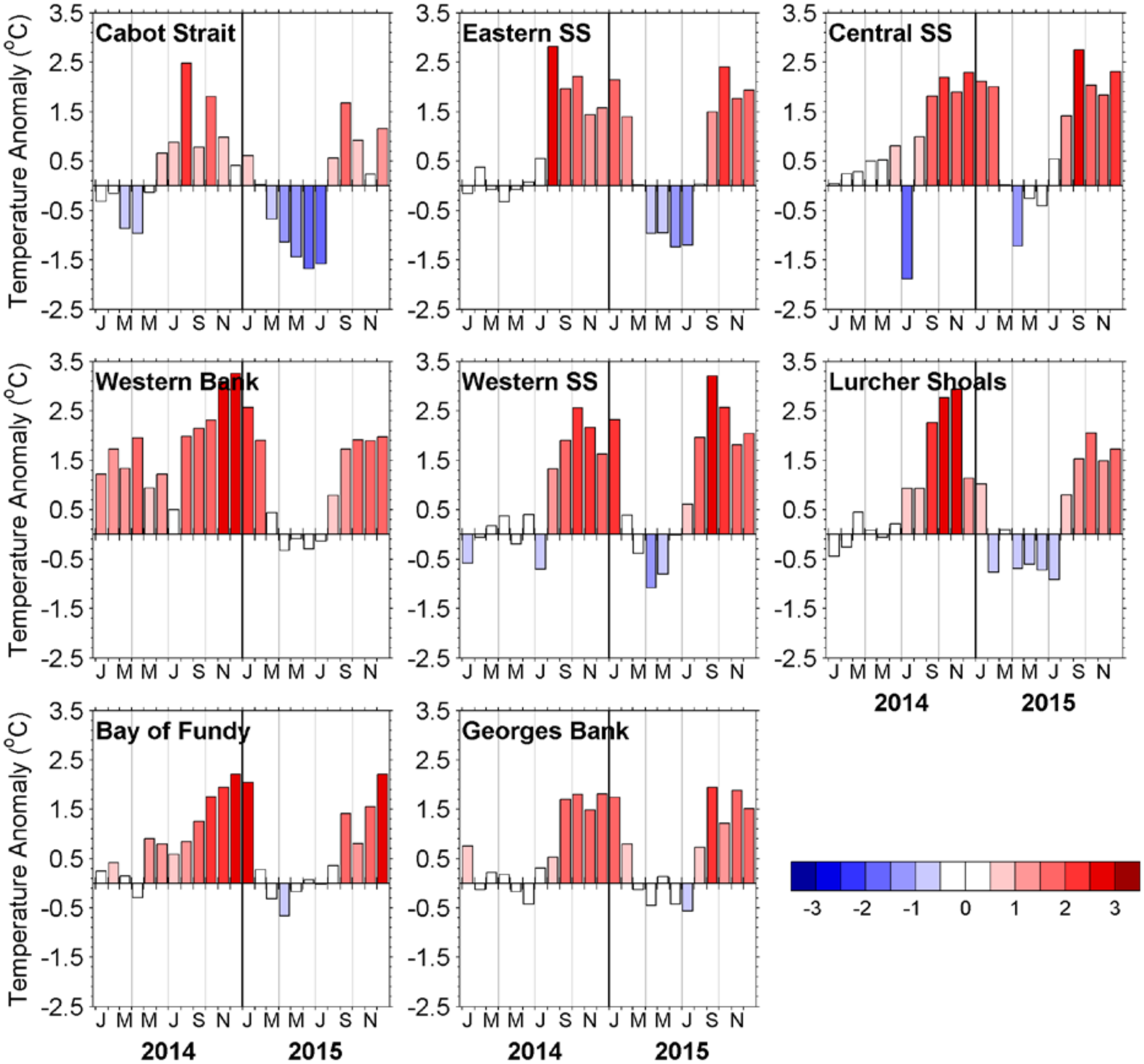

Figure 9. Monthly surface temperature anomalies for 2014 and 2015 for the regions shown in Figure 8. The colours of the bars are the normalized anomalies.

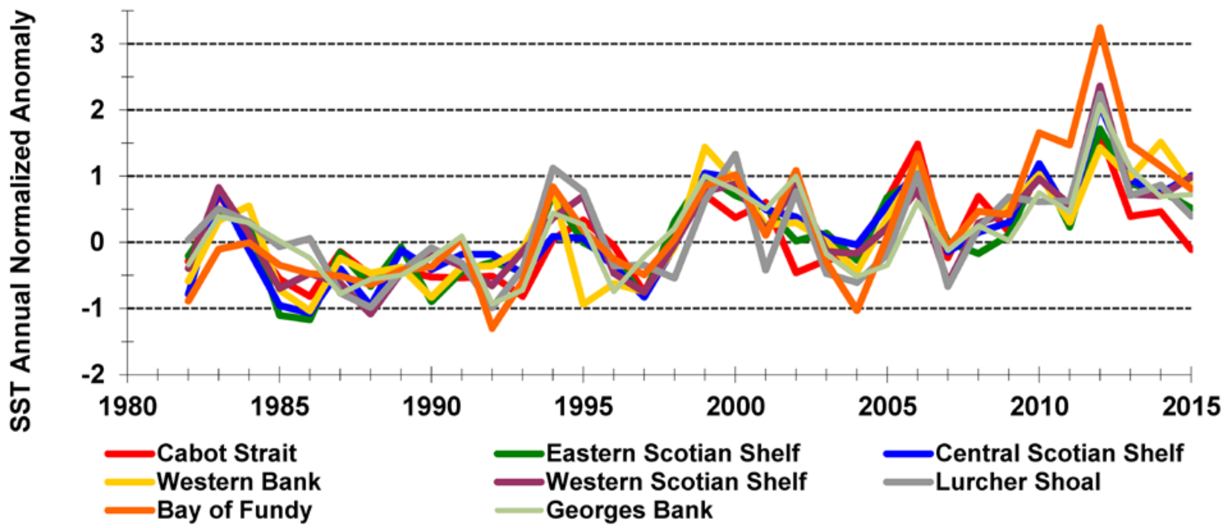

Figure 10. The annual sea surface temperature anomalies derived from satellite imagery compared to their long-term monthly means (eight Scotian Shelf and Gulf of Maine regions - Cabot Strait, Eastern Scotian Shelf, Central Scotian Shelf, Western Bank, Western Scotian Shelf, Lurcher Shoals, Bay of Fundy,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

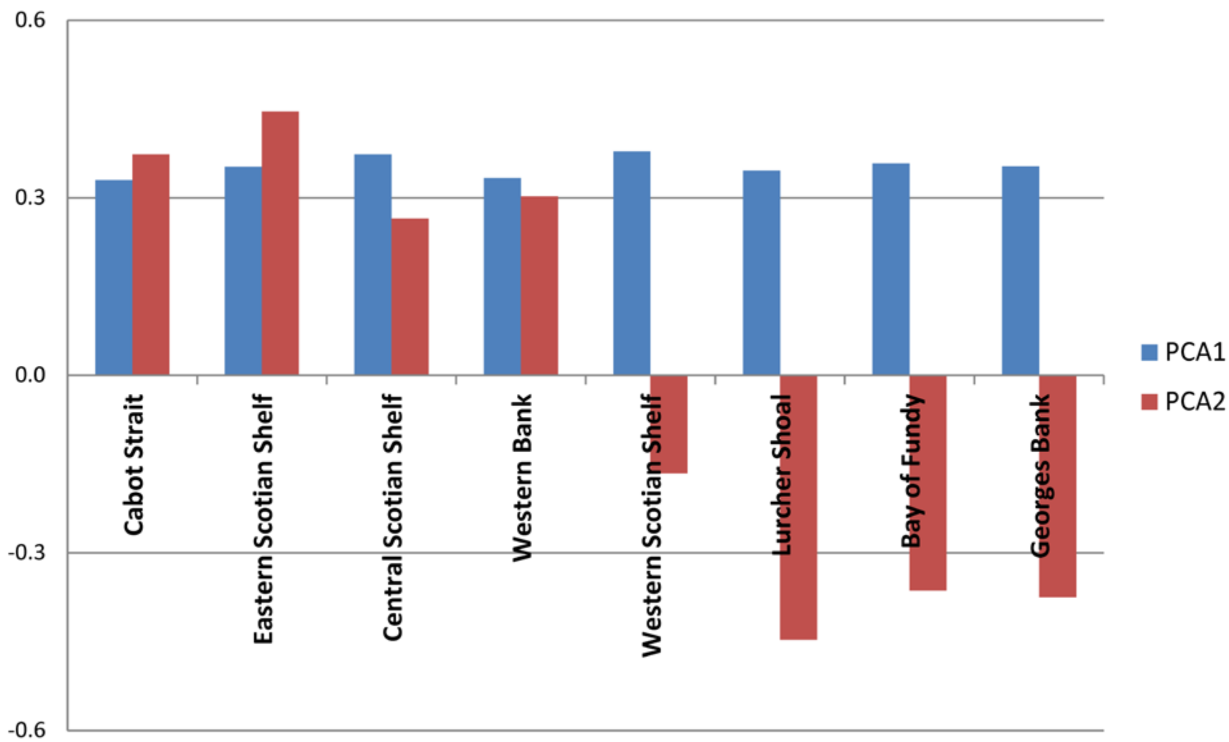

Figure 11. First (PCA1: 83% of the variance) and second (PCA2: 8% of the variance) loadings from a principal components analysis of the annual mean temperature anomalies (Figure 14 for the eight Scotian Shelf and Gulf of Maine regions (Cabot Strait, Eastern Scotian Shelf, Western Bank, Central Scotian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

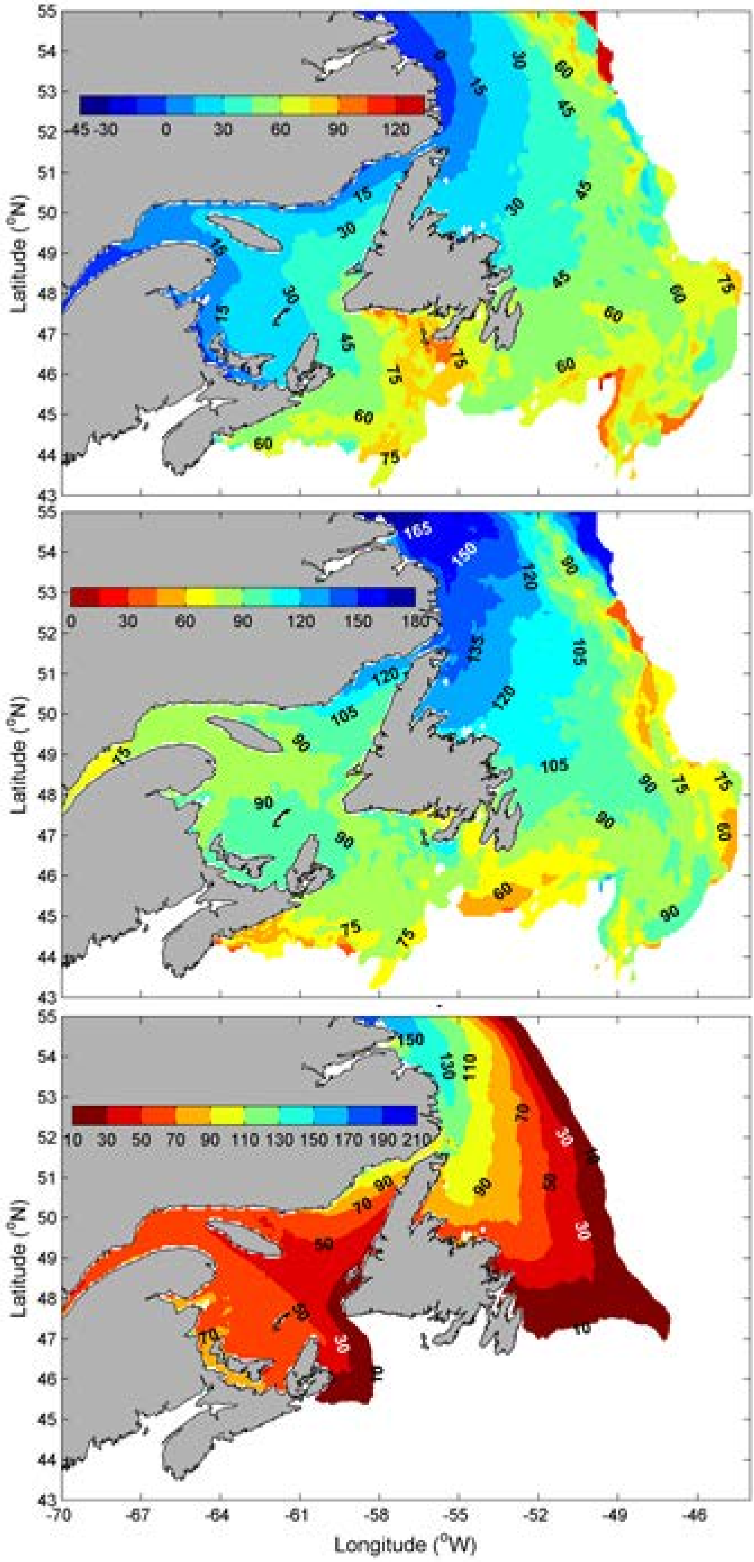

Figure 12. The 1981-2010 mean time when ice in the Gulf of St. Lawrence, Scotian, Newfoundland and Labrador shelves first appeared in days from the beginning of the year (top panel), the time when ice was last seen (middle panel) and the duration of ice (only regions where duration was 10 days or longer 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.

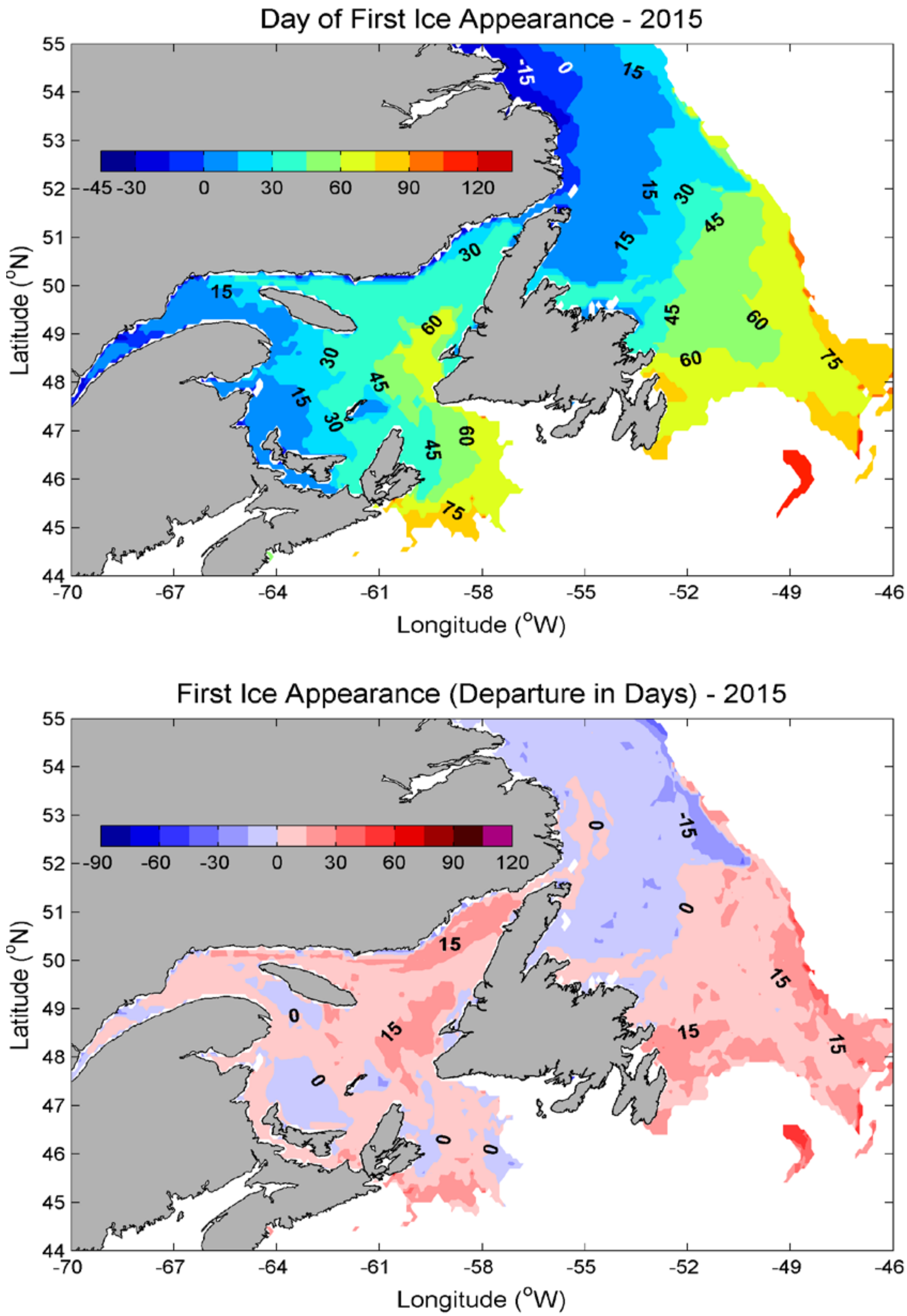

Figure 13. The time when ice in the Gulf of St. Lawrence, Scotian, Newfoundland and Labrador shelves first appeared during 2015 in days from the beginning of the year (top panel) and its anomaly from the 1981-2010 mean in days (bottom panel). Negative (positive) anomalies in blue (red) indicate earlier (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.

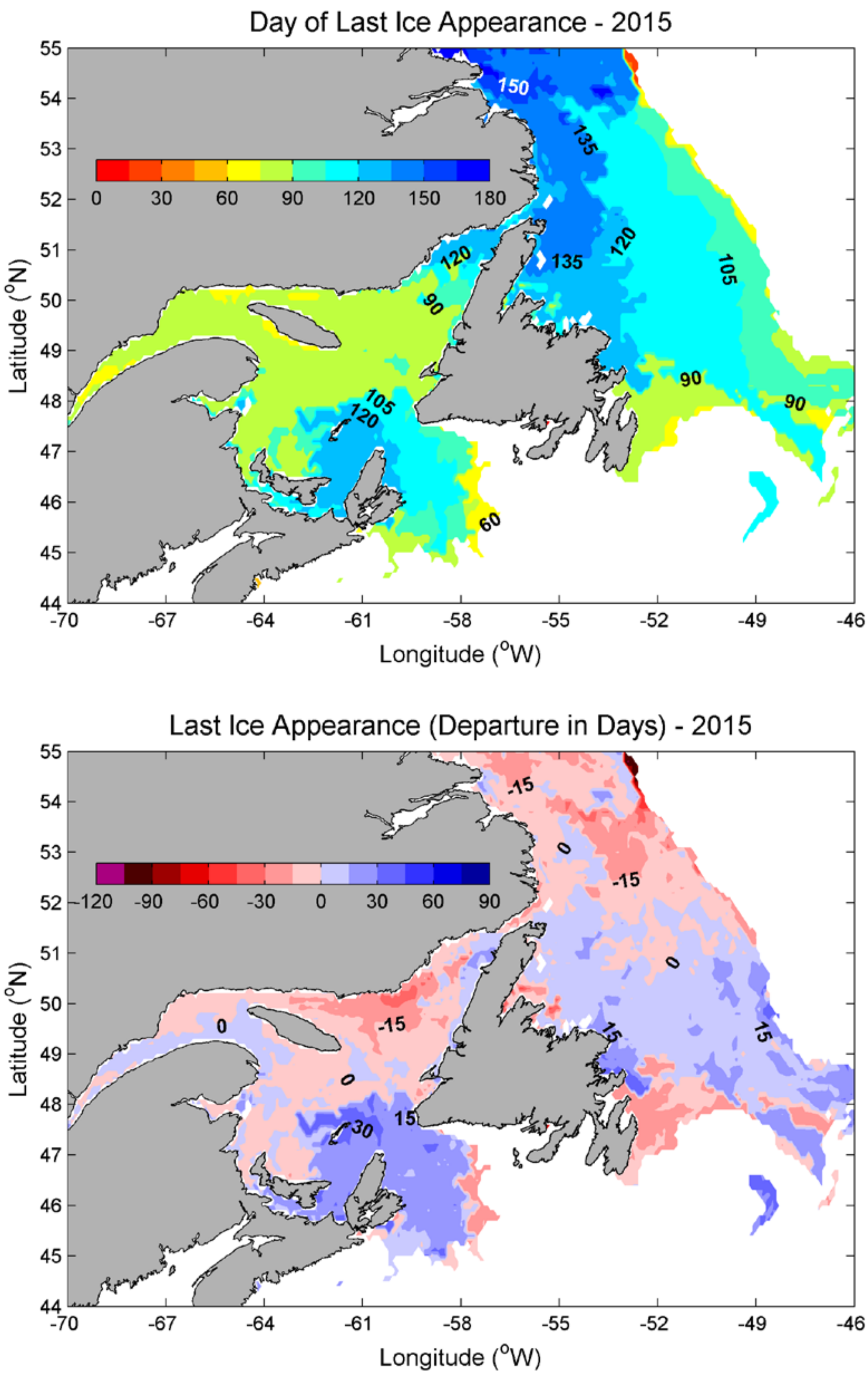

Figure 14. The time when ice in the Gulf of St. Lawrence, Scotian, Newfoundland and Labrador shelves was last seen in 2015 in days from the beginning of the year (top panel) and its anomaly from the 1981-2010 mean in days (bottom panel). Negative (positive) anomalies in red (blue) indicate earlier (later) 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.

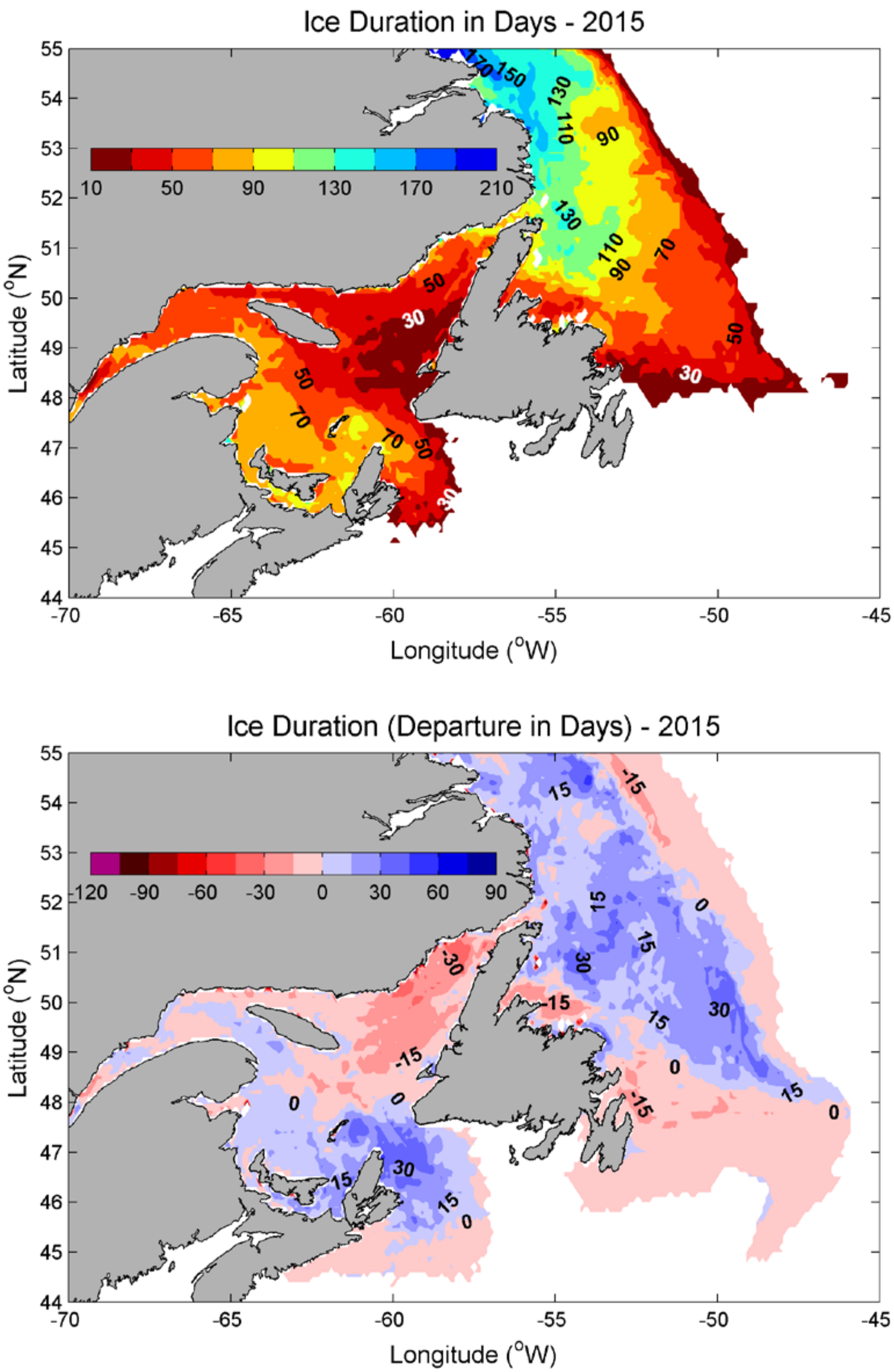

Figure 15. The duration of ice in the Gulf of St. Lawrence, Scotian, Newfoundland and Labrador shelves in days (top panel) during 2015 and the anomalies from the 1981-2010 mean in days (bottom panel). Positive (negative) anomalies in blue (red) indicate durations longer (shorter) than the mean. Note 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.

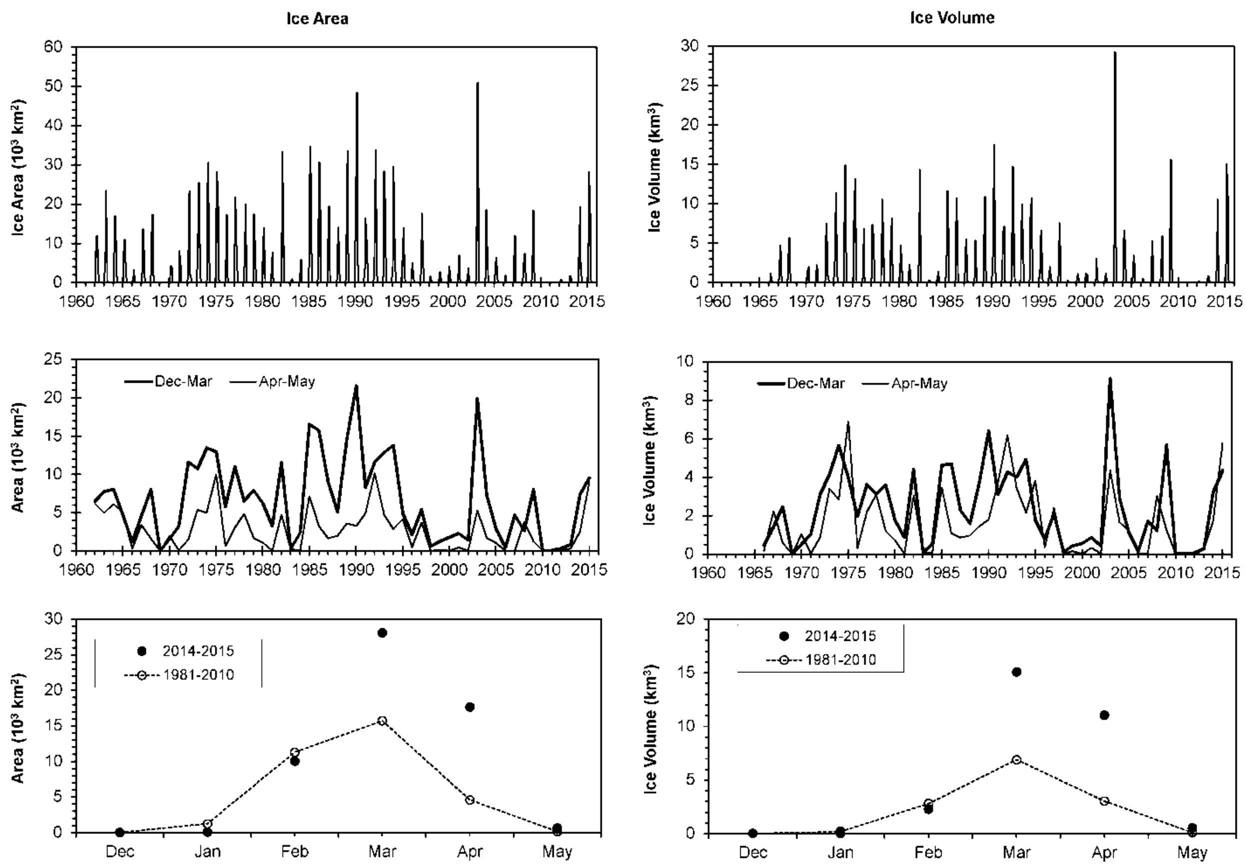

Figure 16. Time series of the monthly mean ice area and volume for the Scotian Shelf (top panels), the average ice area and volume during the usual periods of advancement (January-March) and retreat (April-May) (middle panels), and the comparison of the 2014-2015 monthly areas and volumes to the 1981-2010 means (bottom panels). Note that the 2010-2013 ice area and volume is basically zero.

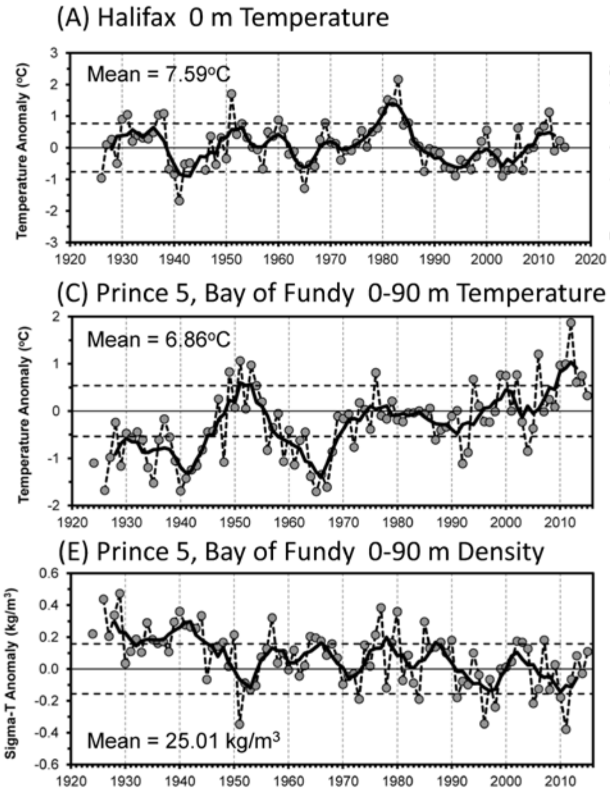

Figure 17. The annual surface temperature anomalies (dotted line with circles) and their five year running means (heavy black line) for: (A) Halifax Harbour and (B) St. Andrews; annual depth-averaged (0-90 m) (C) temperature, (D) salinity, and (E) density anomalies for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Horizontal dashed lines are mean plus and minus 1 SD.

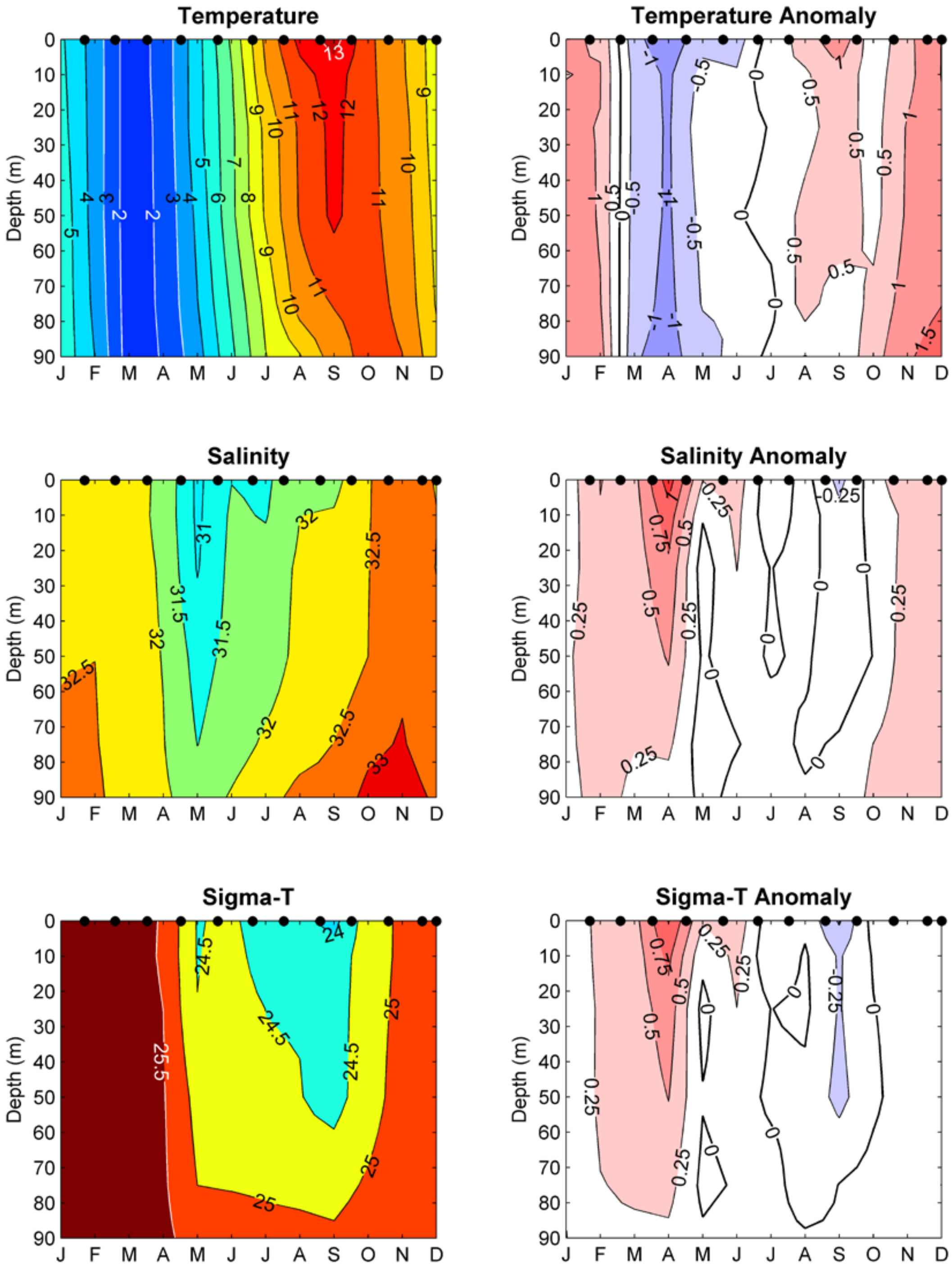

Figure 18. The 2015 annual cycle of temperature (top panel), salinity (middle panel) and density (lower panel) and their anomalies with respect to 1981-2010 monthly means (right panels) for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Bullets indicate periods of sampling.

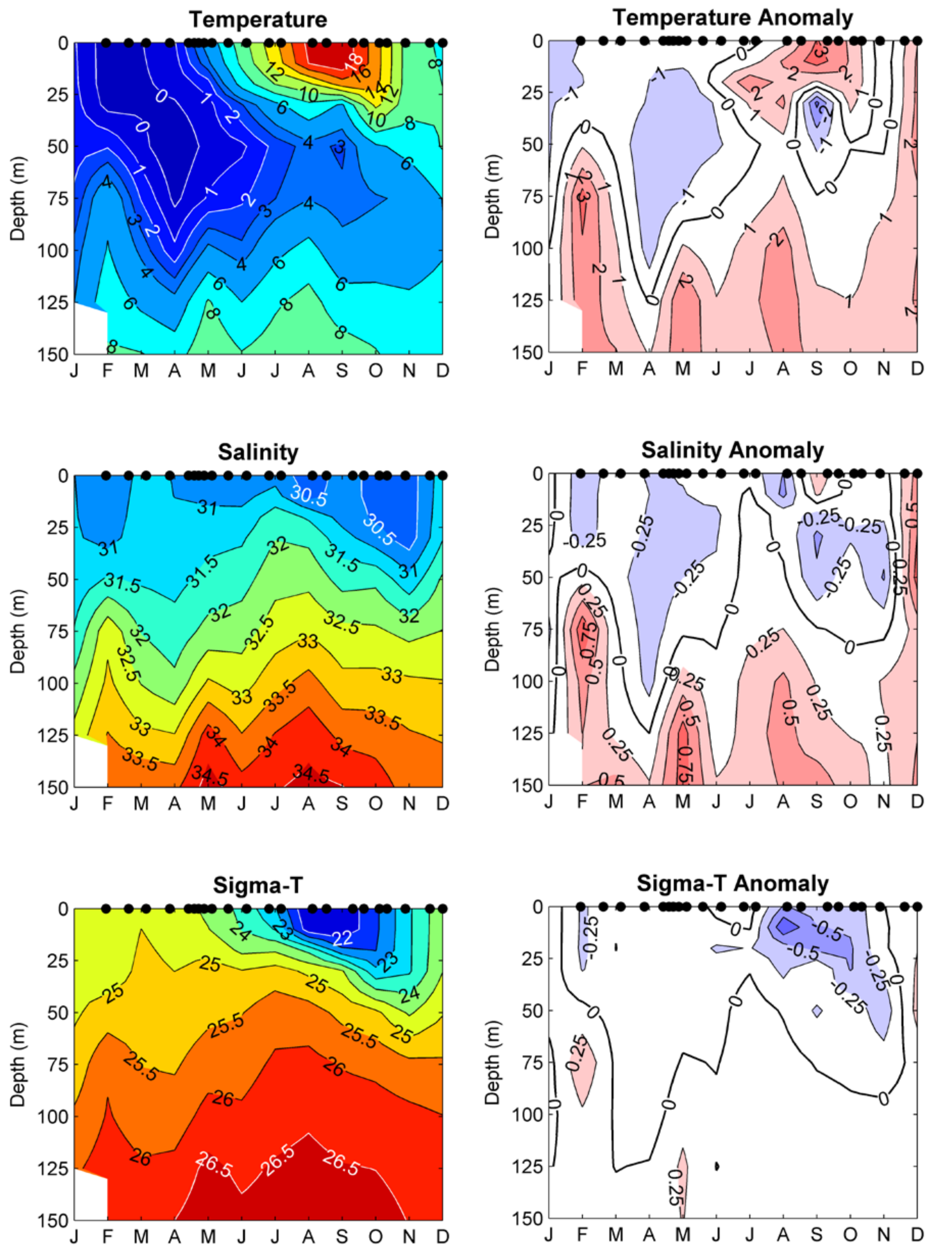

Figure 19. The 2015 annual cycle of temperature (top panel), salinity (middle panel) and density (lower panel) and their anomalies with respect to 1981-2010 monthly means (right panels) for Halifax station 2. Bullets indicate periods of sampling.

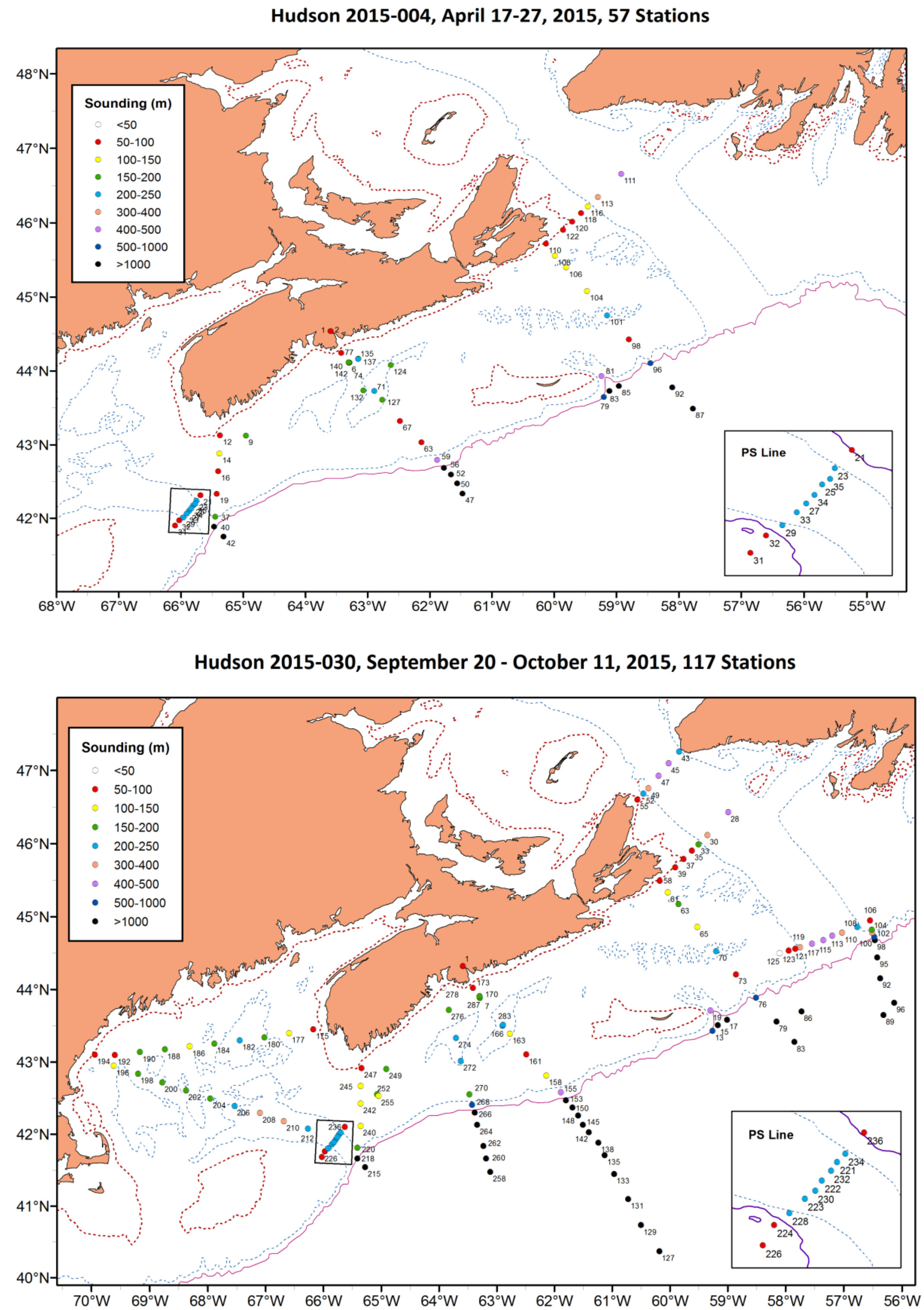

Figure 20. The 2015 sampling of the Scotian Shelf/Gulf of Maine for Spring (top panel) and Fall (bottom panel) surveys.

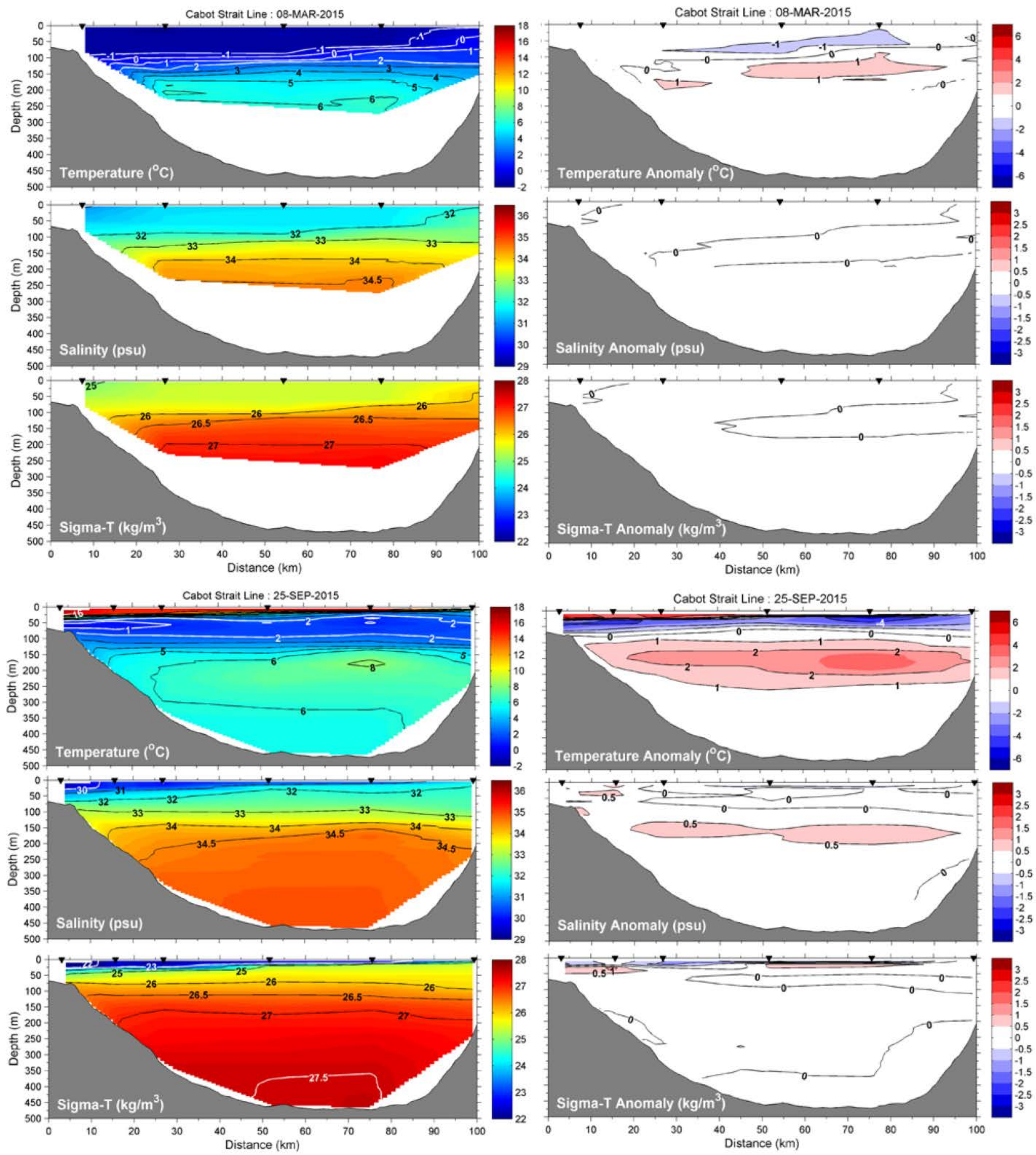

Figure 21. The 2015 sampling of the Cabot Strait Line for Spring (top three panels) and Fall (bottom three panels). Temperature (top panel in each group), salinity (middle panel in each group) and density (lower panel in each group) and their anomalies with respect to 1981-2010 monthly means (right panels). Bullets indicate periods of sampling.

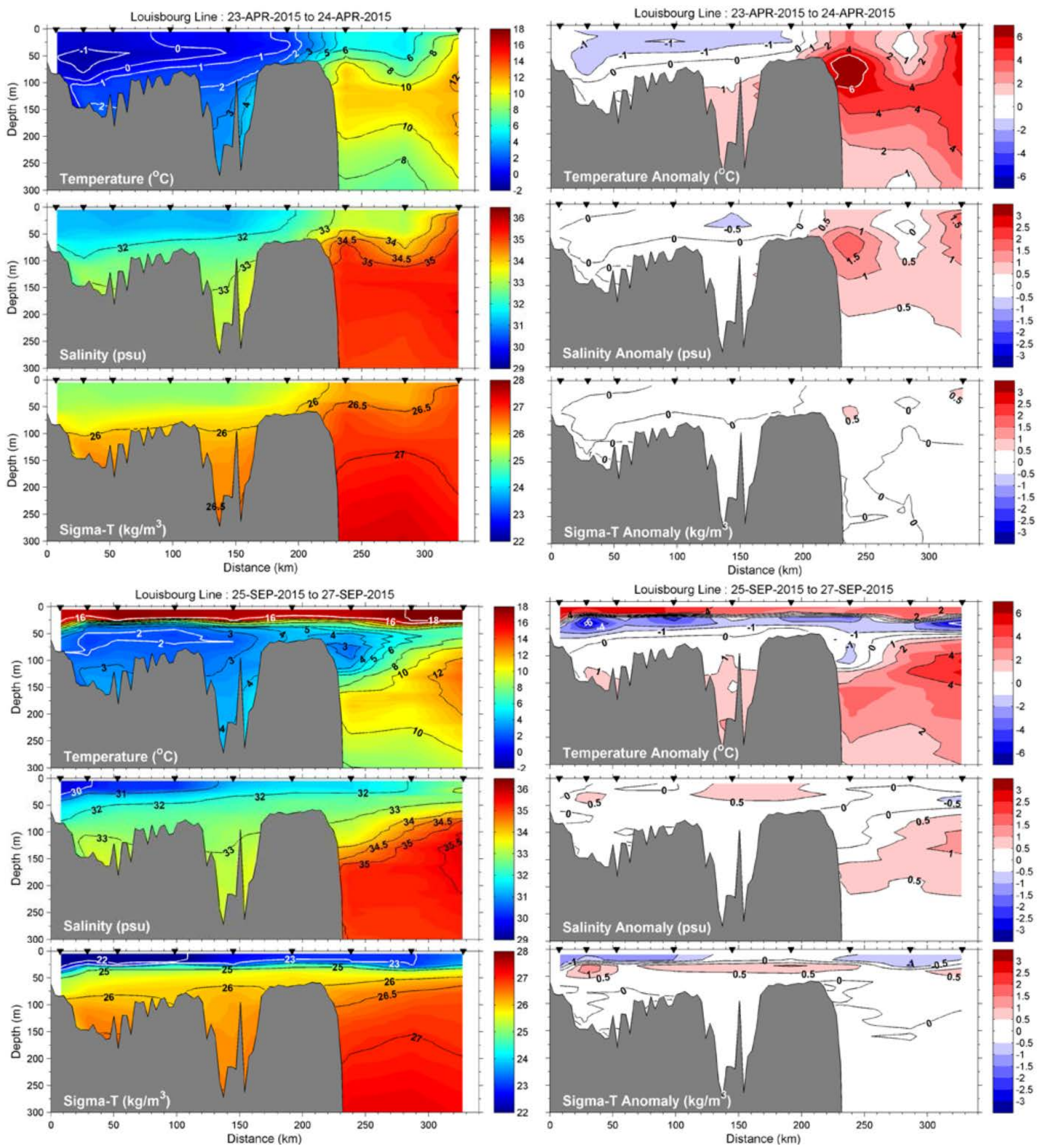

Figure 22. The 2015 sampling of the Louisbourg Line for Spring (top three panels) and Fall (bottom three panels). Temperature (top panel in each group), salinity (middle panel in each group) and density (lower panel in each group) and their anomalies with respect to 1981-2010 monthly means (right panels). Bullets indicate periods of sampling.

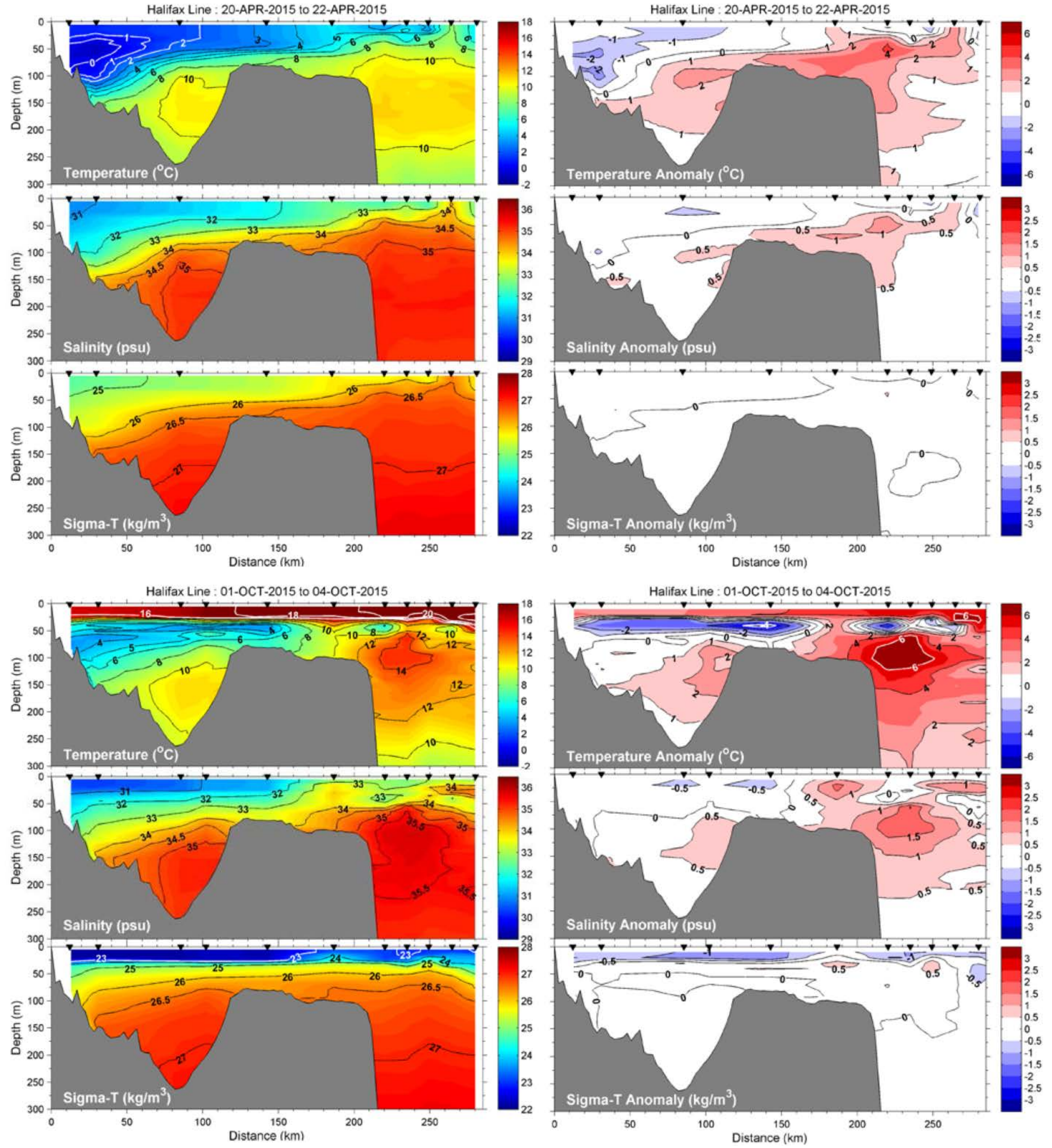

Figure 23. The 2015 sampling of the Halifax Line for Spring (top three panels) and Fall (bottom three panels). Temperature (top panel in each group), salinity (middle panel in each group) and density (lower panel in each group) and their anomalies with respect to 1981-2010 monthly means (right panels). Bullets indicate periods of sampling.

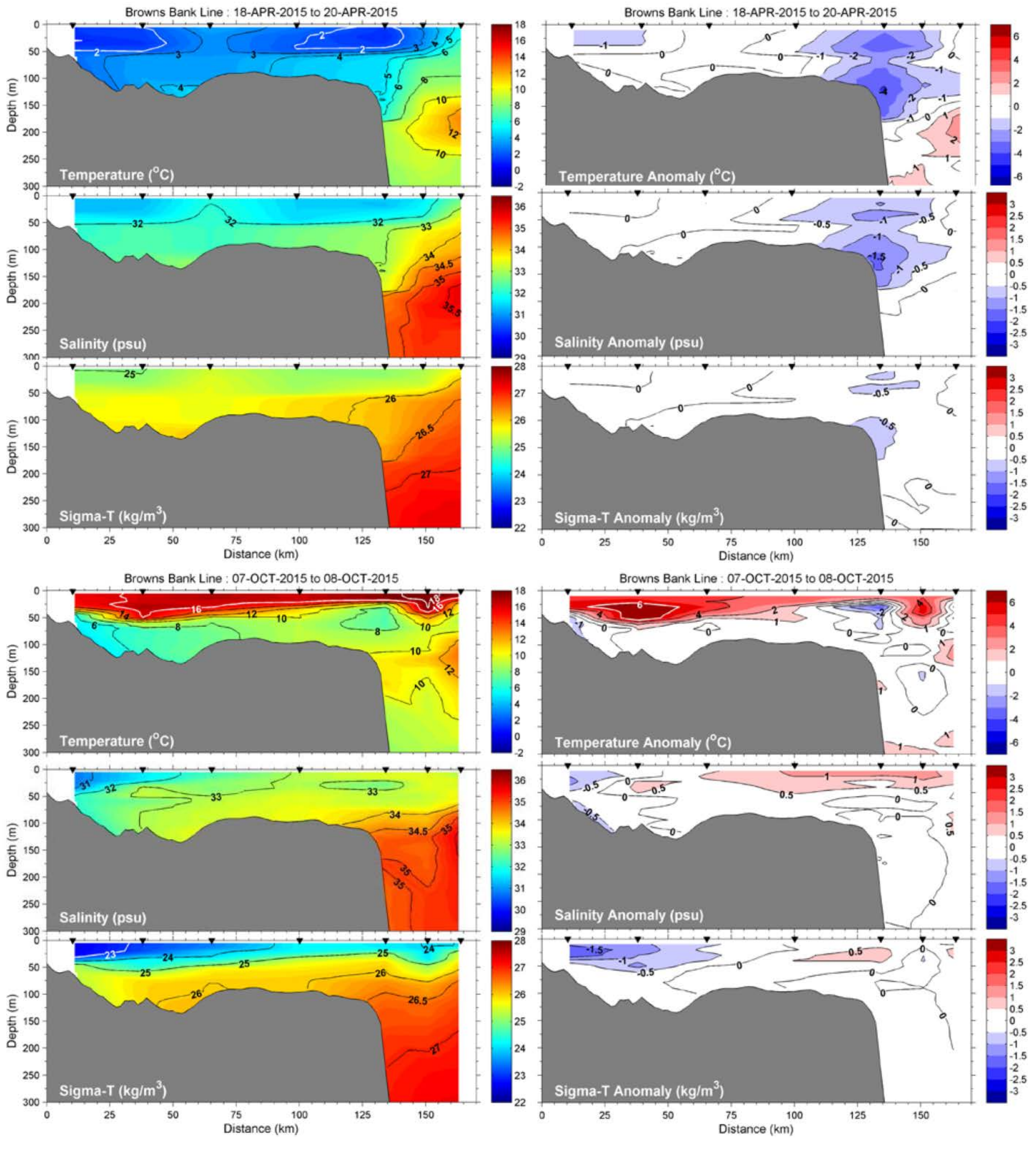

Figure 24. The 2015 sampling of the Browns Bank Line for Spring (top three panels) and Fall (bottom three panels). Temperature (top panel in each group), salinity (middle panel in each group) and density (lower panel in each group) and their anomalies with respect to 1981-2010 monthly means (right panels). Bullets indicate periods of sampling.

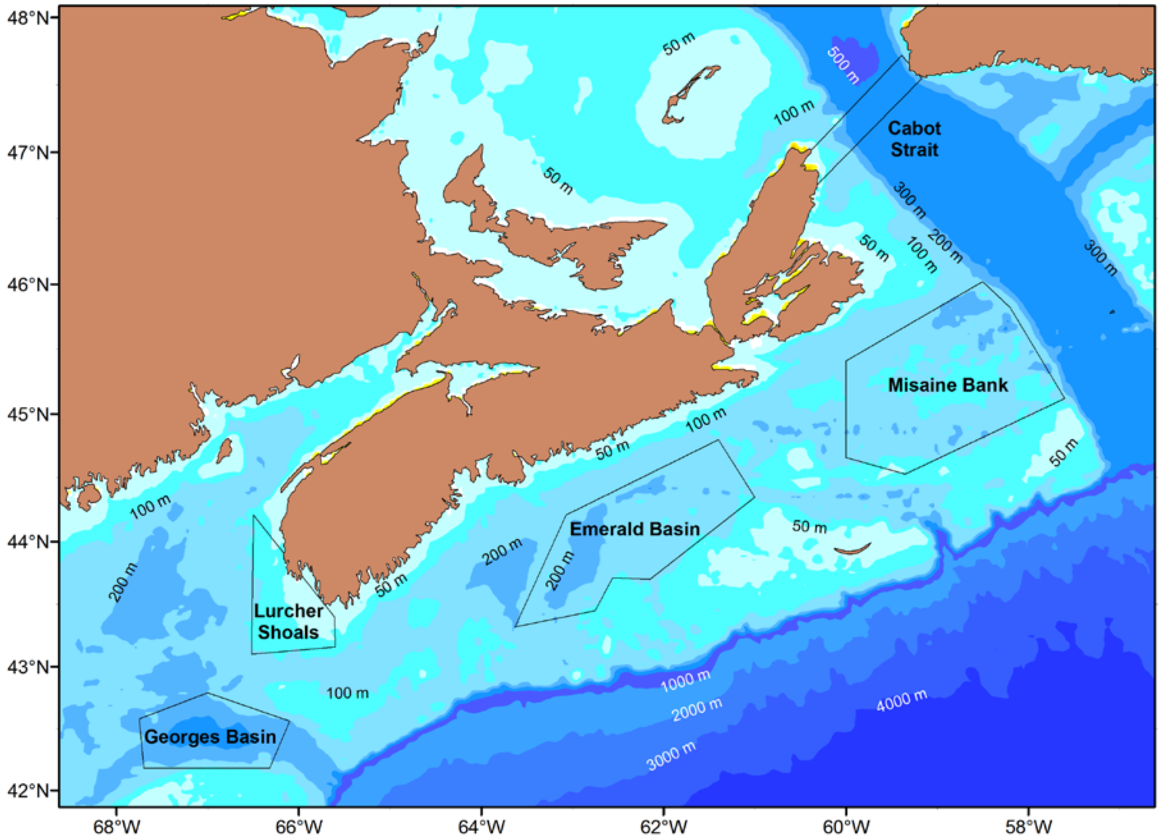

Figure 25. Areas on the Scotian Shelf and eastern Gulf of Maine depicting the different water masses: Cabot Strait; Misaine Bank; Emerald Basin; Lurcher Shoals; and Georges Basin.

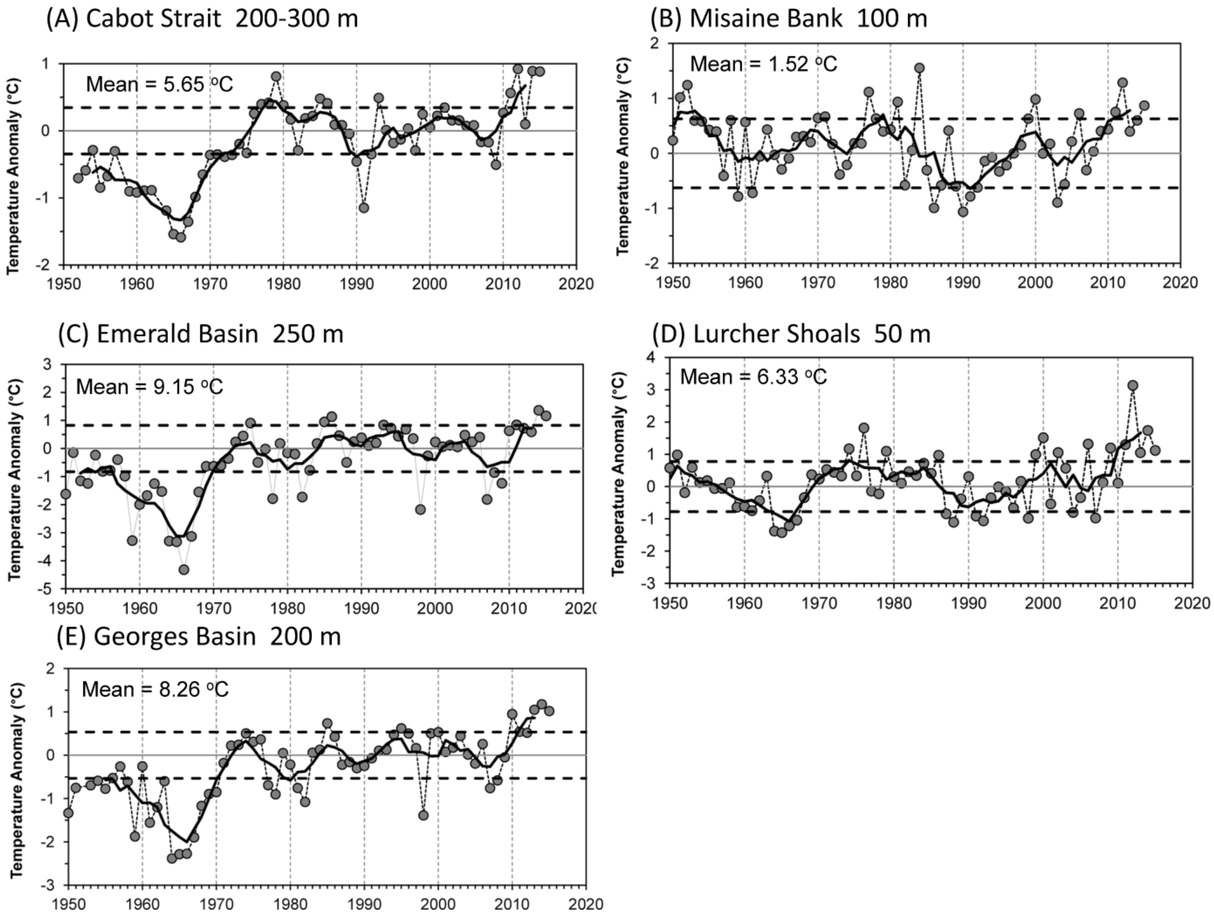

Figure 26. The annual mean temperature anomaly time series (dotted line with circles) and the five year running mean filtered anomalies (heavy solid line) on the Scotian Shelf and in the Gulf of Maine at: (A) Cabot Strait at 200-300 m; (B) Misaine Bank at 100 m; (C) Emerald Basin at 250 m; (D) Lurcher 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 1 SD.

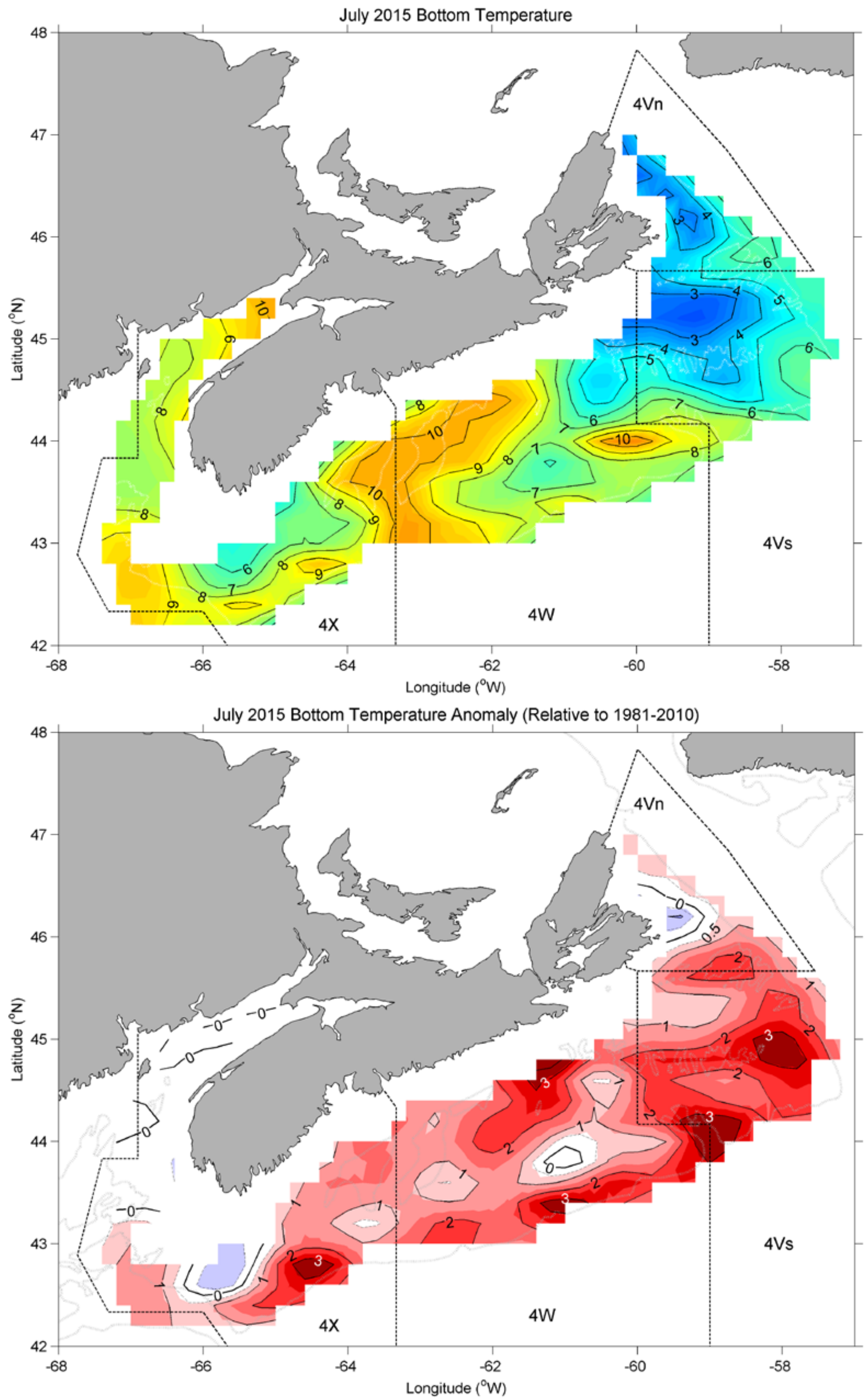

Figure 27. July bottom temperature (upper panel) and anomaly (lower panel; relative to 1981-2010) maps for 2015. NAFO Divisions 4Vn, 4Vs, 4X and 4W are shown.

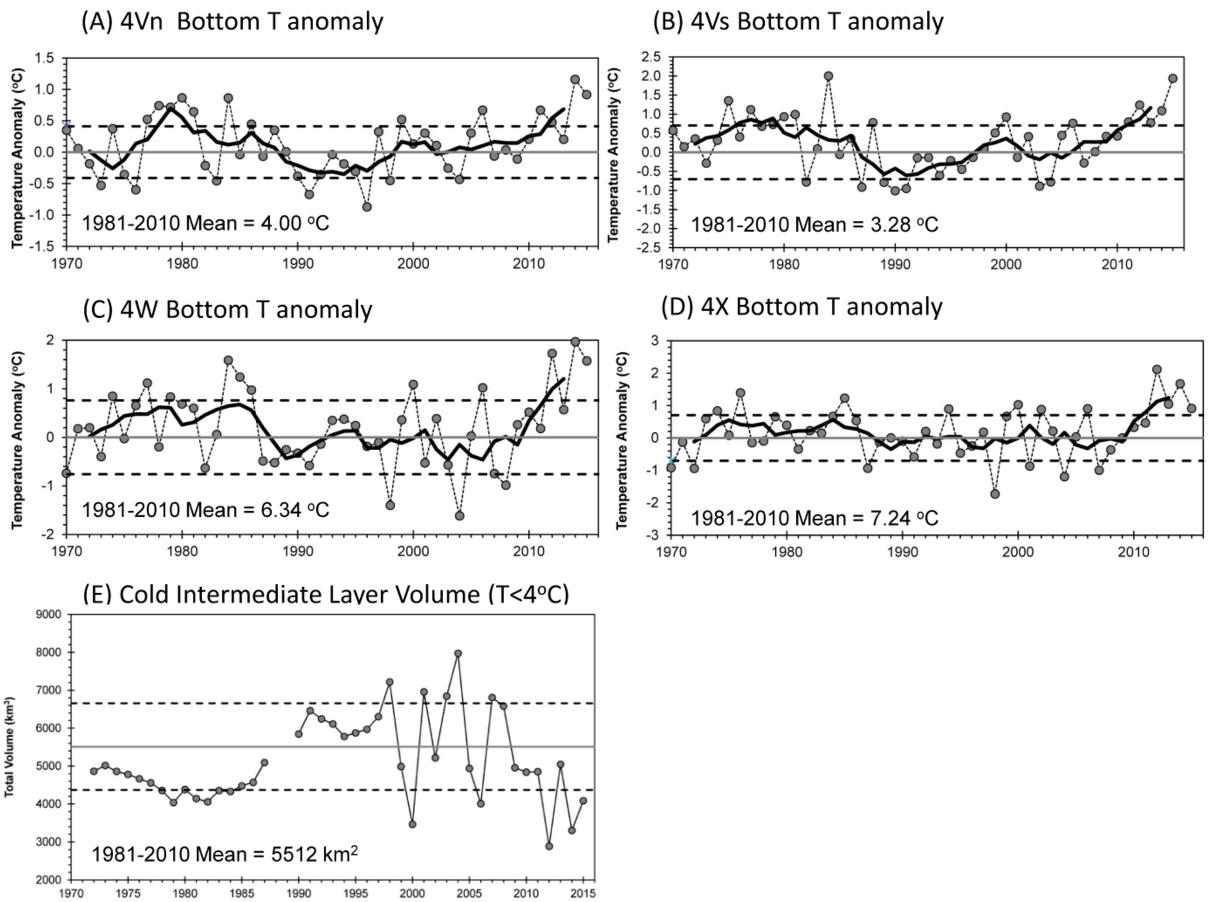

Figure 28. Time series of July bottom temperature anomalies (thin lines with circles) and five year running mean filtered series (heavy line) for NAFO Divisions: (A) 4Vn, (B) 4Vs, (C) 4W, and (D) 4X. (E) Time series of the Cold Intermediate Layer (CIL; defined as waters with temperature <4°C) volume 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 1 SD.

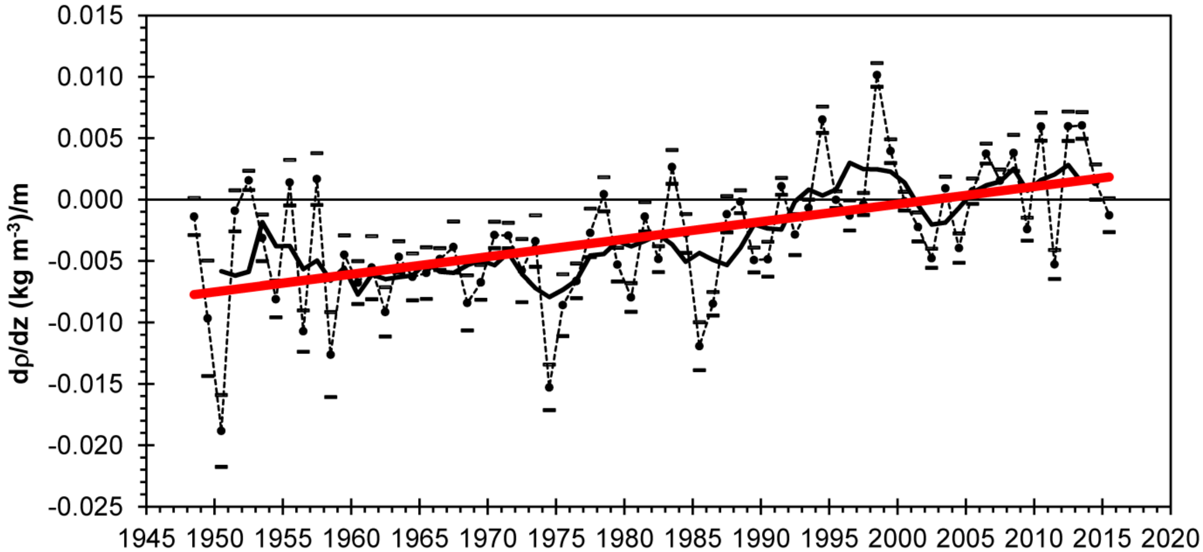

Figure 29. Stratification index (0-50 m density gradient) mean annual anomaly (black dashed line with circles) and five year running mean (black heavy solid line) averaged over the Scotian Shelf. Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a change in the 0-50 m density difference of 0.36 kg m^{-3} over 50 years.

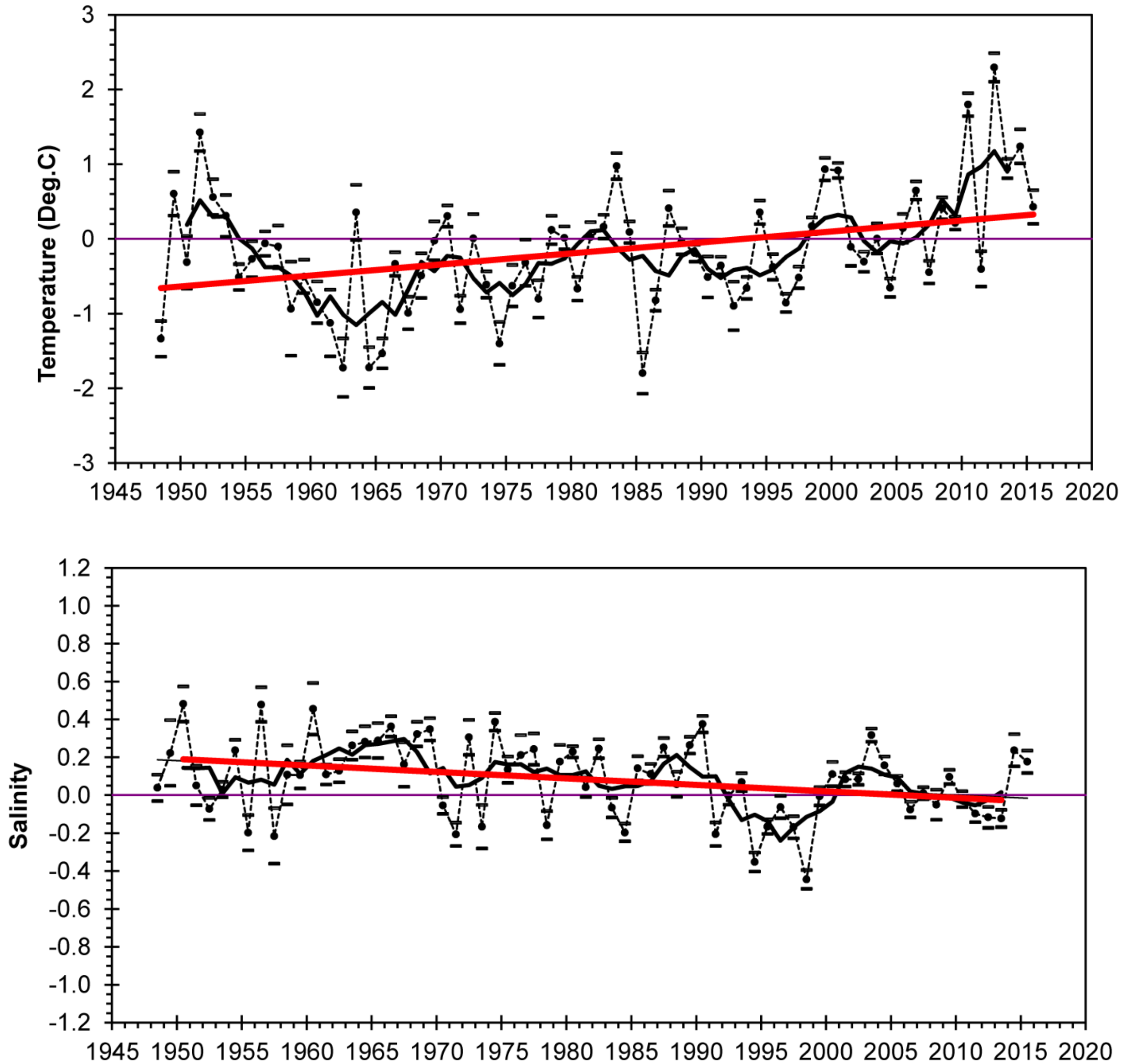

Figure 30. The mean annual surface temperature (top panel) and salinity (lower panel) anomalies (black dashed line with circles) and five year running mean (black heavy solid line) averaged over the Scotian Shelf. Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a warming of 0.74^{o}C and a freshening of 0.15 over a 50 year period.

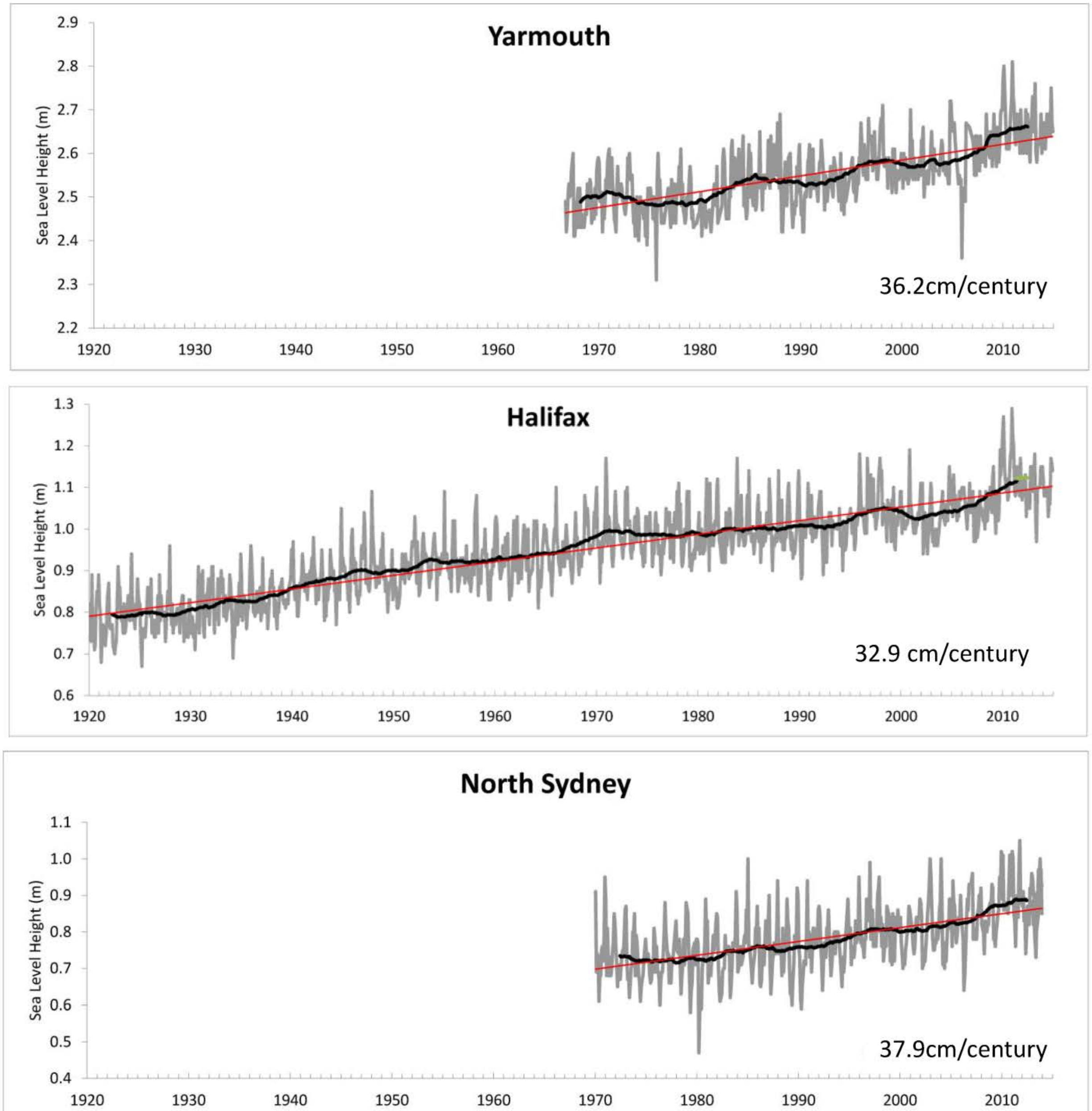

Figure 31. The time series of the monthly means (grey line) and a five year running mean (black line) of the relative sea level elevations at Yarmouth (top panel), Halifax (middle panel) and North Sydney (bottom panel), along with the linear trend (red line) over the observation period.

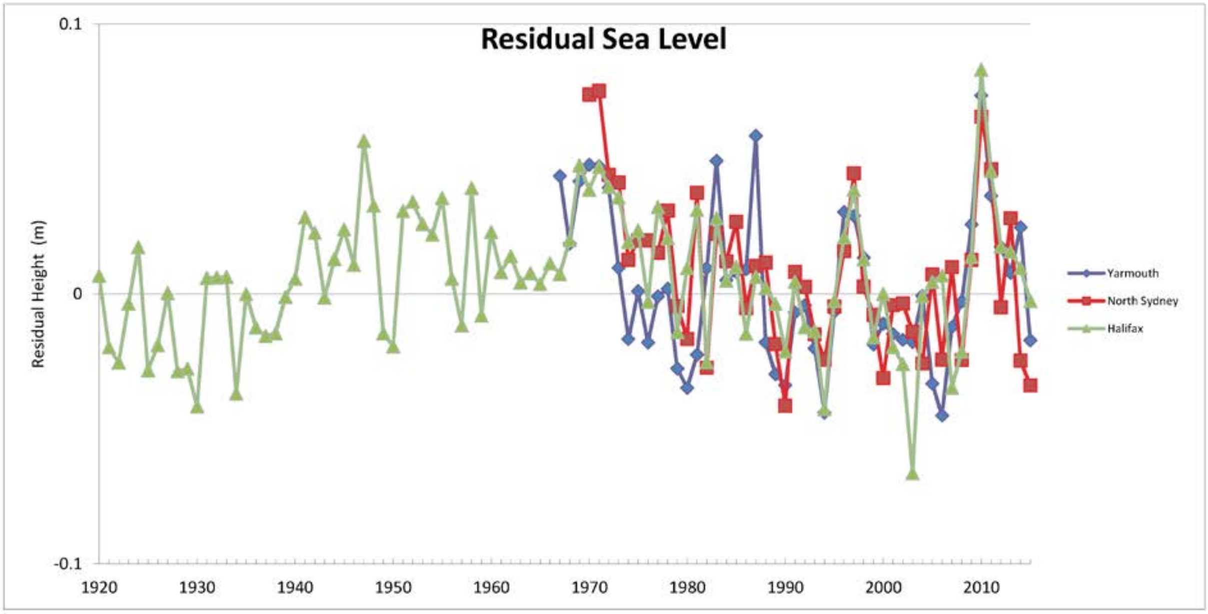

Figure 32. Residual relative sea level (monthly observed values – (1981-2010) linear trend, averaged to annual estimate for Yarmouth (blue line with diamonds), Halifax (green line with triangles) and North Sydney (red line with squares).

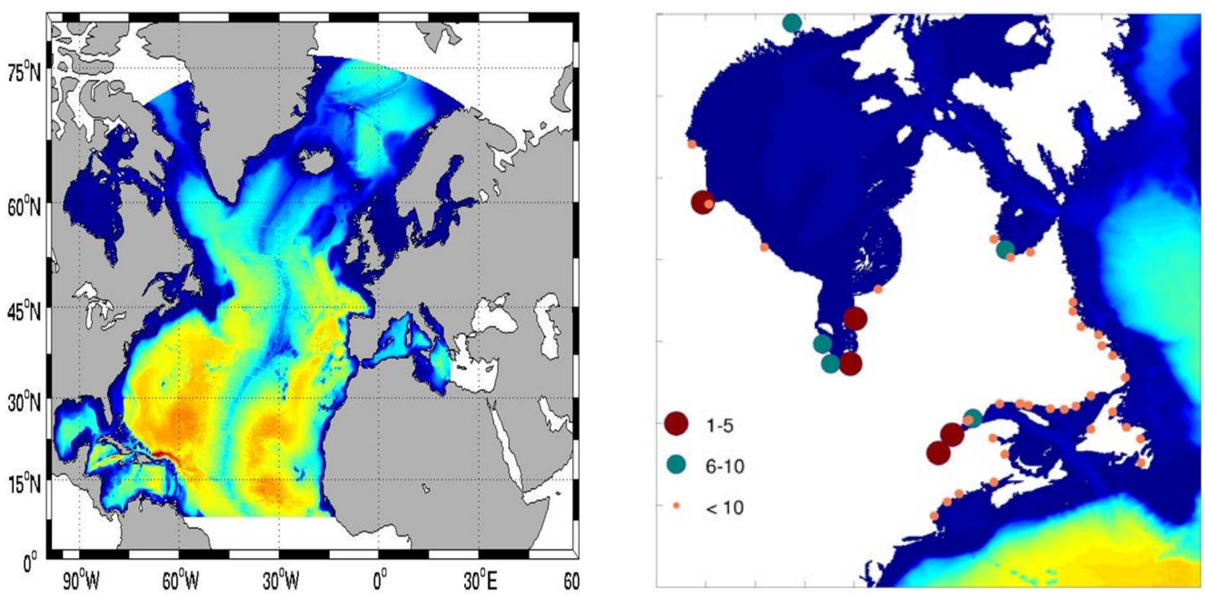

Figure 33. The North Atlantic Ocean model (NAO) domain (left panel). Bathymetry coloured from red (deep) to blue (shallow). The locations of the 45 rivers, colour-coded based on ranked discharge (right panel). The top four rivers are the St. Lawrence, Nelson, Saguenay and La Grande.

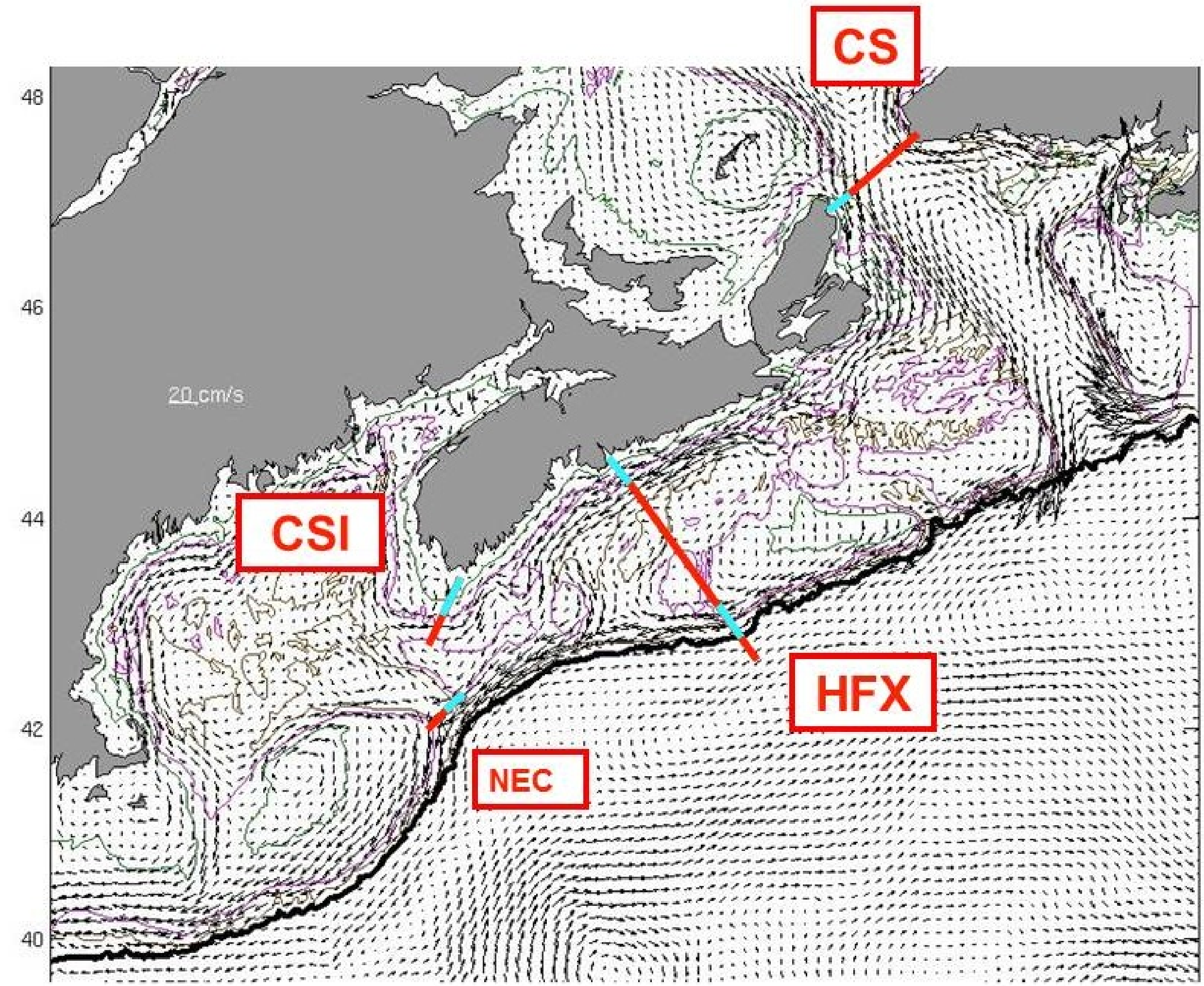

Figure 34. Annual average depth-averaged circulation illustrating the principal flow pathways from the southern Gulf of St. Lawrence to the Gulf of Maine and the subsections where transport calculations were made (cyan). CS = Cabot Strait; HFX = Halifax; CSI = Cape Sable Island/Browns Bank; NEC = Northeast Channel.

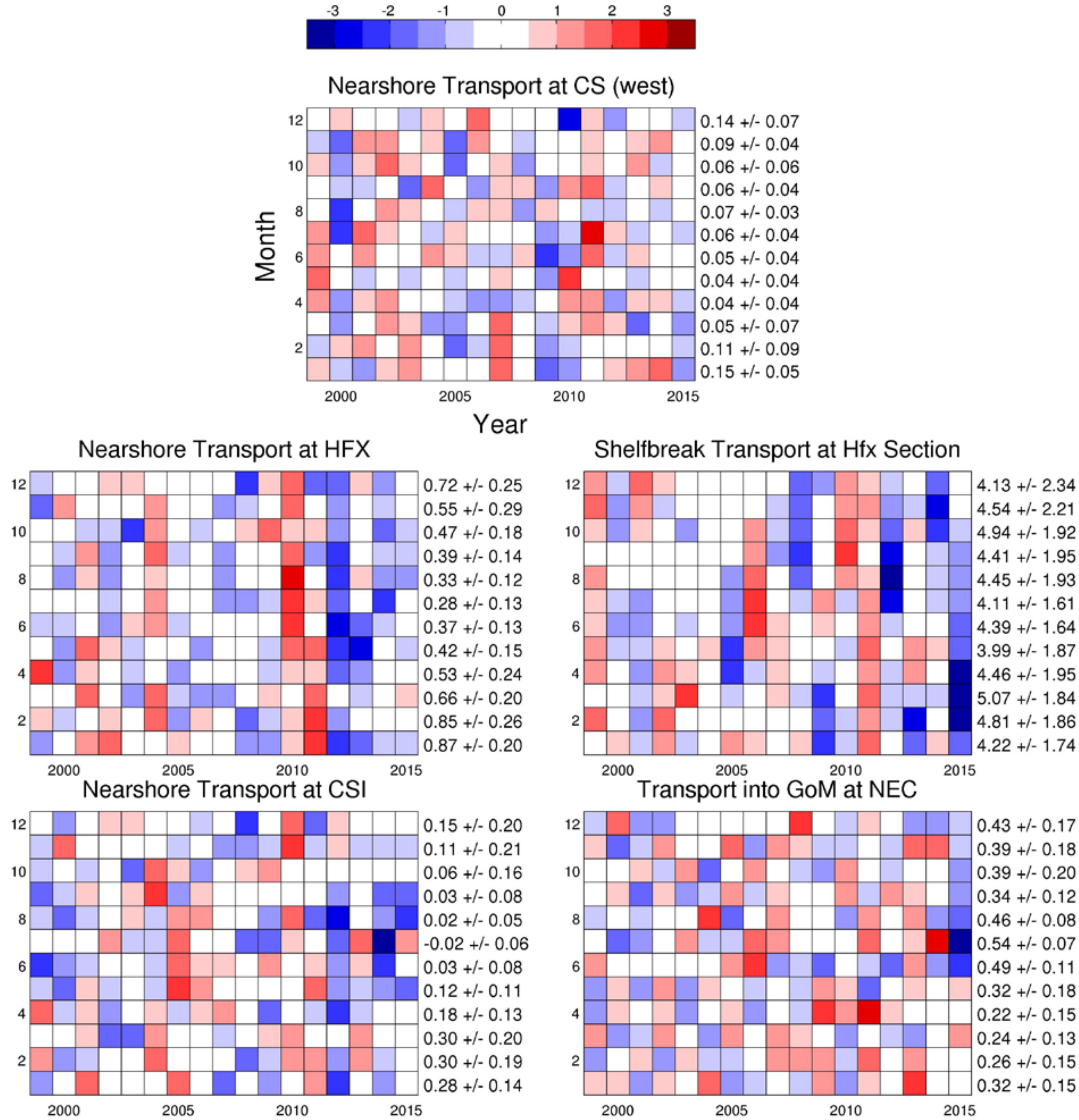

Figure 35. Standardized anomalies of the monthly transport for years 1999-2015 for four Maritime sections: (top) Cabot Strait (CS) west nearshore; (middle) Halifax (HFX) nearshore and shelfbreak; (bottom) Cape Sable Island (CSI) nearshore, and the Northeast Channel (NEC). Numbers to the right are monthly means and standard deviations.

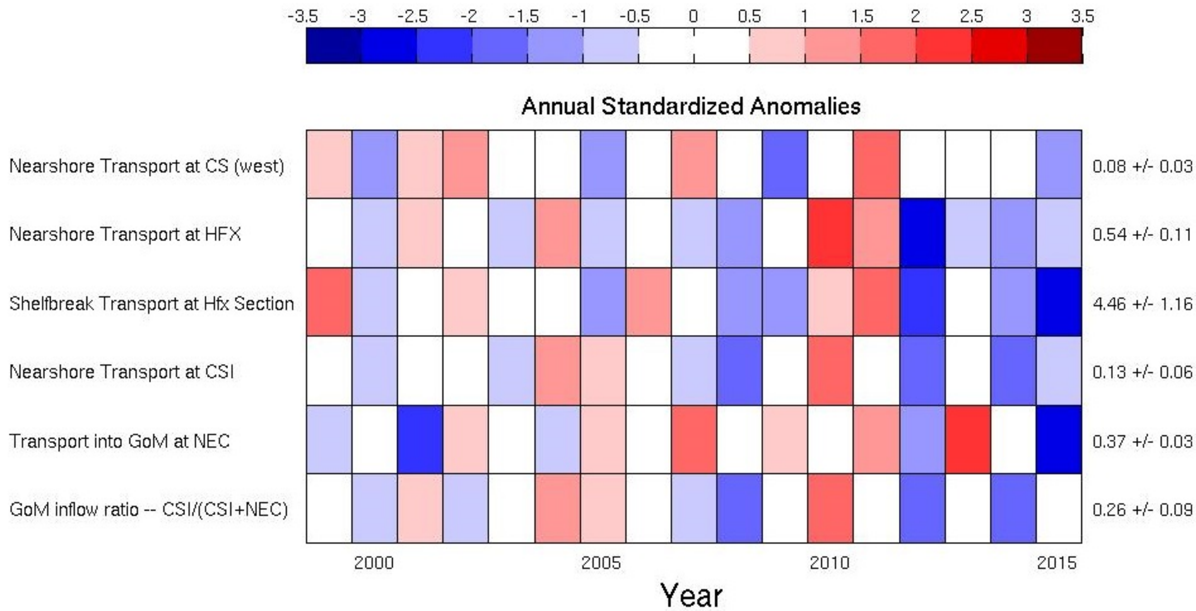

Figure 36. Annual transport anomalies scaled by the standard deviation for the variables in Figures 35 and 38 for years 1999-2014 (top panel). Numbers to the right are annual means and standard deviations. Note: the inflow at the Northeast Channel (NEC) was omitted, as it is not independent. CS = Cabot Strait; HFX = Halifax; CSI = Cape Sable Island; NEC = Northeast Channel.

Transport (SV)									
Month / Year	2008	2009	2010	2011	2012	2013	2014	2015	Grand Total
12	-0.46	-0.59	-0.58	-0.33	-0.50	-0.83	-0.42		-0.53
11	-0.22	-0.34	-0.52	-0.49	-0.43	-0.30	-0.50		-0.40
10	-0.22	-0.51	-0.36	-0.30	-0.32	-0.22	-0.21		-0.31
9	-0.43	-0.21	-0.30	-0.12	-0.14	-0.03	-0.17		-0.20
8	-0.40	-0.26	-0.32	-0.23	-0.13	-0.08	-0.12		-0.22
7	-0.04	-0.29	-0.39	-0.37	-0.11	-0.15	-0.07		-0.20
6		-0.31	-0.54	-0.40	-0.09	-0.16	-0.28		-0.30
5		-0.33	-0.52	-0.43	-0.22	-0.12	-0.26		-0.31
4		-0.34	-0.33	-0.48	-0.23	-0.37	-0.39	-0.32	-0.35
3		-0.48	-0.47	-0.55	-0.64		-0.53	-0.63	-0.55
2		-0.66	-0.68	-0.85	-0.59	-0.64	-0.44	-0.62	-0.64
1		-0.80	-0.65	-0.67	-0.38	-0.60	-0.45	-0.74	-0.61
Grand Total	-0.30	-0.43	-0.47	-0.43	-0.32	-0.32	-0.32	-0.58	-0.39

Figure 37. Monthly transport (1 Sv = 10^6 m^3 s^{-1}) for years 2008-2015 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.

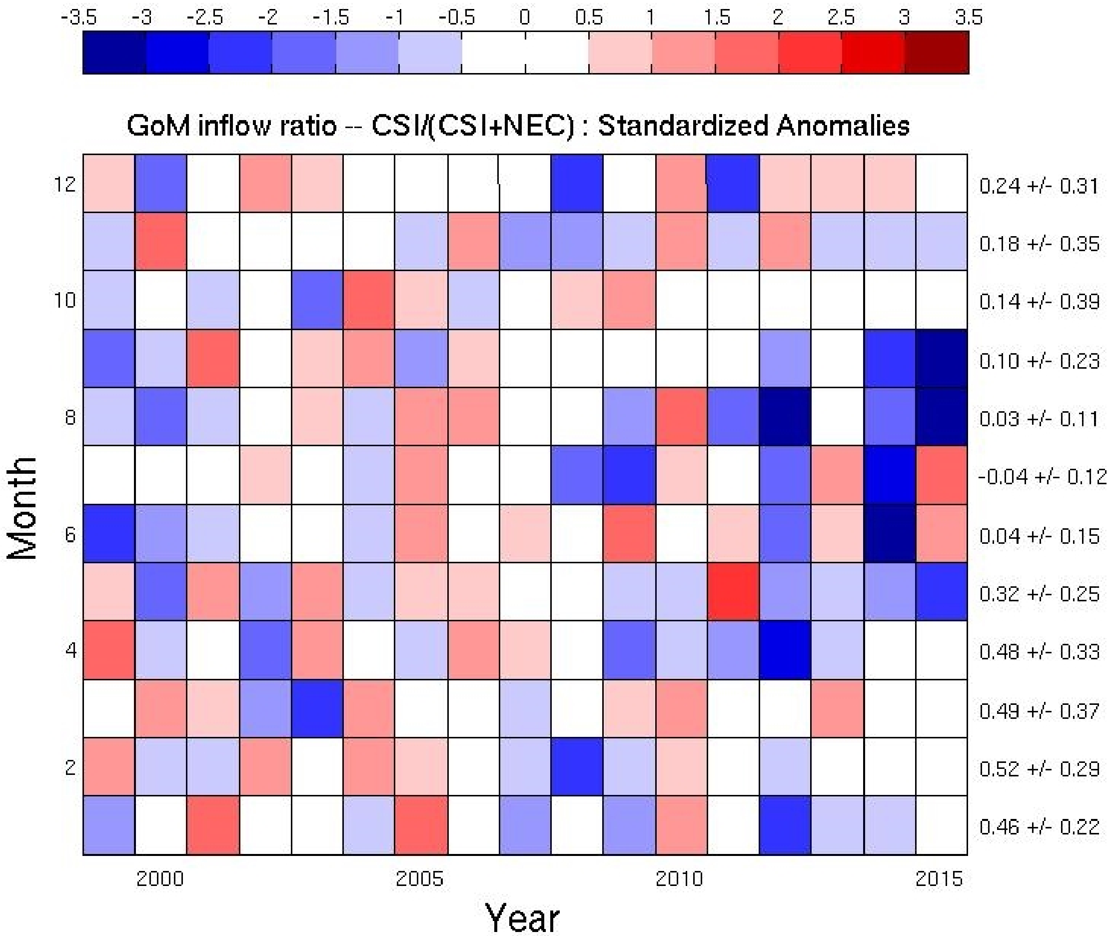

Figure 38. Standardized anomalies of the Gulf of Maine (GoM) inflow ratio for years 1999-2015. Numbers to the right are monthly means and standard deviations. CSI = Cape Sable Island; NEC = Northeast Channel.

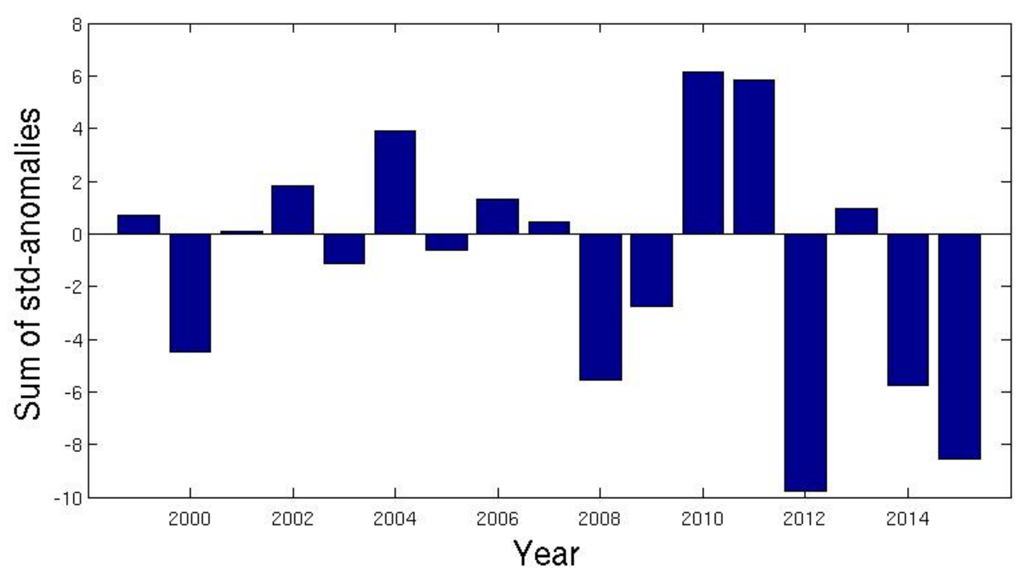

Figure 39. Sum of standardized anomalies for 1999-2015, for the variables in Figures 35 and 38. See text for further details.

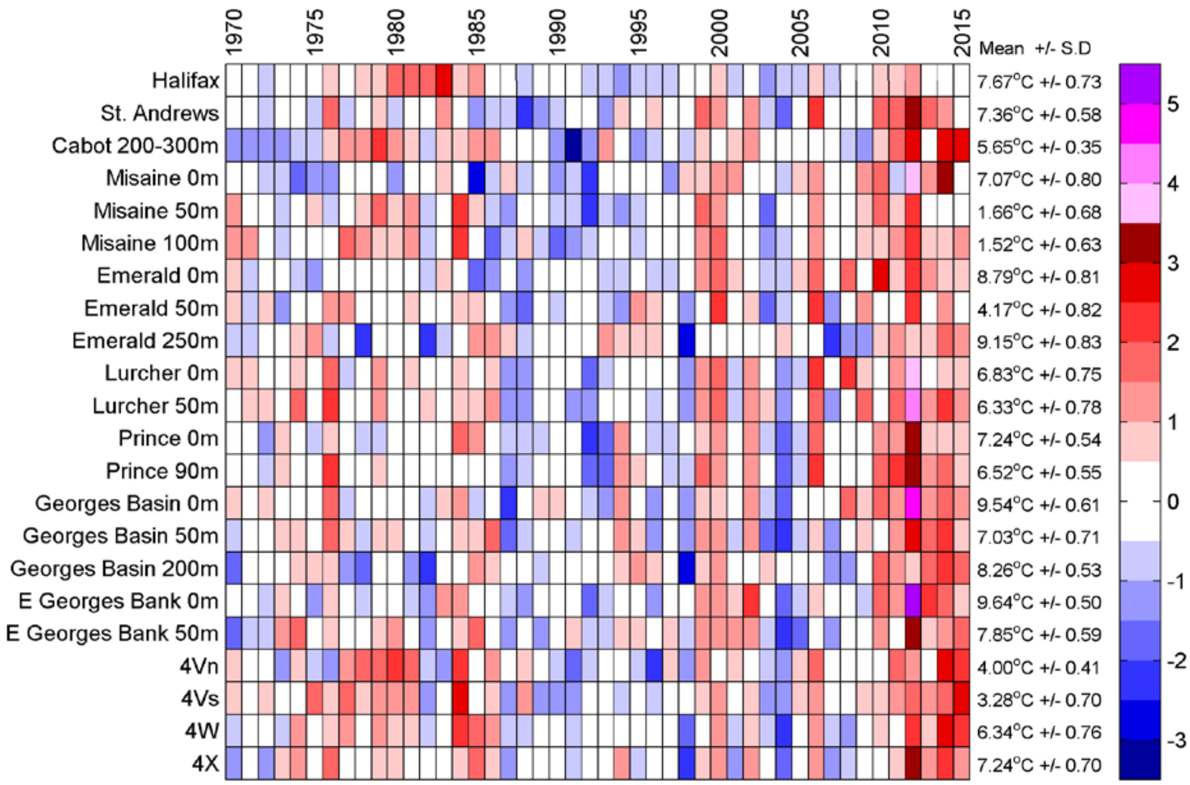

Figure 40. Normalized annual anomalies of temperatures at the bottom and discrete depths for the Scotian Shelf-Gulf of Maine region. These anomalies are based on the 1981-2010 means divided by the standard deviation. Blue colours indicate below normal anomalies, red and purple (for 2012, the colour scale had to be increased above +3.5 SD and is shaded in purple) colours above normal anomalies.

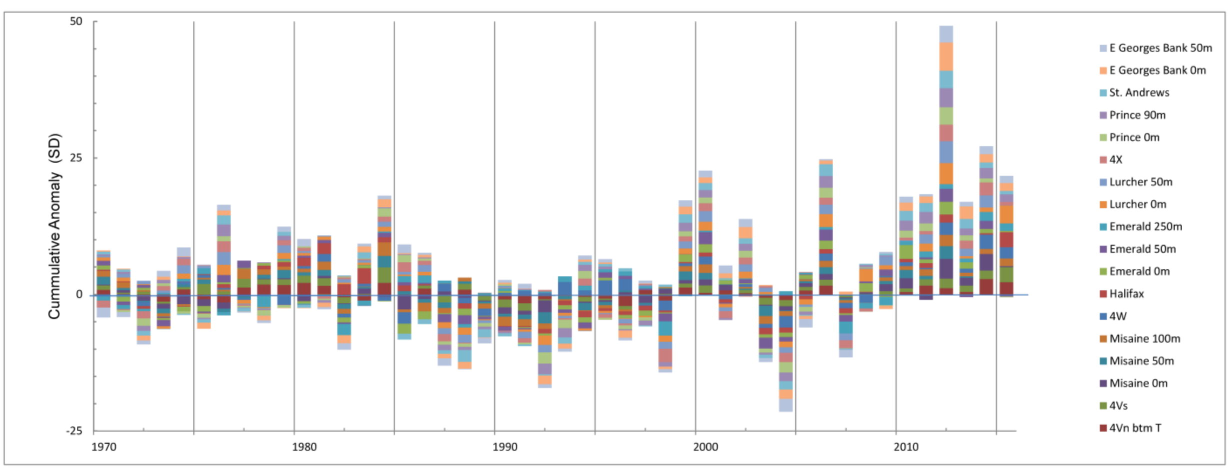

Figure 41. The contributions of each of the normalized anomalies are shown as a stacked bar chart.