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Meteorological, Sea Ice and Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2013

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

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.

Research documents are produced in the official language in which they are provided to the Secretariat.

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ABSTRACT

In 2013, the North Atlantic Oscillation index was below the 1981-2010 mean (-3.4 mb, -0.4 SD [standard deviation]) after having a positive anomaly last year and three years after its record low. Mean annual air temperature anomalies were from +0.1°C (Saint John, New Brunswick) to +0.8°C (Sable Island, Nova Scotia), +0.2 to +1.1 SD, above normal in 2013 but lower than those observed in 2012. There has been very little ice on the Scotian Shelf from April 2009 until the end of the season in May 2013. The ice volume during 2013 was the seventh lowest in the 52 year long record. Years 2010, 2011 and 2012 had the second to fourth lowest coverage and volume. Positive sea surface temperature (SST) anomalies prevailed throughout the region during 2013, with representative values of about +0.4 to +1.2°C (+0.4 to +1.5 SD). Long-term coastal monitoring sites at St. Andrews (New Brunswick) and Halifax (Nova Scotia) recorded annual SST anomalies of +1.0°C (+1.7 SD) and -0.04°C (-0.05 SD), respectively, in 2013, and +1.0°C below those observed in 2012, at both sites. At selected sites across the region, annual water temperature anomalies were positive in 2013: +0.1°C (+0.2 SD) for Cabot Strait 200-300 m depth range, +0.2°C (+0.4 SD) for Misaine Bank at 100 m, +0.6°C (+0.7 SD) for Emerald Basin at 250 m, +1.0°C (+1.3 SD) for Lurcher Shoals at 50 m, and +1.1°C (+0.9 SD) for Georges Basin at 200 m (the warmest year in the last 64 years). Bottom temperature anomalies in Northwest Atlantic Fisheries Organization areas 4VWX were all positive in 2013 and ranged from +0.2°C (+0.5 SD) in 4Vn to +1.0°C (+1.5 SD) in 4X. Average stratification on the Scotian Shelf strengthened slightly compared to 2012 and was the third strongest in the record. Since 1948, the stratification has slowly been increasing on the Scotian Shelf due mainly to a freshening (45%) and warming (35%) of the surface waters. A composite index consisting of 18 ocean temperature time series from surface to bottom across the region indicated that 2013 was the eighth warmest of 44 years, with an averaged normalized anomaly of +0.9 SD relative to the 1981-2010 period.

Conditions météorologiques, de la glace de mer et océanographiques physiques sur le plateau néo-écossais et dans le golfe du Maine en 2013

RÉSUMÉ

En 2013, l'indice d'oscillation nord-atlantique en hiver se situait au-dessous de la moyenne de 1981 à 2010 (-3,4 mb, -0,4 ÉT [écart type]), après l'anomalie que représentait la valeur positive de l'année dernière et trois ans après avoir atteint la valeur la plus basse jamais enregistrée. La moyenne annuelle des anomalies de la température atmosphérique variait entre +0,1 °C (Saint John, au Nouveau-Brunswick) et +0,8 °C (île de Sable, en Nouvelle-Écosse), avec un écart type de +0,2 à +1,1, des valeurs qui se situent au-dessus de la normale en 2013, mais au-dessous des valeurs observées en 2012. Il y a eu très peu de glace sur le plateau néo-écossais du mois d'avril 2009 jusqu'à la fin de la saison en mai 2013. Le volume de glace en 2013 se classe au septième rang des volumes les plus bas enregistrés en 52 ans. Le volume et la couverture de glace en 2010, 2011 et 2012 se classaient du deuxième au quatrième rang. On a observé des anomalies de température de la surface de la mer (SST) de valeur positive dans toute la région en 2013, avec des valeurs représentatives d'environ +0,4 à +1,2 °C (+0,4 à +1,5 ÉT). Aux sites de surveillance côtière à long terme de St. Andrews (Nouveau-Brunswick) et de Halifax (Nouvelle-Écosse), on a enregistré en 2013 des anomalies de la SST annuelle de +1,0 °C (+1,7 ÉT) et de -0,04 °C (+0,05 ÉT) respectivement, qui se situent à +1 °C au-dessous des valeurs observées en 2012 dans ces deux emplacements. À certains endroits de la région, les anomalies annuelles de température de l'eau étaient positives en 2013 : de +0,1 °C (+0,2 ÉT) dans le détroit de Cabot à des profondeurs entre 200 et 300 m, de +0,2 °C (+0,4 ÉT) dans le banc de Misaine Néo à 100 m de profondeur, de +0,6 °C (+0,7 ÉT) dans le bassin d'Émeraude à 250 m de profondeur, de +1,0 °C (+1,3 ÉT) dans le haut-fond Lurcher à 50 m de profondeur et de +1,1 °C (+0,9 ÉT) dans le bassin de Georges à 200 m de profondeur (l'année la plus chaude des 64 dernières années). Les anomalies de température au fond dans les divisions 4VWX de l'Organisation des pêches de l'Atlantique Nord-Ouest étaient toutes positives en 2013 et allaient de +0,2 °C (+0,5 ÉT) dans la zone 4Vn à + 1,0 °C (+ 1,5 ÉT) dans la zone 4X. Par rapport à 2012, la stratification moyenne sur le plateau néo-écossais a augmenté légèrement; il s'agit de la troisième en importance jamais enregistrée. Depuis 1948, la stratification a lentement augmenté sur le plateau néo-écossais, principalement en raison de la dessalure (45 %) et du réchauffement (35 %) des eaux superficielles. D'après un indice composite qui tient compte, à l'échelle de la région, de 18 séries chronologiques de la température océanique de la surface au fond, 2013 se classe au huitième rang des années les plus chaudes depuis 44 ans.

INTRODUCTION

This document discusses air temperature trends, winds, ice cover, sea surface temperatures (SST) and physical oceanographic variability during 2013 on the Scotian Shelf, Bay of Fundy and the Gulf of Maine (Figure 1). 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 Galbraith et al., 2014; Colbourne et al., 2014). 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, i.e. 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 8-13^{o}C and salinities from 34.7-35.6, and Labrador Slope Water, with temperatures from 3.5^{o}C-8^{o}C and salinities from 34.3-35. 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 northern North Atlantic. It is a measure of 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, 2009-2013), Santa Maria (1998-2005), and Lajes (2006-2008) in the Azores, and at Akureyri in Iceland. The small number of missing data early in the time series was 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 2013, the winter NAO index was negative following last year's fourth largest positive value and the record low value in 2010; -3.4 mb (-0.4 SD) below the 1981-2010 mean (Figure 2, upper panel). The lower panels of Figure 2 show the sea level pressure conditions during the winter of 2013 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. However, the pressure difference between Ponta Delgada and Akureyri was less than the long-term average.

AIR TEMPERATURES

Surface air temperature anomalies relative to the 1981-2010 means for the North Atlantic Region are available from the US National Oceanic and Atmospheric Administration's (NOAA, 2013) interactive website. The annual anomalies were above normal by more than 0.4°C over the Scotian Shelf and up to 0.6°C in the Gulf of Maine in 2013 (Figure 3). The seasonal anomaly of these regions is positive for most of the year but near normal during end of the year (Figure 4).

Monthly air temperature anomalies for 2012 and 2013 relative to their 1981-2010 means at six sites in the Scotian Shelf-Gulf of Maine region are shown in Figure 5. The anomalies are presented in two ways: the heights of the bars represent the anomalies in degrees Celsius (°C); the colours of the bars represent the number of SDs the anomalies differ from their long-term means. Monthly data for the Canadian sites were from the Canadian Climate Summaries (CCS) at the Environment Canada website and from the Monthly Climatic Data for the World (NOAA, 2013) 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 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. The observed and normalized annual anomalies for these stations are listed in Table 1. In 2013, the annual anomalies were positive at all sites, ranging from +0.1(+0.2 SD) at Saint John to +0.8°C (+1.1 SD) at Sable Island. Except for Sable Island, these annual anomalies are all smaller than the within year monthly SD (Table 1). 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 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) of +1.1°C (+0.7°C, +1.5°C), +1.1°C (+0.7°C, +1.4°C), +1.6°C (+1.2°C, +1.9°C), +0.7°C (+0.4°C, +1.1°C), +0.4°C (-0.0°C, +0.8°C), and +1.8°C (+1.4°C, +2.2°C) per century, 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: for most years the anomalies have the same sign, i.e. the stacked bars coincide. Since 1900, when all sites were operating, 92 of the 114 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). In addition, 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 summed anomaly in 2013 was +2.6°C, the 13th warmest year in 114 years (with 2012 being the warmest, 2010 being the second and 2011, the sixth warmest years).

Table 1. The 2013 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		SD of Monthly Anomalies (^oC)	1981-2010 Climatology	
	Observed (^oC)	Normalized		Mean (^oC)	SD (^oC)
Sydney	+0.5	+0.6	1.1	5.87	0.81
Sable Island	+0.8	+1.1	0.6	7.88	0.68
Shearwater (Halifax)	+0.6	+0.8	1.0	6.99	0.74
Yarmouth	+0.4	+0.7	0.8	7.16	0.62
Saint John	+0.1	+0.2	1.2	5.19	0.74
Boston	+0.2	+0.4	1.0	10.91	0.60

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 1962-2013. In the current analysis, ice concentrations of greater than or equal to (≥) one-tenth were obtained for a grid with 0.1 degree latitude and 0.1 degree longitude intervals from these ice charts. A climatology (1981-2010) of first and last appearance and duration was generated for each grid point and was subtracted from the values determined for 2013 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. Since observations of ice thickness are not available, ice volumes have been estimated for the region by assigning characteristic thicknesses to particular ice types. 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. 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.”

ATLANTIC REGION

Ice appeared off Labrador, northern Newfoundland and in the Gulf of St. Lawrence in late January to late February in 2013 (Figure 8); over much of the region, the day of first appearance of ice was more than 15 days later than normal. In general, the day of last appearance of ice was earlier than usual off Labrador and Newfoundland by 15 days (Figure 9). Overall, ice duration was shorter than normal over most of the region (Figure 10).

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 and, in 2013, it was present there for only a short period. There has been very little ice on the Scotian Shelf and Cabot Strait since April 2009 (Figure 11).

The ice areas and volumes for 2013 are compiled in Table 2. The December to April 2013 ice coverage and volume was the 7th lowest in the 52 year long record while 2010, 2011 and 2012 had the second to fourth lowest coverage and volume; the differences between these three years are within the uncertainty of the observations.

Table 2. Ice area and volume statistics, Scotian Shelf.

Month	2013 Ice Area (km^2)	2013 Area Anomaly (km^2)	2013 Normalized Area Anomaly	2013 Ice Volume (km^3)	2013 Volume Anomaly (km^3)	2013 Normalized Volume Anomaly
January	79	-1150	-0.5	<0.01	-0.2	-0.5
February	1632	-9660	-0.9	0.24	-2.6	-1.0
March	1579	-14130	-1.0	0.84	-6.0	-0.9
April	644	-3940	-0.8	0.51	-2.5	-0.8

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 2010; to provide data from 2011 and on, the Advanced Very High Resolution Radiometer (AVHRR) SST data downloaded from the NOAA satellites by the remote sensing group in the Ocean Research & Monitoring Section (ORMS) was used. A least-square fit of the Pathfinder and ORMS temperatures during the common time period for several regions led to a conversion equation SST(Pathfinder) = 0.989*SST(ORMS)-0.02 with an r^2=0.98. Using this regression, the ORMS data were converted to be consistent with the longer Pathfinder series. Anomalies were based on 1981-2010 averages.

Annual anomalies were calculated from monthly averaged temperatures for eight subareas in the Scotian Shelf-Gulf of Maine region (Table 3; Figure 12). The annual anomalies during 2013 ranged from +0.4°C (+0.4 SD) in Cabot Strait to +1.2°C (+1.5 SD) in the Bay of Fundy. All eight areas had positive anomalies; all but one was 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 (Lurcher Shoal) to a highest value of +0.7°C/decade (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., 2014). The large increase in the observed SST over this period has likely been enhanced by the cold air temperature period at the beginning of this data and a rapid temperature increase from 2000 (Figure 12).

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 negative loadings in the eastern half of the region, changing to positive values roughly to the west of the Central Scotian Shelf (Figure 13). 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.

Table 3. 2013 SST anomalies and long-term SST statistics including 1982-2013 temperature change based on the linear trend.

Site	2013 SST Anomaly (°C)	2013 SST Anomaly Normalized	1981-2010 Mean Annual SST (°C)	1981-2010 Annual SST Anomaly Std. Dev. (°C)	1982-2013 Temperature Trend (ºC/decade)
Cabot Strait	+0.4	+0.4	5.9	1.0	0.4
Eastern Scotian Shelf	+1.0	+0.9	7.1	1.1	0.4
Central Scotian Shelf	+1.0	+0.9	8.5	1.1	0.5
Western Bank	+1.2	+1.0	8.9	1.2	0.4
Western Scotian Shelf	+0.8	+0.7	8.1	1.1	0.4
Lurcher Shoal	+0.7	+0.7	7.2	1.1	0.3
Bay of Fundy	+1.2	+1.5	7.2	0.8	0.7
Georges Bank	+1.1	+1.1	10.0	1.0	0.4

COASTAL TEMPERATURES AND SALINITIES

Coastal SSTs have been collected at Halifax (Nova Scotia) and St. Andrews (New Brunswick) since the 1920s (Figure 14). In 2013, the SST anomalies were -0.04°C (-0.05 SD) for Halifax, a decrease of 1.0°C from 2012 and +1.0°C (+1.7 SD) for St. Andrews, a decrease of 1.0°C from 2012. Interestingly, the SST at Halifax, located in the harbour, had no significant change from 1981 to 2013, due to a warmer early 1980s (Figure 14), whereas the satellite-based SST showed an increase over the same period (Table 3; Figure 12). 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). The depth-averaged (0-90 m) temperature, salinity and density time series are shown in Figure 14. In 2013, the annual temperature anomaly was +0.6°C (+1.1 SD) and the salinity anomaly was +0.2 (0.8 SD). These represent changes of -1.3°C and less than 0.05 from the 2012 values. The negative density anomaly is accounted for by the temperature anomaly which was larger than the partial density anomaly due to the increased salinity anomaly.

The 2013 annual cycle at Prince 5 shows warmer than normal temperatures throughout the year with no real depth dependence in the anomaly except in winter (Figure 15). The largest temperature anomaly occurred in early 2013, a follow on from the extremely warm 2012. The salinity anomaly 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 2013, the positive salinity anomaly is probably the result of less than normal amount of fresh water arriving there. The anomalies in the spring and summer are likely due to the timing of the freshet.

The 2013 annual cycle at Halifax 2 shows the standard seasonal temperature cycle (Figure 16). The observed temperature anomaly is due to variability of the vertical extent of the summer mixed layer and the overall warmer water observed over the whole Scotian Shelf. There is a negative salinity anomaly in the upper ocean in the spring and at the end of the year. The deeper variability of the salinity occurs in conjunction with temperature and may be indicative of warmer saltier slope water 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 areas on the Scotian Shelf and in the eastern Gulf of Maine that generally corresponded to topographic features such as banks and basins (Figure 17). 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 is presented (Figure 18). The Cabot Strait (see Figure 1) temperatures represent a mix of Labrador Current Water and Slope Water entering the Gulf of St. Lawrence along the Laurentian Channel (e.g. Gilbert et al., 2005); the Misaine Bank (region 5; Figure 18) series characterizes the colder near bottom temperatures on the Eastern Scotian Shelf; the deep Emerald Basin (region 12) 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 18C); the Lurcher Shoals (region 24) observations define the ocean climate in the southwest Scotian Shelf and the shallow waters entering the Gulf of Maine via the Nova Scotia Current; finally, the Georges Basin (region 26) series represents the slope waters entering the Gulf of Maine through the Northeast Channel (NEC). 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, 2013 annual anomalies are based on observations from only four, six, four, two and three months, respectively.

In 2013, the annual anomalies were +0.1^{o}C (+0.2 SD) for Cabot Strait at 200-300 m, +0.2^{o}C (+0.4 SD) for Misaine Bank at 100 m, +0.6^{o}C (+0.7 SD) for Emerald Basin at 250 m, +1.0^{o}C (+1.3 SD) for Lurcher Shoals at 50 m, and +1.1^{o}C (+2.0 SD) for Georges Basin at 200 m (2013 was the warmest year). These values correspond to changes of -0.8^{o}C, -0.8^{o}C, -0.1^{o}C, -2.1^{o}C and +0.6^{o}C, respectively, from the 2012 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 have started to return to normal in 2013, except, of course, for Georges Basin.

TEMPERATURES DURING THE SUMMER GROUNDFISH SURVEYS

The broadest spatial temperature and salinity coverage of the Scotian Shelf is obtained during the annual July Fisheries and Oceans Canada (DFO) ecosystem 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 230 Conductivity-Temperature-Depth (CTD) stations were sampled during the 2013 survey. The groundfish survey takes one month to complete with the area west of Halifax sampled first and the area east of Halifax sampled last.

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. 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 2013 were positive everywhere other than around Sable Island; the largest anomalies near the shelfbreak and coast (Figure 19).

Bottom temperatures ranged from an average of 4.1°C in Northwest Atlantic Fisheries Organization (NAFO) area 4Vs to 8.3°C in 4X during 2013, illustrating the substantial difference in the environmental conditions across the Shelf. The anomalies were positive for these NAFO areas in 2013: +0.2°C (+0.5 SD) in 4Vn; +0.8°C (+1.1 SD) in 4Vs; +0.6°C (+0.8 SD) in 4W; and +1.0°C (+1.5 SD) in 4X (Figure 20A-D). Compared to 2012, bottom temperatures decreased in areas 4Vn, 4Vs, 4W and 4X by 0.3, 0.5, 1.2 and 1.1°C.

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 20). For the period 1970 to 1989, the number of CTD profiles per year was limited; therefore, five year blocks of data, e.g. 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. 1970-74, 1971-75, etc.). This procedure is similar to filtering the data for the 1970-89 period, effectively reducing the variance. Thus the long-term mean and particularly the SD (based on the 1981-2010 data in Figure 20E) 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 20E). In 2013, the observed volume of 5000 km^3 was 0.4 SD less than the 1981-2010 mean value of 5500 km^3, an increase from the smallest volume in the 44 years of surveys that occurred the previous year.

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 by calculating the density (sigma-t) difference between the near-surface and 50 m was examined. The density differences were based on monthly mean density profiles calculated for each area in Figure 17. 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 (figures 17, 21). 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 is characterized by above normal values (Figure 21). Stratification on the Scotian Shelf in 2013 strengthened slightly compared to 2012 and was the third strongest stratification of the series. 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 0.37 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), a combination of warming (39%) and freshening (45%) of the surface waters (Figure 22). The remainder of the density change occurs at 50 m. However, while there was a slight change in stratification from 2012 to 2013, the surface and 50 m temperatures both decreased by 1.4°C in 2013.

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 (1967-2013), Halifax (1920-2013) and North Sydney (1970-2013) are plotted as monthly means and as a filtered series using a five year running-mean filter (Figure 23). The linear trend of the monthly mean data has a positive slope of 35.5 cm/century (Yarmouth), 32.7 cm/century (Halifax), and 38.5 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 25.2 cm/century, 18.0 cm/century and 21.7 cm/century, respectively. In 2013, the relative sea level at Yarmouth and Halifax continued to decrease from the peak in 2010, while North Sydney increased from the 2012 level (Figure 24). An interesting feature of the data is the long-term variation that has occurred since the 1920s. In Figure 24, 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 trend. The residual sea level data for the common period 1970-2013 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, twenty years of observed Gulf Stream transport does not show a significant decrease (Rossby et al., 2014).

CALCULATIONS FROM NUMERICAL CIRCULATION MODEL

Currents and transports are derived from a numerical model of the Gulf of St. Lawrence, Scotian Shelf, and Gulf of Maine. The model is prognostic, i.e. allows for evolving temperature and salinity fields, and includes the five principal tidal constituents and 78 river inputs. It has a spatial resolution of 1/12° with 46 z-levels in the vertical. Atmospheric forcing is derived from the Global Environmental Multiscale Model (GEM) model run at the Canadian Meteorological Center (CMC). Freshwater runoff is obtained from observed data and a hydrological model (for details, see Galbraith et al., 2013).

A simulation is produced for the entire AZMP period (1999-2013) using a version of the circulation model that incorporates a simple scheme to assimilate the temperature and salinity (TS) data from AZMP and other programs for these years. The temperature and salinity dataset contains about 250 profiles per year for 1999-2004, and about 6000 profiles per year for 2005-2013. The model run for the current year typically carries on from the end of the previous simulation (1999-2012). However, more TS data became available for 2012, so 2012 was re-run as part of the simulation.

The simulation also includes open boundary conditions derived from a simulation of the North Atlantic circulation for the same time period (Dr. Z. Wang, DFO Maritimes, pers. comm., 2013), thus allowing changes in interior flows related to interannual variability at the open boundaries to be captured. The model domain and open boundary condition are shown in Figure 25.

Some calculations intended to help interpret data collected by the AZMP are presented. Results are presented in terms of standardized anomalies (deviation from the 1999-2010 mean, divided by the standard deviation), to facilitate comparison to other AZMP analyses.

The reader is cautioned that the results outlined below are not measurements but 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 Maritime Canada can be characterized as a general northeast-to-southwest flow through from the Strait of Belle Isle, through Cabot Strait, and along the Scotian Shelf toward the Gulf of Maine. 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 shelfbreak and contributes to the Gulf of Maine inflow at the NEC. Variations in these currents may influence the distributions 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 NEC 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 1999-2013 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 26). From these data, standardized anomaly plots were constructed to illustrate transport variability. This was done 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 shelfbreak at HFX, and the inflow at NEC (Figure 27). From the inflows through the CSI and NEC sections the 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 Gulf of Maine. For NEC, positive transport denotes flow into the Gulf of Maine.)

Transport variability on the Scotian Shelf (Figure 27) shows a fairly coherent pattern of anomalies for CS, HFX (nearshore and shelfbreak) and CSI. These series begin with mostly negative monthly anomalies in 1999-2000, switching to more neutral and positive anomalies thereafter. The year 2004 is notable for the strong positive anomalies for almost all months. An opposite pattern is observed for NEC, likely related to conservation of volume in the Gulf of Maine (i.e. more inflow at CSI is compensated by less through NEC). The anomaly series, excluding NEC, were all positively correlated with correlations ranging from 0.51 to 0.92. NEC was negatively correlated with the other five series, with values ranging from -0.49 to -0.42.

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), 150 m (T2) and 180 m (T3) isobaths to monitor the velocity field associated with the Nova Scotia Current along the Halifax Line. 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 supposedly 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^3s^{-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 T1 failed from August 2012 to October 2012). 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 weaker flow (Figure 28), a feature that appears in the model simulation as well (see HFX nearshore panel of Figure 27).

The fraction of transport into the Gulf of Maine (GoM) through CSI inflow ratio (Figure 29) exhibits a seasonal cycle with a minimum during the summer months. Interannually, this ratio was anomalously low from 1999-2003, strongly positive in 2004, alternated between positive and negative anomalies from 2005-2010, and exhibited normal conditions thereafter (Figure 30, top). On average, the model predicts that about one third of the transport into the Gulf of Maine enters through the CSI section.

For comparison to other AZMP analyses, an overall annual scorecard was computed (Figure 30, bottom) 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 have significantly lower than normal flow-through in 1999-2000 and 2008 and higher than normal flow-through in 2004, 2006 and 2010.

SUMMARY

In 2013, the NAO index was negative (-3.4 mb, -0.4 SD from the 1981-2010 mean) after last year's fourth largest value and record low three years ago. Mean annual air temperatures for 2013 were 0.1 to 0.8^{o}C above normal across the whole region. In 2013, ice coverage on the Scotian Shelf was the 7th lowest in the 52 year record. 2010, 2011 and 2012 had the second to fourth lowest coverage and volume; the differences between these years are within the uncertainty of the observations. The analysis of satellite data indicates that positive SST anomalies prevailed throughout the Scotian Shelf and Gulf of Maine region in 2013 with values from +0.4 to +1.2^{o}C (+0.4 to +1.5 SD) above the 1981-2010 mean values but down from 2012.

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 2010-2013 were warmer than normal (Figure 31). The period 1979-1986 also tends to be warmer than normal. It is apparent that 2012 was an exceptional year based on these series. In fact, additional positive values had to be added to the scale. In 2013, 20 of 22 series shown had positive anomalies; 11 variables were more than 1 SD above their normal values. Of these, only two were more than 2 SD above normal and they were on East Georges Bank. In 2012, 14 were above 2 SD. In 2013, the average (median) normalized anomaly was 1.0 (1.0), the fourth highest in the 43 year series. The SD of the normalized anomalies was 0.7. These statistics indicate that 2013 was a warm year with a fairly uniform distribution of anomalies throughout the region.

Eighteen selected variables of the mosaic plot are summarized as a combination bar plot in Figure 32. This plot represents an overall climate index for the area. These include selected "profiles" 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 July groundfish survey bottom temperatures (4Vn, 4Vs, 4W and 4X) and surface temperatures for Halifax and St. Andrews 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 2013 was the eighth warmest of 44 years, with an averaged normalized anomaly of +0.9 SD relative to the 1981-2010 period. The anomalies did not show a strong spatial distribution in 2013. The leading mode of a principal component analysis of the 18 series captured 47% of the variance with all loadings having the same sign. The loadings of 17 of the 18 variables were strong (0.16 to 0.29) with weak contributions only from the Emerald Basin 250 m (0.06) series.

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FIGURES

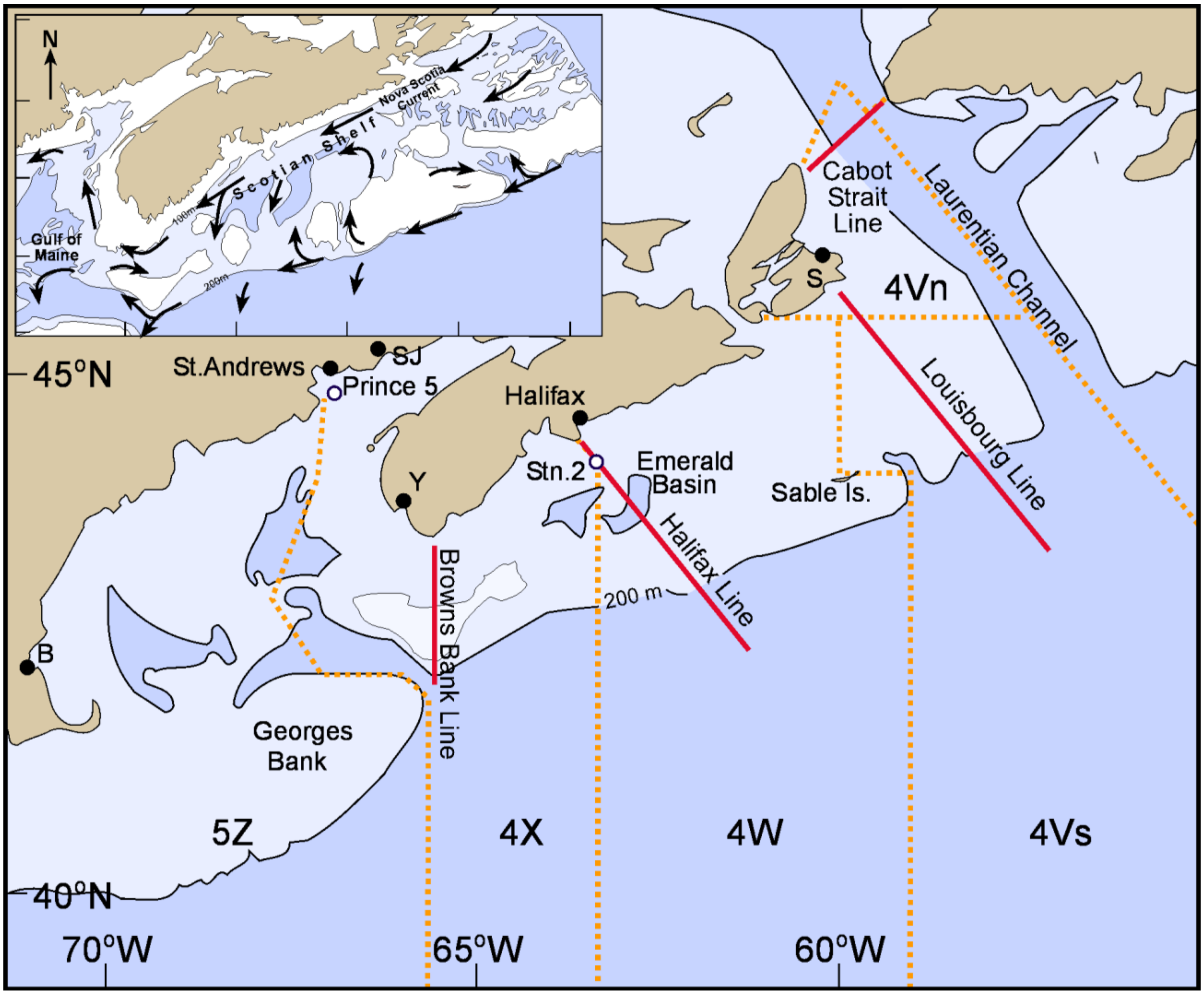

Figure 1. Map of the Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the Northwest Atlantic Fisheries Organization (NAFO) Subareas. Inset depicts major circulation features. Air temperature stations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

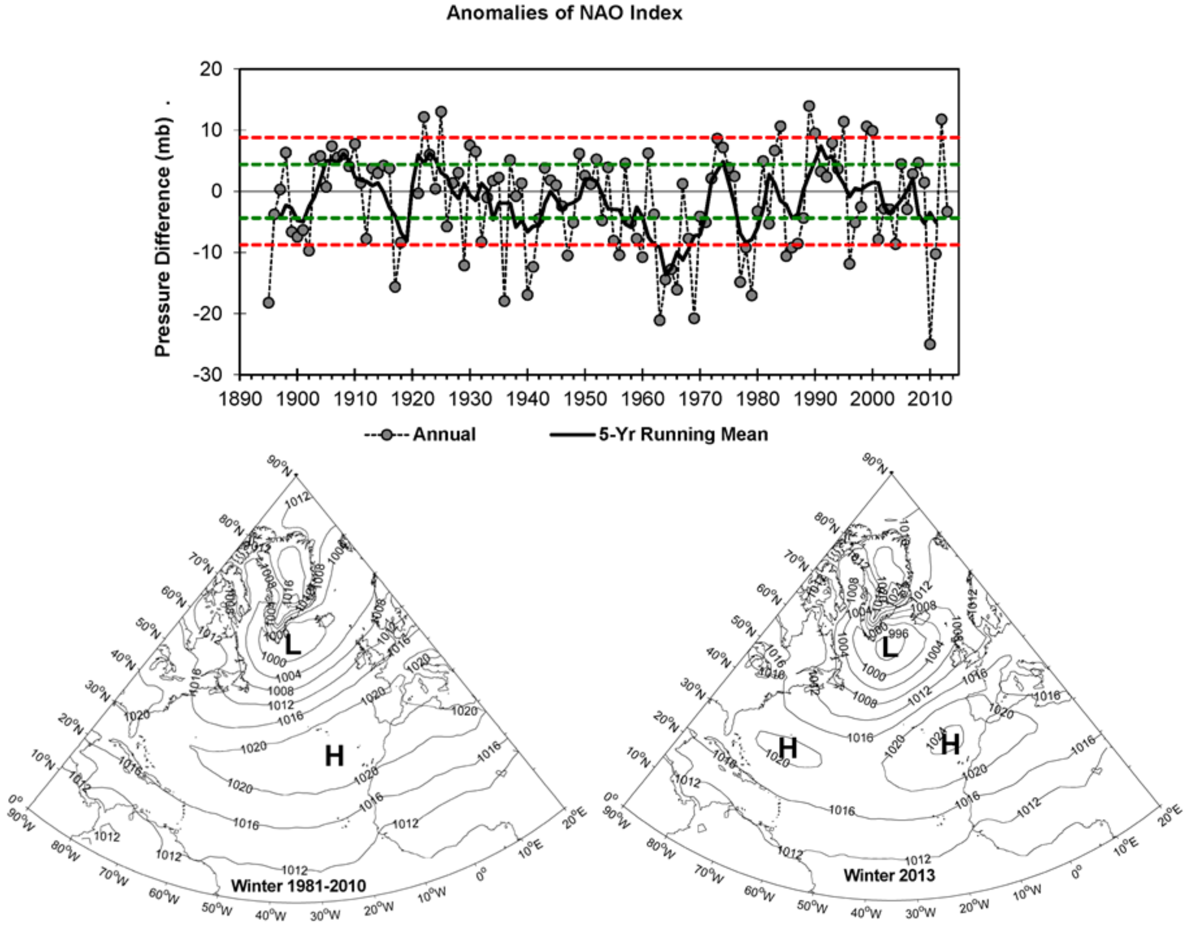

Figure 2. Anomalies of the North Atlantic Oscillation (NAO) index, defined as the winter (December, January, February) sea level pressure difference between the Azores and Iceland, relative to the 1981-2010 mean. The 0.5 (green broken lines) and 1.0 (red broken lines) standard deviations (SDs) are shown (upper panel). The lower panels show the 1981-2010 December-February mean (bottom left panel) and December 2012-February 2013 mean (bottom right panel) sea level pressure over the North Atlantic.

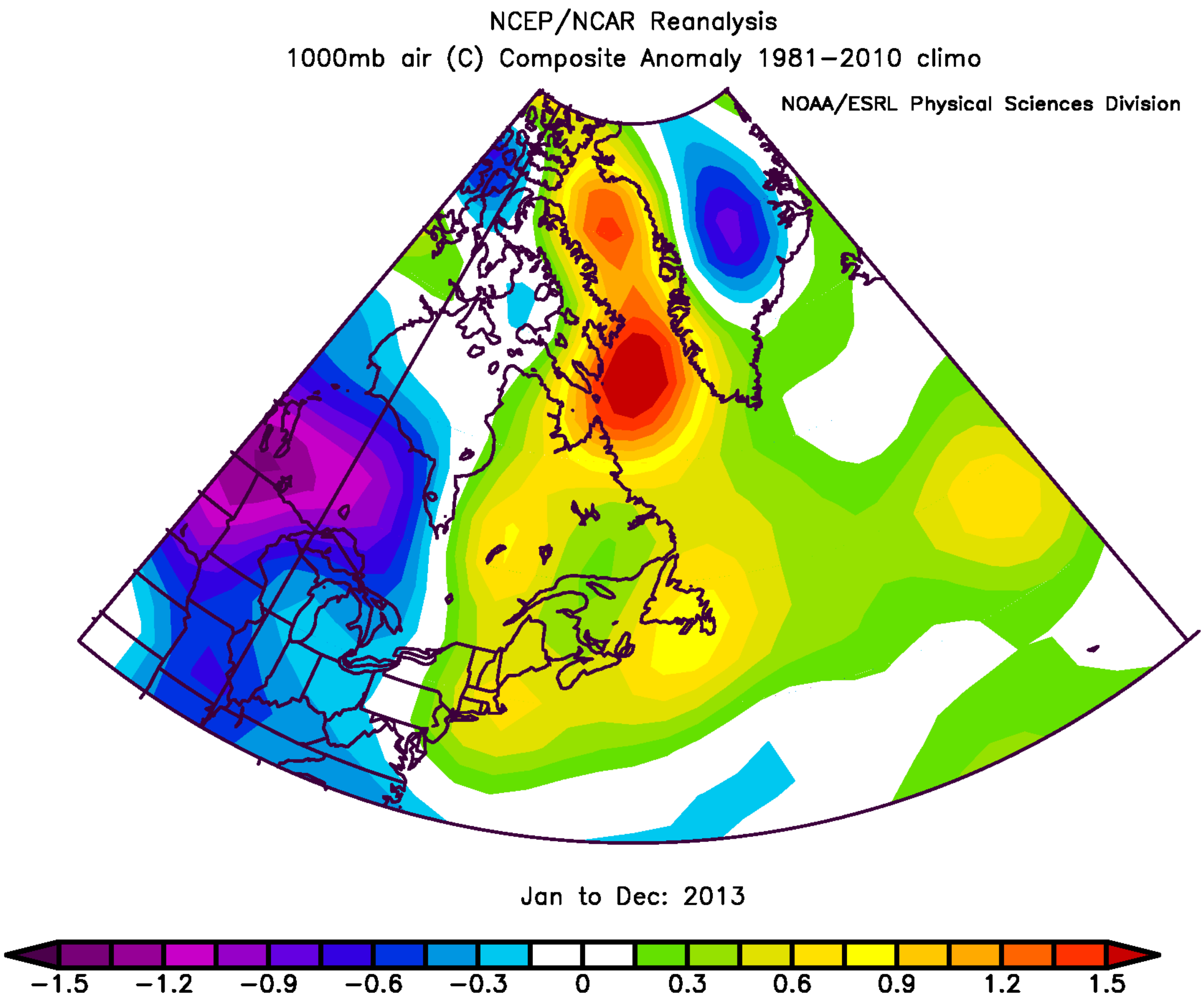

Figure 3. Annual air temperature anomalies (ºC) over the Northwest Atlantic relative to the 1981-2010 means; data were obtained from [NOAA Internet site] (accessed 6 January 2014).

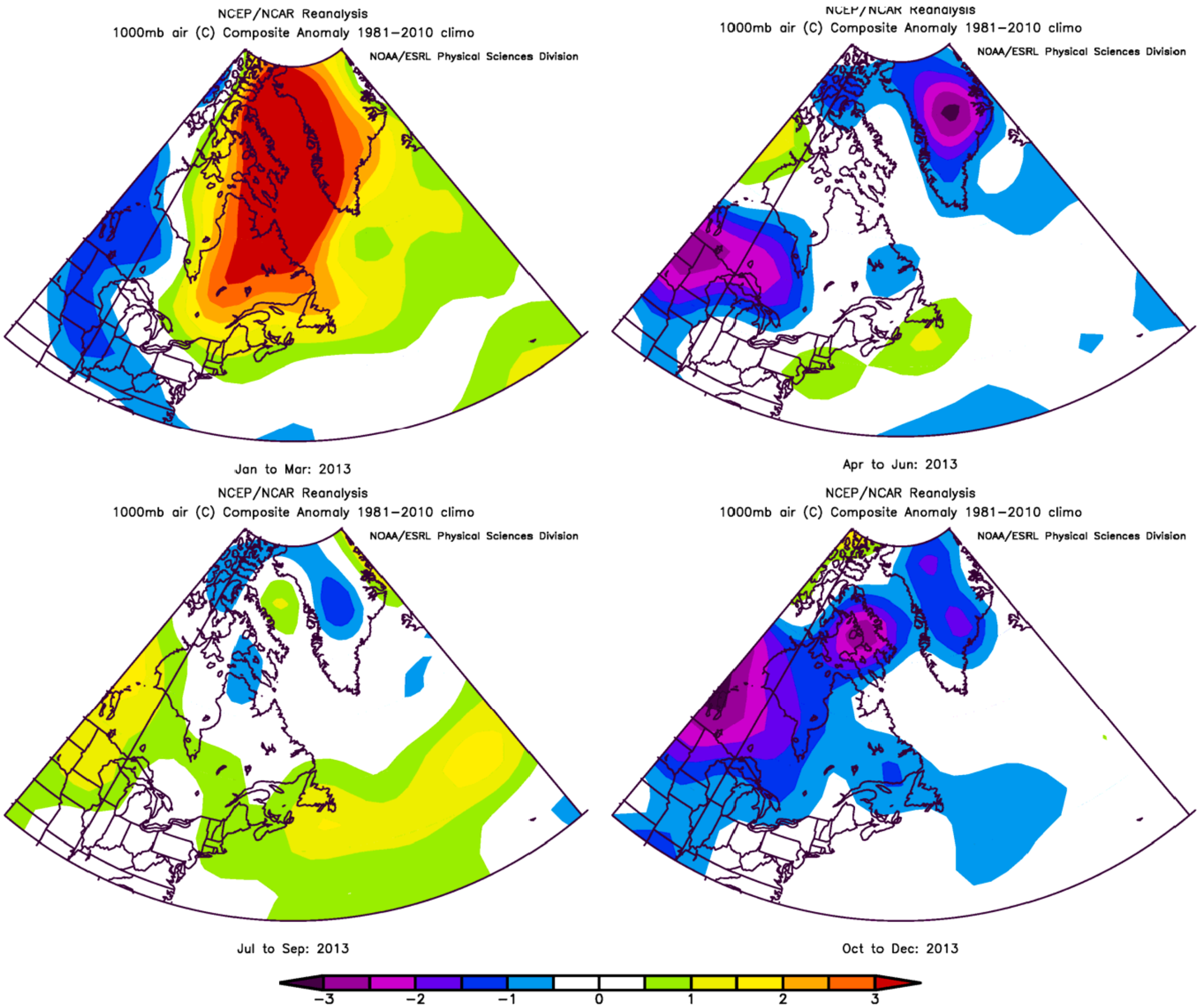

Figure 4. Seasonal air temperature anomalies (ºC) over the Northwest Atlantic relative to the 1981-2010 means; data were obtained from [NOAA Internet site](#) (accessed 6 January 2014).

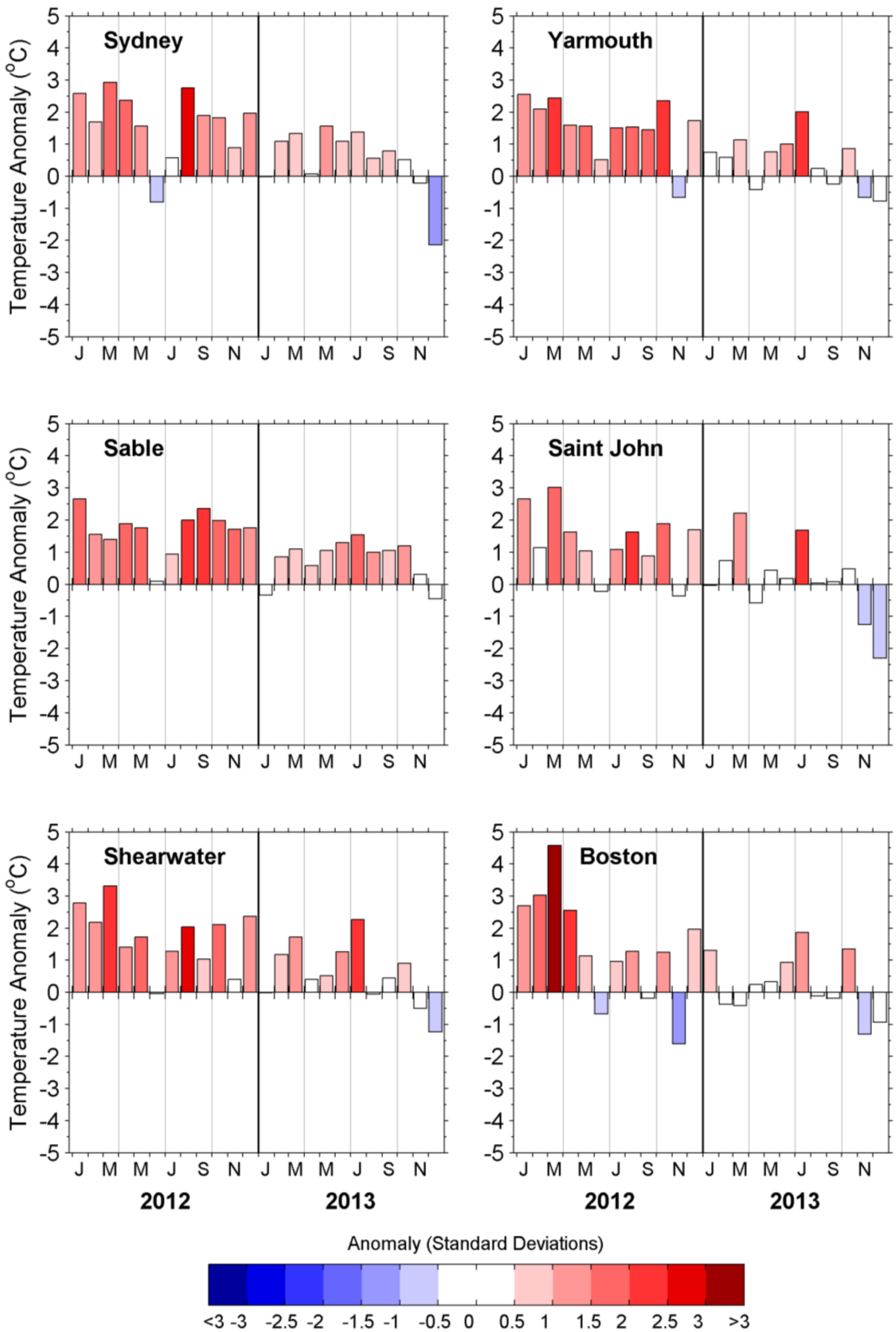

Figure 5. Monthly air temperature anomalies (°C) for 2012 and 2013 (JMMJSN on x-axis represent January, March, May, June, September and November) at coastal sites in Scotian Shelf-Gulf of Maine region (see Figure 1 for locations). Anomalies are colour coded in terms of the numbers of SD above or below normal relative to monthly statistics.

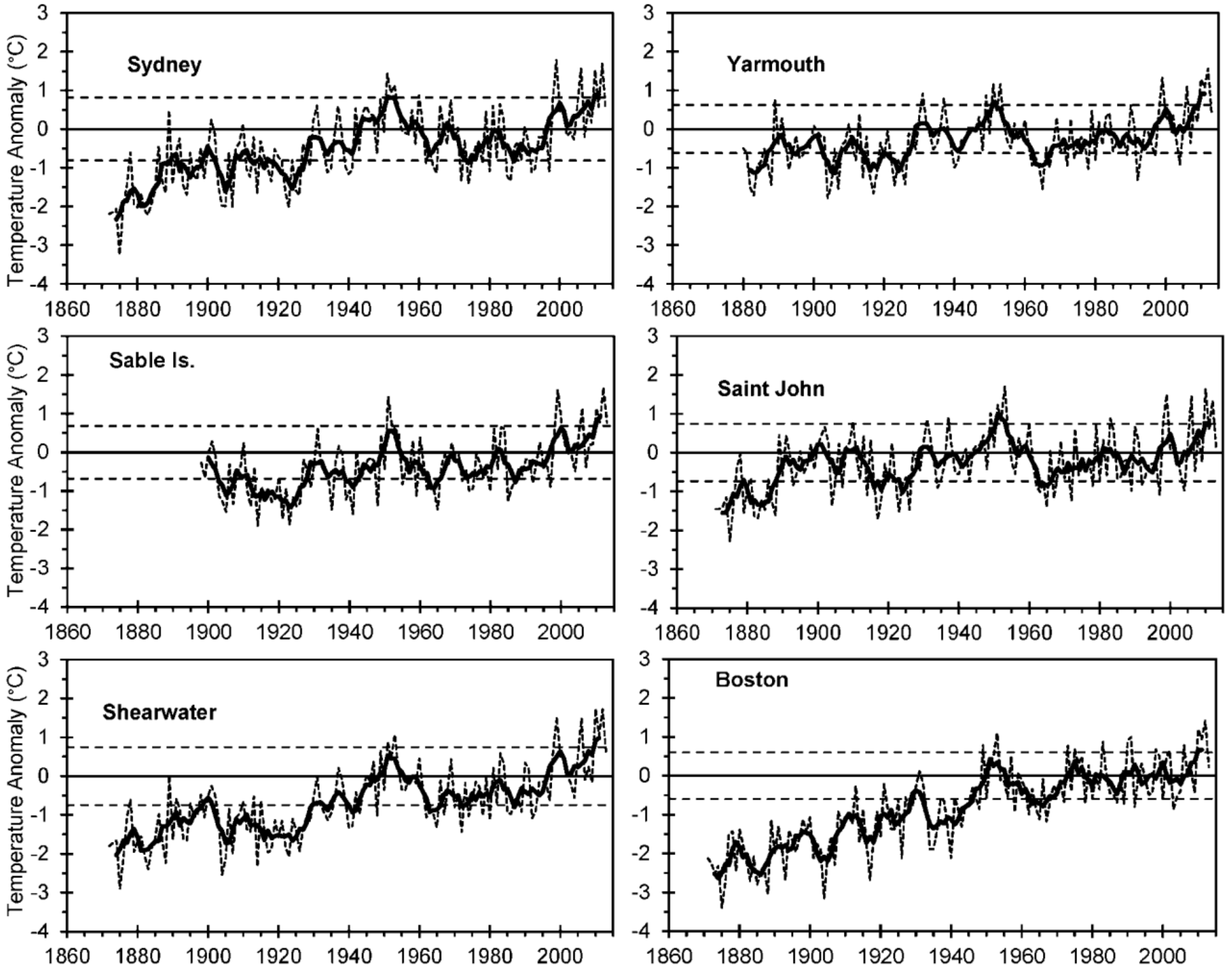

Figure 6. Annual air temperature anomalies in °C (dashed line) and five year running means (solid line) at selected sites (Sydney, Sable Island, Shearwater, Yarmouth, Saint John and Boston) in Scotian Shelf-Gulf of Maine region (years 1860 to 2013). Horizontal dashed lines represent +/- 1 SD for the 1981-2010 period.

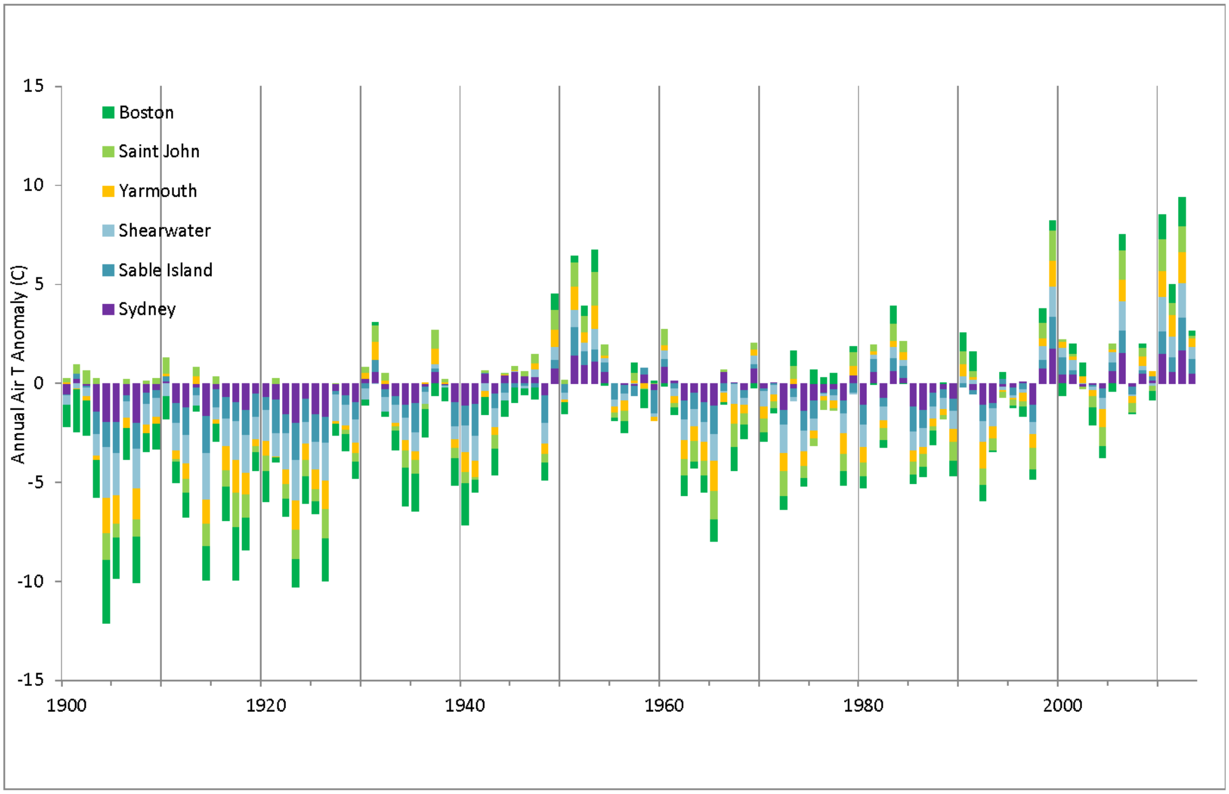

Figure 7. The contributions of each of the annual air temperature anomalies for six Scotian Shelf-Gulf of Maine sites (Boston, Saint John, Yarmouth, Shearwater, Sable Island and Sydney) are shown as a stacked bar chart. Anomalies referenced to 1981-2010.

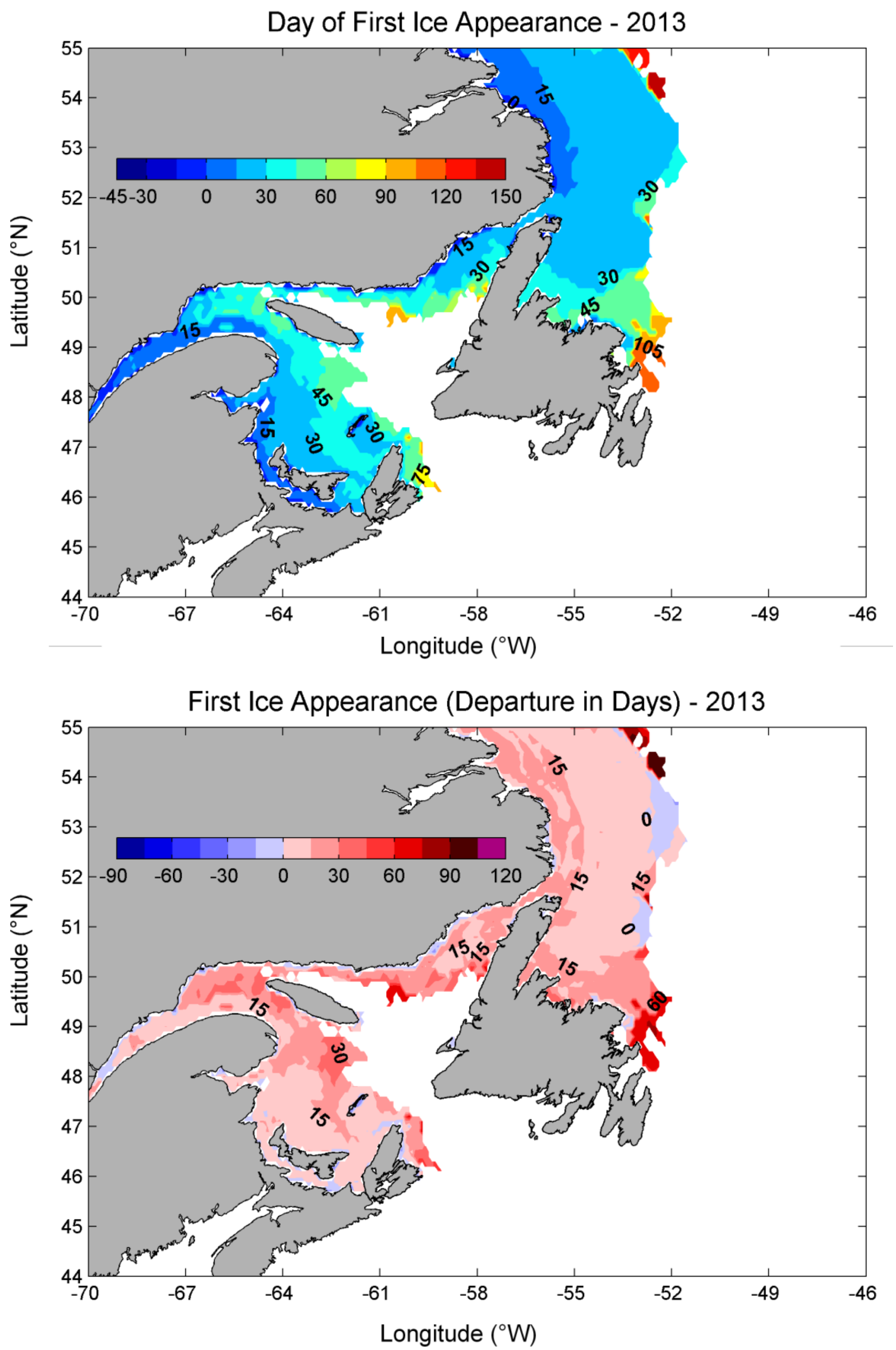

Figure 8. The time when ice first appeared during 2013 in days from the beginning of the year (top panel) and its anomaly from the 1981-2010 mean in days (bottom panel). Negative (positive) anomalies in blue (red) indicate earlier (later) than normal appearance. Longitude in degrees on the x-axis (negative values are West) and Latitude in degrees (positive values are North) on the y-axis.

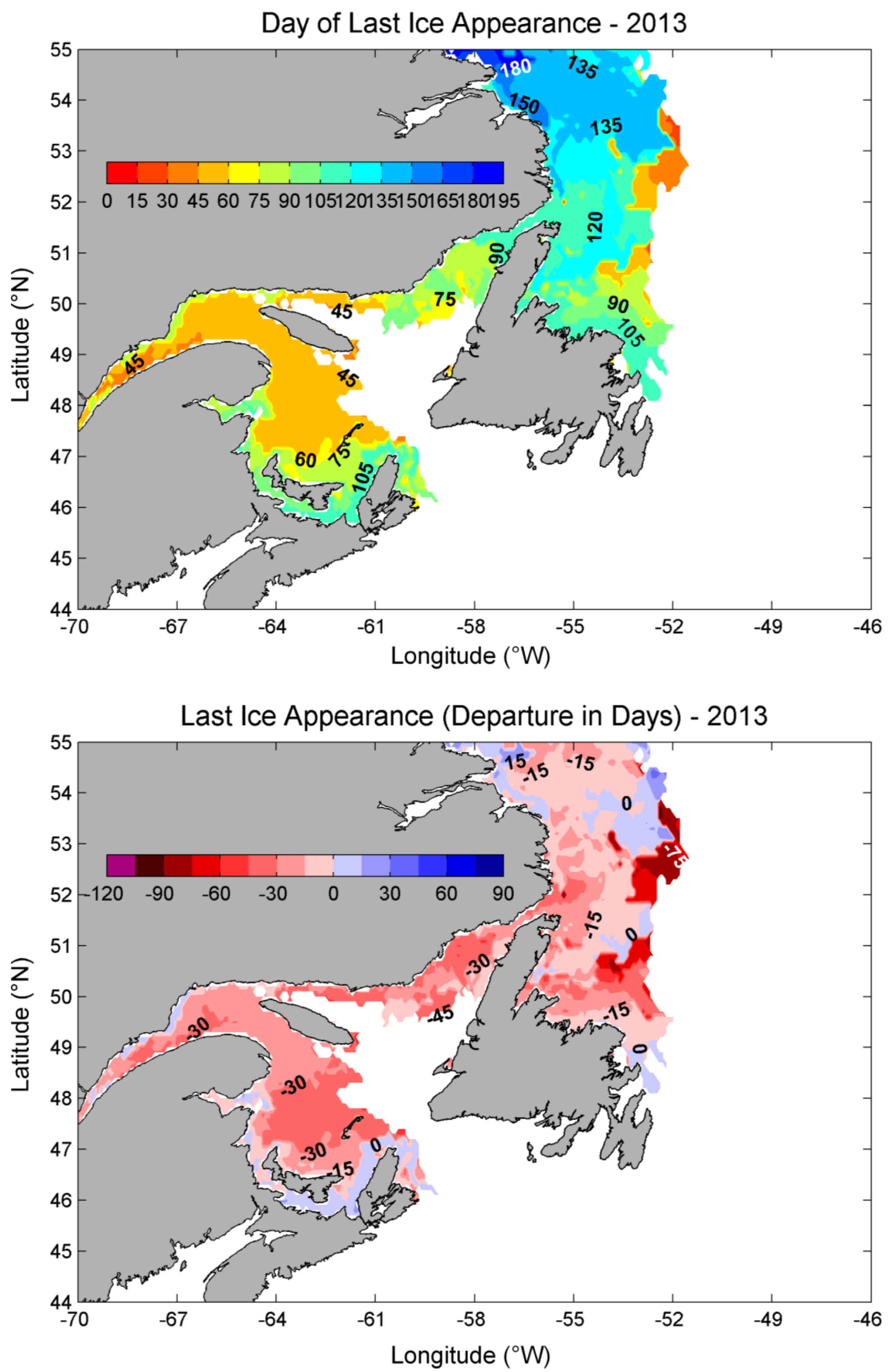

Figure 9. The time when ice was last seen in 2013 in days from the beginning of the year (top panel) and its anomaly from the 1981-2010 mean in days (bottom panel). Negative (positive) anomalies in red (blue) indicate earlier (later) than normal disappearance. Longitude in degrees on the x-axis (negative values are West) and Latitude in degrees (positive values are North) on the y-axis.

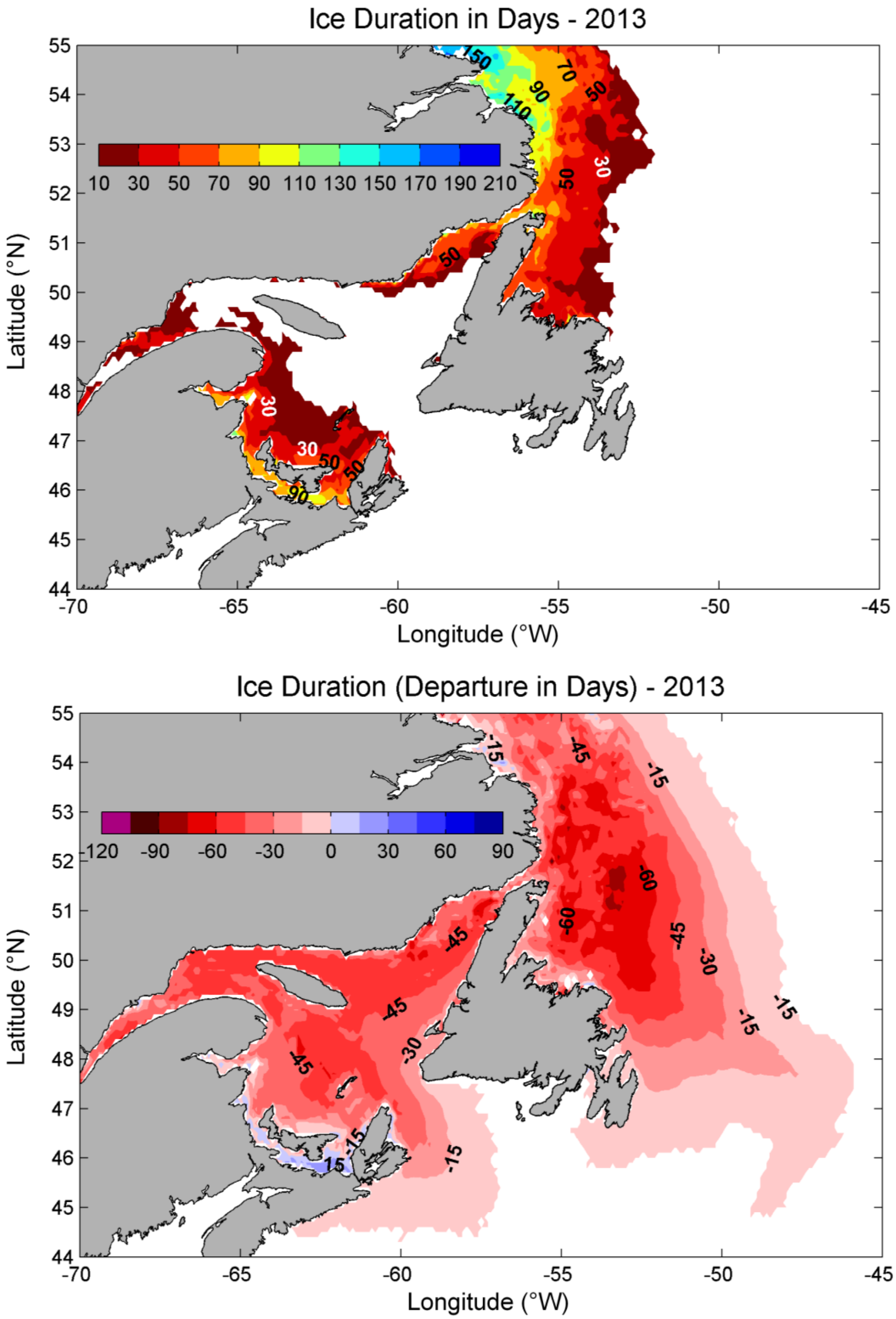

Figure 10. The duration of ice in days (top panel) during 2013 and the anomalies from the 1981-2010 mean in days (bottom panel). Positive (negative) anomalies in blue (red) indicate durations longer (shorter) than the mean. Note that areas of duration approximately ten days are not displayed. The anomaly 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.

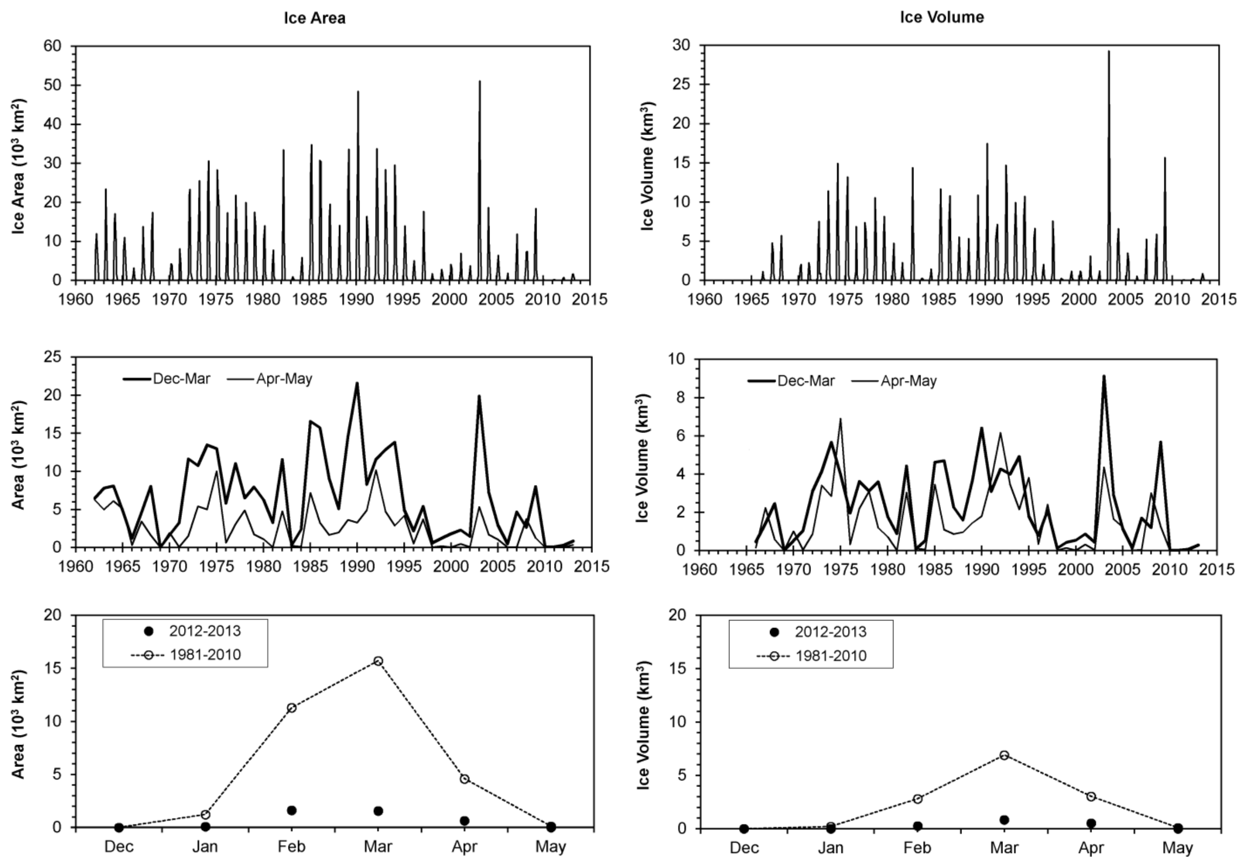

Figure 11. Time series of the monthly mean ice area and volume for the Scotian Shelf (top panels), the average ice area and volume during the usual periods of advancement (January-March) and retreat (April-May) (middle panels), and the comparison of the 2012-2013 monthly areas and volumes to the 1981-2010 means (bottom two panels). Note that the 2010-2012 ice area and volume is basically zero.

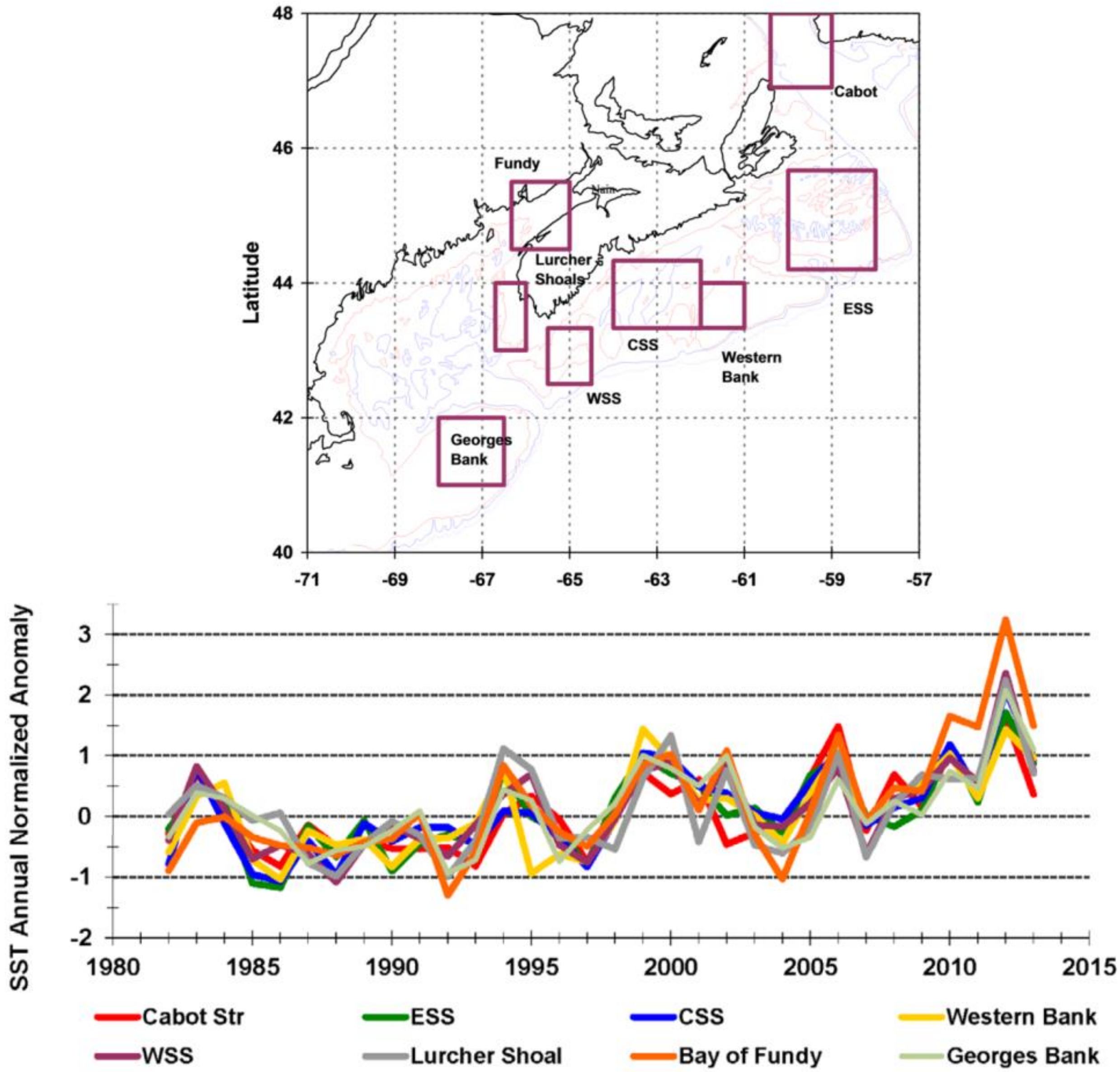

Figure 12. Scotian Shelf-Gulf of Maine areas (Cabot Strait, Eastern Scotian Shelf (EES), Western Bank, Central Scotian Shelf (CSS), Western Scotian Shelf (WSS), Georges Bank, Lurcher Shoals and Bay of Fundy) used for extraction of sea surface temperature (upper panel). The annual sea surface temperature anomalies derived from satellite imagery compared to their long-term monthly means (lower panel).

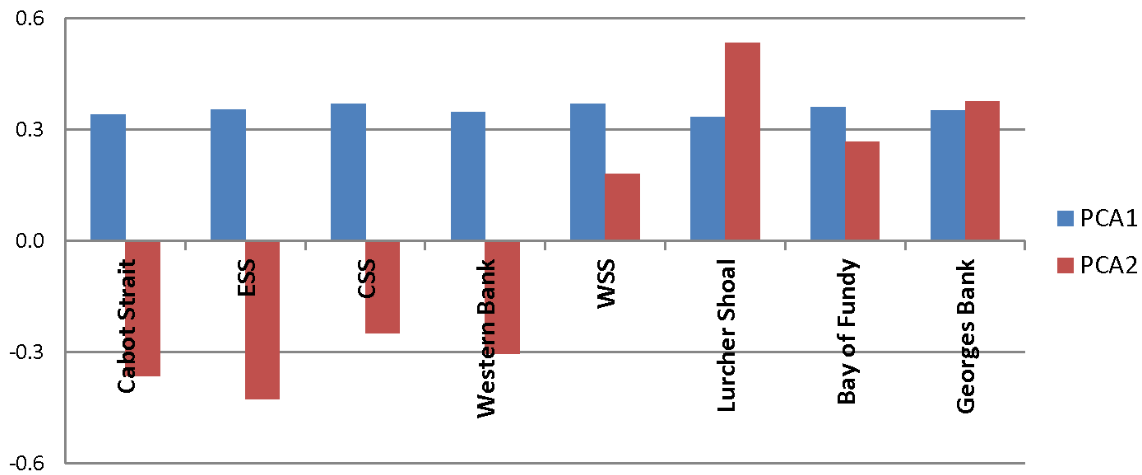

Figure 13. First (PCA1: 83% of the variance) and second (PCA2: 8% of the variance) loadings from a principal components analysis of the annual mean temperature anomalies (Figure 12, lower panel) for the eight Scotian Shelf and Gulf of Maine regions (Cabot Strait, Eastern Scotian Shelf (EES), Western Bank, Central Scotian Shelf (CSS), Western Scotian Shelf (WSS), Georges Bank, Lurcher Shoals and Bay of Fundy - Figure 12, upper panel).

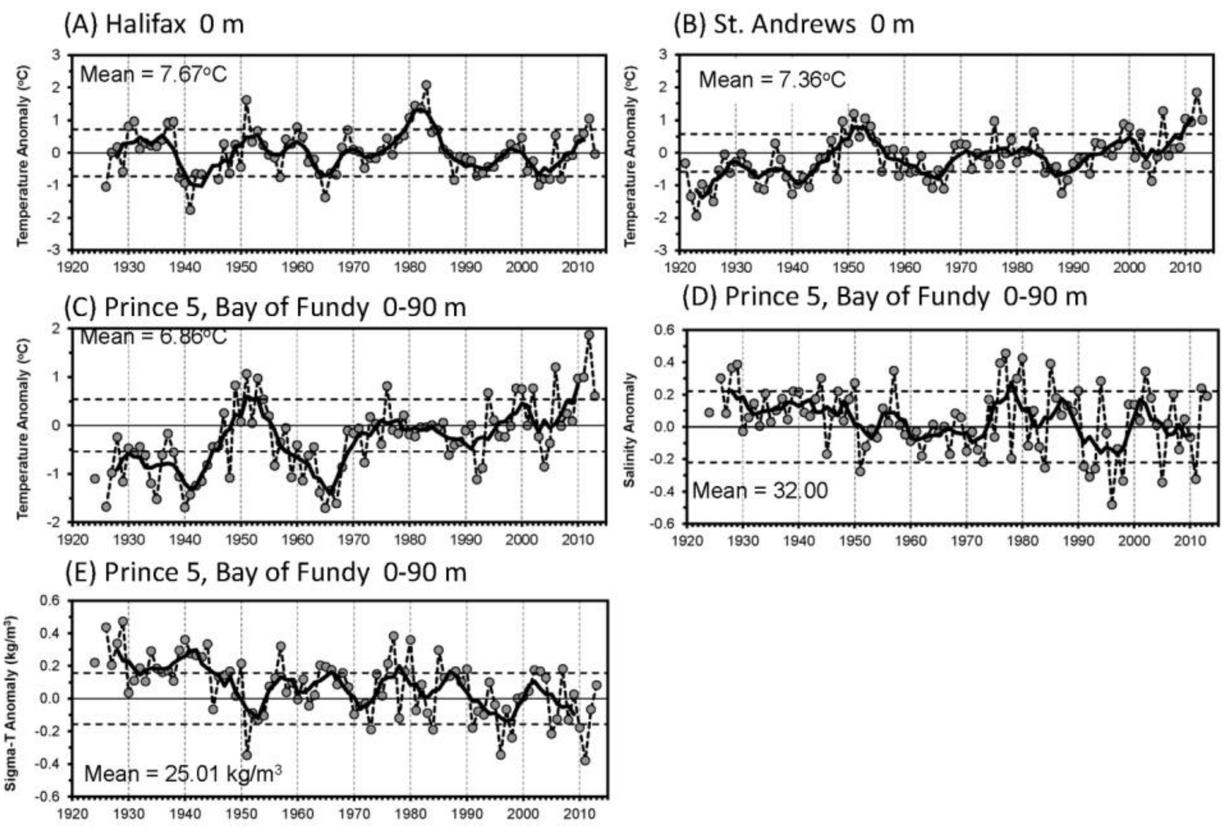

Figure 14. The annual surface temperature anomalies (dotted line with circles) and their five year running means (heavy black line) for: (A) Halifax Harbour and (B) St. Andrews; annual depth-averaged (0-90 m) (C) temperature, (D) salinity, and (E) density anomalies for the Prince 5 monitoring station at the mouth of the Bay of Fundy.

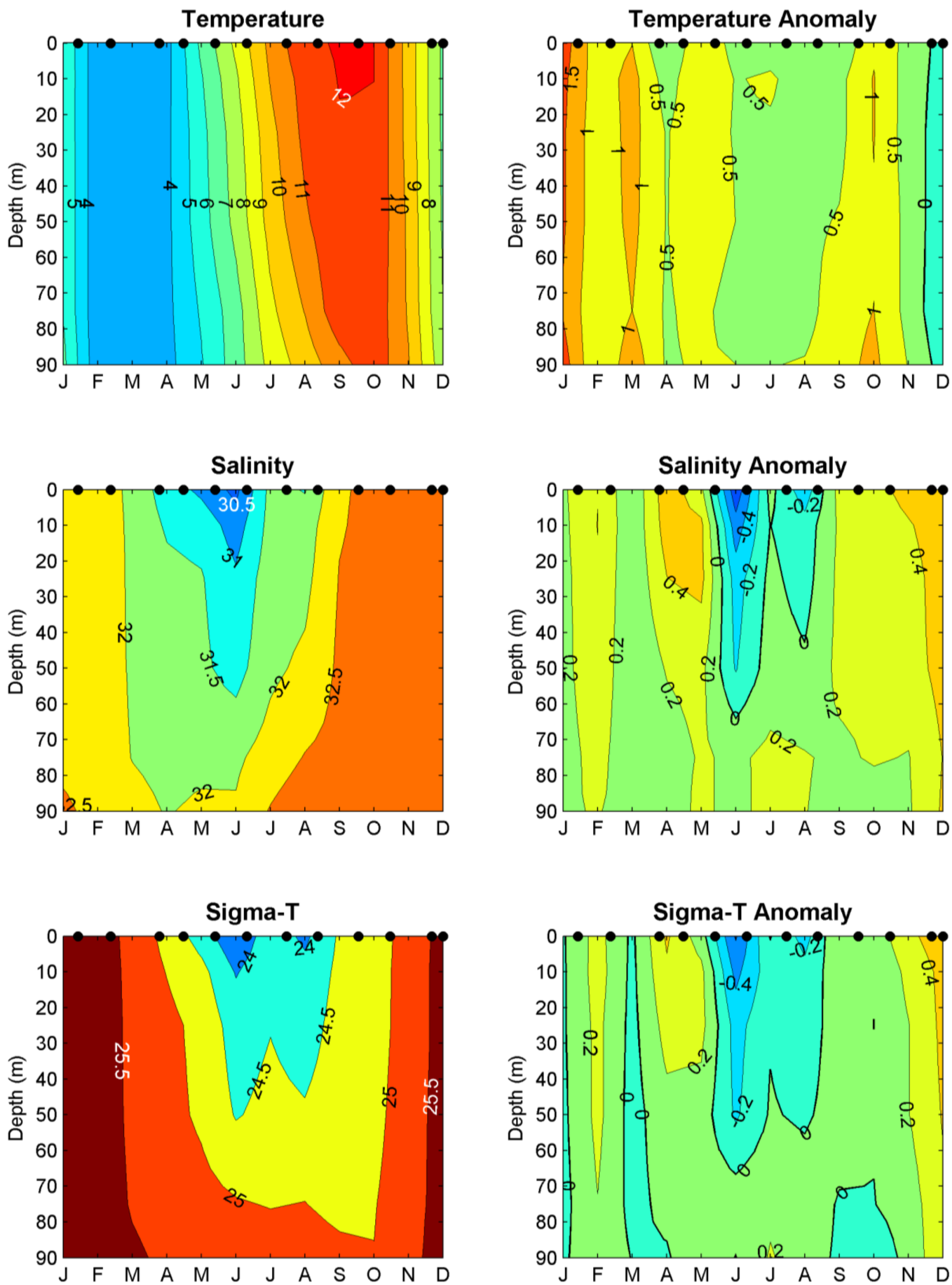

Figure 15. The 2013 annual cycle of temperature (top panel), salinity (middle panel) and density (lower panel) and their anomalies with respect to 1981-2010 monthly means (right panels) for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Bullets indicate periods of sampling.

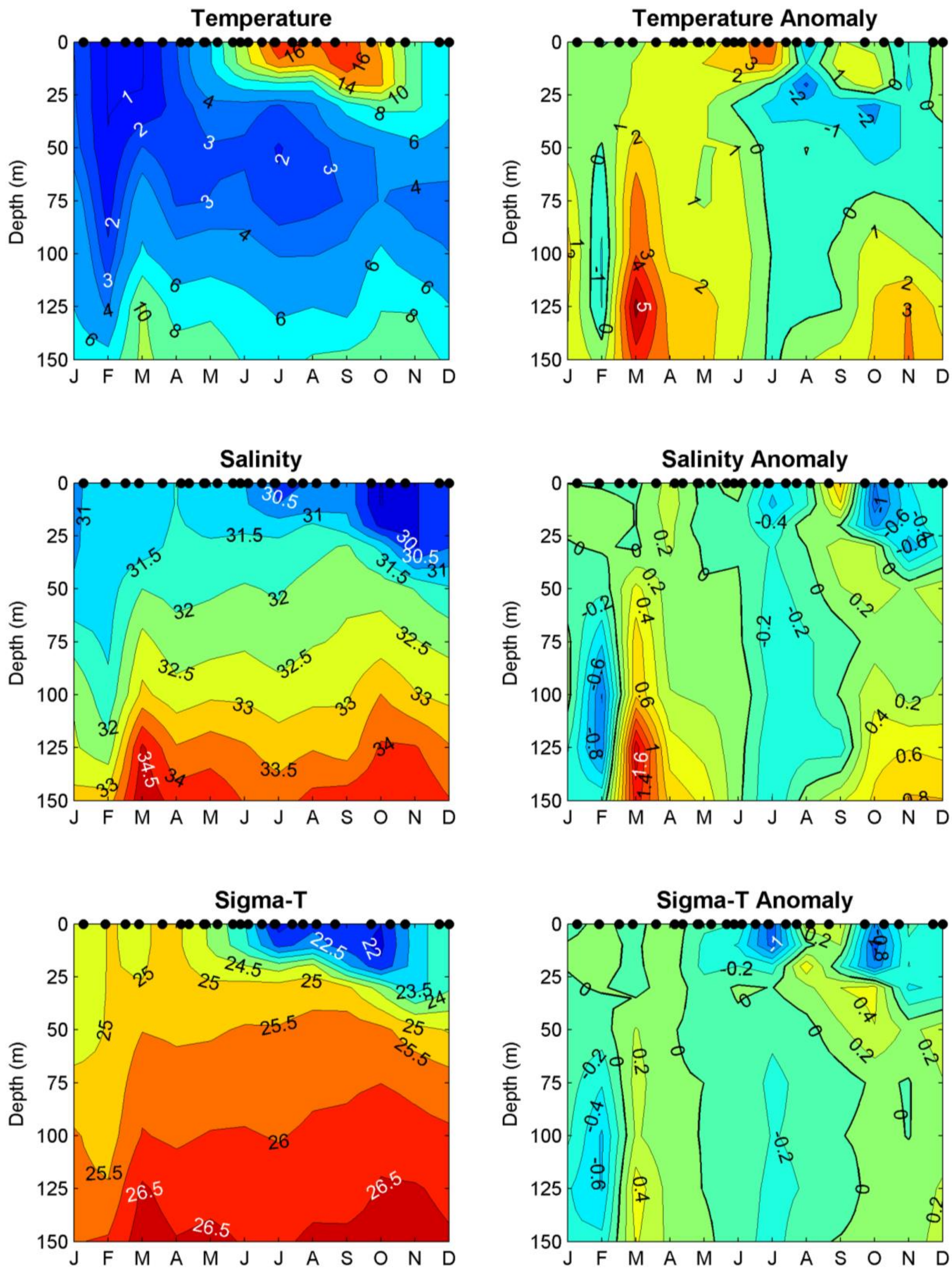

Figure 16. The 2013 annual cycle of temperature (top panel), salinity (middle panel) and density (lower panel) and their anomalies with respect to 1981-2010 monthly means (right panels) for Halifax station 2. Bullets indicate periods of sampling.

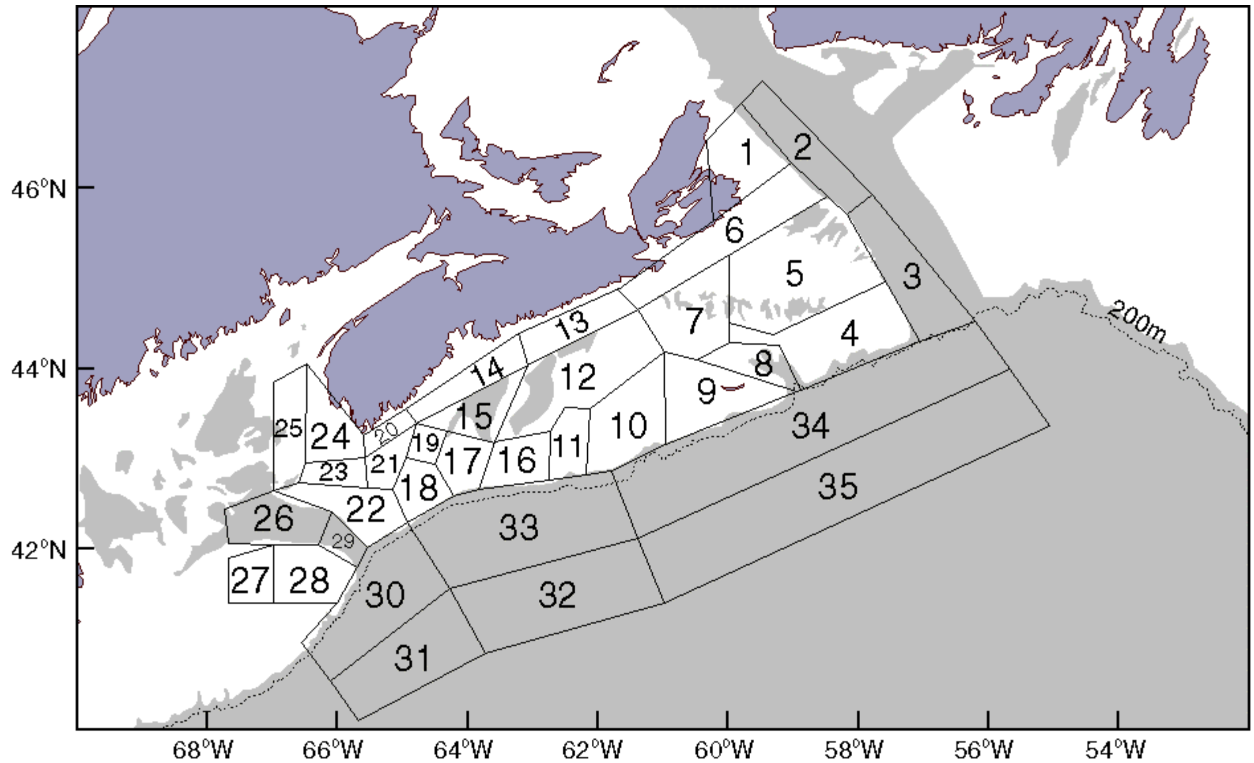

Figure 17. Areas (see names below) on the Scotian Shelf and eastern Gulf of Maine from Drinkwater and Trites (1987).

Location key for Scotian Shelf and eastern Gulf of Maine map areas:

1. Sydney Bight
2. N. Laurentian Channel
3. S. Laurentian Channel
4. Banquereau
5. Misaine Bank
6. Canso
7. Middle Bank
8. The Gully
9. Sable Island
10. Western Bank
11. Emerald Bank
12. Emerald Basin
13. Eastern Shore
14. South Shore
15. LaHave Basin
16. Saddle
17. LaHave Bank
18. Baccaro Bank
19. Roseway Bank
20. Shelburne
21. Roseway Basin
22. Browns Bank
23. Roseway Channel
24. Lurcher Shoals
25. E. Gulf of Maine
26. Georges Basin
27. Georges Shoal
28. E. Georges Bank
29. N. E. Channel
30. Southern Slope
31. Southern Offshore
32. Central Offshore
33. Central Slope
34. Northern Slope
35. Northern Offshore

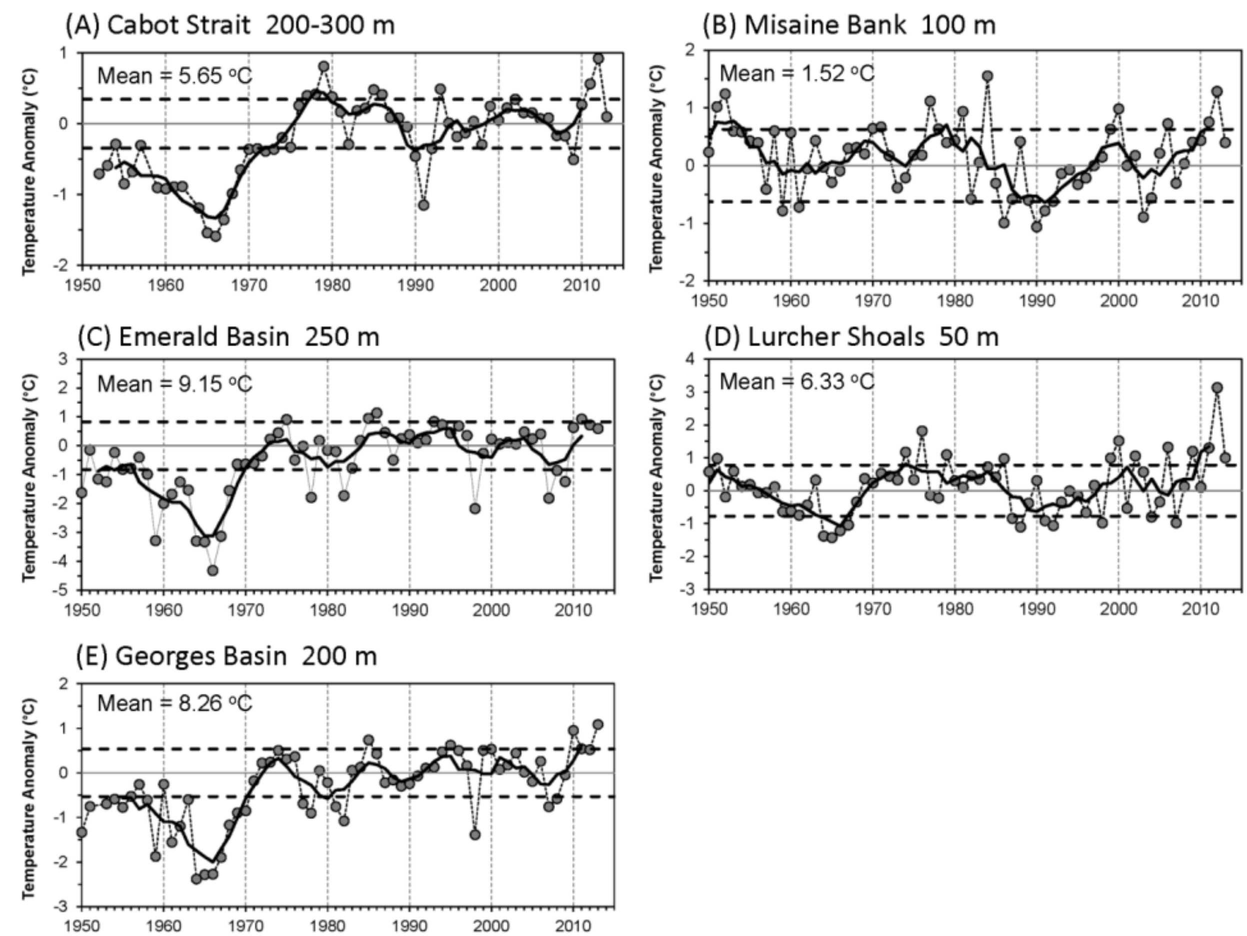

Figure 18. The annual mean temperature anomaly time series (dotted line with circles) and the five year running mean filtered anomalies (heavy solid line) on the Scotian Shelf and in the Gulf of Maine at: (A) Cabot Strait at 200-300 m; (B) Misaine Bank at 100 m; (C) Emerald Basin at 250 m; (D) Lurcher Shoals at 50 m; and Georges Basin at 200 m (see Figure 17 for locations of regions).

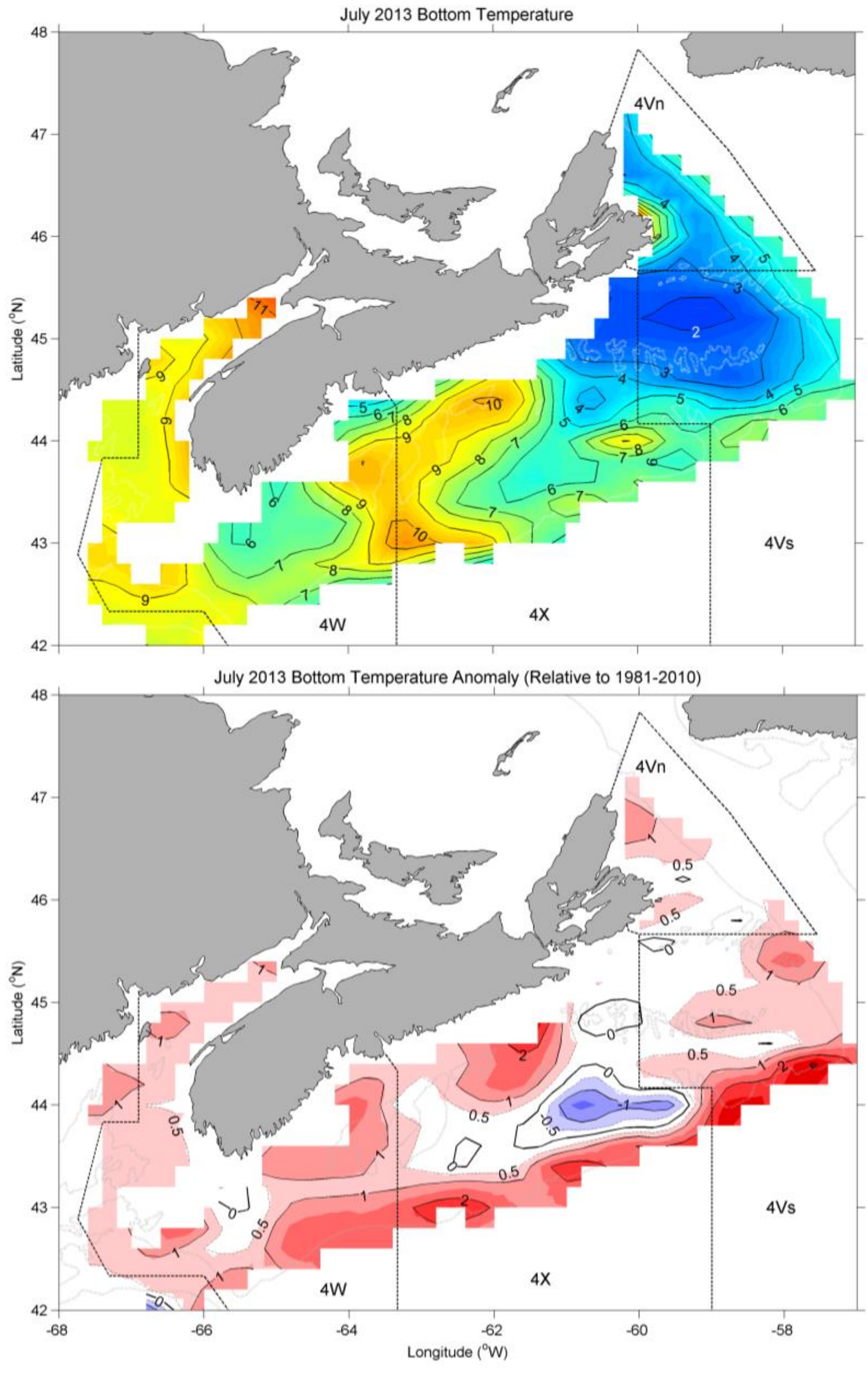

Figure 19. July bottom temperature (upper panel) and anomaly (lower panel; relative to 1981-2010) maps for 2013. NAFO areas 4Vn, 4Vs, 4X and 4W are shown.

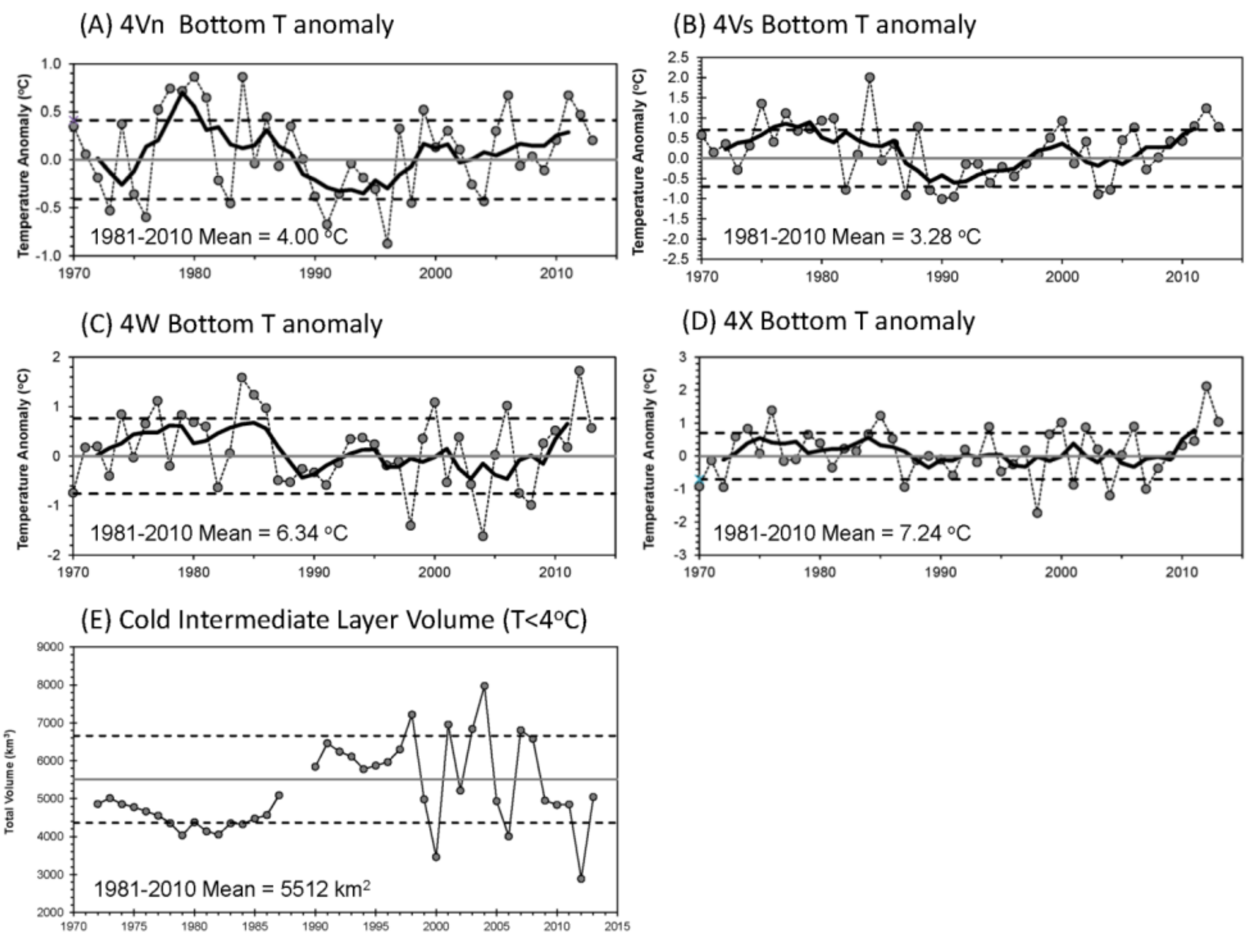

Figure 20. Time series of July bottom temperature anomalies (thin lines with circles) and five year running mean filtered series (heavy line) for areas: (A) 4Vn, (B) 4Vs, (C) 4W, and (D) 4X. (E) Time series of the Cold Intermediate Layer (CIL; defined as waters with temperature <4^{o}C) volume on the Scotian Shelf based on the July ecosystem survey. The solid horizontal line is the 1981-2010 mean CIL volume and dashed lines represent 1 SD.

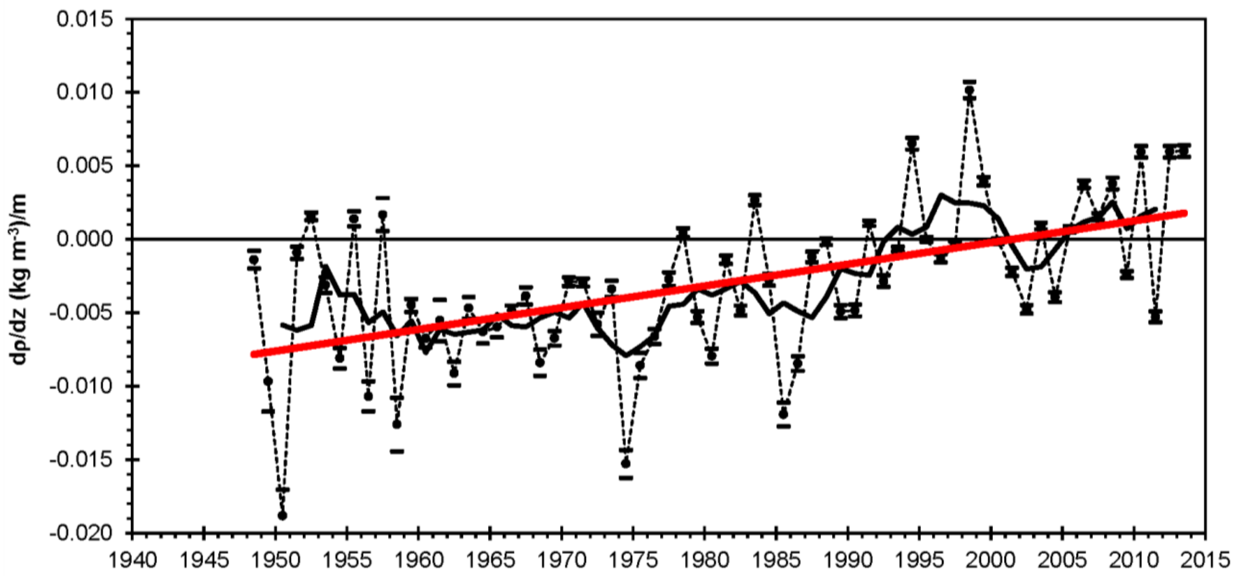

Figure 21. The mean annual anomaly (black dashed line with circles) and five year running mean (black heavy solid line) of the stratification index (0-50 m density gradient) averaged over the Scotian Shelf (areas 4-23 inclusive, see Figure 16). Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a change in the 0-50 m density difference of 0.37 kg m^{-3} over 50 years.

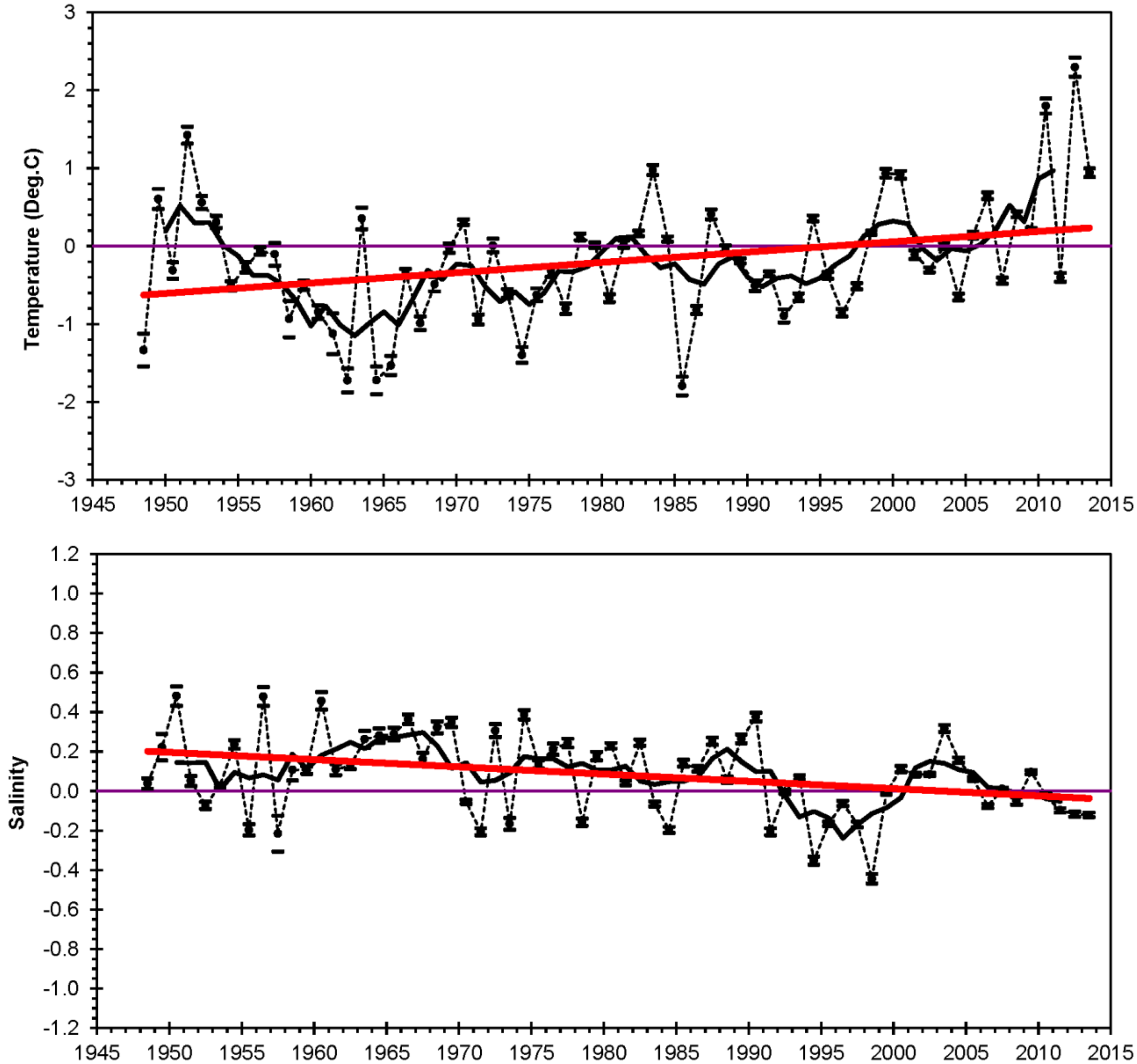

Figure 22. The mean annual surface temperature (top panel) and salinity (lower panel) anomalies (black dashed line with circles) and five year running mean (black heavy solid line) averaged over the Scotian Shelf (areas 4-23 inclusive, see Figure 16). Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a warming of 0.66^{o}C and a freshening of 0.18 over a 50 year period.

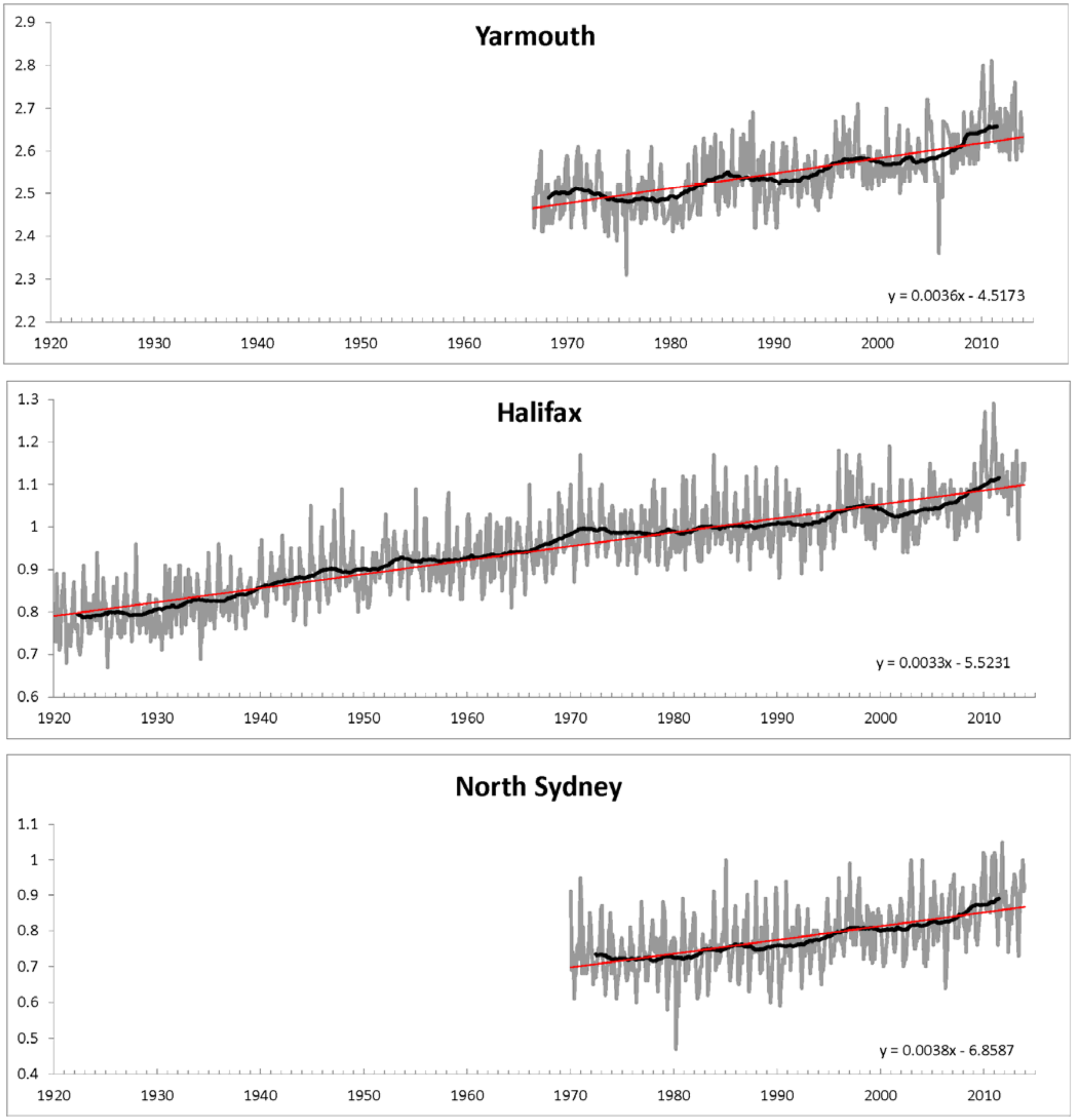

Figure 23. The time series of the monthly means (grey line) and a five year running mean (black line) of the relative sea level elevations at Yarmouth (top panel), Halifax (middle panel) and North Sydney (bottom panel), along with the linear trend (red line) over the observation period.

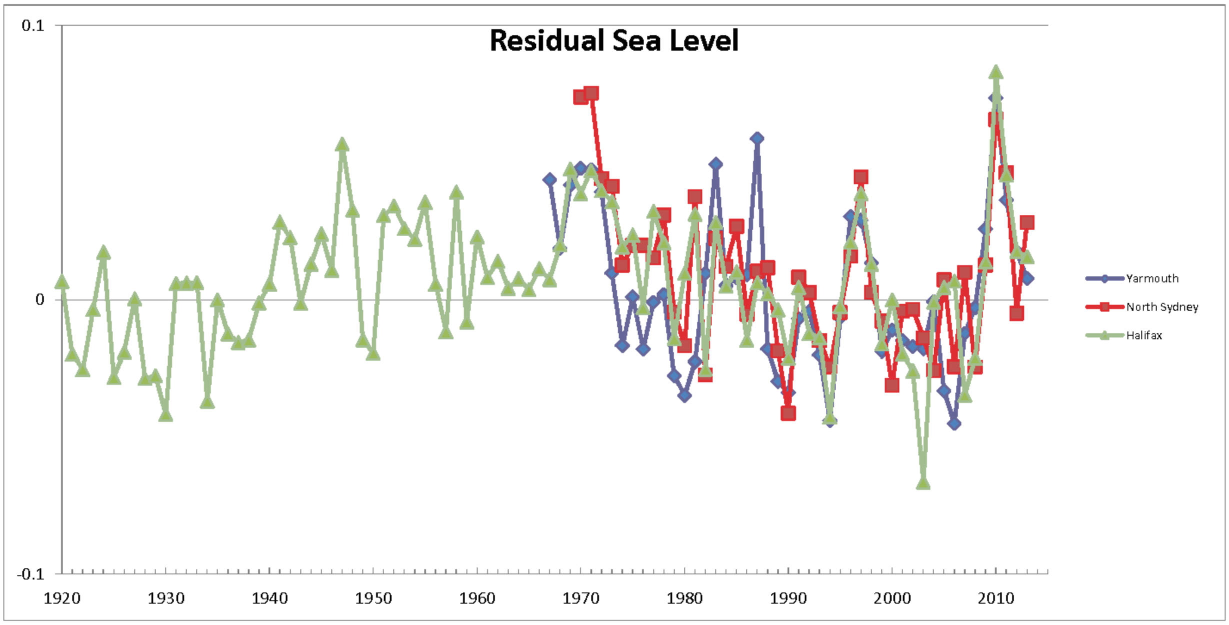

Figure 24. Residual relative sea level (monthly observed values – (1981-2010) linear trend, averaged to annual estimate for Yarmouth (blue line with diamonds), Halifax (green line with triangles) and North Sydney (red line with squares).

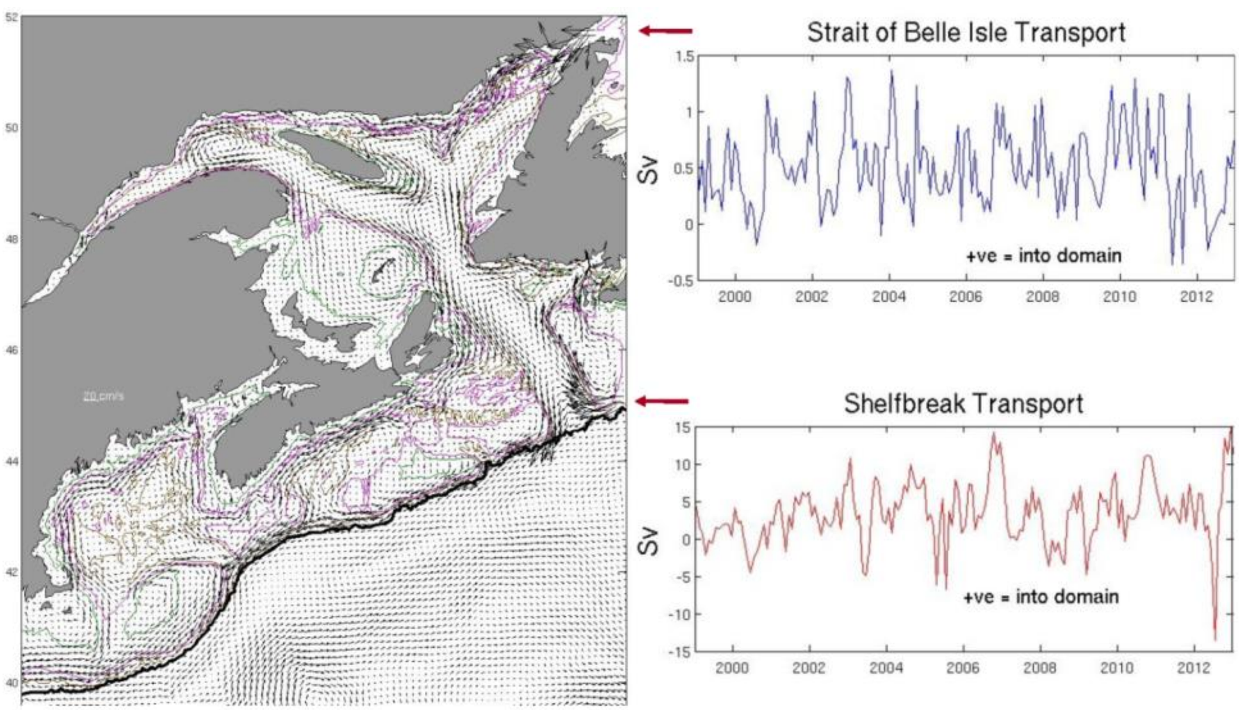

Figure 25. Maritime Canada domain map (left panel) showing annual and depth-averaged circulation and locations where open boundary transports are applied. Time series of transports applied to open boundary locations (right panels), derived from a simulation of the North Atlantic circulation for the same time period conducted by Dr. Z. Wang (BIO).

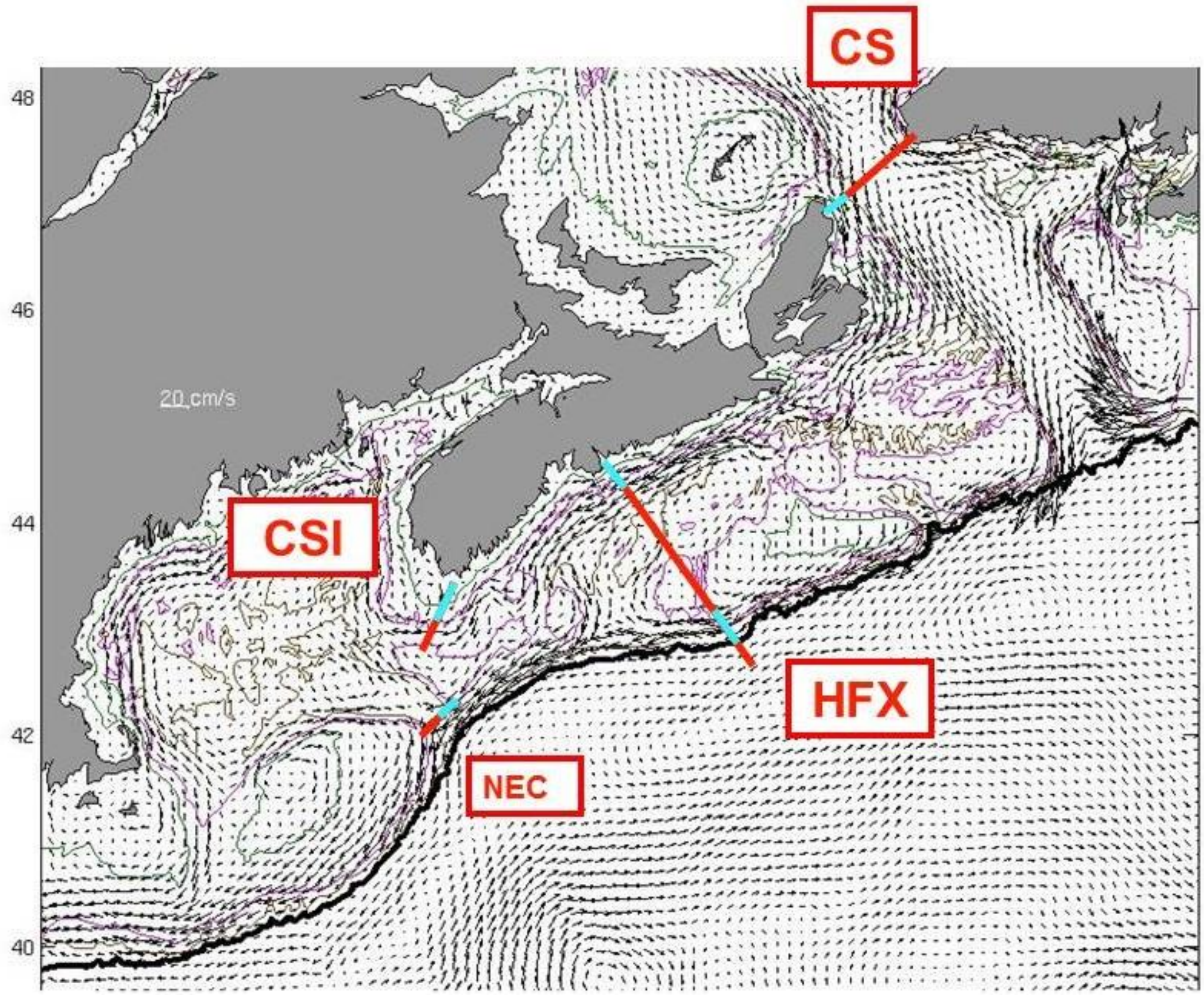

Figure 26. Annual average depth-averaged circulation illustrating the principal flow pathways from the southern Gulf of St. Lawrence to the Gulf of Maine and the subsections where transport calculations were made (cyan). CS = Cabot Strait; HFX = Halifax; CSI = Cape Sable Island/Browns Bank; NEC = Northeast Channel.

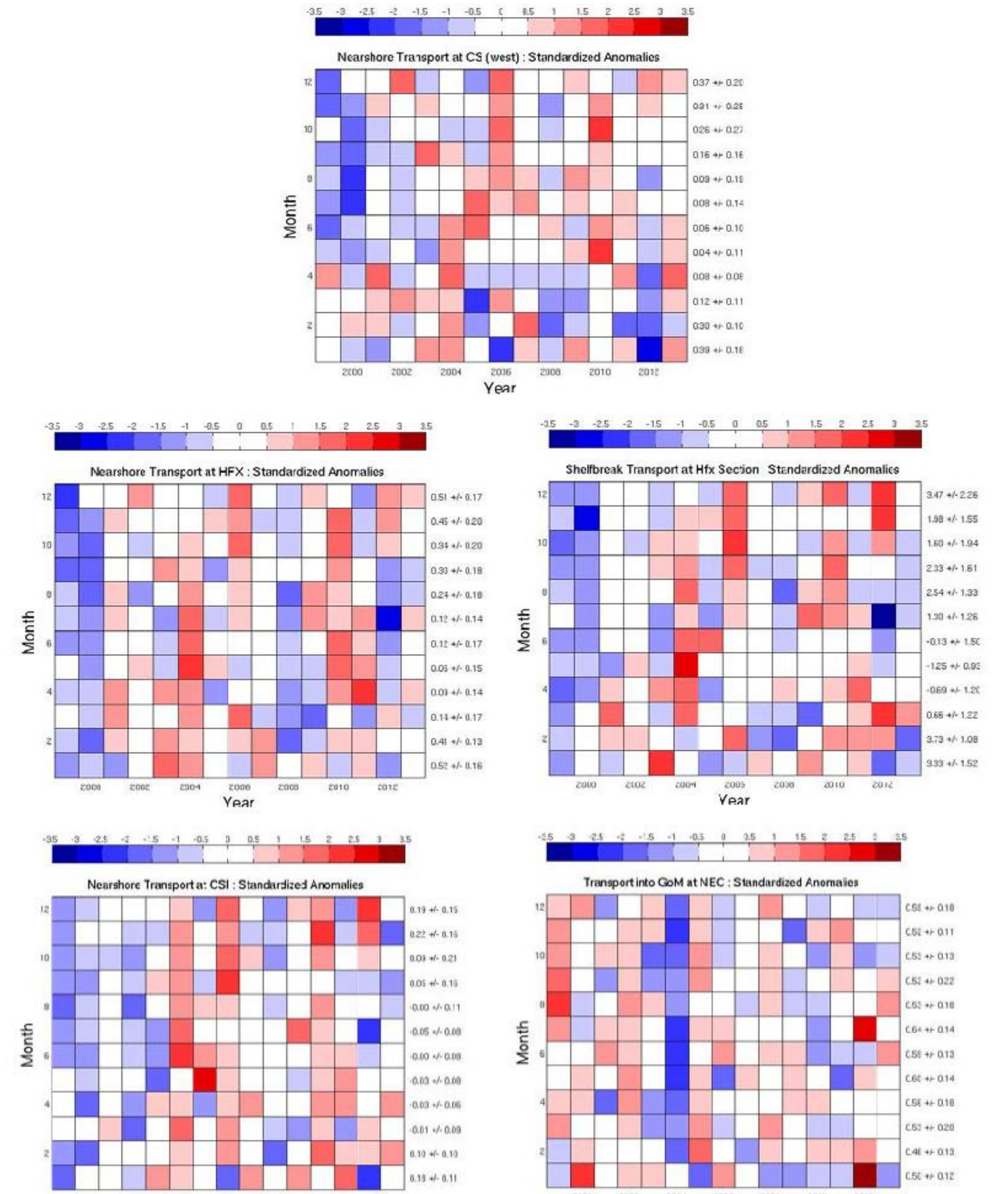

Figure 27. Standardized anomalies of the monthly transport for years 1999-2013 for four Maritime sections: (top) Cabot Strait (CS) west nearshore; (middle) Halifax (HFX) nearshore and shelfbreak; (bottom) Cape Sable Island (CSI) nearshore, and the Northeast Channel (NEC). Numbers to the right are monthly means and standard deviations.

Transport (SV)							
Month / Year	2008	2009	2010	2011	2012	2013	Grand Total
12	-0.46	-0.59	-0.58	-0.33	-0.50		-0.49
11	-0.22	-0.34	-0.52	-0.49	-0.43		-0.40
10	-0.22	-0.51	-0.36	-0.30	-0.32		-0.34
9	-0.43	-0.21	-0.30	-0.12	-0.14	-0.03	-0.21
8	-0.40	-0.26	-0.32	-0.23	-0.13	-0.08	-0.24
7	-0.04	-0.29	-0.39	-0.37	-0.11	-0.15	-0.22
6		-0.31	-0.54	-0.40	-0.09	-0.16	-0.30
5		-0.33	-0.52	-0.43	-0.22	-0.12	-0.32
4		-0.34	-0.33	-0.48	-0.23	-0.37	-0.35
3		-0.48	-0.47	-0.55	-0.64		-0.54
2		-0.66	-0.68	-0.85	-0.59	-0.64	-0.68
1		-0.80	-0.65	-0.67	-0.38	-0.60	-0.62
Grand Total	-0.30	-0.43	-0.47	-0.43	-0.32	-0.27	-0.38

Figure 28. Monthly transport (1 Sv = 10^6 m^3 s^{-1}) for years 2008-2013 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, e.g. less southwestward (green) or below, stronger southwestward (red) than the monthly average observed for the observation period (numbers to the right).

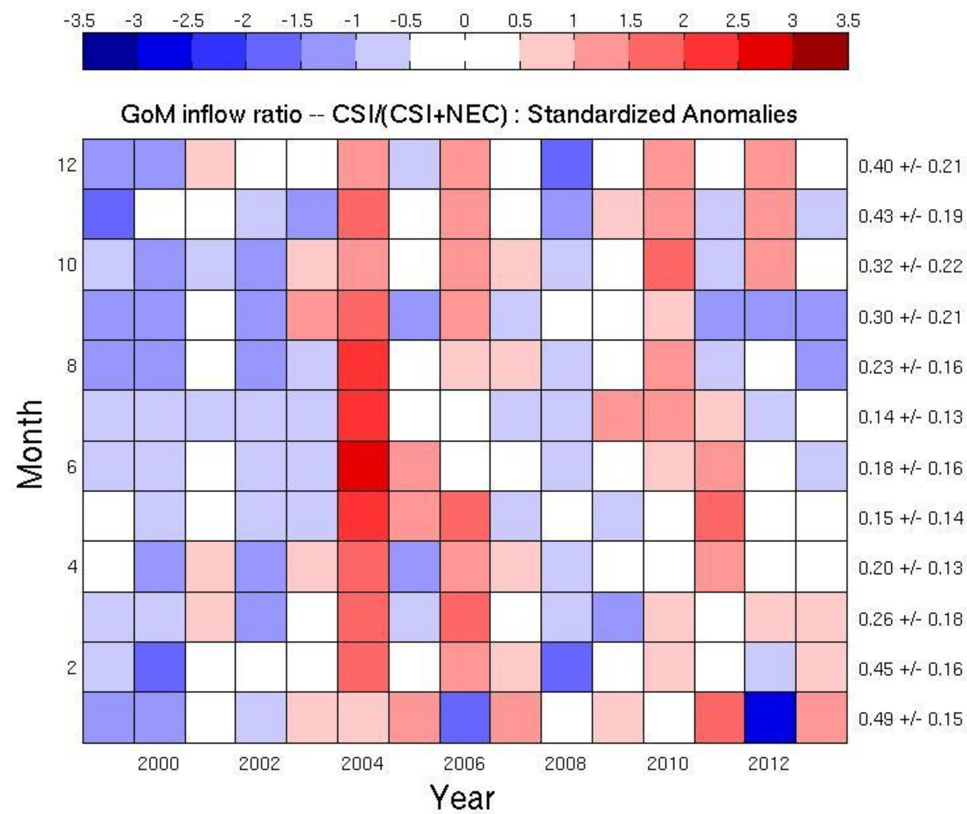

Figure 29. Standardized anomalies of the Gulf of Maine (GoM) inflow ratio, for years 1999-2013. Numbers to the right are monthly means and standard deviations. CSI = Cape Sable Island; NEC = Northeast Channel.

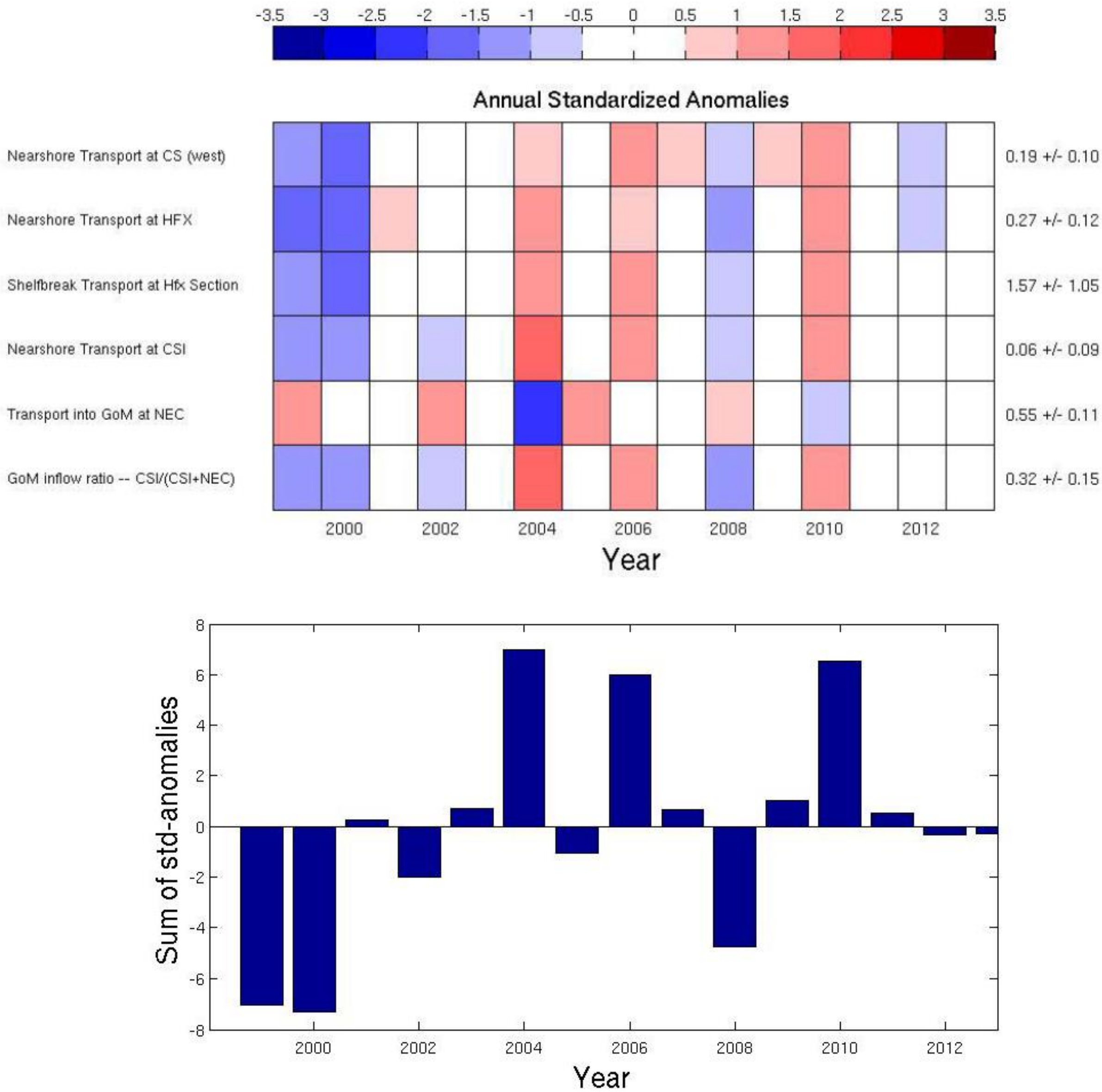

Figure 30. Annual transport anomalies scaled by the standard deviation for the variables in figures 28 and 30 for years 1999-2013. (top panel). Numbers to the right are annual means and standard deviations. Sum of standardized anomalies for 1999-2013 (bottom panel). NB: the inflow at the Northeast Channel (NEC) was omitted, as it is not independent. CS = Cabot Strait; HFX = Halifax; CSI = Cape Sable Island; NEC = Northeast Channel.

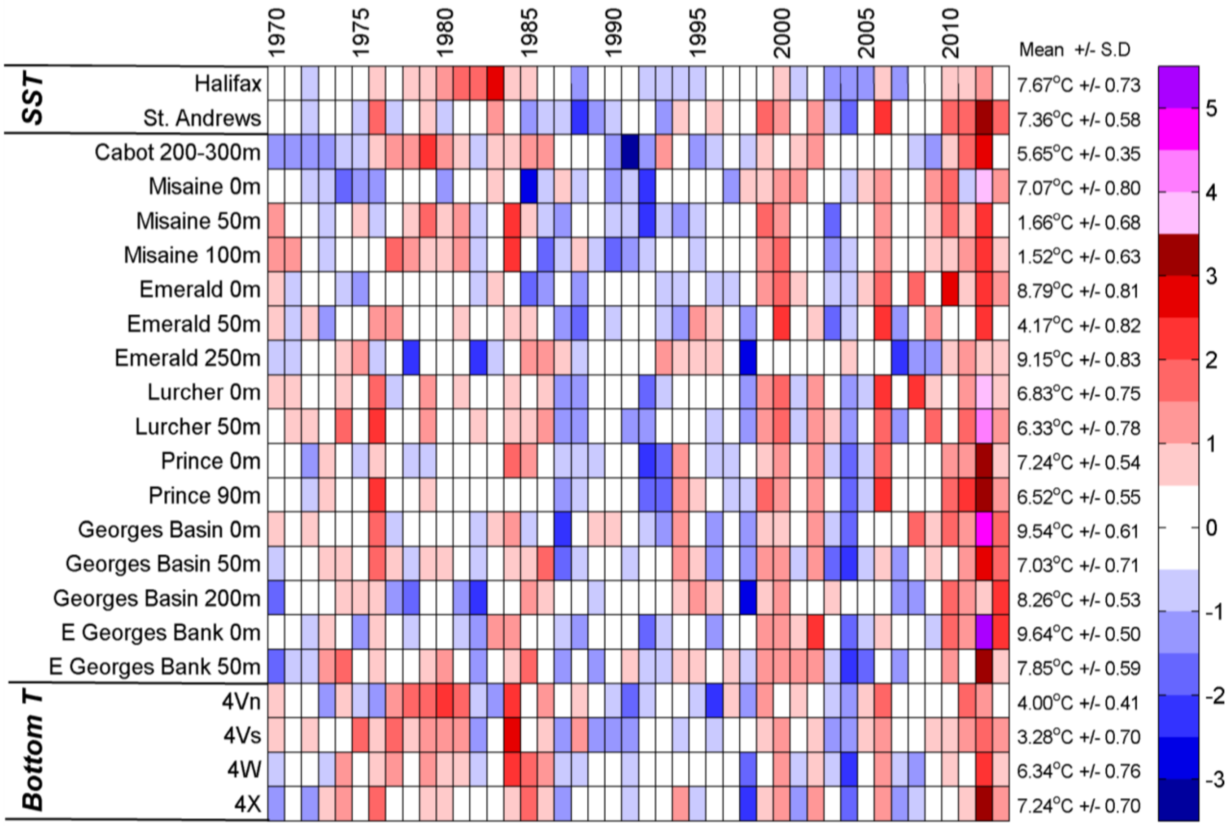

Figure 31. Normalized annual anomalies of temperatures at the bottom and discrete depths for the Scotian Shelf-Gulf of Maine region. These anomalies are based on the 1981-2010 means, divided by the standard deviation. Blue colours indicate below normal anomalies, red and purple (for 2012, the colour scale had to be increased above +3.5 SD and is shaded in purple) colours above normal anomalies.

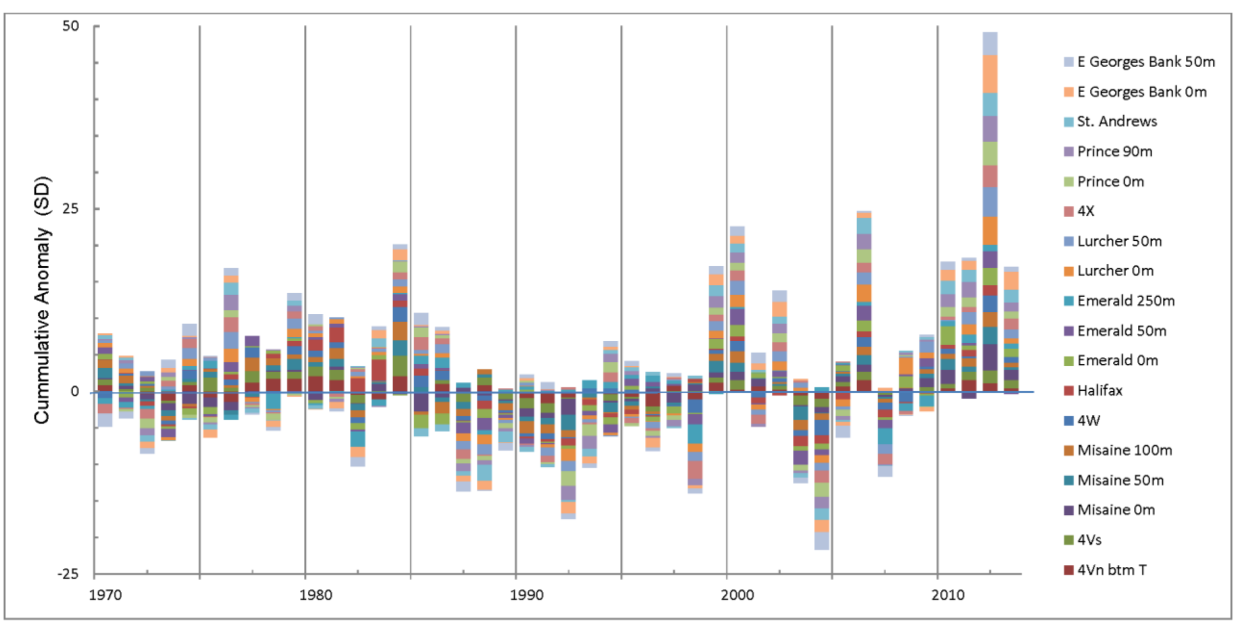

Figure 32. The contributions of each of the normalized anomalies are shown as a stacked bar chart.