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Maritimes Region

Meteorological, Sea Ice and Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2012

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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 2012, the North Atlantic Oscillation index was above the 1981-2010 mean (+11.8 mb, +1.3 SD [standard deviation]) reaching its 4th highest value two years after its record low. Mean annual air temperatures were from +1.3°C (Saint John, New Brunswick) to +1.7°C (Shearwater (Halifax), Sable Island and Sydney, Nova Scotia), +1.8 to +2.5 SD, above normal in 2012 and higher than those observed in 2011. There has been essentially no ice on the Scotian Shelf from April 2009 until the end of the season in May 2012. The ice volume during 2012 was the fourth lowest in the 51 year long record. Only 1969, 2010 and 2011 had lower coverage and volume. Positive sea surface temperature (SST) anomalies prevailed throughout the region during 2012, with representative values of about +1.7 to +2.5°C (+1.4 to +3.2 SD). Long-term coastal monitoring sites at St. Andrews (New Brunswick) and Halifax (Nova Scotia) recorded positive annual SST anomalies of +1.8°C (+3.2 SD) and +1.0°C (+1.4 SD) in 2012 and +1°C and +0.5°C above those observed in 2011. At selected sites across the region, annual water temperature anomalies were positive in 2012: +0.9°C (+2.7 SD) for Cabot Strait 200-300 m (the warmest in 61 years), +1.3°C (+2.0 SD) for Misaine Bank 100 m (2nd warmest year), +0.7°C (+0.9 SD) for Emerald Basin 250 m, +3.4°C (+4.3 SD) for Lurcher Shoals 50 m (warmest year), and +0.5°C (+0.9 SD) for Georges Basin 200 m (the previous two years had the highest temperatures). Bottom temperature anomalies in Northwest Atlantic Fisheries Organization areas 4VWX were all positive in 2012 and ranged from +0.5°C (+1.2 SD) in 4Vn to +2.1°C (+3.0 SD) in 4X. Average stratification on the Scotian Shelf strengthened significantly compared to 2011, reaching a value similar to 2010 and the fourth strongest stratification in the record. This increase in stratification from 2011 to 2012 was due mainly to an increase in surface temperature. Since 1950, the stratification has slowly been increasing on the Scotian Shelf due mainly to a freshening of the surface waters. A composite index consisting of ocean temperatures from surface to bottom across the region indicated that 2012 was the warmest of 43 years, with an averaged normalized anomaly of +2.8 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 2012

RÉSUMÉ

En 2012, l'indice d'oscillation nord-atlantique en hiver était supérieur à la moyenne de 1981 à 2010 (+ 11,8 hPa, + 1,3 ÉT [écart type]), se classant ainsi au quatrième rang des valeurs les plus élevées, et ce, deux ans après avoir atteint la valeur la plus basse enregistrée. Supérieures à celles observées en 2011, les températures atmosphériques moyennes s'échelonnaient entre + 1,3 °C (Saint John, au Nouveau-Brunswick) et + 1,7 °C (Shearwater [Halifax], île de Sable et Sydney, en Nouvelle-Écosse) au-dessus de la normale en 2012, avec un écart type de + 1,8 à + 2,5. Il n'y a pratiquement pas eu de glace sur le plateau néo-écossais à partir du mois d'avril 2009, jusqu'à la fin de la saison en mai 2012. Le volume de glace pour 2012 se situait au quatrième rang des volumes les plus bas enregistrés en 51 ans. Seules les années 1969, 2010 et 2011 ont connu une couverture et un volume de glace plus faibles. Des anomalies de température positive de la surface de la mer (SST) ont prévalu dans toute la région en 2012, avec des valeurs représentatives d'environ + 1,7 à + 2,5 °C (+ 1,4 à + 3,2 ÉT). Aux sites de surveillance côtière à long terme de St. Andrews, au Nouveau-Brunswick, et de Halifax, en Nouvelle-Écosse, on a enregistré de faibles anomalies de SST annuelle de + 1,8 °C (+ 3,2 ÉT) et de + 1 °C (+ 1,4 ÉT) en 2012, qui étaient supérieures de + 1 °C et de + 0,5 °C à celles observées en 2011. À des endroits choisis à l'échelle de la région, les anomalies annuelles de température étaient positives en 2012 : + 0,9 °C (+ 2,7 ÉT) entre 200 et 300 m dans le détroit de Cabot (le plus chaud en 61 ans), + 1,3 °C (+ 2 ÉT) dans la strate de 100 m du banc de Misaine (second rang des années les plus chaudes), + 0,7 °C (+ 0,9 ÉT) dans la strate de 250 m du bassin Émeraude, + 3,4 °C (+ 4,3 ÉT) dans la strate de 50 m du haut-fond Lurcher (année la plus chaude) et + 0,5 °C (+ 0,9 ÉT) dans la strate de 200 m du bassin Georges (les deux années précédentes ont connu les températures les plus élevées). Les anomalies de température au fond dans les divisions 4VWX de l'Organisation des pêches de l'Atlantique Nord-Ouest étaient toutes positives en 2012 et allaient de + 0,5 °C (+ 1,2 ÉT) dans la zone 4Vn à + 2,1 °C (+ 3 ÉT) dans la zone 4X. La stratification moyenne sur le plateau néo-écossais a considérablement augmenté par rapport à 2011, atteignant une valeur semblable à celle observée en 2010 de même que le quatrième rang sur le plan de la stratification la plus forte jamais enregistrée. Cette augmentation de la stratification de 2011 à 2012 s'explique principalement par la hausse de la température de la surface. Depuis 1950, la stratification a lentement augmenté sur le plateau néo-écossais principalement en raison d'une dessalure des eaux superficielles. Un indice composite composé des températures de la mer de la surface au fond à l'échelle de la région révèle que 2012 était l'année la plus chaude en 43 ans, avec une anomalie normalisée de + 2,8 ÉT par rapport à la période allant de 1981 à 2010.

INTRODUCTION

This research document discusses air temperature trends, winds, ice cover, sea surface temperatures (SST) and physical oceanographic variability during 2012 on the Scotian Shelf 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., 2013; Colbourne et al., 2013). 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°C and salinities from 34.7-35.6, and Labrador Slope Water, with temperatures from 3.5°C to 8°C and salinities from 34.3 to 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 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, 2009-2011), 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 2012, the winter NAO index reached its 4th largest value a mere two years after its record low; 11.8 mb (1.3 SD) above the 1981-2010 mean (Figure 2, upper panel). The lower panels of Figure 2 show the sea level pressure conditions during the winter of 2012 compared to the 1981-2010 mean. The Icelandic low was near its typical value while the Azores high was approximately 8 mb higher than the mean. With a positive NAO index, it is expected that air temperatures in the Maritimes Region would have been lower than normal. However, this was not the case.

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 (NOAA, 2012) interactive website at http://www.cdc.noaa.gov/cgi-bin/data/getpage.pl. The annual anomalies are above normal by more than 1.25°C over the Scotian Shelf and by up to 1.5°C in the Gulf of Maine in 2012 (Figure 3). The annual anomaly of these regions is positive throughout the year but larger during the winter period (Figure 4).

Monthly air temperature anomalies for 2011 and 2012 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. Data for the Canadian sites were from the Environment Canada website http://climate.weatheroffice.gc.ca/prods_servs/cdn_climate_summary_e.html and from the *Monthly Climatic Data for the World* (NOAA, 2012) for Boston (http://www.nws.noaa.gov/climate/index.php?who=box). In 2012, at several stations, there was a switch from Environment Canada instruments to new NAV CANADA sensors and reporting tools. For this new data, the daily (0300-0200 local standard time) minimum and maximum temperatures were determined from the hourly data. From these temperatures, the daily and monthly averaged were determined. After the switchover, there are several months with missing days of data. The observed and normalized annual anomalies for these stations are listed in Table 1. In 2012, the annual anomalies were positive at all sites, ranging from +1.3 to +1.7°C, approximately 2 SD above normal at all sites. Except for Boston, these annual anomalies are all larger 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. Over shorter periods, there are times when there is no trend or a decreasing trend in the temperature (Figure 6). 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 (+0.6°C, +1.5°C), +1.0°C (+0.7°C, +1.4°C), +1.5°C (+1.2°C, +1.9°C), +0.7°C (+0.4°C, +1.1°C), +0.4°C(-0.0°C, +0.7°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, 91 of the 113 years had five or more stations with the annual anomalies having the same signs; for 63 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 2012 was +9.4°C, the warmest year in 113 years (with 2010 being the 2nd and 2011, the 6th warmest years).

Table 1. The 2012 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	1981-2010 Climatology	
	Observed (°C)	Normalized	Anomalies(°C)	Mean (°C)	SD (°C)
Sydney	+1.7	+2.1	0.9	5.87	0.81
Sable Island	+1.7	+2.4	0.7	7.88	0.68
Shearwater (Halifax)	+1.7	+2.3	1.0	6.99	0.74
Yarmouth	+1.6	+2.5	0.9	7.16	0.62
Saint John	+1.3	+1.8	1.0	5.19	0.74
Boston	+1.4	+2.4	1.7	10.91	0.60

WINDS AND PRECIPITATION

For an indication of the winds and precipitation on the Scotian Shelf for 2012, hourly mean wind speeds and daily total precipitation on Sable Island for the period 1956-2012 were examined. It has been suggested with increasing global warming that there could be an increase in the variability of extreme events (Hegerl et al, 2007). The hourly wind speeds for each year from 1956 to 2012 on Sable Island were examined to determine if the distribution of wind speeds for each year and each season (January-March, April-June, July-September, October-December) showed a trend in extreme events. A whisker and box plot of the distribution of the hourly winds speed is shown in Figure 8. There is no obvious trend in more extreme events or an increase in the mean wind speed on Sable Island. Likewise, the distributions of daily precipitation rates were examined (Figure 9). As with the wind speed, no obvious trends were observed in the daily precipitation rates.

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 http://ice-glaces.ec.gc.ca/ for the period 1962-2012. In the current analysis, ice concentrations of ≥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 2012 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 the number of days 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 using a look up table that assigns 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 2012 (Figure 10); over much of the region, the day of first appearance of ice was more than 15 to 30 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 11). Overall, ice duration was shorter than normal over most of the region (Figure 12).

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 2012, it was present there for only a short period, lasting about one week. There has been essentially no ice on the Scotian Shelf since April 2009 (Figure 13).

The ice areas and volumes for 2012 are compiled in Table 2. The January to April 2012 ice coverage and volume was the 4th lowest in the 51 year long record. Only 1969, 2010, and 2011 had lower 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	2012 Ice Area (km^2)	2012 Area Anomaly (km^2)	2012 Normalized Area Anomaly	2012 Ice Volume (km^3)	2012 Volume Anomaly (km^3)	2012 Normalized Volume Anomaly
January	1.5	-1200	-0.6	<0.01	-0.2	-0.7
February	432.0	-10900	-1.0	0.08	-2.8	-1.0
March	752.0	-14900	-1.0	0.16	-6.7	-1.0
April	<0.1	-4580	-0.9	<0.01	-3.0	-1.0

REMOTELY-SENSED SEA SURFACE TEMPERATURE (SST)

A 4 km resolution Pathfinder 5.2 (Casey et al., 2010) SST database is kept at the Bedford Institute of Oceanography (BIO; Dartmouth, Nova Scotia). The Pathfinder dataset runs from November 1981 to December 2010; to provide data for 2011 and 2012, 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. Comparison of the Pathfinder and ORMS temperatures during the common time period led to a conversion equation SST(Pathfinder) = 0.989*SST(ORMS)-0.02 with an r^2=0.98. The NOAA observations were adjusted to bring them in line 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 14). The annual anomalies during 2012 ranged from +1.7°C (+1.4 SD) over Western Bank to +2.5°C (+3.2 SD) in the Bay of Fundy. All eight areas had positive anomalies; all but one was greater than +1.4 SD. Over the lengths of the records, all areas show increasing temperature trends, based on a linear least squares fit, corresponding to temperature changes from a lowest value +0.9°C (Lurcher Shoal) to a highest value of +2.0°C (Bay of Fundy). A similar trend in SST from AVHRR measurements was found in the Gulf of St. Lawrence (Galbraith et al., 2012). The large increase in the observed SST over this period has likely been enhanced by the cold period at the beginning of the AVHRR period and a rapid temperature increase from 2011 to 2012 (Figure 6).

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 15).

Table 3. For 2012, SST anomalies and long-term SST statistics including 1982-2012 temperature change based on the linear trend.

Site	2012 SST Anomaly (°C)	2012 SST Anomaly Normalized	1981-2010 Mean Annual SST (°C)	1981-2010 Annual SST Anomaly Std. Dev. (°C)	ΔT (°C) 1982-2012
Cabot Strait	+1.7	+1.6	5.9	1.0	1.2
Eastern Scotian Shelf	+1.9	+1.7	7.1	1.1	1.2
Central Scotian Shelf	+2.3	+2.1	8.5	1.1	1.5
Western Bank	+1.7	+1.4	8.9	1.2	1.2
Western Scotian Shelf	+2.5	+2.3	8.1	1.1	1.3
Lurcher Shoal	+2.4	+2.2	7.2	1.1	0.9
Bay of Fundy	+2.5	+3.2	7.2	0.8	2.0
Georges Bank	+2.0	+2.1	10.0	1.0	1.0

COASTAL TEMPERATURES AND SALINITIES

Coastal SSTs have been collected at Halifax (Nova Scotia) and St. Andrews (New Brunswick) since the 1920s (Figure 16). In 2012, the SST anomalies were +1.0°C (+1.4 SD) for Halifax, an increase of 0.4°C from 2011 and +1.8°C (+3.2 SD) for St. Andrews, an increase of 0.9°C from 2011. Interestingly, the SST at Halifax, located in the harbour, had no significant change from 1981 to 2012, due to a warmer early 1980s (Figure 16), whereas the satellite-based SST showed an increase over the same period (Table 3; Figure 14). Slight changes in timing of warming and cooling events can affect estimates of trends over short periods. For example, the trend in the Halifax temperature between 1988 and 2012 was the equivalent of an increase of 0.7°C for that period.

Temperature and salinity measurements through the water column, for the most part are sampled monthly 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 16. In 2012, the annual temperature anomaly was +1.9°C (+3.5 SD) and the salinity anomaly was +0.2 (1.1 SD). These represent changes of +0.9°C and +0.6 from the 2011 values. The negative density anomaly is accounted for by the temperature anomaly which was larger than density anomaly due to the increased salinity anomaly.

The 2012 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 17). The largest temperature anomaly occurred in the spring and summer. The 0-90 m average temperature indicates that 2012 had the warmest water on record (Figure 16). The salinity anomaly observed at Prince 5 is due to the arrival of fresh water in the upper ocean with the Saint John River, a nearby source. For 2012, the positive salinity anomaly is probably the result of less than normal amount of fresh water arriving there.

The 2012 annual cycle at Halifax 2 shows the standard seasonal temperature cycle (Figure 18). 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 the positive 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 19). Petrie et al. (1996) updated their report using these same areas and all available hydrographic data. A time series of annual mean and filtered (five year running means) temperature anomalies at selected depths for five areas is presented (Figure 20). The Cabot Strait (see Figure 1) temperatures represent a mix of Labrador 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 19) series characterizes the colder near bottom temperatures on the Eastern Scotian Shelf; the deep Emerald Basin (region 12) 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 20C); the Lurcher Shoals (region 24) observations define the ocean climate in southwest Nova Scotia 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. 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, 2012 annual anomalies are based on observations from only 4, 4, 5, 2 and 5 months, respectively.

In 2012, the annual anomalies were +0.9°C (+2.7 SD) for Cabot Strait 200-300 m (the warmest and 2nd saltiest year in 61 years; 2011 was the 3rd warmest year), +1.3°C (+2.0 SD) for Misaine Bank 100 m (2nd warmest year), +0.7°C (+0.9 SD) for Emerald Basin 250 m, +3.4°C (+4.3 SD) for Lurcher Shoals 50 m (warmest year), and +0.5°C (+0.9 SD) for Georges Basin 200 m (2010 was the warmest year and 2011 was the 3rd warmest year). These values correspond to changes of +0.4°C, +0.5°C, -0.2°C, +2.1°C and -0.3°C, respectively, over the 2011 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).

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 Northeast Channel into the Gulf of Maine towards the Bay of Fundy. A total of 219 Conductivity-Temperature-Depth (CTD) stations were sampled during the 2012 survey and an additional 181 bottom temperature stations were obtained using Vemco Minilog temperature recorders as part of the ITQ (Individual Transferable Quota) fleet 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 both surveys 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, …) 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 2012 were positive everywhere; the largest anomalies near the coast and Lurcher Shoals (Figure 21). The July surface temperatures are the warmest on the Eastern Scotian Shelf and coldest near southwest Nova Scotia. It should be noted some of this variability could be do temporal changes over the length of the survey. The temperature anomalies were positive over the whole Scotian Shelf, reaching up to 4°C in places (Figure 22). This is consistent with the satellite-based SST observations.

Bottom temperatures ranged from an average of 4.5°C in Northwest Atlantic Fisheries Organization (NAFO) areas 4Vs and 4Vn to 9.4°C in 4X during 2012, illustrating the substantial difference in the environmental conditions across the Shelf (see Figure 1 for locations of the NAFO regions). The anomalies were positive for these NAFO areas in 2012: +0.5°C (+1.2 SD) in 4Vn; +1.2°C (+1.8 SD) in 4Vs; +1.7°C (+2.3 SD) in 4W; and +2.1°C (+3.0 SD) in 4X (Figure 23A-D). Compared to 2011, bottom temperatures increased in areas 4Vs, 4W and 4X by 0.4, 1.5, and 1.7°C; temperature decreased by 0.2°C in area 4Vn.

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 23). 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, …). 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 23E) 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 23E). In 2012, the observed volume of 2900 km^3 was 2.3 SD less than the 1981-2010 mean value of 5500 km^3 and the smallest volume in the 43 years of surveys.

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 19. 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 (Figure 19, 24). 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 24). Stratification on the Scotian Shelf in 2012 strengthened significantly compared to 2011; obtaining a value similar to 2010 and the fourth strongest stratification of the series. Since 1950, 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 freshening of the surface waters (Figure 25). The density difference due to the change in the surface salinity accounted for 48% of the change in stratification. Changes in density to surface warming, changes in temperature and salinity at 50 m accounted for 20%, 16% and 16%, respectively, of the stratification change. However, the change in stratification from 2011 to 2012 was mainly the result of an increase in the surface temperature in 2012 although temperature at 50 m had increased as well but not as much as the surface.

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 (1967-2012), Halifax (1920-2012) and North Sydney (1970-2012) are plotted as monthly means and as a filtered series using a five year running-mean filter (Figure 26). The linear trend of the monthly mean data has a positive slope of 35.2 cm/ century (Yarmouth), 32.9 cm/century (Halifax), and 37.2 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 24.9 cm/century, 18.2 cm/century and 20.4 cm/century, respectively. In 2012, the relative sea level at Yarmouth, Halifax and North Sydney decreased from the 2011 level although sea level rise appears to have increased rapidly in 2009-10. An interesting feature of the data is the long-term variation that has occurred since the 1920s. In Figure 27, 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 1970-2012 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 are 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).

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 taken from observed data and the hydrological model (for details, see Galbraith et al., 2013).

A simulation was run for the AZMP years 1999-2012 using a version of the circulation model that incorporated a simple scheme to assimilate the AZMP temperature and salinity data for these years. This year’s simulation included an extended temperature and salinity dataset for 2005-2012. This increased the number of profiles for these years to an average of about 6000 per year, versus about 250 per year for 1999-2004. The simulation also included 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 28.

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 SD), 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 Northeast Channel (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 1999-2012 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 29). 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 30). From the inflows through the CSI and NEC sections the GoM inflow ratio CSI / (CSI + NEC) was computed (Figure 32). (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 30) 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 of 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 50° relative to True North to obtain the velocity field normal to the Halifax Line. 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 (Figure 31).

The fraction of transport into the Gulf of Maine (GoM) through CSI inflow ratio, Figure 32) exhibits a seasonal cycle with a minimum during the summer months. Interannually, this ratio was anomalously low from 1999-2003, strongly positive in 2004, and alternated between positive and negative anomalies thereafter (Figure 33, 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, annual scorecard versions were computed (Figure 33, 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 would be found that the model hindcasts are significantly lower than normal flow-through in 1999-2000 and 2008 and higher than normal flow-through in 2004, 2006 and 2010.

SUMMARY

In 2012, the NAO index was high (+11.8 mb, +1.3 SD above the 1981-2010 mean). In 2010, the NAO index was at its lowest value (-25.1 mb, -2.5 SD) since records were started in 1895. Two years later, the index was the 4th largest. Mean annual air temperatures for 2012 were 1.3 to 1.7^{o}C above normal across the whole region. In 2012, there was basically no ice on the Scotian Shelf; the areal coverage and volume was the 4th lowest in the 51 year record. Only 1969, 2010, and 2011 had lower coverage and volume. The analysis of satellite data indicates that positive SST anomalies prevailed throughout the Scotian Shelf and Gulf of Maine region in 2012 with values from +1.7 to +2.5^{o}C (+1.4 to +3.2 SD) above the 1981-2010 mean values.

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 2010-2012 were warmer than normal (Figure 34). 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 2012, all 22 series shown had positive anomalies; only two variables were less than 1 SD above their normal values and were in deep basin waters. Of the 20 remaining series, 14 were more than 2 SD above normal and four of these were more than 4 SD above normal. In 2012, the average (median) normalized anomaly was 2.7 (2.4), the highest in the 43 year series. The SD of the normalized anomalies was 1.2. These statistics indicate that 2012 was an exceptionally 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 35. 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 anomalies did not show a strong spatial distribution in 2012. The leading mode of a principal component analysis of the 18 series captured 50% 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 (0.05) series.

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FIGURES

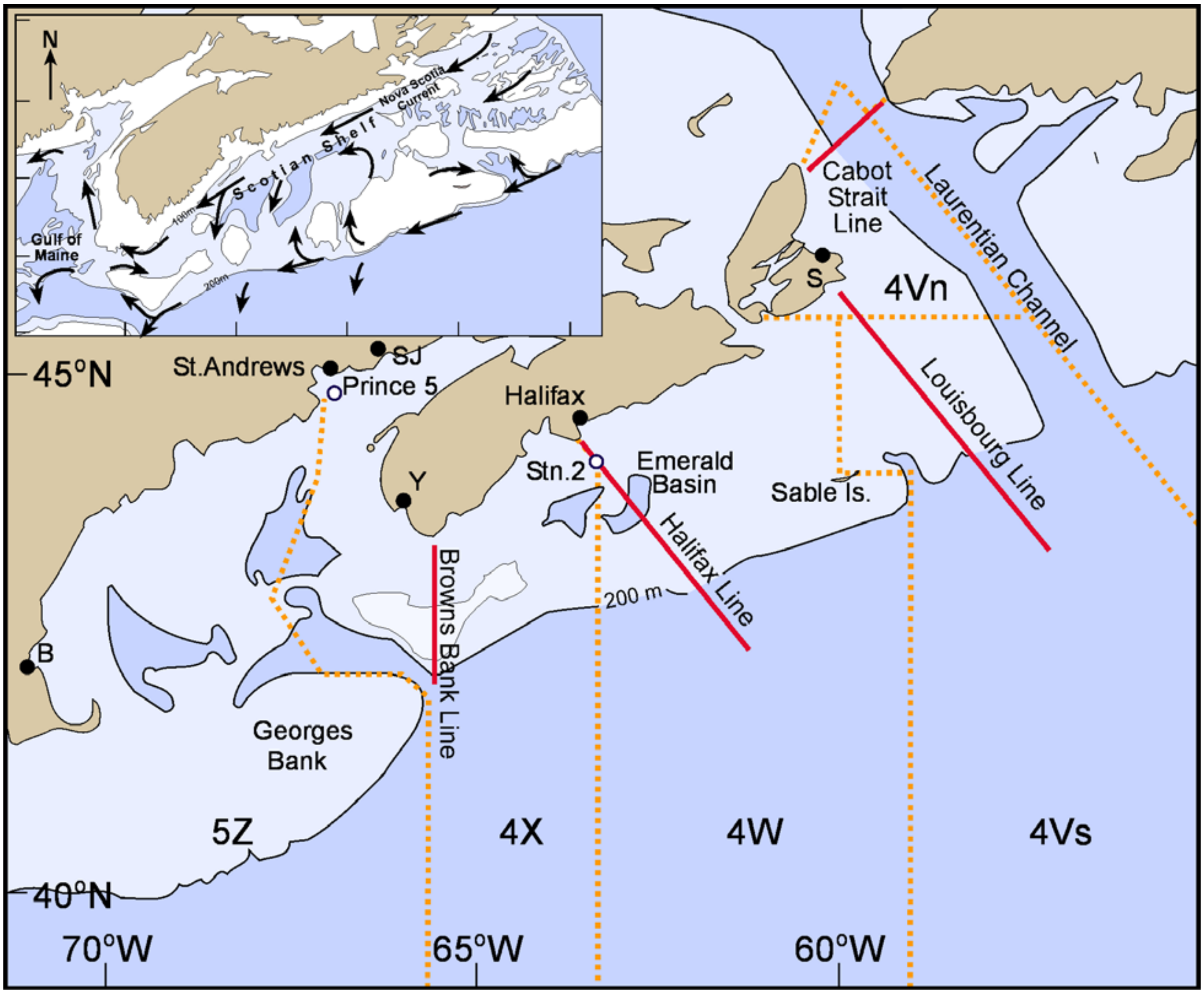


Figure 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the Northwest Atlantic Fisheries Organization (NAFO) Subareas. Inset depicts major circulation features. Air temperature stations at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

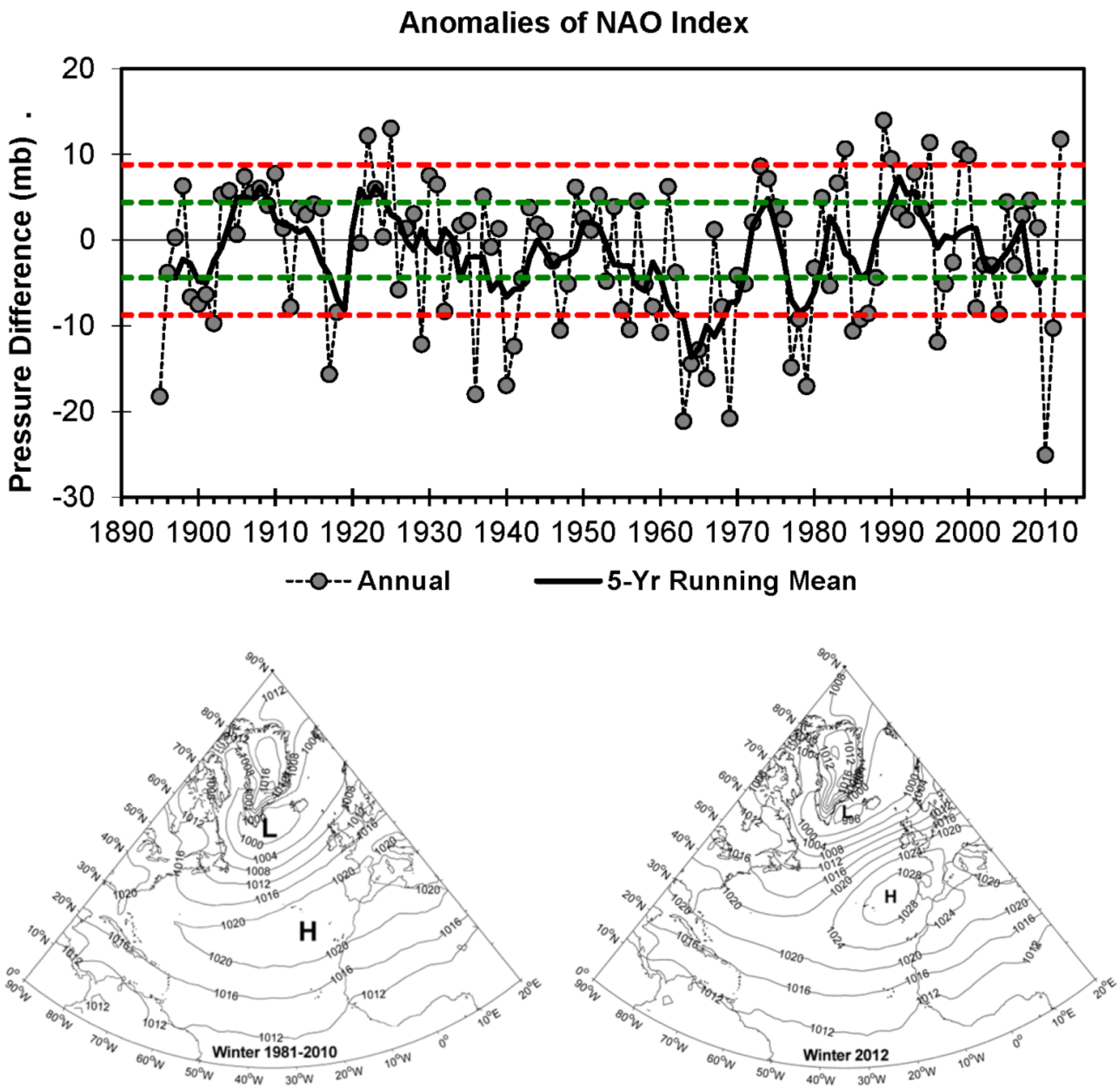


Figure 2. Anomalies of the North Atlantic Oscillation (NAO) index, defined as the winter (December, January, February) sea level pressure difference between the Azores and Iceland, relative to the 1981-2010 mean. The 0.5 (green broken lines) and 1.0 (red broken lines) standard deviations (SDs) are shown (upper panel). The lower panels show the 1981-2010 December-February mean (bottom left panel) and December 2011-February 2012 mean (bottom right panel) sea level pressure over the North Atlantic.

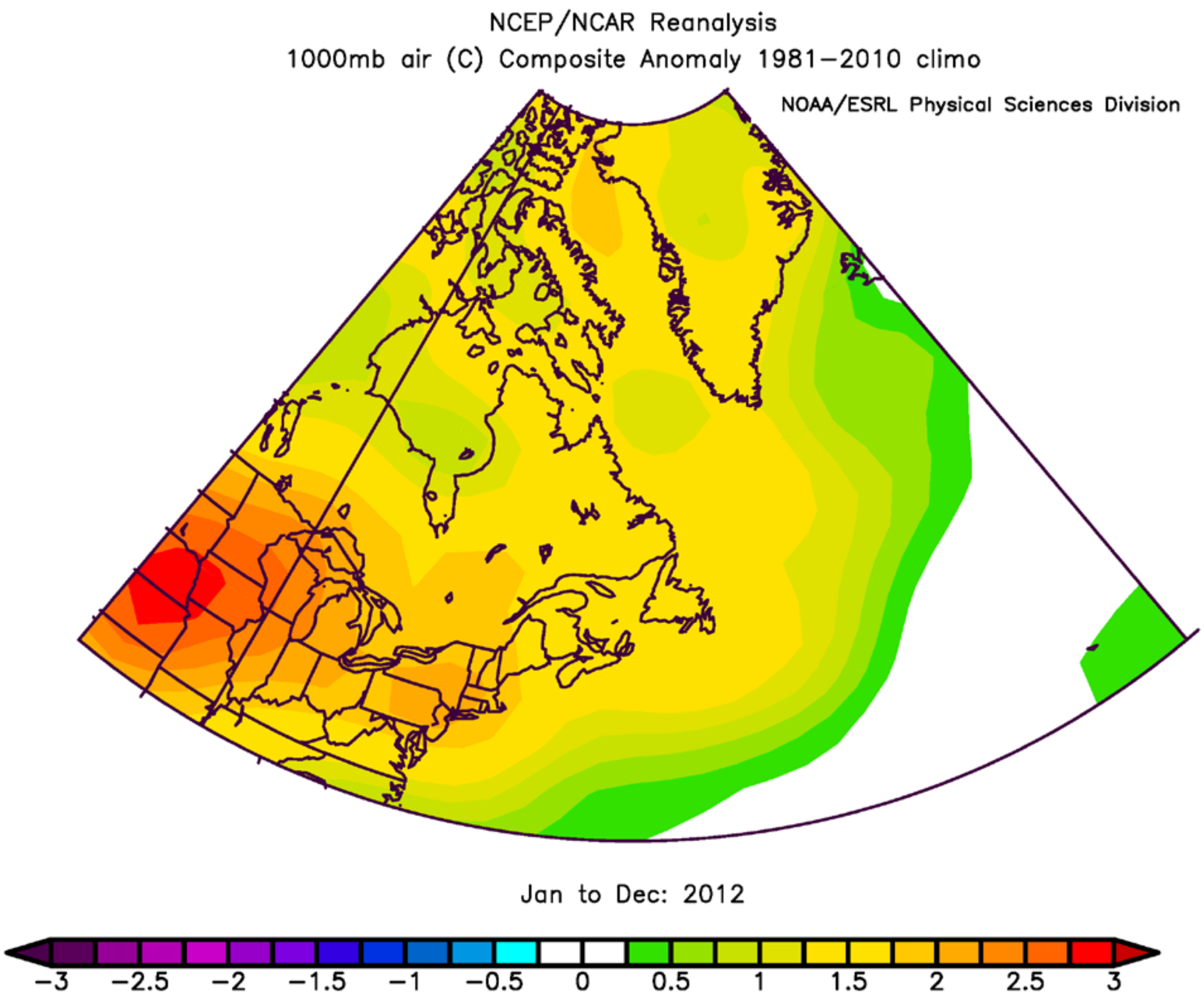


Figure 3. Annual air temperature anomalies (ºC) over the Northwest Atlantic relative to the 1981-2010 means; data were obtained from Internet site http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl *(accessed 7 January 2013).*

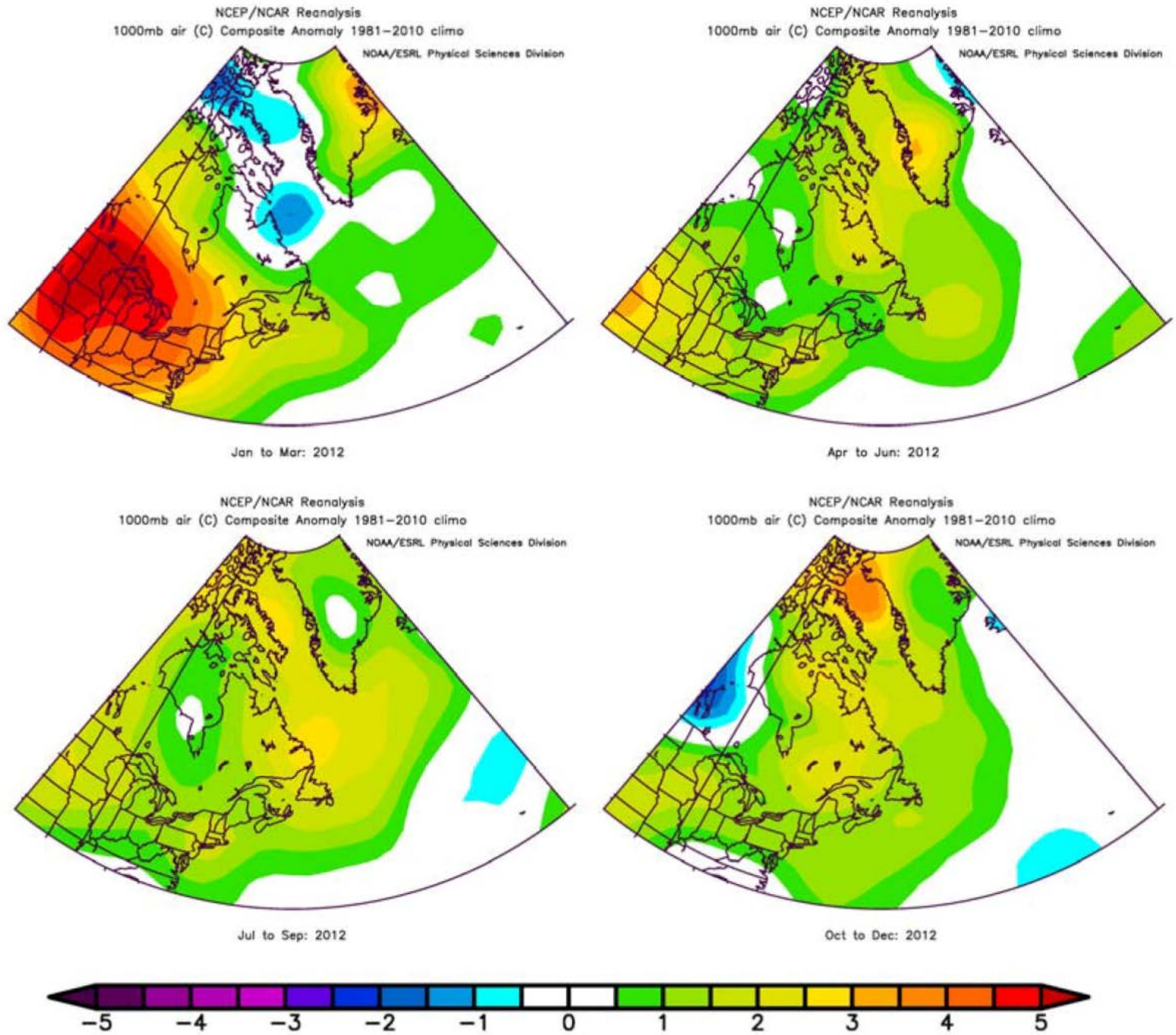


Figure 4. Seasonal air temperature anomalies (ºC) over the Northwest Atlantic relative to the 1981-2010 means; data were obtained from Internet site http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl *(accessed 7 January 2013).*

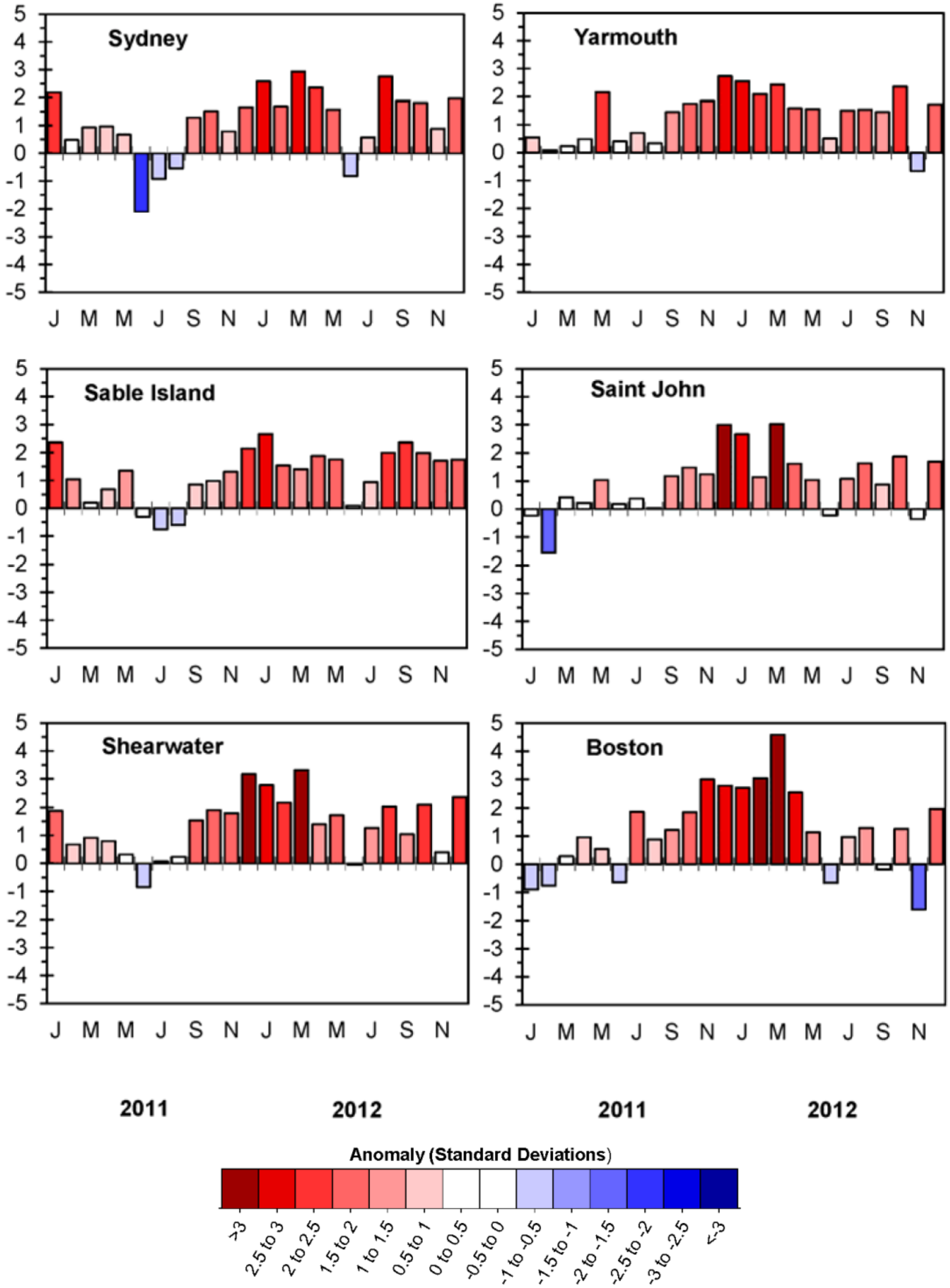


Figure 5. Monthly air temperature anomalies in ^{o}C for 2011 and 2012 (JMMJSN on x-axis represent January, March, May, June, September and November) at coastal sites in Scotian Shelf-Gulf of Maine region (see Figure 1 for locations). Anomalies are colour coded in terms of the numbers of SD above or below normal.

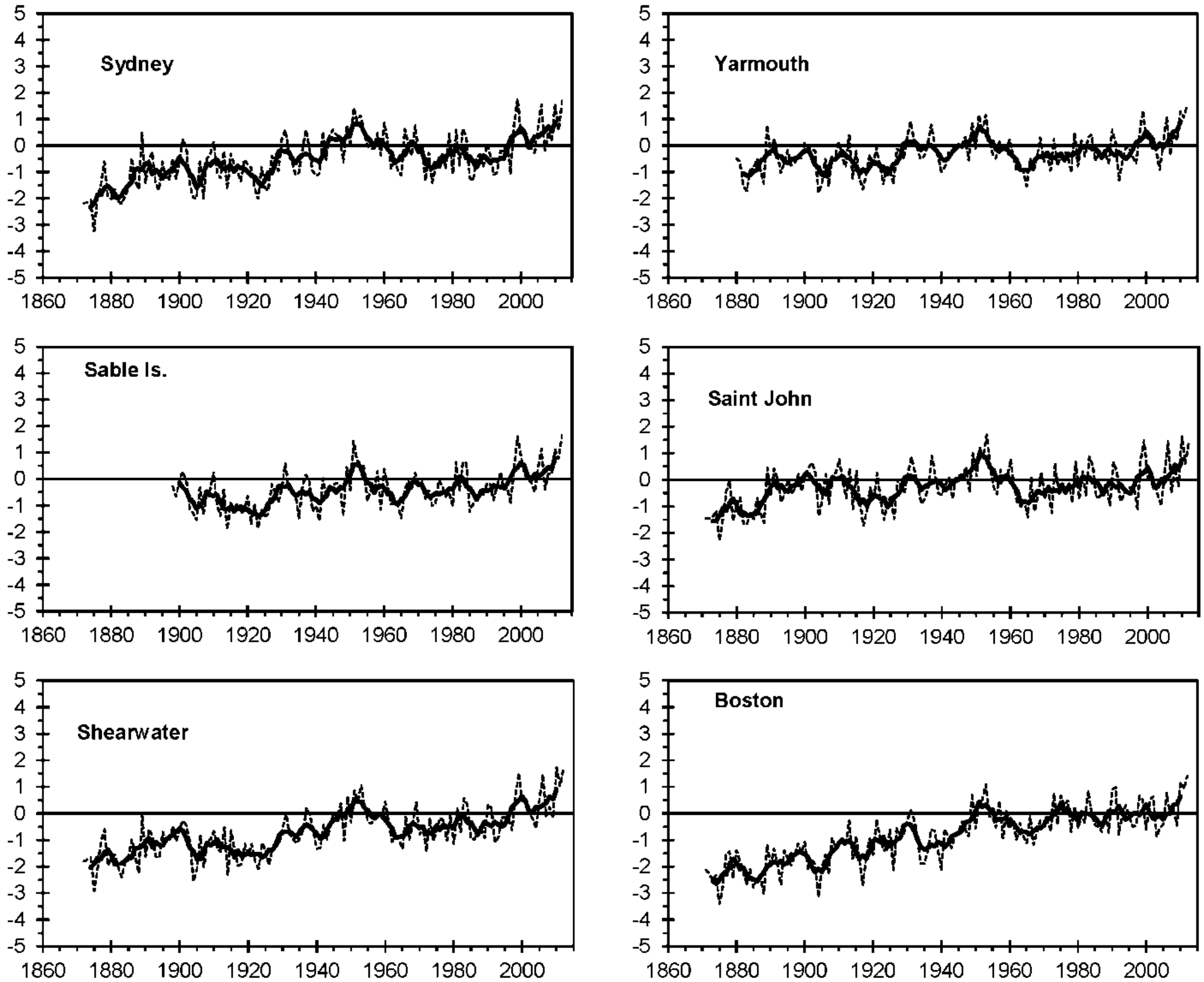


Figure 6. Annual air temperature anomalies in °C (dashed line) and five year running means (solid line) at selected sites (Sydney, Sable Island, Shearwater, Yarmouth, Saint John and Boston) in Scotian Shelf-Gulf of Maine region (years 1860 to 2000).

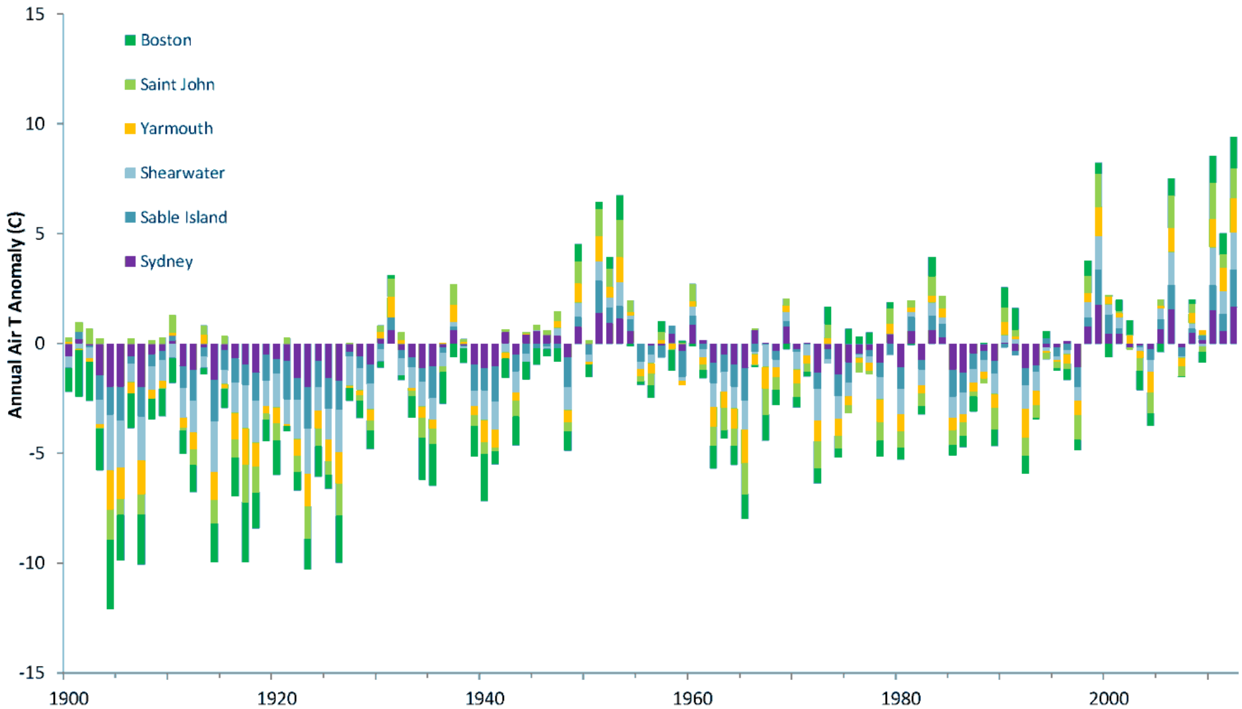


Figure 7. The contributions of each of the annual air temperature anomalies for six Scotian Shelf-Gulf of Maine sites (Boston, Saint John, Yarmouth, Shearwater, Sable Island and Sydney) are shown as a stacked bar chart. Anomalies referenced to 1981-2010.

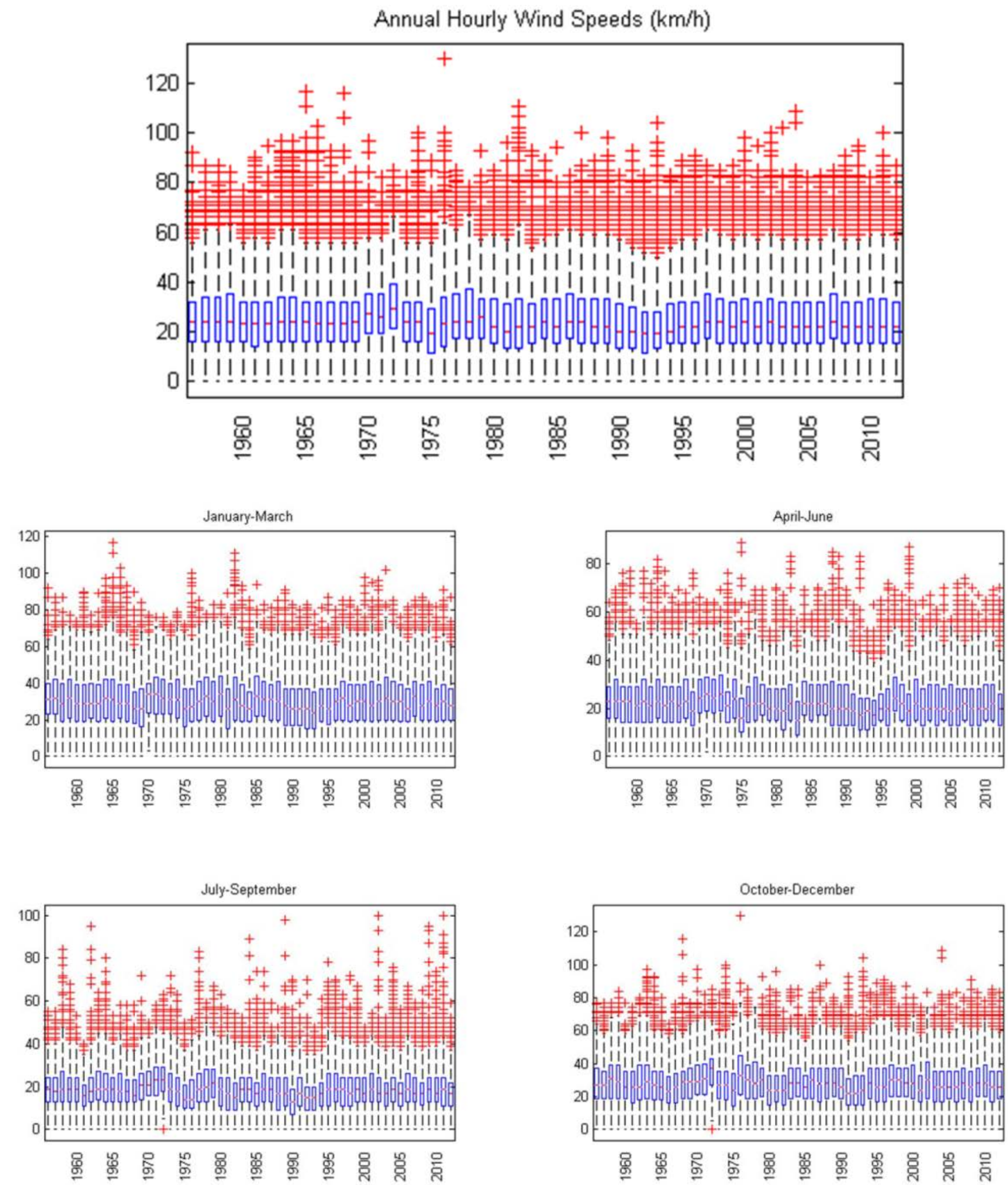


Figure 8. Whisker and box plot of the annual (top panel) and seasonal (lower panels) of the hourly wind speed (y-axis) on Sable Island for each year from 1956 to 2012 (x-axis). The blue boxes encompass the 25th to 75th percentiles with the red line being the median value. The black whiskers represent the range of observations within 1.5 times the width of the blue boxes beyond the 25th and 75th percentiles. For a normally distributed population, this region is approximately +/- 2.7 SD (99.3% of the distribution). The red + (plus sign) represent all data points outside this region.

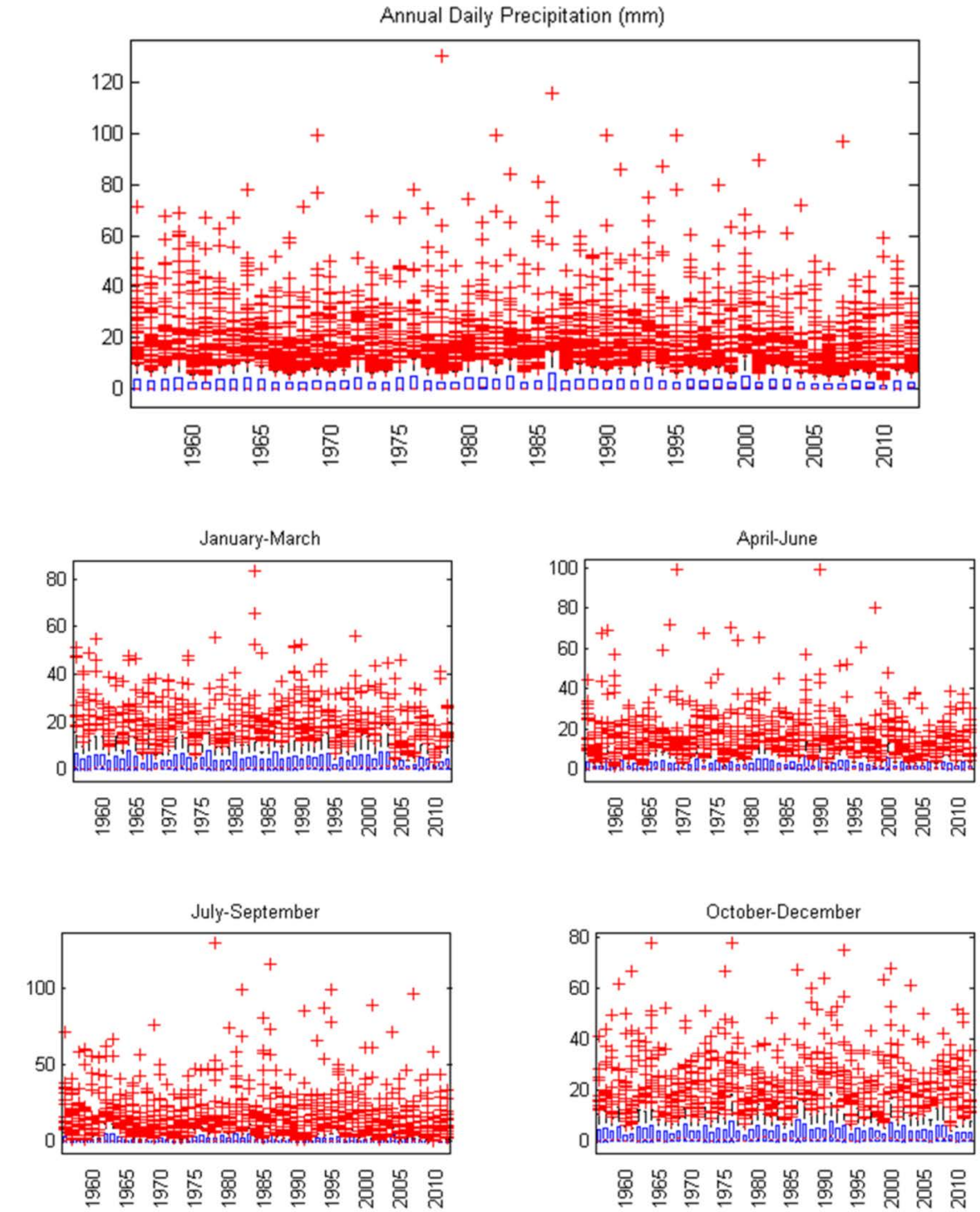


Figure 9. Whisker and box plot of the annual (top panel) and seasonal (lower panels) of the daily total precipitation in mm (y-axis) on Sable Island for each year from 1956 to 2012 (x-axis). The blue boxes encompass the 25th to 75th percentiles with the red line being the median value. The black whiskers represent the range of observations within 1.5 times the width of the blue boxes beyond the 25th and 75th percentiles. For a normally distributed population, this region is approximately +/- 2.7 SD (99.3% of the distribution). The red + (plus sign) represent all data points outside this region.

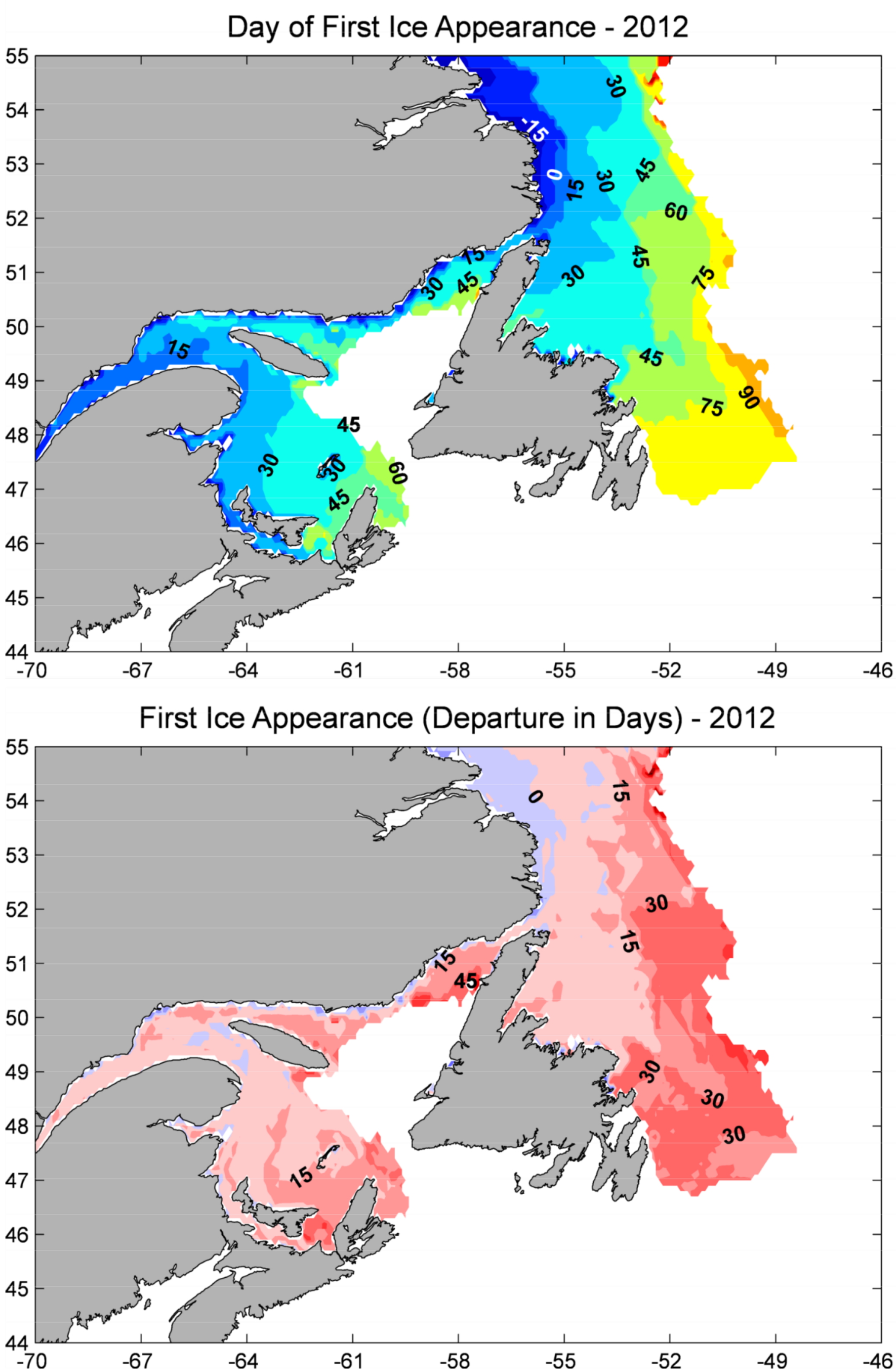


Figure 10. The time when ice first appeared during 2012 in days from the beginning of the year (top panel) and its anomaly from the 1981-2010 mean in days (bottom panel). Negative (positive) anomalies in blue (red) indicate earlier (later) than normal appearance. Longitude in degrees on the x-axis (negative values are West) and Latitude in degrees (positive values are North) on the y-axis.

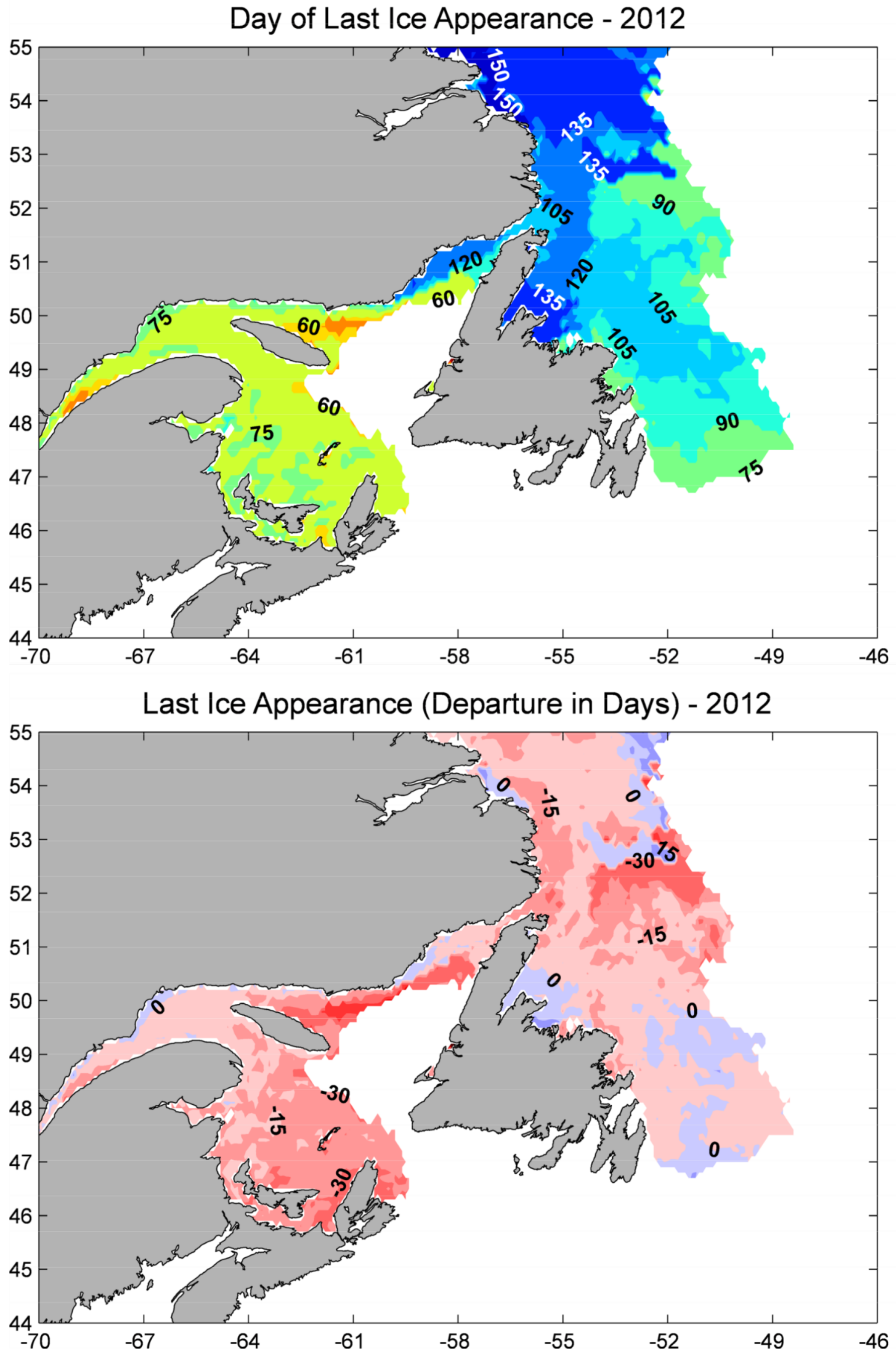


Figure 11. The time when ice was last seen in 2012 in days from the beginning of the year (top panel) and its anomaly from the 1981-2010 mean in days (bottom panel). Negative (positive) anomalies in red (blue) indicate earlier (later) than normal disappearance. Longitude in degrees on the x-axis (negative values are West) and Latitude in degrees (positive values are North) on the y-axis.

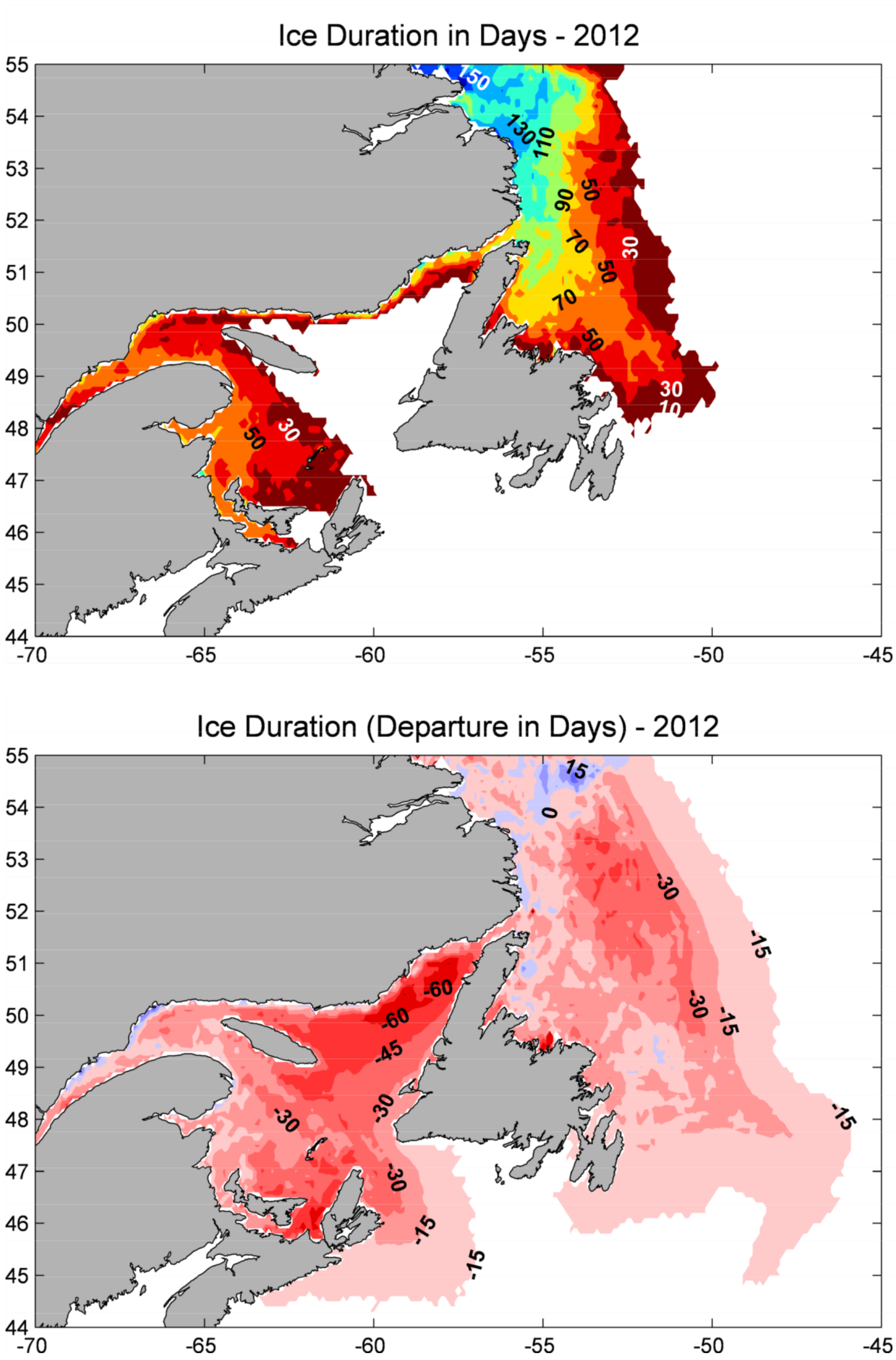


Figure 12. The duration of ice in days (top panel) during 2012 and the anomalies from the 1981-2010 mean in days (bottom panel). Positive (negative) anomalies in blue (red) indicate durations longer (shorter) than the mean. Note that areas of duration approximately ten days are not displayed. The anomaly 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.

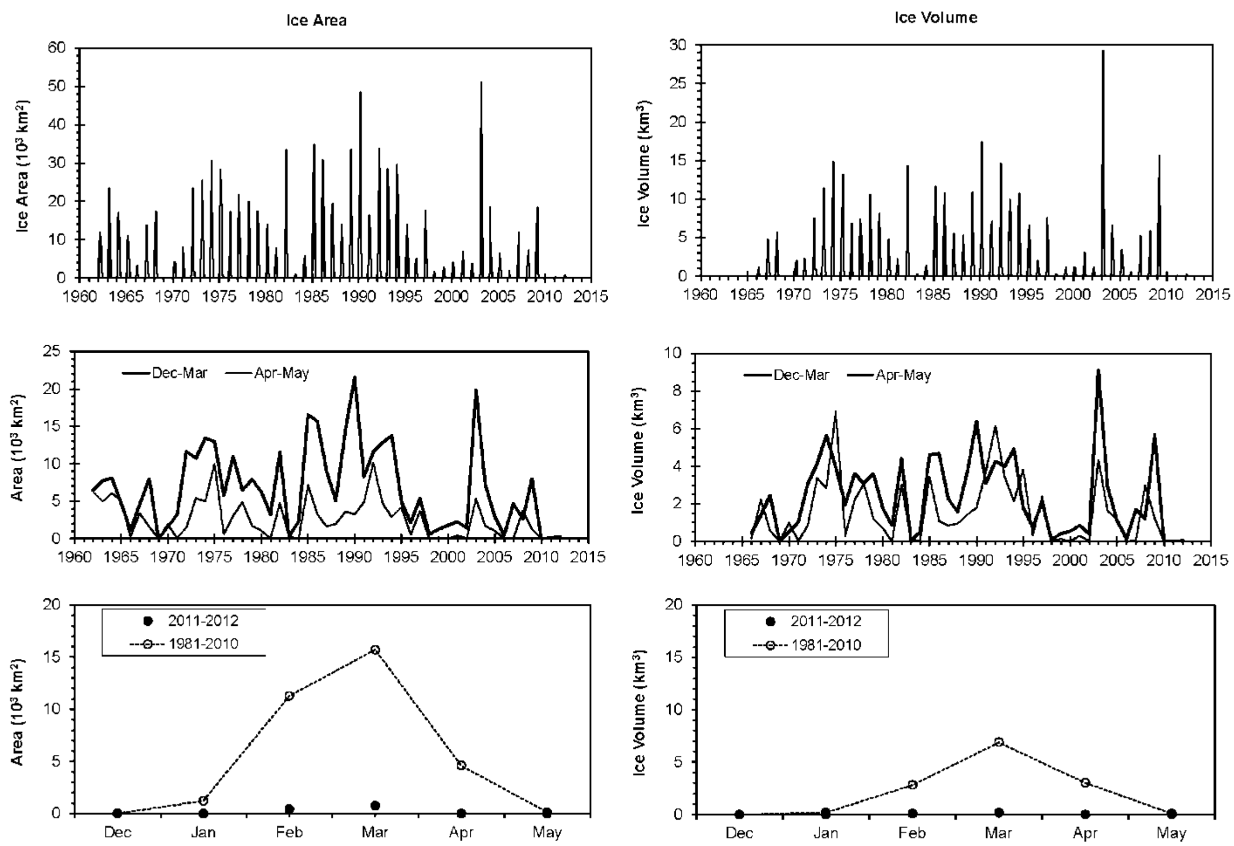


Figure 13. Time series of the monthly mean ice area and volume for the Scotian Shelf (top panels), the average ice area and volume during the usual periods of advancement (January-March) and retreat (April-May) (middle panels), and the comparison of the 2011-2012 monthly areas and volumes to the 1981-2010 means (bottom two panels). Note that the 2010-2012 ice area and volume is basically zero.

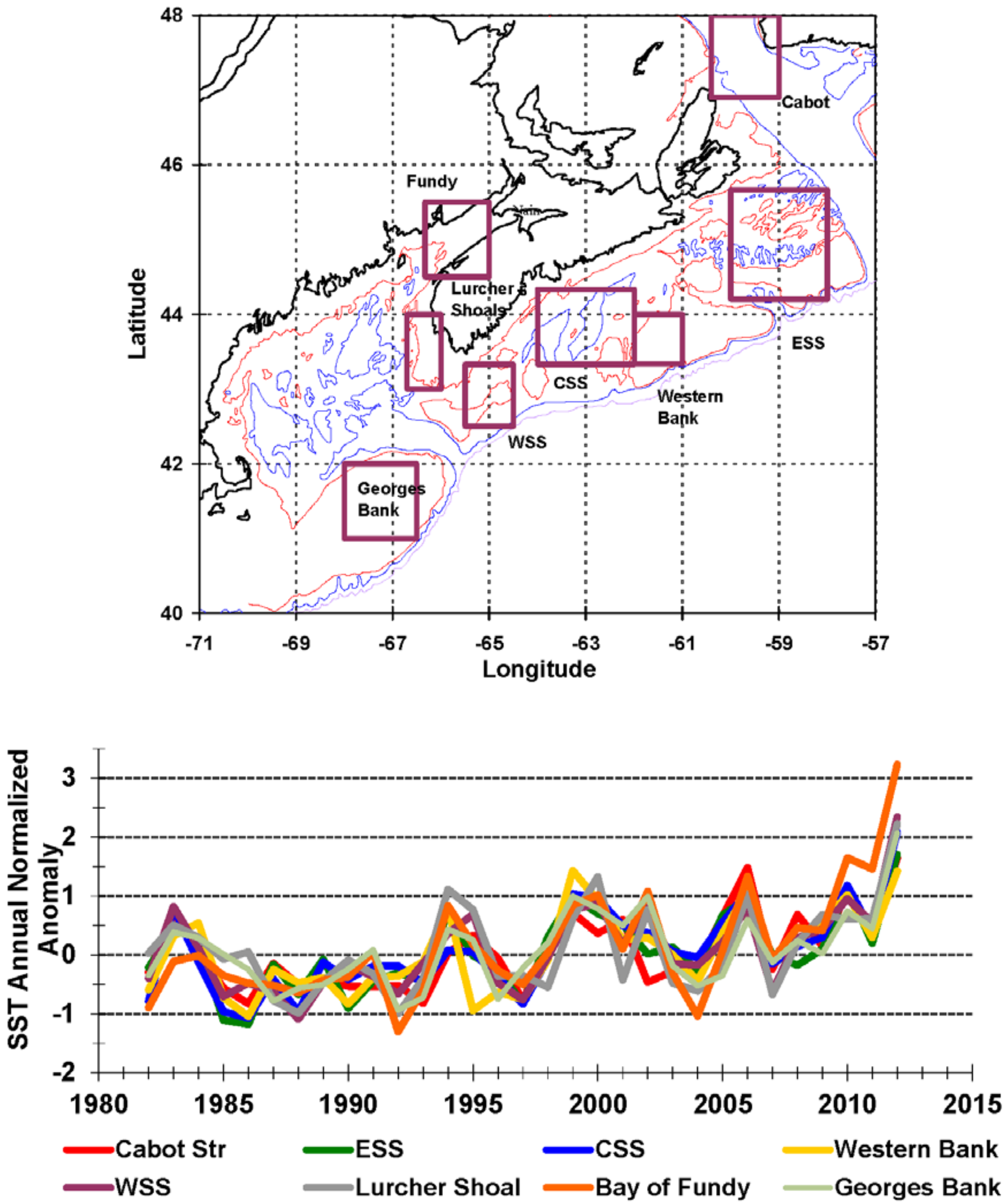


Figure 14. Scotian Shelf-Gulf of Maine areas (Cabot Strait, Eastern Scotian Shelf (EES), Western Bank, Central Scotian Shelf (CSS), Western Scotian Shelf (WSS), Georges Bank, Lurcher Shoals and Bay of Fundy) used for extraction of sea surface temperature (upper panel). The annual sea surface temperature anomalies derived from satellite imagery compared to their long-term monthly means (lower panel).

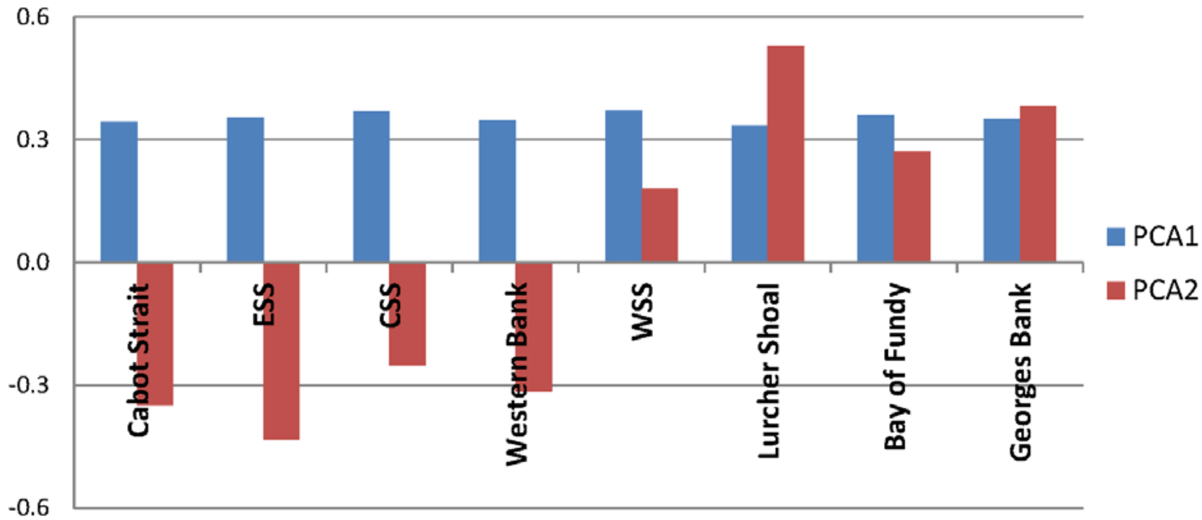


Figure 15. First (PCA1: 83% of the variance) and second (PCA2: 8% of the variance) loadings from a principal components analysis of the annual mean temperature anomalies (Figure 14, lower panel) for the eight Scotian Shelf and Gulf of Maine regions (Cabot Strait, Eastern Scotian Shelf (EES), Western Bank, Central Scotian Shelf (CSS), Western Scotian Shelf (WSS), Georges Bank, Lurcher Shoals and Bay of Fundy -Figure 14, upper panel).

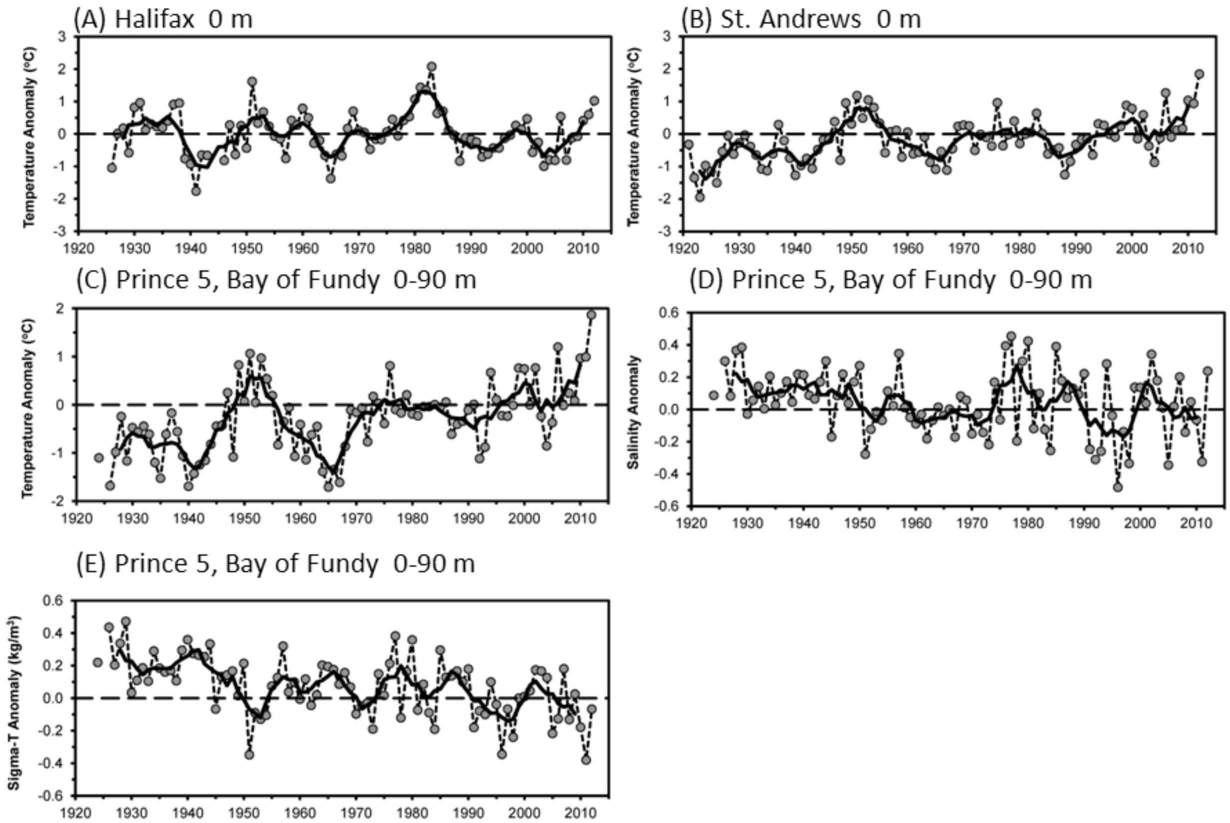


Figure 16. The annual surface temperature anomalies (dotted line with circles) and their five year running means (heavy black line) for (A) Halifax Harbour and (B) St. Andrews; annual depth-averaged (0-90 m) (C) temperature, (D) salinity, and (E) density anomalies for the Prince 5 monitoring station at the mouth of the Bay of Fundy.

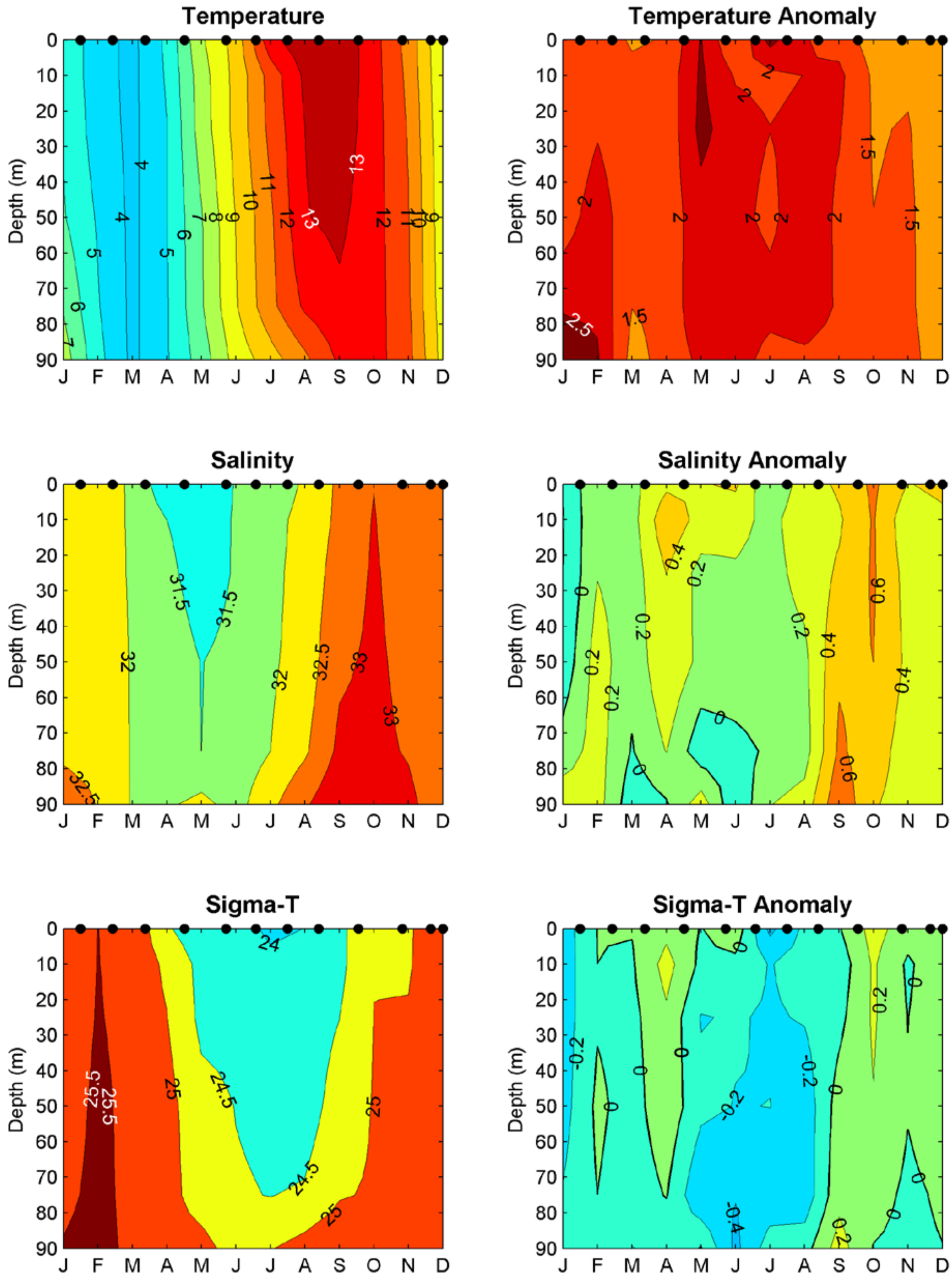


Figure 17. The 2012 annual cycle of temperature (top panel), salinity (middle panel) and density (lower panel) and their anomalies with respect to 1981-2010 monthly means (right panels) for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Bullets indicate periods of sampling.

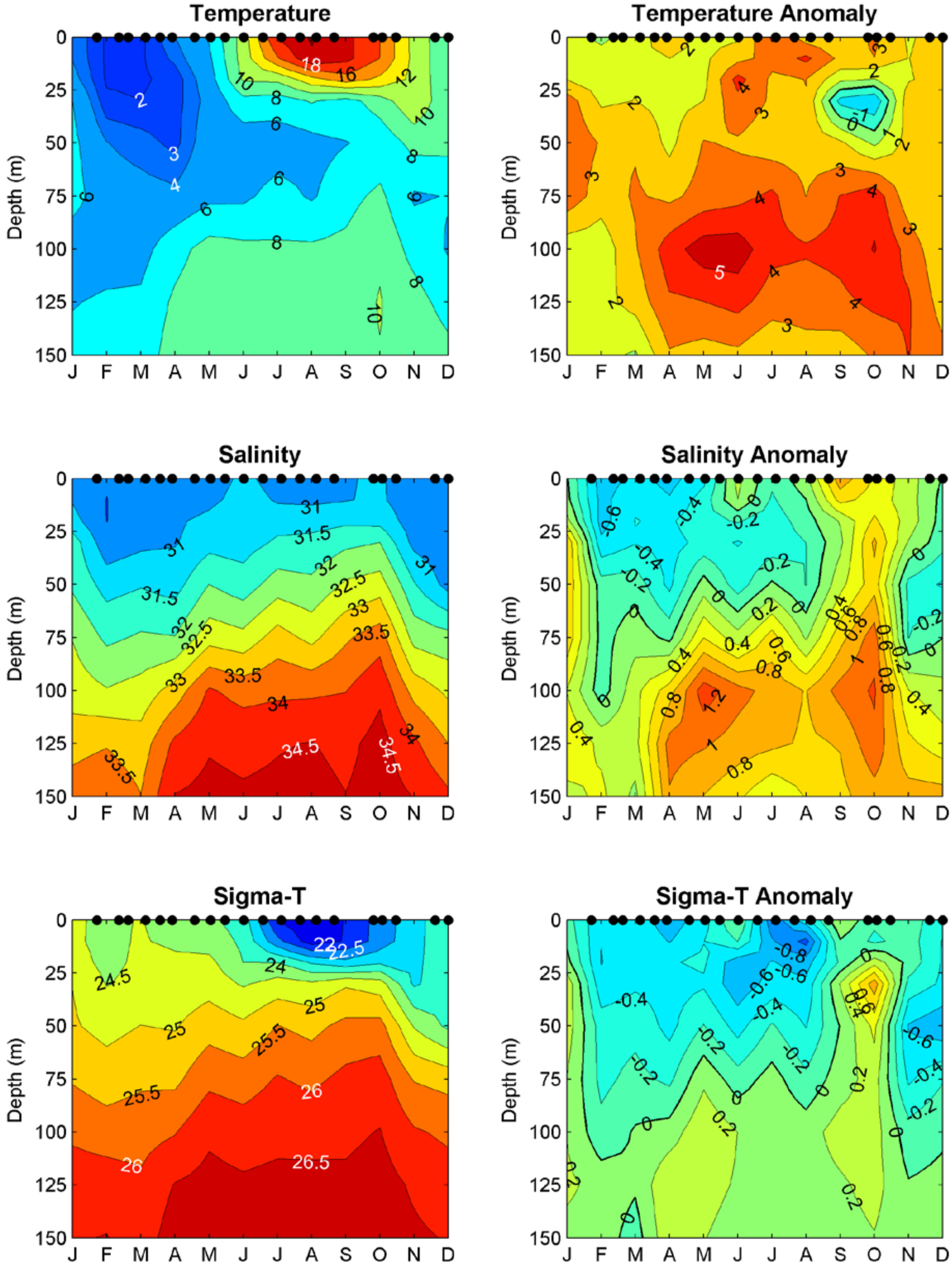
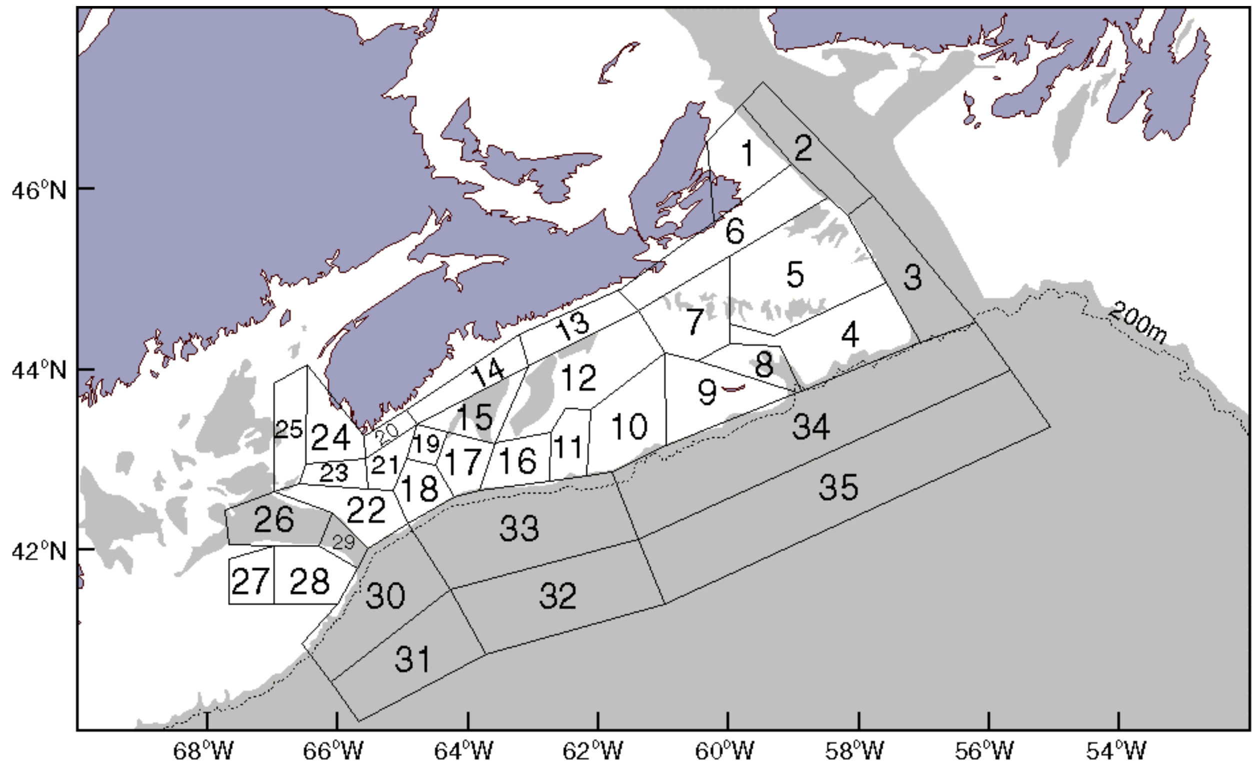


Figure 18. The 2012 annual cycle of temperature (top panel), salinity (middle panel) and density (lower panel) and their anomalies with respect to 1981-2010 monthly means (right panels) for Halifax station 2. Bullets indicate periods of sampling.



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

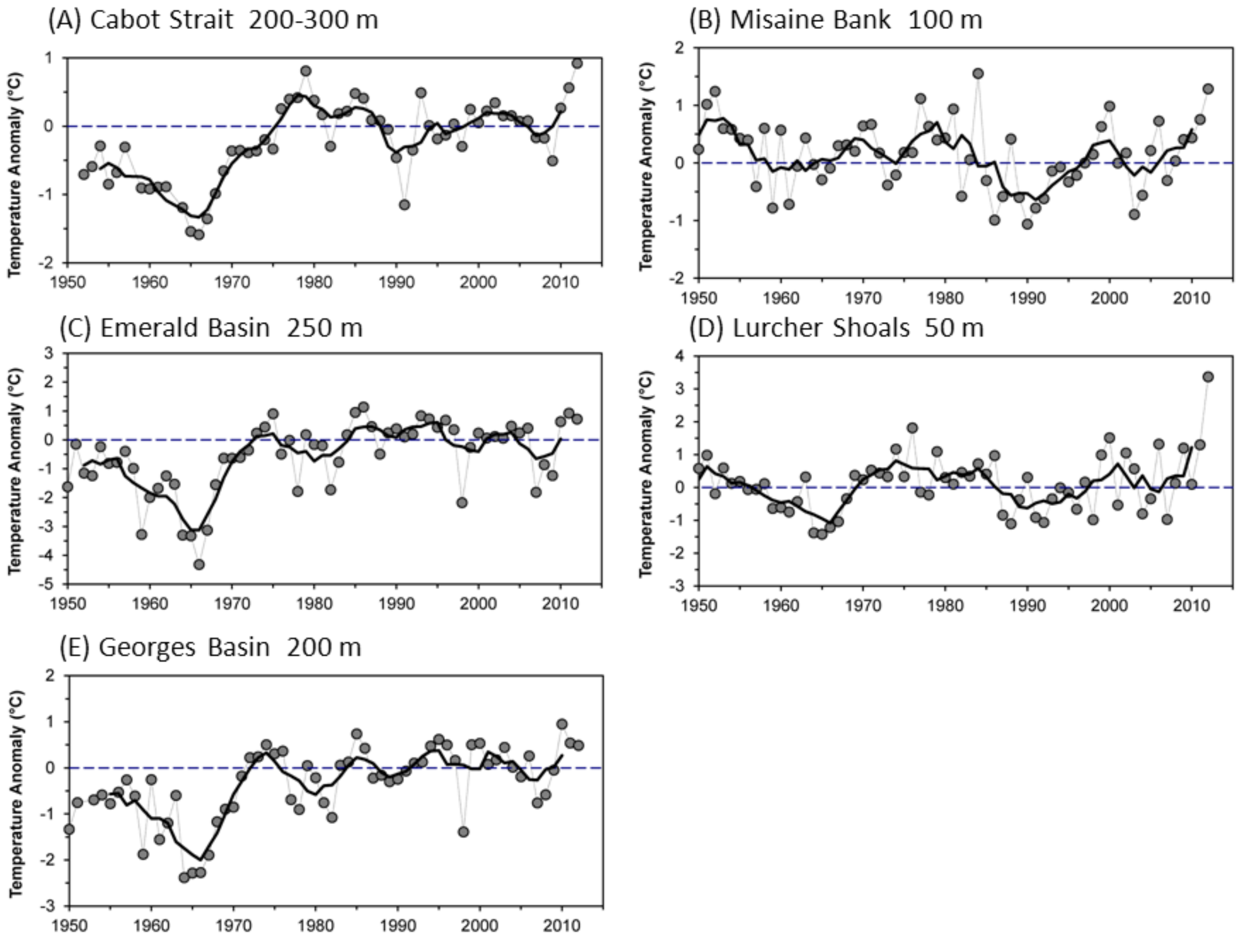


Figure 20. The annual mean temperature anomaly time series (dotted line with circles) and the five year running mean filtered anomalies (heavy solid line) on the Scotian Shelf and in the Gulf of Maine at (A) Cabot Strait 200-300 m; (B) Misaine Bank 100 m; (C) Emerald Basin 250 m; (D) Lurcher Shoals 50 m; and Georges Basin (200 m) (see Figure 18).

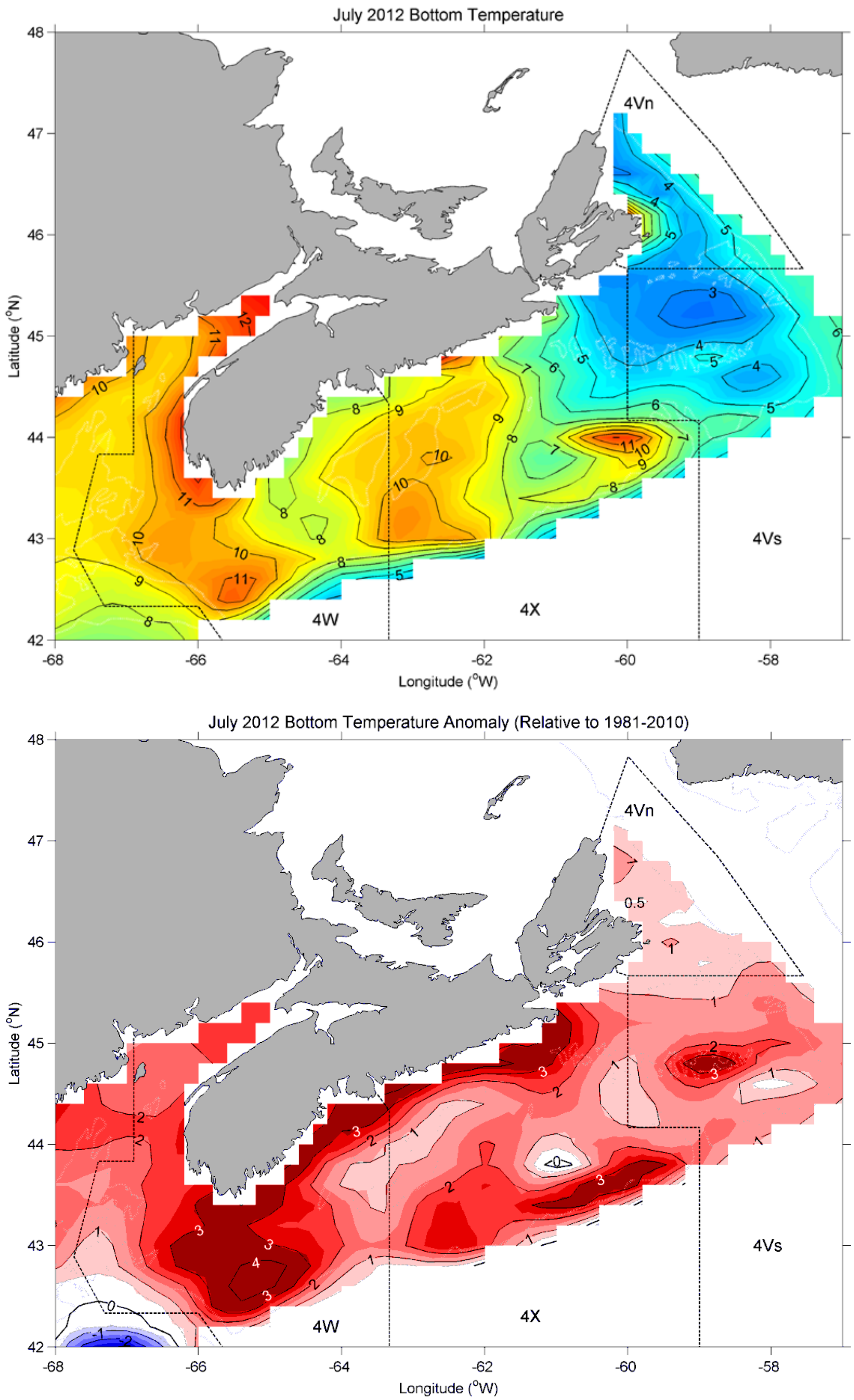


Figure 21. July bottom temperature (upper panel) and anomaly (lower panel; relative to 1981-2010) maps for 2012.

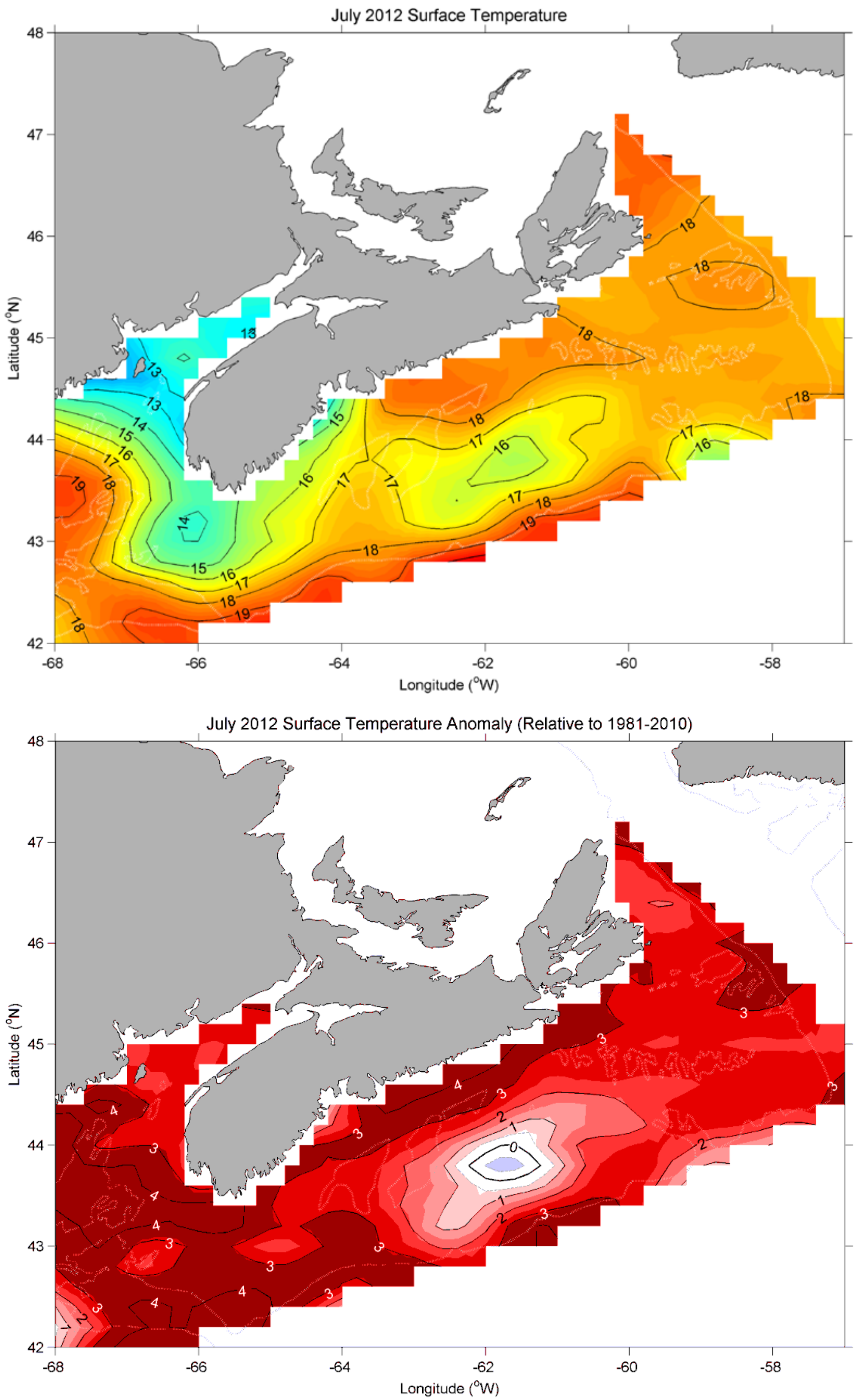


Figure 22. July surface temperature (upper panel) and anomaly (lower panel; relative to 1981-2010) maps for 2012.

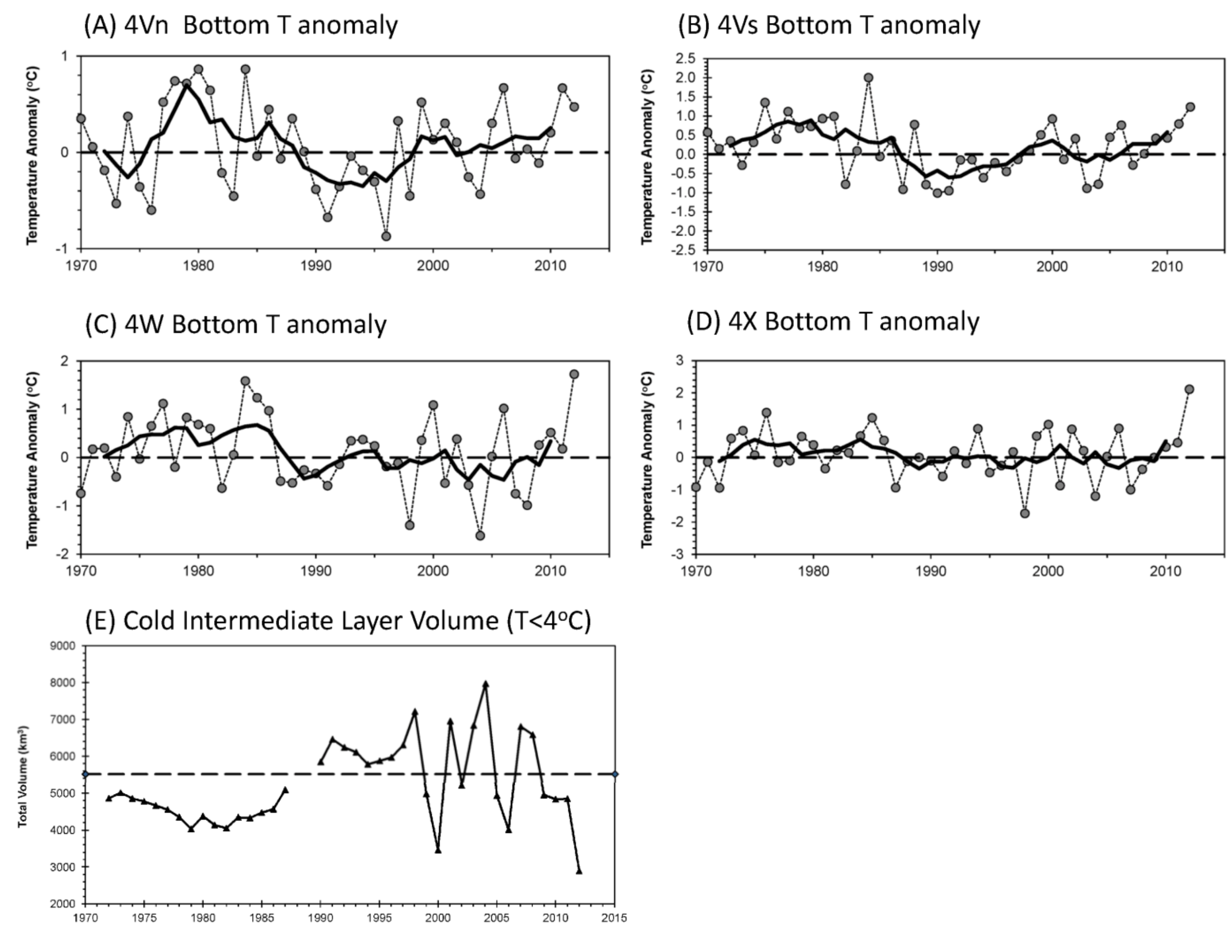


Figure 23. Time series of July bottom temperature anomalies (thin lines with circles) and five year running mean filtered series (heavy line) for areas (A) 4Vn, (B) 4Vs, (C) 4W, and (D) 4X. (E) Time series of the Cold Intermediate Layer (CIL; defined as waters with temperature <4^{o}C) volume on the Scotian Shelf based on the July ecosystem survey. The dashed horizontal line is the 1981-2010 mean CIL volume.

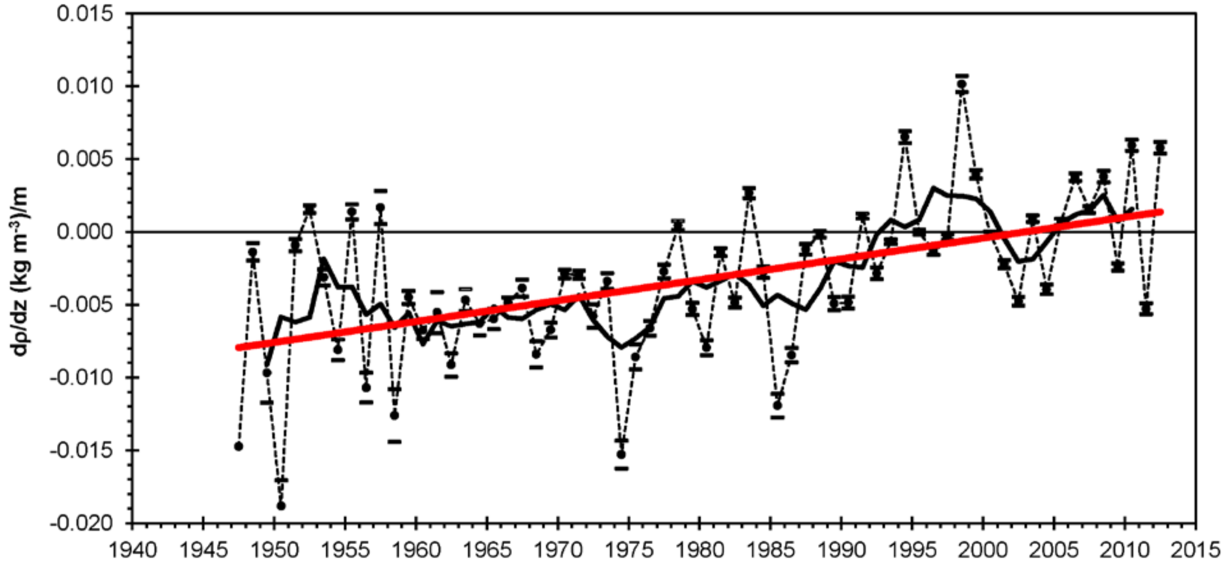


Figure 24. The mean annual anomaly (black dashed line with circles) and five year running mean (black heavy solid line) of the stratification index (0-50 m density gradient) averaged over the Scotian Shelf (areas 4-23 inclusive, see Figure 18). Standard error estimates for each annual anomaly value are 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.

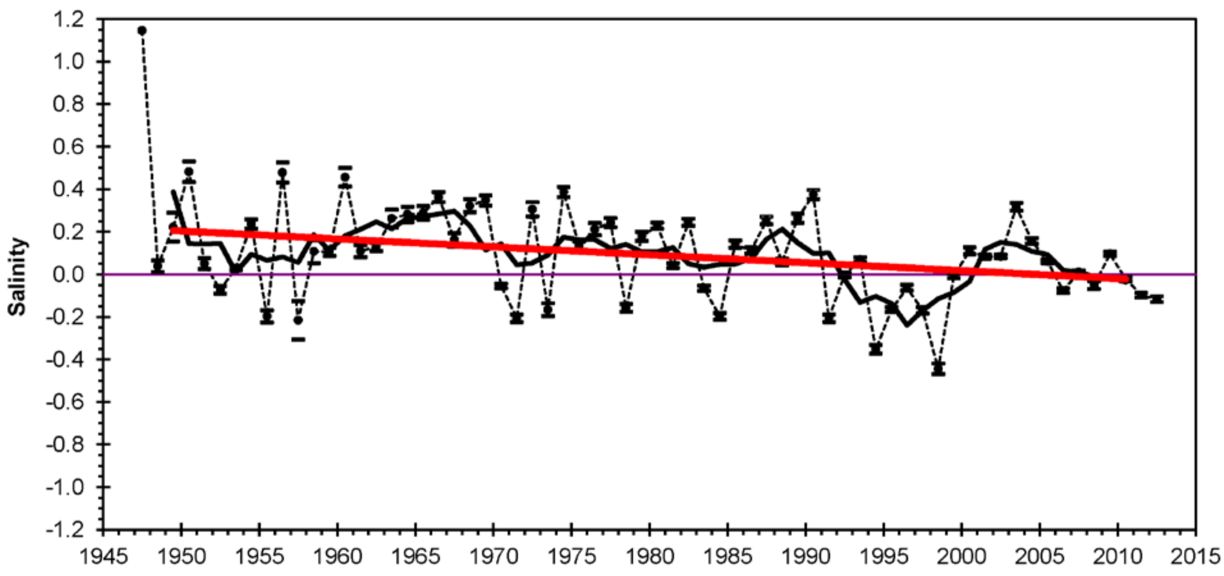


Figure 25. The mean annual surface salinity anomaly (black dashed line with circles) and five year running mean (black heavy solid line) averaged over the Scotian Shelf (areas 4-23 inclusive, see Figure 18). Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a freshening of 0.18 over a 50 year period.

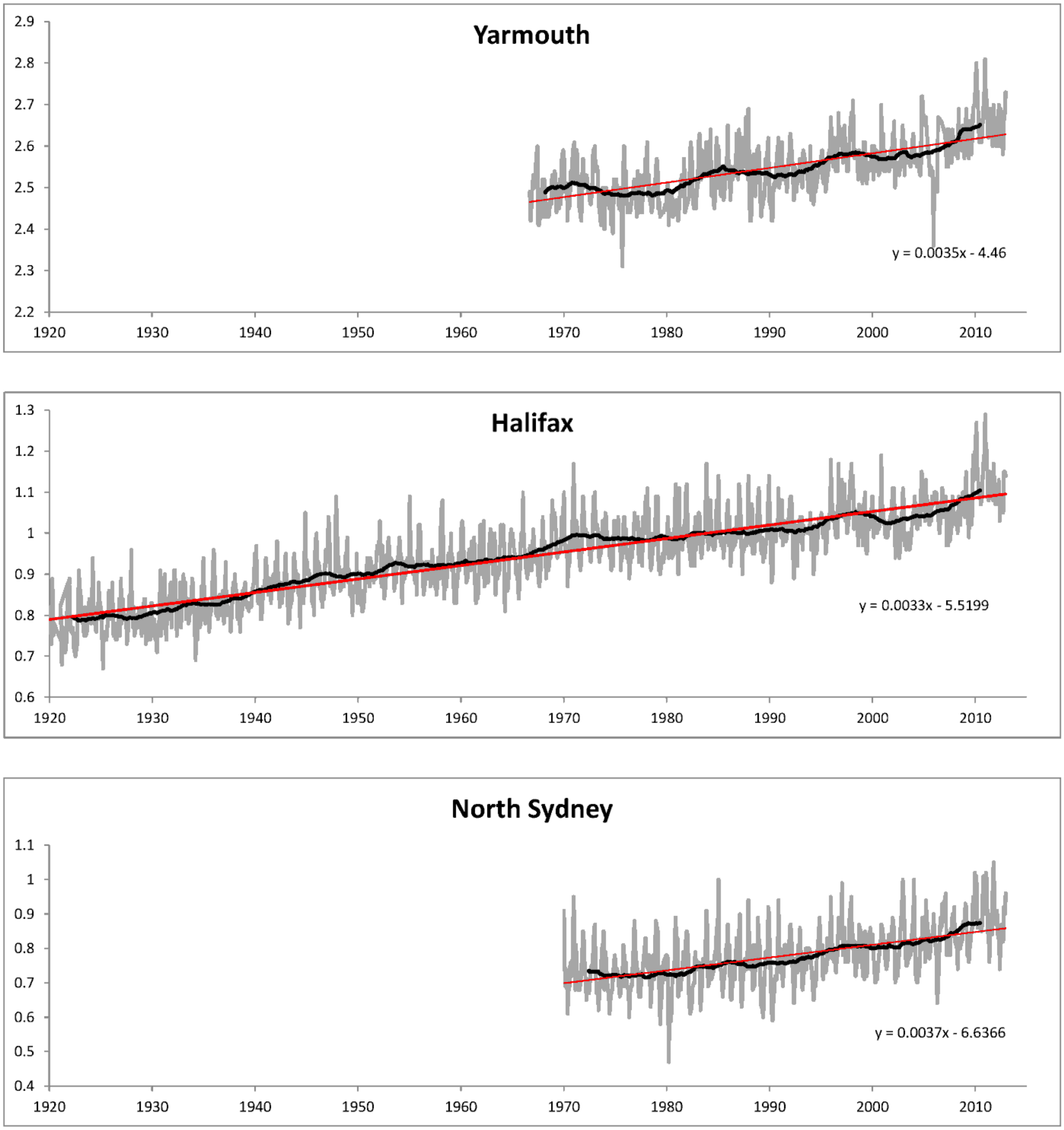


Figure 26. The time series of the monthly means (grey line) and a five year running mean (black line) of the relative sea level elevations at Yarmouth (top panel), Halifax (middle panel) and North Sydney (bottom panel), along with the linear trend (red line) over the observation period.

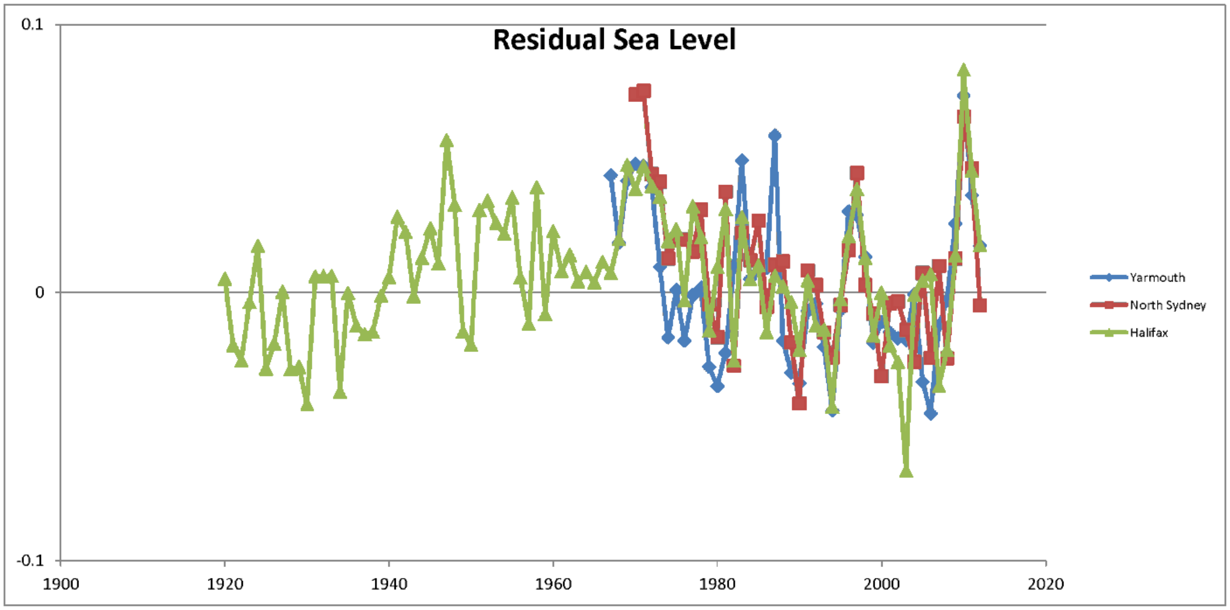


Figure 27. Residual relative sea level (monthly observed values – (1981-2010) linear trend, averaged to annual estimate for Yarmouth (blue line with diamonds), Halifax (green line with triangles) and North Sydney (red line with squares)..

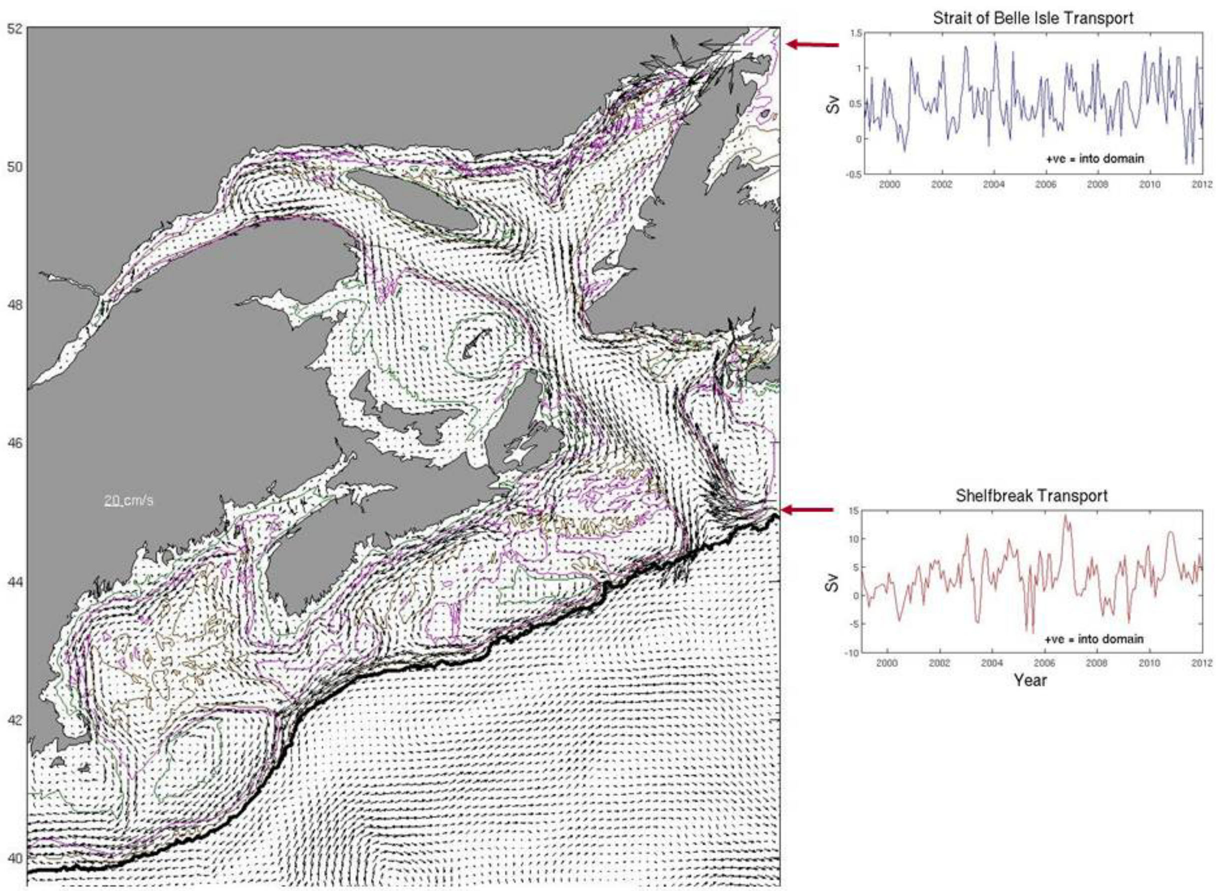


Figure 28.Maritime Canada domain map (left panel) showing annual and depth-averaged circulation and locations where open boundary transports are applied. Time series of transports applied to open boundary locations (right panels), derived from a simulation of the North Atlantic circulation for the same time period conducted by Dr. Z. Wang (BIO).

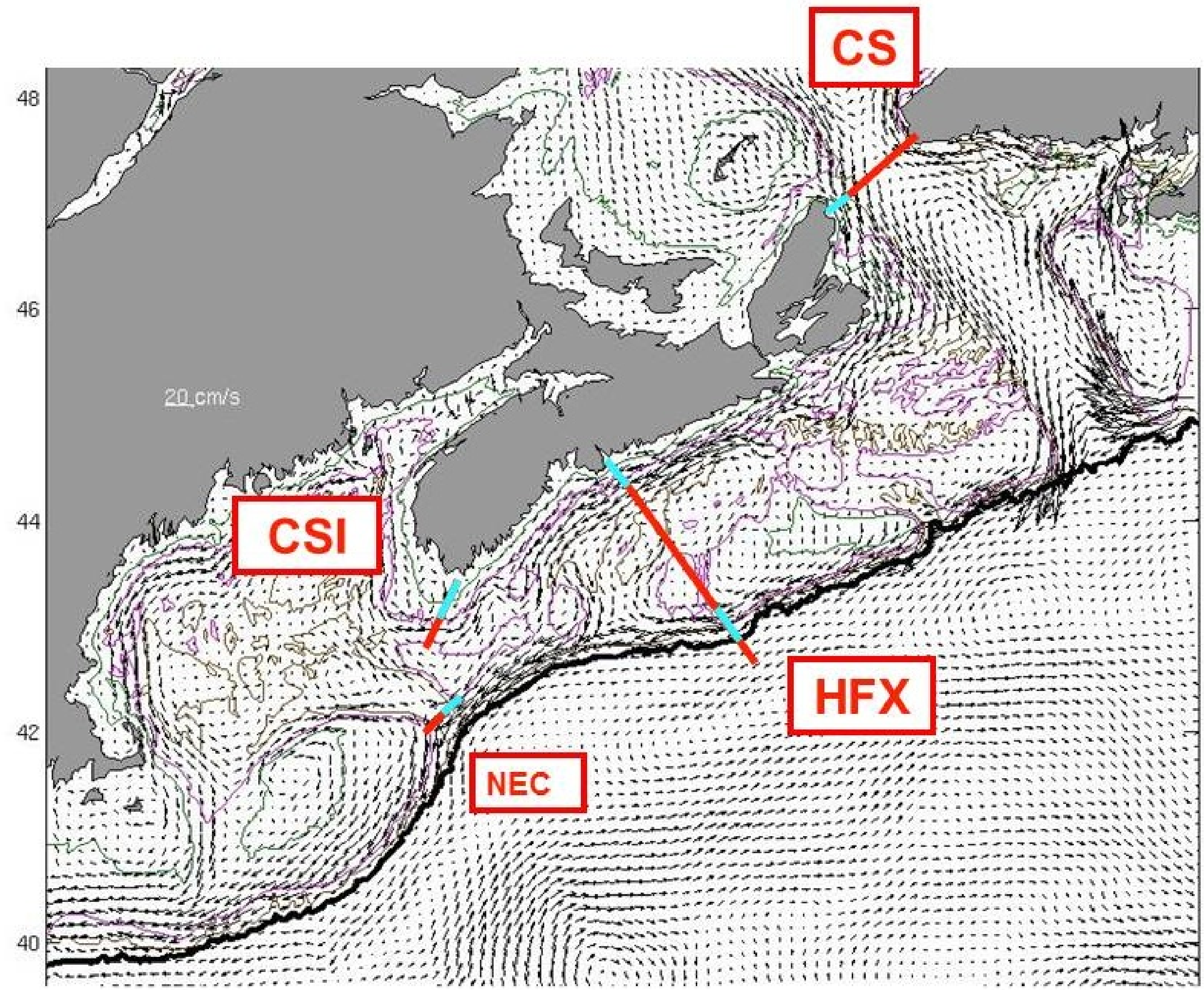


Figure 29. Annual average depth-averaged circulation illustrating the principal flow pathways from the southern Gulf of St. Lawrence to the Gulf of Maine and the subsections where transport calculations were made (cyan). CS=Cabot Strait; HFX = Halifax; CSI = Cape Sable Island/Browns Bank; NEC = Northeast Channel.

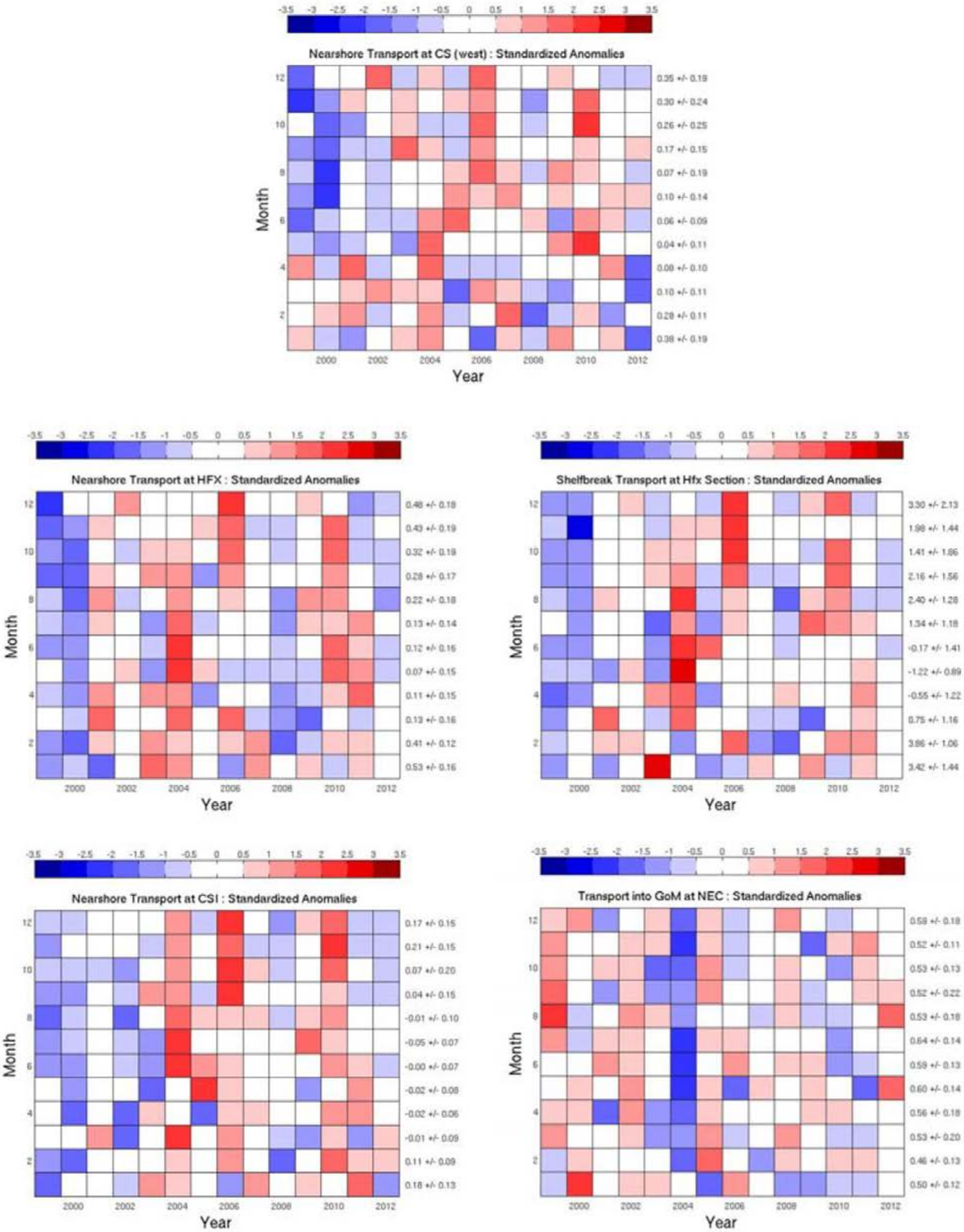


Figure 30. Standardized anomalies of the monthly transport for years 1999-2012 for four Maritime sections: (top) Cabot Strait (CS) west nearshore; (middle) Halifax (HFX) nearshore and shelfbreak; (bottom) Cape Sable Island (CSI) nearshore, and the Northeast Channel (NEC). Numbers to the right are monthly means and standard deviations.

Transport (SV) Month	2008	2009	2010	2011	2012	Grand Total
12	-0.46	-0.59	-0.58	-0.33		-0.49
11	-0.22	-0.34	-0.52	-0.49		-0.39
10	-0.22	-0.51	-0.36	-0.30		-0.35
9	-0.43	-0.21	-0.30	-0.12		-0.27
8	-0.40	-0.26	-0.32	-0.23	-0.11	-0.26
7	-0.04	-0.29	-0.39	-0.37	-0.11	-0.24
6		-0.31	-0.54	-0.40	-0.09	-0.33
5		-0.33	-0.52	-0.43	-0.22	-0.38
4		-0.34	-0.33	-0.48	-0.23	-0.35
3		-0.48	-0.47	-0.55	-0.64	-0.54
2		-0.66	-0.68	-0.85	-0.59	-0.69
1		-0.80	-0.65	-0.67	-0.38	-0.62
Grand Total	-0.30	-0.43	-0.47	-0.43	-0.30	-0.40

Figure 31. Monthly transport (1 Sv = 10^6 m^3 s^{-1}) for years 2008-2012 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).

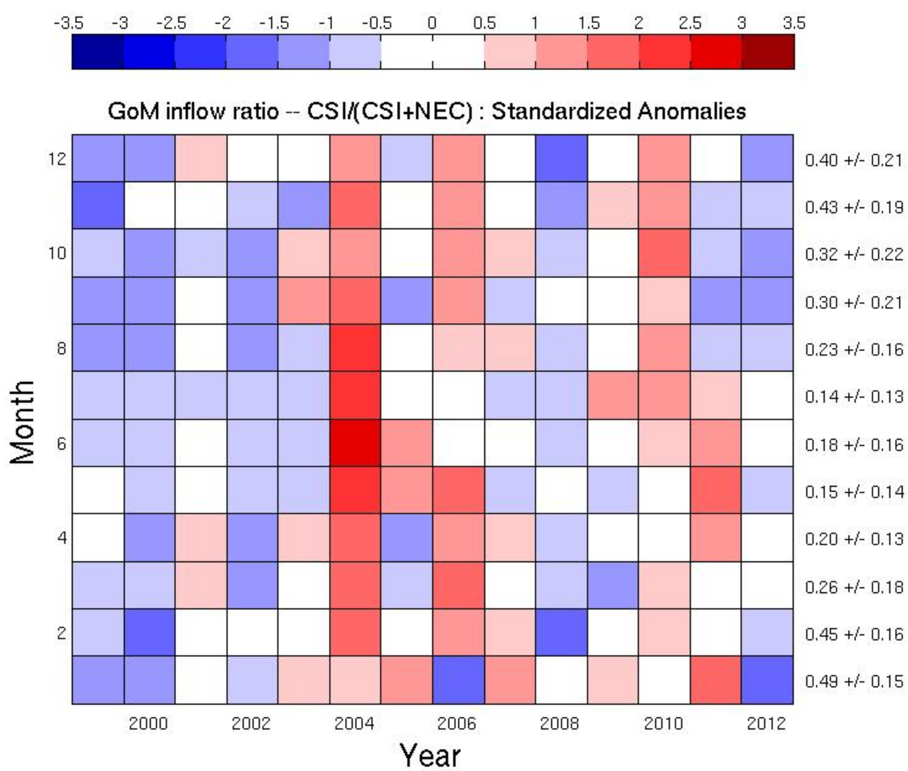
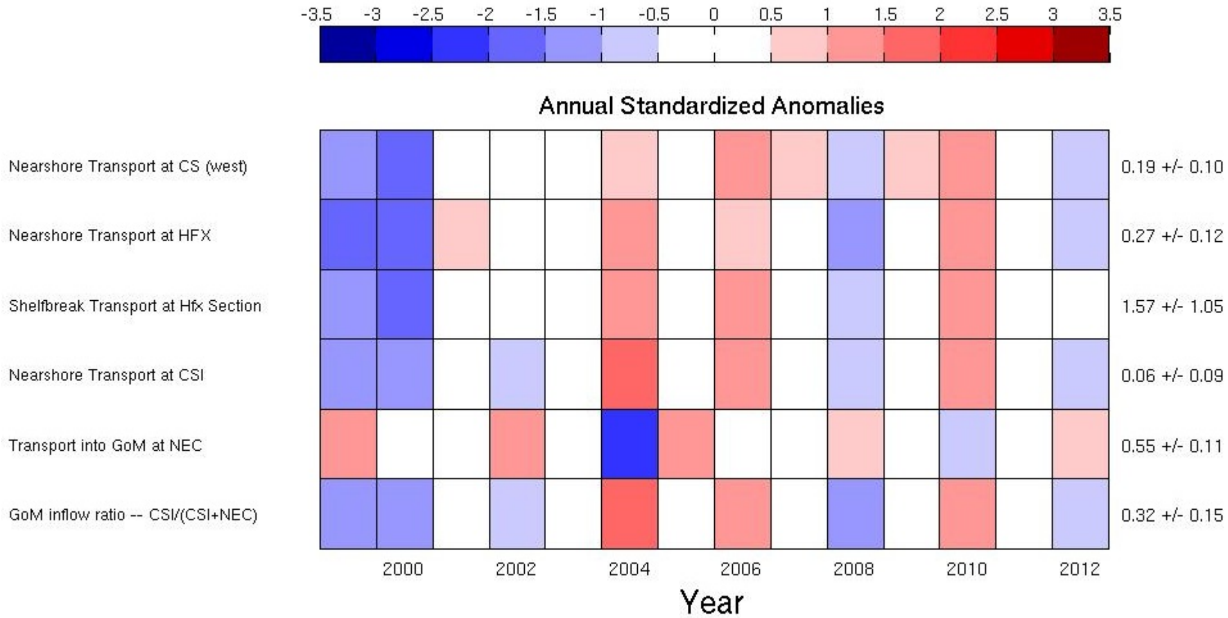


Figure 32. Standardized anomalies of the Gulf of Maine (GoM) inflow ratio, for years 1999-2012. Numbers to the right are monthly means and standard deviations. CSI = Cape Sable Island; NEC = Northeast Channel.



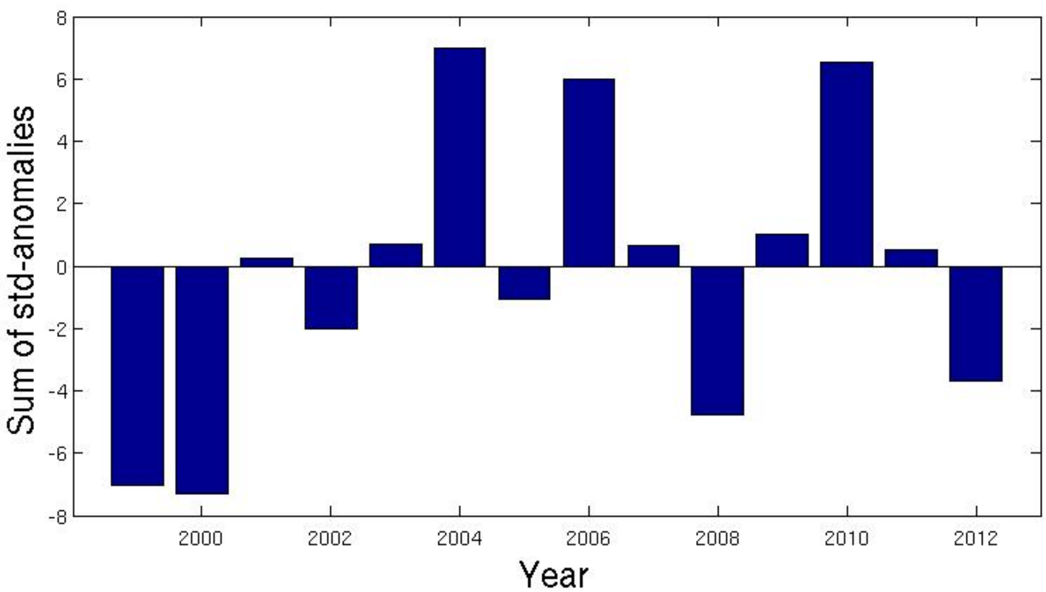


Figure 33. Annual transport anomalies scaled by the standard deviation for the variables in Figures 30 and 32 for years 1999-2012. (top panel). Numbers to the right are annual means and standard deviations. Sum of standardized anomalies for 1999-2012 (bottom panel). NB: the inflow at the Northeast Channel (NEC) was omitted, as it is not independent. CS=Cabot Strait; HFX = Halifax; CSI = Cape Sable Island; NEC = Northeast Channel.

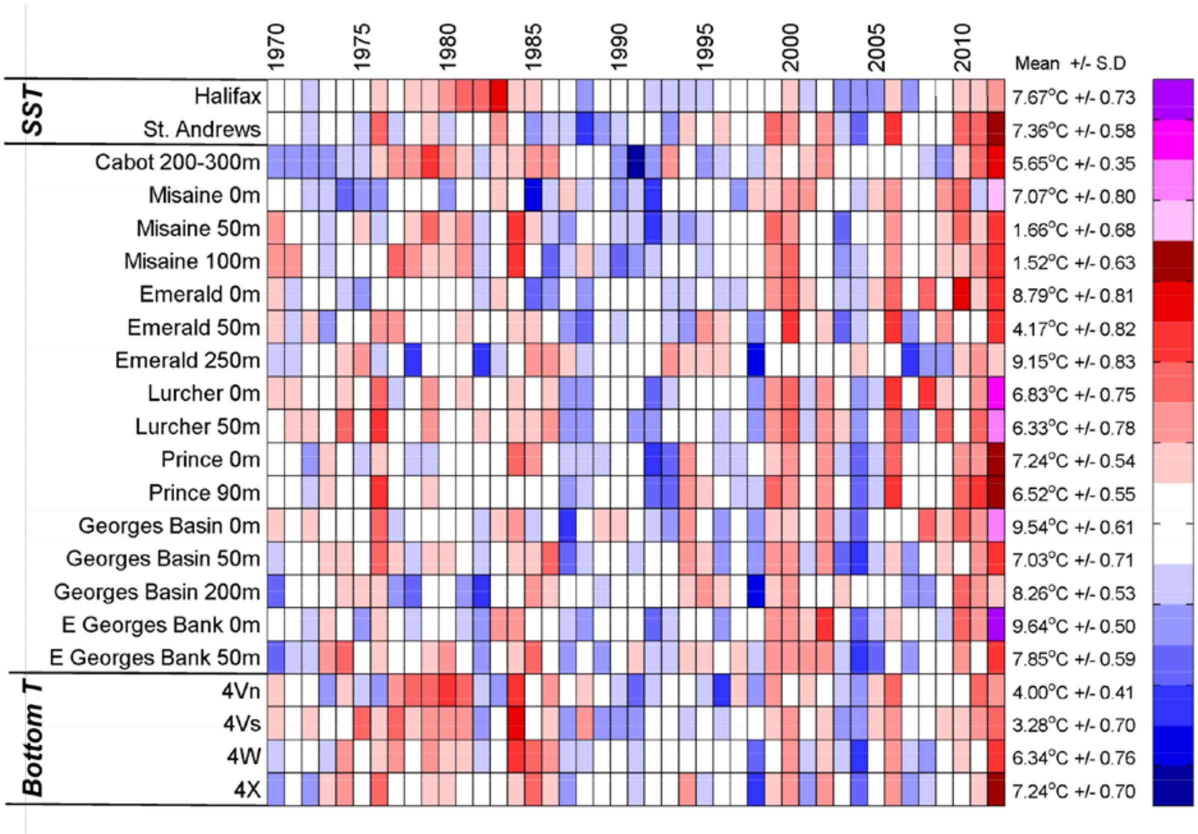


Figure 34. Normalized annual anomalies of temperatures at the bottom and discrete depths for the Scotian Shelf-Gulf of Maine region. These anomalies are based on the 1981-2010 means, divided by the standard deviation. Blue colours indicate below normal anomalies, red colours above normal anomalies. (For 2012, the colour scale had to be increased above +3.5 SD and is shaded in purple.)

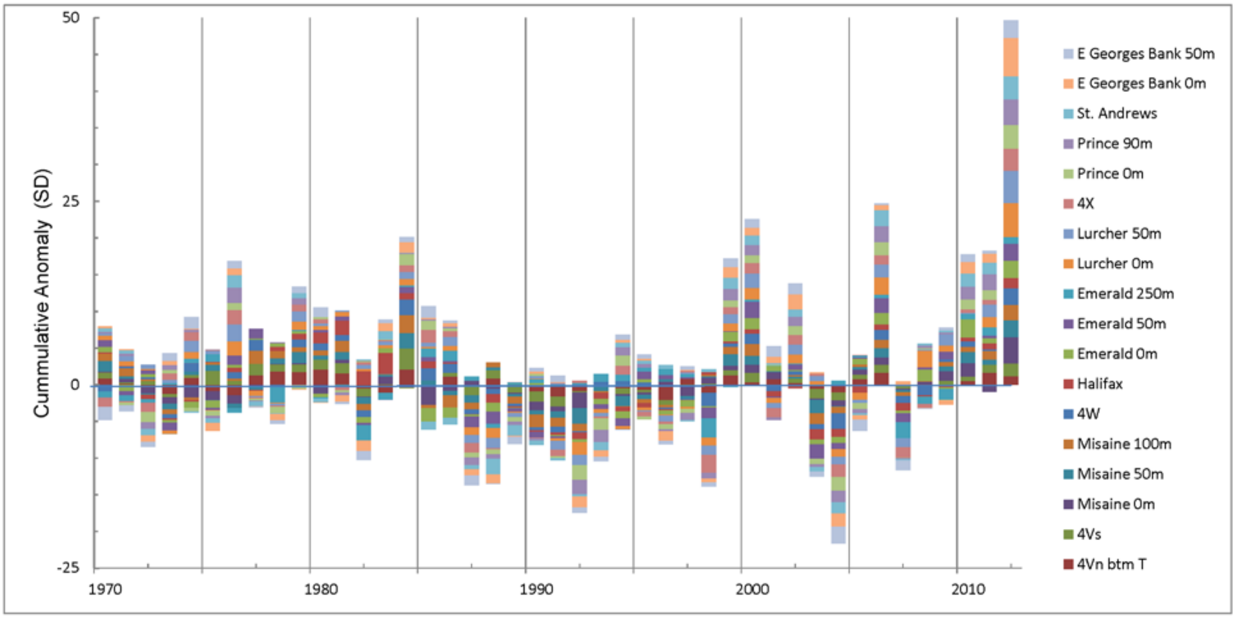


Figure 35. The contributions of each of the normalized anomalies are shown as a stacked bar chart.