NOT TO BE CITED WITHOUT PRIOR
REFERENCE TO THE AUTHOR(S)

Northwest Atlantic Fisheries Organization

Serial No. N6654 **NAFO SCR Doc. 17-009**

SCIENTIFIC COUNCIL MEETING – JUNE 2017

Physical Oceanographic Conditions on the Scotian Shelf and in the eastern Gulf of Maine (NAFO Divisions 4V,W, X) during 2016

D. Hebert and R. G. Pettipas

Department of Fisheries and Oceans, Maritimes Region
Ocean and Ecosystem Sciences Division, Bedford Institute of Oceanography
P.O. Box 1006, Dartmouth, N.S. B2Y 4A2

Abstract

A review of the 2016 physical oceanographic conditions on the Scotian Shelf and in the eastern Gulf of Maine and adjacent offshore areas indicates that conditions corresponding to warmer than normal prevailed. The climate index, a composite of 18 selected, normalized time series, averaged +2.1 standard deviations (SD) making 2016 the second warmest year in the last 47 years. The anomalies did not show a strong spatial variation. Bottom temperatures were above normal with anomalies for NAFO Divisions 4Vn, 4Vs, 4W, 4X of +0.9°C (+2.1 SD), +1.5°C (+2.1 SD), +1.7°C (+2.3 SD), and +1.9°C (+2.6 SD) respectively. Compared to 2012, the year where record or near record bottom temperatures were observed, bottom temperatures were different by +0.4°C, +0.2°C, +0.0°C and -0.3°C in Divisions 4Vn, 4Vs, 4W and 4X, respectively.

Introduction

This document describes air temperature, ice area and volume, and ocean temperature variability of Scotian Shelf and Gulf of Maine waters during 2016 (see Fig. 1 for the study area). The results are derived from data obtained at coastal and long-term monitoring stations, on annual ecosystem surveys and the Atlantic Zone Monitoring Program (AZMP) missions and from ships-of-opportunity and other research cruises and DFO fisheries surveys.

In order to detect interannual variability and long-term trends of the time series presented, we have removed the potentially large seasonal cycle by determining the monthly differences, i.e. the anomalies, from the long-term means. In some cases, we present the standardized anomaly (anomaly divided by the standard deviation). When possible, long-term monthly and annual means, and standard deviations (SD) are based on 1981-2010 averaging period.

Temperature and salinity conditions in the Scotian Shelf, 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 (see inset, Fig. 1). The Current, whose path is strongly affected by topography, has a general southwestward drift over the Scotian Shelf and continues into the Gulf of Maine where it contributes to the counter-clockwise mean circulation. Mixing with offshore waters from the continental slope modifies the properties of shelf waters. These offshore waters are generally of two types, Warm Slope Water, with temperatures in the range of 8-12°C and salinities from 34.7-35.5, and Labrador Slope Water, with temperatures from 4°C to 8°C and salinities from 34.3 to 35 (Gatien, 1976). Shelf water properties have large seasonal cycles, east-west and inshore-offshore gradients, and vary with depth (Petrie et al., 1996).

Air Temperatures

Annual air temperature anomalies for six sites in the Scotian Shelf-Gulf of Maine region are shown in Fig. 2 and Table 1. In 2016, all annual air temperature anomalies were positive with values ranging from +0.5°C at Halifax to +1.3°C at Saint John. The time series of annual anomalies indicates that all sites have 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 (Fig. 3). Linear trends from 1900 to present from Boston, Saint John, Yarmouth, Shearwater, Sable Island and Sydney correspond to changes (and 95% confidence limits) per century of +1.8°C (+1.4°C, +2.1°C), +0.7°C (+0.3°C, +1.1°C), +1.1°C (+0.8°C, +1.4°C), +1.2°C (+0.8°C, +1.5°C), +1.3°C (+1.0°C, +1.7°C) and +0.3°C (+0.0°C, +0.7°C), respectively.

The anomalies for all 6 sites are displayed in Fig. 3 as a composite sum and illustrate two points. 1) In the 117 year time series shown, 2016 was the 5th warmest year for the region as a whole (with 2012 being the warmest). For most years the anomalies have the same sign. Since 1900, 94 of the 117 years had five or more stations with the annual anomalies having the same signs; for 65 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 among sites. In fact, plotting the correlation between annual anomalies against station separations yields an e-folding scale of 1800 km (Petrie et al., 2009). The e-folding scale (=1/k) is determined from a least squares fit of an exponential function 1*exp(-kx) to the correlations among the six time series; it represents the distance at which the correlation equals 1/e, where e is the base of natural logarithms. 2) The time scale of the dominant variability has been changing from longer periods for 1900-1954 to shorter periods for 1955-2010. For the earlier period, a lagged autocorrelation analysis gives an e-folding scale of 3 years; whereas, for the later period, the scale was 0.6 years, i.e. less than the sampling interval of the series. In this case, the e-folding scale is based on the autocorrelation of the average annual temperature anomaly for the 6 sites (Petrie et al., 2009).

Table 1. The 2016 annual mean air temperature anomaly in degrees and standardize anomaly (relative to the 1981-2010 climatology) for Scotian Shelf and Gulf of Maine.

Site	Annual Anomaly		1981-2010 Climatology	
	Observed (°C)	Normalized	Mean (°C)	SD (°C)
Sydney	+0.8	+0.9	5.87	0.81
Sable Island	+1.2	+1.8	7.88	0.68
Shearwater (Halifax)	+1.0	+1.6	6.99	0.74
Yarmouth	+1.2	+1.9	7.16	0.62
Saint John	+0.8	+0.9	5.19	0.74
Boston	+1.0	+1.6	10.91	0.60

Sea Ice

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 southern coast of Cape Breton are typically the only areas heavily affected by ice in the region. In 2016, ice was not present at these locations (Fig. 4).

There has been very little ice on the Scotian Shelf from April 2009 until 2014 (Fig. 5). The ice areas and volumes for the 2015-2016 seasons are compiled in Table 2. After having about normal ice levels in late winter last year, ice was below normal coverage and volume in 2015-2016. The December 2015 to April 2016 coverage and ice volume were the 2nd and 3rd lowest levels in the 55 year record. After near normal February 2015 values and above normal values in March and April last year, ice conditions returned to conditions found in the 2010-2013 period which had extremely low coverage and volume.

Table 2. Ice area and volume statistics, Scotian Shelf

Month	2016 Ice Area (km^2)	2016 Area Anomaly (km^2)	2016 Normalized Area Anomaly	2016 Ice Volume (km^3)	2016 Volume Anomaly (km^3)	2016 Normalized Volume Anomaly
January	2	-1230	-0.6	0.00	-0.2	-0.6
February	9	-11280	-1.1	0.00	-2.8	-1.0
March	76	-15640	-1.1	0.02	-6.9	-1.0
April	11	-45700	-0.9	0.00	-3.0	-1.0

Remotely-Sensed Sea Surface Temperature

A 4 km resolution Pathfinder 5.2 (Casey et al., 2010) sea surface temperature database is maintained at the Bedford Institute of Oceanography. The Pathfinder dataset runs from November 1981 to December 2015; to provide data for 2016 and on, we used the 1-km resolution Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature data downloaded from the National Oceanic and Atmospheric Administration (NOAA) and European Organisation for the

Exploration of Meteorological Satellites (EUMETSAT) satellites by the remote sensing group in the Bedford Institute of Oceanography (BIO). A least-square fit of Pathfinder and BIO temperatures during the 1981-2010 period for several regions led to a conversion equation SST(Pathfinder) = 0.988*SST(BIO)-0.02 with an r^2=0.98. Using this regression, the BIO 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 (Fig. 6, Table 3). The annual anomalies during 2016 ranged from
+0.5°C (+0.5 SD) in Cabot Strait to +1.7°C (+1.6 SD) in the Bay of Fundy. All eight areas had positive anomalies; of those, seven were equal to or greater than +0.8 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 0.3°C/decade (Cabot Strait) to a highest value of 0.6°C/decade (Central Scotian Shelf and Western Bank). A similar trend in SST from AVHRR measurements was found in the Gulf of St. Lawrence (Galbraith et al., 2012) and on the Newfoundland and Labrador Shelf (Colbourne et al. 2016). The large increase in the observed SST over this period has likely been enhanced by the cold period at the beginning of the AVHRR period (Fig. 2) and a rapid temperature increase from 1997 (Fig. 6).

The overall coherent variability of the annual temperature anomalies in the eight regions suggested a principal component analysis might be revealing. The leading mode, PCA1, captured 82% of the variance and all loadings had similar amplitudes, meaning roughly equal contributions from each series; PCA2 accounted for an additional 7% of the variance with positive loadings in the eastern half of the region, changing to negative values roughly to the west of the central Scotian Shelf (Fig. 7). 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. 2016 SST annual anomalies and long-term SST statistics including 1982-2016 temperature change based on linear trend.

Site	2016 SST Anomaly (°C)	2016 SST Anomaly Normalized	1981-2010 Mean Annual SST (°C)	1981-2010 Annual SST Anomaly Std. Dev. (°C)	1982-2016 Temperature Trend (ºC/decade)
Cabot Strait	+0.5	+0.5	5.9	1.0	0.3
Eastern Scotian Shelf	+0.9	+0.8	7.1	1.1	0.4
Central Scotian Shelf	+1.5	+1.3	8.5	1.1	0.6
Western Bank	+1.3	+1.0	8.9	1.2	0.6
Western Scotian Shelf	+1.3	+1.2	8.1	1.1	0.5
Lurcher Shoal	+1.5	+1.4	7.2	1.1	0.4
Bay of Fundy	+1.7	+1.6	7.2	0.8	0.5
Georges Bank	+1.3	+1.4	10.0	1.0	0.4

Coastal Temperatures and Salinities

Coastal sea surface temperatures have been collected at Halifax (Nova Scotia) and St. Andrews (New Brunswick) since the 1920s (Fig. 8). In 2016, the SST anomalies were +1.0°C (+1.5 SD) for Halifax, an increase of 1.2°C from 2015 and +1.4°C (+2.5 SD) for St. Andrews, an increase of 1.2°C from 2015.

Temperature and salinity measurements through the water column, for the most part sampled monthly, have been taken since 1924 at Prince 5, at the entrance to the Bay of Fundy (Fig. 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 anomaly time series are shown in Fig. 8(C-E). In 2016, the annual temperature anomaly was +1.6°C (+3.0 SD) and the salinity anomaly was +0.2 (+0.9 SD). These represent changes of +1.3°C and +0.0 from the 2015 values. The negative density anomaly is accounted for by the salinity anomaly that was offset a bit by the partial density anomaly due to the increase in the temperature.

Scotian Shelf and Gulf of Maine Temperatures from Long-term Stations

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 correspond to topographic features such as banks and basins. Petrie et al. (1996) updated their report using these same areas and all available hydrographic data. An updated time series of annual mean and filtered (5 year running means) temperature anomalies at selected depths for five areas (Fig. 9) is presented (Fig. 10). The Cabot Strait temperatures represent a mix of Labrador Current Water and Warm Slope Water (e.g., Gilbert et al., 2005) entering the Gulf of St. Lawrence along Laurentian Channel; the Misaine Bank series characterizes the colder near bottom temperatures on the eastern Scotian Shelf; the deep Emerald Basin anomalies represent the Slope Water intrusions onto the Shelf that are subsequently trapped in the deep inner basins (note the large anomaly "events" in Fig. 10C); the Lurcher Shoals observations define the ocean climate on the southwest Scotian Shelf and the shallow waters entering the Gulf of Maine via the Nova Scotia Current; finally, the Georges Basin series indicates the slope waters entering the Gulf of Maine through the Northeast Channel. Annual anomalies are based on the averages of monthly values; however, observations may not be available for each month in each area. For Cabot Strait, Misaine Bank, Emerald Basin, Lurcher Shoals and Georges Basin, 2016 annual anomalies are based on observations from only four, six, four, four and five months, respectively.

In 2016, the annual anomalies were +1.9°C (+3.6 SD) for Cabot Strait 200-300 m (the largest anomaly; the second, third and fourth largest anomalies were in 2012, 2014 and 2015), +1.2°C (+1.9 SD) for Misaine Bank at 100 m, +1.6°C (+1.9 SD) for Emerald Basin at 250 m a record high), +1.0°C (+1.2 SD) for Lurcher Shoals at 50 m, and +1.4°C (+2.6 SD) for Georges Basin at 200 m (a record high with 2014 was the second warmest year). These values correspond to changes of +0.4°C, +0.2°C, +0.4°C, -0.2°C and +0.4°C, respectively from the 2015 values. The 2010 and 2011 North Atlantic Oscillation 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 but increased to record or near record values in 2014 and continued to remain high in 2016.

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 250 CTD stations were sampled during the 2016 survey. The groundfish survey normally takes one month to complete with the area west of Halifax sampled first and the area east of Halifax sampled last.

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. 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 for at the standard depths (e.g. 0 m, 10m, 20m, …) and for near the bottom. Only the bottom temperatures are presented here.

Bottom temperatures ranged from an average of 4.8°C in NAFO Division 4Vs to 9.1°C in 4X during 2016, illustrating the difference in the environmental conditions across the Shelf (Fig. 11). The anomalies were positive for these NAFO Divisions in 2016: +0.9°C (+2.1 SD) in 4Vn; +1.5°C (+2.1 SD) in 4Vs; +1.7°C (+2.3 SD) in 4W; and +1.9°C (+2.6 SD) in 4X (Fig. 12 A-D). Compared to 2014 record warm year for 4Vn and 4W, 4Vn was the 4th warmest year, 0.3°C lower than the record and 4W was the 2nd warmest year, 0.2°C lower than the record. 4Vs was the 3rd warmest year; 2015 was the 2nd warmest. 4X was the 2nd warmest year, 0.3°C lower than the 2012 record temperature.

The volume of the Cold Intermediate Layer (CIL), defined as waters with temperatures <4°C, was estimated from the full depth CTD profiles for the region from Cabot Strait to Cape Sable (Fig. 12E). For the period 1970 to 1989, the number of CTD profiles per year was limited; therefore, 5-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 1 year and a new set of estimates made (i.e., 1970-74, 1971-75, …). This procedure is similar to filtering (5-year running mean) 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 Fig. 12E) 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 (Fig. 12E). In 2016, the observed volume of 4200 km^3 was 1.2 SD less than the 1981-2010 mean value of 5500 km^3, being the 9th lowest volume in the 43 years of surveys. The smallest volume was in 2012.

Density Stratification

Stratification of the near surface layer influences physical and biological processes in the ocean such as 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 0 and 50 m was examined. The density differences were based on monthly mean density profiles calculated for areas 4-23 on the Scotian Shelf as defined by Petrie et al. (1996). 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. This could be misleading if, in a particular year, most data were collected in months when stratification was weak, while in another year, sampling occurred when stratification was strong. However, initial results, using normalized monthly anomalies, were qualitatively similar to the plots presented here. The annual anomalies and their 5-year running means were then calculated for an area-weighted combination of subareas 4-23 on the Scotian Shelf (see figure 17 in Hebert et al., 2014 for map). 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 that featured generally below average stratification in contrast to the past 20 years that is characterized by above normal values (Fig. 13). Stratification on the Scotian Shelf in 2016 increased after several years weakening and was greater than the 1981-2010 mean value. Since 1948, there has been an increase in stratification on the Scotian Shelf, resulting in a change in the 0-50 m density difference of 0.36 kg m^{-3} over 50 years. This change in mean stratification is due mainly to a decrease in the surface density (76% of the total density change), composed equally of warming and freshening. The remainder of the density change occurs at 50 m, mainly due to an increase of salinity. There was an increase in stratification from 2015 to 2016 due to an increase in surface density as a result of warmer temperature, an increase of 1.0°C and lower salinity, a decrease of 0.2.

Summary

A graphical summary of many of the time series already shown indicates that the periods 1987-1993 and 2003-2004 were predominantly colder than normal and 1999-2000 and 2010-2014 were warmer than normal (Fig. 14). The period 1979-1986 also tends to be warmer than normal. In this figure, annual anomalies based on the 1981-2010 means have been normalized by dividing by the 1981-2010 standard deviations for each variable. The results are displayed as the number of standard deviations above (red and purple) and below (blue) normal. It is apparent that 2012 was an exceptional year based on these series with 14 above 2 SD. In 2016, all 22 series shown had positive anomalies; 20 variables were more than 1 SD above their normal values. Of these, 14 were more than 2 SD above normal and three more than 3 SD (Prince 5 at 90 m, Georges Basin at 50 m and deep Cabot Strait). In 2016, the average (median) normalized anomaly was 2.2 (2.2), the second highest in the 47 year series. The SD of the normalized anomalies was 0.7. These statistics indicate that 2016 was an extremely warm year with a fairly uniform distribution of anomalies throughout the region.

Eighteen selected variables of the mosaic plot are summarized as a stacked bar plot in Fig. 15. This plot is an attempt to derive an overall climate index for the area. We have selected time series for the eastern (Misaine), central (Emerald) and western (Lurcher) Scotian Shelf, the Bay of Fundy (Prince 5) and Georges Bank. In addition, we have included the spatially comprehensive but temporally limited July groundfish survey bottom temperatures (4Vn, 4Vs, 4W and 4X) and surface temperatures for Halifax and St. Andrews 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 2016 was the second warmest of 47 years, with an averaged normalized anomaly of +2.1 SD relative to the 1981-2010 period. The anomalies did not show a strong spatial distribution in 2016. The leading mode of a principal component analysis of the 18 series captured 54% of the variance with all loadings having the same sign. The loadings of 17 of the 18 variables were strong (0.18 to 0.28) with weak contributions only from the Emerald Basin 250 m series (0.10).

Acknowledgements

The authors thank all those who provided data for this paper, including: Mathieu Ouellet of the Integrated Data Management Group in Ottawa and Sarah Scouten of the Biological Station in St. Andrews, for providing St. Andrews and Prince 5 data.

References

Casey, K.S., T.B. Brandon, P. Cornillon and R. Evans, 2010: The Past, Present and Future of the AVHRR Pathfinder SST Program, In Oceanography from Space: Revised, eds. V. Barale, J.F.R. Gower and I. Alberotanza, Spinger, doi: 10.1007/978-90-481-8681-5_16.

Colbourne, E., Holden, J., Senciall, D., Bailey, W., Craig, J., and S. Snook. 2016. Physical oceanographic conditions on the Newfoundland and Labrador Shelf during 2014. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/079.

Drinkwater, K.F. and R.W. Trites, 1987: Monthly means of temperature and salinity in the Scotian Shelf region, Can. Tech. Rep. Fish. Aquat. Sci., 1539, 101 p.

Galbraith, P.S., P. Larouche, J. Chassé and B. Petrie, 2012: Sea-surface temperature in relation to air temperature in the Gulf of St. Lawrence: Interdecadal variability and long term trends, Deep Sea Res. II, Vol 77-80, p10-20. doi://10.1016/j.dsr2.2012.04.001.

Gatien, M.G., 1976: A study in the slope water region south of Halifax, J. Fish. Res. Board Can., 33, 2213-2217.

Gilbert, D., B. Sundby, C. Gobriel, A. Mucci and G.-H. Tremblay, 2005: A seventy-two-year record of diminishing deep-water oxygen in the St. Lawrence estuary: The northwest Atlantic connection, Limnol. Oceanogr., 50, 1654-1666.

Hebert, D., R. Pettipas, D. Brickman, and M. Dever. 2014. Meteorological, Sea Ice and Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/070. v + 40 p.

Petrie, B., 2007: Does the North Atlantic Oscillation affect hydrographic properties on the Canadian Atlantic Continental Shelf?, Atmos.-Ocean, 45, 141-151.

Petrie, B., K. Drinkwater, D. Gregory, R. Pettipas, and A. Sandström, 1996: Temperature and salinity atlas for the Scotian Shelf and the Gulf of Maine, Can. Data Rep Hydrog. Ocean Sci. 171, 398 p.

Petrie, B., R.G. Pettipas and W. Petrie, 2009: Meteorological, Sea Ice and Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2008, DFO Can. Sci. Advis. Sec. Res. Doc. 2009/041, vi+32p.

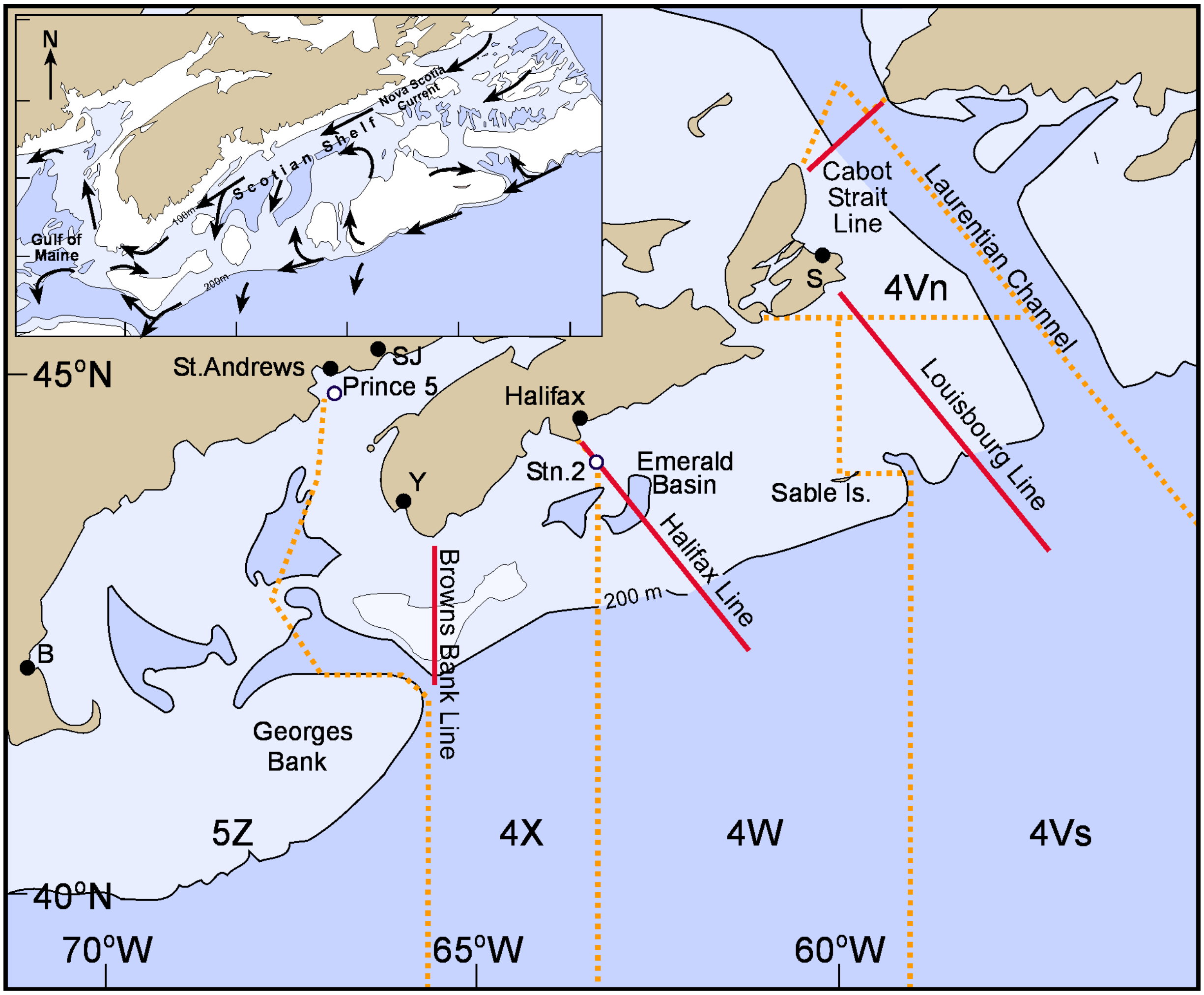


Fig. 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the NAFO Subareas. Inset depicts major circulation features. Air temperature stations at Sydney (S), Yarmouth (Y), Saint John (SJ), and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

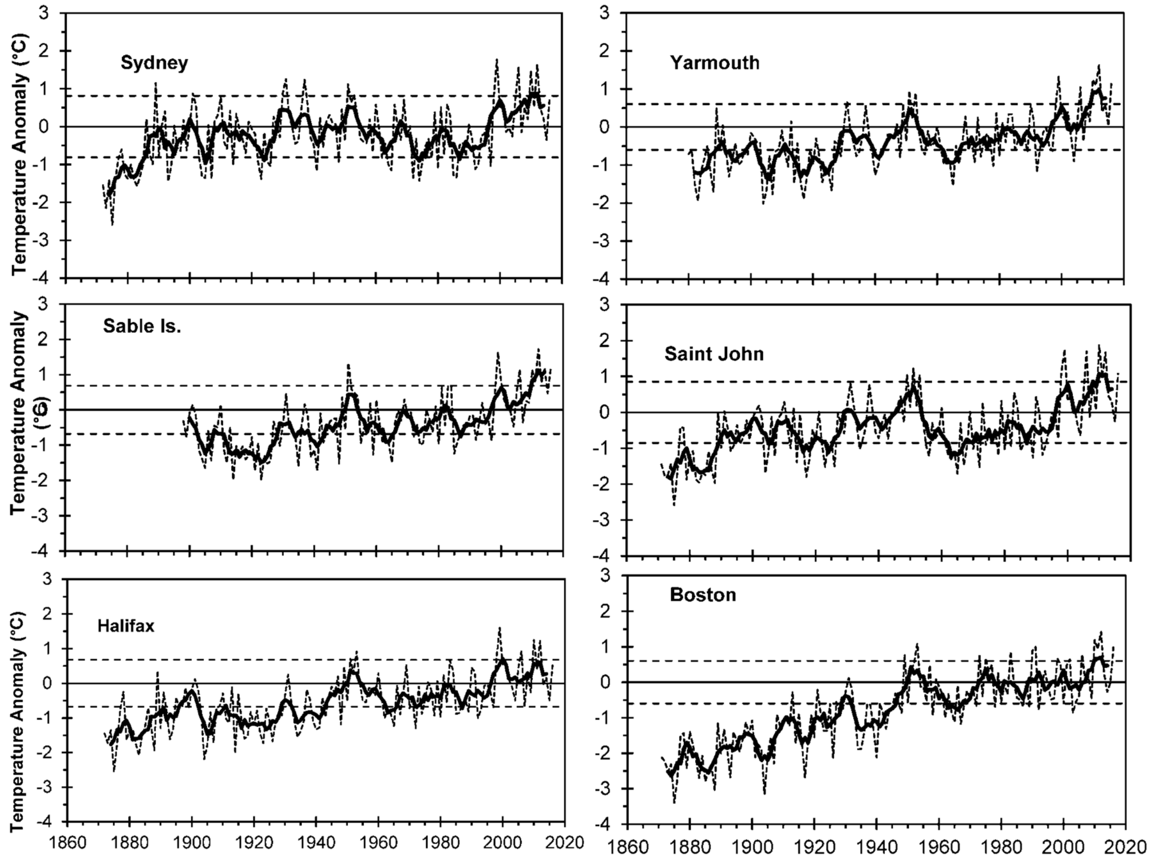


Fig. 2. Annual air temperature anomalies in °C (dashed line) and five year running means (solid line) at selected sites (Sydney, Sable Island, Shearwater, Yarmouth, Saint John and Boston) in Scotian Shelf-Gulf of Maine region (years 1860 to 2016). Horizontal dashed lines represent +/- 1 SD for the 1981-2010 period.

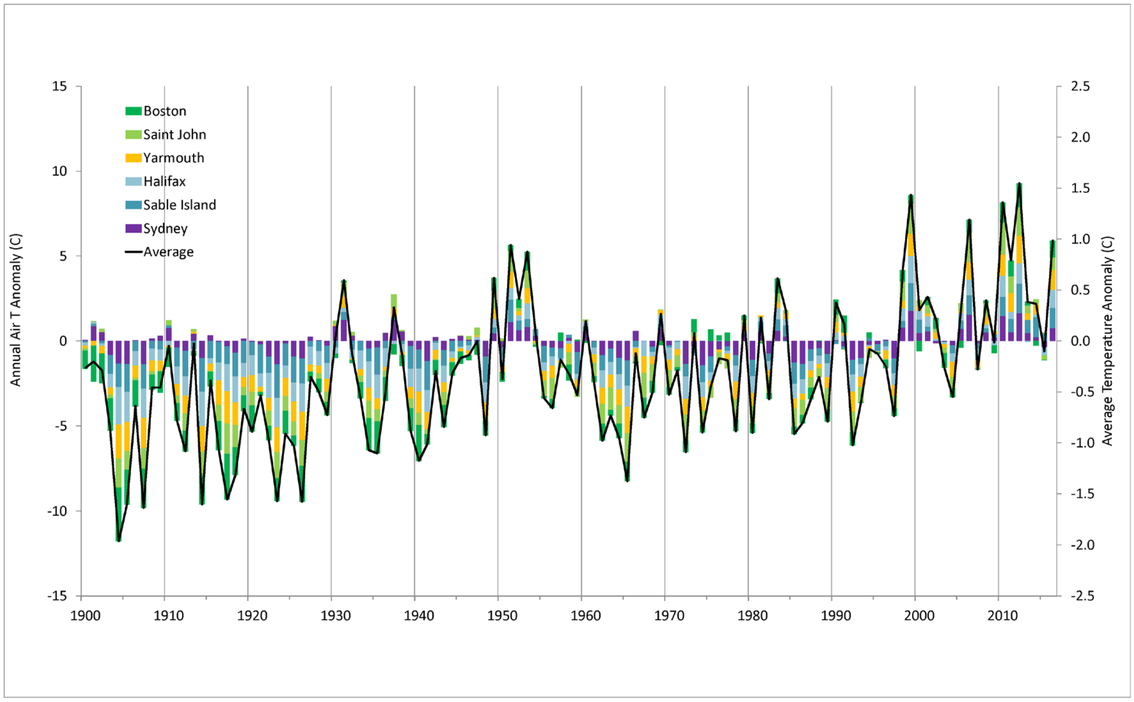


Fig. 3. The contributions of each of the annual temperature anomalies for 6 Scotian Shelf-Gulf of Maine sites (Boston, Saint John, Yarmouth, Shearwater, Sable Island and Sydney) are shown as a stacked bar chart and the average anomaly as a line. Anomalies referenced to 1981-2010.

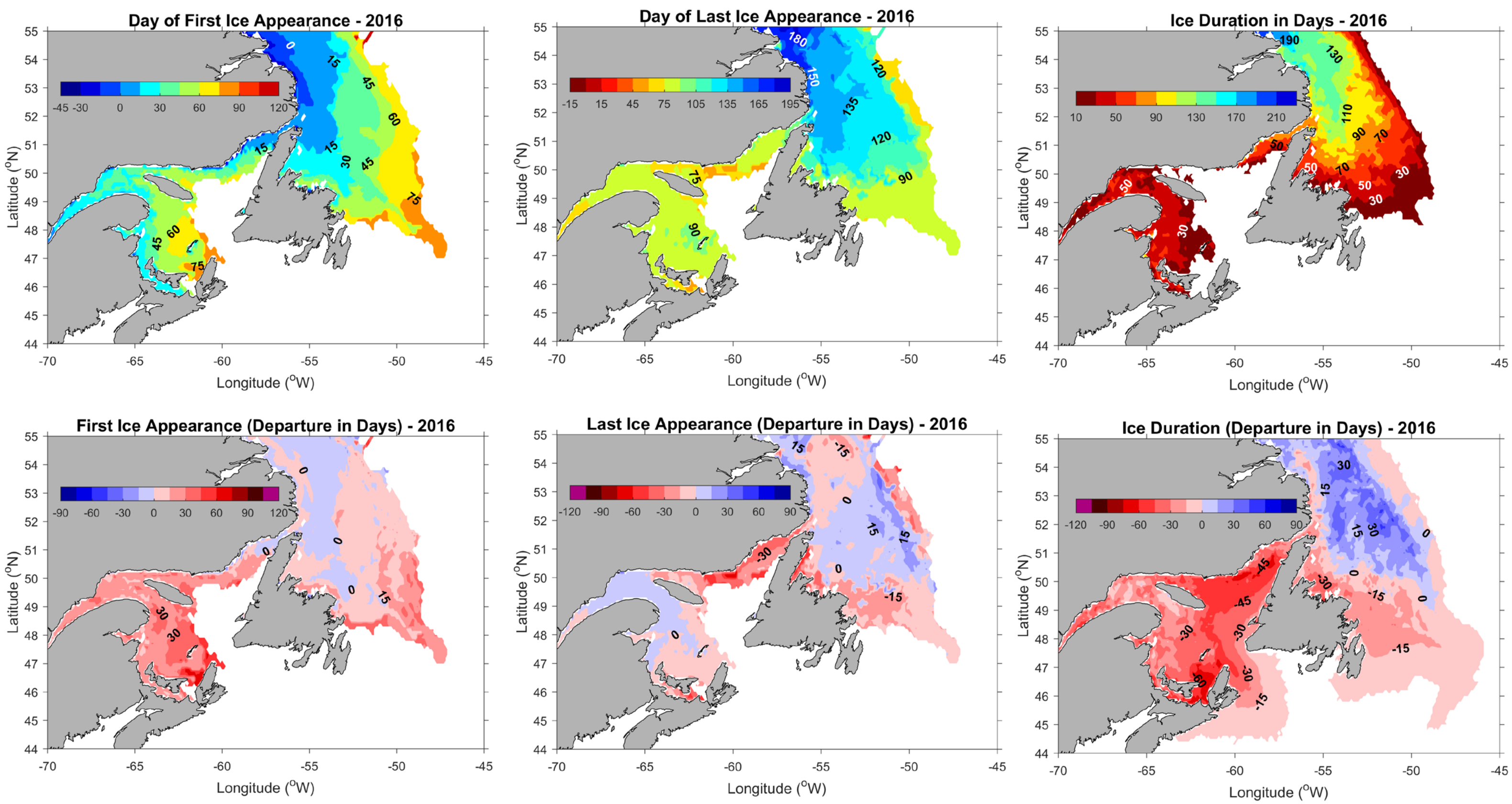


Fig. 4. The time when ice first appeared during 2016 in days from the beginning of the year (left, top panel) and its anomaly from the 1981-2010 mean in days (left, bottom panel). Negative (positive) anomalies indicate earlier (later) than normal appearance. The time when ice was last seen in 2016 in days from the beginning of the year (centre, top panel) and its anomaly from the 1981-2010 mean in days (centre, bottom panel). Positive (negative) anomalies indicate later (earlier) than normal disappearance. The duration of ice in days (right, top panel) during 2016 and the anomalies from the 1981-2010 mean in days (right, bottom panel). Positive (negative) anomalies indicate durations longer (shorter) than the mean.

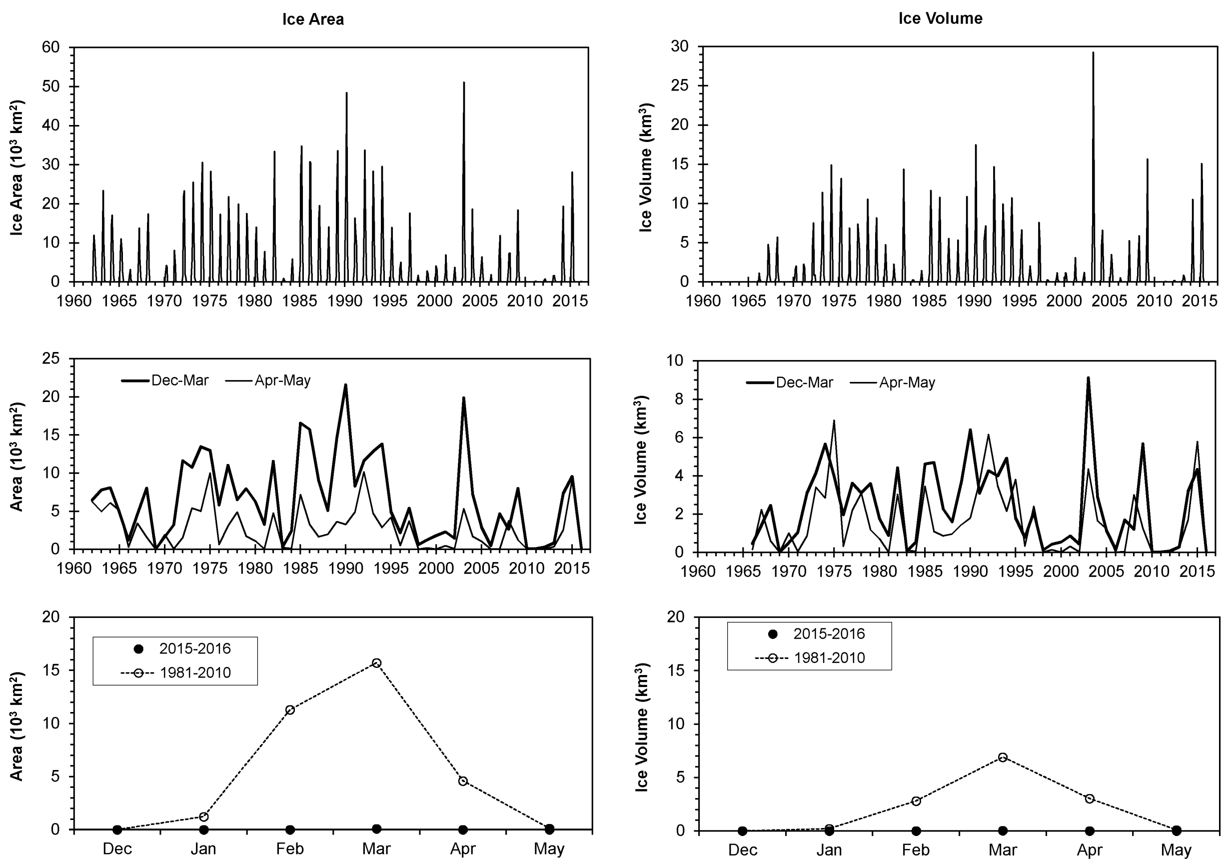


Fig. 5. Time series of the monthly mean ice area and volume for the Scotian Shelf (top panels), the average ice area during the usual periods of advancement (January-March) and retreat (April-May) (middle panels) and the comparison of the monthly areas and volumes to the 1981-2010 means (bottom panels).

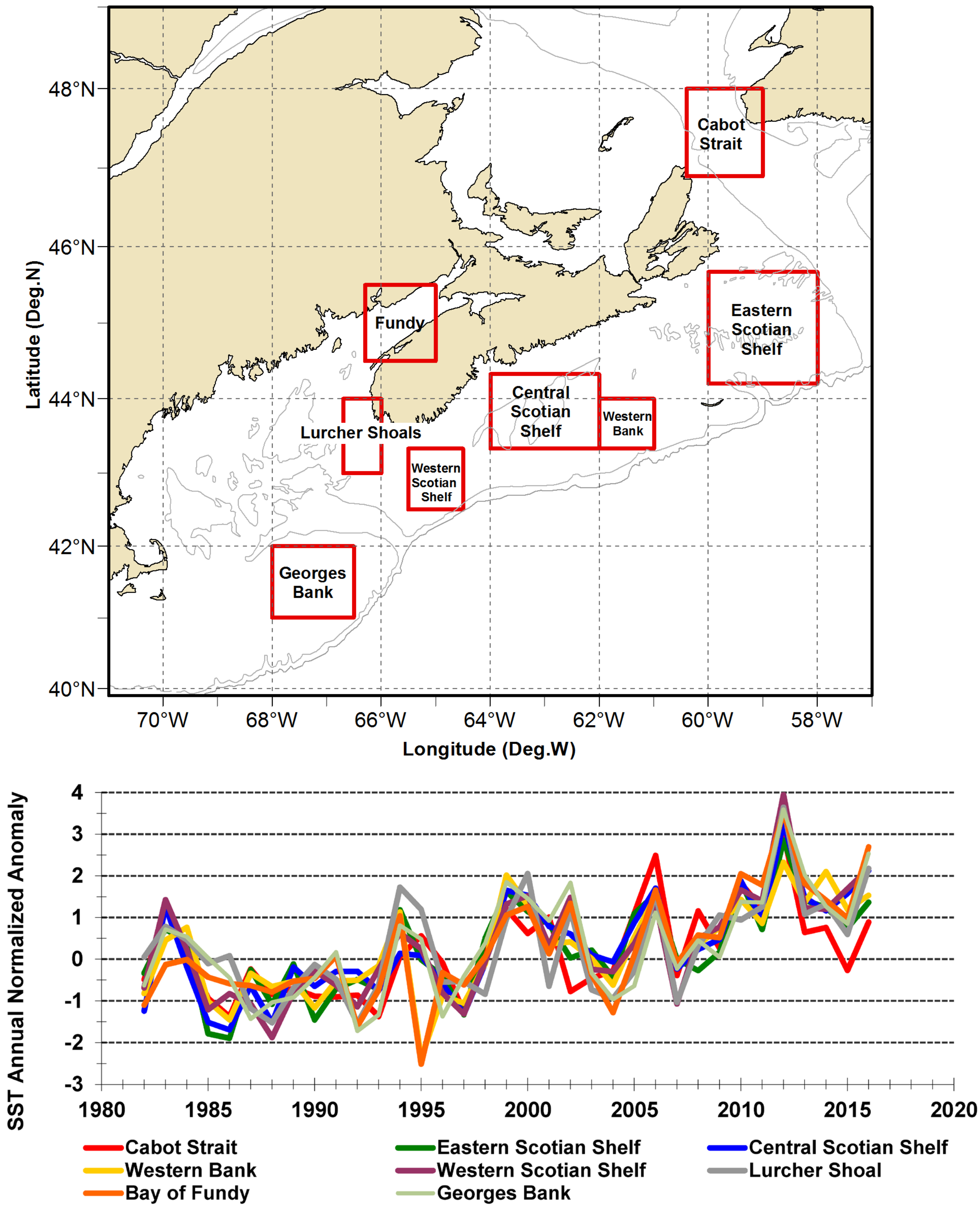


Fig. 6. Scotian Shelf-Gulf of Maine areas (Cabot Strait, Eastern Scotian Shelf (EES), Western Bank, Central Scotian Shelf (CSS), Western Scotian Shelf (WSS), Georges Bank, Lurcher Shoals and Bay of Fundy) used for extraction of sea surface temperature (upper panel). The annual sea surface temperature anomalies derived from satellite imagery compared to their long-term monthly means (lower panel).

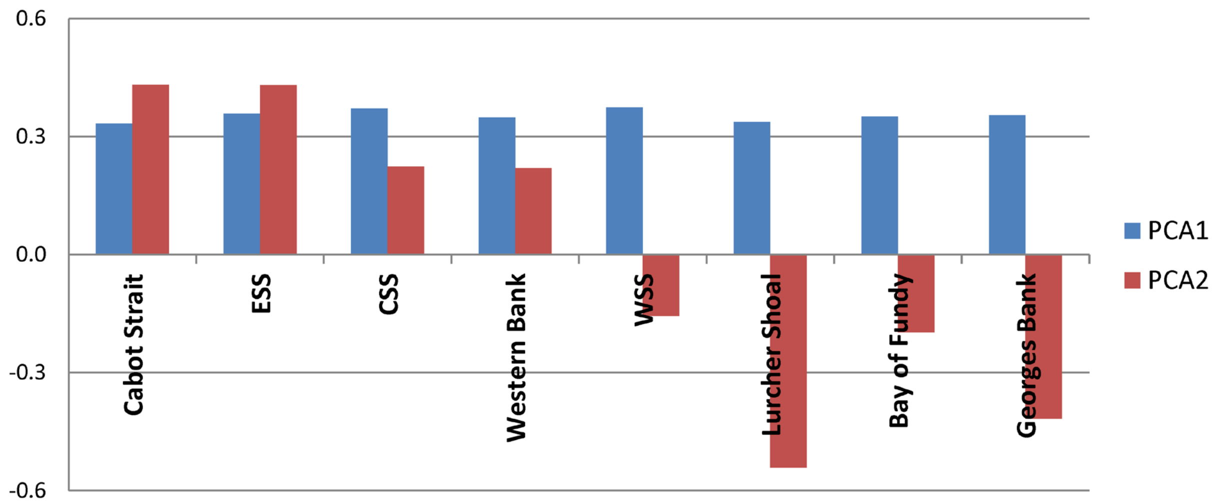


Fig. 7. First (PCA1: 82% of the variance) and second (PCA2: 7% of the variance) loadings from a principal components analysis of the annual mean temperature anomalies (Figure 6, lower panel) for the eight Scotian Shelf and Gulf of Maine regions (Cabot Strait, Eastern Scotian Shelf (EES), Western Bank, Central Scotian Shelf (CSS), Western Scotian Shelf (WSS), Georges Bank, Lurcher Shoals and Bay of Fundy -Figure 6, upper panel).

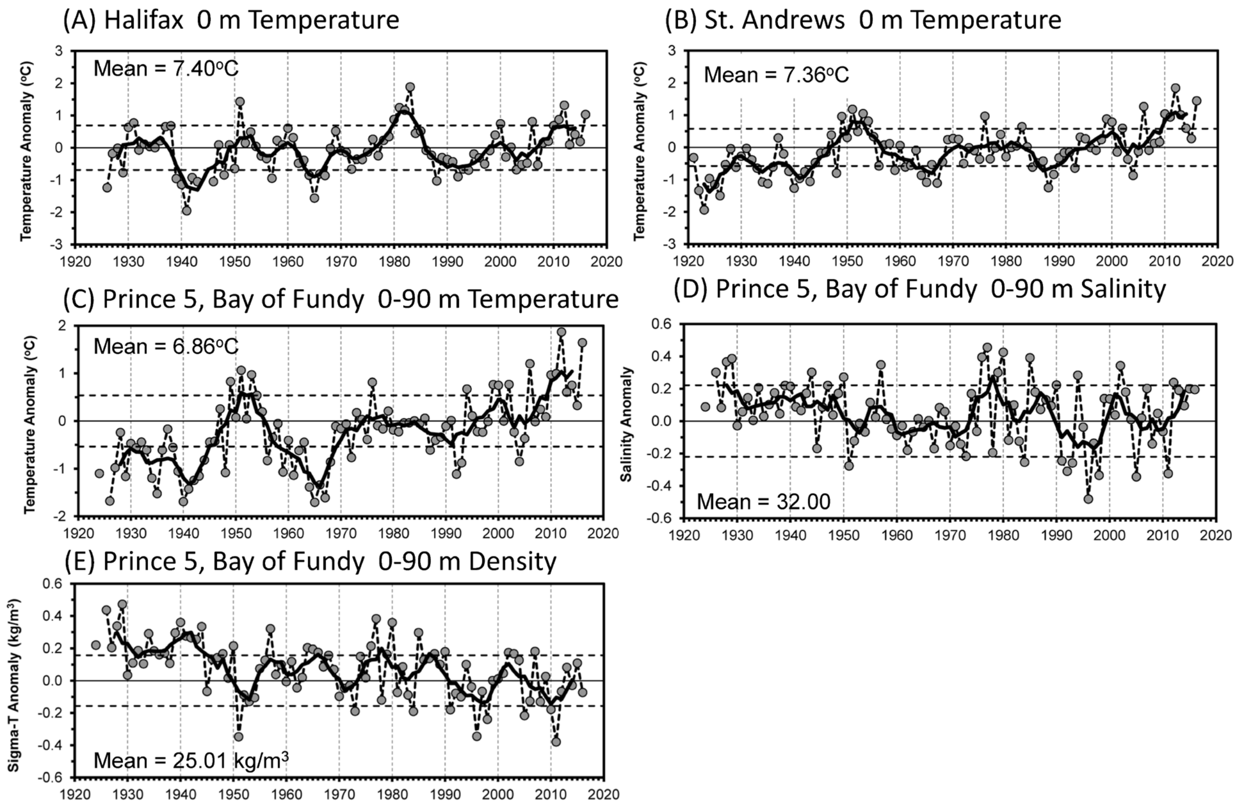


Fig. 8. The annual surface temperature anomalies (dotted line with circles) and their 5-year running means (heavy black line) for (A) Halifax Harbour and (B) St. Andrews; annual depth-averaged (0-90 m) (C) temperature, (D) salinity and (E) density anomalies for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Horizontal dashed lines are mean plus and minus 1 SD.

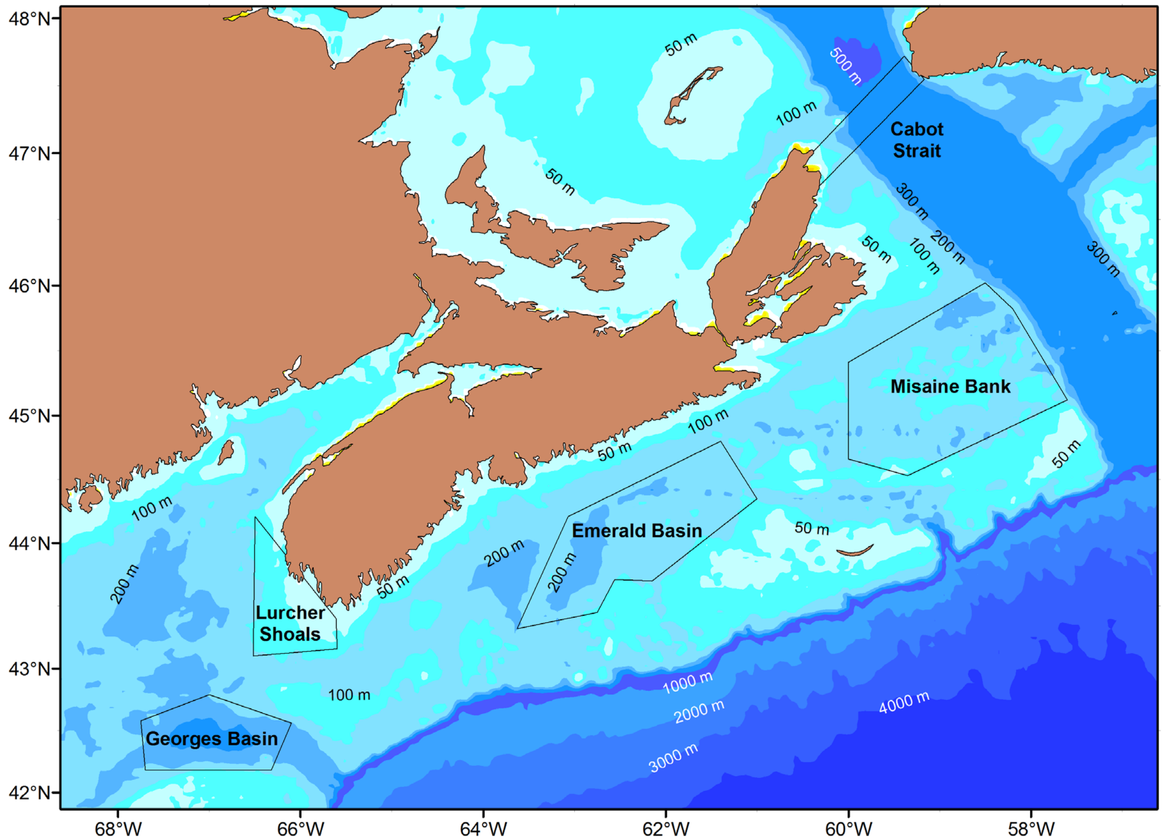


Fig. 9. Areas on the Scotian Shelf and eastern Gulf of Maine depicting the different water masses.

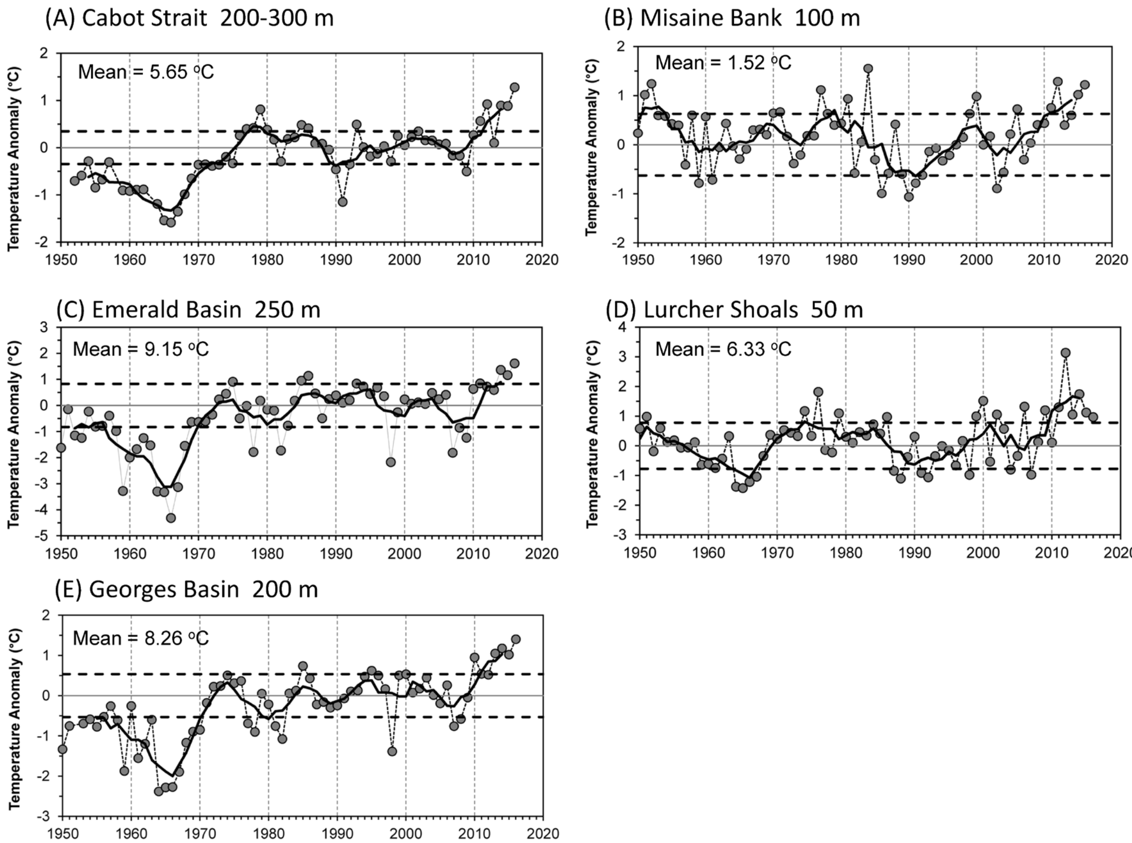
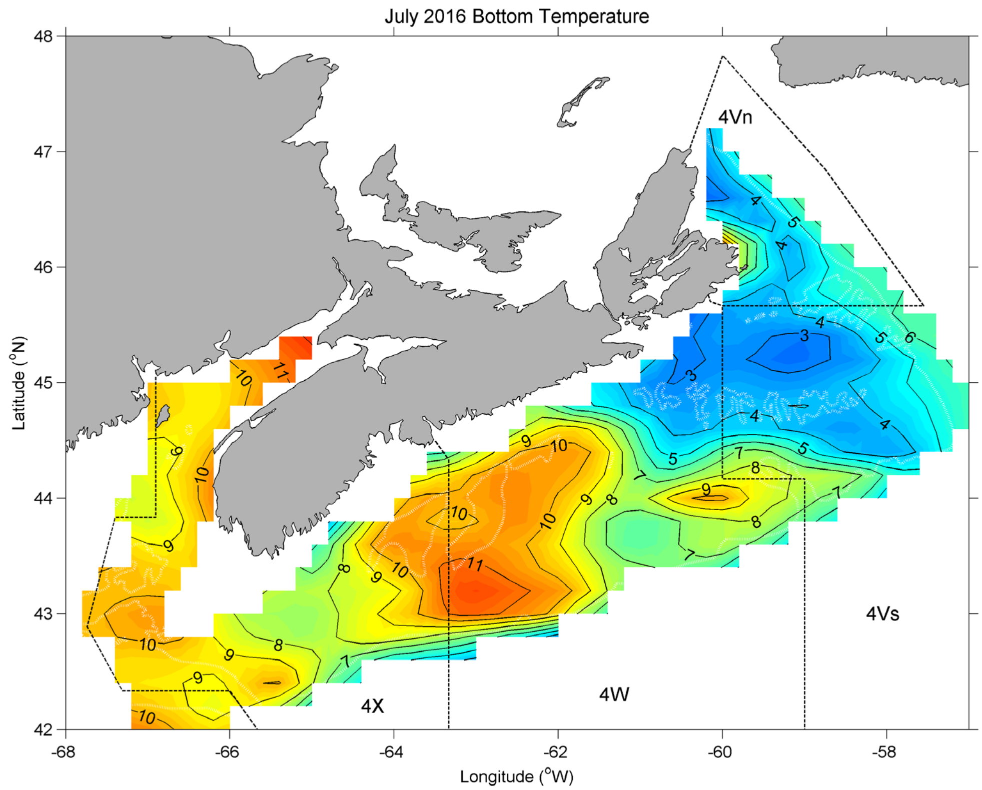


Fig. 10. The annual mean temperature anomaly time series (dotted line with circles) and the 5 year running mean filtered anomalies (heavy solid line) on the Scotian Shelf and in the Gulf of Maine at (A) Cabot Strait (200-300 m); (B) Misaine Bank (100 m); (C) Emerald Basin (250 m); (D) Lurcher Shoals (50 m); and Georges Basin (200 m) (see Fig. 2). Horizontal dashed lines are mean plus and minus 1 SD.



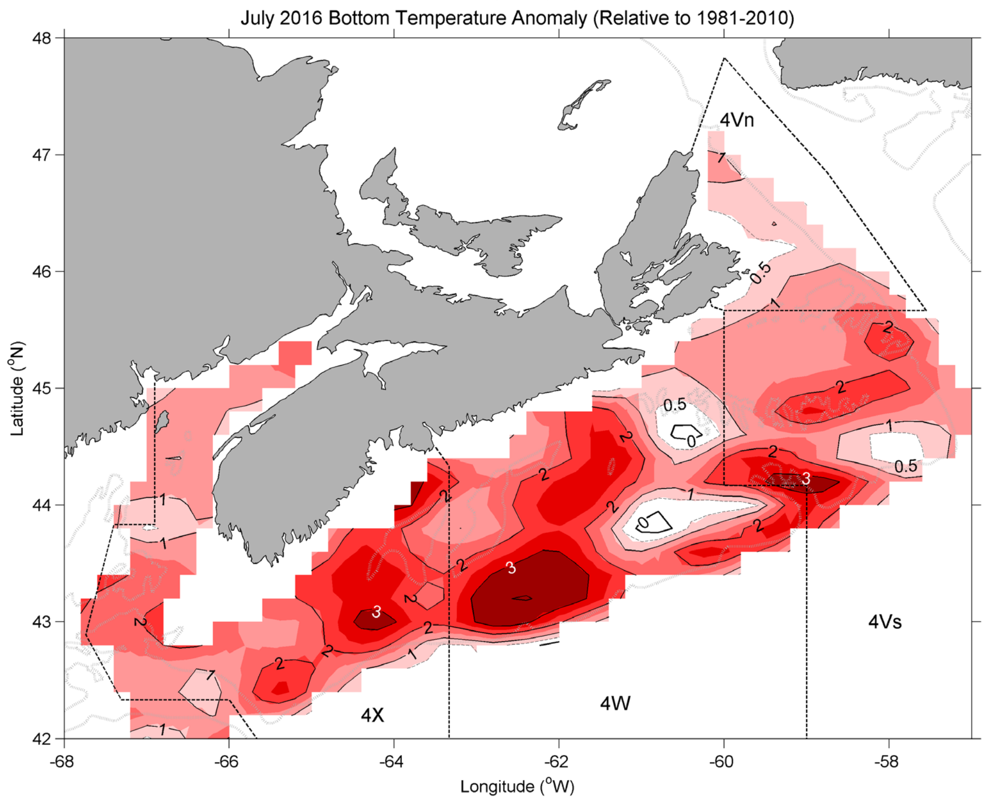


Fig. 11. July bottom temperature (upper panel) and anomaly (lower panel) maps for 2016. NAFO areas 4Vn, 4Vs, 4X and 4W are shown.

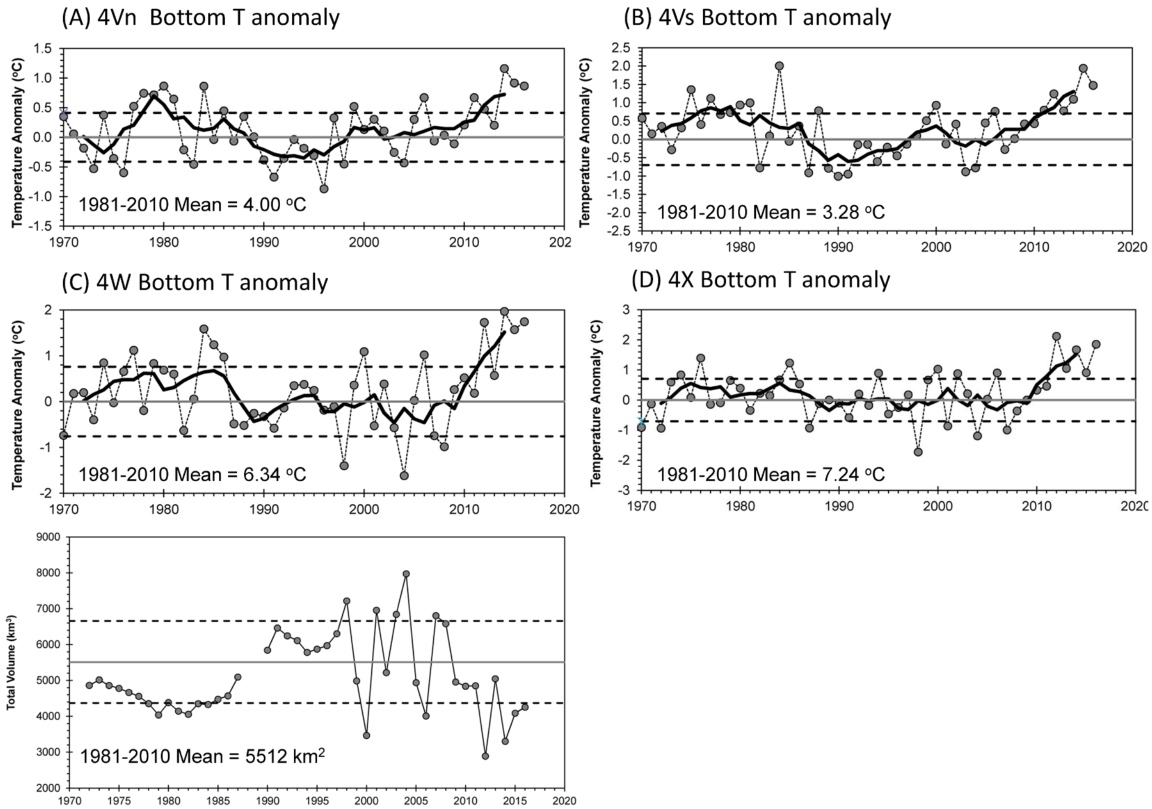


Fig. 12. Time series of July bottom temperature anomalies (dashed lines with circles) and 5 year running mean filtered series (heavy line) for areas (A) 4Vn, (B) 4Vs, (C) 4W and (D) 4X. (E) Time series of the Cold Intermediate Layer (CIL, defined as waters with T<4°C) volume on the Scotian Shelf based on the July ecosystem survey. The solid horizontal line is the 1981-2010 mean CIL volume and dashed lines represent 1 standard deviation.

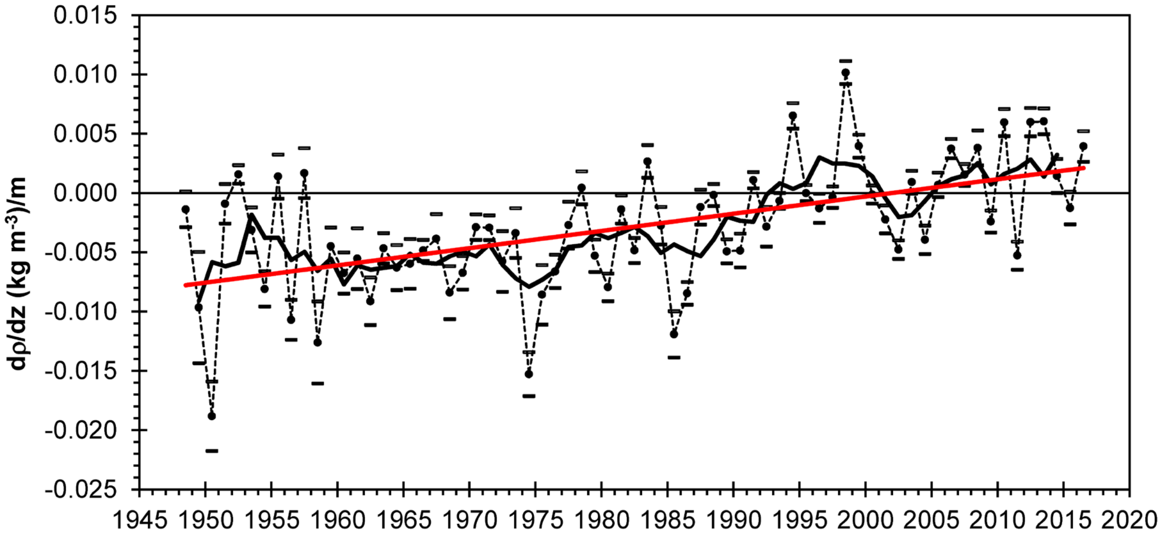


Fig. 13. The mean annual anomaly (dashed line with circles) and 5-yr running mean (heavy solid line) of the stratification index (0-50 m density gradient) averaged over the Scotian Shelf. Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a change in the 0-50 m density difference of 0.36 kg m^{-3} over 50 years.

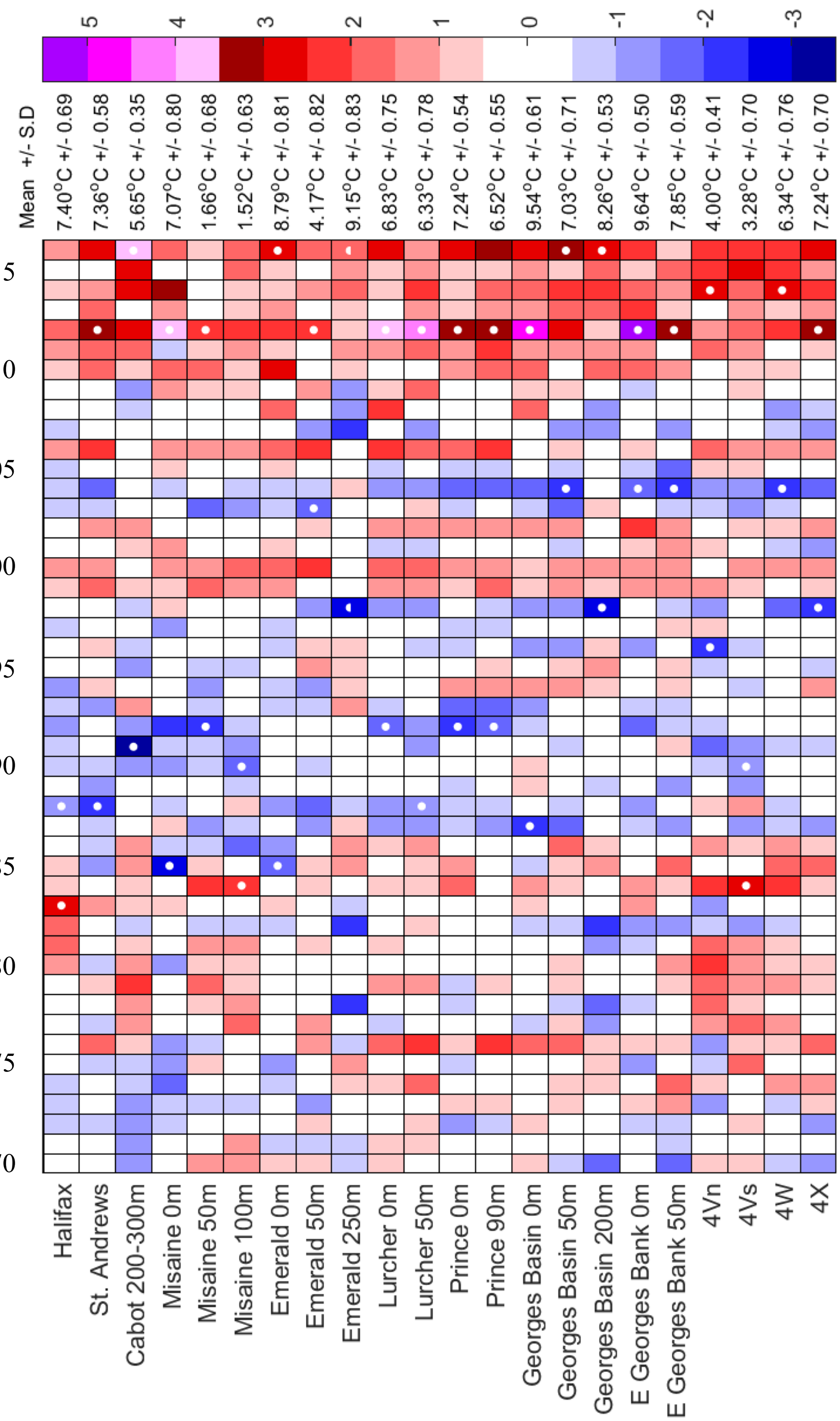


Fig. 14. Normalized annual anomalies of temperatures at the bottom and discrete depths for the Scotian Shelf-Gulf of Maine region. These normalized, annual anomalies are based on the 1981-2010 means, divided by the standard deviation. Blue colours indicates below normal anomalies, red and purple (for 2012, the colour scale had to be increased above +3.5 SD and is shaded in purple) colours above normal anomalies.

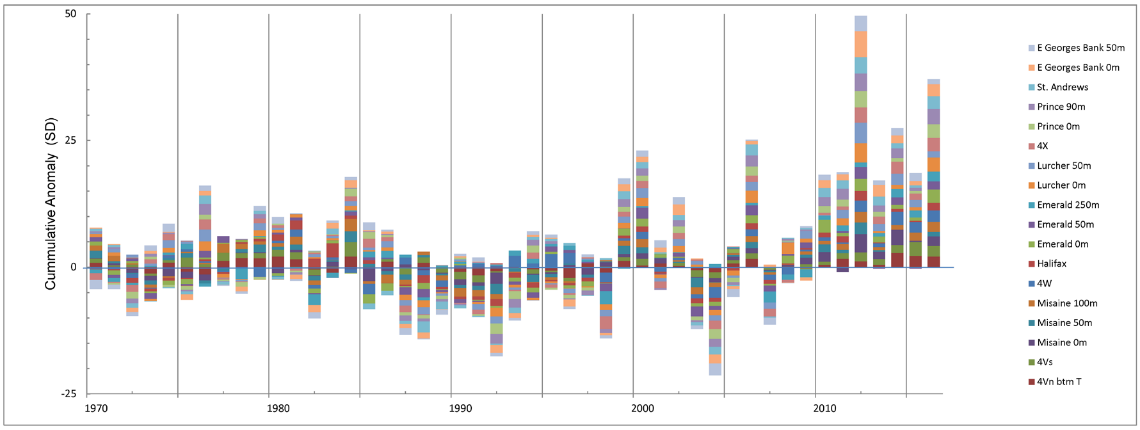


Fig. 15. The contributions of each of the normalized anomalies are shown as a stacked bar chart.