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Physical Oceanographic Conditions on the Scotian Shelf and in the eastern Gulf of Maine (NAFO areas 4V,W,X) during 2011

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Abstract

A review of the 2011 physical oceanographic conditions on the Scotian Shelf and in the eastern Gulf of Maine and adjacent offshore areas indicates that above normal conditions prevailed. The climate index, a composite of 18 selected, normalized time series, averaged +0.9 SD with 17 of the 18 variables more than 0.5 SD above normal; compared to the other 42 years, 2011 ranks as the 6th warmest. The anomalies did not show a strong spatial variation. Bottom temperatures were above normal with anomalies for NAFO areas 4Vn, 4Vs, 4W, 4X of +0.7°C (+1.6 SD), +0.8°C (1.1 SD), +0.3°C (+0.3 SD), and +0.5°C (+0.6 SD) respectively. Compared to 2010, bottom temperatures increased in areas 4Vn, 4Vs and 4X by 0.5, 0.4 and 0.1°C; temperate decreased by 0.3°C in area 4W.

Introduction

This document briefly describes air temperature, ice area and volume, and ocean temperature variability of Scotian Shelf and Gulf of Maine waters during 2011 (see Fig. 1 for the study area, Fig. 2 for area names of time series presented in document). The results are derived from data obtained at coastal and long-term monitoring stations, on annual ecosystem surveys and Atlantic Zone Monitoring Program (AZMP) missions, and from ships-of-opportunity and other research cruises. Most of the data are available in the BIO temperature and salinity (CLIMATE) database[1], which is updated several times per year from the national archive maintained by Integrated Science Data Management (ISDM), Department of Fisheries and Oceans (DFO) in Ottawa. Additional hydrographic data were obtained directly from DFO fisheries surveys.

Many of the products which have been presented previously in the overview are now available on the ISDM website devoted to the AZMP program[2]. The products available include sections from the AZMP spring and fall surveys, time series of physical properties from fixed stations, climate indexes such as coastal temperature series, frontal positions, and bottom temperatures from ecosystem surveys. In addition, the availability of quality controlled data from sources such as CLIMATE allows individuals to develop the product that most suits their needs. For these reasons, we present an abbreviated overview to give a general idea of environmental variability in 2011.

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 data.

[1] http://www.mar.dfo-mpo.gc.ca/science/ocean/database/data_query.html
[2] http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/index-eng.html

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. The properties of shelf waters are modified by mixing with offshore waters from the continental slope. These offshore waters are generally of two types, Warm Slope Water, with temperatures in the range of 8-13^{o}C and salinities from 34.7-35.6, and Labrador Slope Water, with temperatures from 3.5^{o}C to 8^{o}C and salinities from 34.3 to 35. 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. 3 and Table 1. In 2011, annual air temperature anomalies were positive at all sites and ranged from +0.6°C (Sydney and Saint John) to +1.1°C (Yarmouth). These values represent a decrease from 2010 observations but all are approximately 1 to 2 standard deviations above the long-term mean; furthermore, the time series of annual anomalies indicates that all sites feature increasing temperatures over the long term with decadal scale variability superimposed. For shorter periods, this can lead to no trend or decreasing temperatures (Fig. 3). Linear trends from 1900 to present from Boston, Shearwater, Sydney and Sable Island correspond to changes of +1.8°C, +1.5°C, 1.0°C and 1.0°C/century respectively; the trends from Yarmouth and Saint John are smaller, 0.6 and 0.3°C/century.

The anomalies for all 6 sites are displayed in Fig. 4 as a composite sum, illustrate three points. 1) In the 112 year time series shown, 2011 was the 6th warmest year for the region as a whole. 2) For most years the anomalies have the same sign. Since 1900, 90 of the 112 years had 5 or more stations with the annual anomalies having the same signs; for 62 years, all 6 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. 3) 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. Air temperature statistics 2011 for Scotian Shelf and Gulf of Maine

Site	Annual Anomaly 2011 (°C)		Monthly SD 2011 (°C)	1981-2010 Annual	
	Observed	Normalized		Mean (°C)	SD (°C)
Sydney	+0.6	+0.7	1.2	5.87	0.81
Sable I.	+0.8	+1.1	1.0	7.88	0.68
Shearwater (Halifax)	+1.0	+1.4	1.1	6.99	0.74
Yarmouth	+1.1	+1.7	0.9	7.16	0.62
Saint John	+0.6	+0.8	1.1	5.19	0.74
Boston	+0.9	+1.6	1.3	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 pushed 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 and in 2011 it was present for only a short period, lasting about 1 week. In 2011, there was no ice on the Scotian Shelf from December 2010 until the end of the season in May 2011 (Fig. 5). Over the winter, ice duration was below normal. Note that in the duration maps, regions of duration less than 1 week are not shown.

The ice areas and volumes are shown in Fig. 6 and compiled in Tables 2 and 3. The heaviest months, January to April, featured below normal coverage and volumes. Overall, the January to April 2011 coverage and ice volume were the third lowest in the 43 year long record. Only 1969 and 2010 had lesser coverage and volume; the difference between these 3 years is within the uncertainty of the observations.

Table 2. Ice area statistics, Scotian Shelf

Month	10-11 Ice Year (km^2)	1981-2010 Mean (km^2)	Anomaly (km^2)	Normalized
Jan	4.8	1200	-1200	-0.5
Feb	95	11300	-13200	-1.1
Mar	204	15700	-15500	-1.1
Apr	4.3	4600	-4600	-1.0

Table 3. Ice volume statistics, Scotian Shelf

Month	10-11 Ice Year (km^3)	1971-2000 Mean (km^3)	Anomaly (km^3)	Normalized
Jan	<0.01	0.2	-0.2	-0.7
Feb	0.01	2.8	-2.8	-1.0
Mar	0.06	6.9	-6.8	-1.0
Apr	<0.01	3.0	-3.0	-1.0

Remotely-Sensed Sea Surface Temperature

A 4 km resolution Pathfinder 5.0 (Casey et al., 2010) sea surface temperature database is maintained at BIO. The Pathfinder dataset runs from January 1985 to December 2009; to provide data for 2010 and 2011, we used the sea surface temperature data downloaded from the satellites by the remote sensing group in the Ocean Research & Monitoring Section (ORMS). Comparison of the Pathfinder and ORMS temperatures during the common time period led to a conversion equation SST(Pathfinder) = 0.976*SST(ORMS)+0.46 with an r^2=0.98. We adjusted the ORMS observations to bring them in line with the longer Pathfinder series. Anomalies were based on 1985-2011 averages.

Annual anomalies for 8 subareas in the Scotian Shelf-Gulf of Maine region were determined from the averages of monthly anomalies (Fig. 7, Table 4). On average, periods of 1 year and longer accounted for 38% of the overall variance determined from the monthly anomalies. The annual anomalies during 2011 ranged from +0.1°C (+0.1 SD) over Georges Bank to +0.8°C (+0.7 SD) in the Bay of Fundy. All eight areas had positive anomalies; only one was greater than +0.5 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 0.4°C (Georges Bank) to a highest value of 1.4°C (eastern and central Scotian Shelf). 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 could have been enhanced by the cold period at the beginning of the AVHRR period (Fig. 3).

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 71% of the variance and all loadings had similar amplitudes, meaning roughly equal contributions from each series; PCA2 accounted for an additional 18% 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 (Fig. 8).

Table 4. 2011 SST anomalies and long-term SST statistics.

Site	2011 SST Anomaly (^{o}C)	2011 SST Anomaly Normalized	1985-2011 Mean Annual SST (^{o}C)	1985-2011 SST Anomaly Std. Dev. (^{o}C)	ΔT (^{o}C) 1985-2011
Cabot Strait	+0.5	+0.4	6.2	1.0	1.2
Eastern Scotian Shelf (ESS)	+0.3	+0.3	8.8	1.2	1.4
Central Scotian Shelf (CSS)	+0.5	+0.4	7.4	1.0	1.4
Western Bank	+0.3	+0.3	10.7	1.1	1.2
Western Scotian Shelf (WSS)	+0.3	+0.3	7.9	1.0	0.9
Lurcher Shoal	+0.3	+0.3	8.8	1.0	0.5
Bay of Fundy	+0.8	+0.7	9.3	0.8	1.0
Georges Bank	+0.1	+0.1	7.9	0.8	0.4

Coastal Temperatures and Salinities

Coastal sea surface temperatures have been collected at St. Andrews (New Brunswick) and Halifax (Nova Scotia) since the 1920s (Fig. 9). In 2011, the SST anomalies were +0.9^{o}C (+1.6 SD) for St. Andrews, a decrease of 0.1^{o}C from 2010 and +0.6^{o}C (+0.8 SD) for Halifax, an increase of 0.2^{o}C from 2010.

Temperature and salinity measurements, 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. 9(C-E). In 2011, the annual temperature anomaly was +1.0^{o}C (+1.8 SD) and the salinity anomaly was -0.3 (-1.4 SD). These represent changes of +0.0^{o}C and -0.2 from the 2010 values. The density anomaly is largely accounted for by the salinity anomaly (63%) and secondarily by the temperature anomaly (37%).

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 (Fig. 2). Petrie et al. (1996) updated their report using these same areas and all available hydrographic data. We present time series of annual mean and filtered (5 year running means) temperature anomalies at selected depths for five areas (Fig. 9). The Cabot Strait temperatures represent a mix of Labrador Sea Water and Slope Water (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; the Lurcher Shoals observations define the ocean climate in SW Nova Scotia 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 are not available for each month in each area. For Cabot Strait, Misaine Bank, Emerald Basin, Lurcher Shoals and Georges Basin, 2011 annual anomalies are based on observations from only 5, 4, 4, 1 and 4 months.

In 2011, the annual anomalies were +0.6^{o}C (+1.6 SD) for Cabot Strait 200-300 m (the 2nd warmest year in 60 years), +0.8^{o}C (+1.2 SD) for Misaine Bank 100 m, +0.9^{o}C (+1.1 SD) for Emerald Basin 250 m, +1.3^{o}C (+1.7 SD) for Lurcher Shoals 50 m, and +0.8^{o}C (+1.5 SD) for Georges Basin 200 m (the 2nd highest anomaly with last year being the highest). These values correspond to changes of +0.3^{o}C, +0.4^{o}C, +0.3^{o}C, +1.2^{o}C and -0.1^{o}C, respectively over 2010 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-1060s, cooler deep water temperatures might have been expected in this region for 2011 (Petrie, 2007).

Temperatures during the Summer Groundfish Surveys

The broadest spatial CTD coverage of the Scotian Shelf is obtained during the annual July 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 200 m isobath along the shelf break at the Laurentian Channel, the outer Scotian Shelf, and the Northeast Channel into the Gulf of Maine towards the Bay of Fundy. A total of 257 CTD stations were taken during the 2011 survey and an additional 121 bottom temperature stations were obtained 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. 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 30 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 0, 50, 100 m and near bottom.

Bottom temperatures ranged from 4.1°C in NAFO area 4Vs to 7.7°C in 4X, illustrating the difference in the environmental conditions across the Shelf. The anomalies were positive for these NAFO areas in 2011: +0.7°C (+1.6 SD) in 4Vn; +0.8°C (+1.1 SD) in 4Vs; +0.2°C (+0.3 SD) in 4W; and +0.5°C (+0.6 SD) in 4X (Fig. 11 A-D). Compared to 2010, bottom temperatures increased in areas 4Vn, 4Vs and 4X by 0.5, 0.4 and 0.1°C; temperature decreased by 0.3°C in area 4W.

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. 11E). 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 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. 11E) could be affected. We expect 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. 11E). In 2011, the observed volume of 4800 km^3 was 0.6 SD less than the 1981-2010 mean value of 5500 km^3 and similar to that observed in the previous two years.

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. We examined the variability in stratification by calculating the density (sigma-t) difference between 0 and 50 m. The density differences were based on monthly mean density profiles calculated for each area in Fig. 2. 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 (Fig. 2, 12). 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 which featured generally below average stratification in contrast to the past 20 years which is characterized by above normal values. Stratification on the Scotian Shelf in 2011 weakened significantly compared to 2010; obtaining a value near that seen in 2002 and a record low since 1986. The change was mainly due to a decrease in sea surface temperature, although surface salinity was the lowest in a decade. Since 1950, there has been a slow 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. The density difference due to the decrease in surface salinity accounted for 48% of the change in stratification.

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 (-10.3 cm/century), Halifax (-14.7 cm/century) and North Sydney (-16.8 cm/century) have been obtained from NRCan's gridded GPS-based vertical velocities (Philip MacAulay, pers. comm., 2012; Craymer et al., 2011).

Relative sea level at Halifax (1920-2010) is plotted as monthly means and as a filtered series using a 5-year running-mean filter (Fig. 13). The linear trend of the monthly mean data has a positive slope of 32.8 cm/century, slightly lower than the value of 36.7 cm/century (1897-1980) given by Barnett (1984). In 2011, relative sea level at Halifax decreased from the 2010 level although sea level rise appears to have increased rapidly in 2009/2010. An interesting feature of the data is the long-term variation that has occurred since the 1920s. In Fig. 13 we show the differences of the annual sea level from the 1971-2011 long-term trend for Yarmouth, Halifax and North Sydney. .It is apparent that from the 1920s to the early 1970s, the trend was greater than the trend calculated using all of the data The residual sea level data for the common period 1971-2011 shows that the variability has a large spatial structure given the coherence between these sites. Several potential causes of this decadal scale variability have been examined; however, we still do not understand the cause of these changes.

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 was 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 below (blue) normal. In 2011, 20 of the 22 series shown had positive anomalies; 4 variables were within 0.5 SD of their normal values and were concentrated in the western end of the region. Of the 18 remaining series, all, except Misaine 0 m temperature (which was below normal) were more than 0.5 SD greater than normal. In 2011, the average (median) normalized anomaly was 0.9 (0.7), the sixth (third) highest in the 42 year series. The standard deviation of the normalized anomalies was 0.7. These statistics indicate that 2011 was an exceptional 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 "profiles" 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,s, 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 anomalies did not show a strong spatial distribution in 2011. The leading mode of a principal component analysis of the 18 series captured 43% of the variance with all loadings having the same sign. The loadings of 16 of the 18 variables were strong (0.19 to 0.30) with weak contributions from the Emerald Basin 250 m (0.04) and Misaine Bank 0 m (0.09) series.

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References

Barnett, T., 1984: The estimation of “global” sea level change: a problem of uniqueness. J. Geophys. Res. 89, 7980-7988.

Casey, K.S., T.B. Brandon, P. Cornillon and R. Evans, 2910: 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.

Craymer, M.R., J. Henton, M. Piraszewski, E. Lapelle, 2011: An updated GPS velocity field for Canada, EOS Transactions, AGU, 92(51), Fall Meeting Supplement, Abstract G21A-0793.

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. Chasse 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, (in press).

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.

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

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.

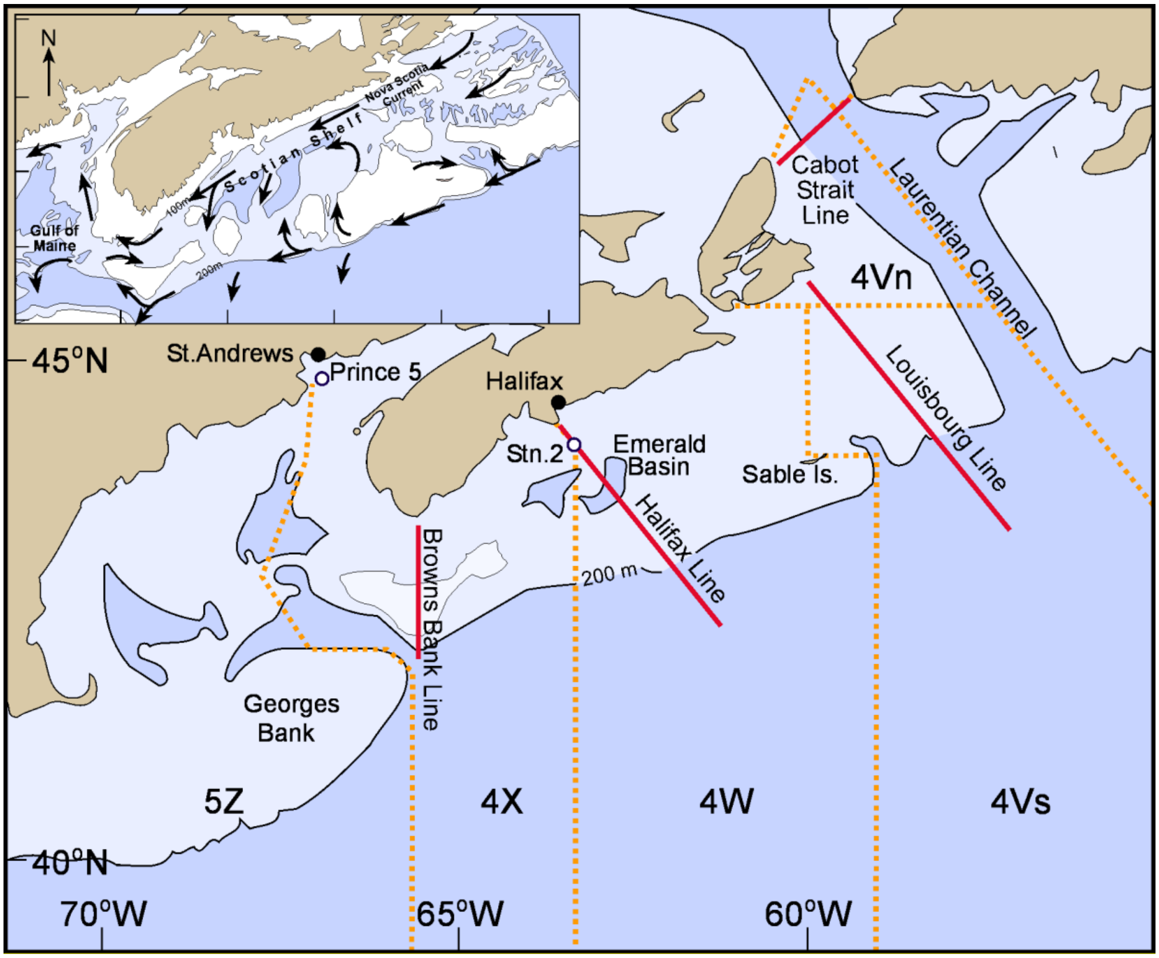
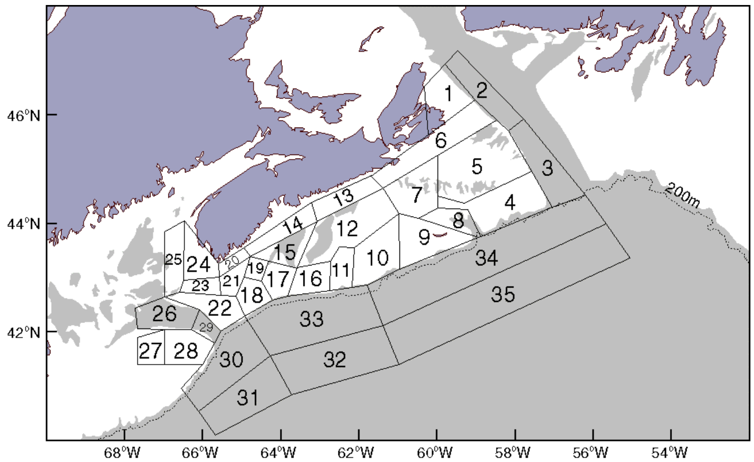


Fig. 1. The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the NAFO Subareas. Inset depicts major circulation features.



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

Fig. 2. Areas on the Scotian Shelf and eastern Gulf of Maine from Drinkwater and Trites (1987).

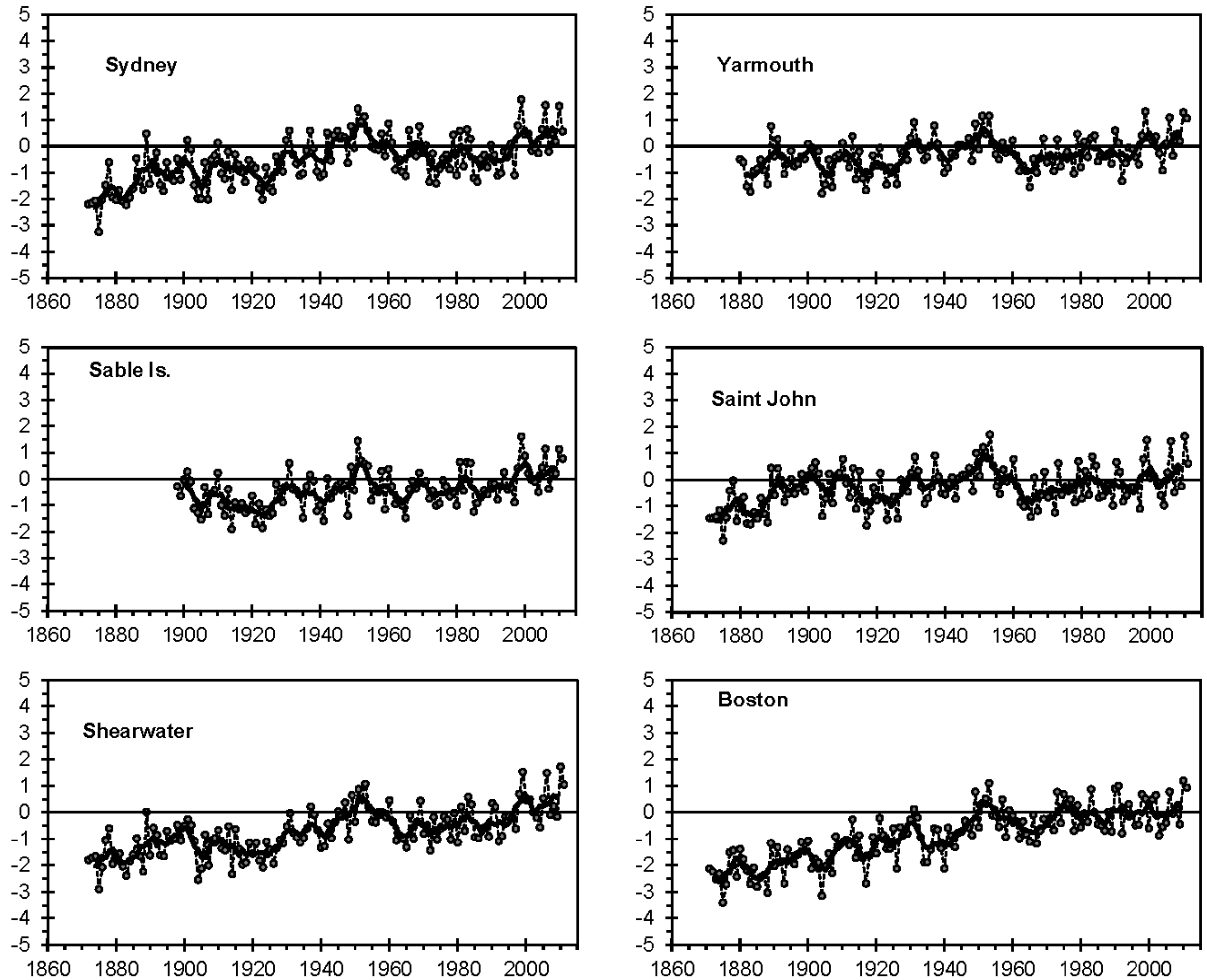


Fig. 3. Annual air temperature anomalies (dashed line) and 5-yr running means (solid line) at selected sites in Scotian Shelf-Gulf of Maine region.

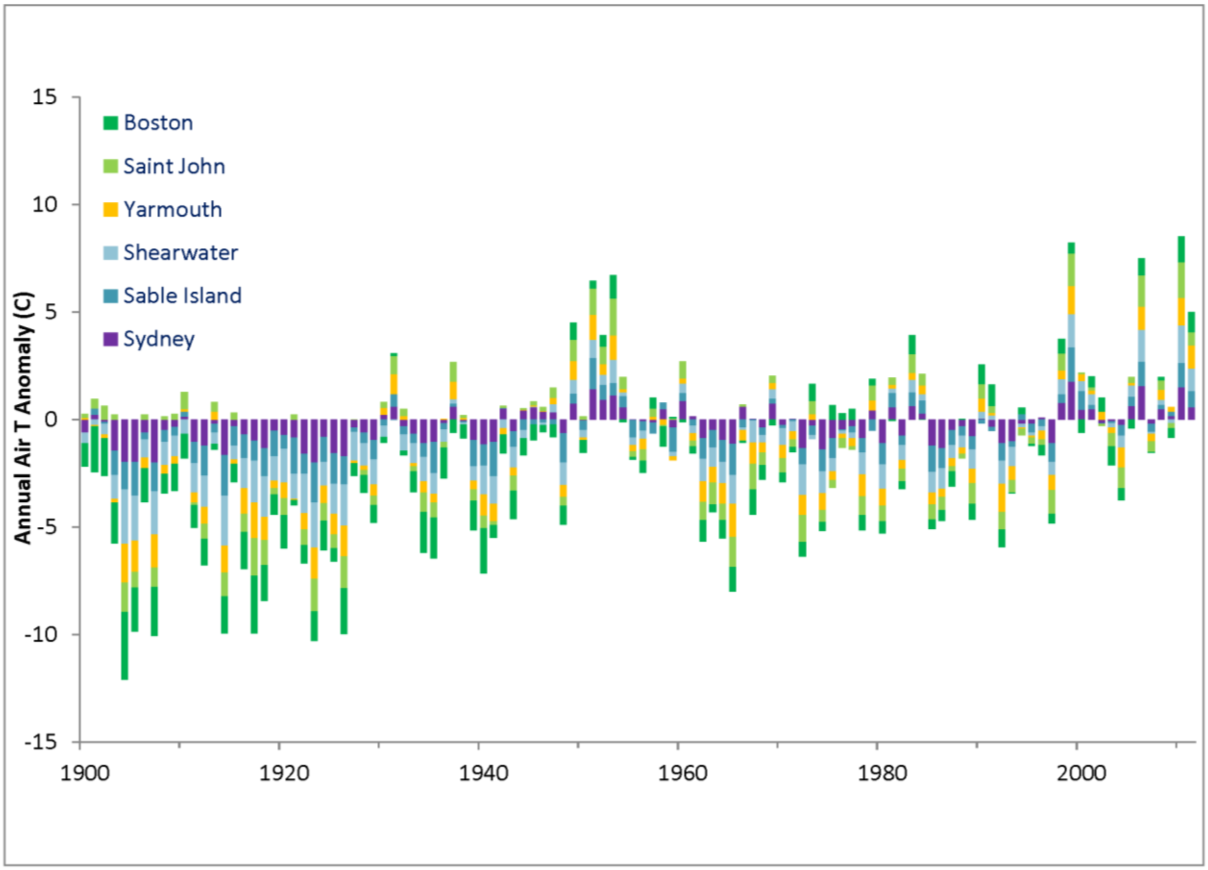


Fig. 4. The contributions of each of the annual temperature anomalies for 6 Scotian Shelf-Gulf of Maine sites are shown as a stacked bar chart.

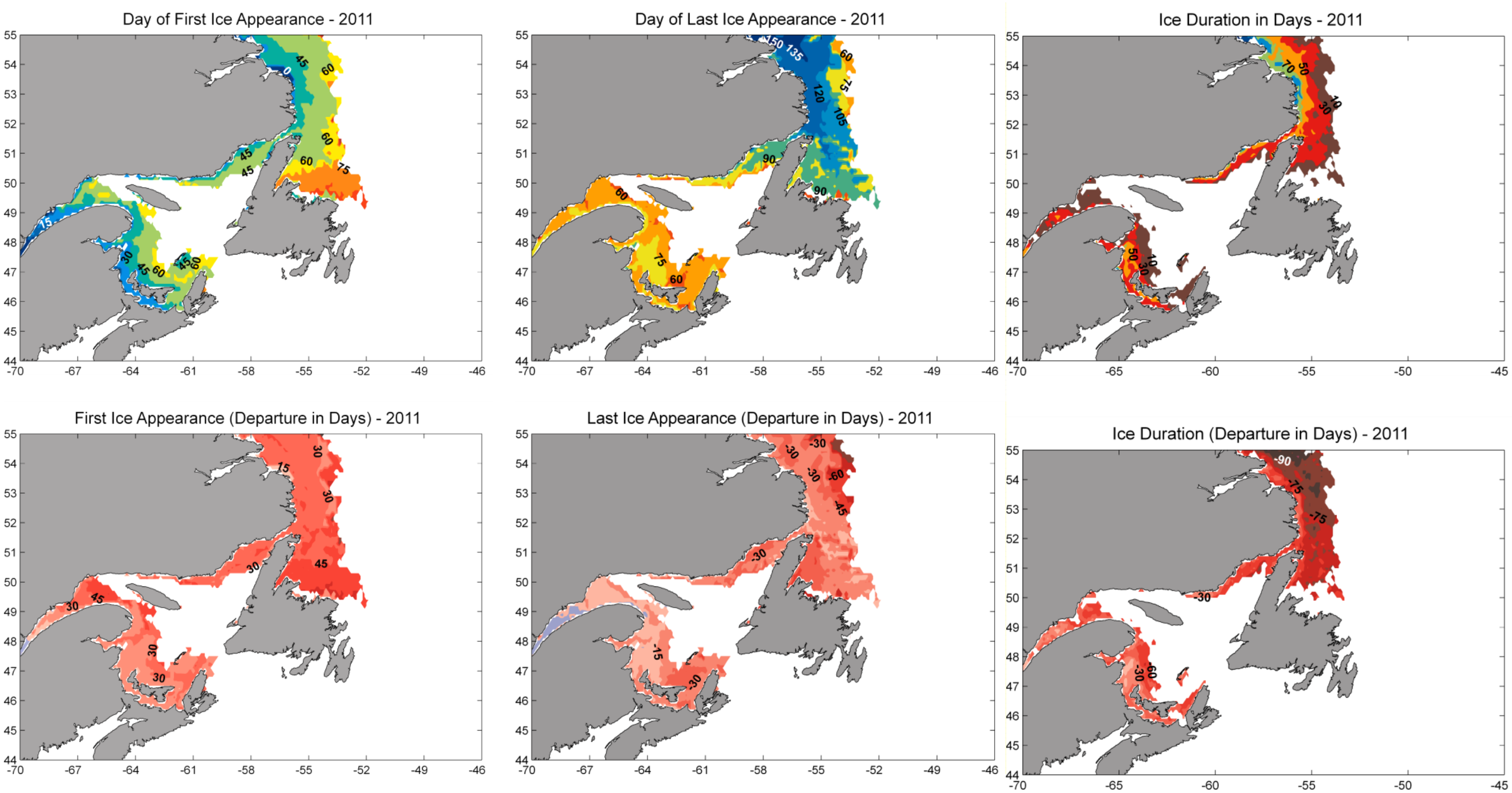


Fig. 5. The time when ice first appeared during 20101in days from the beginning of the year (left, top panel) and its anomaly from the 1981-2010 mean in days (left, bottom panel). Negative (positive) anomalies indicate earlier (later) than normal appearance. The time when ice was last seen in 2011 in 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 2011 and the anomalies from the 1981-2010 mean in days (right, bottom panel). Positive (negative) anomalies indicate durations longer (shorter) than the mean.

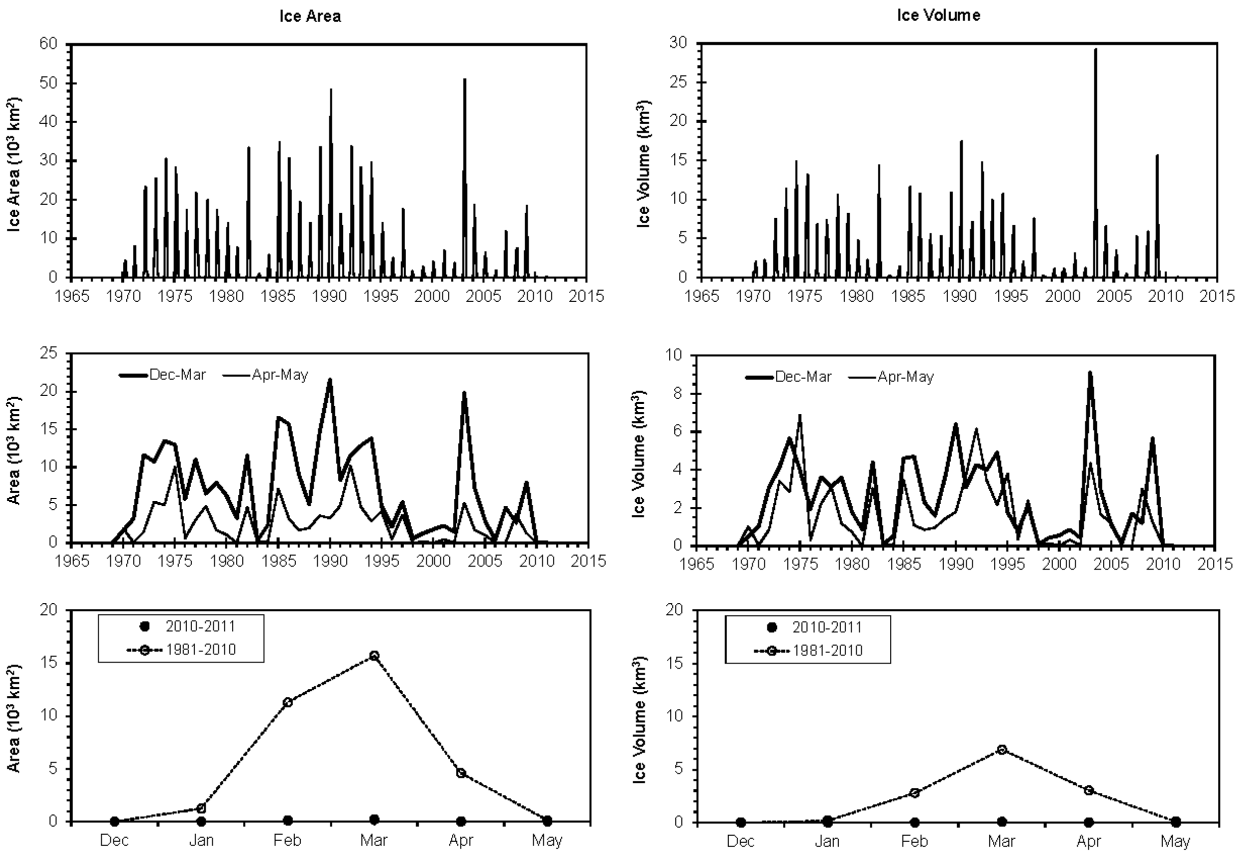


Fig. 6. Time series of the monthly mean ice area and volume for the Scotian Shelf (top panels), the average ice area during the usual periods of advancement (January-March) and retreat (April-May) (middle panels) and the comparison of the monthly areas and volumes to the 1981-2010 means (bottom panels)

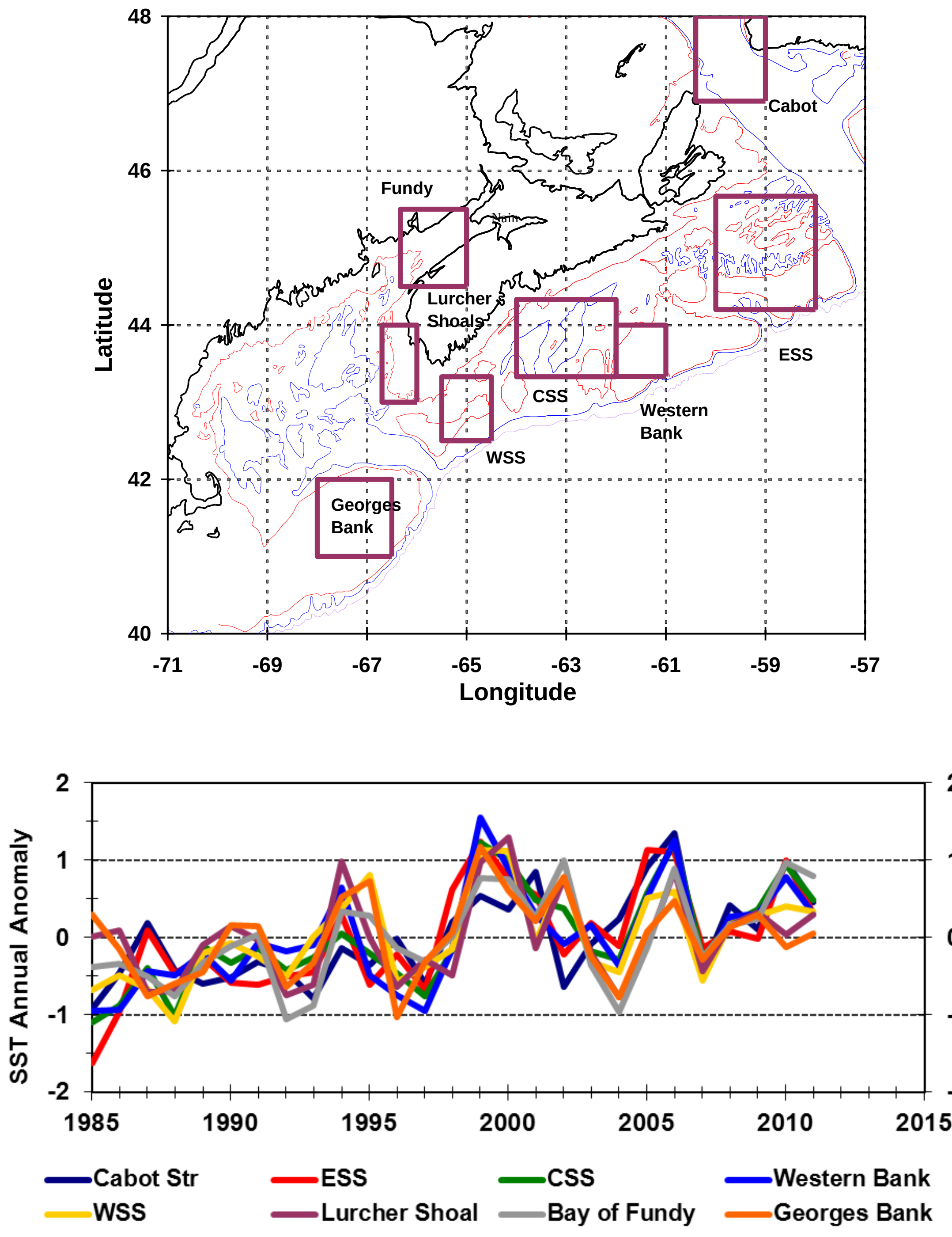


Fig. 7 Scotian Shelf-Gulf of Maine areas used for extraction of sea-surface temperature (upper panel). The annual sea surface temperature anomalies derived from satellite imagery compared to their long-term means (lower panel).

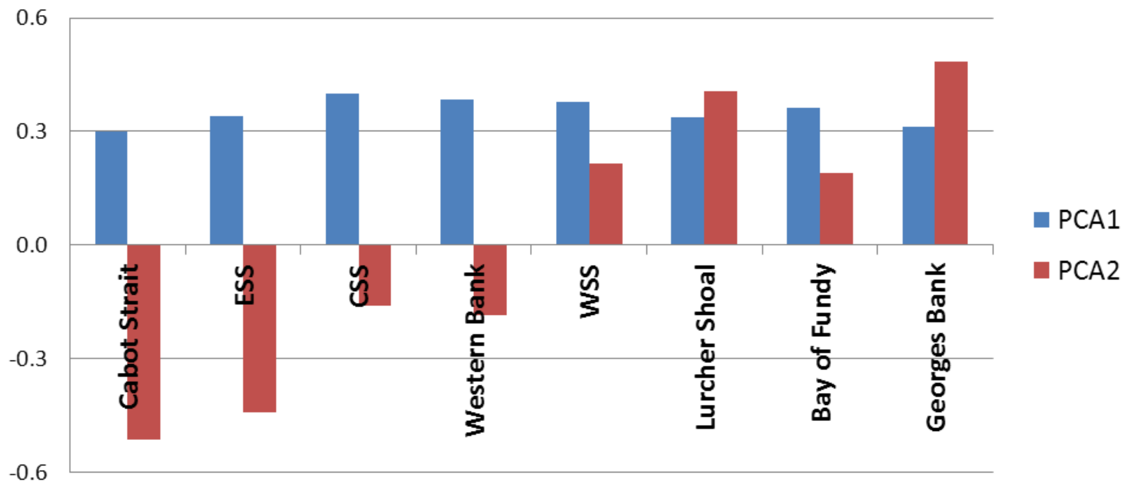


Fig. 8. PCA 1 (71% of variance) and PCA2 (18%) loadings from a principal components analysis of the annual mean temperature anomalies (Fig. 7, lower panel) for the eight Scotian Shelf and Gulf of Maine regions (Fig. 7, upper panel).

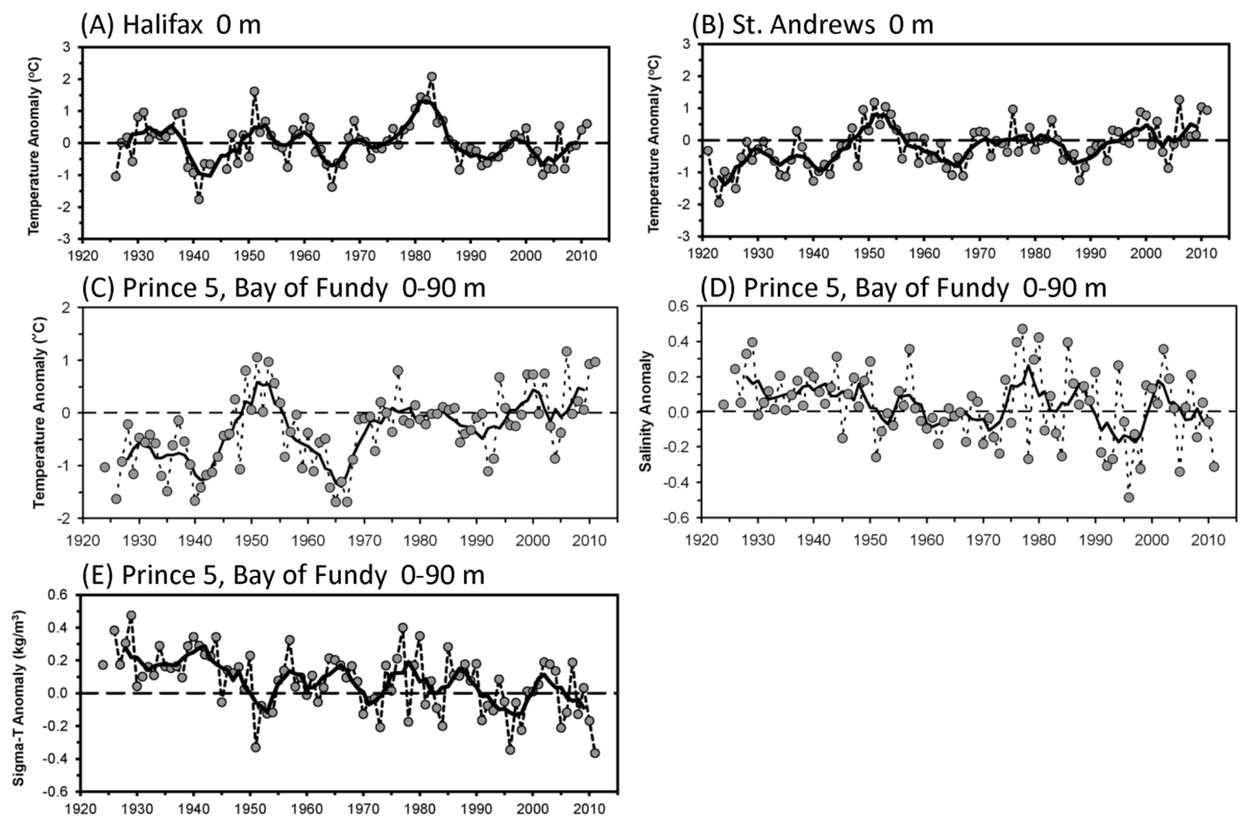


Fig. 9. The annual surface temperature anomalies (dotted line with circles) and their 5-year running means (heavy black line) for (A) Halifax Harbour and (B) St. Andrews; annual depth-averaged (0-90 m) (C) temperature, (D) salinity and density anomalies for the Prince 5 monitoring station at the mouth of the Bay of Fundy.

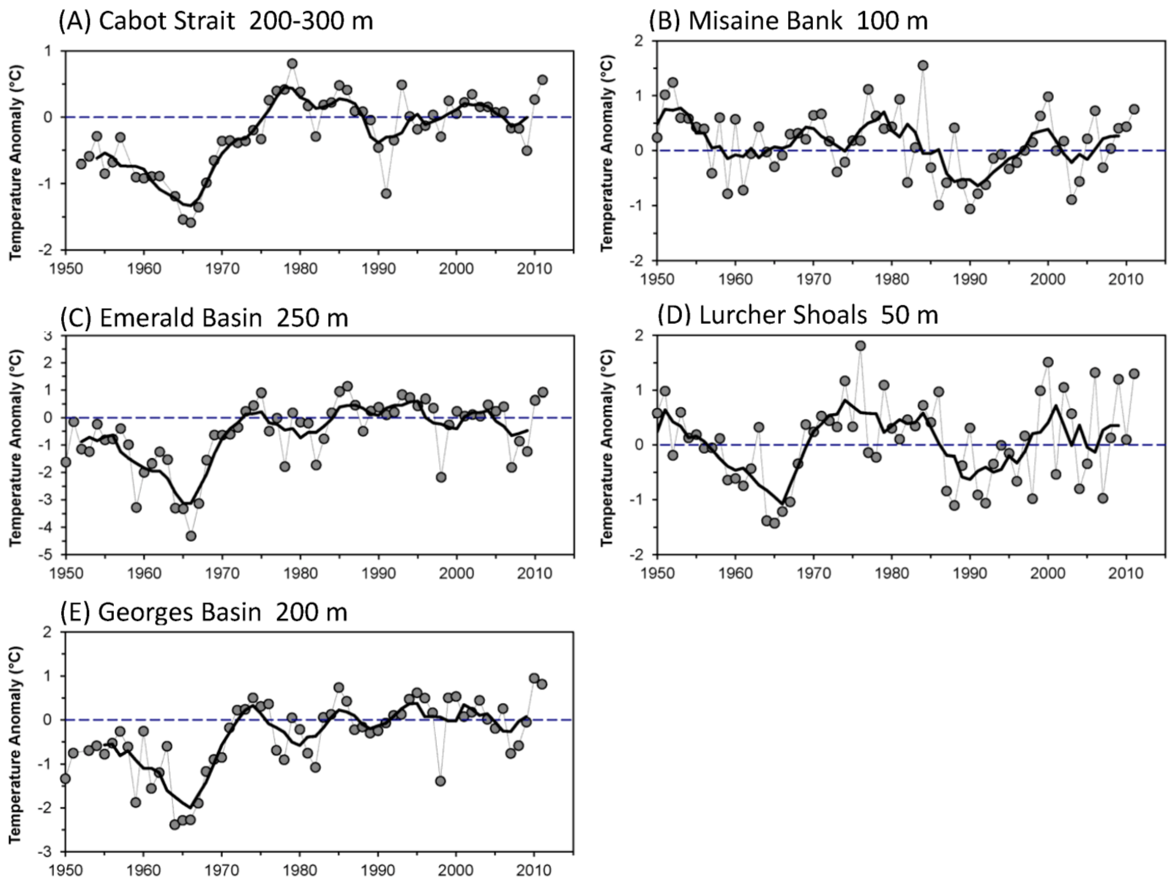


Fig. 10. The annual mean temperature anomaly time series (dotted line with circles) and the 5 year running mean filtered anomalies (heavy solid line) on the Scotian Shelf and in the Gulf of Maine at (A) Cabot Strait 200-300 m; (B) Misaine Bank 100 m; (C) Emerald Basin 250 m; (D) Lurcher Shoals 50 m;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

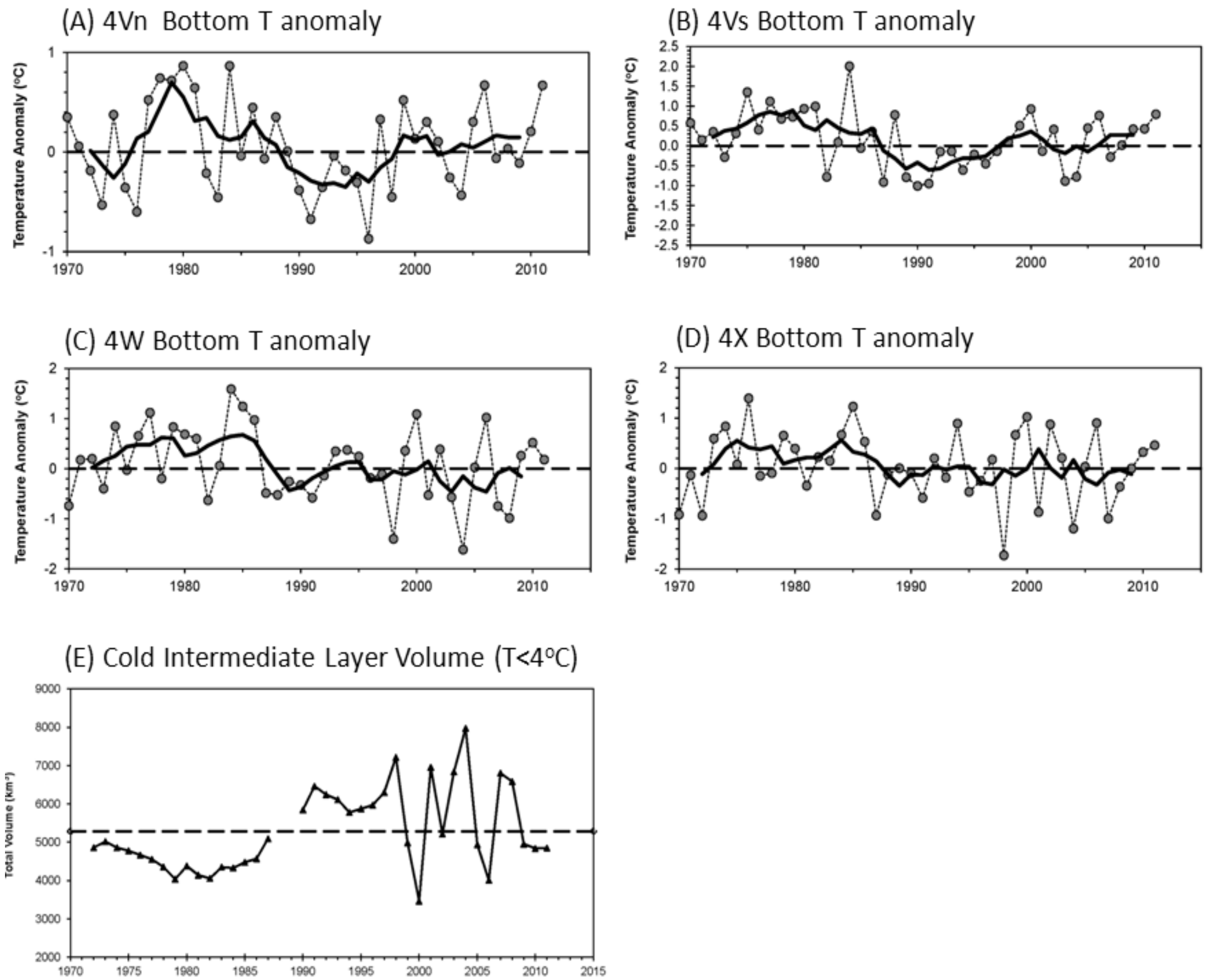


Fig. 11. Time series of July bottom temperature anomalies (dashed lines with circles) and 5 year running mean filtered series (heavy line) for areas (A) 4Vn, (B) 4Vs, (C) 4W and (D) 4X. (E) Time series of the Cold Intermediate Layer (CIL, defined as waters with T<4^{o}C) volume on the Scotian Shelf based on the July ecosystem survey. The dashed horizontal line is the long-term mean.

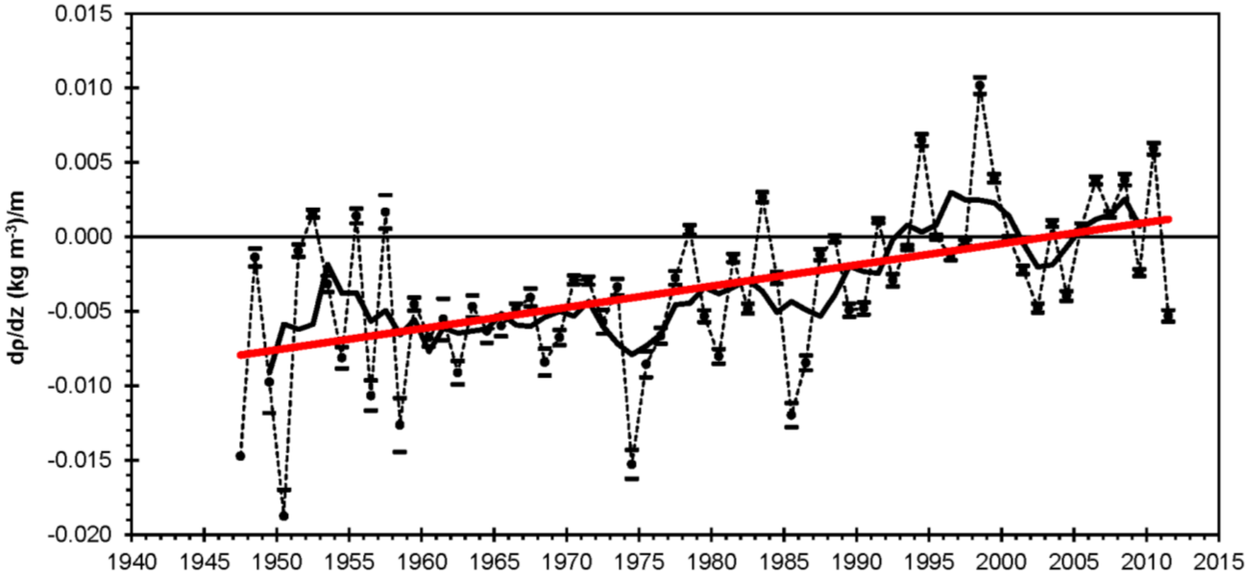
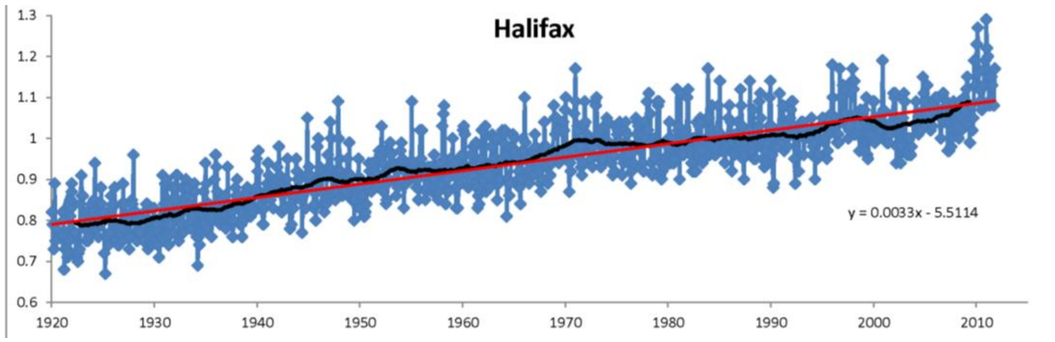


Fig. 12. The mean annual anomaly (dashed line with circles) and 5-yr running mean (heavy solid line) of the stratification index (0-50 m density gradient) averaged over the Scotian Shelf (areas 4-23 inclusive, see Fig. 2). Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a change in the 0-50 m density difference of 0.36 kg m^{-3} over 50 years.



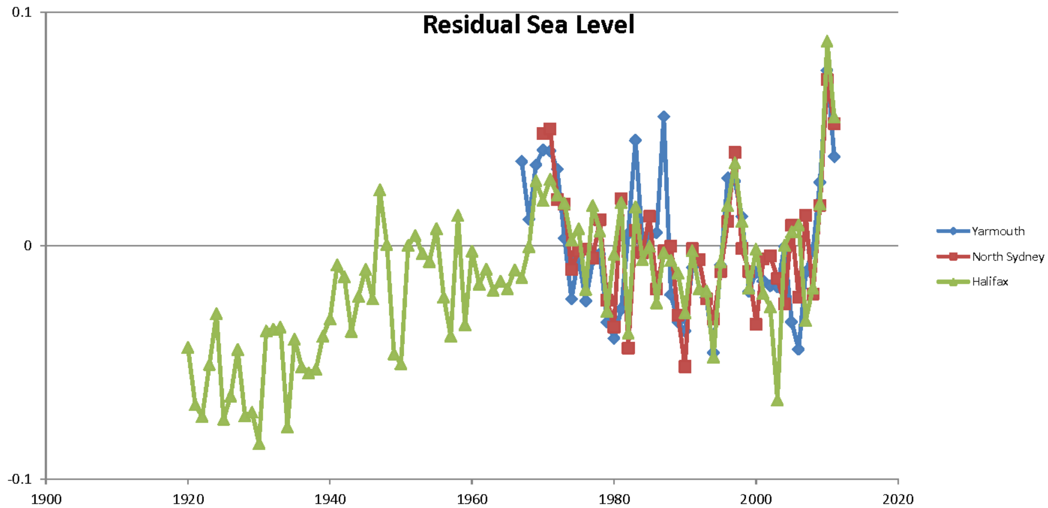


Fig. 13. The time series of the monthly means (blue) and a 5 year running mean (black) of the relative sea level elevations at Halifax, along with the linear trend (red) over 1920-2011 (upper panel). Residual relative sea level (monthly observed values – (1971-2011) linear trend, averaged to annual estimates) for Halifac (green), Yarmouth (blue) and North Sydney (red).

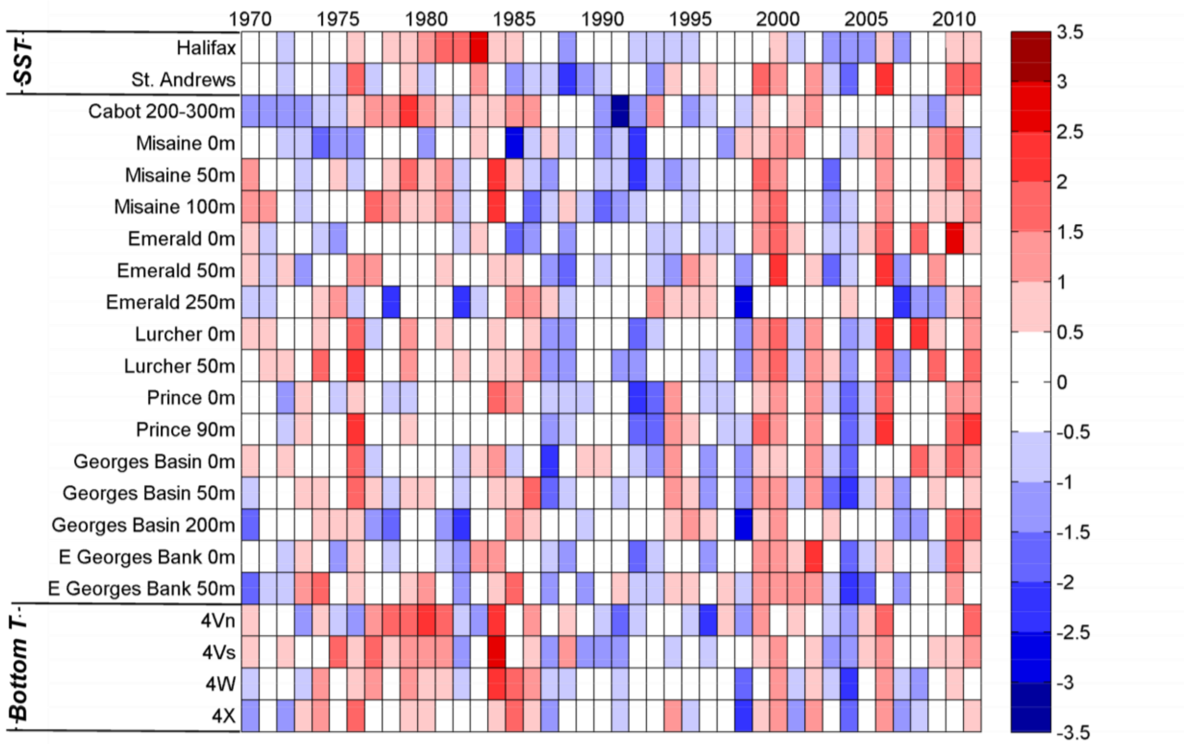


Fig. 14. Normalized annual anomalies of temperatures at the bottom and discrete depths for the Scotian Shelf-Gulf of Maine region. These normalized, annual anomalies are based on the 1981-2010 means, divided by the standard deviation. The scale represents the number of standard deviations an anomaly is from normal; blue indicates below normal, red above normal.

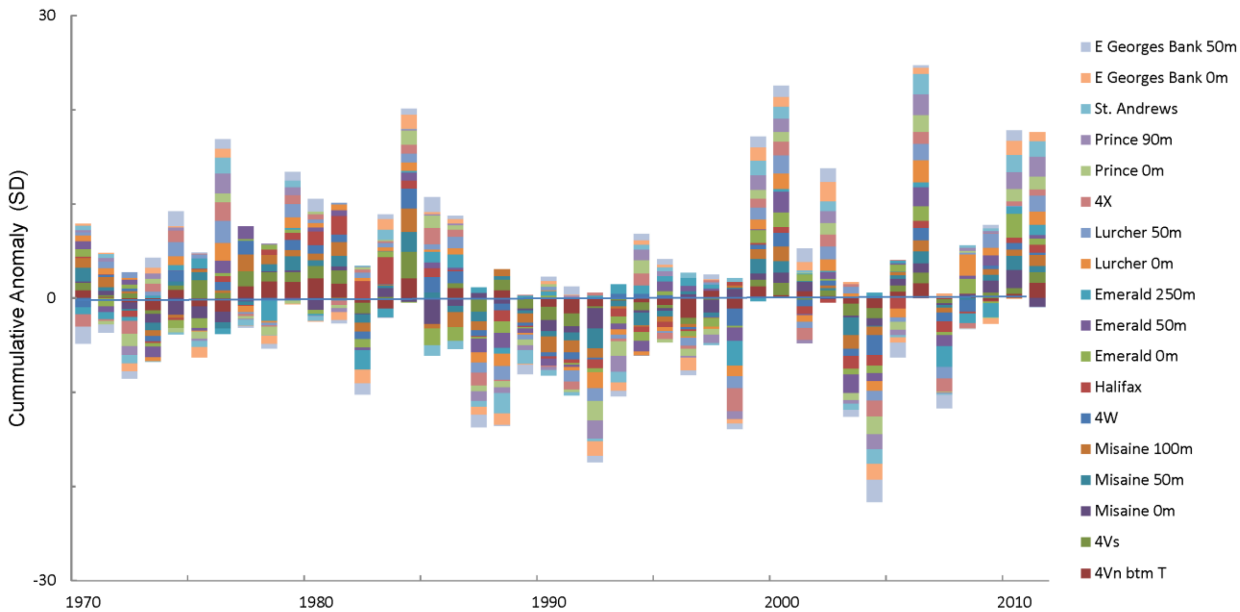


Fig. 15. The contributions of each of the normalized anomalies are shown as a stacked bar chart.