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Meteorological, Sea Ice and Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2009 and 2010

Conditions météorologiques, des conditions de la glace de mer et des océanographiques physiques sur le plateau néo-écossais et dans le golfe du Maine en 2009 et 2010

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ABSTRACT

In 2009, the North Atlantic Oscillation (NAO) index was positive (+1.5 mb, +0.2 SD) and slightly lower than its 2008 value (+4.3 mb, +0.5 SD); in 2010, the NAO index was at its lowest value in the entire record analyzed, -25.1 mb, 2.9 SD below normal. Mean annual air temperatures were from 0.5°C below to 0.2°C above normal in 2009; in 2010, annual air temperatures were 1.1 to 1.7°C above normal making this year the warmest since 1900. In 2009, the average January to April ice volume on the Scotian Shelf was the 7th highest in the 42 year series, whereas, the volume during 2010 was the second lowest and not significantly different from the lowest volume on record. Positive sea surface temperatures (SST) anomalies prevailed throughout the region during 2009 and 2010 with representative values of about +0.2 and 0.4°C (+0.4 and 0.6 SD). Long-term coastal monitoring sites at St. Andrews and Halifax recorded weak annual SST anomalies of 0.2°C and -0.3°C in 2009, and stronger positive anomalies, 1.0°C and 0.4°C in 2010. Across the region annual temperature anomalies were mixed in 2009: -0.5°C for Cabot Strait 200-300 m, +0.3°C for Misaine Bank 100 m, -1.3°C for Emerald Basin 250 m, +1.1°C for Lurcher Shoals 50 m, and -0.1°C for Georges Basin 200 m. Anomalies were generally positive throughout the region in 2010: +0.3°C for Cabot Strait 200-300 m, +0.4°C for Misaine Bank 100 m, +0.6°C for Emerald Basin 250 m, +0.1°C for Lurcher Shoals 50 m, and +1°C for Georges Basin 200 m. Bottom temperature anomalies in NAFO areas 4VWX ranged from -0.1°C to +0.2°C in 2009, +0.2°C to +0.6°C in 2010. Stratification was near normal in 2009 but exceptionally strong, the 3rd highest in the 64 year record, in 2010. A composite index consisting of ocean temperatures from surface to bottom across the region indicated that 2009 was the 13th warmest of 41 years, with a normalized anomaly of +0.4 relative to the 1981-2010 period; 2010 was an exceptional year, the 4th warmest in the 41 year record with a normalized anomaly of +2.4.

RÉSUMÉ

L'indice de l'oscillation nord-atlantique (NAO) était positif (+ 1,5 hPa, + 0,2 SD) en 2009 et de valeur légèrement moindre à ce qu'elle était en 2008 (+ 4,3 hPa, + 0,5 SD), tandis qu'en 2010, il se situait à la valeur la plus faible du jeu de données analysé (- 25,1 hPa, 2,9 SD sous la normale). Les températures moyennes annuelles de l'air allaient de 0,5 °C sous la normale à 0,2 °C au-dessus de la normale en 2009, tandis qu'en 2010, elles étaient de 1,1 à 1,7 °C au-dessus de la normale, ce qui signifie que 2010 était l'année la plus chaude depuis 1900. Le volume moyen de glace entre janvier et avril sur la plate-forme néo-écossaise en 2009 était le septième plus élevé de la série de données couvrant 42 ans, alors que le volume en 2010 était le deuxième moins élevé; ce dernier n'était pas significativement différent du volume le plus faible enregistré. Des anomalies de température positive de la surface de la mer (SST) ont prévalu dans toute la région en 2009 et 2010, avec des valeurs représentatives d'environ + 0,2 et 0,4 °C (+ 0,4 et 0,6 SD). Aux sites de surveillance côtière à long terme de St. Andrews et de Halifax, de faibles anomalies de SST annuelle de 0,2 °C et - 0,3 °C ont été enregistrées en 2009, et des anomalies de SST positive plus marquées de 1,0 °C et 0,4 °C en 2010. À l'échelle de la région, les anomalies annuelles de température étaient mixtes en 2009 : - 0,5 °C entre 200 et 300 m dans le détroit de Cabot; + 0,3 °C dans la strate de 100 m du banc de Misaine; - 1,3 °C dans la strate de 250 m du bassin Émeraude; + 1,1 °C dans la strate de 50 m du haut-fond Lurcher; et - 0,1 °C dans la strate de 200 m du bassin Georges. Les anomalies étaient généralement positives dans l'ensemble de la région en 2010 : + 0,3 °C entre 200 et 300 m dans le détroit de Cabot; + 0,4 °C dans la strate de 100 m du banc de Misaine; + 0,6°C dans la strate de 250 m du bassin Émeraude; + 0,1 °C dans la strate de 50 m du haut-fond Lurcher; et + 1 °C dans la strate de 200 m du bassin Georges. Les anomalies de température au fond dans les divisions 4VWX de l'OPANO allaient de - 0,1 °C à + 0,2 °C en 2009 et de + 0,2 °C à + 0,6 °C en 2010. La stratification se situait près de la normale en 2009, mais elle était exceptionnellement prononcée en 2010, s'avérant le troisième niveau le plus élevé de la série chronologique couvrant 64 ans. Un indice composite composé des températures de la mer de la surface au fond à l'échelle de la région révèle que 2009 était la treizième année la plus chaude en 41 ans, avec une anomalie normalisée de + 0,4 par rapport à la période allant de 1981 à 2010 et que 2010 était une année exceptionnelle, étant la quatrième année la plus chaude de cette même période, avec une anomalie normalisée de + 2,4.

INTRODUCTION

This document discusses air temperature trends, winds, ice cover, sea surface temperatures (SST) and physical oceanographic variability during 2009 and 2010 on the Scotian Shelf and the Gulf of Maine (Fig. 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. 2011, Colbourne et al. 2011). 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 standard deviations are calculated for the 30-year base period, 1981-2010, with the exception of variables associated with ice. The use of standardized anomalies and the same base period allow direct comparison of anomalies among sites and variables. Note that this year marks the change from the 1971-2000 (Petrie et al. 2009a,b) to the 1981-2010 reference period. Environmental overviews of 2009 conditions were not produced in 2010 although some results were presented by Petrie and Pettipas (2010); this report covers 2009 and 2010 and uses the updated reference period when possible for both years.

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 (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 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

Air Temperatures

Monthly surface air temperature anomalies relative to the 1968-1996 means for the North Atlantic Ocean are available from the US National Oceanic and Atmospheric Administration (NOAA 2010) interactive website at http://www.cdc.noaa.gov/cgi-bin/data/getpage.pl. The annual anomalies are within 0.5°C of normal values over the Scotian Shelf and in the Gulf of Maine in 2009 (Fig. 2, upper panel). In 2010, the same region featured anomalies ranging from within 1°C of the long-term mean to 1-2°C above normal (Fig. 2, lower panel).

Monthly air temperature anomalies for 2009 and 2010 relative to their 1981-2010 means at 6 sites in the Scotian Shelf-Gulf of Maine region are shown in Fig. 3. The anomalies are presented in 2 ways: the heights of the bars represent the anomalies in °C; the colours of the bars represent the number of standard deviations the anomalies differ from their long-term means. Data from the Canadian sites were from the Environment Canada website and from the *Monthly Climatic Data for the World* (NOAA 2010) for Boston. The observed and normalized annual anomalies for these stations are listed in Table 1. In 2009, annual air temperature anomalies were a mixture of positive and negative values; they ranged from -0.5 to +0.2°C in the region (Table 1). These values are in agreement with the broader spatial scale map (Fig. 2, upper panel) even though the reference period differed. In 2010, the annual anomalies were positive at all sites, ranging from +1.1 to +1.7°C, approximately 2 standard deviations above normal at all sites. These anomalies are smaller than the monthly variability for each year (Table 1).

Table 2 compares the long-term means and standard deviations at the six sites for the 30 year periods 1971-2000 and 1981-2010. The report this year marks the change from the earlier reference period to the new one. The three easternmost stations showed increases of the long-term mean by about 0.3°C; the temperature increases for the three westernmost stations were smaller. While variability of the annual temperatures increased at five of six sites, the changes were all less than 0.1°C.

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. 4). Linear trends from 1911 to present for Sydney, Sable Island, Shearwater, Yarmouth, Saint John and Boston correspond to changes of +1.0°C, +1.2°C, +1.5°C, +0.6°C, +0.5°C and +1.5°C per century, respectively.

Table 1. *Air temperature statistics 2009, 2010 (Standard Deviation (SD)).*

Site	Annual Anomaly 2009, 2010 (°C)		SD of Monthly Anomalies 2009, 2010 (°C)	1981-2010 Annual	
	Observed	Normalized		Mean (°C)	SD (°C)
Sydney	+0.2, +1.5	+0.2, +1.9	1.3, 1.4	5.87	0.81
Sable I.	+0.2, +1.1	+0.3, +1.7	0.9, 0.7	7.88	0.68
Shearwater (Halifax)	-0.2, +1.7	-0.2, +2.3	0.9, 0.9	6.99	0.74
Yarmouth	+0.2. +1.3	+0.3, +2.1	0.9, 0.7	7.16	0.62
Saint John	-0.2, +1.6	-0.9, +2.2	1.4, 1.3	5.19	0.74
Boston	-0.5, +1.2	-0.8, +2.0	1.5, 1.3	10.91	0.60

Table 2. *Comparison of long-term means and standard deviations for 1971-2000 and 1981-2010.*

	1971-2000 Annual Mean and Standard Deviation		1981-2010 Annual Mean and Standard Deviation		Difference (1981-2010) minus (1971-2000)
Site	Mean (°C)	SD (°C)	Mean (°C)	SD (°C)	Mean (SD)
Sydney	5.53	0.76	5.87	0.81	+0.34, +0.05
Sable I.	7.61	0.68	7.88	0.68	+0.27, 0
Shearwater (Halifax)	6.67	0.67	6.99	0.74	+0.32, +0.07
Yarmouth	6.95	0.57	7.16	0.62	+0.21, +0.05
Saint John	5.02	0.67	5.19	0.74	+0.17, +0.07
Boston	10.88	0.57	10.91	0.60	+0.03, +0.03

The air temperature anomalies for the 6 Scotian Shelf-Gulf of Maine sites, summarized in Fig. 5, illustrate two points: for most years the anomalies have the same sign; i.e. the stacked bars and the scatter plot coincide. Since 1900, when all sites were operating, 89 of the 111 years had 5 or more stations with the annual anomalies having the same signs; for 61 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 between sites. Previous analyses yielded an e-folding scale of 1800 km (Petrie et al. 2009a). 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 2009 was -0.3°C, an average of ~0°C at each site, ranking 31st warmest over 111 years; in 2010, the sum was +8.5°C, an average of +1.4°C at each site and the highest for the 111 year record.

North Atlantic Oscillation (NAO) Index

The 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. The NAO anomalies were calculated by subtracting the 1981-2010 mean. The changes from the 1971-2000 to the 1981-2010 averaging periods were small: the average decreased from 20.8 to 20.4, the standard deviation increased from 8.6 to 8.8.

A high NAO index corresponds to a deepening of the Icelandic Low and a strengthening of 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 2009, the winter NAO index was positive and within 0.5 SD of the long-term normal value (+1.5 mb, 0.2 SD above normal): in 2010, the winter NAO index was at it lowest value in the record shown, -25.1 mb, 2.9 SD below normal (Fig. 6, upper panel). The lower panels of Fig. 6 show the unusual sea level pressure conditions during the winter of 2010 compared to the 1981-2010 mean. In 2010, the low pressure was situated to the east of St. John’s and resulted in a tendency for weak winter winds from the northeast (Greenland) over the Labrador Sea in contrast to the typical condition of winds from the northwest (i.e. off the North American continent). The warmer air temperatures experienced in the Maritimes region are likely related to this NAO sea level pressure distribution.

Winds

The initiation of the spring phytoplankton bloom is thought to occur when incoming solar radiation provides enough heat in the upper layer of the ocean to create a vertical density gradient. Phytoplankton confined to this shallow layer receive sufficient light to begin photosynthesis and consequently increase the chlorophyll concentration. However, on the Scotian Shelf the spring bloom is frequently observed to occur without the development of this stratified layer (G. Harrison, pers. comm.). A possible explanation for the initiation of the bloom despite the absence of stratification is the lack of turbulent mixing in the upper layer, caused by weak wind speeds in the region. Several studies have indicated the importance of wind in initiating and ending blooms on the Scotian Shelf (Greenan et al. 2002, 2004, 2008). In 2009, in situ chlorophyll at Halifax fixed station 2 showed that the spring bloom occurred between March 17th and 27th, with very high concentrations on the 27th (Fig. 7). The maximum density difference, 0.04 kg m^{-3} on the 27th was between 10 and 15 m and is comparable to the long-term mean for this site. This very weak stratification is unlikely sufficient to allow the development of the bloom. In contrast, the conditions at the onset of the 2010 bloom, which occurred between February 2nd and March 9th (Fig. 7), featured strong stratification between 15 and 25 m with a density difference of 0.44 kg m^{-3}, considerably greater than the long term mean of 0.05 kg m^{-3}. To address the potential connection between wind and the onset of the bloom we examined the daily mean Sable Island wind speed (2009-10) and the 30 year average wind speed averages (Fig. 7). In 2009, the data indicate that the bloom occurred following a period of high wind speed, thus reduced turbulence at shallow depths were unlikely to have prevailed. Similarly, the 2010 bloom occurred after a period of enhanced winds. It is doubtful that either the 2009 or the 2010 blooms were initiated because of quiescent conditions at shallow depths because of reduced wind forcing.

SEA ICE OBSERVATIONS

The spatial distribution and concentrations of sea ice are available from the daily ice charts published by the Canadian Ice Service (CIS) of Environment Canada in Ottawa, Ontario. The current year's ice statistics with the long-term median, maximum, and minimum positions of the ice edge (concentrations above 10%) based on the *1971-2000* data (Canadian Ice Service 2002) are compared. Also included is an analysis of the time of onset, duration, and last presence of sea ice based upon the sea ice database maintained at the Bedford Institute of Oceanography (Dartmouth, Nova Scotia) for the Newfoundland region (Peterson and Prinsenberg 1990) and for the Gulf of St. Lawrence and the Scotian Shelf (Drinkwater et al. 1999). In the current analysis, ice concentrations of ≥1 tenth were sampled at 0.1 degree latitude by 0.1 degree longitude intervals from the CIS weekly composite ice charts for the period 1969-2010. A climatology (1971-2000) of first and last appearance and duration was generated for each grid point and was subtracted from the values determined for 2009 and 2010 to generate anomaly maps. Grid points for which the climatology had less than 5 years with data or where the duration was <10 days were excluded from further analysis. Ice areas, extents, and volumes were computed using the CIS weekly composite GIS formatted charts available from the CIS website: http://ice-glaces.ec.gc.ca/. 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 provides an index that 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 3 regions 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 Canadian Ice Service does not generally compute ice volume estimates for Canadian waters.

They give 2 main reasons for this (S. McCourt, pers. comm..; steve.mccourt@ec.gc.ca): “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 mid- to late January in 2009 (Fig. 8); over much of the region, the day of first appearance of ice was up to 15 days later than normal. In general, the day of last appearance of ice was later than usual off Labrador and Newfoundland and normal in the Gulf of St. Lawrence. Overall, ice duration was shorter than normal over most of the region with the exceptions of the southeastern Gulf and off northern Newfoundland.

In 2010, where ice appeared (western part of the Gulf of St. Lawrence and northern Newfoundland and Labrador), it was 30 days later than normal (Fig. 9). In general, the day of last appearance of ice, where it appeared, was earlier than usual by approximately 30 days. The duration of ice in the Gulf of St. Lawrence was 30 days less than normal, while the duration of ice off northern Newfoundland and Labrador was up to more than 90 days less than normal.

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 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 2009, ice first appeared on the Scotian Shelf in mid-February, about normal (Fig. 8). Ice lasted until mid- to late March, again about normal. In 2010, there was nearly no ice on the Scotian Shelf from December 2009 until the end of the season in May 2010 (Fig. 9).

The ice areas and volumes are shown in Fig. 10 and compiled in Tables 3 and 4. TheJanuary to April periods, featured below normal coverage overall and above volumes for February and March in 2009. Overall, the January to April 2009 coverage was -0.2 SD (19th highest in the 42 year record) whereas the ice volume was +1.1 SD (7th highest in the 42 year record). Consider the amount of cooling that the melting of the ice would cause on the Scotian Shelf. If 20 km^3 of Gulf ice were melted (a rough estimate and probably a lower bound, see Table 4), then this would lower a 16 m thick layer of water on the open Shelf by about 1^{o}C. The January to April 2010 ice coverage and volume was the second lowest in the 42 year long record. Only 1969 had lesser coverage and volume; the difference between these 2 years is within the uncertainty of the observations. Note that the ice statistics are based on the period 1971-2000 because the update to the new base period of 1981-2010 is a lengthy, complex task; in the coming year the base period will be revised to 1981-2010.

Table 3. *Ice area statistics, Scotian Shelf.*

Month	2009 Ice Year (km^2)	2010 Ice Year (km^2)	1971-2000 Mean (km^2)	2009 Anomaly (km^2)	2009 Normalized Anomaly	2010 Anomaly (km^2)	2010 Normalized Anomaly
Jan	1100	90	1700	-600	-0.2	-1600	-0.6
Feb	12400	60	13900	-1500	-0.2	-13800	-1.4
Mar	18000	10	18000	0	0.0	-18000	-1.5
Apr	2400	2	5800	-3600	-0.7	-5800	-1.1

Table 4. *Ice volume statistics, Scotian Shelf.*

Month	2009 Ice Year (km^3)	2010 Ice Year (km^3)	1971-2000 Mean (km^3)	2009 Anomaly (km^3)	2009 Normalized Anomaly	2010 Anomaly (km^3)	2010 Normalized Anomaly
Jan	0.2	<0.01	0.25	-0.1	-0.2	-0.25	-0.6
Feb	6.9	<0.01	3.5	+3.4	+1.3	-3.4	-1.3
Mar	15.7	<0.01	7.4	+1.7	+1.7	-7.3	-1.5
Apr	2.5	<0.01	3.6	-1.1	-0.3	-3.6	-1.0

REMOTELY-SENSED SEA SURFACE TEMPERATURE

A 9 km resolution Pathfinder sea surface temperature database is maintained at BIO. The Pathfinder dataset runs from January 1985 to December 2009; to provide data for 2010, 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 1985-2009 averages.

Annual anomalies for 8 subareas in the Scotian Shelf-Gulf of Maine region were determined from the averages of monthly anomalies (Fig. 11, Table 5). Periods of 1 year and longer accounted on average for 38% of the overall variance determined from the monthly anomalies. The annual anomalies during 2009 ranged from 0.0°C (0.0 SD) over the eastern Scotian Shelf to +0.4°C over the central Scotian Shelf (+0.7 SD) and Western Bank (+0.5 SD). All eight areas (the eastern Scotian Shelf anomaly was slightly above 0°C) had positive anomalies; six areas had normalized anomalies greater than +0.5 SD. The annual anomalies during 2010 ranged from -0.4°C (-0.7 SD) over Georges Bank to +0.9°C (+1.3 SD) on the eastern Scotian Shelf and +0.9°C (+1.5 SD) in Cabot Strait. Six of the eight areas had positive anomalies; all six were greater than or equal to +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 (Georges Bank) to a highest value of 1.4°C (ESS).

The overall coherent variability of the annual temperature anomalies in the seven regions suggested that 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 19% 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. 12).

Table 5. *2009 and 2010 SST anomalies and long-term SST statistics.*

Site	2009 SST Anomaly (°C)	2010 SST Anomaly (°C)	2009 SST Anomaly Normalized	2010 SST Anomaly Normalized	1985-2010 Mean Annual SST (°C)	1985-2010 SST Std. Dev. (°C)	ΔT (°C) 1985-2010
Cabot Strait.	+0.2	+0.9	+0.3	+1.5	6.16	0.59	1.2
Eastern Scotian Shelf (ESS)	+0.0	+0.9	+0.0	+1.3	7.37	0.70	1.4
Central Scotian Shelf (CSS)	+0.4	+0.7	+0.7	+1.1	8.86	0.63	1.3
Western Bank	+0.4	+0.6	+0.5	+0.6	9.30	0.65	1.1
Western Scotian Shelf (WSS)	+0.3	+0.5	+0.5	+0.8	8.60	0.59	0.9
Lurcher Shoal	+0.3	-0.1	+0.6	-0.2	7.77	0.59	0.4
Bay of Fundy	+0.3	+0.4	+0.6	+0.8	7.88	0.55	0.8
Georges Bank	+0.3	-0.4	-0.5	-0.7	10.56	0.54	0.3

COASTAL TEMPERATURES AND SALINITIES

Coastal sea surface temperatures (SST) have been collected at St. Andrews (New Brunswick) and Halifax (Nova Scotia) since the 1920s (Fig. 13). In 2009, the SST anomalies were +0.2°C (+0.3 SD) for St. Andrews and -0.1°C (-0.1 SD) for Halifax, increases of less than 0.1°C from 2008 values. In 2010, the SST anomalies were +1.0°C (+1.8 SD) for St. Andrews and +0.4°C (+0.5 SD) for Halifax, increases of 0.9°C and 0.5°C from 2009 values.

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 and salinity time series are shown in Fig. 13. In 2009, the annual temperature anomaly was +0.1°C (+0.2 SD) and the salinity anomaly was +0.1 (+0.2 SD). These represent changes of +0.2°C and +0.2 from the 2008 values. In 2010, the annual temperature anomaly was +1.0°C (+2.0 SD) and the salinity anomaly was -0.1 (-0.3 SD). These represent changes of +0.9°C and -0.1 from the 2009 values. The density anomaly is largely accounted for by the salinity anomaly (73%) and secondarily by the temperature anomaly (27%).

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 (Fig. 14). 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. 15). The Cabot Strait (see Fig.1) temperatures represent the slope waters entering the Gulf of St. Lawrence along Laurentian Channel; the Misaine Bank (region 5, Fig. 15) series characterizes the 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; the Lurcher Shoals (region 24) 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 (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 are not available for all months in each area. For Cabot Strait, Misaine Bank, Emerald Basin, Lurcher Shoals and Georges Basin, 2009 (2010) annual anomalies are based on observations from 6 (4), 7 (3), 6 (2), 3 (2) and 6 (4) months. The apparent decrease of sampling from 2009 to 2010 is largely due to a delay in the updating of the hydrographic database.

In 2009, the annual anomalies were -0.5°C (-1.3 SD) for Cabot Strait 200-300 m, +0.3°C (+0.4 SD) for Misaine Bank 100 m, -1.3°C (-1.6 SD) for Emerald Basin 250 m, +1.1°C (+1.4 SD) for Lurcher Shoals 50 m, and -0.1°C (-0.1 SD) for Georges Basin 200 m. These values correspond to changes of -0.3°C, +0.5°C, -0.4°C, +1.0°C and +0.5°C, respectively over 2008 values. In 2010, the annual anomalies were +0.3°C (+0.8 SD) for Cabot Strait 200-300 m, +0.4°C (+0.7 SD) for Misaine Bank 100 m, +0.6°C (+0.8 SD) for Emerald Basin 250 m, +0.1°C (+0.1 SD) for Lurcher Shoals 50 m, and +1.0°C (+1.8 SD; the highest anomaly in the 61 year record) for Georges Basin 200 m. These values correspond to changes of +0.8°C, +0.0°C, +1.9°C, -1.1°C and +1.8°C, respectively over 2009 values.

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 the 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 203 (195) CTD stations were taken during the 2009 (2010) survey and an additional 174 (171) 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 (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 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. Near bottom temperature anomalies for 2009 and 2010 shown considerable spatial variability in the anomaly patterns (Fig. 16).

Bottom temperatures ranged from 3.7°C (3.7°C) in area 4Vs to 7.2°C (7.6°C) in 4X during 2009 (2010), illustrating the substantial difference in the environmental conditions across the Shelf. The anomalies were small in 2009: -0.1°C (-0.3 SD) in 4Vn; +0.2°C (+0.3 SD) in 4Vs; +0.1°C (+0.1 SD) in 4W; and -0.1°C (-0.2 SD) in 4X (Fig. 17 A-D). Compared to 2008, bottom temperatures in areas 4Vn decreased by 0.2°C and increased in areas 4Vs, 4W and 4X by 0.4, 1.3 and 0.4°C. The anomalies were positive for these NAFO areas in 2010: +0.2°C (+0.5 SD) in 4Vn; +0.4°C (+0.6 SD) in 4Vs; +0.6°C (+0.7 SD) in 4W; and +0.3°C (+0.5 SD) in 4X (Fig. 17 A-D). Compared to 2009, bottom temperatures increased in areas 4Vn, 4W and 4X by 0.3, 0.3 and 0.3°C; temperature remained the same in area 4Vs.

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. 17E). 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 1972-2000 data in Fig. 17E) 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 since 1998 (Fig. 17E). In 2009 (2010), the observed volume of 5000 (4800) km^3 was 0.1 SD (0.2 SD) less than the long-term mean value of 5500 km^3 and significantly down from 2008.

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 speciation. 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. 14. 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 standard deviations, 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. 14, 18). 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 (Fig. 18). Stratification on the Scotian Shelf in 2010 strengthened compared to 2009 which was near normal; overall 2010 ranked as the third most stratified in the 64 year record.

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. Tushingham and Peltier (1991) estimate a PGR component of the sea level trend of 23 cm/century at Halifax.

Relative sea level at Halifax (1920-2010) is plotted as monthly means and as a filtered series using a 12-month running-mean filter (Fig. 19A). The linear trend of the monthly mean data has a positive slope of 32.6 (±0.7) cm/century, lower than the value of 36.7 cm/century (1897-1980) given by Barnett (1984). In 2010, relative sea level at Halifax increased by 6.9 cm above the 2009 level and 10.7 cm above the 2008 level. However, the interesting feature of the data is the long-term variation that has occurred since the 1920s. In Fig. 19B we show the differences of the annual sea level from the long-term trend. It is apparent that from the 1920s to the early 1970s, the trend was greater than the trend calculated using all of the data. In fact, the trend from 1920-72 was 40.4 (±1.4) cm/century; for the period 1972-2010, the value was 26.0 (±4.6) cm/century, i.e. close to the PGR value predicted by the Tushingham-Peltier model. Several potential causes of this decadal scale variability have been examined; we still do not understand the cause of these changes.

SUMMARY

In 2009, the NAO index was slightly positive (+1.5 mb, +0.2 SD) while, in 2010, the NAO index was at its lowest value (-25.1 mb, -2.5 SD) since records were started in 1895. Mean annual air temperatures for 2010 were 1.1 to 1.7°C above normal across the whole region. The January to April 2009 ice coverage for the Scotian Shelf was average; whereas, the ice volume was the 7th highest in 42 years. In 2010, the ice coverage and volume was the 2nd lowest in the 42 year record. The analysis of satellite data indicates that positive SST anomalies prevailed throughout the Scotian Shelf and Gulf of Maine region in 2009 and 2010 with a representative value of approximately +0.3°C (+0.1 SD) in 2009 and +0.4°C (+0.5 SD) in 2010. Only Georges Bank in 2010 had a negative anomaly.

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 was warmer than normal (Fig. 20). 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. It is apparent that 2010 was an exceptional year based on these series. In 2010, 20 of the 22 series shown had positive anomalies; 6 variables were within 0.5 SD of their normal values and were concentrated in the western end of the region. Of the 16 remaining series, all were more than 0.5 SD greater than normal. In 2010, the average (median) normalized anomaly was 1.0 (0.8), the fourth (eighth) highest in the 41 year series. The standard deviation of the normalized anomalies was 0.8, the 24th highest in the series. These statistics indicate that 2010 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 combination bar and line-scatter plot in Fig. 21. This plot represents 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 sum of the normalized anomalies (difference between the positive and negative stacks) is shown as a black line connecting grey circles. This is a measure of whether the year tended to be colder or warmer than normal and can serve as an overall climate index.

The cold periods of 1987-1993 and 2003-2004 and the warm period of 1999-2000 are apparent. Systematic differences from the overall tendency within a given year are also evident. The overall index in 2010 averaged +1.0 (±0.8) SD with 13 of the 18 variables more than 0.5 SD above normal; compared to the other 41 years, 2010 ranks as the 4th warmest. The anomalies did not show a strong spatial distribution in 2010. In contrast, the 2009 index was slightly above normal, making it the 13th warmest of 41 years. The leading mode of a principal component analysis of the 18 series captured 40% of the variance with all loadings having the same sign. The loadings of 16 of the 18 variables were strong (0.18 to 0.30) with weak contributions from the Emerald Basin 250 m (0.02) and Misaine Bank 0 m (0.1) series. The temporal variability of the leading mode was essentially the same (r^2 = 0.99) as shown by the sum of the anomalies (Fig. 21).

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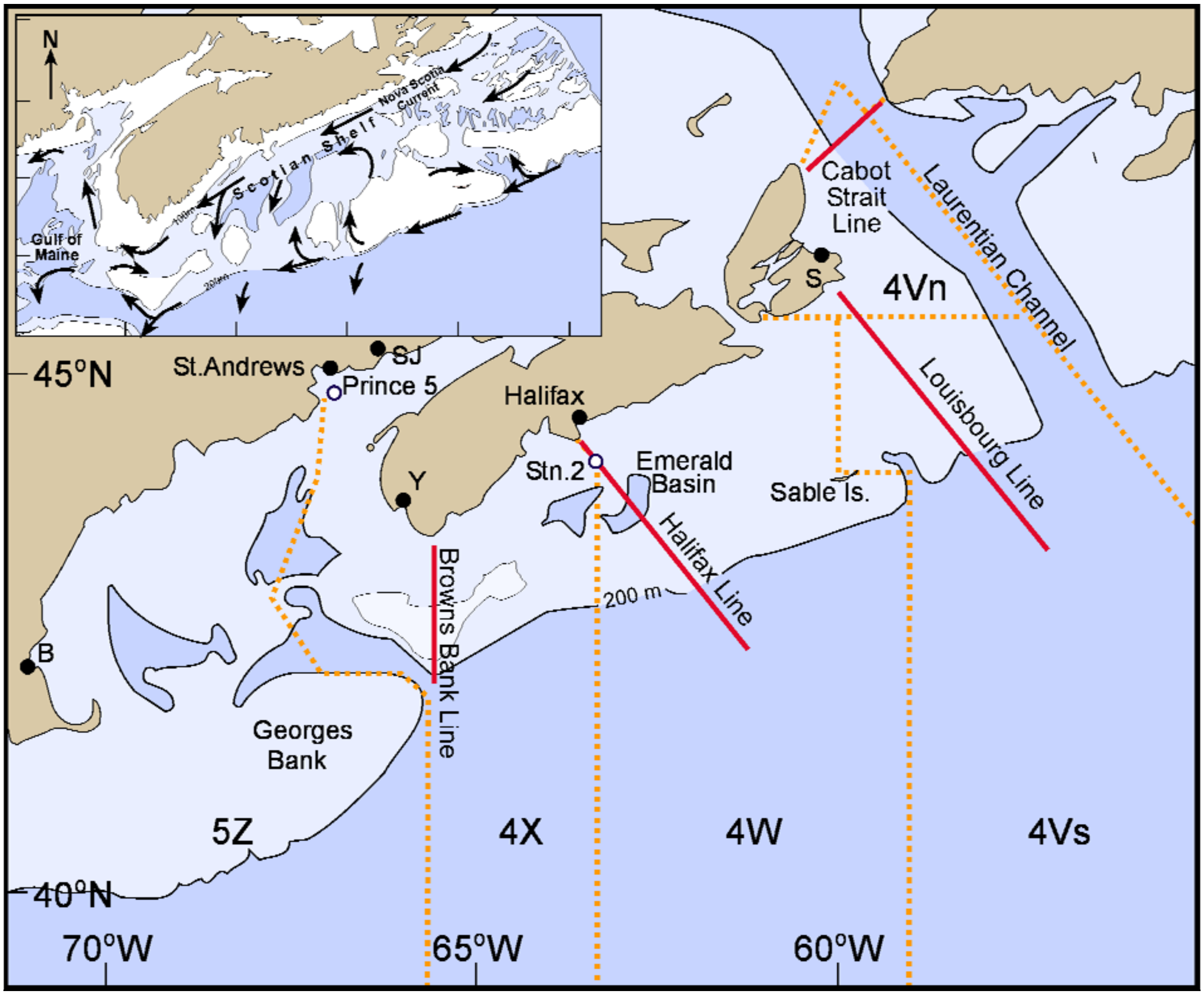
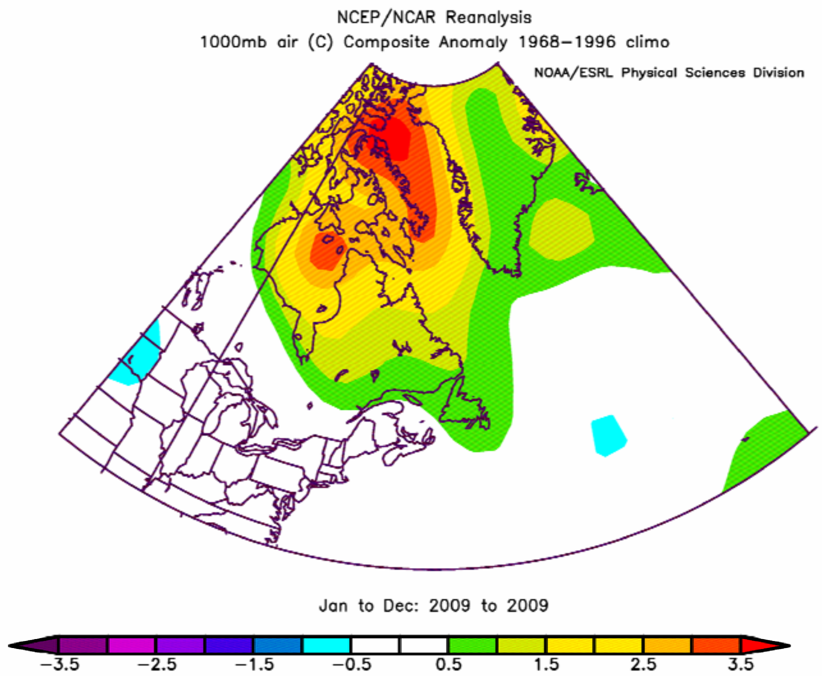


Fig. 1. *The Scotian Shelf and the Gulf of Maine showing hydrographic stations, standard sections and topographic features. The dotted lines indicate the boundaries of the NAFO Subareas. Inset depicts major circulation features. Air temperature stations at Sydney (S), Yarmouth (Y), Saint John (SJ) and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



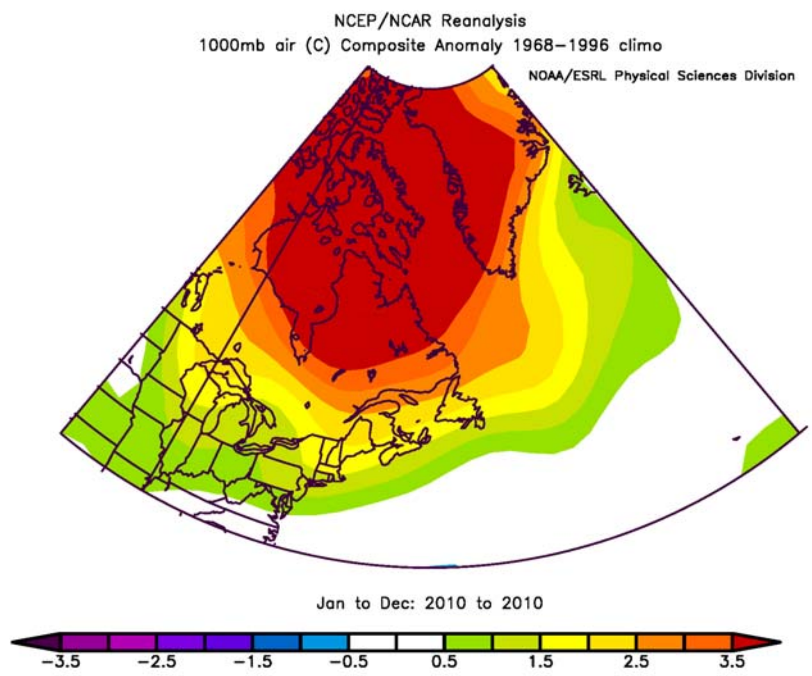


Fig. 2. *The 2009 (upper) and 2010 (lower) annual air temperature anomalies (ºC) over the Northwest Atlantic relative to the 1968-1996 means; data were obtained from http://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl.*

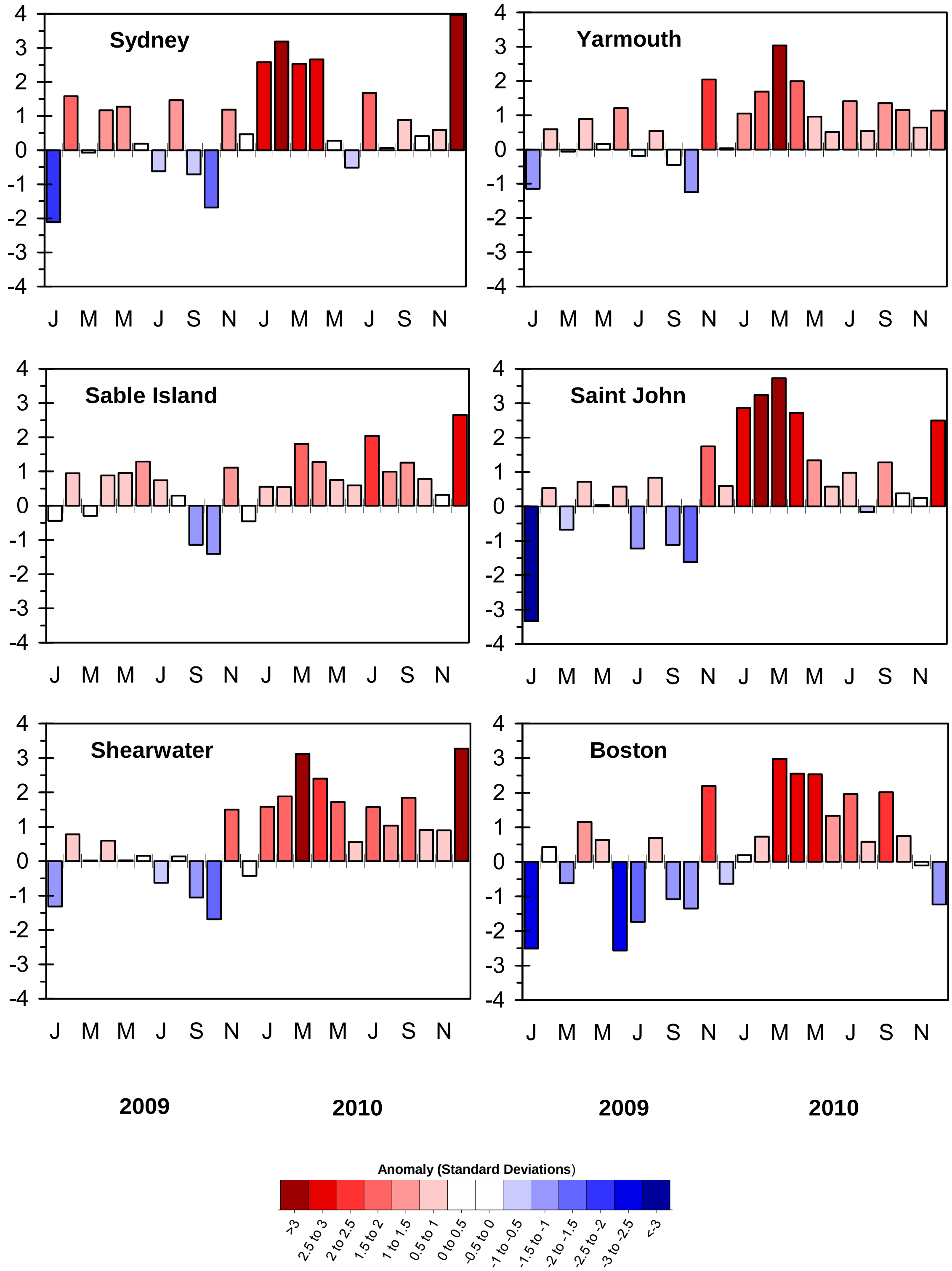


Fig. 3*. Monthly air temperature anomalies in 2009 and 2010 at coastal sites in Scotian Shelf-Gulf of Maine region (see Fig. 1 for locations). Anomalies are colour coded in terms of the numbers of Standard Deviation (SD) above or below normal.*

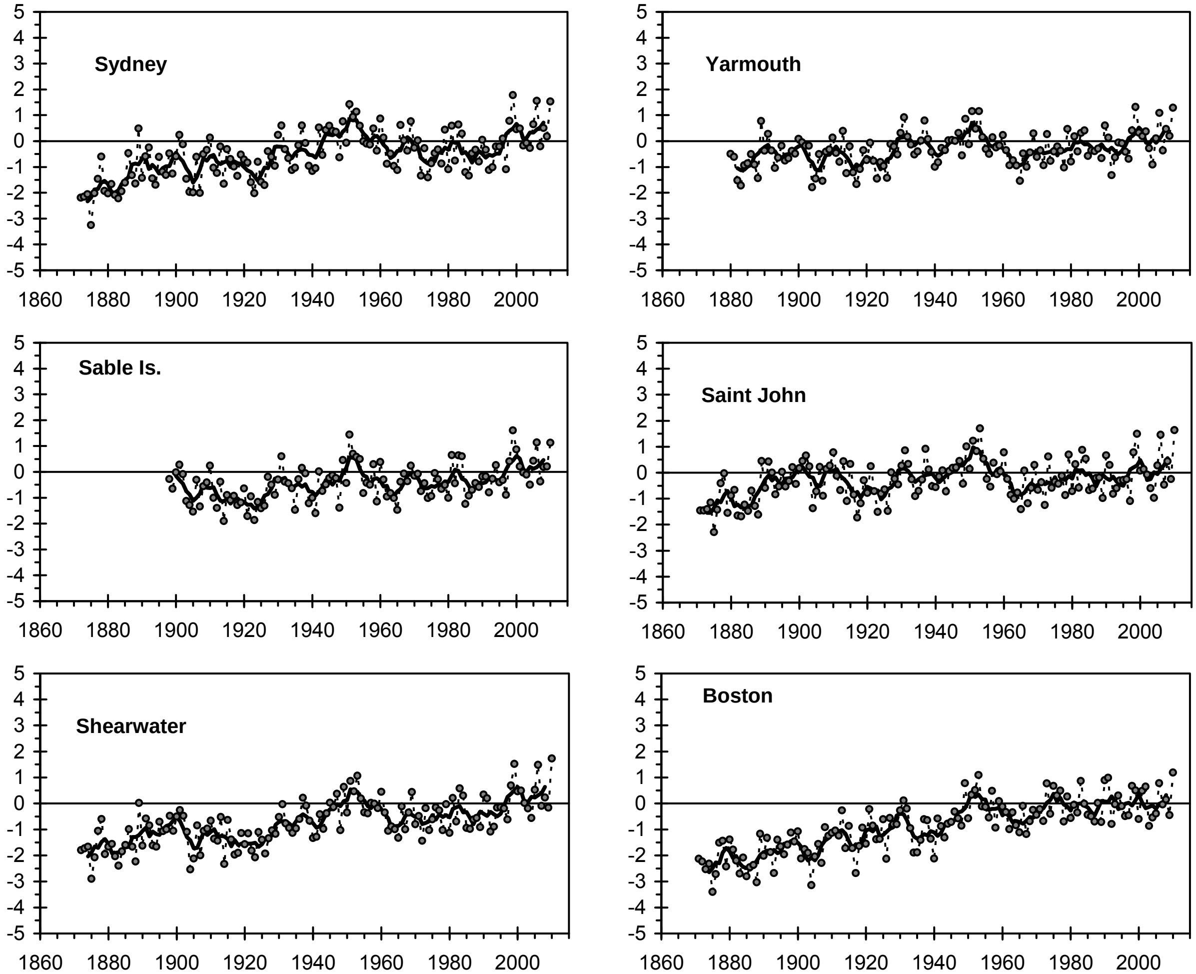


Fig. 4. *Annual air temperature anomalies (dashed line) and 5-year running means (solid line) at selected sites in Scotian Shelf-Gulf of Maine region.*

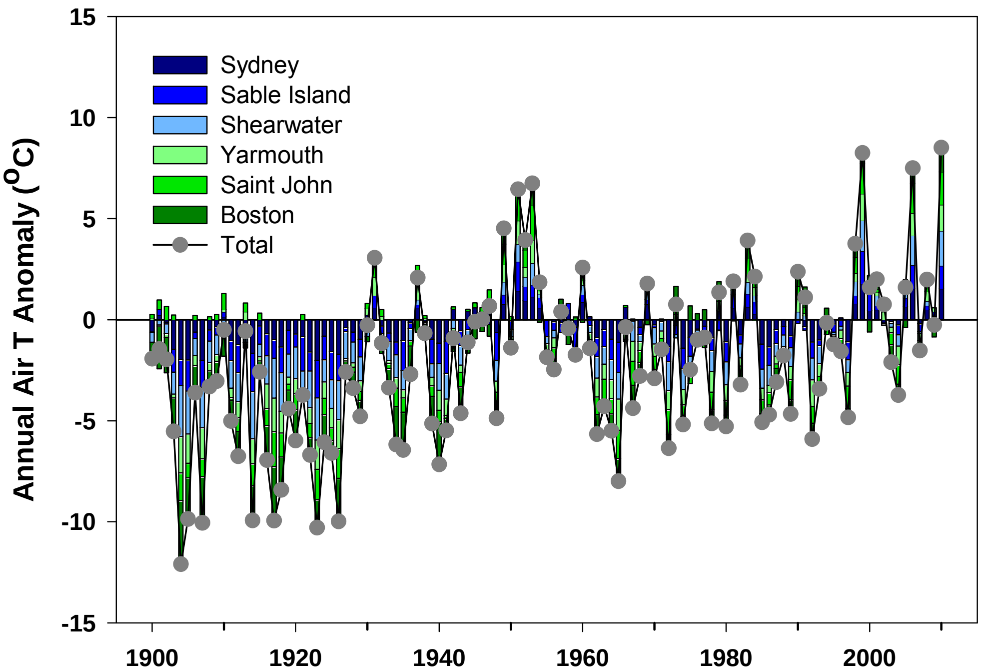


Fig. 5. *The contributions of each of the annual air temperature anomalies for 6 Scotian Shelf-Gulf of Maine sites are shown as a bar chart, and their summation as a time series (grey circles, black line). Anomalies referenced to 1981-2010.*

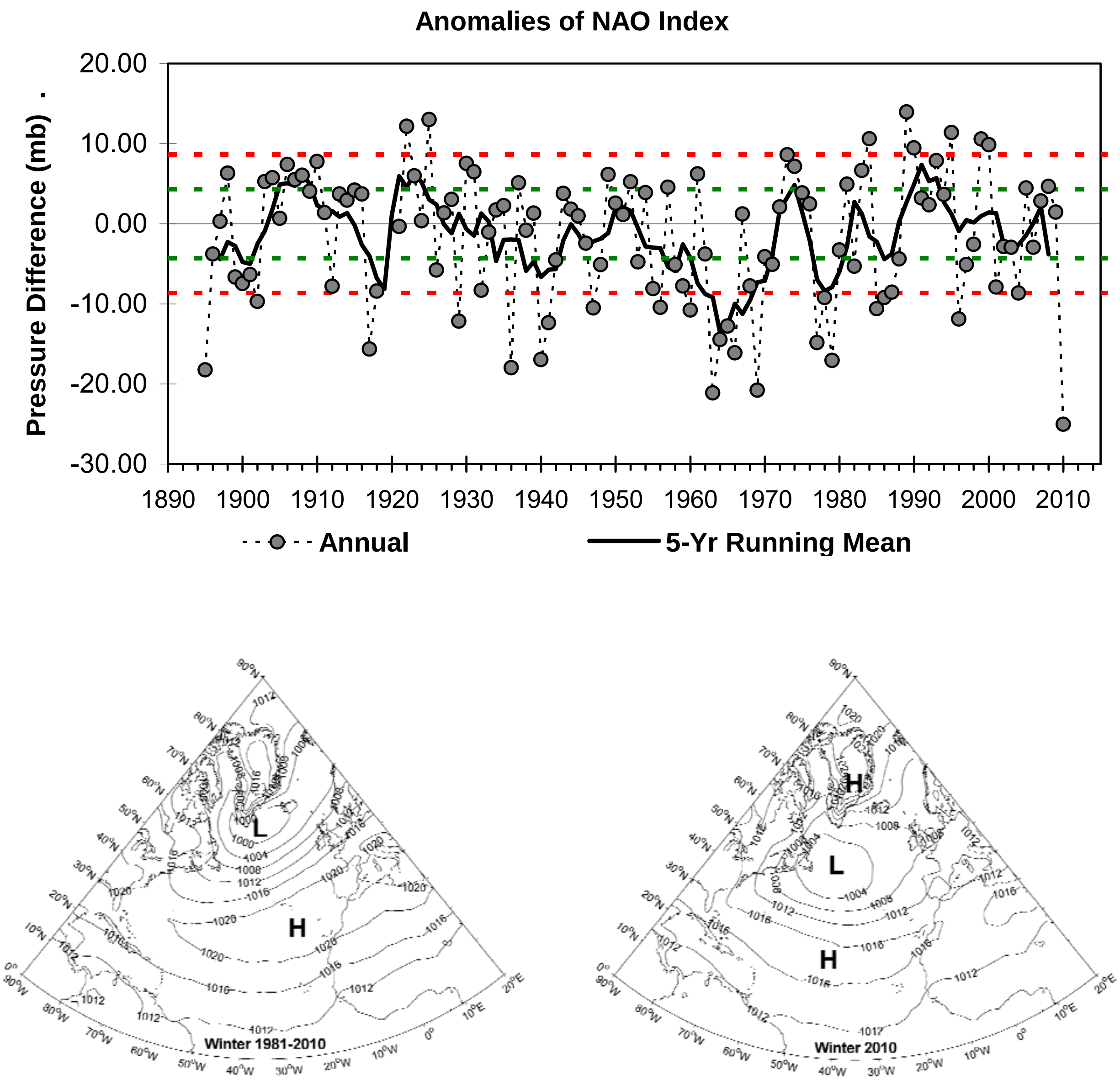


Fig. 6. *Anomalies of the North Atlantic Oscillation index, defined as the winter (December, January, February) sea level pressure difference between the Azores and Iceland, relative to the 1981-2010 mean. The 0.5 (green broken lines) and 1.0 (red) standard deviations are shown (upper panel). The lower panels show the 1981-2010 Dec-Feb mean (left) and 2010 Dec-Feb mean (right) sea level pressure over the North Atlantic.*

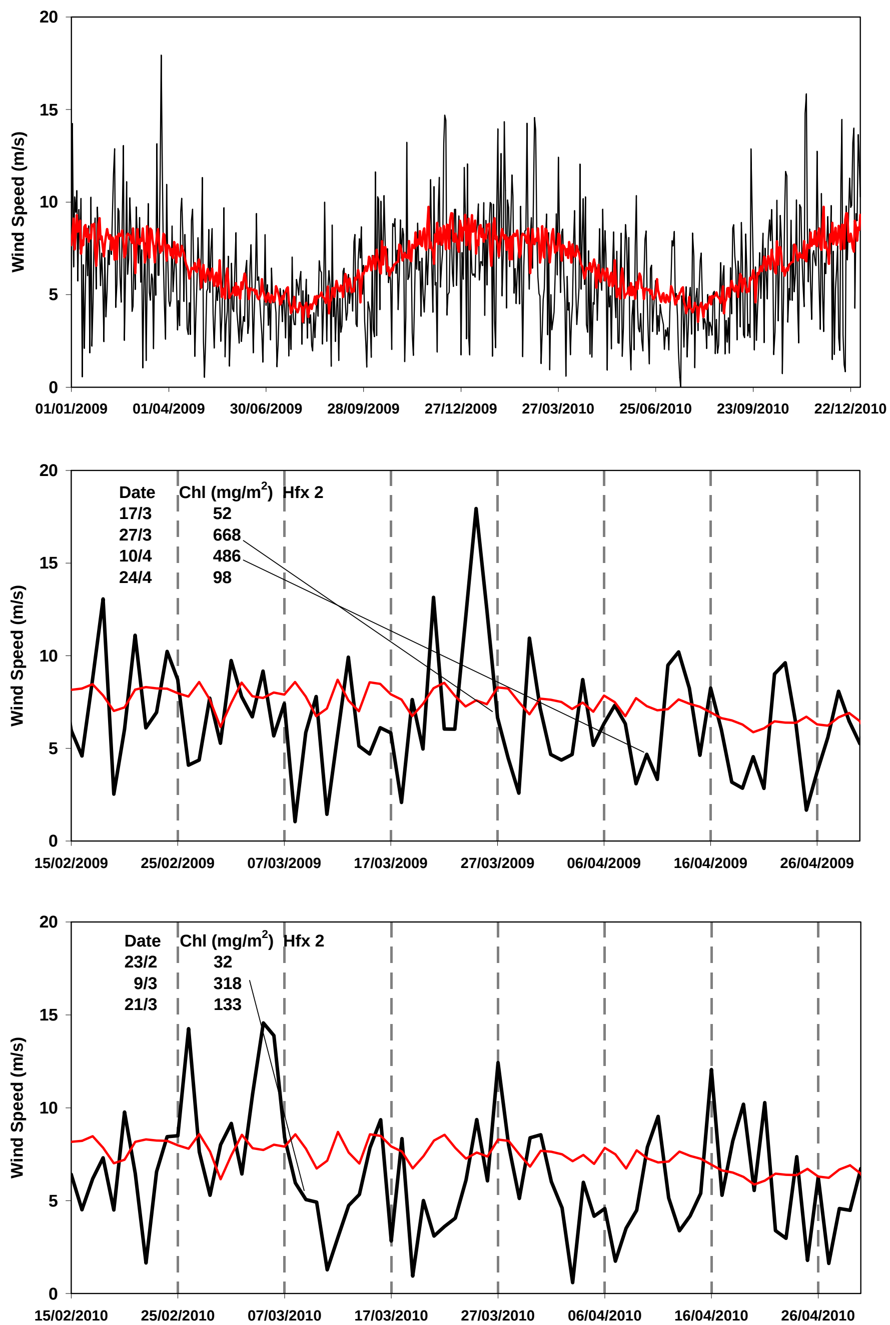


Fig. 7. *The Sable Island wind speed for 2009-10 (black line, upper panel) and 30 year (1970-99) average wind speed (red line). The time series of 2009 (middle panel) and 2010 (bottom panel) wind speed and long term average wind speed with integrated chlorophyll (0 to 100 m) at Halifax fixed station 2 tabulated.*

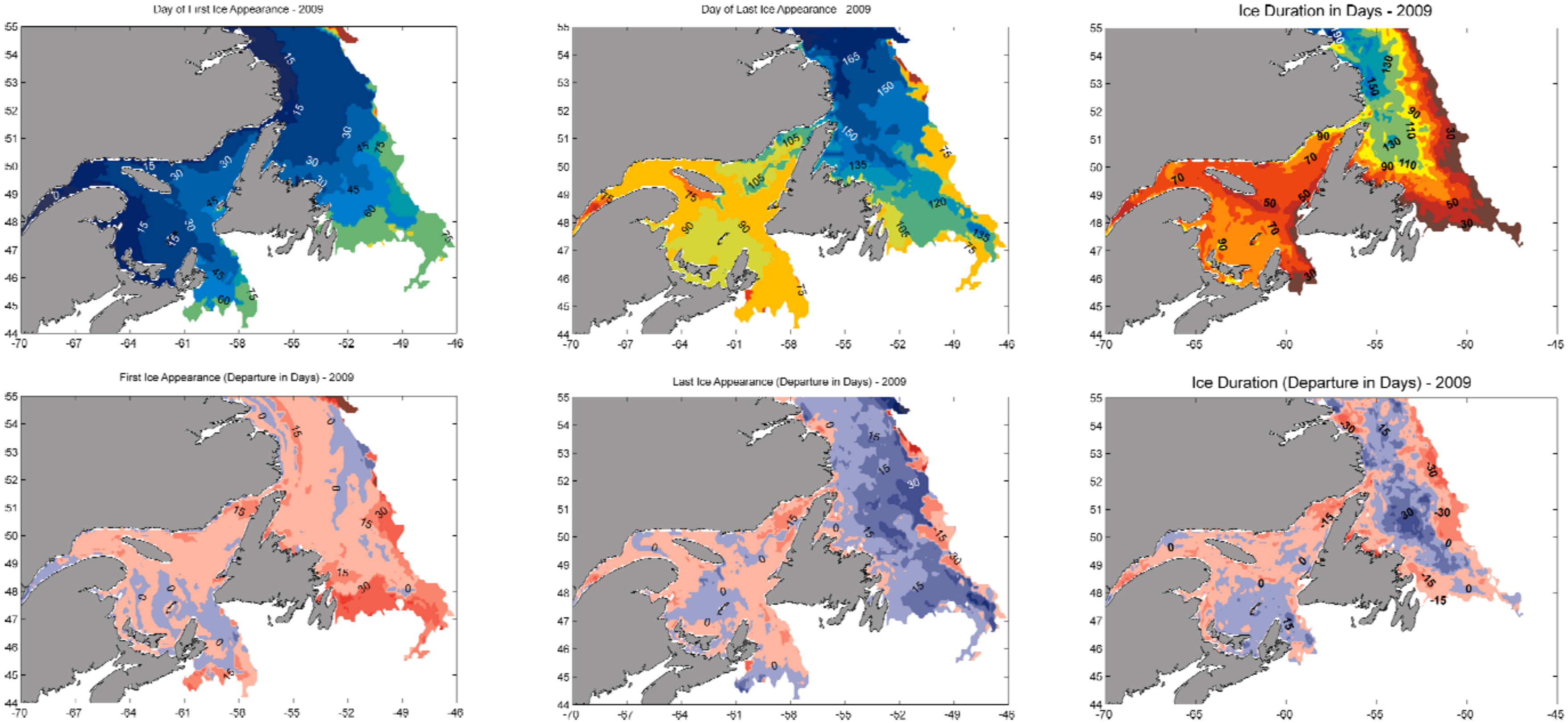


Fig. 8. *The time when ice first appeared during 2009 in days from the beginning of the year (left top panel) and its anomaly from the 1971-2000 mean in days (left bottom panel). Negative (positive) anomalies in blue (red) indicate earlier (later) than normal appearance. The time when ice was last seen in 2009 in days from the beginning of the year (centre top panel) and its anomaly from the 1971-2000 mean in days (centre bottom panel). Negative (positive) anomalies in red (blue) indicate earlier (later) than normal disappearance. The duration of ice in days (right top panel) during 2009 and the anomalies from the 1971-2000 mean in days (right bottom panel). Positive (negative) anomalies in blue (red) indicate durations longer (shorter) than the mean.*

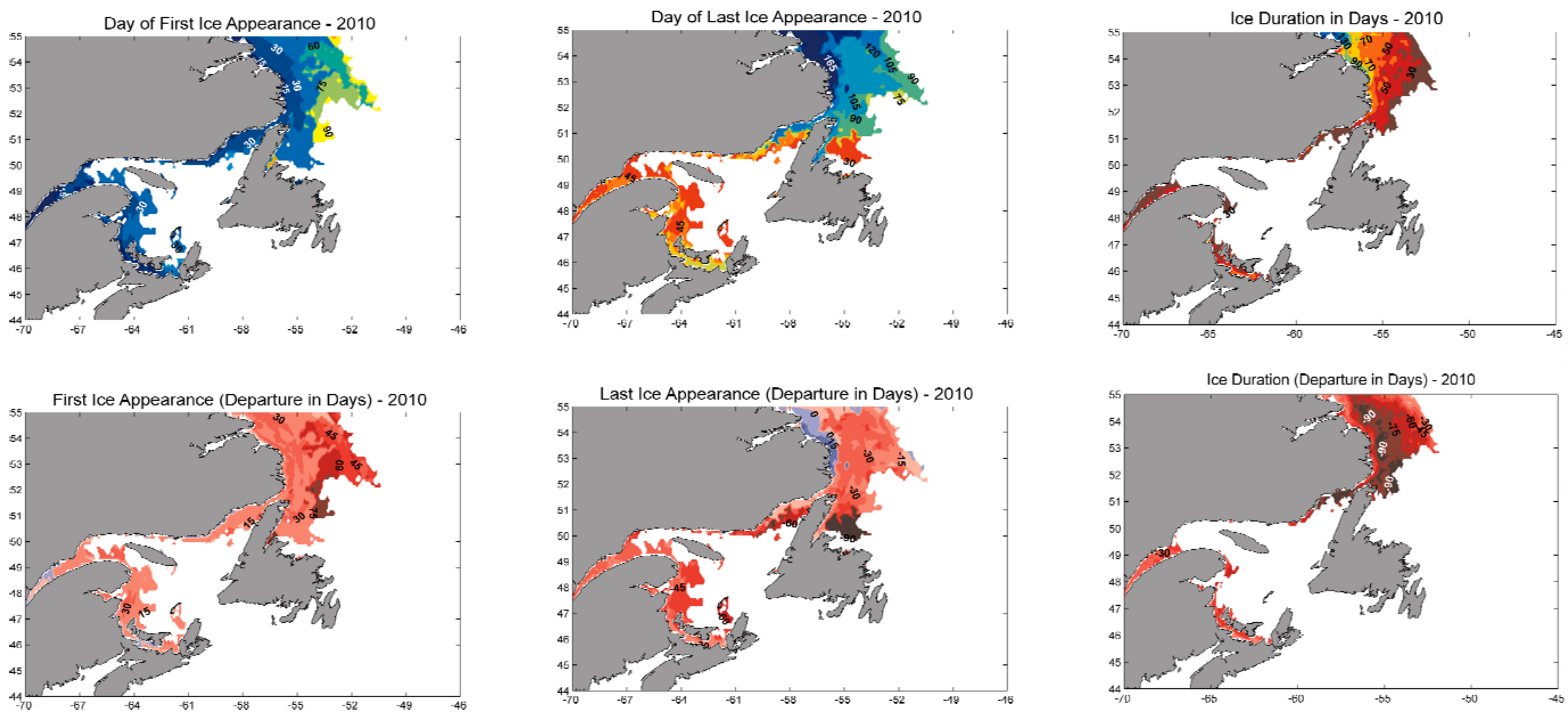


Fig. 9. *The time when ice first appeared during 2010 in days from the beginning of the year (left top panel) and its anomaly from the 1971-2000 mean in days (left bottom panel). Negative (positive) anomalies in blue (red) indicate earlier (later) than normal appearance. The time when ice was last seen in 2010 in days from the beginning of the year (centre top panel) and its anomaly from the 1971-2000 mean in days (centre bottom panel). Negative (positive) anomalies in red (blue) indicate earlier (later) than normal disappearance. The duration of ice in days (right top panel) during 2010 and the anomalies from the 1971-2000 mean in days (right bottom panel). Positive (negative) anomalies in blue (red) indicate durations longer (shorter) than the mean.*

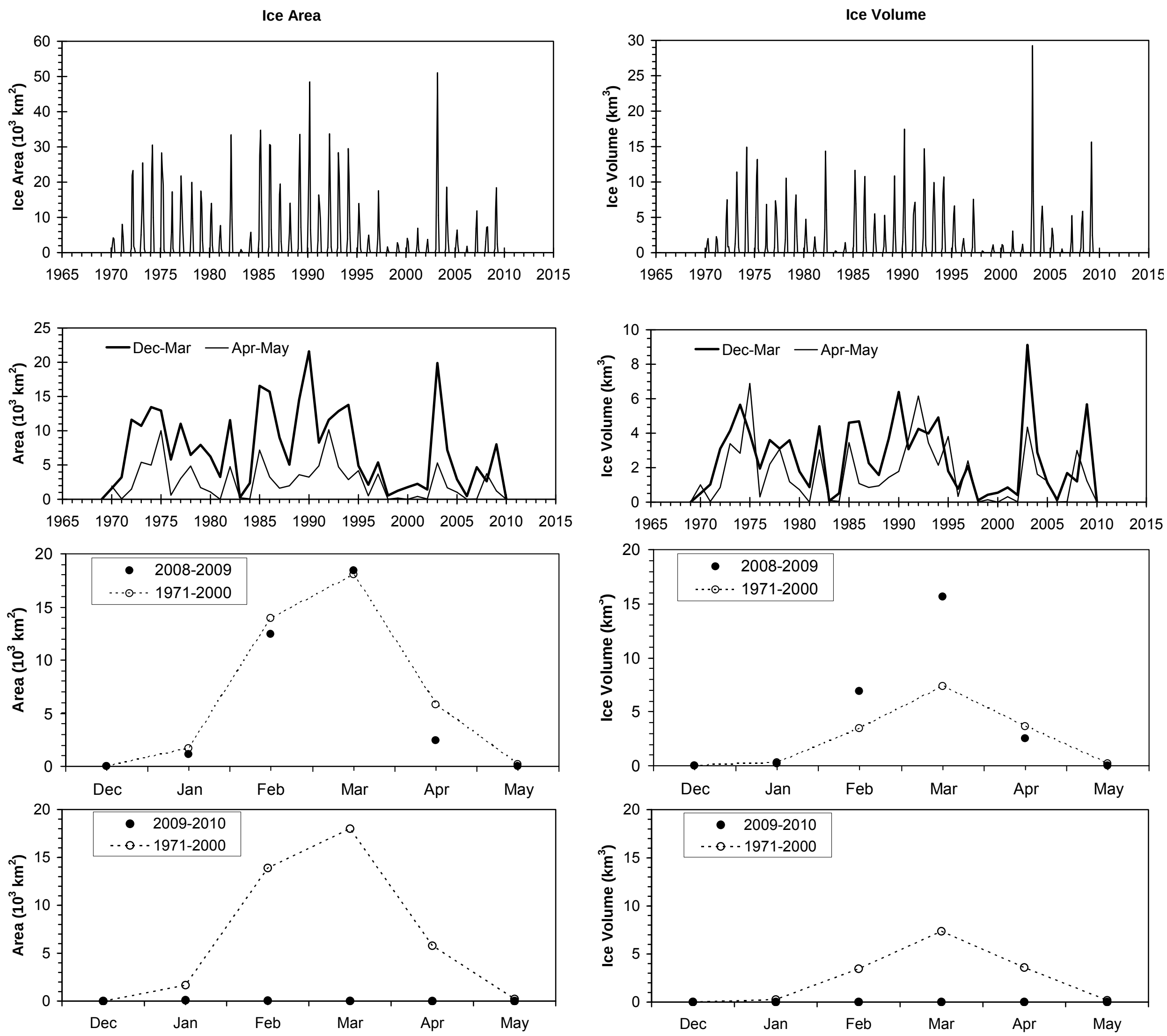


Fig. 10. *Time series of the monthly mean ice area for the Scotian Shelf (top panel), the average ice area during the usual periods of advancement (January-March) and retreat (April-May) (upper middle panel), and the comparison of the 2008-09 and 2009-10 monthly areas and volumes to the 1971-2000 means (bottom two panels).*

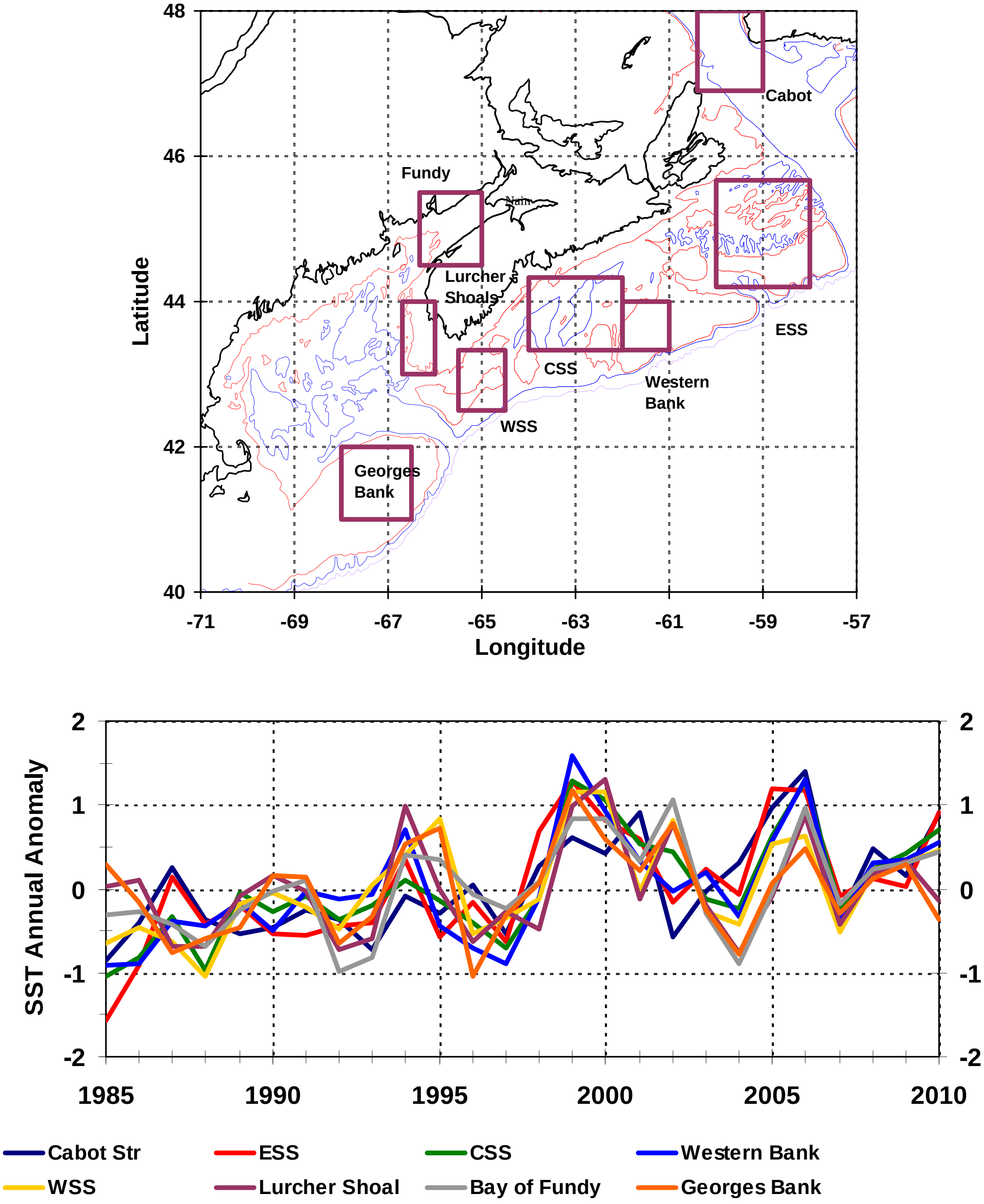


Fig 11. *Scotian Shelf-Gulf of Maine areas used for extraction of sea-surface temperature (upper panel). The annual sea surface temperature anomalies derived from satellite imagery compared to their long-term means (lower panel). Pathfinder estimates were used for September 1985-December 2009. Estimates for 2010 were from the remote sensing laboratory, Ocean Research and Monitoring Section of the Ecosystem Research Division at BIO. These values were adjusted by the regression Pathfinder=0.976*ORMS+0.46 based on a comparison between overlapping Pathfinder-ORMS data.*

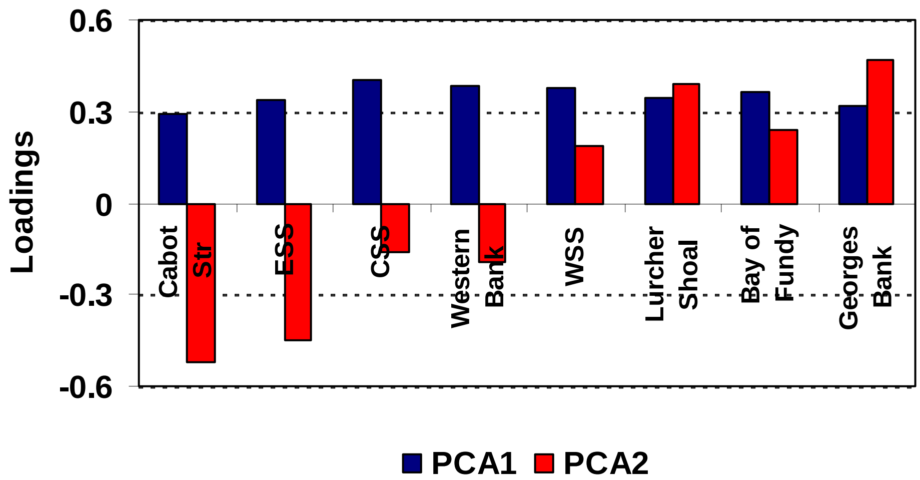


Fig. 12. *PCA 1 (71% of variance) and PCA2 (19%) loadings from a principal components analysis of the annual mean temperature anomalies (Fig. 7a, lower panel) for the seven Scotian Shelf and Gulf of Maine regions (Fig. 7a, upper panel).*

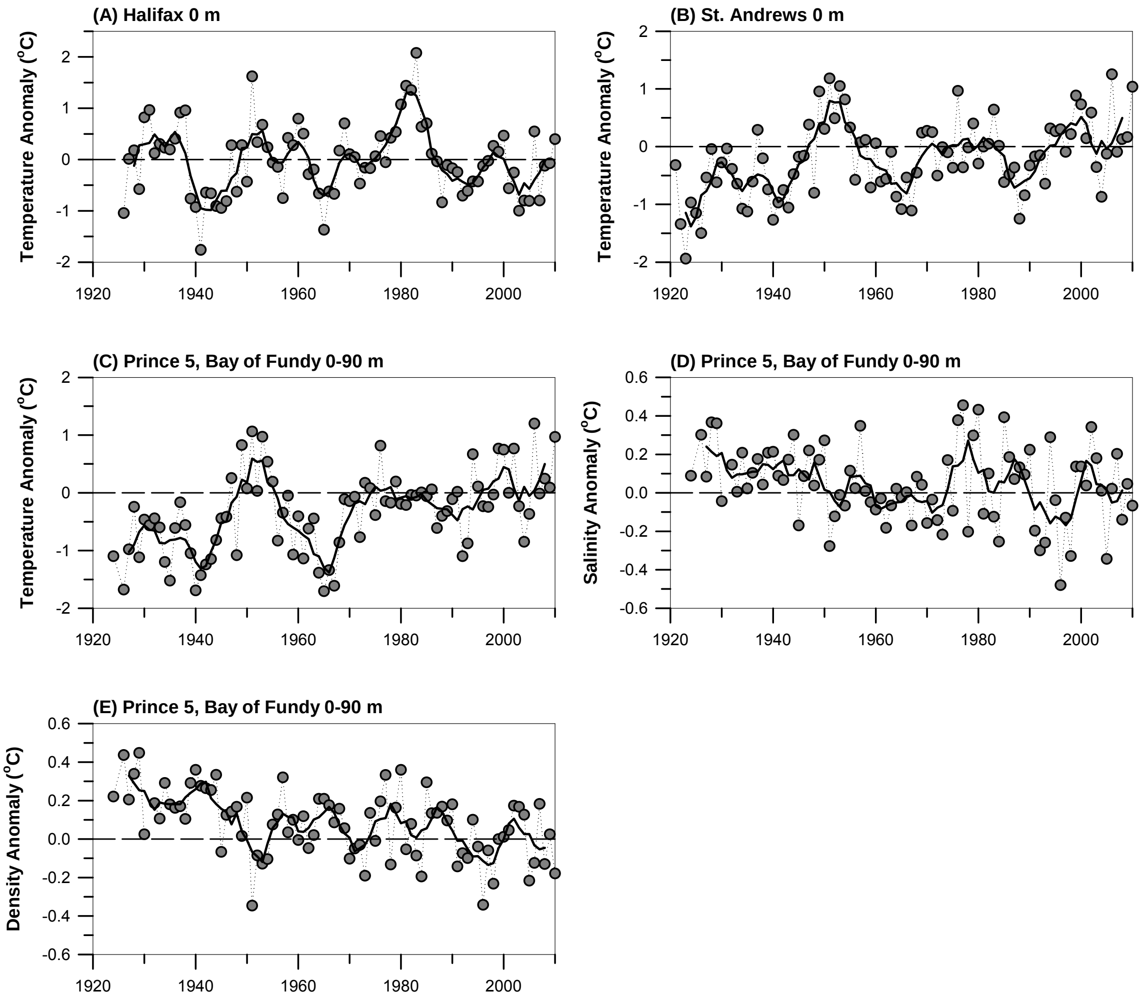
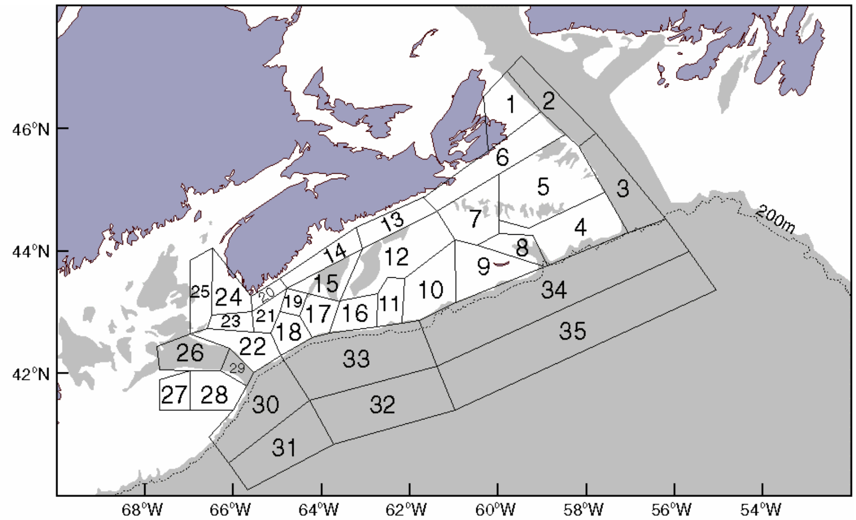


Fig. 13. *The annual surface temperature anomalies (dotted line with circles) and their 5-year running means (heavy black line) for (A) Halifax Harbour and (B) St. Andrews; annual depth-averaged (0-90 m) (C) temperature, (D) salinity and (E) density anomalies for the Prince 5 monitoring station at the mouth of the Bay of Fundy.*



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

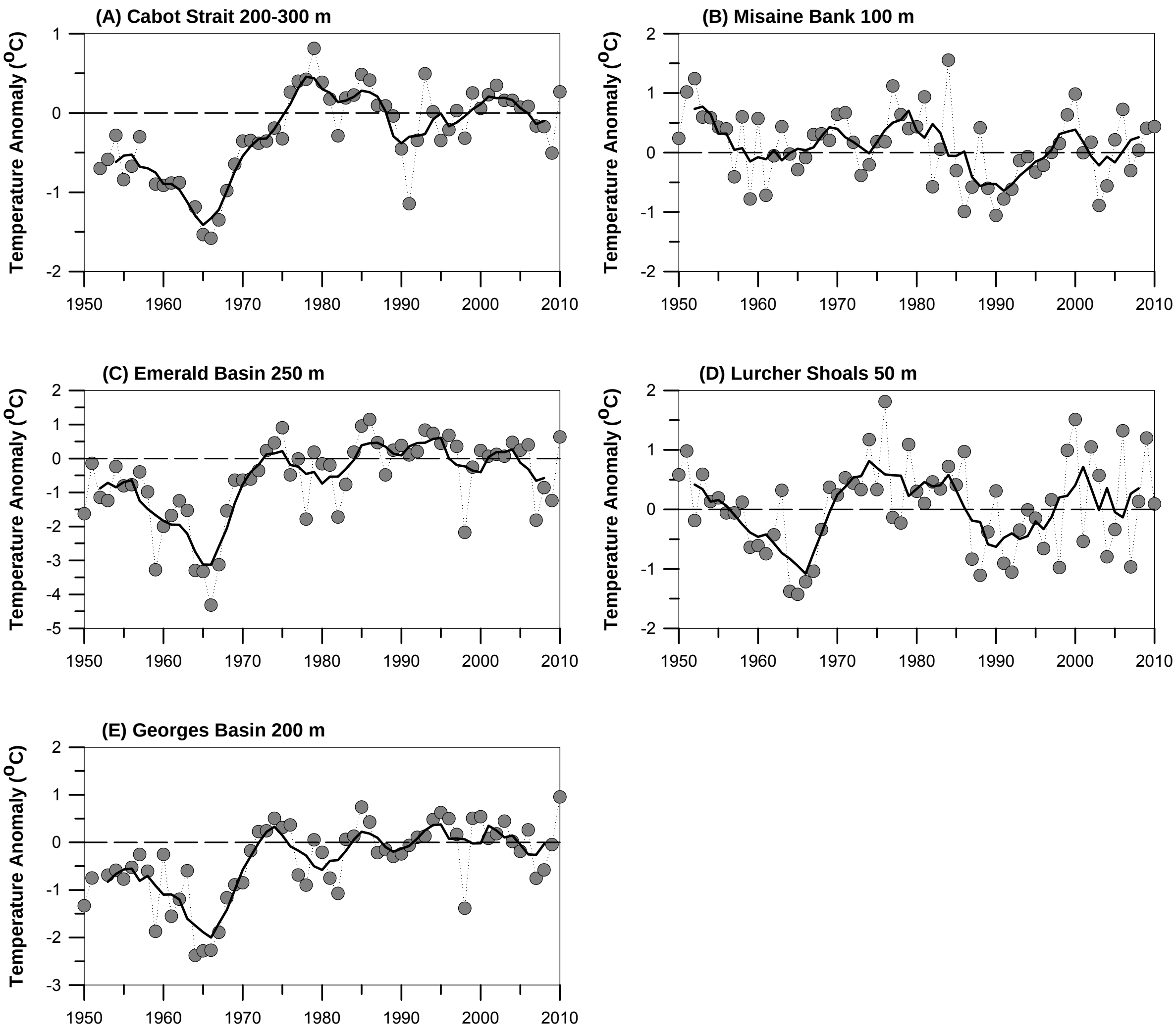


Fig. 15. *The annual mean temperature anomaly time series (dotted line with circles) and the 5 year running mean filtered anomalies (heavy solid line) on the Scotian Shelf and in the Gulf of Maine at (A) Cabot Strait 200-300 m; (B) Misaine Bank 100 m; (C) Emerald Basin 250 m; (D) Lurcher Shoals 50 m; and Georges Basin (200 m) (see Fig. 14).*

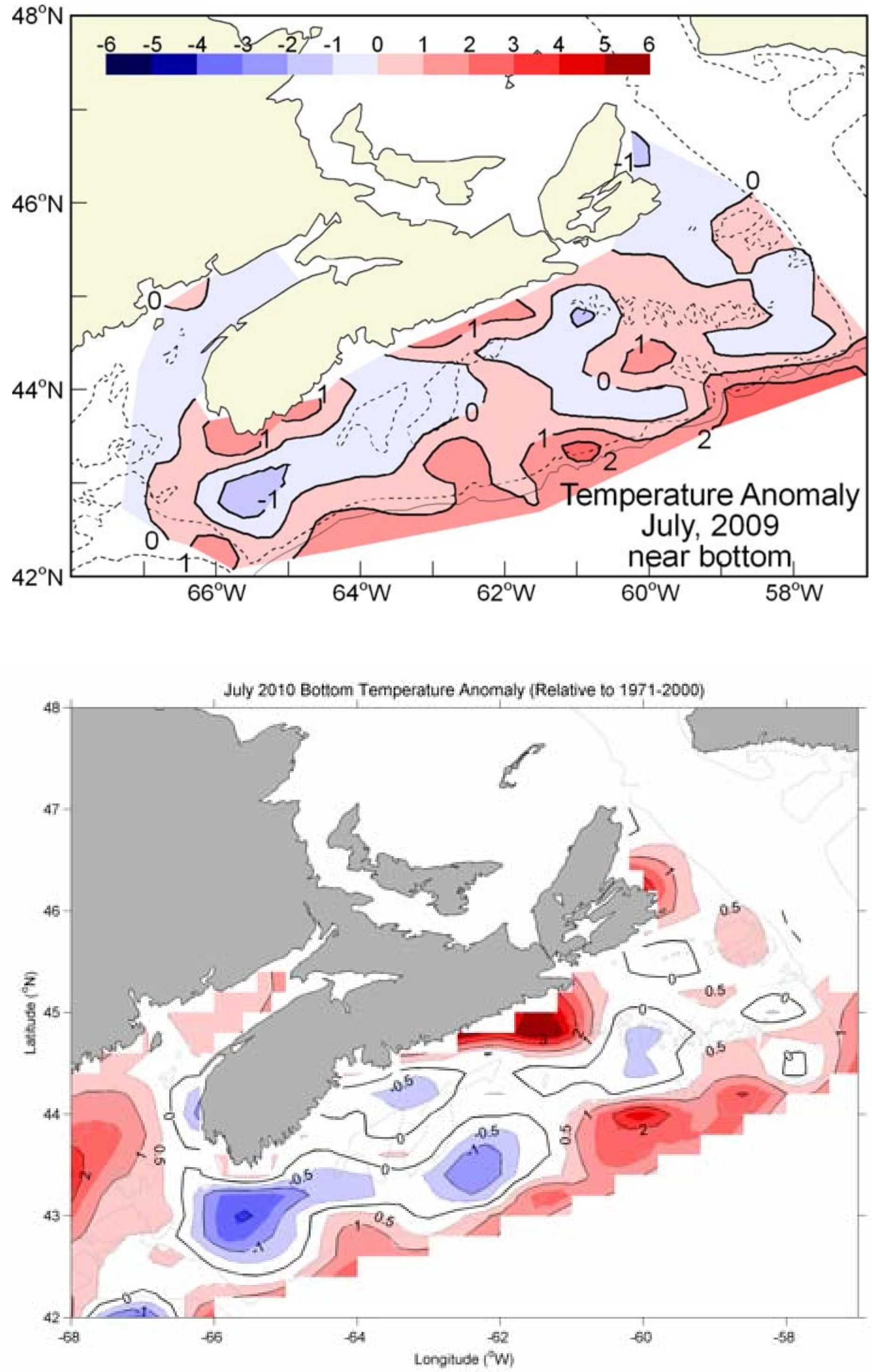


Fig. 16. *July bottom temperature anomaly maps for 2009 (upper panel) and 2010 (lower panel).*

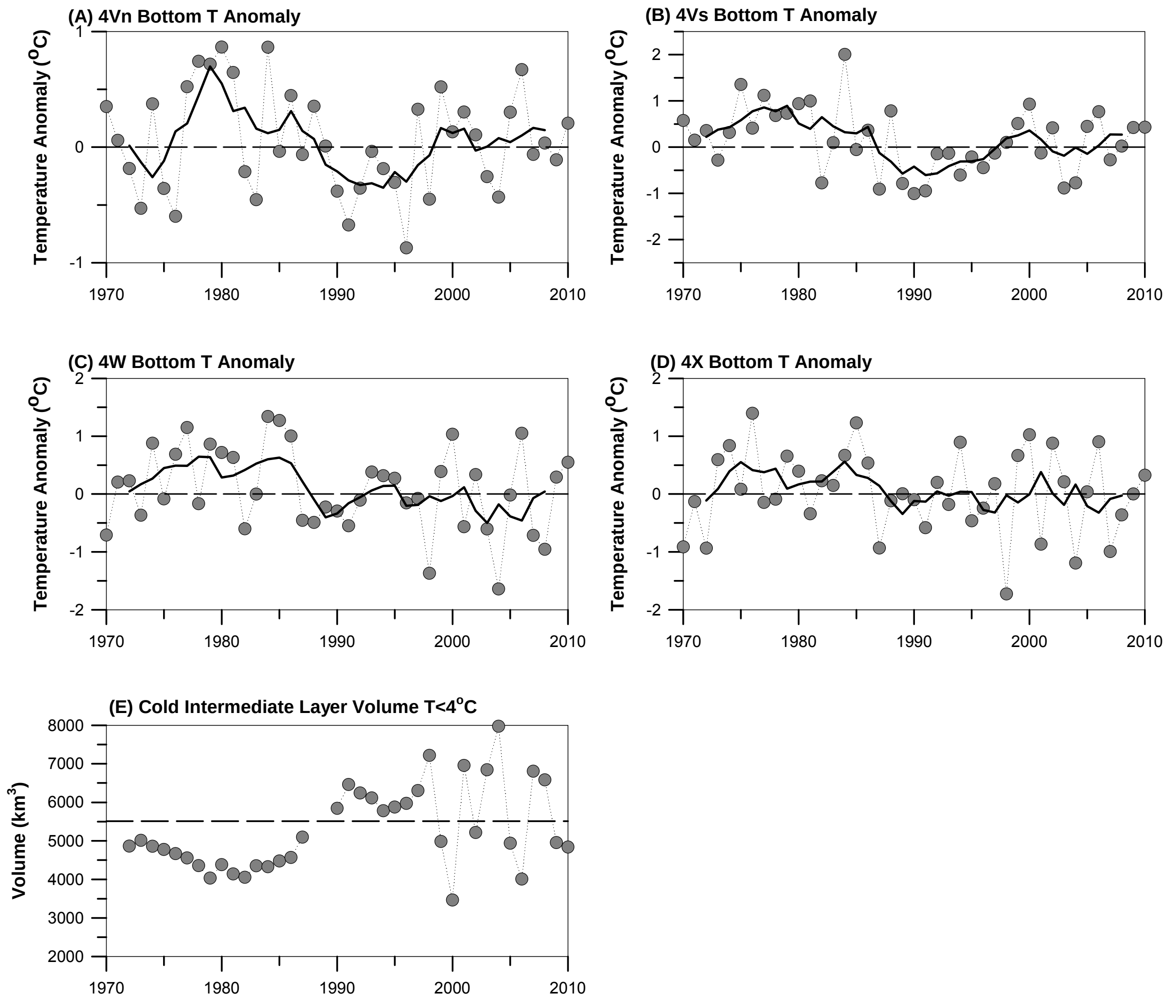


Fig. 17. *Time series of July bottom temperature anomalies (dashed lines with circles) and 5 year running mean filtered series (heavy line) for areas (A) 4Vn, (B) 4Vs, (C) 4W and (D) 4X. (E) Time series of the Cold Intermediate Layer (CIL, defined as waters with T<4°C) volume on the Scotian Shelf based on the July ecosystem survey. The dashed horizontal line is the long-term mean.*

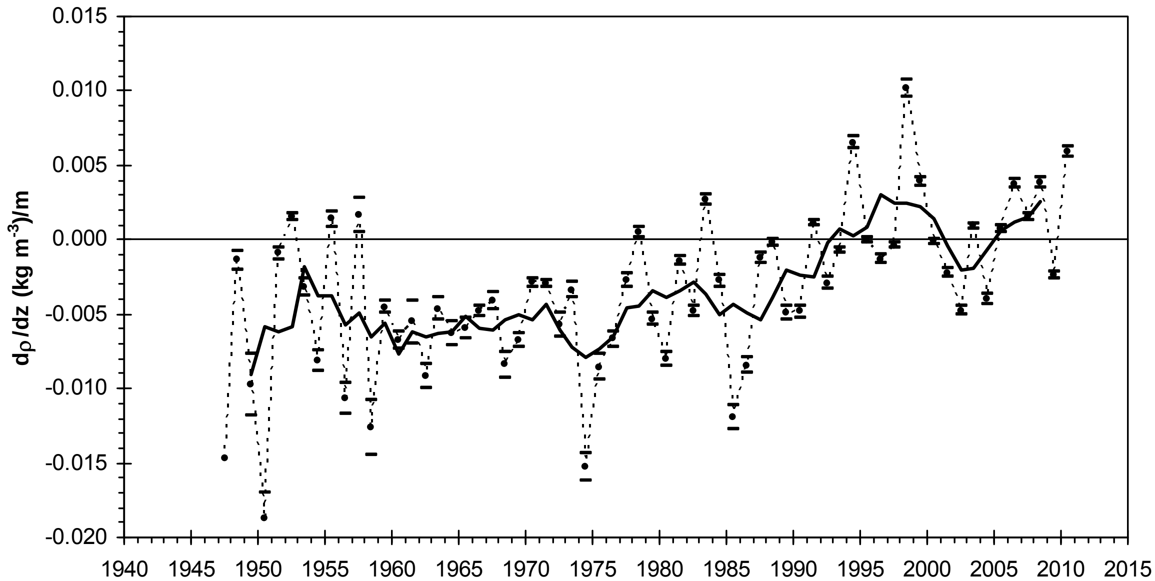


Fig. 18. *The mean annual anomaly (dashed line with circles) and 5-yr running mean (heavy solid line) of the stratification index (0-50 m density gradient) averaged over the Scotian Shelf (areas 4-23 inclusive, see Fig. 8). Standard error estimates for each annual anomaly value are also shown.*

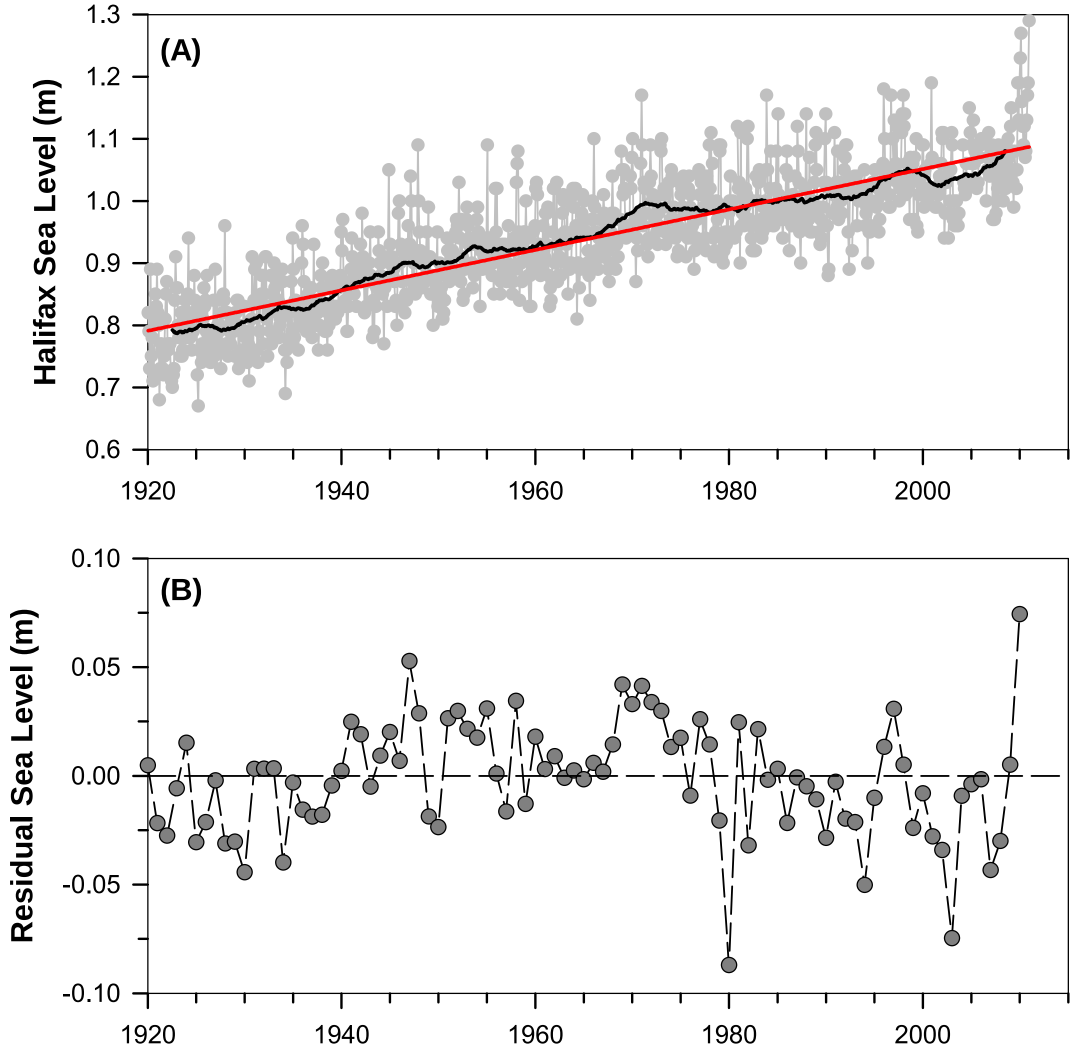


Fig. 19. *(A) The time series of the monthly means (grey) and a 5 year running mean (black) of the relative sea level elevations at Halifax, along with the linear trend (1920-2010, red). (B) Residual relative sea level (monthly observed values – linear trend, averaged to annual estimates).*

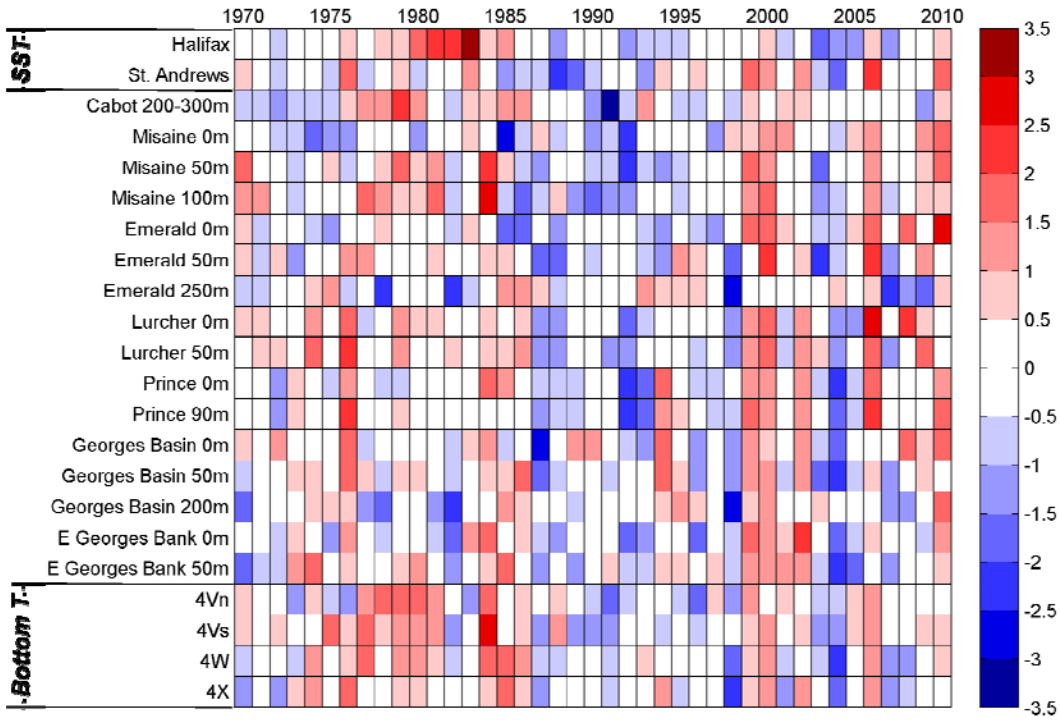


***Fig. 20**. Normalized annual anomalies of temperatures at the bottom and discrete depths for the Scotian Shelf-Gulf of Maine region. These normalized, annual anomalies are based on the 1981-2010 means, divided by the standard deviation. The scale represents the number of standard deviations an anomaly is from normal; blue indicates below normal, red above normal.*

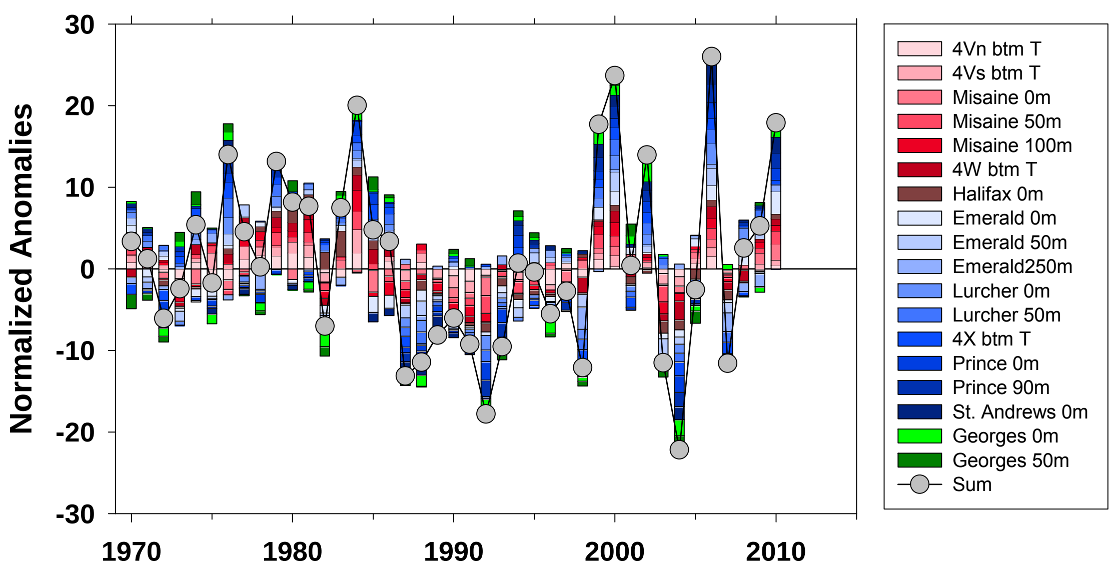


***Fig. 21.** The contributions of each of the normalized anomalies are shown as a bar chart and their summation as a time series (grey circles, black line).*