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Environmental and Physical Oceanographic Conditions during 2018 on the Eastern Canadian shelves (NAFO Sub-areas 2, 3 and 4)

by

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ABSTRACT

Oceanographic and meteorological observations in NAFO Sub-areas 2, 3 and 4 during 2018 are presented and referenced to their long-term (1981-2010) means. The winter North Atlantic Oscillation (NAO) index, a key indicator of the direction and intensity of the winter wind field patterns over the Northwest Atlantic was strongly positive during 2018. However, the spatial patterns of the associated atmospheric sea-level pressure fields resulted in a normal annual air temperature, characterized by a warm month of March, a cold spring and a warm summer. On the Scotian Shelf and Gulf of Maine, the annual air temperature was above normal in 2018. The sea ice volume across the Newfoundland and Labrador Shelf, although close to the long-term mean over 2018, exhibited a strong negative anomaly in March as a consequence of warm air temperature over the Arctic during this month. Annual sea-surface temperature (SST based on infrared satellite imagery) trends on the Newfoundland and Labrador Shelf, while showing an increase of about 1°C since the early 1980s, were mostly below normal during 2018 for NAFO Divisions 2 and 3 (e.g., up to -1.6 SD and -1.9 SD for Hamilton Bank and Hudson Strait, respectively) and above normal for NAFO Division 4 (e.g., +2.0 SD for the Bay of Fundy and the Western Scotian Shelf). In 2018, vertically averaged salinity at station 27 was at its freshest value (negative anomaly) since the beginning of the time series in 1948. Observations from the summer AZMP oceanographic survey indicated that after a predominance of colder than average conditions since 2012. The volume of cold-intermediate-layer (CIL, <0°C) however reduced in 2018, specially in the northern part of the region where it was -1.6 SD below normal at Seal Island section (second smallest volume since 1980). The spatially averaged bottom temperature during the spring in 3LNOPs remained slightly above normal at +1.0 SD in 2018. For the fall, bottom temperature in 2J3KLNO was also above normal at +0.8 SD, a return to positive anomaly after the cold anomaly of 2017 (the first one since 1995). In Divisions 4X, bottom temperatures in 2018 were the 5th warmest year on record at 2.0 SD above average. Vertically averaged temperature and salinity anomalies at long-term Station Prince 5 were 2.0 SD and 0.8 SD above average, respectively. Labrador Current transport index along the Labrador and northern Newfoundland shelf slope in 2018 was at a record high since the beginning of the time series in 1993 (equal with 1994 at +1.7 SD) while it was lower than average on the Scotian slope.

INTRODUCTION

This manuscript presents an overview of the 2018 environmental and physical oceanographic conditions in NAFO sub-areas 2, 3 and 4 on eastern Canadian shelves (see Figure 1). This is a change to the approach used in recent years in which Newfoundland and Labrador Region and Scotian Shelf and Gulf of Maine regions were presented separately (e.g., Colbourne et al., 2018 and Hebert and Pettipas, 2018). This report complements similar reviews of environmental conditions on the Northeast US Shelf, the Labrador Sea and West Greenland Waters as part of the Scientific Council's annual review of environmental conditions in the NAFO Convention Area.

The information presented for 2018 is derived from various sources:

1. Observations made throughout the year at historical monitoring stations 27 (near St. John's, NL), Prince-5 (Bay of Fundy) and Halifax-2 (Scotian Shelf);
2. Measurements made during the summer along standard NAFO and Atlantic Zone Monitoring Program (AZMP) (Therriault et al. 1998) cross-shelf sections (Figure 1);
3. Oceanographic observations made during multi-species and ground fish resource assessment surveys (NAFO sub-areas 2 to 4);
4. SST data based on infrared satellite imagery of the Northwest Atlantic extracted in standard geographical boxes (e.g., see Figure 13);
5. Other multi-source historical data (ships of opportunity, international campaign, other DFO regions surveys, Argo program, etc.);
6. Ice data are from the Canadian Ice Service and meteorological data are from Environment Canada and other sources cited in the text.

Unless otherwise specified, these data are available from MEDS archives and maintained in a regional data archive at the Northwest Atlantic Fisheries Centre (NAFC) in St. John's, NL and at the Bedford Institute of Oceanography (BIO) in Dartmouth, NS.

Time series of temperature and salinity anomalies and other derived climate indices were constructed by removing the annual cycle computed over a standard climatological period from 1981 to 2010. "*Normal*" is thus defined here as the average over this period. Annual or seasonal anomalies were sometimes normalized by dividing the values by the standard deviation (SD) of the data time series over the climatological period. A value of 2, for example, indicates that the index was 2 SD higher than its long-term average. As a general guide, anomalies within ±0.5 SD are considered to be normal.

The normalized values of water properties and derived climate indices presented in this document are color-coded in "scorecards" with gradations of 0.5 SD (Figure 2). Shades of blue represent cold-fresh environmental conditions and reds warm-salty conditions. In some instances (NAO, ice and cold water areas or volumes, for example) negative anomalies may indicate warm conditions and hence are colored red. Most of the colormaps used in this report are taken from the *cmocean* colormaps package for oceanography (Thyng et al., 2016).

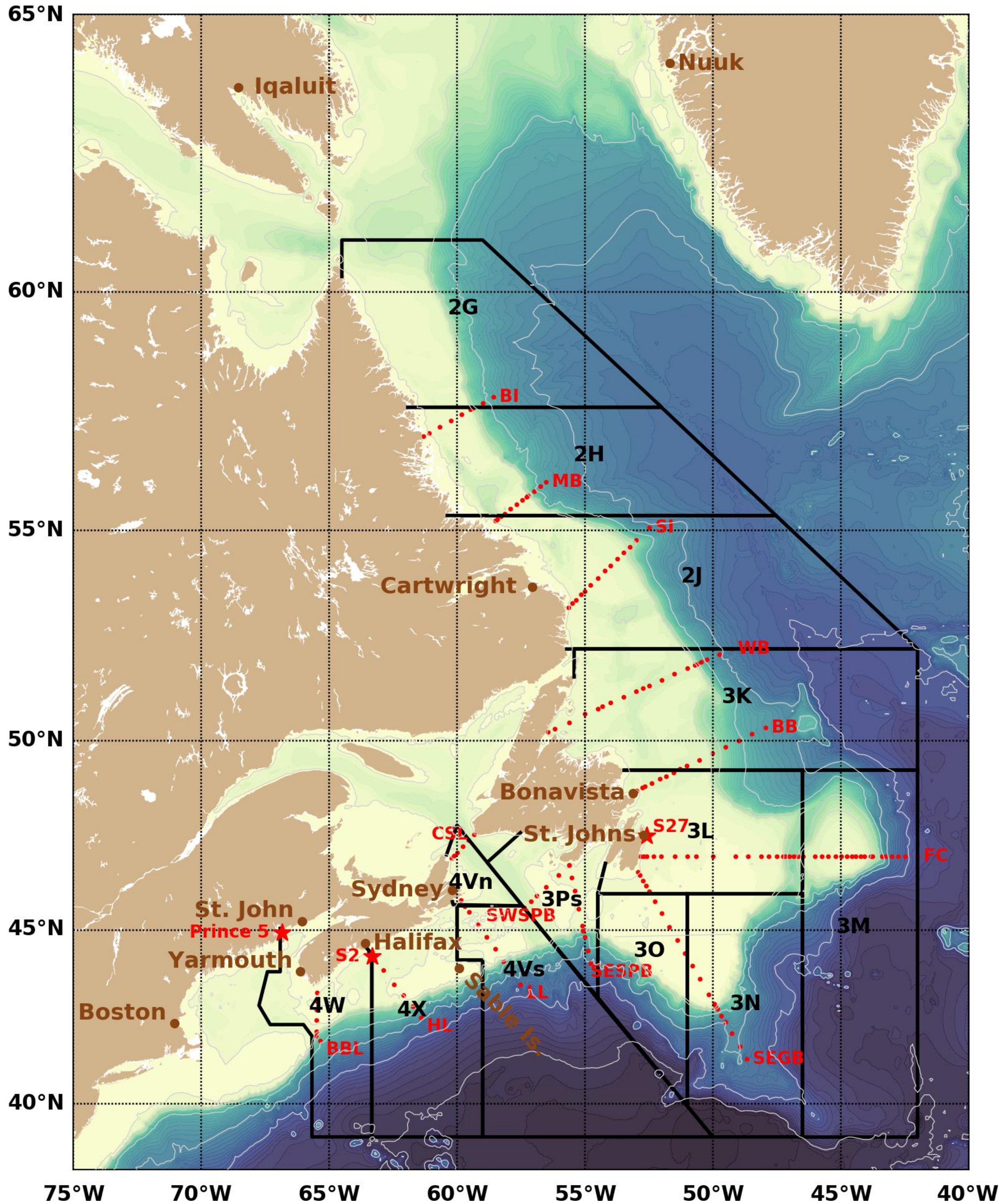


Figure 1. Map showing NAFO Divisions and main bathymetric features of the Northwest Atlantic. The hydrographic sections reported here are shown with red dots and the fixed stations by red stars. The stations used for air temperature time series and in brown.

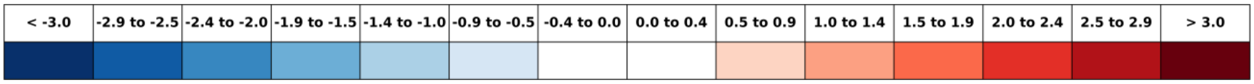


Figure 2. Colorscale used for the presentation of standardized anomalies. Color levels are incremented by 0.5 standard deviation (SD), where blue is below normal and red above normal. Values between 0 and ±0.5 SD are left in white indicating normal conditions.

METEOROLOGICAL CONDITIONS

The winter North Atlantic Oscillation (NAO) is defined as anomaly in the sea-level pressure (SLP) difference between the sub-tropical high (average location near the Azores) and the sub-polar low (average location near Iceland). Several definitions of the NAO exists and the definition used here is the one from the National Center for Environmental Information of the National Oceanic and Atmospheric Administration (NOAA) and available online at https://www.ncdc.noaa.gov/teleconnections/nao/. The winter NAO is defined as the average over the months of December, January and February, which is often a measure of the strength of the winter westerly and north westerly winds over the Northwest Atlantic. A high (positive phase) NAO index occurs from an intensification of the Icelandic Low and Azores High. This favors strong Northwest winds, cold air and sea temperatures and heavy ice conditions on the Newfoundland and Labrador (NL) Shelf regions (Colbourne et al. 1994; Drinkwater 1996, Petrie et al. 2007).

However, there are exceptions to this response pattern (e.g. 1999, 2000 and 2018) due to shifting locations in the SLP features. In 2018, the winter NAO was relatively high (1.3 SD above normal; first row in Figure 3), but the high-low pattern was reversed in March, which caused record-high temperature above the Arctic during this month (data not shown here). This trend of high winter NAO phase is ongoing since 2012 (including 120 year record high in 2015 at +2.0 SD above normal). In 2010 it was at a record low at -3.1 SD below normal. A larger scale index, but intimately linked to the NAO, is the Arctic Oscillation (AO, https://www.ncdc.noaa.gov/teleconnections/ao/). During positive phase, the arctic air outflow to the Northwest Atlantic increases, resulting in colder winter air temperatures over much of the NAFO convention area in the NL and adjacent shelf regions. Similar to 2017, the AO was slightly above normal in 2018. This is in contrast with 2015 where it was 1.5 SD above normal (cold air temperature) and 2010 where it was -2.3 SD below normal (warm air temperature).

	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	$\bar{x}$	sd
-- Climate indices --																																									
NAO_{winter}	-0.4	0.6	-0.4	0.9	0.9	-1.6	-0.3	-1.0	0.6	1.4	0.2	0.6	0.2	0.8	1.1	1.6	-1.5	-0.6	-0.9	0.5	1.5	-0.4	-0.1	-0.6	-0.4	0.9	-0.3	0.1	0.5	-0.6	-3.1	-1.5	1.6	-0.5	0.8	2.0	1.5	0.5	1.5	0.3	0.7
AO	-1.4	-0.9	0.8	0.1	-0.4	-1.1	0.3	-1.2	0.2	2.3	2.4	0.5	1.1	0.3	1.3	-0.6	-1.0	0.0	-0.6	0.3	0.0	-0.3	0.2	0.4	-0.4	-0.8	0.4	0.7	0.5	-0.7	-2.3	1.3	-0.3	0.1	-0.1	1.5	-0.2	0.7	0.5	0.0	0.4
-- Winter Air Temperature --																																									
StJohns	-0.3	0.9	0.0	0.8	0.6	-0.6	-0.1	-0.9	0.0	-1.4	-2.1	-1.1	-1.6	-1.5	-1.2	-0.8	0.4	0.2	0.3	1.3	1.5	-0.6	0.3	-0.6	1.0	0.7	1.7	0.3	0.0	1.1	1.3	2.5	1.2	0.7	-0.7	0.7	1.0	0.3	1.5	-3.7	1.2
Bonavista	0.2	0.9	0.0	0.1	0.0	-0.7	-0.1	-0.5	0.2	-1.1	-2.0	-1.1	-1.5	-1.9	-1.5	-0.6	0.8	0.1	0.5	1.1	1.3	0.0	0.6	-0.6	1.2	0.7	1.8	0.3	-0.2	0.7	1.4	2.3	1.0	0.9	-1.0	0.4	1.0	0.3	1.4	-3.5	1.3
Cartwright	0.5	1.0	0.3	-1.2	-0.9	-0.1	0.2	-0.1	0.1	-1.2	-1.2	-1.3	-1.5	-1.4	-1.0	-0.7	0.7	0.3	0.8	0.5	0.3	0.0	0.4	0.3	1.8	0.0	0.7	0.9	-0.8	0.2	2.9	2.2	0.1	0.9	-0.7	-1.2	0.4	-0.1	0.3	-12.3	2.5
Iqaluit	0.6	0.9	1.0	-1.8	-1.6	0.8	1.7	-0.9	-0.1	-1.3	-0.8	-1.3	-0.6	-1.7	-0.5	0.1	0.4	0.3	-0.4	0.1	0.4	0.5	0.1	0.5	0.9	-0.3	0.6	1.3	-0.7	0.2	2.3	2.2	0.8	0.8	0.7	-0.8	0.3	0.5	0.3	-25.0	3.4
Nuuk	0.7	0.3	0.3	-2.0	-2.5	0.5	1.8	-0.2	0.4	-0.8	-0.3	-0.6	-0.9	-1.7	-0.4	-0.8	0.5	0.2	0.1	-0.1	0.2	0.6	0.2	0.9	1.1	0.3	0.6	0.9	-1.0	0.6	1.9	1.2	0.2	0.6	0.2	-0.6	0.1	0.2	-0.3	-7.7	3.0
-- Annual Air Temperature --																																									
StJohns	-1.2	1.0	-1.0	0.5	0.2	-1.7	-1.0	-0.5	0.2	-0.6	-0.5	-1.4	-1.7	-1.5	-0.5	-0.7	0.3	-1.1	0.6	1.9	1.0	0.3	-0.4	0.4	0.6	0.7	1.6	-0.1	0.8	0.9	1.7	0.6	2.3	0.8	0.4	-0.7	0.7	0.4	0.4	5.0	0.8
Bonavista	-1.0	0.7	-1.0	0.1	-0.4	-1.4	-0.9	-0.2	0.2	-0.2	-0.6	-1.8	-1.8	-1.8	-0.7	-0.7	0.6	-0.9	0.6	1.5	0.8	0.6	-0.1	0.5	1.0	1.2	1.7	0.0	0.7	0.5	1.6	0.8	1.7	1.1	0.5	-0.5	0.6	0.1	0.8	4.7	0.9
Cartwright	-0.1	1.1	-1.3	-0.5	-1.1	-0.6	-0.9	0.5	-0.3	-0.6	-1.3	-1.6	-1.4	-1.3	-0.6	-0.3	0.5	-0.3	0.6	1.1	0.5	0.6	-0.3	0.4	1.1	0.9	1.8	0.1	0.1	0.4	2.5	0.7	1.4	0.5	0.0	-1.2	-0.3	0.2	-0.2	0.1	1.3
Iqaluit	0.6	1.3	-0.8	-1.5	-1.1	1.1	-0.7	-0.7	-0.1	-1.1	-1.2	-0.5	-1.7	-1.7	-0.4	0.5	0.5	0.3	0.2	0.1	0.4	0.6	-0.1	0.8	0.1	0.9	1.4	0.2	-0.1	0.5	2.7	0.5	0.6	0.2	0.4	-1.2	0.4	0.7	-0.2	-9.1	1.8
Nuuk	0.6	0.1	-1.0	-1.8	-2.0	1.2	0.1	0.0	0.3	-1.2	-0.7	-0.4	-1.4	-1.6	-0.6	-0.2	0.4	0.1	0.2	-0.2	0.4	0.8	0.2	1.3	0.6	1.1	0.7	0.5	0.2	0.5	2.6	-0.2	0.9	0.6	0.5	-1.0	1.3	0.4	-0.2	-1.4	1.5

Figure 3. Scorecard of standardized air temperature anomalies (winter and annual) from 1980 to 2018.

Air temperature anomalies (winter and annual values) at five sites in or close to NAFO subdivisions 2 and 3 (Nuuk Greenland, Iqaluit Baffin Island, Cartwright Labrador, Bonavista and St. John's Newfoundland; see map Figure 1) are shown in Figure 3 in terms of standardized anomalies values between 1980 and 2018 and in Figure 4 and 5 as cumulative annual and monthly anomalies, respectively. These air temperature data, are from the second generation of the Adjusted and Homogenized Canadian Climate Data (AHCCD), which accounts for shifts in the location of stations and changes in observing methods (Vincent et al. 2012). Winter values in 2017, except at Iqaluit and Cartwright, decreased over the previous year with all sites reporting near normal values ranging from 0.1 to 0.5 SD above normal. The annual values were near normal at all station except Bonavista (+0.8 SD). The predominance of warmer-than-normal air temperatures at all sites from the mid-1990s to 2013 are evident with values in 2010 at Cartwright on the mid-Labrador Coast and at Iqaluit on southern Baffin Island reaching 2.5 and 2.7 SD above normal setting 77 and 65 year records, respectively. The cumulative annual air temperature index was close to normal in 2018 after decreasing to the lowest value since 1994 in 2015 (Figure 4). This however masks warmer normal conditions for all stations in March with more than 7°C above normal for Cartwright and Iqaluit followed by a cold spring in May and June for all stations (Figure 5). The NAO-related SLP pattern above the North Atlantic discussed above explains these intra-annual differences.

Figure 4. Cumulative standardized annual air temperature anomalies time series at Nuuk, Iqaluit,

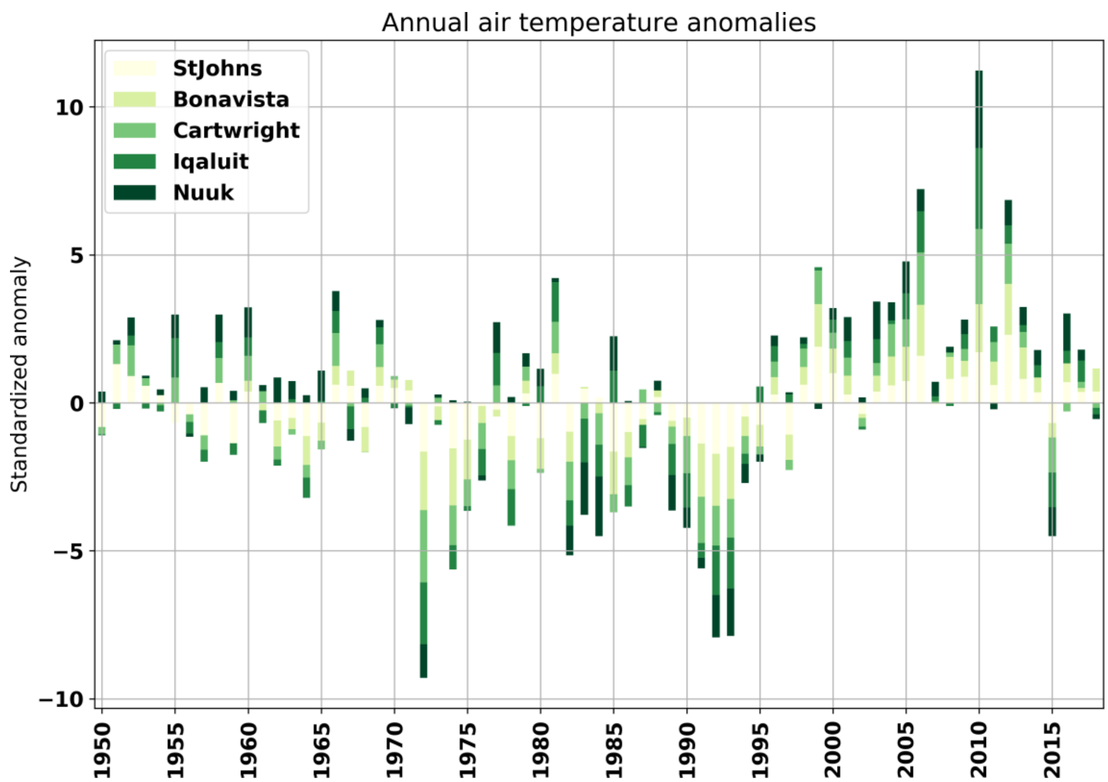


Figure 4. Cumulative standardized annual air temperature anomalies time series at Nuuk, Iqaluit, Cartwright, Bonavista and St. John's.

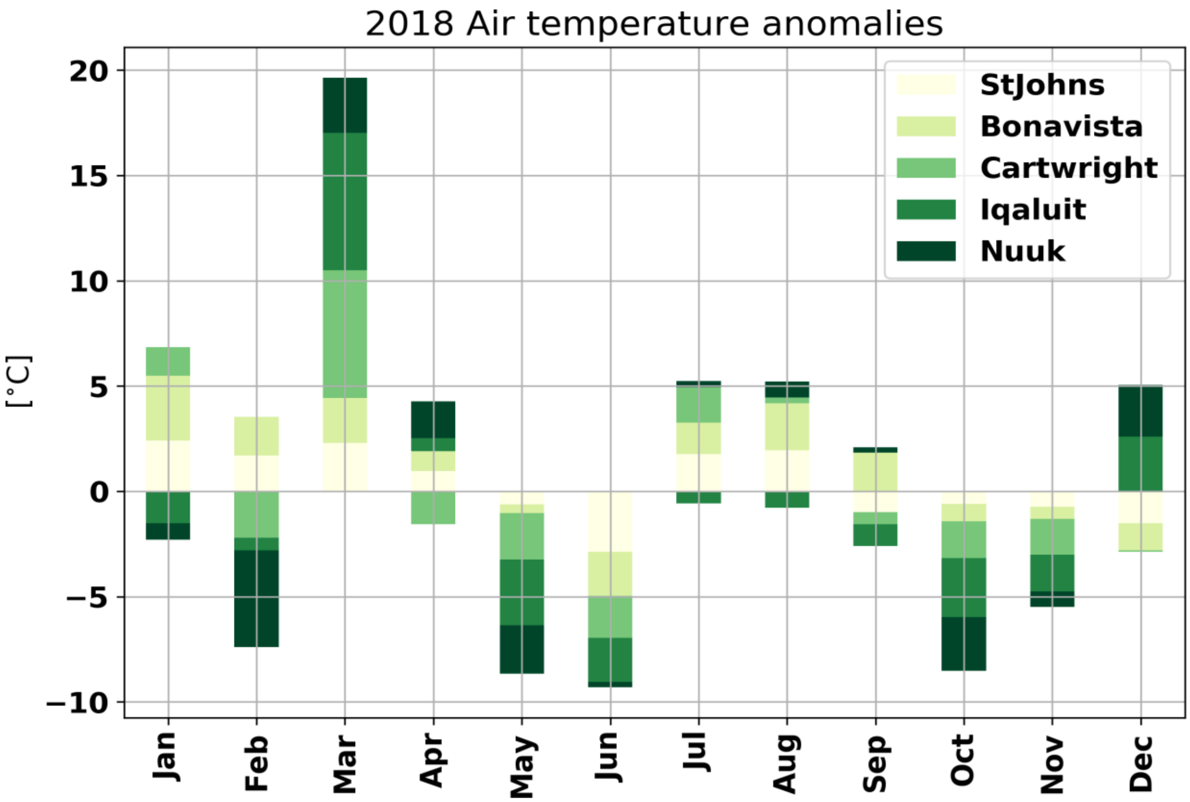


Figure 5. Cumulative monthly air temperature anomalies at Nuuk, Iqaluit, Cartwright, Bonavista and St. John's for 2018.

Annual air temperature anomalies for six sites in the Scotian Shelf-Gulf of Maine region (location in Figure 1) are shown in Figure 6 and Table 1. In 2018, all annual air temperature anomalies were positive with values ranging from +0.2°C at Saint John to +0.8°C at Boston and Yarmouth. 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), +0.8°C (+0.4°C, +1.2°C), +1.1°C (+0.8°C, +1.4°C), +1.2°C (+0.9°C, +1.5°C), +1.3°C (+1.0°C, +1.7°C) and +0.4°C (+0.0°C, +0.8°C), respectively.

The anomalies for all 6 sites are displayed in Figure 7 as a composite sum and illustrate two points: 1) In the 119 year time series shown, 2018 was the 14th warmest year for the region as a whole (with 2012 being the warmest). For most years the anomalies have the same sign. Since 1900, 96 of the 119 years had five or more stations with the annual anomalies having the same signs; for 67 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.

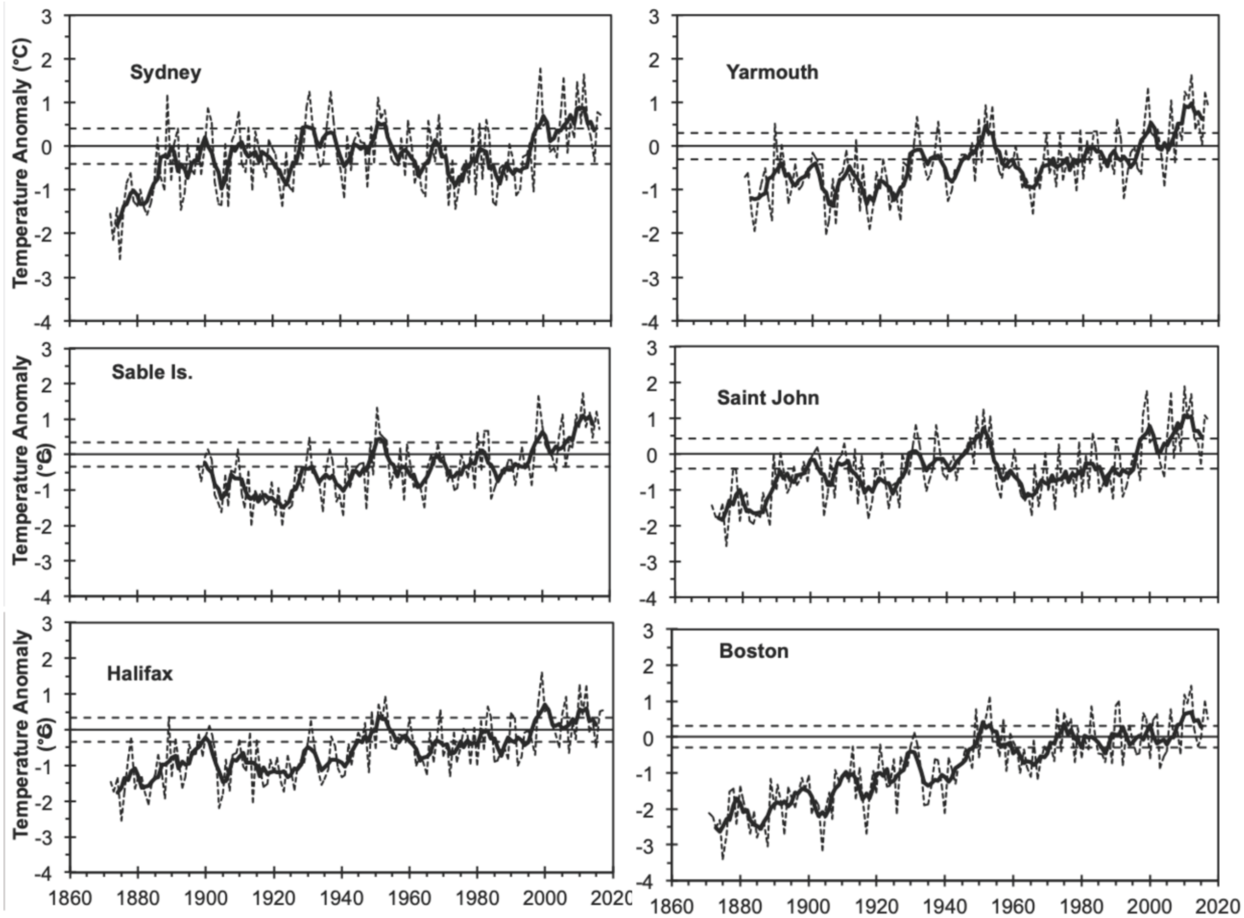


Figure 6. Annual air temperature anomalies in °C (dashed line) and five year running means (solid line) at selected sites (Sydney, Sable Island, Shearwater, Yarmouth, Saint John and Boston) in Scotian Shelf-Gulf of Maine region (years 1860 to 2018). Horizontal dashed lines represent +/-0.5 SD for the 1981-2010 period.

Table 1. The 2018 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	+0.3	+0.3	5.87	0.81
Sable Island	+0.5	+0.8	7.88	0.68
Shearwater (Halifax)	+0.8	+1.2	6.99	0.74
Yarmouth	+0.8	+1.2	7.16	0.62
Saint John	+0.2	+0.2	5.19	0.74
Boston	+0.8	+1.3	10.91	0.60

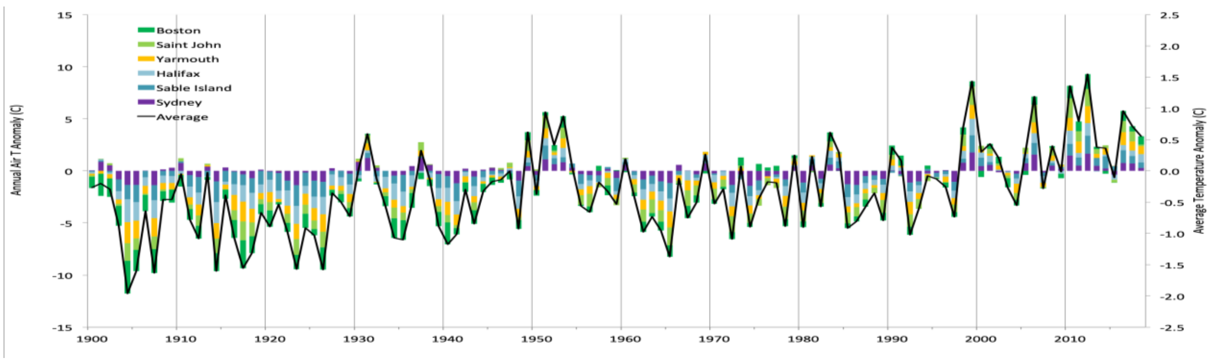


Figure 7. The contributions of each of the annual temperature anomalies for 6 Scotian Shelf-Gulf of Maine sites (Boston, Saint John, Yarmouth, Shearwater, Sable Island and Sydney) are shown as a s tacked bar chart and the average anomaly as a line. Anomalies referenced to 1981-2010.

SEA-ICE CONDITIONS

Ice cover area, volume and season duration are estimated from ice cover products obtained from the Canadian Ice Service (CIS). These are weekly Geographic Information System (GIS) charts covering the period 1969-2019 and daily charts covering the current year of interest. All charts were further processed into regular 0.01° latitude by 0.015° longitude grids (approximately 1 km resolution), with ice concentrations and growth stages attributed to each grid point. Average thicknesses (and therefore regional volumes) are estimated from standard thicknesses attributed to each stage of ice growth from new ice and nilas (5 cm), grey ice (12.5 cm), grey-white ice (22.5 cm), thin first year ice (50 cm), medium first year (95 cm) and thick first year ice (160 cm). Prior to 1983, the CIS reported ice categories into fewer classification using a single category of first year ice (≥ 30 cm) with a suggested average thickness of 65 cm. We have found this value to lead to underestimates of the seasonal maximum thickness and volume based on high inter-annual correlations between the estimated volume of the weekly seasonal maximums with its area and with sea-ice season duration. The comparisons of these correlations pre- and post-1983 provided estimates of 85 cm in the Gulf of St. Lawrence and of 95 cm on the Newfoundland and Labrador Shelf for this single first year ice category, which were used instead of the suggested 65 cm.
Several products were computed to describe the sea-ice cover inter-annual variability. The day of first and last occurrence and duration (Figure 8) and the distribution of ice thickness during the week of maximum volume (Figure 9) are presented as maps. Regional scorecards of anomalies in the first and last day of ice, duration of the sea ice season and maximum ice volume are presented in Figure 10 for the Labrador and Newfoundland shelves. Here, the area defined as Labrador shelf spans from 52° 15’ N to 55° 20’ N, matching the latitude limits of NAFO Division 2J, and the area defined as the Newfoundland Shelf is anywhere south of that. Daily evolution of the ice volume during the 2018 ice season is presented in Figure 11 for Labrador (top) and Newfoundland (bottom) shelves in relation to the climatology and historical extremes. Time series of seasonal maximum ice volume, area (excluding thin new ice) and ice season duration in relation with December-to-May air temperature anomaly at Cartwright is presented in Figure 12.

Ice typically forms first in December along the Labrador coast and only by late February at the southern extent of sea-ice presence (Figure 8). Last occurrence is typically in late June to early July on the Labrador coast, leading to sea-ice season durations of 23 weeks or more. There has been a declining trend in ice cover severity since the early 1990s reaching the lowest values of the time series in 2011 and 2010, with a rebound in 2014 (Figure 10 and 12). The sea ice metrics of annual maximum ice volume, annual maximum area ice cover duration are well correlated with each other (R^2 = 0.77; Figure 12), and the best correlation found with air temperature was between the December-May air temperature anomaly at Cartwright and the sea-ice metrics of the Newfoundland Shelf (R^2 = 0.70-0.81), indicative of the advective nature of the Newfoundland Shelf sea ice; i.e. strong ice covers are associated with cold air temperatures in the source area. Sensitivity of the Newfoundland Shelf ice cover to air temperature increase (e.g. through climate change) can thus be estimated using 1969-2018 co-variations between winter air temperature and sea-ice parameters, which indicate losses of 16 km^3, 26,000 km^2 and 17 days of sea-ice season for each 1°C increase in winter air temperature. These values are similar to those obtained for the Gulf of St. Lawrence (Galbraith et al., 2018).

In 2018, the sea-ice cover first appeared at a date ranging from near-average to later than normal by a few weeks (Figure 8), leading to regional averages that were earlier-than normal average on the Labrador Shelf and near-normal on the Newfoundland Shelf (Figure 11). Last occurrence varied between later than normal near-shore to earlier than normal offshore (Figure 8), averaging out to near-normal timing (Figure 11). Sea ice cover volume progressed below normal until April on the Labrador Shelf, and up to late February on the Newfoundland Shelf (Figure 11). The ice cover declined sharply on the Newfoundland Shelf in March before rebounding to near-normal conditions for the time of year by late April. The seasonal maximum combined ice volume was below normal at 94 km^3 (-0.8 SD), occurring the week of April 16^{th} (Figure 11) which is a bit late; The durations of 170 and 113 days respectively on the Labrador Shelf and Newfoundland Shelf were near-normal (-1.1 SD).

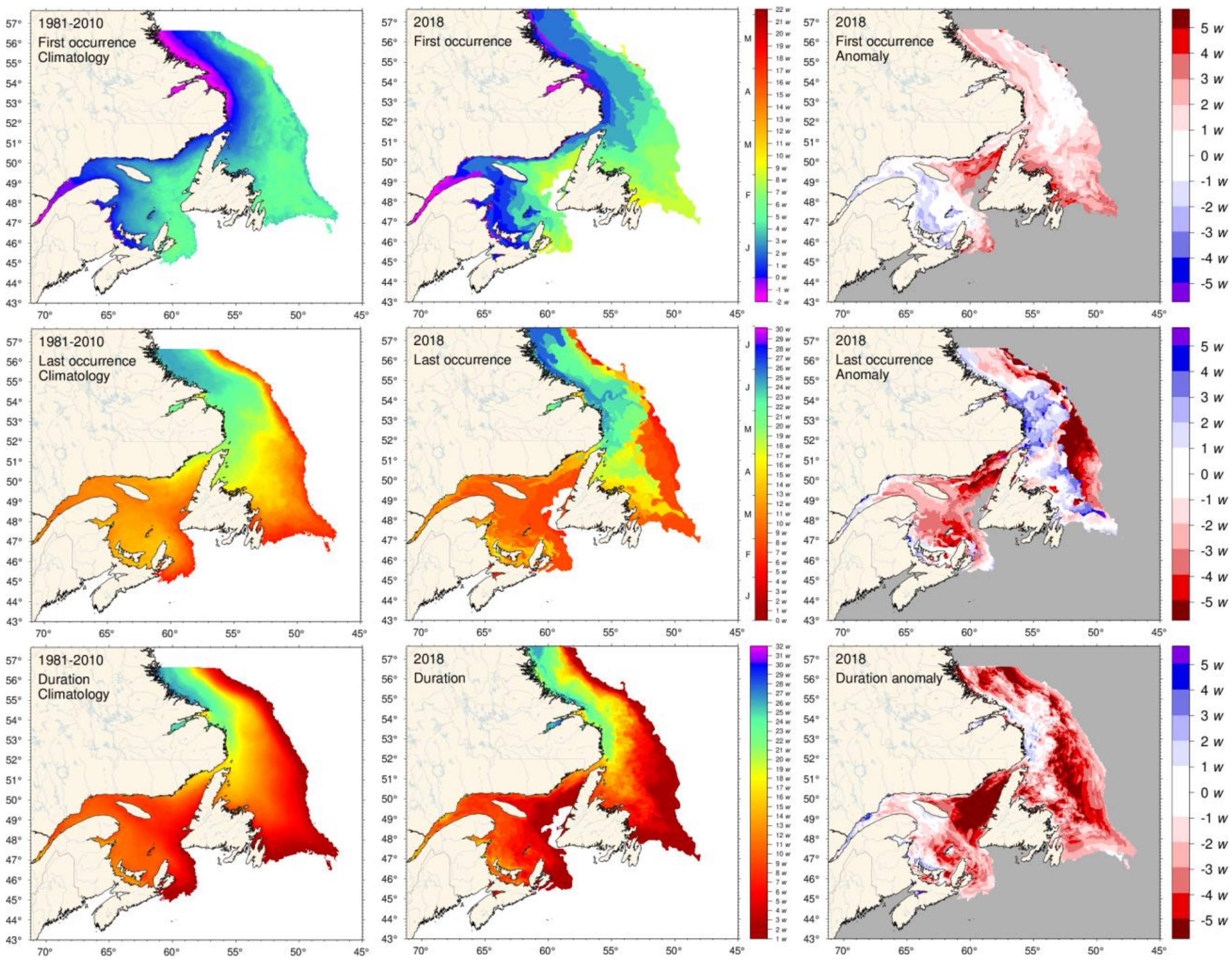


Figure 8. First and last occurrence of ice and ice season duration based on weekly data. The 1981-2010 climatologies are shown (left) as well as the 2018 values (middle) and anomalies (right). First and last occurrence is defined here as the first and last weekly chart in which any amount of ice is recorded for each pixel and are illustrated as day-of-year. Ice duration sums the number of weeks with ice cover for each pixel. Climatologies are shown for pixels that had at least 15 years out of the 30 with occurrence of sea-ice, and therefore also show the area with 50% likelihood of having some sea-ice at any time during any given year. The duration anomaly map includes pixels with no ice cover where some was expected based on the climatology.

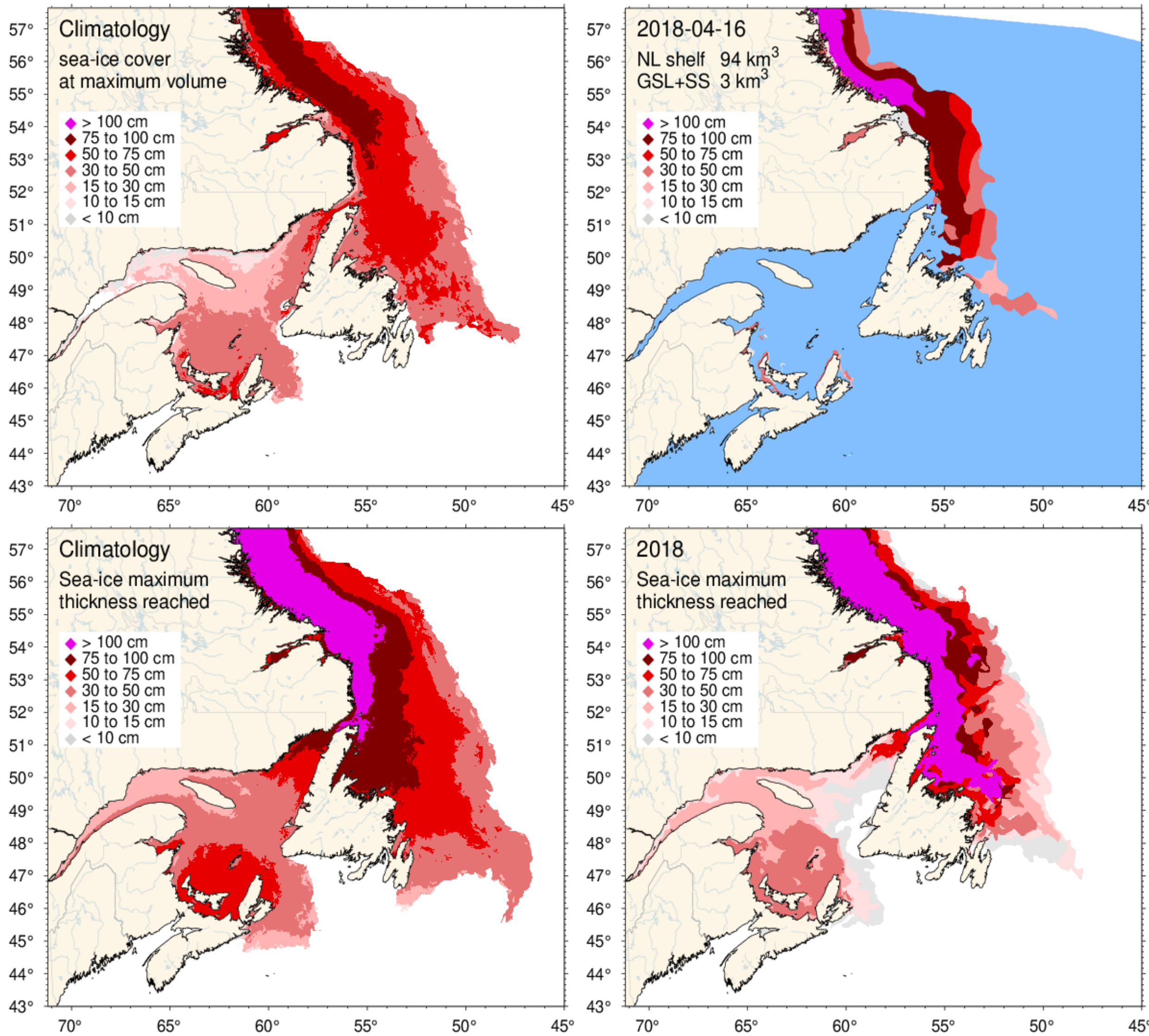


Figure 9. Ice thickness map for 2018 for the week of the year with the maximum annual volume on the Newfoundland and Labrador Shelf (upper right panel) and similarly for the 1981-2010 climatology of the weekly maximum (upper left panel). Note that these maps reflect the ice thickness distribution on that week, and not the maximum observed at any given location during the year. That information is shown by the lower panels, showing the 1981-2010 climatology and 2018 distribution of the thickest ice recorded during the season at any location.

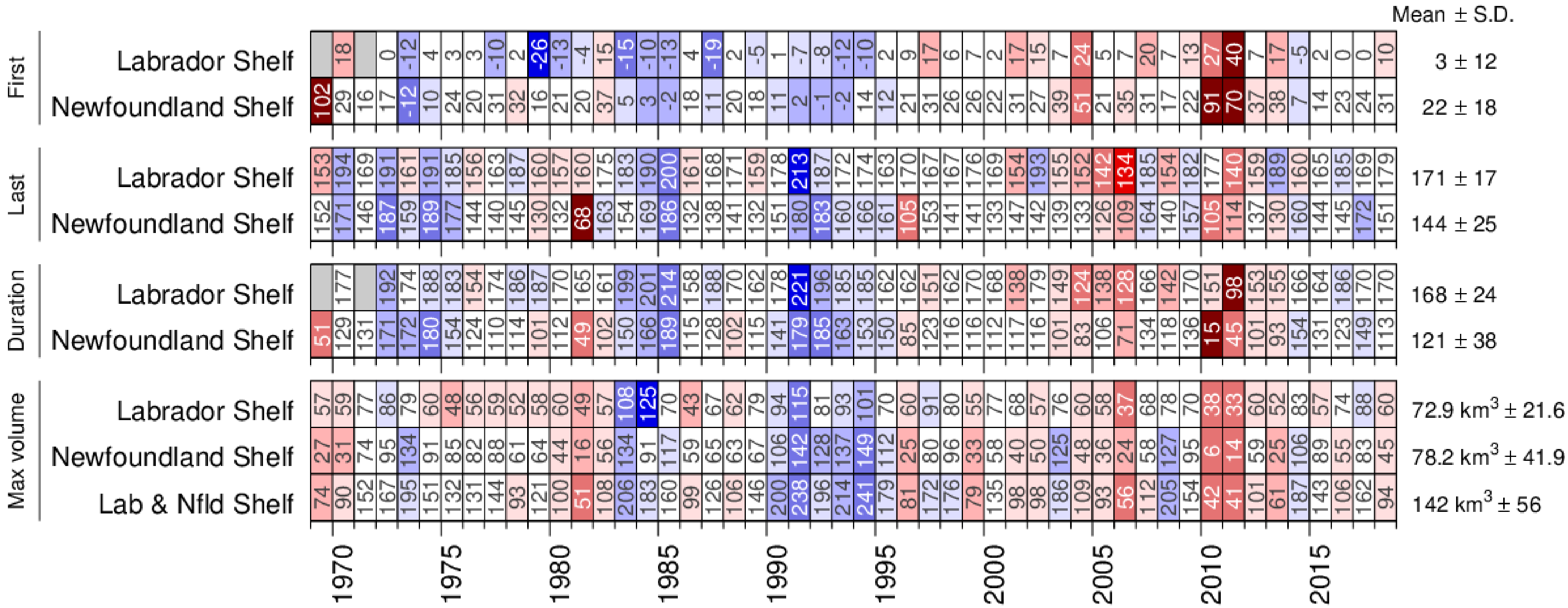


Figure 10. First and last day of ice occurrence, ice duration and maximum seasonal ice volume by region. The time when ice was first and last seen in days from the beginning of each year is indicated for each region, and the color code expresses the anomaly based on the 1981–2010 climatology, with blue (cold) representing earlier first occurrence and later last occurrence. The threshold is 5% of the climatological average of the seasonal maximum ice volume. Numbers in the table are the actual day of the year or volume, but the color coding is according to normalized anomalies based on the climatology of each region. Duration is the numbers of days that the threshold was exceeded.

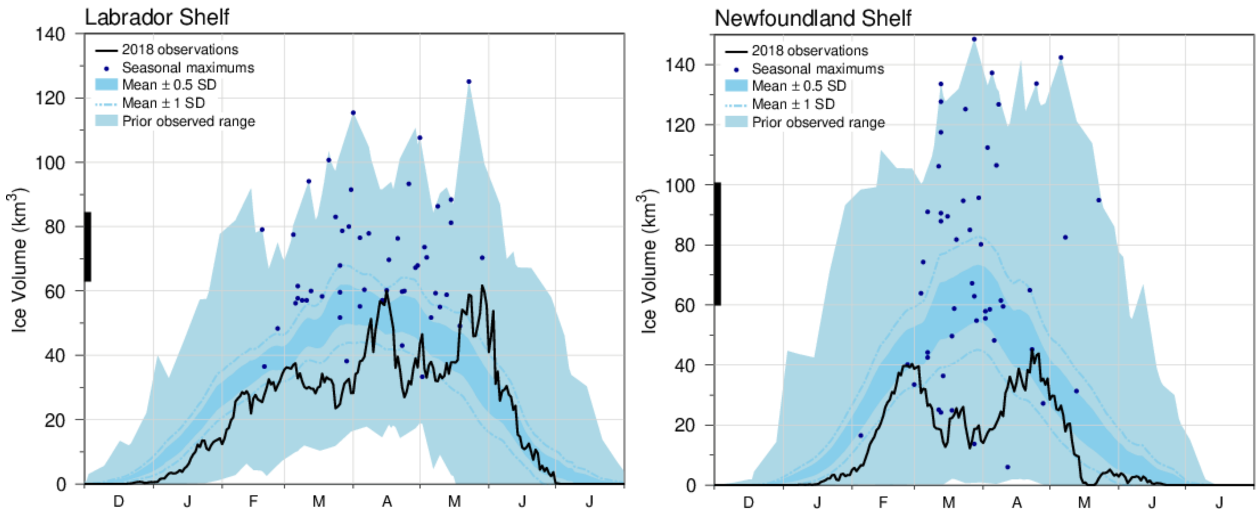


Figure 11. Time series of the 2017-2018 daily mean ice volume (black lines) for the Labrador Shelf (top) and Newfoundland Shelf), the 1981-2010 climatological mean volume plus and minus 0.5 and 1 SD (dark blue area and dashed line), the minimum and maximum span of 1969- 2018 observations (light blue) and the date and volumes of 1969-2018 seasonal maximums (blue dots). The black thick line on the left indicates the mean volume plus and minus 0.5 SD of the annual maximum ice volume, which is higher than the peak of the mean daily ice volume distribution.

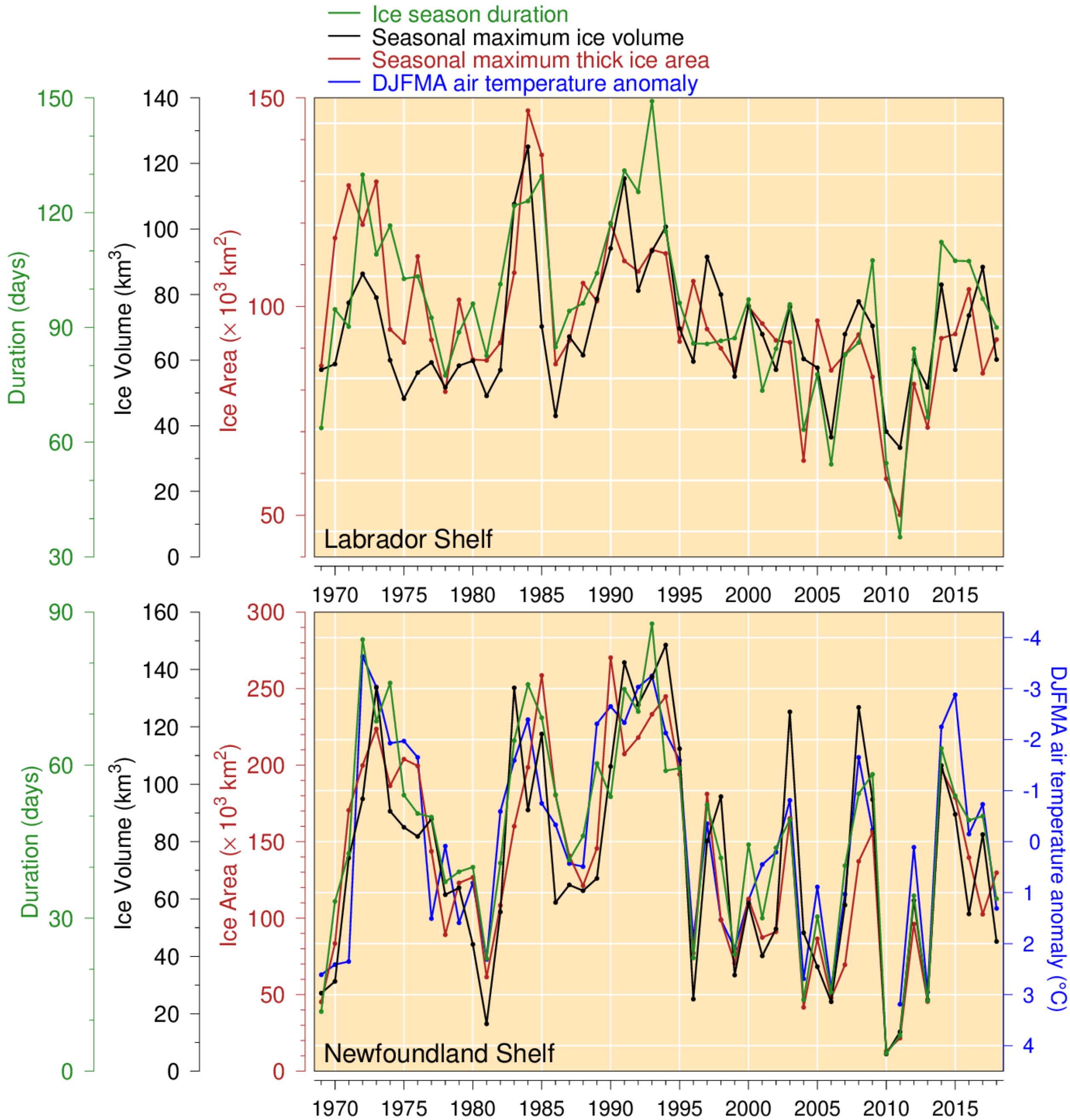


Figure 12. Seasonal maximum ice volume and area including the portion on the Scotian Shelf (excluding ice less than 15 cm thick), ice season duration and December-to-April air temperature anomaly at Cartwright.

Satellite Sea-Surface Temperature Conditions

The 4 km resolution Pathfinder 5.2 sea surface temperature (SST) database (Casey et al., 2010) was used to provide annual estimates of the SST within defined sub-areas in the Northwest Atlantic from southern Newfoundland to Hudson Strait, the Labrador Sea and West Greenland (see map Figure 13). We used this data set from 1981 to 2010 and in more recent years (2011-2018) we use data from NOAA and EUMETSAT satellite data provided by the remote sensing group in the Marine Ecosystem Section at the Bedford Institute of Oceanography (BIO).

A least squares fit of the Pathfinder and NOAA temperatures during the period (1997-2012) is given by SST (Pathfinder) = 0.989*SST (NOAA) -0.02 with an r^2=0.98 (Hebert et al. 2012). The recent NOAA SST data were then adjusted accordingly and anomalies computed based on 1981-2010 averages. A comparison of the Pathfinder data with near-surface measurements indicate that SST derived from night satellite passes provided the best fit with *in situ* data. Data were not available for every month in some of the northern areas due to sea ice cover.

2018 monthly SST anomalies for 16 areas from West Greenland to Hudson Strait to Green and St. Pierre Banks off southern Newfoundland (see map Figure 13) are presented in Figure 14 and show that SST were generally colder than normal between April and July and warmer than normal between August and October. In November, while most of the regions exhibited colder than normal conditions, SST for the Greenland Shelf box was 2.0 SD above average.

Figure 15 show scorecards of annual anomalies for these regions. This figure exhibit generally colder than normal conditions for all region between 1981 and 1993, followed by warmer than normal conditions that lasted until approximately 2014. The recent years have shown slightly colder than normal conditions, including for 2018 that was specially cold along the Labrador coast, e.g. -1.9, -1.6 and -0.9 SD below normal for Hudson Strait, Hamilton Bank and St. Antony Basin, respectively. The annual time series of the average SST anomalies over all these regions is presented in Figure 16 as a bar plot graphic. On average for all the 16 regions, the SST was -0.6 SD below normal, in accordance with the near decadal pattern described above.

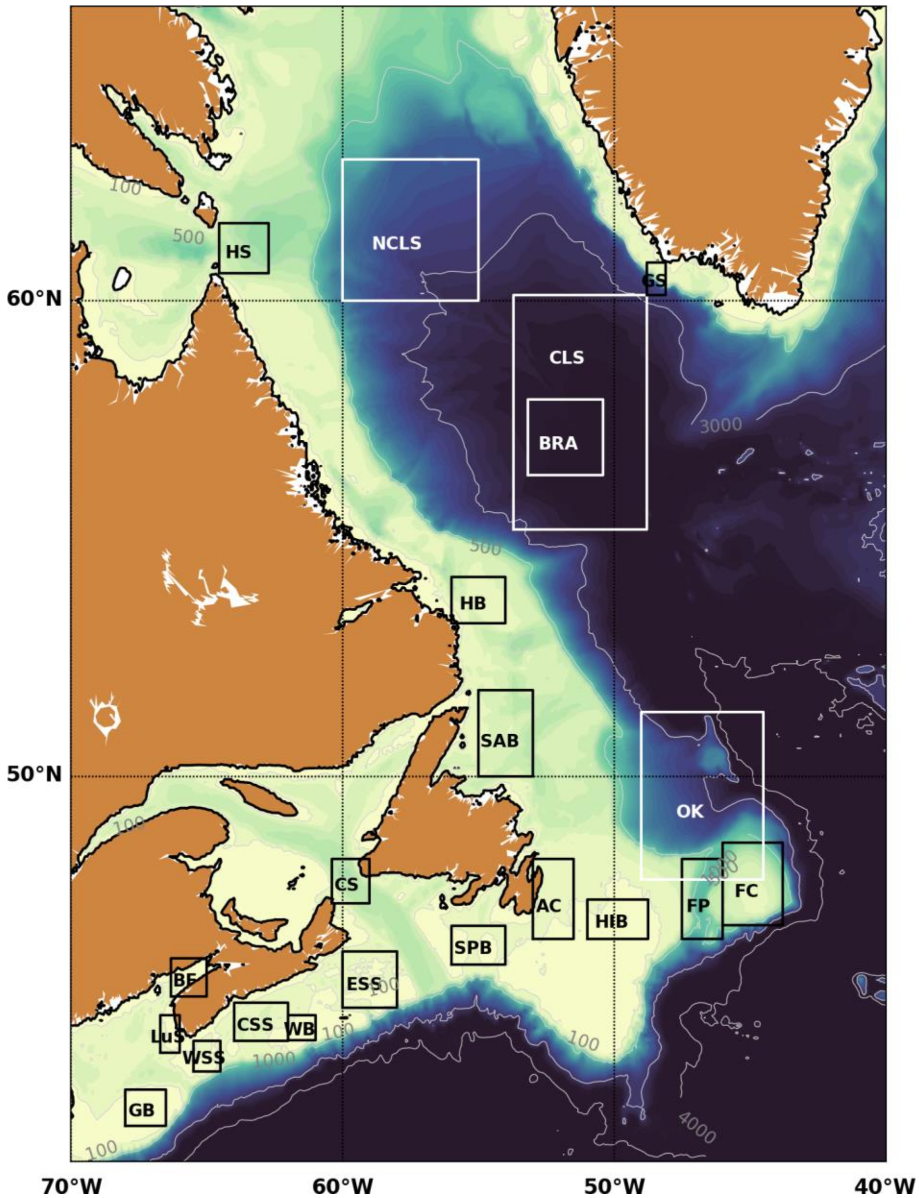


Figure 13. Map showing the standard boxes used to extract sea surface temperature anomalies presented in this report. These regions, from north to south, are: Northern Labrador Shelf (NCLS), Hudson Strait (HS), Central Labrador Sea (CLS), Station Bravo (BRA), Hamilton Bank (HB), St. Antony Basin (SAB), Orphan Knoll (OK), Flemish Cap (FC), Flemish Pass (FP), Hibernia (HIB), Avalon Channel (AC), Green-St. Pierre Bank (SPB), Cabot Strait (CS), Eastern Scotian Shelf (ESS), Bay of Fundy (BF), Western Bank (WB), Central Scotian Shelf (CSS), Lurcher Shoals (LuS), Western Scotian Shelf (WSS) and Georges Bank (GB).

	-- 2018 Monthly Sea Surface Temperature anomalies --											
	J	F	M	A	M	J	J	A	S	O	N	D
Avalon Channel (AC)	0.9	1.0	0.6	-0.6	-0.3	-1.8	-2.2	1.0	1.1	0.6	-1.1	-0.6
Bravo (BRA)	0.0	-0.4	0.6	0.2	-0.5	0.1	-0.6	-0.1	-0.5	-0.8	-0.5	-1.3
Cent. Lab. Sea (CLS)	-0.2	0.0	0.1	0.0	-0.5	-0.2	-0.7	-0.2	-0.5	-0.7	-0.8	-0.8
Flemish Cap (FC)	-0.6	-0.1	-0.1	-0.8	-1.4	-1.4	-1.8	0.6	1.2	1.2	-1.6	-1.1
Flemish Pass (FP)	-0.4	-0.7	-0.1	-0.6	-1.1	-1.5	-1.8	0.9	1.2	0.7	-1.4	-0.1
Greenland Shelf (GS)	-0.7	-0.6	-0.6	-0.2	-0.3	-0.3	-1.1	1.3	1.1	0.9	2.0	0.6
St.Pierre Bank (SPB)	0.0	1.6	0.7	-0.1	-0.2	-1.5	-1.7	1.0	1.7	1.0	-0.9	-1.0
Hamilton Bank (HB)	-0.6	-0.6	-0.7	-0.9	-0.8	-1.5	-0.5	-0.6	-2.0	-0.9	-0.1	-0.9
Hudson Strait (HS)	-0.5		-0.5	-0.4	-1.2	-2.2	-2.0	-0.8	-0.7	-0.2	-1.8	-0.8
Hibernia (HIB)	0.9	1.2	0.9	-0.1	0.0	-0.9	-2.0	0.8	1.3	0.4	-0.7	-1.1
NC Lab. Sea (NCLS)	0.1	0.0	-0.1	-0.3	-1.2	-1.3	-0.9	-0.1	-0.1	-0.2	-0.6	0.3
NE NF shelf (NENS)	0.0	-0.6	-0.7	-1.6	-1.0	-2.1	-0.7	1.1	0.5	-0.3	-0.5	0.1
Orphan Knoll (OK)	0.0	-0.2	0.6	0.0	-0.7	-1.5	-1.4	0.2	0.8	0.6	-0.9	-0.2
St. Antony B. (SAB)	-1.0	-0.8	-0.7	-1.6	-0.8	-1.7	-0.2	0.2	-0.4	-0.5	0.2	0.8

Figure 14. 2018 standardized monthly anomalies of SST for NL regions (see boxes Figure 13)

	-- Sea Surface temperature anomalies --																																							
	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	$\bar{x}$	sd
Avalon Channel (AC)	-1.8	-0.8	0.8	-0.1	-1.8	-1.4	-0.1	0.9	-0.7	-0.3	-1.6	-1.2	-0.7	1.0	0.4	-0.1	-1.2	0.6	1.2	1.1	0.2	-0.5	0.4	0.8	1.4	1.9	0.0	0.9	0.0	0.6	0.3	1.6	1.0	0.8	0.0	0.3	0.2	-0.4	4.9	0.7
Bravo (BRA)	-1.3	-1.1	-2.0	-1.6	-1.1	-0.8	-0.4	-0.4	-0.7	-1.1	-0.4	-0.5	-0.4	-0.3	0.0	0.0	0.8	0.6	0.1	-0.2	0.5	0.2	1.5	1.1	1.4	1.6	1.0	1.3	0.3	1.7	0.4	1.1	0.5	1.0	0.0	0.5	0.3	-0.4	4.3	0.8
Cent. Lab. Sea (CLS)	-0.9	-1.4	-1.7	-2.0	-0.9	-0.5	-0.2	-0.2	-0.8	-1.1	-0.3	-0.4	-0.9	-0.1	-0.6	0.0	0.8	0.7	0.0	-0.2	0.7	0.3	1.5	1.2	1.3	1.5	1.0	1.1	0.3	1.8	0.3	0.8	0.6	0.8	-0.1	0.5	0.3	-0.4	4.2	0.9
Flemish Cap (FC)	-0.4	-0.7	0.5	-0.6	-2.4	-1.0	0.3	0.6	-0.4	-1.0	-1.4	-1.3	-1.2	-1.0	0.1	0.4	0.0	0.7	1.1	0.7	0.3	-0.3	0.4	1.1	1.9	1.7	0.7	1.0	-0.6	0.8	0.6	1.8	0.7	-0.6	-1.5	-0.9	-0.4	-0.7	7.1	0.9
Flemish Pass (FP)	-0.6	-0.7	0.4	-0.5	-2.2	-0.8	0.2	1.0	-0.5	-1.4	-1.5	-1.4	-1.5	-0.3	0.3	0.0	-0.3	0.9	1.1	1.0	0.3	-0.2	0.8	1.1	1.8	1.5	0.4	1.0	-0.7	0.7	0.3	1.4	0.4	-0.6	-1.3	-0.7	0.4	-0.7	5.7	0.8
Greenland Shelf (GS)	-1.6	-1.5	-1.8	-1.2	0.7	-0.1	0.3	-0.3	-1.6	-0.8	0.3	-0.7	-0.2	0.3	1.9	0.0	0.6	-0.2	-0.9	-0.3	0.1	0.5	1.8	1.0	1.0	0.0	0.1	-0.1	0.7	2.0	-0.3	0.4	0.4	0.5	-0.3	1.1	0.3	0.2	1.5	0.9
St.Pierre Bank (SPB)	0.3	-0.5	1.1	0.4	-2.5	-1.4	-0.2	-0.2	-0.5	-0.9	-1.5	-1.3	-0.5	1.1	0.0	-0.1	-1.1	0.7	1.6	1.3	0.1	-0.7	0.1	0.3	1.5	1.4	-0.3	0.8	0.1	0.8	0.2	2.4	1.3	1.2	0.2	1.1	0.4	-0.2	6.1	0.7
Hamilton Bank (HB)	-1.7	-0.6	-0.5	-1.0	-0.9	-0.5	-0.5	-0.5	-0.1	0.0	-1.1	-1.1	0.4	1.1	2.6	-1.5	-0.2	0.5	-0.5	0.7	0.0	-0.9	0.9	0.8	0.9	1.5	-0.5	1.6	-0.3	1.1	0.7	1.6	-0.6	0.3	-0.3	-0.6	-0.1	-1.6	1.5	0.5
Hudson Strait (HS)	-1.5	-0.1	-0.3	-1.1	-0.3	1.3	0.6	-0.6	-1.2	0.8	0.5	0.6	1.1	1.2	2.8	0.2	-0.7	-0.8	-1.9	-0.2	-0.2	0.0	-0.2	0.2	0.5	-0.4	-1.1	-0.8	-0.2	1.7	-0.8	0.0	-1.3	-0.6	-1.3	-0.5	-1.6	-1.9	0.1	0.4
Hibernia (HIB)	-0.9	-0.7	1.0	0.0	-2.0	-1.6	-0.4	0.8	0.1	-0.6	-1.5	-1.4	-1.2	0.3	0.6	0.1	-0.9	1.1	1.3	1.3	0.1	-0.5	0.4	0.5	1.0	2.1	0.7	0.6	-0.4	0.4	0.3	2.3	0.9	0.3	0.0	-0.2	-0.7	-0.1	5.7	0.8
NC Lab. Sea (NCLS)	-1.4	-1.1	-1.4	-1.4	-0.3	0.4	-0.8	-0.1	-1.1	-1.1	-0.4	-0.5	-0.9	-0.4	-0.4	0.4	0.7	0.8	-0.5	-0.3	0.9	0.8	1.4	1.6	1.5	1.2	0.7	-0.3	-0.3	2.2	0.0	-0.2	0.0	-0.1	-0.7	0.4	-0.1	-0.4	2.8	1.1
NE NF shelf (NENS)	-2.3	-0.6	-0.2	-0.5	-0.9	-0.6	-0.2	0.0	-0.1	0.2	-1.7	-1.4	-0.7	1.3	1.9	-0.5	-0.7	0.7	0.4	0.5	0.2	-0.5	0.3	0.9	1.5	1.9	-0.4	1.2	-0.5	0.8	0.5	1.1	0.3	0.8	-0.8	-0.4	-0.3	-0.5	3.5	0.7
Orphan Knoll (OK)	-1.3	-0.6	-0.3	-1.4	-2.0	-0.5	0.1	0.3	-0.9	-0.8	-1.4	-1.1	-0.9	-0.9	0.2	0.1	0.4	0.8	0.5	0.5	0.6	0.0	0.5	1.3	1.9	1.9	0.7	1.2	-0.1	1.3	0.8	1.7	0.8	0.6	-0.9	0.0	0.4	-0.3	6.0	0.8
St. Antony B. (SAB)	-1.9	-0.8	-0.4	-0.8	-0.5	-0.6	-0.5	-0.2	0.8	-0.8	-1.1	-1.1	-0.8	1.5	-0.5	-0.8	-0.1	0.7	0.3	0.8	0.2	-0.7	0.7	1.1	1.7	2.3	-0.7	1.5	-0.5	1.1	0.6	1.7	-0.3	0.6	-0.8	-0.5	-0.3	-0.9	2.6	0.6

Figure 15. Annual standardized anomalies of SST for the NL regions (see boxes Figure 13)

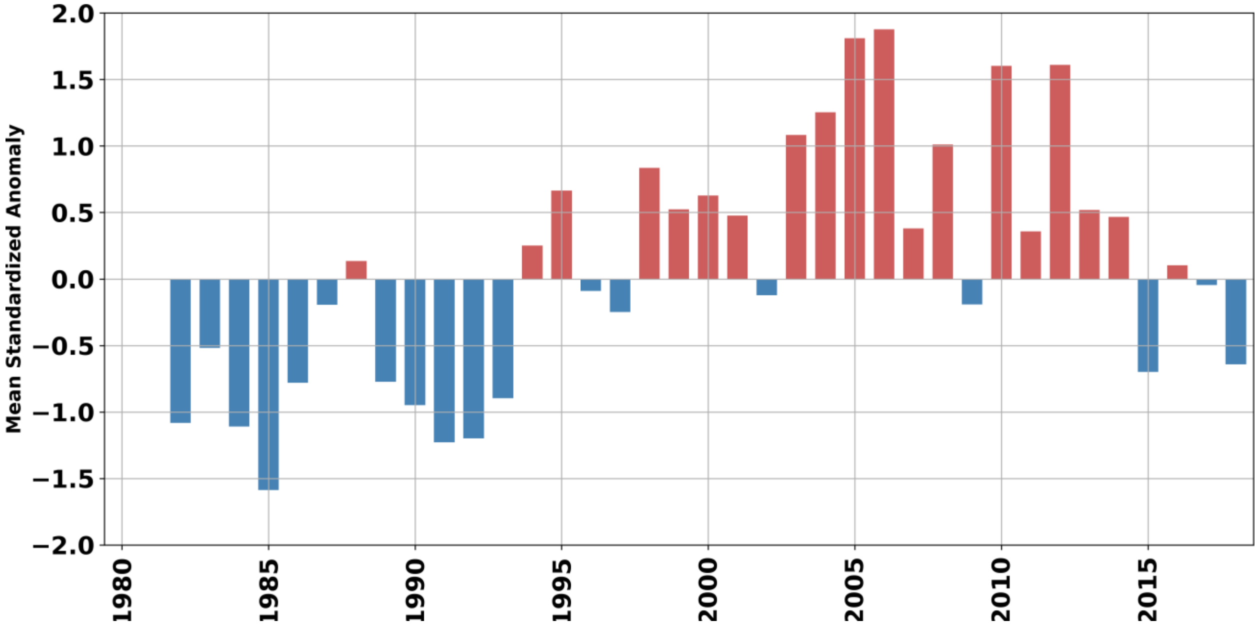


Figure 16. Mean standardized anomalies of SST for all NL regions (average over all rows of the scorecard of Figure 15).

Annual anomalies were calculated from monthly averaged temperatures for 8 subareas in the Scotian Shelf-Gulf of Maine region (see map Figure 13) and are presented in Figure 17 and in Table 2. The annual anomalies during 2018 ranged from -0.4ºC (-0.6 SD) in Cabot Strait to +1.2ºC (+2.0 SD) in the Bay of Fundy. 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 0.3ºC/decade (Cabot Strait) to a highest value of 0.6ºC/decade (Central Scotian Shelf, Western Scotian Shelf and Bay of Fundy). A similar trend in SST from AVHRR measurements was found in the Gulf of St. Lawrence (Galbraith et al., 2012) and on the NL 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 and a rapid temperature increase from 1997 as part of the decadal cycles described above (e.g., Figure 16).

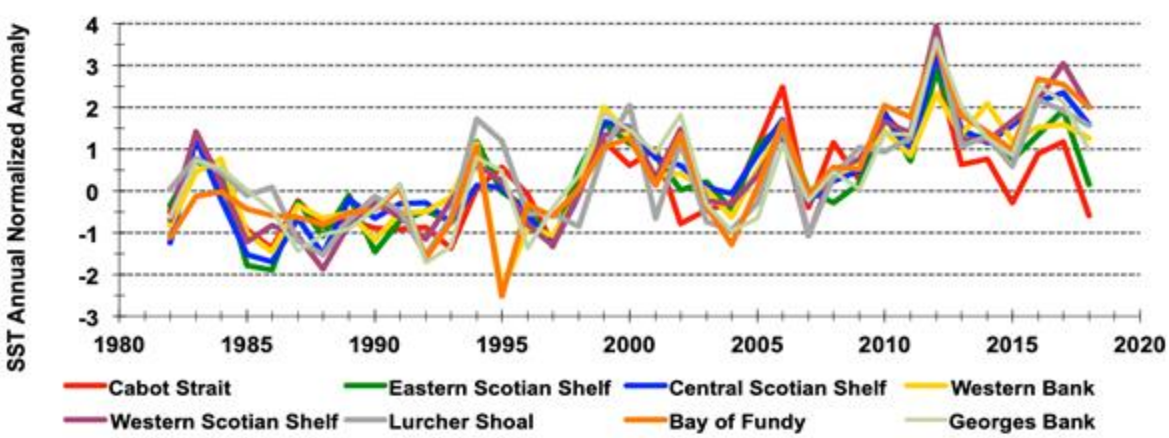


Figure 17. Time series of the annual SST standardized anomaly for all 8 regions of the Scotian Shelf and Gulf of Maine areas (see map Figure 13).

Table 2. SST statistics for all 8 regions of the Scotian Shelf and Gulf of Maine areas. Abbreviation correspond to the boxes drawn in the map of Figure 13. The last column represent the warming trend per decade.

Site	2018 SST anomaly (ºC)	2018 SST std anomaly	1981-2010 average (ºC)	1981-2010 Std. Dev. (ºC)	1982-2018 Trend (ºC/decade)
Cabot Strait (CS)	-0.4	-0.6	5.9	0.6	0.3
Eastern Scotian Shelf (ESS)	+0.1	+0.2	7.1	0.7	0.4
Central Scotian Shelf (CSS)	+1.1	+1.6	8.5	0.7	0.6
Western Bank (WB)	+1.1	+1.3	8.9	0.8	0.6
Western Scotian Shelf (WSS)	+1.2	+2.0	8.1	0.6	0.5
Lurcher Shoal (LuS)	+1.1	+1.6	7.2	0.7	0.4
Bay of Fundy (BF)	+1.3	+2.0	7.2	0.6	0.6
Georges Bank (GB)	+0.5	+1.0	10.0	0.5	0.4

OCEAN CONDITIONS ON NEWFOUNDLAND AND LABRADOR SHELF
(NAFO SUB-DIV 2 AND 3)

Long-term observations at Station 27

Station 27 (47° 32.8' N, 52° 35.2' W), is located in the Avalon Channel off Cape Spear, NL (Figure 1). It is one of longest hydrographic time series in Canada with frequent occupations (near-monthly basis) since 1948. In 2018, the station was occupied 36 times (27 CTD casts, including 16 biogeochemical sampling and 9 XBT). No observations were available for January and February and only one occupation was done in March. In addition, a total of 202 CTD profiles were collected from an automatic profiling system installed on a surface buoy (type *Viking*) between 15 July and 14 November 2018 (see Figure 18). This figure shows the seasonal warming of the top layer (~20m), with temperature peaking in August before being mixed during the fall. The cold intermediate layer, a remnant of previous winter cold layer and defined as temperature below 0^{o}C is also evident below 100m throughout the summer. This layer is discussed in the next section. In 2018, the surface layer was freshest between early September and mid-October, with salinities <31. These low near-surface salinities, generally from early summer to late fall is a prominent feature of the salinity cycle on the Newfoundland Shelf and is due largely to the melting of sea-ice off the coast.

Averaged over the entire water column (0-176 m), the annual temperature and salinity anomalies calculated from all occupations of the station are presented in Figure 19. In 2018, the vertically averaged temperature was above normal by about 0.3^{o}C, coherent with the dominance of warmer than normal temperatures observed since the early 2000s. The vertically averaged salinity was at its freshest state since the beginning of the time series in 1950 with more than 0.3 salinity units below the climatological mean (note that 2017 was the 3rd freshest). This beats the previous record from 1970, which corresponded to a period called the *Great Salinity Anomaly* in the North Atlantic (Dickson et al., 1988).

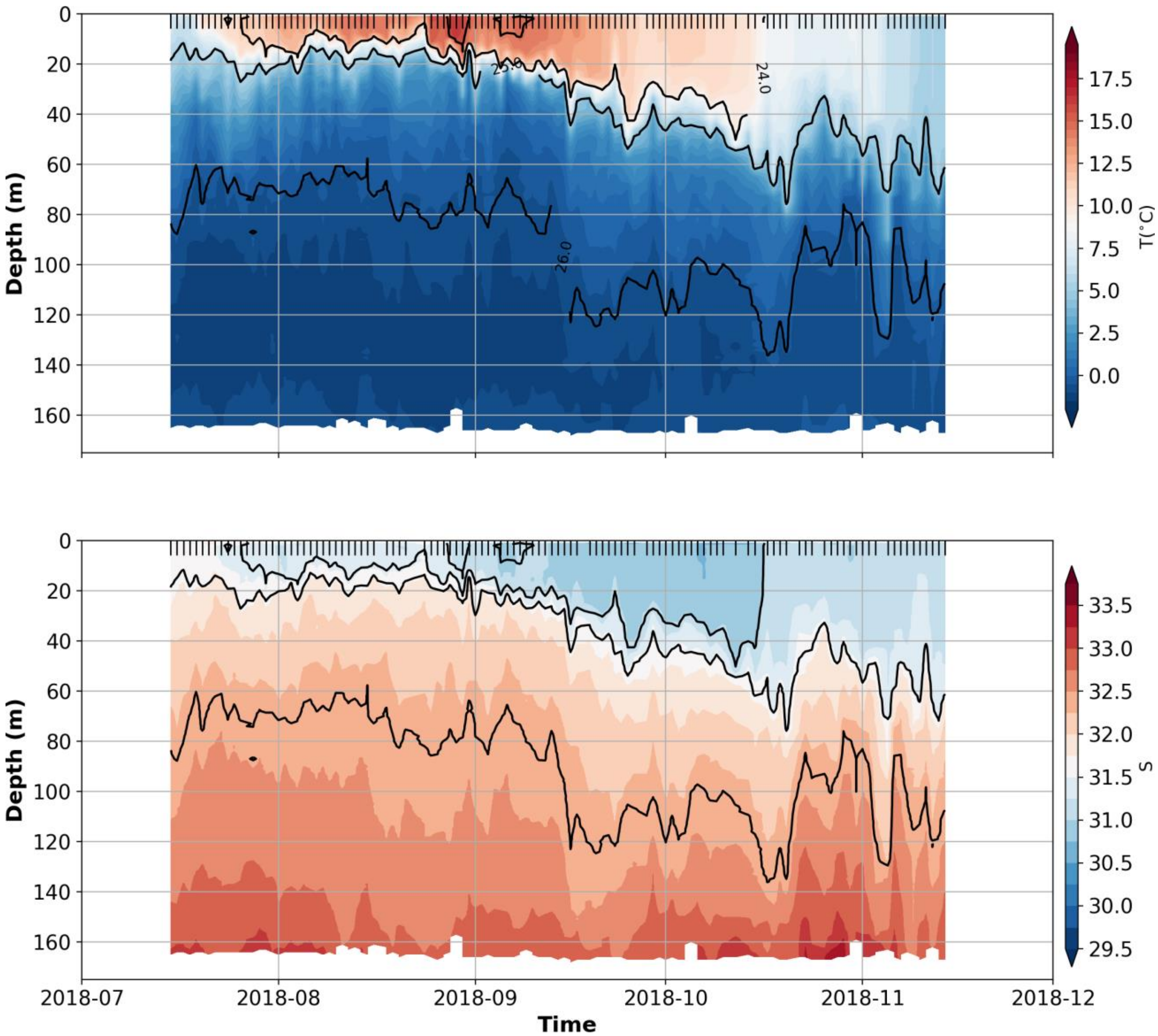
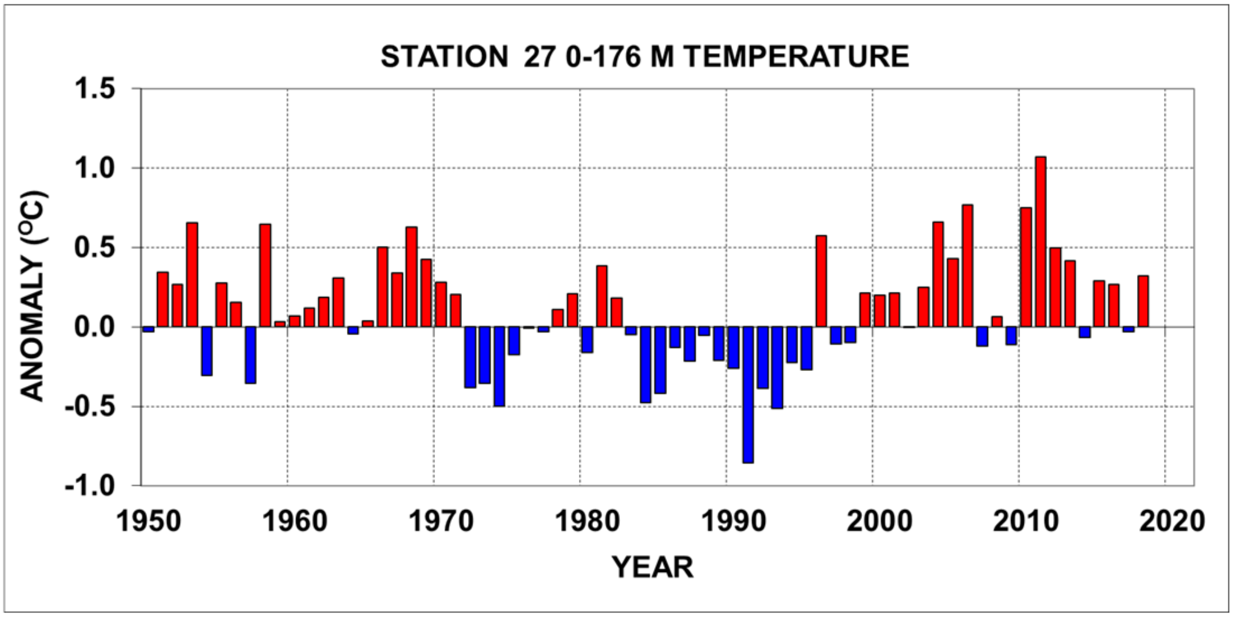


Figure 18. Temperature (top) and salinity (bottom) fields as measured by the Viking buoy automatic profiling system. Isopycnals (σ_t, black lines) are identified on top panel. All casts have been averaged in daily mean profiles (marked as black tick marks on the top of the Figure) before being linearly interpolated in time.



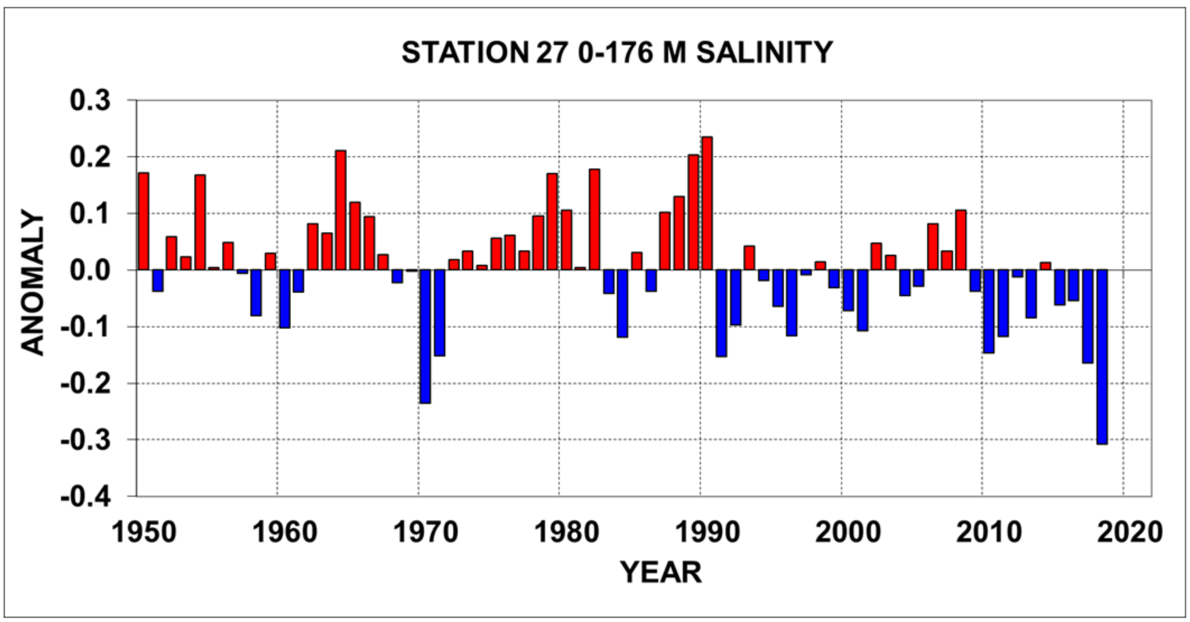


Figure 19. Verticaly averaged (0-176m) temperature (top) and salinity (bottom) anomalies at Station 27 since 1950.

Standard Hydrographic Sections

In the early 1950s, several countries under the auspices of the International Commission for the Northwest Atlantic Fisheries (ICNAF) carried out systematic monitoring along hydrographic sections in Newfoundland and Labrador waters. In 1976, ICNAF standardized a suite of oceanographic monitoring stations along sections in the Northwest Atlantic Ocean from Cape Cod (USA) to Egedesminde (West Greenland) (ICNAF 1978). In 1998 under the Atlantic Zone Monitoring Program (AZMP) of Fisheries and Oceans Canada, the Seal Island (SI), Bonavista Bay (BB), Flemish Cap (47°N) (FC) and Southeast Grand Bank (SEGB) historical stations were selected as core monitoring sections. The White Bay section (WB) was continued to be sampled during the summer as a long time series ICNAF/NAFO section (see map Figure 1).

Two ICNAF sections on the mid-Labrador Shelf, the Beachy Island (BI) and the Makkovik Bank (MB) sections were selected to be sampled during the summer if survey time permitted. Starting in the spring of 2009, a section crossing to the south-west of St. Pierre Bank (SWSPB) and one crossing to the south-east of St. Pierre Bank (SESPB) was added to the AZMP surveys.

In 2018, SWSPB and SEGB were sampled during the spring (April) and fall (November/December) surveys, WB, SI, MB and BI during the summer survey (July) and BB and FC during all three surveys (although only the inshore portion of BB was sampled in spring). In this manuscript we present the summer cross sections of temperature and salinity and their anomalies along the SI, BB and FC sections to represent the vertical temperature and salinity structure across the NL Shelf during 2018.

Temperature and Salinity Variability

The water mass characteristics observed along the standard sections crossing the NL Shelf are typical of sub-polar waters with a sub-surface temperature range on the shelf of -1.5°C - 2°C and salinities of 31.5 - 33.5. Labrador Slope water flows southward along the shelf edge and into the Flemish Pass and Flemish Cap regions. This water mass is generally warmer and saltier than the sub-polar shelf waters with a temperature range of 3° - 4°C and salinities in the range of 34 - 34.75. Surface temperatures normally warm to 10° - 12°C during late summer, while bottom temperatures remain <0°C over much of the Grand Banks but increase to 1° - 3.5°C near the shelf edge below 200 m and in the deep troughs between the banks. In the deeper (>1000 m) waters of the Flemish Pass and across the Flemish Cap, bottom temperatures generally range from 3° - 4°C. In general, the near-surface water mass characteristics along the standard sections undergo seasonal modification from annual cycles of air-sea heat flux; wind forced mixing, and the formation and melting of sea ice. These mechanisms cause intense vertical and horizontal temperature and salinity gradients, particularly along the frontal boundaries separating the shelf and slope water masses. The seasonal changes in the temperature and salinity fields along the Bonavista section are presented in Colbourne et al. 2015.

The summer temperature and salinity structures along the Seal Island, Bonavista Bay and Flemish Cap (47ºN), hydrographic sections during 2018 are highlighted in Figures 20, 21 and 22. The dominant thermal feature along these sections is the mass of cold and relatively fresh water overlying the shelf. This water mass is separated from the warmer and denser water of the continental slope region by strong temperature and salinity fronts. The winter chilled water mass is commonly referred to as the cold intermediate layer (CIL; Petrie et al. 1988) and its cross sectional area (or volume) bounded by the 0°C isotherm (highlighted as a thick black contour in the temperature panels of Figures 20-22). The CIL is generally regarded as a robust index of ocean climate conditions on the eastern Canadian Continental Shelf.

While the CIL area undergoes significant annual variability, the changes are highly coherent from the Labrador Shelf to the Grand Banks. The shelf water mass remains present throughout most of the year as summer heating and salinity changes increase the stratification in the upper layers to a point where heat transfer to the lower layers is slowed. The CIL area gradually decays during the fall as increasing winds deepen the seasonally heated surface layer.

During 2018, temperatures were generally above normal for most of the Seal Island section, except in the offshore waters were they were close to normal (Figure 20, bottom left). Along Bonavista section, temperatures were generally above normal at depth and in coastal surface areas, but colder than normal in subsurface above the shelf and at surface offshore (Figure 21, bottom left). For Flemish Cap section, temperatures were much warmer than normal at depth (more than 2.5°C above normal just above the CIL) and much colder than normal at surface (by more 2.5°C below normal in some areas; Figure 22, bottom left). The colder than normal temperature near the surface is in agreement with cold SSTs in most of the NL areas as determined by remote sensing and discussed in a previous section. Warmer than normal temperature at depth also signifies warmer bottom conditions in a large portion of the Grand Banks as we will see later.

The corresponding salinity cross-sections show a relatively fresh upper layer shelf water with sources from arctic outflow and the Labrador Shelf with values <33 contrasting to the saltier Labrador Slope water further offshore with values >34 (Figures 20 to 22, right panels). In 2018, sub-surface salinities along the Seal Island section were generally lower than normal, except for a localized area above the shelf (between 50-100km of the section, Figure 20, bottom right). Salinities from Bonavista and Flemish Cap sections show contrasting salinity anomalies between the shelf (fresher than normal) and the offshore (saltier than normal) areas. This is likely due to an unusual extension of the saltier Labrador Current on the slope in 2018 compared to the climatology (see difference in salinity field between the top right two panels in Figure 21).

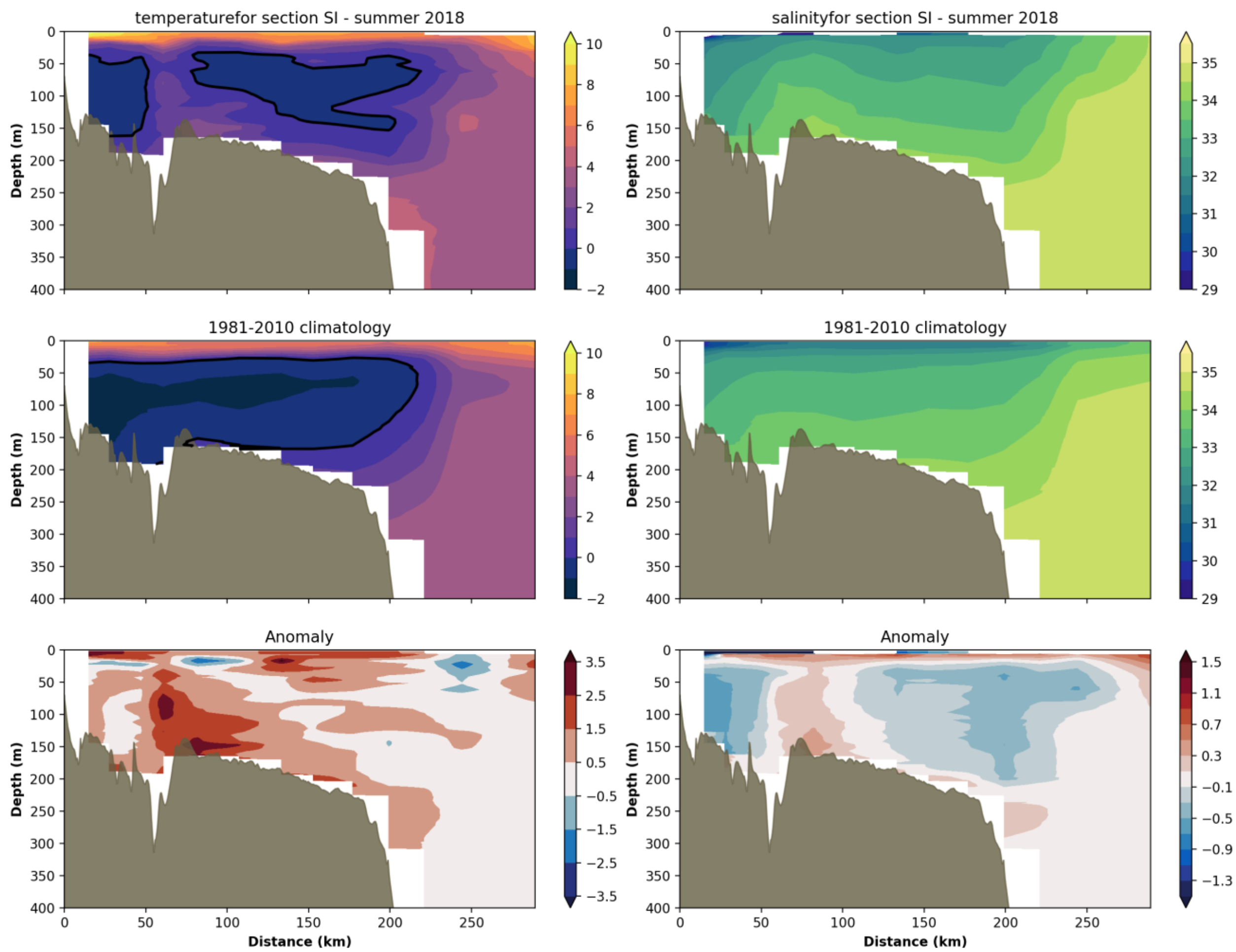


Figure 20. Contours of temperature (°C) and salinity during summer 2018 (top row) and well as their climatological average (middle row) for Seal Island (SI) hydrographic section (see map Figure 1 for location). Their respective anomalies for 2018 are plotted in the bottom panel.

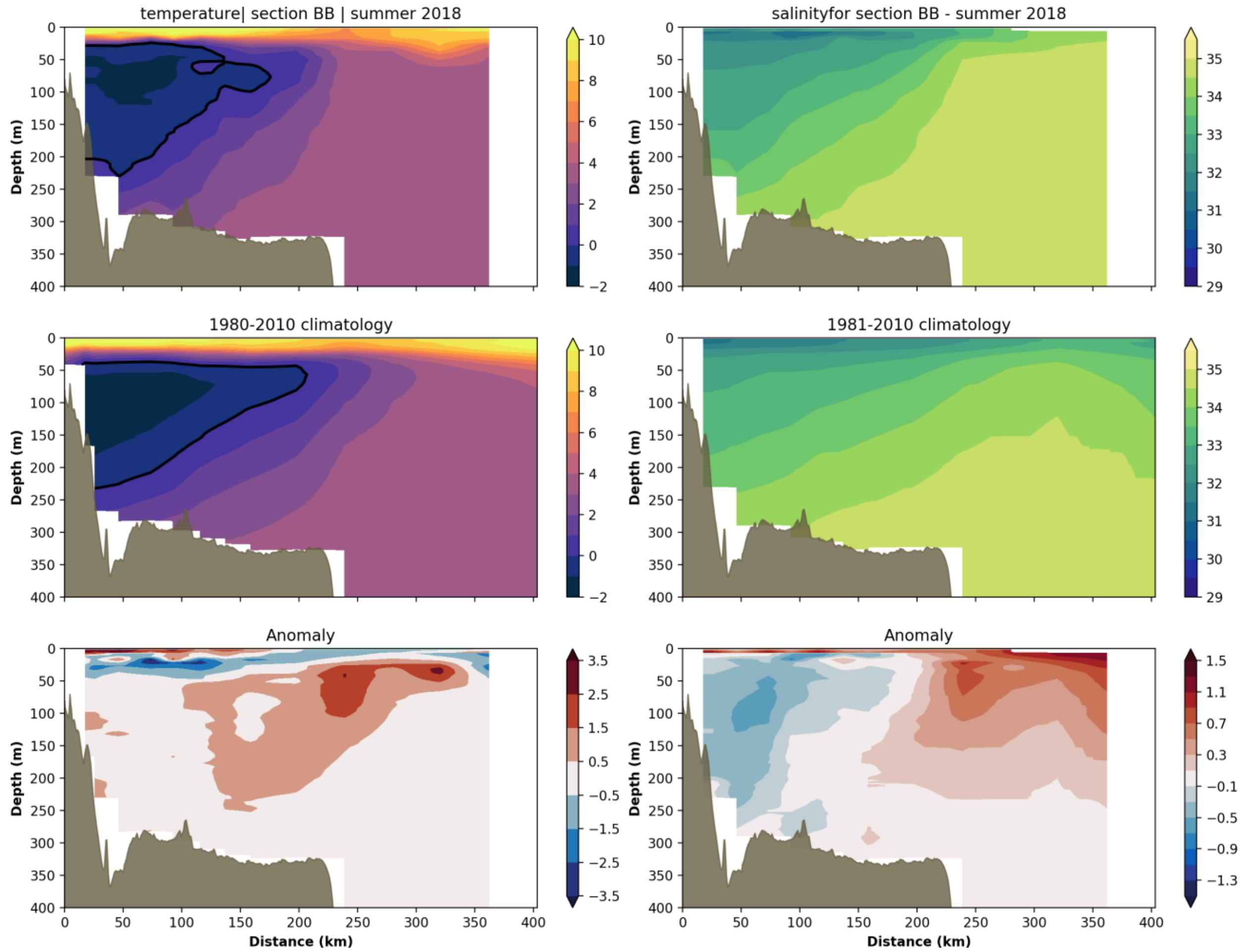


Figure 21. Same as in Figure 20, but for Bonavista Bay (BB) hydrographic section (see map Figure 1 for location).

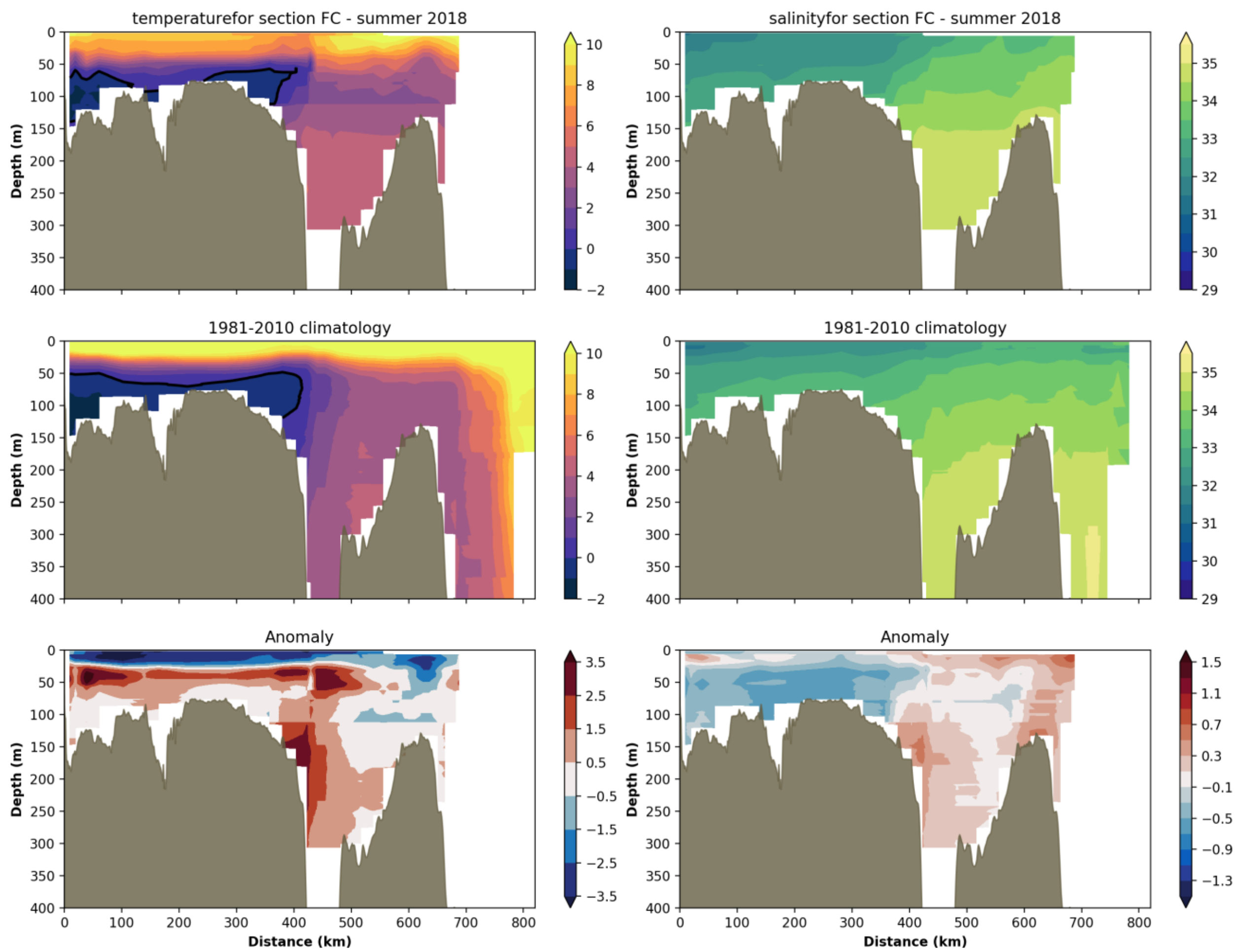


Figure 22. Same as in Figure 20, but for Flemish Cap (FC) hydrographic section (see map Figure 1 for location).

Cold Intermediate Layer Variability

Statistics of summer CIL anomalies for the three sections discussed above (Seal Island, Bonavista and Flemish Cap) are presented in Figure 23. The climatological average cross-sectional area of the summer CIL along Seal Island, Bonavista and Flemish Cap sections are 20.3 ± 4.5 km^2, 23.8 ± 8.2 km^2 and 11.7 ± 8.9 km^2, respectively. The averaged anomalies of the CIL core temperature (minimum temperature of this layer) and volume (defined as the cross-sectional area) for these three section is summarized in Figure 24 as a time series going back to 1950. In general, summer CIL have been predominantly warmer/smaller than average since the mid 1990's, with a cooling trend emerging since about 2012 or 2014. The most striking aspect of this long time series is however the very warm conditions that prevailed in the 1960's (that stands as a unique feature for this nearly 70-year time series), followed by a cold period that lasted from the mid-1980's to the mid-1990's.

In 2018, the mean CIL for the three sections studied here are back to warmer than normal conditions after 4 years of colder conditions (Figure 24). This change seems however driven by a shrinking of the CIL (smaller volume) starting from the northern part of the basin (large negative area anomaly for Seal Island, moderate for

Bonavista and normal for Flemish Cap). Interestingly, while the core temperature at Seal Island section is 2.5 SD above average, it is normal for Bonavista and Flemish Cap sections.

	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	x̄	sd
-- Seal Island section --																																									
CIL area (km²)	-0.1	-1.5	0.3	-0.9	1.6	0.5	-0.3	-0.1	0.1	-3.2	1.5	1.6	1.0	1.3	-0.1	-0.3	0.2	-0.6	0.0	-1.4	-0.2	0.8	-0.1	0.6	-0.9	0.0	-0.2	-0.1	-0.3	0.9	-0.1	-0.9	1.6	-0.7	0.1	1.5	-0.5	1.3	-1.6	20.3	4.5
CIL core (°C)	0.3	0.5	0.0	-1.2	-1.2	-0.9	0.6	0.1	-0.1	3.0	-0.8	-1.1	-0.9	-1.2	-0.7	1.6	-0.4	-0.6	-0.5	0.7	-0.6	0.8	-0.6	0.4	1.8	0.7	0.8	-0.2	-0.7	-0.4	0.9	2.2	-0.5	0.9	-1.2	0.0	-0.4	-0.7	2.5	-1.5	0.2
core depth (m)	0.2	0.6	-0.7	0.6	-0.7	-0.5	1.6	1.7	0.0	1.2	1.6	1.6	-0.3	0.0	1.0	-0.3	-0.9	0.2	0.4	-0.7	-1.5	-1.3	0.0	0.4	-0.2	-1.3	-0.2	0.8	-0.2	-1.3	-1.7	-0.9	0.0	0.0	2.6	-0.2	0.2	-0.9	0.6	70.4	25.4
-- Bonavista section --																																									
CIL area (km²)	-0.8	-0.2	-2.8	0.6	2.7	1.2	-0.3	-0.4	0.5	0.2	1.5	2.0	0.1	0.6	0.4	-0.5	-0.1	-0.7	-0.2	-0.3	0.2	-0.4	-0.3	0.2	-1.2	-0.7	-0.9	-0.3	-0.8	0.1	-0.2	-2.0	-0.1	-0.5	1.2	0.7	0.3	0.1	-0.5	23.8	8.2
CIL core (°C)	1.6	0.7	4.1	-1.3	-0.9	-0.7	0.0	0.1	0.6	-0.8	-0.7	-0.9	-0.3	-0.5	-0.8	-0.3	0.4	-0.4	-0.5	-0.2	-0.3	0.1	-0.2	-0.3	1.2	0.4	1.5	0.4	-0.3	-0.6	0.4	1.5	-0.6	0.1	-0.8	-0.7	-0.5	-0.7	0.4	-1.5	0.2
core depth (m)	-0.3	-0.6	0.9	1.3	-1.2	-0.8	0.1	0.5	-0.3	0.3	1.7	0.5	0.7	0.9	0.3	2.7	-0.1	-0.1	-1.0	0.7	0.3	-1.0	1.1	0.3	-0.3	-1.4	-0.6	-1.8	0.1	-1.4	-1.4	0.3	1.1	-0.6	0.7	1.9	-1.0	-0.3	-0.1	90.2	24.8
-- Flemish Cap section --																																									
CIL area (km²)	0.2	0.3	-1.3	2.0	1.2	0.9	0.2	-0.4	-0.2	0.8	1.7	1.3	0.3	0.9	-0.4	0.0	-0.3	-0.6	0.9	-0.6	-1.1	-1.3	-0.8	-0.9	-1.0	-0.4	0.0	2.0	-1.0	-1.2	-0.9	-1.1	-1.3	-0.6		0.0	-0.2	-1.3	-0.3	11.7	8.9
CIL core (°C)	-0.4	0.5	2.9	-0.9	-0.3	-0.9	-0.6	-0.7	0.0	-0.8	-0.5	-0.9	-0.7	-0.7	-0.7	-1.4	0.0	-0.3	-0.6	0.4	0.3	3.1	0.2	0.4	0.3	0.1	0.9	0.1	-0.2	0.0	0.9	1.2	0.3	1.1		0.1	0.0	0.0	0.0	-1.3	0.5
core depth (m)	-1.5	-2.1	-0.4	-0.7	-0.1	-0.1	1.6	-0.9	-0.7	-0.9	0.2	-0.9	-0.9	1.3	-0.9	1.0	2.1	0.2	0.7	1.6	-0.1	1.3	-0.1	-0.7	-0.7	-0.9	-0.1	1.1	0.2	-0.9	1.0	-1.2	1.6	1.0		-0.7	-0.1	1.6	1.6	83.4	18.0

Figure 23. Scorecards of the cold intermediate layer (CIL) summer statistics along Seal Island, Bonavista and Flemish Cap hydrographic sections. The CIL area is defined as all water below 0°C (see black contours in Figures 20 to 22), the CIL core temperature and core depth are respectively the minimum temperature of the CIL and the depth at which it is encountered. Color code for area and depth have been reversed (positive is blue) because they represent cold conditions. Grayed cells means absence of data.

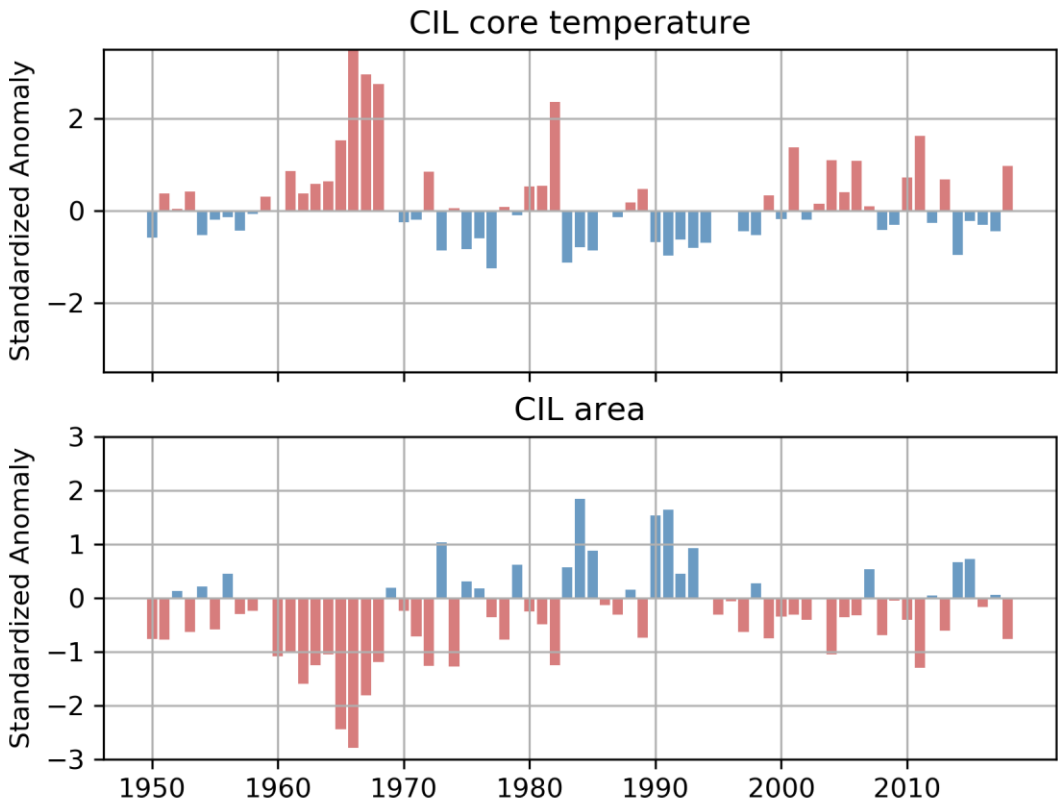


Figure 24. Mean standardized anomalies of the CIL core temperature (top) and volume (bottom) over Seal Island, Bonavista and Flemish Cap sections since 1950 (values for each separate section since 1980 can be found in Figure 23).

Bottom Observations in NAFO sub-areas

Canada has been conducting stratified random bottom trawl surveys in NAFO Sub-areas 2 and 3 on the NL Shelf since 1971. Areas within each division, with a selected depth range, were divided into strata and the number of fishing stations in an individual stratum was based on an area-weighted proportional allocation (Doubleday, 1981). Temperature profiles (and salinity since 1990) are available for most fishing sets in each stratum. These surveys provide large spatial-scale oceanographic data sets for the Newfoundland and Labrador Shelf. During the spring NAFO Subdivision 3Ps on the Newfoundland south coast and Divisions 3LNO on the Grand Banks are surveyed and in the fall Division 2HJ off Labrador in the north, 3KL off eastern Newfoundland and 3NO on the southern Grand Bank are surveyed. The hydrographic data collected on these surveys are routinely used to assess the spatial and temporal variability in the thermal habitat of several fish and invertebrate species. A number of products based on the data are used to characterize the oceanographic bottom habitat. Among these are contoured maps of the bottom temperatures and their anomalies, the area of the bottom covered by water in various temperature ranges, spatial variability in the volume of the cold intermediate layer and water-column stratification and mixed-layer depth spatial maps. In addition, species specific 'thermal habitat' indices are often used in marine resource assessments for snow crab and northern shrimp.

In previous NAFO Scientific Council Research documents (e.g., Colbourne et al., 2018), these data were combined with AZMP hydrographic surveys to derive bottom temperature and salinity. A new method for calculating these parameters is introduced here. While most of the data used here also use also acquired by DFO-NL during multi-species surveys and AZMP hydrographic campaigns, observations are completed with data from other origins made available by MEDS (surveys from other DFO regions, international oceanographic campaigns, Argo program, etc.)

Moreover, the calculation method of the bottom conditions also slightly differs. While previous calculation consisted on a flat 2D interpolation of the closest observations to the bottom, this new method now consider the bathymetry during the determination of the bottom conditions of the observed fields. For consistency, historical time series presented in this section have been re-calculated using the same methodology. Small discrepancies may thus exist between the results presented here and the same quantities from previous year's reports.

This new method is similar to the approach in the annual physical oceanographic conditions for the Gulf of St. Lawrence (e.g., Galbraith et al. 2018) and details are given here. First, all available annual profiles of temperature and salinity are vertically averaged in 5m bins and vertically interpolated to fill missing bins. Then, for each season (April-June for spring and October-December for fall) all data are averaged on a regular 0.1° x 0.1° (latitudinal x longitudinal) grid to obtain one seasonal profile per grid cell. Since this grid has missing data in many cells, each depth level is horizontally linearly interpolated. For each grid point, the bottom observation is considered as the data at the closest depth to the GEBCO_2014 Grid bathymetry (version 20150318), to a maximum of 50m difference. In the following, bottom observations deeper than 1000 m are clipped. This method is applied for all years between 1980 and 2018 from which the 1981-2010 climatology is derived. Anomalies for 2018 are calculated as the difference between annual observations and the climatology.

Spring Conditions

Spring climatological bottom temperature and salinity maps, together with 2018 observations and anomalies for NAFO divisions 3LNOPs are presented in Figure 25 and Figure 26, respectively (see center panel for station occupation coverage). In 2018, bottom temperatures in 3L are generally below 0°C except in the northern part and near the shelf edge where they range from 2° to 4°C. Over the central and southern areas of the Grand Bank (3NO), bottom temperatures ranged from 0° on the bank to 6°C on the slopes. Bottom temperature anomalies were slightly warmer than normal over 3LNO where anomalies of 0.5 to 3.5°C are observed. On St. Pierre Bank (eastern 3Ps) temperatures were generally below 0° in the shallower shelf and above 5°C in the Laurentian Channel. Bottom temperature were also warmer than normal by 0.5 to 2.5°C.

Spring bottom salinities are presented in Figure 26. In 3LNO they generally range from 32 – 33 over the central Grand Bank, and from 33 – 35 closer to the shelf edge. In 3Ps, salinities are between 32 and 33 over shallower areas and above 34.5 in the Laurentian channel. A widespread fresh anomaly is observed over the entire 3LNOPs, reaching -0.4 to -0.6 salinity units lower than normal.

Climate indices based on normalized spring temperature anomalies between 1980 and 2017 are shown in a color-coded scorecard in Figure 27. Overall, the table colors visually highlight two main periods of this time series that are the cold period of the late 80's / early 90's (mostly blue cells) and the warm period of the early 2010's (mostly red cells). During the spring of 2011 in Divisions 3LNO, none of the bottom area was covered by <0°C water, the only such occurrence since the surveys began in the early 1970s, corresponding to 2.1 SD below normal. This warm period lasted between 2010 and 2013 before returning towards to normal values: between 2015 and 2017 the bottom area that was covered by <0°C was only -0.1 to 0.1 SD above normal. In 2018, the average bottom temperature for 3LNO was again above below by 0.5 SD.

In Division 3Ps bottom temperatures exhibit some similarities with 3LNO, with warm years of 1999-2000 and 2005-2006 separated by a colder period between 2001-2004 (2003 is the coldest year on record since 1991 at -1.0 SD). With the exception of 2007 (cold at -0.6 SD) and 2008 (normal), all years between 2005 and 2018 were warmer than normal with the warmest year being 2016 at 1.9 SD above normal. 2018 was +1.4 SD above normal. The spring of 2011 had the lowest area of <0°C bottom water of the time series at 1.7 SD below normal, also corresponding to little or no bottom waters with temperatures of <0°C. The area of <0°C water increased somewhat in recent years, including in 2018 (+1.0 SD).

The mean standardized anomaly derived from Figure 27 is presented in Figure 28 as a bar plot integrating all bottom temperature rows of the scorecards (i.e., not considering the thermal habitat areas). An overall bottom temperature increasing trend since the early 1990s to 2011 is observed, although with important inter-annual variability (e.g. 2003 being the most significant cooling in the last two decades). Bottom temperatures reached record high values in 2011 but have experienced a decreasing trend to near-normal values by 2015. On average, 2018 was about 1.0 SD above normal for the entire 3LNOPs.

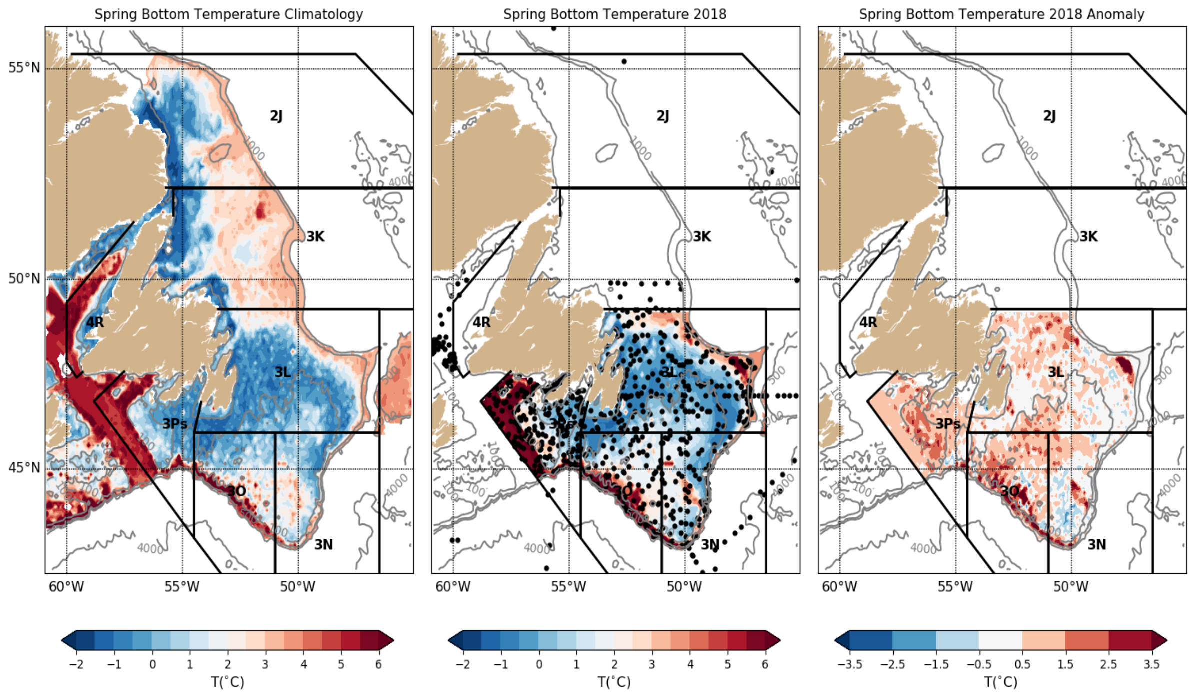


Figure 25. Maps of the mean 1981-2010 spring bottom temperature (left), and spring 2017 bottom temperature (center) and anomalies (right) for NAFO Divisions 3LNOPs only. The location of observations used to derive the temperature field is shown as black dots in center panel.

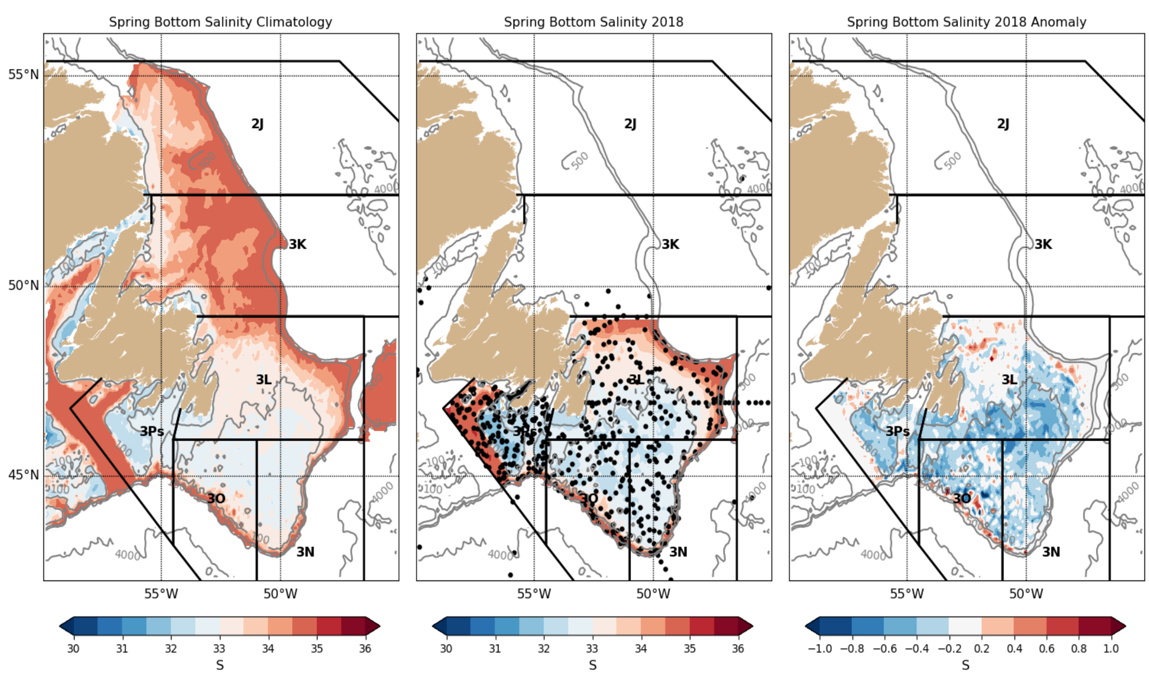


Figure 26. Maps of the mean 1981-2010 spring bottom salinity (left), and spring 2017 bottom salinity (center) and anomalies (right) for NAFO Divisions 2J3KLNO only. The location of observations used to derive the salinity field is shown as black dots in center panel.

	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	$\bar{x}$	sd
-- NAFO division 3LNO --																																									
T_{bot}	0.2	1.7	-0.4	0.7	-0.6	-1.1	-0.9	-0.2	0.3	-1.0	-1.7	-1.7	-1.4	-0.9	-1.2	-0.5	0.3	-0.5	0.8	1.6	0.9	0.4	0.2	-0.7	1.6	0.9	0.9	0.5	0.5	0.5	1.2	2.4	1.7	1.4	-0.2	0.3	0.0	0.2	0.7	0.9	0.6
$T_{bot<200m}$	0.1	1.8	-0.3	1.0	-0.5	-1.1	-1.0	-0.1	0.3	-0.8	-1.7	-1.7	-1.4	-0.9	-1.2	-0.5	0.3	-0.7	0.9	1.7	1.0	0.4	0.1	-0.9	1.5	0.8	0.7	0.4	0.3	0.5	1.1	2.4	1.6	1.4	-0.3	0.2	0.0	0.1	0.5	0.5	0.6
$Area_{>2°C}$	0.1	1.5	-1.1	0.8	-0.4	-1.2	-0.9	-0.1	0.2	-1.1	-1.7	-1.4	-1.5	-0.8	-1.1	-0.2	0.1	-0.5	0.5	1.7	0.7	-0.1	0.1	-0.6	2.0	0.9	0.8	0.7	0.9	0.9	0.6	2.8	1.7	0.8	-0.2	0.8	-0.1	0.3	0.3	64.9	22.7
$Area_{<0°C}$	-0.6	-1.4	-0.1	0.0	0.7	1.0	0.9	0.6	0.2	0.8	1.3	1.5	1.1	1.0	1.0	0.5	-0.4	0.6	-0.9	-1.4	-0.4	-0.4	-0.1	0.7	-2.0	-1.1	-1.8	-0.1	-0.1	0.2	-1.9	-2.2	-1.1	-1.3	0.5	0.1	0.0	-0.1	-0.5	105.9	44.7
-- NAFO division 3Ps --																																									
T_{bot}	0.7	2.8	0.0	0.5	0.5	-1.3	-0.3	-1.8	0.3	-0.8	-1.8	-1.6	-0.2	-0.5	-0.6	-0.2	0.3	-0.5	0.2	1.0	1.3	-0.4	0.1	-1.0	0.3	1.0	1.0	-0.6	0.3	0.8	0.9	1.5	1.3	1.1	0.9	1.1	1.9	0.7	1.4	2.1	0.6
$T_{bot<200m}$	0.4	3.2	0.2	0.4	0.8	-0.6	-0.2	-1.1	1.1	-0.3	-1.0	-1.0	1.0	-1.4	-1.1	-0.7	0.0	-1.0	0.2	0.9	1.1	-0.7	-0.4	-1.5	0.1	0.9	0.7	-0.7	0.1	0.5	0.4	1.2	0.8	0.7	0.3	0.4	1.0	-0.2	0.8	0.8	0.8
$Area_{>2°C}$	0.4	3.2	0.3	0.8	-0.4	-2.0	-0.4	-1.3	0.3	-0.5	-1.8	-1.7	-0.5	0.0	-0.2	0.3	-0.1	-0.3	0.2	1.3	1.2	-0.4	0.0	-0.4	0.0	0.5	0.7	-0.2	0.5	0.4	0.4	1.1	0.2	0.5	0.4	0.5	0.7	0.1	1.2	26.5	6.3
$Area_{<0°C}$	-0.4	-1.6	-0.4	-0.6	-0.9	0.9	0.1	1.3	-1.2	0.0	0.9	0.6	-0.5	1.6	1.2	1.1	-0.4	1.3	-0.1	-0.7	-1.1	0.6	0.2	2.1	-1.1	-1.4	-1.4	0.6	0.0	-0.3	-0.9	-1.7	-1.4	-1.4	-0.4	-0.8	-1.1	0.2	-1.0	16.3	9.6

Figure 27. Temperature indices derived from data collected in 3LNO (top) and 3Ps (bottom). The anomalies are normalized with respect to their standard deviations.

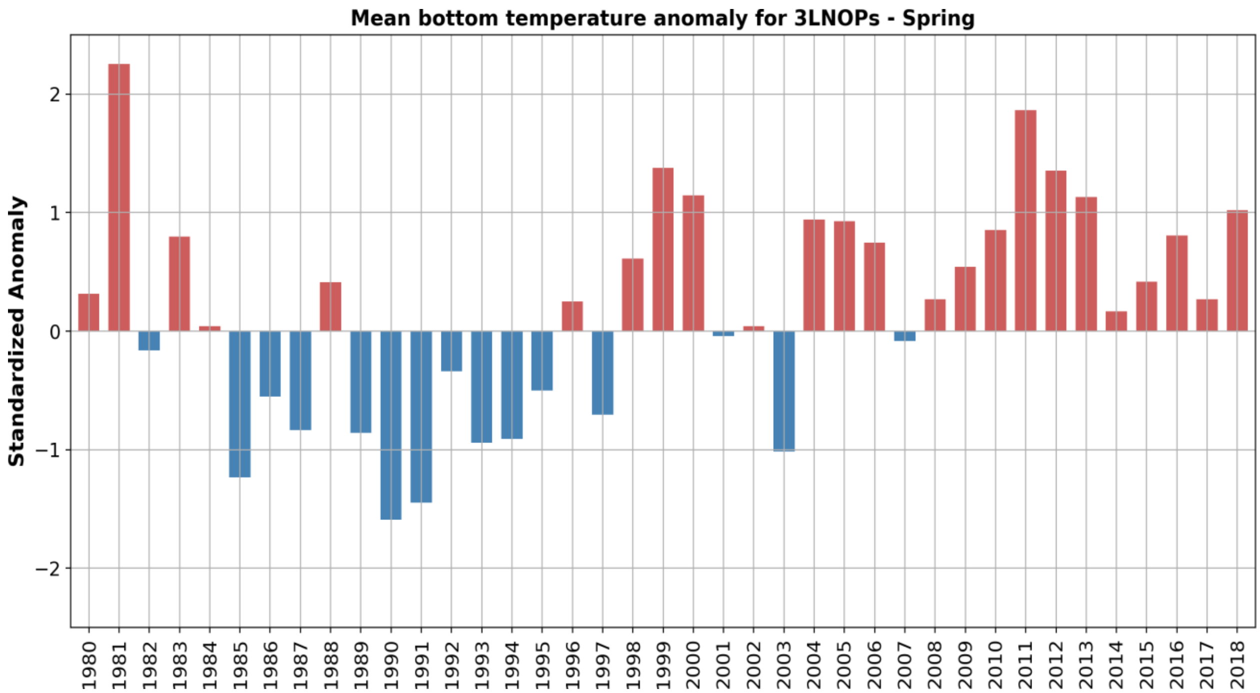


Figure 28. Mean standardized spring bottom temperature anomalies in NAFO Divisions 3LNOPs.The values are the average of bottom temperature rows in Figure 27 (thermal habitat area are ignored).

Fall Conditions

Fall climatological bottom temperature and salinity maps, together with 2018 observations and anomalies for NAFO divisions 2J3KLNO are presented in Figure 29 and in Figure 30, respectively (see center panel for station occupation coverage). There is a north-south gradient of bottom temperature anomalies in 2J3KLNO, with warmer than normal conditions in the north: up to +2.5°C in most 2J; +0.5°C to +2.5°C in 3KL and a mixture of both colder and warmer than normal in 3NO, expect for the tail of the Grand Banks that was warmer than normal at +2.5°C. Bottom salinities are presented in Figure 30. In divisions 2J and 3K there is generally an inshore-offshore salinity gradient between <33 in inshore to 34 to 35 at the shelf edge. The Grand Banks bottom salinities ranged from <33 to 35, with the lowest values on the southeast shoal. In 2018, however, a widespread fresh anomaly decreased the salinity below 33 in most the Grand Banks, with fresh anomalies of more than 0.6 unit below normal in most 3NO (including anomalies close to 1 salinity unit in some areas), and fresher by 0.4 unit in most of 3L. While 3K was near normal, a fresh anomaly is also observed in the inshore areas of 2J.

Standardized bottom temperature and other derived indices anomalies are presented in Figure 31. While bottom temperature for 2017 was normal in 2J3K and below normal in 3LNO (first negative occurrence in a decade), they were above normal and normal in 2018, respectively.

The mean standardized anomaly derived from Figure 31 is presented in Figure 32 as a bar plot integrating all rows of the scorecards, except the thermal habitat >2°C. Presented this way, the figure shows the low frequency patterns (~15 year half-cycle) with colder temperature between the early 80's to the mid-90's, followed by a warmer period until the late 2010's). Since the record high in 2011 temperature conditions have decreased significantly to near-normal values in both 2014 and 2015, somewhat warm in 2016 but decreased to normal conditions in the spring and to below normal during the fall of 2017 (coldest since 1994, as mentioned above). In 2018, however, bottom temperature conditions were back to above normal condition at 0.8 SD for 2J3KLNO, the warmest year since the record high temperature in 2011.

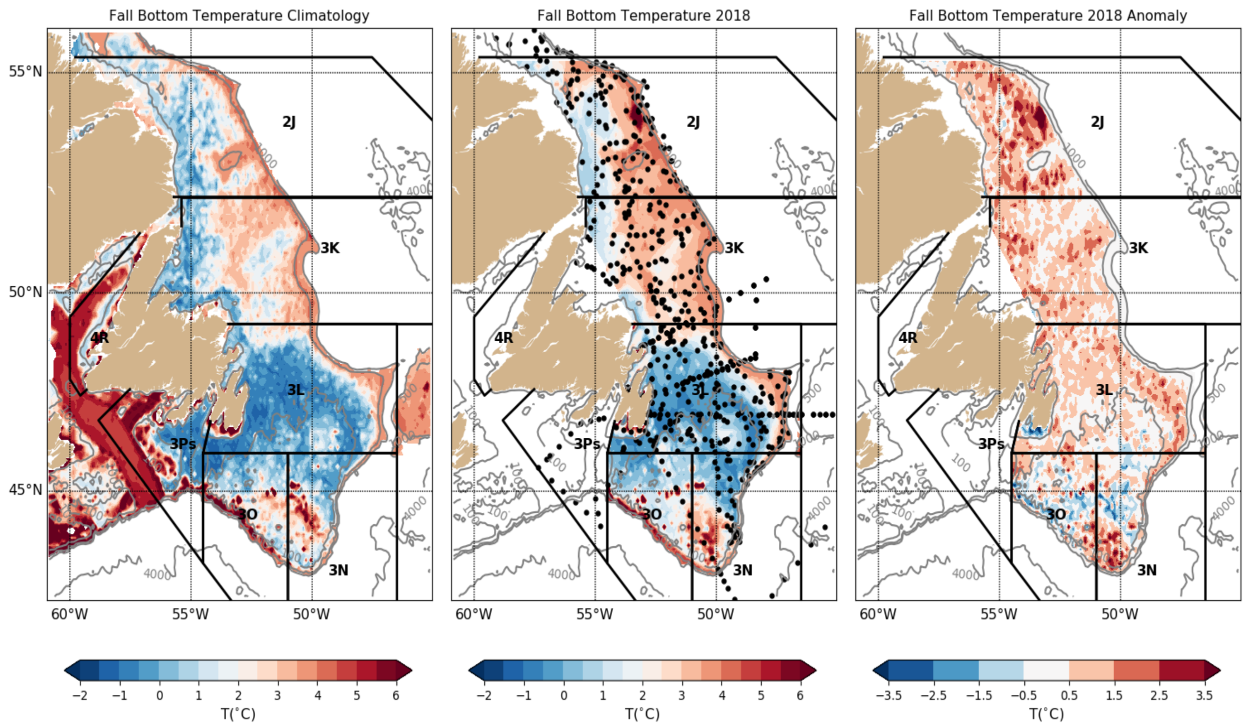


Figure 29. Maps of the mean 1981-2010 fall bottom temperature (left), and fall 2017 bottom temperature (center) and anomalies (right) for NAFO Divisions 2J3KLNO only. The location of observations used to derive the temperature field is shown as black dots in center panel.

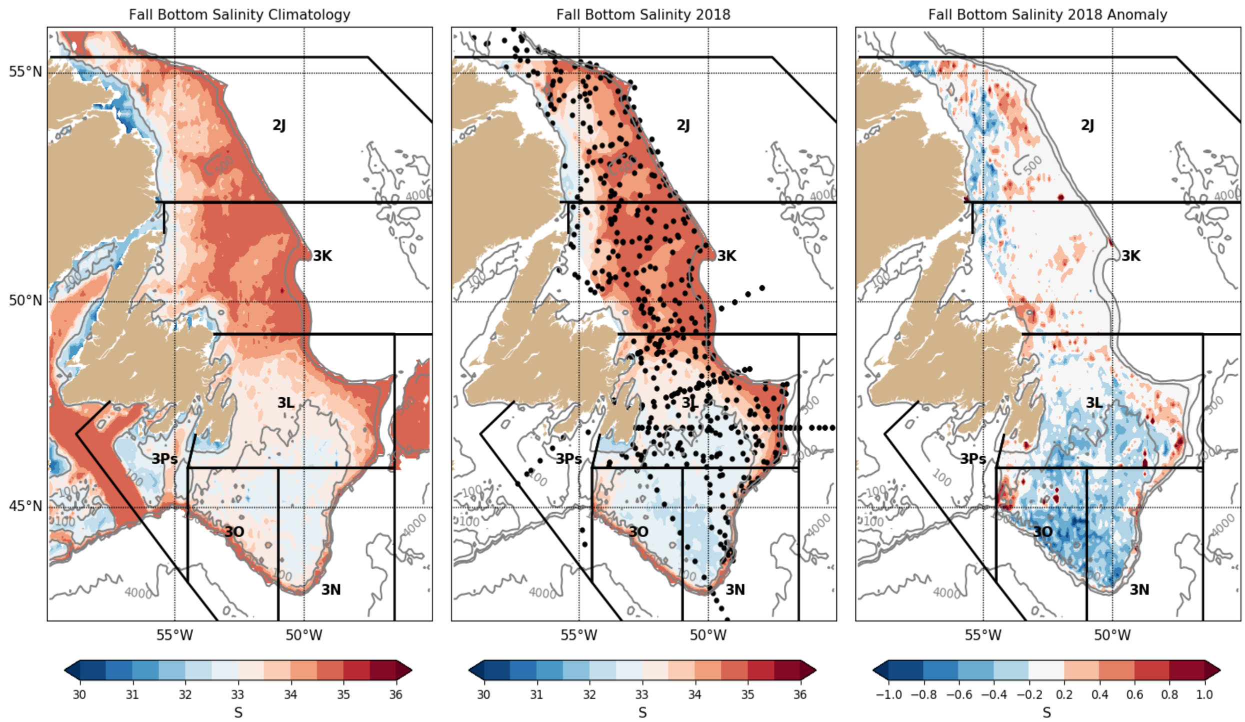


Figure 30. Maps of the mean 1981-2010 fall bottom salinity (left), and fall 2017 bottom salinity (center) and anomalies (right) for NAFO Divisions 2J3KLNO only. The location of observations used to derive the salinity field is shown as black dots in center panel.

	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	x̄	sd
-- NAFO division 2J --																																									
T_{bot}	-0.2	0.3	-1.1	-0.9	-1.9	-1.5	0.3	-1.2	0.1	-0.4	-1.1	-0.7	-1.4	-1.4	-0.8	0.0	0.7	0.4	0.4	0.7	0.1	0.9	0.6	1.0	1.3	1.4	0.1	1.5	0.4	0.5	1.8	1.8	0.4	0.4	-0.1	-0.1	0.6	0.2	1.1	2.0	0.6
$T_{bot_{<200m}}$	0.1	0.4	-0.8	-1.2	-1.8	-1.2	0.4	-1.2	0.1	-0.4	-0.9	-0.9	-1.5	-1.4	-0.8	0.0	0.8	0.3	0.2	0.8	0.0	1.0	0.7	1.0	1.1	1.5	-0.3	1.5	0.2	0.5	1.8	2.0	0.2	0.1	-0.5	-0.3	1.1	0.1	1.0	0.7	0.8
$Area_{>2^{\circ}C}$	0.0	0.2	-1.4	-0.5	-1.4	-1.3	0.3	-0.9	0.0	-0.7	-1.0	-0.6	-1.0	-1.1	-0.7	-1.6	1.0	0.6	0.3	0.2	0.2	0.9	0.7	1.0	1.2	1.6	0.2	1.8	-0.1	0.1	2.0	2.2	0.0	0.2	-0.1	0.0	0.6	0.1	0.9	46.4	16.3
$Area_{<1^{\circ}C}$	0.1	-0.4	1.2	1.1	1.5	1.3	-0.5	1.4	-0.5	0.5	1.2	1.0	1.2	1.4	0.9	-1.0	-0.7	-0.4	-0.2	-1.1	0.1	-1.0	-0.7	-1.1	-0.9	-1.5	0.3	-1.4	0.1	-0.4	-1.5	-1.5	0.1	0.0	0.4	0.3	-1.4	0.0	-0.9	26.1	17.0
-- NAFO division 3K --																																									
T_{bot}	0.1	0.1	-0.2	-0.5	-1.1	-2.0	-0.1	-0.9	-0.3	-0.2	-1.6	-0.7	-1.6	-1.6	-1.1	-0.6	0.1	0.7	0.6	1.0	0.6	0.3	0.8	1.0	1.6	1.1	0.4	1.2	0.9	0.5	1.7	2.3	0.6	0.7	0.0	0.3	0.0	-0.3	0.9	2.4	0.5
$T_{bot_{<200m}}$	0.3	0.1	-1.4	-1.2	-1.4	-1.3	0.4	-1.1	-0.5	-0.3	-1.1	-1.0	-1.1	-1.3	-0.9	0.5	0.9	0.2	0.0	0.8	0.0	0.7	0.9	1.1	1.5	1.2	0.2	1.4	0.2	0.3	2.2	2.0	0.5	0.1	-0.3	0.3	1.3	0.1	1.2	0.2	0.8
$Area_{>2^{\circ}C}$	0.1	0.4	-0.1	-0.7	-0.9	-2.1	0.2	-0.9	-0.3	-0.4	-1.5	-0.5	-1.4	-1.5	-1.2	-0.9	0.0	0.9	0.8	0.9	0.7	0.2	1.1	0.8	1.3	1.2	0.4	1.1	0.9	-0.2	1.8	1.6	0.4	0.8	-0.2	0.3	-0.3	-0.4	1.1	73.4	14.9
$Area_{<1^{\circ}C}$	-0.1	-0.2	0.1	0.7	0.9	2.0	-0.8	0.3	-0.2	-0.1	2.1	0.9	1.4	1.9	1.3	-0.2	-0.8	-0.3	-0.2	-0.6	0.0	-0.4	-0.9	-1.0	-1.4	-1.2	0.0	-1.2	-0.2	-0.1	-1.6	-1.6	-0.2	-0.5	0.1	-0.3	-1.0	0.3	-1.2	17.5	10.3
-- NAFO division 3LNO --																																									
T_{bot}	0.5	0.0	1.3	0.3	-0.4	-1.1	0.2	-0.7	-1.1	0.4	-1.0	-1.5	-1.4	-2.2	-1.4	-0.2	0.2	0.1	1.0	2.2	-0.2	0.3	0.2	-0.1	1.2	0.5	0.8	0.1	-0.4	0.8	1.8	3.1	0.7	0.9	0.5	0.1	0.7	-1.0	0.4	1.1	0.4
$T_{bot_{<200m}}$	0.8	0.1	1.6	0.4	-0.3	-0.9	0.4	-0.7	-1.0	0.4	-0.7	-1.4	-1.1	-2.2	-1.4	0.0	0.4	-0.1	0.9	2.3	-0.5	0.2	0.0	-0.3	1.0	0.4	0.8	-0.1	-0.8	0.8	1.8	3.1	0.6	0.9	0.6	-0.2	0.7	-1.1	0.3	0.7	0.5
$Area_{>2^{\circ}C}$	0.2	-0.1	0.6	0.7	0.3	-1.4	0.3	-0.6	-1.6	0.9	-1.0	-1.0	-1.4	-1.9	-1.3	-0.4	0.0	0.0	1.3	2.6	0.1	0.2	-0.1	-0.2	1.0	0.4	0.4	0.1	-0.5	0.8	1.5	2.9	1.0	1.1	0.9	0.3	0.8	-0.7	0.0	71.2	20.0
$Area_{<0^{\circ}C}$	-1.0	0.7	-0.1	0.8	1.1	0.2	-0.3	0.3	0.2	-0.1	0.5	1.5	1.2	2.2	1.5	-0.5	-0.2	0.1	-0.6	-1.7	0.7	-0.2	-0.7	-0.2	-2.3	-0.8	-1.4	-0.1	0.3	-0.3	-1.7	-3.4	0.0	-0.3	-0.2	-0.1	0.1	1.3	-0.8	100.9	27.2

Figure 31. Temperature indices derived from data collected in 2J (top), 3K (middle) and 3LNO (bottom). The anomalies are normalized with respect to their standard deviations.

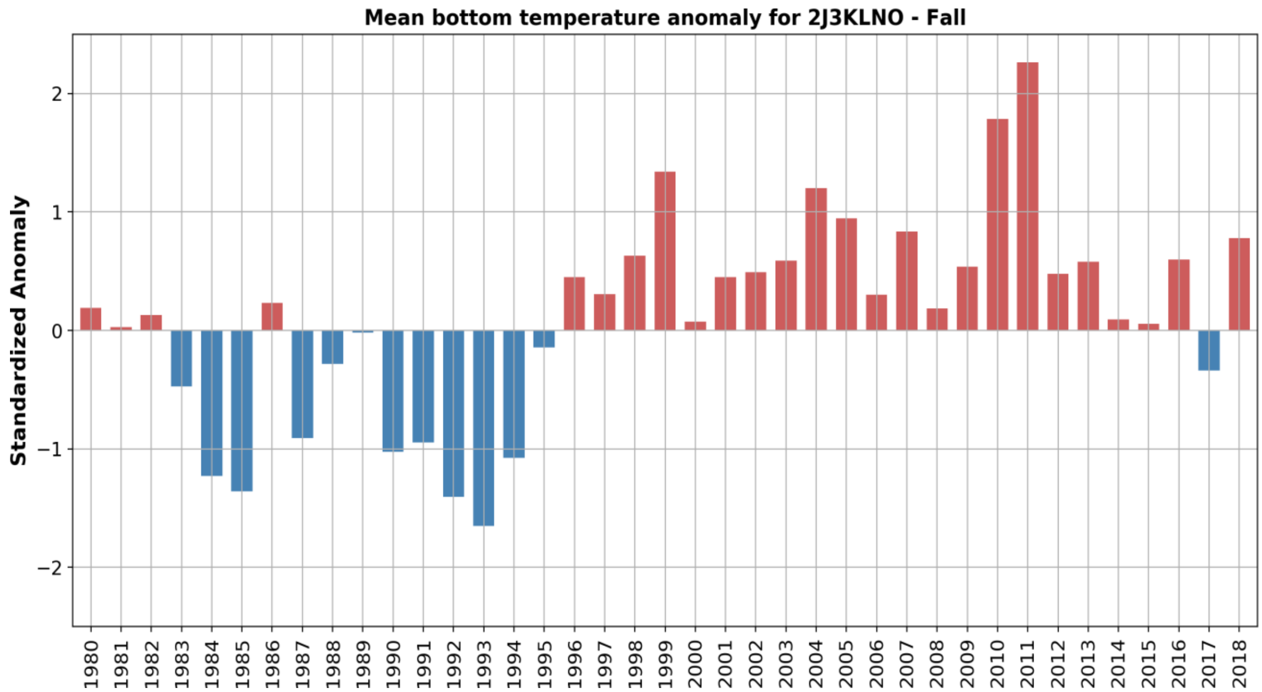


Figure 32. Mean standardized fall bottom temperature anomalies in NAFO Divisions 3LNOPs.The values are the average of all rows in Figure 30, except for the thermal habitat >2°C.

OCEAN CONDITIONS ON THE SCOTIAN SHELF AND GULF OF MAINE (NAFO SUB-DIV 4)

Coastal Temperatures and Salinities

Coastal sea surface temperatures have been collected at Halifax (Nova Scotia) and St. Andrews (New Brunswick) since the 1920s (Figure 33). In 2018, the SST anomalies were +0.6ºC (+0.8 SD) for Halifax, a decrease of 0.2ºC from 2016 and +1.0ºC (+1.0 SD) for St. Andrews, an increase of 0.2ºC from 2017.

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 (Figure 1). It is the longest continuously operating hydrographic monitoring site in eastern Canada. Its waters are generally well-mixed from the surface to the bottom (90 m). The depth-averaged (0-90 m) temperature, salinity and density anomaly time series are shown in Fig. 8(C-E). In 2018, the annual temperature anomaly was +1.1ºC (+2.0 SD) and the salinity anomaly was +0.2 (+0.8 SD). These represent changes of +0.3ºC and +0.3 from the 2017 values. The near-normal density anomaly is accounted for by the positive temperature anomaly offset by the positive salinity anomaly.

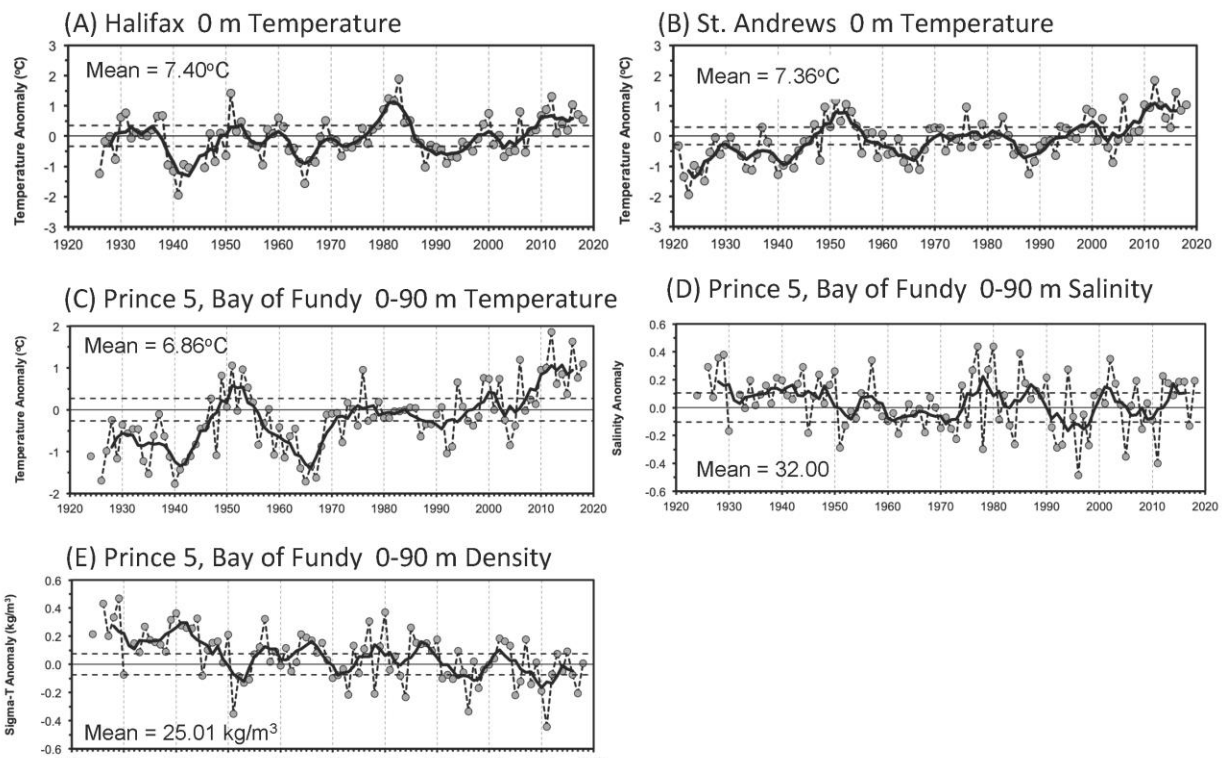


Figure 33. The annual surface temperature anomalies (dotted line with circles) and their 5-year running means (heavy black line) for (A) Halifax Harbour and (B) St. Andrews; annual depth-averaged (0-90 m) (C) temperature, (D) salinity and (E) density anomalies for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Horizontal dashed lines are mean plus and minus 0.5 SD.

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 (see map Figure 34) is presented in Figure 35. 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 Figure 35C); 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, Georges Basin and Lurcher Shoals, 2018 annual anomalies are based on observations from only four, two, eight, five and two months, respectively.

In 2018, the annual anomalies were +0.9°C (+2.4 SD) for Cabot Strait 200-300 m (the third largest anomaly; the largest, second, fourth, fifth and sixth largest anomalies were in 2016, 2017, 2012, 2014 and 2015, respectively), +0.7°C (+1.2 SD) for Misaine Bank at 100 m, +1.6°C (+1.9 SD) for Emerald Basin at 250 m (the second highest, 2016 was a record high and 2017 was third highest), +2.0°C (+3.7 SD) for Georges Basin at 200 m (a record high with 2017 and 2013 as the second and third warmest years) and +2.0°C (+2.5 SD) for Lurcher Shoals at 50 m (second highest with 2012 having the record). These values correspond to changes of -0.2°C, +0.3°C, +0.1°C and +0.5°C, respectively (except for Lurch Shoals which had no data in 2017) from the 2017 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 2018.

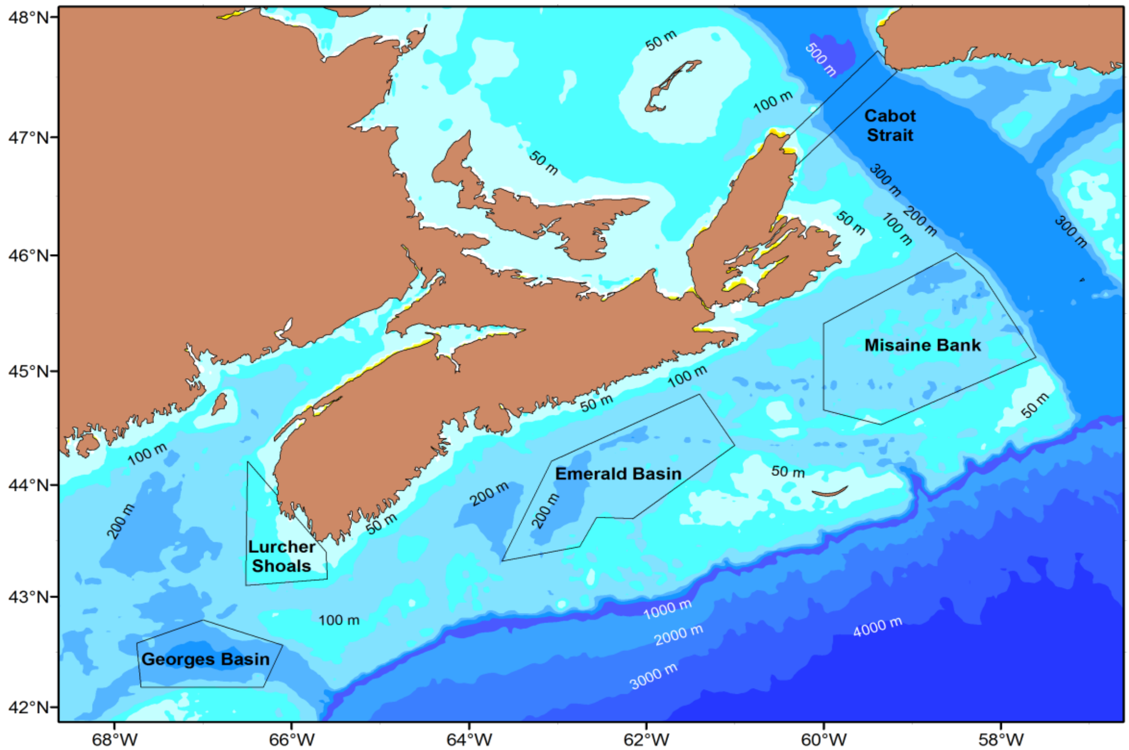


Figure 34. Areas on the Scotian Shelf and eastern Gulf of Maine depicting the different water masses.

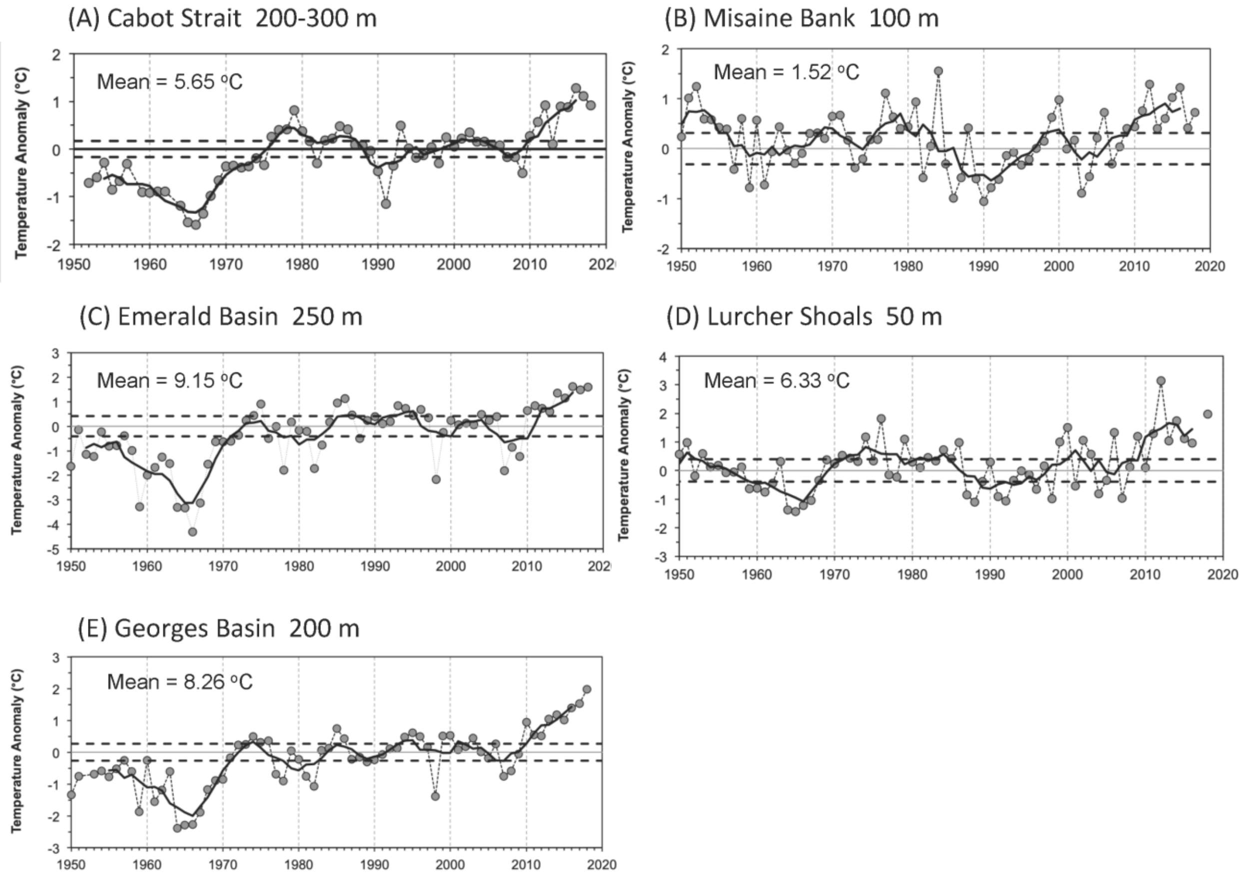


Figure 35. The annual mean temperature anomaly time series (dotted line with circles) and the 5 year running mean filtered anomalies (heavy solid line) on the Scotian Shelf and in the Gulf of Maine at (A) Cabot Strait (200-300 m); (B) Misaine Bank (100 m); (C) Emerald Basin (250 m); (D) Lurcher Shoals (50 m); and Georges Basin (200 m) (see Fig. 2). Horizontal dashed lines are mean plus and minus 0.5 SD.

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 84 CTD stations were sampled during the 2018 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. Due to vessel availability, the survey could only cover the NAFO Division 4X.

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, 10 m, 20 m, etc.) and for near the bottom. Only the bottom temperatures are presented here.

Bottom temperatures anomalies for 2018 were positive for most of NAFO Division 4X (Figure 36), with an anomaly of +1.4°C (+2.0 SD) in 2018 (Figure 37 A-D). In 4X, 2018 was the 5th warmest year, 0.7°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 (Figure 37E). 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 Figure 37E) could be affected. It is expected that the true SD is higher than the one derived here. There is considerable variation in the volume of the CIL from 1998 until 2009 (Figure 37E). The smallest volume was in 2012. The CIL volume could not be determined in 2018.

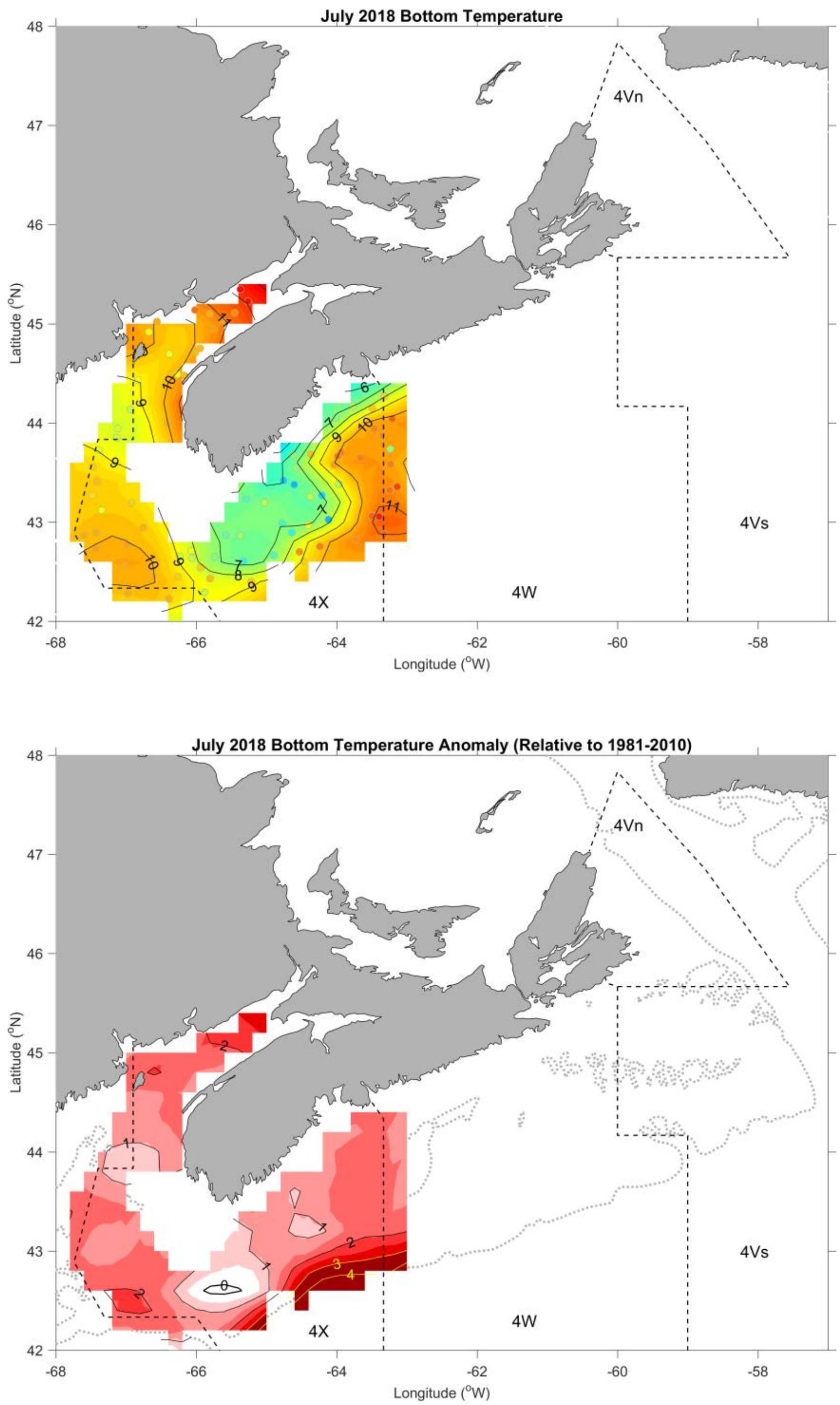


Figure 36. July bottom temperature (upper panel) and anomaly (lower panel) maps for 2018. NAFO areas 4Vn, 4Vs, 4X and 4W are shown.

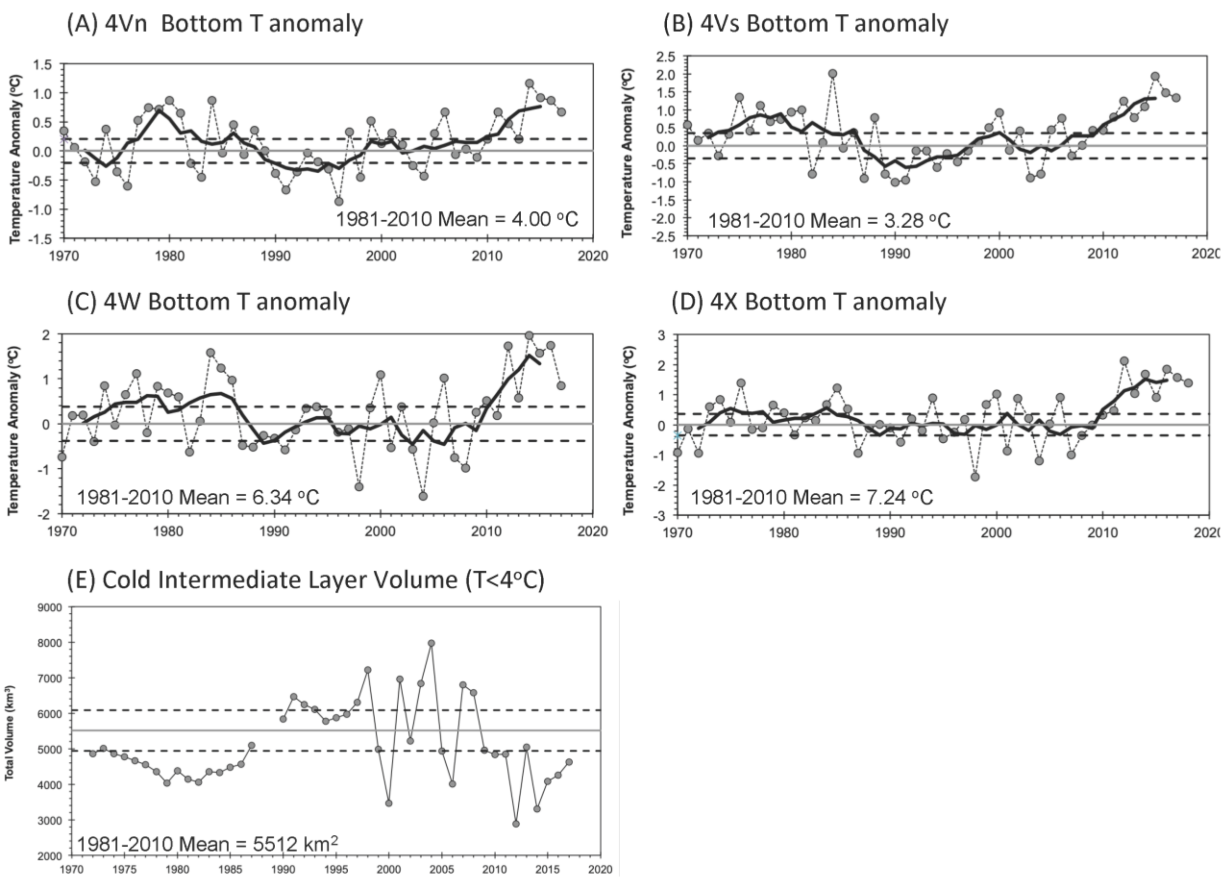


Figure 37. Time series of July bottom temperature anomalies (dashed lines with circles) and 5 year running mean filtered series (heavy line) for areas (A) 4Vn, (B) 4Vs, (C) 4W and (D) 4X. (E) Time series of the Cold Intermediate Layer (CIL, defined as waters with T<4°C) volume on the Scotian Shelf based on the July ecosystem survey. The solid horizontal line is the 1981-2010 mean CIL volume and dashed lines represent +/-0.5 SD.

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 (σ_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 sub-areas 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 25 years that is characterized by above normal values (Figure 38). 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, composed of equally of warming and freshening. Stratification in 2018 was significantly less than in 2017 where surface freshening and warming occurred.

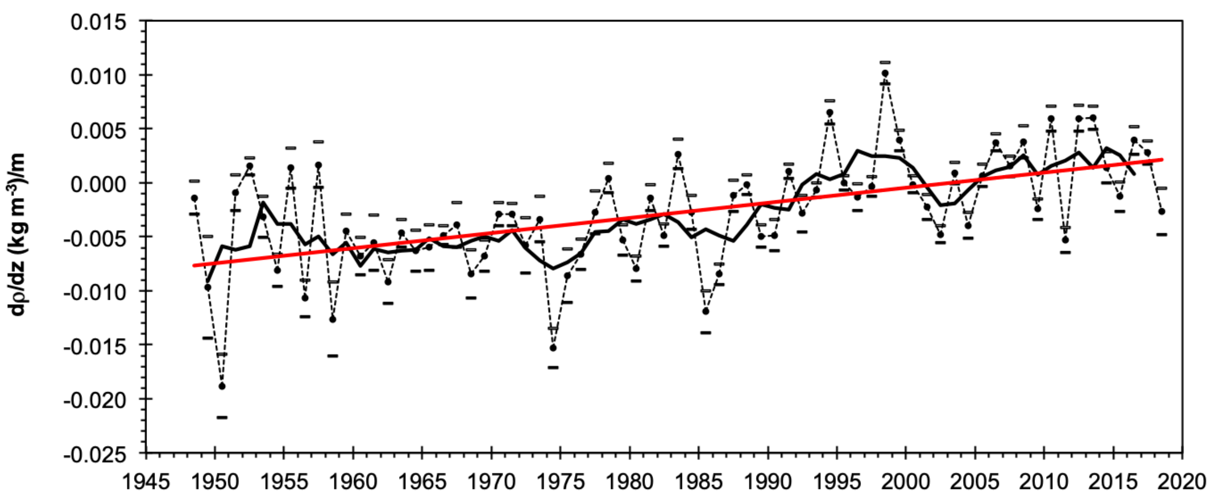


Figure 38. The mean annual anomaly (dashed line with circles) and 5-yr running mean (heavy solid line) of the stratification index (0-50 m density gradient) averaged over the Scotian Shelf. Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a change in the 0-50 m density difference of 0.35 kg m-3 over 50 years.

LABRADOR CURRENT VARIABILITY IN NAFO SUB-DIVISION 2,3 AND 4

The circulation pattern through most of the standard NAFO/AZMP sections in the Newfoundland and Labrador area is dominated by the south-eastward flowing Labrador Current, which floods the eastern shelf areas with cold and relatively fresh sub-polar waters. This flow can significantly affect physical and biological environments off Atlantic Canada on seasonal and interannual time scales. The shelf current originates near the northern tip of Labrador where outflow through Hudson Strait combines with the east Baffin Island Current and flows south eastward along the Labrador coast and is strongly influenced by the seabed topography, following the various cross shelf saddles and inshore troughs. A separate offshore branch flows south eastward along the western boundary of the Labrador Sea. This current is part of the large-scale Northwest Atlantic circulation consisting of the West Greenland Current that flows northward along the West Coast of Greenland, a branch of which turns westward and crosses the northern Labrador Sea forming the northern section of the Northwest Atlantic sub-polar gyre.

Further south, near the northern Grand Bank, the inshore branch becomes broader and less defined. In this region, most of the inshore flow combines with the offshore branch and flows eastward, with a portion of the combined flow following the bathymetry southward around the south-east Grand Bank and the remainder continuing eastward and then southward around the Flemish Cap. A smaller inshore component flows through the Avalon Channel, around the Avalon Peninsula, and then westward along the Newfoundland south coast. Off the southern Grand Bank the offshore branch flows westward along the continental slope some of which flows into the Laurentian Channel and eventually onto the Scotian Shelf. Additionally, there are strong interactions between the offshore branch of the Labrador Current and large-scale circulation. Significant part of the offshore branch combines with the North Atlantic Current and forms the southern section of the sub-polar gyre. Further east, the Flemish Cap is located in the confluence zone of sub-polar and sub-tropical western boundary currents of the North Atlantic. Labrador Current water flows to the east along the northern slopes of the Cap and south around the eastern slopes of the Cap. In the eastern Flemish Pass area, warmer high salinity North Atlantic Current water flows northward contributing to a topographically induced anticyclonic gyre over the central portion of the Cap.

Satellite altimetry data are used over a large spatial area to calculate the annual-mean anomalies of the Labrador Current transport (Han et al. 2014). A total of nine cross-slope satellite altimetry tracks are used to cover the Labrador and northeast Newfoundland Slopes from approximately 47 to 58^{o}N latitude (see map Figure 39). Similarly, five tracks from approximately 55 to 65^{o}W longitude are used for the Scotian Slope. The nominal cross-slope depth ranges used for calculating the transport are from 200 to 3,000 m isobaths over the Labrador and northeast Newfoundland Slopes and from 200 to 2,000 m isobaths over the Scotian Slope, with the nominal depth range from 0 m to 500 m for the former and from 0 m to 100 m for the latter.

An empirical orthogonal function (EOF) analysis of the annual-mean Labrador Current transport anomalies was carried out. The index was developed from the time series of the first EOF mode, standardized by dividing the time series by its standard deviation. The mean transport values are provided based on ocean circulation model output over the Labrador and northeast Newfoundland Slopes (Han et al. 2008) and over the Scotian Slope (Han et al.1997). The mean transport on the Labrador and NE Newfoundland Slope is 13 Sv with a standard deviation of 1.4 Sv and on the Scotian Slope it is 0.6 Sv with a standard deviation of 0.3 Sv. The mean transport values will be updated as new model output becomes available. The standard deviation values will be updated as knowledge on nominal depth improves.

The annual-mean Labrador Current transport index shows that the Labrador Current transport over the Labrador and northeast Newfoundland Slope was out of phase with that over the Scotian Slope for most of the years over 1993-2018 (Figure 40). The transport was strongest in the early-1990s and weakest in the mid-2000s over the Labrador and northeast Newfoundland Slope, and opposite over the Scotian Slope. The Labrador Current transport index was positively and negatively correlated with the winter North Atlantic Oscillation index over the Labrador and northeast Newfoundland Slopes and over the Scotian Slope, respectively. In the past three years the annual mean transport of the Labrador Current was above normal by about 1 SD over the Labrador and northeast Newfoundland Slopes (+1.2, +1.0 and +1.7, respectively for 2016, 2017 and 2018) while on the Scotian Shelf the transport has been below normal for the past four years (ranging between -0.7 to -1.3 SD).

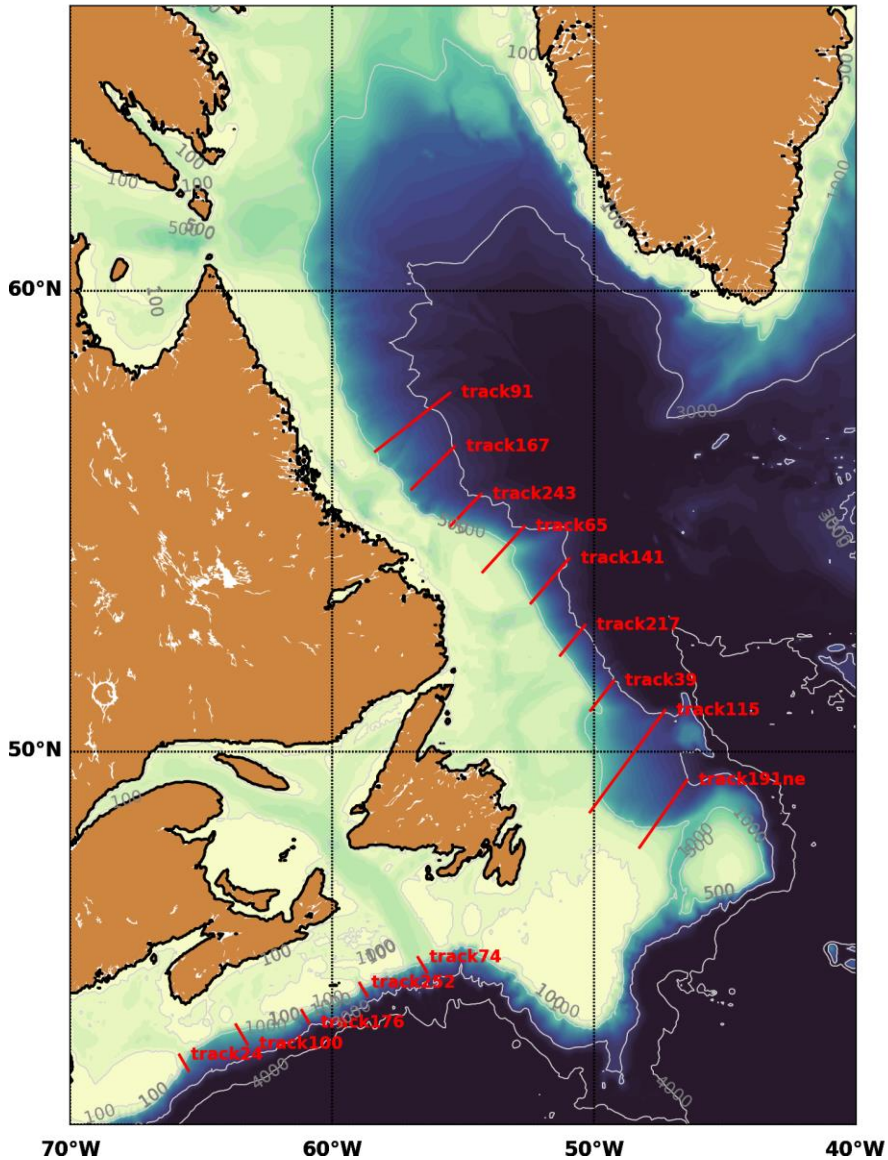


Figure 39. Map showing the Northwest Atlantic bottom topography (depth contours value in light gray). The Labrador Current transport is calculated across the cross-slope sections (red) identified by their satellite ground tracks numbers. The series of northern track are used for the Labrador and northeast Newfoundland slope calculation, while the series of track in the south are used for the Scotian Shelf slope transport calculation.

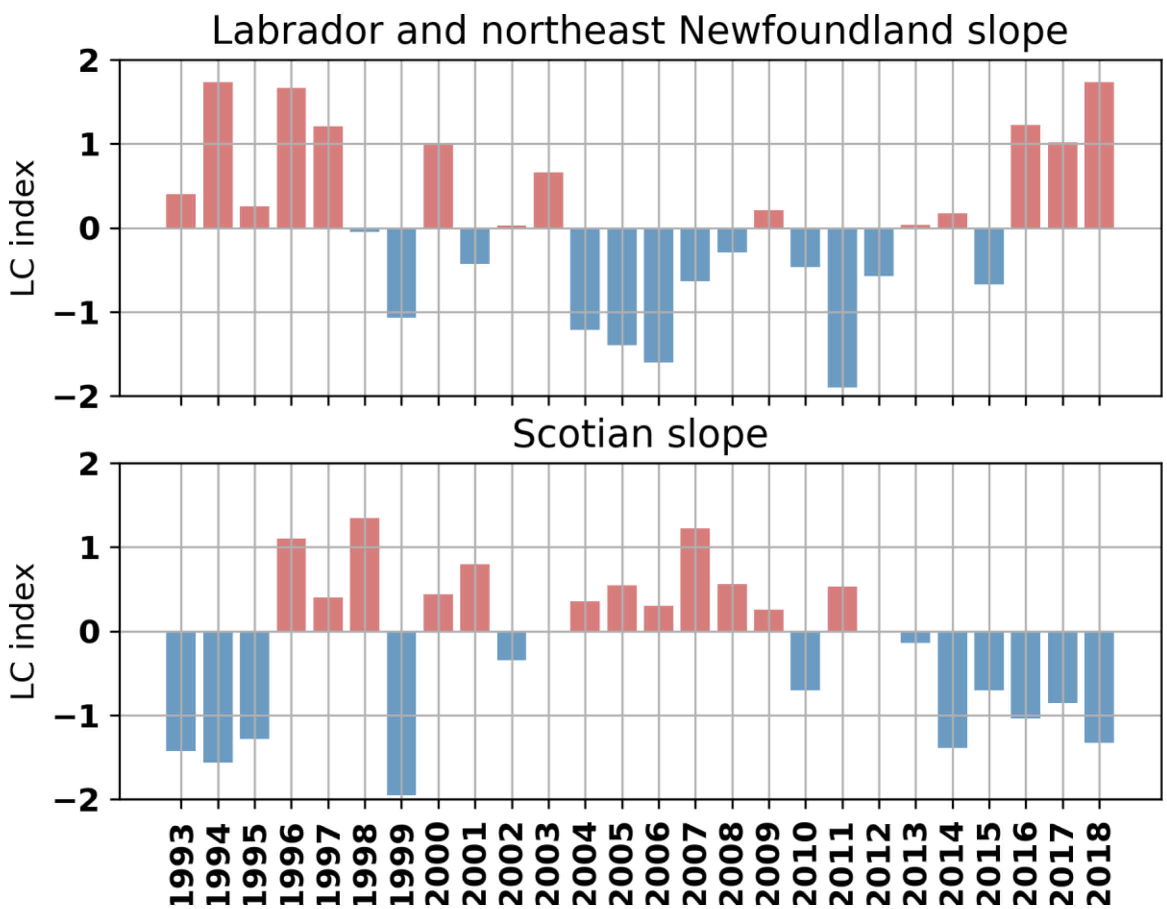


Figure 40. Standardized index of the annual mean Labrador Current transport for the Labrador and northeast Newfoundland Slope (top) and the Scotian Slope (bottom). Long-term averages over 1993-2018 (with standard deviation) are 13±1.4 Sv for Labrador and northeast Newfoundland Slope and 0.6±0.3 Sv for the Scotian Slope.

SUMMARY

An overview of physical environmental conditions for NAFO Divisions 2, 3 & 4 were presented. The highlights of 2018 can be summarized as follows:

- Winter NAO was relatively high at +1.3 SD above normal, but unusual spatial patterns in the sea level pressure over the North Atlantic have led to strong seasonal variations in air temperature (warm March over the Arctic, cold spring in mid-latitude and warm summer).
- Overall in 2018, the air temperatures were normal in Divisions 2 &3 and warmer than normal in Division 4.
- Caused by the warm air temperature in March, the sea-ice seasonal cycle exhibited a large ice volume anomaly mid-season, but finished with normal conditions.
- There was a strong north-south gradient in SST anomalies (cold north of the Grand Banks and warm on the Grand Banks and on Scotian shelf and Gulf of Maine.
- Warm anomalies were measured in all inshore stations, and Station 27 had the largest fresh anomaly since 1948.
- Large warm bottom temperature anomalies were observed in Division 2 along the Labrador shelf and in Division 4. Bottom temperature were slightly warm in most Division 3, except for the center of the Grand Banks that was slightly cold.
- The cold intermediate layer was slightly warmer than normal, as were most subsurface portions of hydrographic sections SI, BB and FC.
- Fresh anomalies were observed in the inshore areas of Seal Island, Bonavista and Flemish Cap hydrographic sections.
- The Labrador Current transport, as measured by satellite altimetry, was higher than normal on the Labrador and northern Newfoundland slope and weaker than normal on the Scotian slope.

ACKNOWLEDGMENTS

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