Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2023

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PHYSICAL OCEANOGRAPHIC CONDITIONS ON THE SCOTIAN SHELF AND IN THE GULF OF MAINE DURING 2023

by

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Mean annual air temperature anomalies relative to 1991–2020 climatology were positive for all sites. Satellite-based Sea Surface Temperature (SST) annual anomalies were positive for all regions. Long-term coastal monitoring recorded the third highest value of annual SST at Halifax (Nova Scotia) and at St. Andrews (New Brunswick). At other selected sites across the region, four of six sites saw annual water temperature anomalies return to near normal conditions, the other two remained above normal. Temperature in Cabot Strait at 200-300 m depth was the third highest of the record (the last five years were the highest; 2022 was the record high). Temperature in Emerald Basin at 250 m was the second highest of the record (the last eight years were the highest; 2019 was the record high). A composite index, consisting of 22 ocean temperature time series from surface to bottom across the region, indicated that 2023 was near to above normal with 3 of the time series greater than two standard deviations above normal.

RÉSUMÉ

Hebert, D., Layton, C., Brickman, D., and Galbraith, P.S. 2024. Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2023. Can. Tech. Rep. Hydrogr. Ocean Sci. 380: vi + 71 p.

Les anomalies annuelles moyennes de la température de l'air par rapport à la climatologie de 1991 à 2020 étaient positives pour tous les sites. Les anomalies annuelles de température de surface de la mer (SST) basées sur les satellites étaient positives pour toutes les régions. Le monitorage côtier à long terme a enregistré la troisième valeur annuelle de SST la plus élevée aux stations de Halifax (Nouvelle-Écosse) et de St Andrews (Nouveau-Brunswick). À d'autres sites sélectionnés dans la région, quatre de six stations ont vu leurs anomalies annuelles de température de l'eau revenir à des conditions près de la normale, tandis que les deux autres sont demeurées au-dessus de la normale. La température dans le détroit de Cabot à 200-300 m de profondeur était la troisième la plus élevée jamais enregistrée (les cinq dernières années ont été les plus élevées ; 2022 a été le record). La température dans le bassin d'Émeraude à 250 m était la deuxième la plus élevée jamais enregistrée (les huit dernières années ont été les plus élevées ; 2019 a été le record). Un indice composite, composé de 22 séries chronologiques de températures océaniques de la surface au fond dans toute la région, a indiqué que 2023 était près de ou supérieure à la normale, avec 3 des séries chronologiques supérieures de deux écarts types ou plus de la normale.

1 INTRODUCTION

This document discusses air temperature trends, Sea Surface Temperatures (SST), and physical oceanographic variability during 2023 on the Scotian Shelf, Bay of Fundy, and the Gulf of Maine (Figure 1), from observations and model results. 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) (Cyr et al. 2023 ; Galbraith et al. 2023) which together serve as a basis for a zonal Science Advisory Report (DFO 2022). 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; that is, the anomaly divided by the Standard Deviation (SD). If the data permit, the long-term means and SDs are calculated for the 30-year base period of 1991–2020. The use of standardized anomalies and the same base period allow direct comparison of anomalies among sites and variables.

Temperature and salinity conditions on the Scotian Shelf, in the Bay of Fundy and Gulf of Maine regions, are determined by many processes: heat transfer between the ocean and atmosphere; inflow from the Gulf of St. Lawrence supplemented by flow from the Newfoundland Shelf; exchange with offshore slope waters; local mixing; freshwater runoff; direct precipitation; and melting of sea-ice. The Nova Scotia Current is the dominant inflow, originating in the Gulf of St. Lawrence and entering the region through Cabot Strait (Figure 1). This current, whose path is strongly affected by topography, has a general southwestward drift over the Scotian Shelf and continues into the Gulf of Maine where it contributes to the counter-clockwise mean circulation. Mixing with offshore waters from the continental slope also modifies the water-mass properties of shelf waters. These offshore waters are generally of two types: Warm Slope Water, with temperatures in the range of 8°C–12°C and salinities from 34.7–35.5; and Labrador Slope Water, with temperatures from 4°C–8°C and salinities from 34.3–35 (Gatien 1976). Shelf-water properties have large seasonal cycles, along- and across-shelf gradients, and vary with depth (Petrie et al. 1996).

2 METEOROLOGICAL OBSERVATIONS

2.1 NORTH ATLANTIC OSCILLATION INDEX

The North Atlantic Oscillation (NAO) index was originally defined as the difference in sea-level atmospheric pressures between the Azores and Iceland (Rogers 1984), and is a measure of the strength of the westerly winds over the Northwest Atlantic. It represents the dominant, large-scale meteorological forcing over the North Atlantic Ocean. The NAO index is based on a Rotated Principal Component Analysis (Barnston and Livezey 1987) applied to the monthly-standardized 500 mb height anomalies (Hurrell et al. 2003), averaged over winter months of December through March. The anomalies are based on the 1950–2000 climatology mean and standard deviation. Monthly data was obtained from the National Oceanic and Atmospheric Administration (NOAA).

A high NAO index corresponds to an intensification of the pressure difference between the

Icelandic Low and the Azores High. Strong northwest winds, cold air and sea temperatures, and heavy ice in the Labrador Sea and on the NL shelf areas, 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 2023, the winter (December–March) NAO index was below the 1991 – 2020 mean, –0.31 (–0.84 SD) (Figure 2A). The lower panels of Figure 2 show the sea-level atmospheric pressure conditions during the winter of 2023 compared to the 1991 – 2020 mean. The 2023 Icelandic low pressure cell was located higher when compared to the seasonal mean. Meanwhile, the 2023 Azores high pressure cell remained similar to the seasonal mean.

2.2 AIR TEMPERATURES

Surface air temperature anomalies maps relative to the 1991–2020 means for the North Atlantic region are available from the U.S. National Oceanic and Atmospheric Administration's interactive website. In 2023, the annual anomalies were normal to above normal over the Scotian Shelf and the Gulf of Maine (Figure 3). The seasonal anomaly of these regions was above normal during the winter, ranged from below normal to above normal during the spring, and then ranged from normal to above normal for summer and fall (Figure 4).

Monthly air temperature anomalies for 2022 and 2023 relative to their 1991–2020 means at six sites in the Scotian Shelf/Gulf of Maine region are shown in Figure 5. Monthly mean-temperature data for Canadian sites are from Environment and Climate Change Canada's Adjusted Homogenized Canadian Climate Data (AHCCD) where available (Vincent et al. 2012). In cases where no data were available, observed monthly mean values from the Canadian Climate Summaries (CCS) at the Environment and Climate Change Canada website were used. Monthly means from the Monthly Climatic Data for the World (Menne et al. 2018) were used for Boston. Overall, January was the warmest month at all six sites, with temperatures exceeding 4°C from the climatological mean, with the exception of Sable Island. July was also a warm month across all sites, except in Boston where air temperature was slightly above normal. November was below-normal at all six sites. For the remaining months, air temperatures ranged from below-normal to above-normal.

In 2023, the mean annual air temperature anomalies relative to 1991–2020 climatology were positive for all sites , with anomalies ranging from +0.8°C (+1.1 SD) for Sable Island to +1.3°C (+1.9 SD) for Boston (Table 1). The time series of annual anomalies indicates that all sites have increasing temperatures over the long-term with decadal-scale variability superimposed (Figure 6). Over decadal and shorter periods, there are times when there is no trend or a decreasing trend in the temperature. Linear trends from 1900 to present for Sydney, Sable Island, Halifax, Yarmouth, Saint John, and Boston correspond to changes (and 95% confidence limits) per century of +1.3°C (+0.9°C, +1.6°C), +1.4°C (+1.1°C, +1.7°C), +2.0°C (+1.7°C, +2.4°C), +1.3°C (+1.0°C, +1.6°C), +1.3°C (+1.0°C, +1.7°C), and +2.8°C (+2.5°C, +3.2°C) , respectively (Figure 6).

The air temperature anomalies for the six Scotian Shelf and Gulf of Maine sites are summarized in Figure 7 as a composite sum that illustrates two points. Firstly, for most years the anomalies have the same sign; that is, the stacked bars coincide. Since 1900, for the 111 years when all sites were operating, 95 had five or more stations with the annual anomalies having the same signs; for 87 years, all six stations had anomalies with the same sign. This indicates that the spatial scale of the air temperature patterns is greater than the largest spacing between sites. Previous analyses yielded an e-folding decorrelation scale of 1800 km (Petrie et al. 2009). Secondly, 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.

3 REMOTELY-SENSED SEA SURFACE TEMPERATURE (SST)

The satellite-based sea surface temperature product used in the previous years' reports blends data from Pathfinder version 5.3 (4 km resolution for 1982–2020; Casey et al. (2010)), Maurice Lamontagne Institute (MLI; 1.1 km resolution for 1985–2013) and Bedford Institute of Oceanography (BIO; 1.5 km resolution for 1997–2022) as detailed in Galbraith et al. (2021). The process selects the products with the best percent coverage for every averaging area and period (week or month). Monthly (and weekly) temperature composites are calculated from averaged available daily anomalies to which monthly (or weekly) climatological average temperatures are added.

The BIO data stopped being produced in June 2022 and so two National Oceanic and Atmospheric Administration (NOAA) operational products were investigated to continue our operational coverage of the Atlantic Zone. The GHRSST NOAA/STAR L3S-LEO-Daily "super-collated" product was retained (0.02 degree resolution for 2007 to current; NOAA/STAR (2021)). Details of how this data is blended is described in Galbraith et al. (2023).

Monthly and annual temperature anomalies relative to the 1991–2020 climatology are calculated for five subareas based on the NAFO divisions in the Scotian Shelf/Gulf of Maine region (Figure 8). In 2023, sea surface temperatures (SST) were well above normal for January and February. For the remainder of the year, temperatures were above or near normal and trended towards near-normal near the end of the year. (Figure 9). Annual anomalies were calculated from monthly-averaged temperatures for the five subareas (Table 2 and Figure 10). The annual anomalies during 2023 ranged from +1.1°C (+1.5 SD) in eastern Gulf of Maine/Bay of Fundy to +1.4°C (+2.3 SD) in 4Vs . SST remained above normal at all NAFO divisions, with the last three years being the three warmest years in 4Vn (record year), 4Vs, 4W, and 4XSS. NAFO division 4X eastern Gulf of Maine/Bay of Fundy remained above normal, but was cooler than the previous two years. A regime shift algorithm to detect a step change using mean levels was applied to the annual time-series (Rodionov 2004). Over the length of the record, the temperature has three distinct periods at all regions, a relatively cooler period from 1982 to 1993, near the climatological mean from 1994 to 2011, and a relatively warmer period from 2012 to present.

4 COASTAL TEMPERATURES AND SALINITIES

Coastal near-surface temperatures have been collected at Halifax (Nova Scotia) and St. Andrews (New Brunswick) since the 1920s (Figure 11). In 2023 , the SST anomalies relative to the 1991 – 2020 mean for Halifax was +1.6°C (+2.7 SD)(the third highest value; the last four years were the warmest on record), an increase of +0.2°C from 2022, and for St. Andrews was +1.2°C (+1.8 SD)(the third highest value; 2022 was the record high), a decrease of -0.3°C from 2022 .

Temperature and salinity measurements through the water column have been sampled monthly for the most part 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), except in the spring. Vessel availability in April and equipment issues in November affected the sampling of the station during 2023. The annual depth-averaged (0–90 m) temperature, salinity, and density time series are shown in Figure 11. In 2023 , the annual temperature anomaly was +1.2°C (+1.6 SD) (the fifth highest value; 2021 was the record high) and the salinity anomaly was -0.3 (-1.6 SD) . These represent changes of -0.2 °C and -0.6 from the 2022 values.

The 2023 annual cycle at Prince 5 shows normal to above normal temperatures throughout the year with no depth dependence. Salinity was below normal throughout the water column from August to December, which explains the lower than normal density (Figure 12). The freshet in the spring was missed since there was no sampling due lack of a vessel.

As an indication of the upper ocean conditions, two variables, stratification index and mixed-layer depth, are examined for annual variability. The stratification index (SI) is the density difference between 50 m and 5 m. The mixed-layer depth (MLD) is the depth at which the density at 5m is exceeded by 0.03 kg/m^3.

In 2023, the SI at Prince 5 was above normal for January and February, below normal from March to July, above normal for August and September, and near-normal for the remainder of the year. (Figure 13). The MLD was near normal from January to July, and then was shallower than normal from August to December.

The 2023 annual temperature, salinity, and density cycles at Halifax 2, located at the mouth of Halifax harbour (Figure 1), are shown in Figure 14. Conditions were, in general, near normal from January to June. Near-surface temperatures between July and November were above normal. Near-bottom temperatures were colder and fresher than normal from October to December. Conditions throughout the remaining time and depths of the water column were, in general, near normal. The SI was below to near normal from January to June and above normal from July to December. The MLD ranged from below to above normal from January to June and was below to near normal from July to December. (Figure 15).

5 STANDARD SECTIONS

There was no sampling in spring 2023 due to lack of vessel availability.

The Maritimes region AZMP core lines, Cabot Strait, Louisbourg, Halifax, and Browns Bank were sampled in fall 2023 (Figure 16). In addition, ancillary lines were occupied. A line across the Laurentian Channel Mouth was occupied to support modelling efforts. In the Marine Protected Areas, St. Anns Bank and The Gully, lines were occupied to continue monitoring efforts. In the Gulf of Maine, the Northeast Channel, Yarmouth, and Portsmouth lines were occupied as part of the cooperative agreement with Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS). The Cabot Strait shows above normal temperature and more fresh, thus less dense, waters in the top 50m from the eastern side to the centre of the strait. On the western side, temperatures are below normal and saltier, thus more dense, in the top 100m. Throughout the remainder of the water column, water properties are near to above normal. Along the entirety of the Louisbourg line, water temperatures were well below normal in the top 50m, and slightly more salty on the shelf, which explains the above normal density (Figure 18). Below 50m, water properties were generally near normal. The colder than normal temperatures along the slope indicate the lack of relatively warm and salty slope waters. Moving more south along the Scotian Shelf, water properties, mainly temperature, in the top 50m along the Halifax line varied. Near-shore temperatures were below normal, temperatures over the deep basin were above normal, and were below normal to normal from the plateau to the end of the line. Below 50m, water properties were generally near normal, with colder than normal temperatures, thus more dense waters, along the slope, similar to Louisbourg line (Figure 19). On the western Scotian Shelf, the Browns Bank line, water temperatures were mainly below normal throughout the entire water column across the entire line, except for the inshore surface layer which was warmer than normal. Also, waters were fresher than normal in the top 50m on the shelf (Figure 20).

The Appendix contains lines in the region conducted by IML for Cabot Strait in spring (Figure A.1) , summer (Figure A.2),and fall (Figure A.3). For the Maritimes fall AZMP mission, additional lines were sampled. This includes the St. Anns Bank Marine Protected area (Figure A.4), The Gully (Figure A.6), the Northeast Channel (Figure A.8), the Yarmouth (Figure A.9), and the Portsmouth (Figure A.10) lines. If there exists a sufficient number of historical occupations of the sections at the same time of year, anomaly sections are also shown. While these data are not discussed in detail, the data are used in other analyses presented in this document.

6 GLIDER OPERATIONS ON THE HALIFAX LINE

In 2018, glider operations were started along the Halifax Line as an enhancement to the normally tri-annual sections. The glider data provides higher temporal and spatial coverage than the vessel-based sampling (Figure 21). For ease of analysis, the glider data are averaged into hourly, 1-m bins. On regular missions, the glider attempts to follow the Halifax Line from approximately HL2 to HL7. Currents can, however, affect the actual trajectory of the glider (Figure 22). Thus, only glider data collected within 15 nm of the Halifax Line are considered, which explains some of the gaps in Figure 21. Station 2 (HL2) is sampled throughout the year from a small vessel and provides the highest temporal resolution of the Halifax Line stations (Figure 23). Glider data do not significantly add information at Station 2 except when vessel sampling is not available.

For this document, the variability in temperature, salinity, and chlorophyll fluorescence is shown for a few of the Halifax Line stations over the 2022 – 2023 period (Figure 24). This is only a small fraction of the data available for analysis. At HL3, HL4, HL5 and HL6, the glider sampling was sufficient to resolve the seasonal cycle of temperature and the spring and fall phytoplankton blooms (Figure 24). Battery upgrades were completed for the entire fleet in year 2022. This allowed for more consistent coverage out to HL7(Figure 21).

7 SCOTIAN SHELF AND GULF OF MAINE TEMPERATURES

Drinkwater and Trites (1987) tabulated monthly mean temperatures and salinities from available bottle data for 35 areas on the Scotian Shelf and in the eastern Gulf of Maine that generally corresponded 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 (five-year running means) temperature anomalies at selected depths for six areas (Figure 25) is presented (Figure 26). The Cabot Strait temperatures represent a mix of Labrador Current Water and Warm Slope Water entering the Gulf of St. Lawrence along the Laurentian Channel (e.g., Gilbert et al. (2005)); the Misaine Bank series characterizes the colder near-bottom temperatures on the Eastern Scotian Shelf, mainly influenced by either inshore Labrador Current water or cold intermediate layer water from the Gulf of St. Lawrence (Dever et al. 2016); the deep Emerald Basin temperature anomalies represent the warmer slope-water intrusions onto the Shelf that are subsequently trapped in the inner deep basins (note the large anomaly “events” in the Emerald Basin panel of Figure 26C, for example, around 1980, 1998, and 2009, indicative of pulses of Labrador Slope Water); the Lurcher Shoals observations define the ocean climate in the southwest Scotian Shelf and the shallow waters entering the Gulf of Maine via the Nova Scotia Current; lastly, the Georges Basin series represents the slope waters entering the Gulf of Maine through the Northeast Channel. Annual anomalies are based on the averages of monthly anomalies; however, observations may not be available for all months in each area. For Cabot Strait, Misaine Bank, Emerald Basin, Lurcher Shoal, Georges Basin, and E Georges Bank , the 2023 annual anomalies are based on observations from two, three, three, two, four, and five months, respectively.

In 2023, the annual anomaly was +1.4°C (+2.2 SD) for Cabot Strait at 200-300 m (the third highest value; the last five years were the warmest on record; 2022 was the record high). For the shallow Misaine Bank on the eastern Scotian Shelf, the annual anomaly was +0.3°C (+0.5 SD) at 100 m (2022 was the record high). For the deep basins on the central Scotian Shelf and Gulf of Maine, the 2023 anomalies were +1.3°C (+1.5 SD) for Emerald Basin at 250 m (the second highest value; the last eight years were the warmest on record; 2019 was the record high) and +0.2°C (+0.3 SD) for Georges Basin at 200 m (2018 was the record high). For the shallow banks in western Nova Scotia, the anomalies were +0.4°C (+0.6 SD) for Eastern Georges Bank at 50 m and +0.7°C (+0.7 SD) for Lurcher Shoals at 50 m (the last two years were the warmest on record; 2012 was the record high). These values correspond to changes of -0.3°C, -1.5°C, +0.4°C, -0.9°C, -1.0°C and -2.1°C , respectively, from the 2022 values. Over the length of the timeseries, temperature patterns at all areas are in general agreement. For the two relatively near-shore and shallow areas, Misaine Bank and Lurcher Shoal, from approximately the mid to late 1960s to the mid 1980s, temperatures were above and near the climatologyical mean, respectively. For both areas, from the mid 1980s to 2010, temperatures were below normal and from 2011 to present have been above normal. For the deeper and off-shore areas, Cabot Strait, Emerald Basin, Georges Basin, and Eastern Georges Bank, temperatures were relatively below normal from 1970 to 2010, and have been above normal since 2011. Until 2023, the transport of the colder shelf break current of Labrador origin has been negative (Cyr et al. 2024). On the Scotian Shelf, near-bottom temperature has started to decrease from the warm anomalies in the previous years.

8 TEMPERATURES DURING THE ECOSYSTEM TRAWL SURVEYS

In the Maritimes Region, Fisheries and Oceans Canada (DFO), conducts two trawl surveys each year. During winter, the survey covers Georges Bank, the Bay of Fundy, and the western Scotian Shelf. The deep-water boundary of the survey is marked roughly by the 200 m isobath. The broadest spatial temperature and salinity coverage of the Scotian Shelf is obtained during the summer trawl survey, which covers the Scotian Shelf from Cabot Strait to the Bay of Fundy. The deep-water boundary of this survey is also marked roughly by the 200 m isobath along the shelf break.

The temperatures from each survey were interpolated onto a 0.2°-by-0.2° latitude-longitude grid using an objective analysis procedure known as Barnes interpolation (Koch et al. 1983). The Barnes method requires four input parameters, the x and y radii of the weighted ellipse, defined as xr and yr, where x and y are relative to east and north respectively, the grid focussing parameter γ, and the number of iterations. For the winter survey, xr = 0.71 , yr = 0.52 , γ = 0.47 , and 3 iterations was used. For the summer survey, xr = 0.81 , yr = 0.58 , γ = 0.53 , and 3 iterations was used. Temperatures were optimally estimated at the standard depths (e.g., 0 m, 10 m, 20 m, etc.) and for near the bottom. Only the near-bottom temperatures are presented here.

8.1 WINTER SURVEY

The winter survey took place from 24 February to 29 March 2023. A total of 146 Conductivity-Temperature-Depth (CTD) stations were sampled (Figure 27). Sampling was mainly on Georges Bank (NAFO Division 5Ze) and Georges Basin (along the boundary between NAFO Division 5Ze and 4X), with additional sampling on western Scotian Shelf and in the Bay of Fundy (NAFO Division 4X). Additional data from the NOAA National Marine Fisheries Service (NMFS) Northeast Fisheries Center (NEFSC) was used to increase coverage on the western portion of the grid. A total of 9 CTD stations were used, which were sampled between 22 April to 26 April 2023. For most of the area, bottom temperatures were above normal, with bottom temperatures in the Lurcher Shoal area being below normal (Figure 28).

8.2 SUMMER SURVEY

The summer survey took place from 29 June to 14 August 2023. A total of 203 Conductivity-Temperature-Depth (CTD) stations were sampled (Figure 29). The survey covered part of Eastern Georges Bank (NAFO Division 5Ze), to the mouth of the Bay of Fundy (northwest portion of NAFO Division 4X), and spanned the entirety of the Scotian Shelf up to Cabot Strait (NAFO Divisions 4X, 4W, 4Vs, and 4Vn). The near-bottom temperature anomalies for 2023 were near normal on Eastern Georges Bank, to the mouth of the Bay of Fundy, and the western portion of 4X. On the eastern portion of 4X and the western portion of 4W, bottom temperatures were above normal. The eastern portion of 4W was normal to below normal. For both 4Vs and 4Vn, bottom temperatures were near normal except near the shelf break, where bottom temperature anomalies were negative. (Figure 30). The anomaly varied for the NAFO Divisions sampled on the Scotian Shelf in 2023 : +0.9°C (+1.1 SD) for 4Vn (the seventh highest value; 2020 was the record high), -0.1°C (-0.1 SD) for 4Vs (2015 was the record high), -0.0°C (-0.0 SD) for 4W (2022 was the record high) and +0.3°C (+0.3 SD) for 4X (the last two years were the warmest on record; 2012 was the record high) (Figure 31). All regions show elevated bottom temperatures since approximately year 2010.

The volume of the Cold Intermediate Layer (CIL), defined as waters with temperatures less than 4°C, was estimated from Barnes interpolated data using the full depth CTD profiles for the region, from Cabot Strait to Cape Sable (Figure 32). For years where grid coverage is less than 70%, a blended CIL volume, which uses the measured CIL for the region where data was collected and uses the climatological data with the temperature adjustment for the regions not sampled (for additional details see (Hebert et al. 2023)). There is considerable variation in the volume of the CIL from 1998 until 2009 (Figure 32). In 2023 , the CIL volume was near normal (Figure 32). The low-frequency variability of the area-weighted average minimum temperature mirrors the CIL volume.

9 DENSITY STRATIFICATION

Stratification of the near-surface layer influences physical and biological processes in the ocean such as the extent of vertical mixing, the ocean's response to wind forcing, the timing of the spring bloom, vertical nutrient fluxes, and plankton distribution. Under increased stratification, there is a tendency for more primary production to be recycled within the upper mixed layer and hence less available for the deeper layers. The variability in stratification was examined by calculating the density (sigma-t) difference between the near-surface and 50 m water depth. The density differences were based on monthly mean density profiles calculated for several hydrographic areas on the Scotian Shelf (see Figure 35) as defined by Petrie et al. (1996). The long-term, monthly mean density gradients for 1991 – 2020 were estimated; these were subtracted from the individual monthly values to obtain monthly anomalies. Annual anomalies for each area were estimated by averaging all available monthly anomalies within a calendar year. These estimates could be biased if, in a particular year, most data were collected in months when stratification was weak, while in another year sampling was in months when stratification was strong. However, initial results using normalized monthly anomalies obtained by dividing the anomalies by their monthly SDs were qualitatively similar to the plots presented here. The Scotian Shelf-wide average annual anomalies and their five-year running means were then calculated for an area-weighted combination of subareas 4–23 on the Scotian Shelf. A stratification of 0.01 (kg m^{-3})/m represents a difference of 0.5 kg m^{-3} over 50 m.

The dominant feature is the period from about 1950 to 1990 with generally below-average stratification in contrast to the past 25 years that are characterized by above-normal values

(Figure 33). Since 1948, there has been an increase in the mean stratification on the Scotian Shelf, resulting in a change in the 0–50 m density difference of 0.38 kg m^{-3} over 50 years. It should be noted the change over time is not linear but could consist of two periods of constant stratification with a jump around 1990. This change in mean stratification is due mainly to a decrease in the surface density, composed equally of warming and freshening (Figure 34). Stratification in 2023 was higher than in 2022 due to the surface becoming warmer and saltier. Examining the 2023 stratification anomaly for areas 4-23 on the Scotian Shelf show that the above normal anomaly for the Scotian Shelf (Figure 33) is due to an area-average of primarily normal to above-normal values (Figure 35).

10 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 Chaleur Bay to sink (rise) in response to glacial retreat; this results in an apparent rise (fall) of sea level. The PGR rates for Yarmouth, Halifax, and North Sydney have been obtained from Natural Resource Canada's gridded GPS-based vertical velocities (Phillip MacAulay, DFO, pers.comm. 2012, Craymer et al. 2011).

Relative sea level at Yarmouth (1966-2023) , Halifax [1] (1920-2023) , and North Sydney (1970-2023) are plotted as monthly means and as a filtered series using a five-year-running-mean filter (Figure 36). The linear trend of the monthly mean data has a positive slope of +38.3 cm/century (Yarmouth), +34.3 cm/century (Halifax), and +41.7 cm/century (North Sydney) . Barnett (1984) found a slightly higher sea-level rise for Halifax (36.7 cm/century) for the period 1897–1980. This is due to the decrease in sea-level rise after 1980 as discussed below. Relative sea level changes over two periods, 1981–2010 and 1991–2020, shows that sea level rise is in increasing with time. With the removal of the PGR for Yarmouth (-10.3 cm/century), Halifax (-14.7 cm/century), and North Sydney (-16.8 cm/ century), sea-level rise is +28.0 cm/century, +19.6 cm/century, and +24.9 cm/century , respectively. An interesting feature of the data is the long-term variation that has occurred since the 1920s (Figure 37). The residual sea-level data for the common period 1970-2023 shows that the variability has a large spatial structure given the coherence between the three sites. Several potential causes of this decadal-scale variability have been examined; however, the cause of these changes is still not understood. Further south, near Delaware, USA, variations in the wind stress in the subtropical gyre appears to be responsible for the low-frequency variation in sea level (Hong et al. 2000); yet, 20 years of observed Gulf Stream transport does not show a significant decrease (Rossby et al. 2014).

[1] The historical station in Halifax failed in early-2014. The nearby tidal station at Bedford Institute of Oceanography in Dartmouth, Nova Scotia, was used for 2014. For the common operating period, there was no significant difference in the two tide gauges.

11 RESULTS FROM A NUMERICAL SIMULATION MODEL

Currents and transports are derived from the Bedford Institute of Oceanography North Atlantic Model (BNAM) ocean circulation model (Wang et al. 2018). The model has a spatial resolution of 1/12° with 50 z-levels in the vertical (22 in the top 100 m), and partial cells in the bottom layer to adapt to the bathymetry. The model is prognostic, that is, it allows for evolving temperature and salinity fields. Atmospheric forcing is derived from NCEP/NCAR reanalysis forcing (Kalnay et al. 1996). The model is run in various configurations. The analyses in this report come from a version of the model that has been used to study various phenomena in the Atlantic monitoring zone (Brickman et al. 2016, 2018; Wang et al. 2016). This version has a simple representation of the major river systems in the Atlantic region and no tidal forcing. The simulation runs from 1990 to the present, with the latest year updated annually when the surface forcing is available. The model domain is shown in Figure 38.

Some calculations intended to help interpret data collected by the AZMP are presented. Results are presented in terms of standardized anomalies to facilitate comparison to other AZMP analyses. The reader is cautioned that the results outlined below are not measurements, and simulations and improvements in the model may lead to changes in them.

11.1 VARIATION IN TRANSPORTS IN THE SCOTIAN SHELF/GULF OF MAINE REGION

The general circulation on the shelf seas of the Maritimes Region of Canada can be characterized as a general northeast-to-southwest flow from the Strait of Belle Isle, through Cabot Strait, and along the Scotian Shelf toward the Gulf of Maine (Figure 39). Part of the water that flows out of the Gulf of St. Lawrence through the western side of Cabot Strait follows the Nova Scotia coastline as the Nova Scotia Current, which ultimately flows into the Gulf of Maine. Another part follows the shelf break and contributes to the Gulf of Maine inflow at the Northeast Channel. Variations in these currents may influence the distribution of various fish and invertebrate larvae from the southern Gulf of St. Lawrence westward to the Gulf of Maine. As well, the currents that stream past Cape Sable Island and through Northeast Channel bring on-shelf and off-shelf water properties into the Gulf of Maine, and the partitioning of the transports is potentially important to processes occurring in the Gulf of Maine.

Monthly mean transports for the 1990–2023 period were extracted from the model simulation for four Maritime sections: Cabot Strait (CS), Halifax (HFX), Cape Sable Island/Browns Bank (CSI) and Northeast Channel (NEC) (Figure 39). From these data, standardized anomaly plots (based on a 1991–2020 averaging period) were constructed to illustrate transport variability. The results for the near-shore regions at CS, HFX, and CSI, the shelf break at HFX, and the inflow at NEC are displayed in Figure 40. Here, nearshore is taken as the subsection between the coastline and 30 km, 80 km, and the 100 m isobath for CS, HFX, and CSI respectively. From the inflows through the CSI and NEC sections the Gulf of Maine (GoM), the inflow ratio CSI/(CSI + NEC) was computed (see below). Note that for all sections except NEC, positive transport denotes a flow direction through CS towards the GoM. For NEC, positive transport denotes flow into the GoM.

Transport variability on the Scotian Shelf shows a fairly coherent pattern of annual anomalies for

CS, HFX (near-shore and shelf-break), and CSI (Figure 41). On a monthly basis, on average, the near-shore series (CS, HFX near-shore, and CSI) and the transport into the GoM at NEC exhibit a seasonal cycle with mid-to-late-year transport minima, while the shelf-break transport along the Halifax section shows no clear seasonality (Figure 40, although note interannual variability).

For a qualitative comparison with the numerical model transport estimates, the monthly transport of the Nova Scotia Current off Halifax was calculated using bottom-mounted Acoustic Doppler Current Profilers (ADCP). Three upward looking ADCPs had been deployed for six-month periods from July 2008 to April 2015 on the 100 m (T1), 170 m (T2), and 180 m (T3) isobaths to monitor the velocity field associated with the Nova Scotia Current along the Halifax Line. Located 12 km east of station 2 (Figure 1 and Figure 39) is T2. T1 and T3 are approximately 15 km to the northwest and southeast of T2, respectively. The observations start from 5 m above the bottom to approximately 10 m below the surface, with a 4 m vertical resolution. The horizontal spacing between ADCPs is about 16 km, with T2 located close to the current maximum. The velocity components are rotated by 58° relative to True North to obtain the velocity field with the maximum variance along the major axis. Daily averages of the alongshore velocity were gridded using linear interpolation and multiplied by the cross-sectional area between T1 and T3 to provide monthly estimates of the Nova Scotia Current transport in $10^6 m^3 s^{-1}$. When data are available from all three stations, these periods are used to establish a linear relationship between the transport estimated using all stations and the transport estimated using only one or two ADCP stations. These relationships have been used to extrapolate the transport estimations to periods where one of the ADCP has failed during the deployment. As of May 2015, only the mooring at T2 has been deployed. Work by Dever (2017) showed a high correlation (r^2 = 0.87) between the depth-integrated current at T2 and the total transport. Transport anomalies are based on the mean for each month using all data available for that month. Red anomalies denote an increase in transport toward the Gulf of Maine, while blue anomalies indicate decreased transport[2]. The data indicate a period of negative anomalies (stronger south-westward flow) starting in mid-2010 and extending to mid-2011, followed by average or weaker flow that persists until summer 2016 (Figure 42). For the fall of 2016 and winter of 2017, the flow was above normal, followed by mostly near-normal transport until September 2018 where above-normal transport was observed until the end of the year. Transport has been mostly near normal from 2019 to the end of 2022, with the exception of a strong increase in transport in April, 2022, while the first eight months of 2023 have been mostly above normal. These trends are overall well simulated by the model, although differences exist. Notably, the positive anomaly in April, 2022, is captured by the model (see HFX nearshore panel of Figure 40).

The fraction of transport into the Gulf of Maine through the Cable Sable Island section (GoM inflow ratio of Figure 43) exhibits a seasonal cycle with a minimum during the summer months. On average, the model predicts that about one half of the transport into the Gulf of Maine enters through the CSI section. Inter-annually (Figure 41) the GoM inflow ratio was near neutral from 1990–2007 (with only 2001 and 2004 above normal), mostly negative from 2008–2014, near-neutral from 2015–2019, strongly negative from 2020-2022, , and near neutral in 2023. From the model simulation, the general warming trend over the last decade, seen in many data series, is evident as increased transport into the GoM at NEC and a reduced GoM inflow ratio.

An overall annual composite transport index was computed (Figure 44) by summing the standardized anomalies (Figures 40 and 41) for five of the six transport variables (the inflow

[2]These anomalies are based on a different averaging period than used for the model simulations.

through NEC was omitted as this metric is not independent of the GoM inflow ratio). If one considers this summation as a measure of the on-shelf flow-through in the system from the southern Gulf of St. Lawrence to the Gulf of Maine, it is found that the model hindcasts generally negative anomalies from 1990–2000, with strong negative anomalies in 1990, 1993–94, and 1999–2000; generally weak positive anomalies from 2001–2007; alternating stronger negative and positive anomalies until 2015 followed by weak positive anomalies until 2021 with 2022 exhibiting strong negative anomalies flip-flopping to strong positive anomalies in 2023.

12 MARINE HEAT WAVES AND COLD SPELLS

A mounted bottom CTD at T2 near HL2 (see description of location in Section 11) provided temperature from 2008 to 2023. Temperature data from the moorings at this location were averaged into daily values. This data was used to determine periods of heat waves and cold spells. To determine these periods, a daily climatology was constructed with the 10^{th} percentile and 90^{th} percentile representing cold spell and and heat wave limits respectively. A $\pm$ 5 day moving average (ignoring February 29) was used to calculate the climatological mean and limits. Those values were smoothed with a 11-day running mean filter. The periods when the observed data was less the 10^{th} limit or greater than the 90^{th} limits were determined. This method follows that used by Hobday et al. (2016) and Oliver et al. (2021). Normally, climatologies are based on 30-years data but Schlegel et al. (2019) showed series of missing less than 25% of data has no appreciable difference.

Cold spells/heat waves were determined as periods greater than five days but allowing for a period of two days or less that didn't meet the criteria. For the period of 2022-2023, the daily bottom temperature observed is presented in Figure 45. The climatology mean temperature for that period (solid line) and 10^{th} and 90^{th} percentile limits (dashed lines) for the time period are also shown. Regions of cold spells and heat waves are shown as the blue and red shaded regions. There was a single cold spell in this two-year period. Whereas, there were many heat waves. There were more events in 2023 compared to 2022.

For the period from 2008 to 2023, annual mean properties were determined based on the events found. Figure 46 shows the number of events for each year, the average length of events and the average temperature of the events. Interestingly, there were no heat waves for the first few years but plenty of cold spells. For later years, the number of cold spells decreased while the number of heat waves increased. The average length of events does not vary with time except at the start of the time series where no heat waves were observed and an extremely long cold spell wave event in 2008. The strength of the events did not change over time. Cold spells have a larger anomaly than heat waves. This is not unexpected as the location of the CTD is in relatively shallow water (165 m) near the coast. Strong cooling events due to winter storms can produce cold periods.

13 SUMMARY

In 2023, the North Atlantic Oscillation index was below normal (–0.31 , –0.84 SD). The analysis of satellite data indicates that sea-surface temperatures were above normal at all regions (a record high at 4Vn) with the last three years being the warmest, except for 4X eastern Gulf of Maine/Bay of Fundy which was cooler than the previous two years.

A graphical summary of selected time series already shown indicates that the periods 1970-1976 and 1987–1998 were predominantly colder than normal (the 1991–2020 average values) and 2010– 2023 were warmer than normal (Figure 47). In 2023 , 10 of 22 variables that were able to be measured were more than 1 SD above their normal values. Of these, 3 were more than 2 SD above normal. There were no record highs in 2023. Two series were the second highest and 3 series the third highest.

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16 TABLES

Table 1. The 2023 annual mean air temperature anomaly in degrees and normalized anomaly (relative to the 1991-2020 climatology) and SD of the monthly anomalies for Scotian Shelf and Gulf of Maine.

	Annual Anomaly		1991-2020 Climatology	
Site	**Observed (℃)**	**Normalized (SD)**	**Mean (℃)**	**SD**
Sydney	+1.1	+1.5	+6.45	+0.72
Sable Island	+0.8	+1.1	+8.35	+0.67
Halifax	+0.9	+1.3	+7.16	+0.70
Yarmouth	+1.1	+1.6	+7.69	+0.71
Saint John	+1.1	+1.5	+5.71	+0.77
Boston	+1.3	+1.9	+10.90	+0.71

Table 2. The 2023 SST anomalies and long-term statistics.

	Annual Anomaly		1991-2020 Climatology	
NAFO Zone	**Observed (℃)**	**Normalized (SD)**	**Mean (℃)**	**SD**
4Vn	+1.3	+2.6	+6.61	+0.50
4Vs	+1.4	+2.3	+7.73	+0.60
4W	+1.1	+1.8	+8.80	+0.63
4XSS	+1.3	+2.0	+8.45	+0.63
4XeGoM+BoF	+1.1	+1.5	+8.27	+0.73

Table 3. The 2023 summer ecosystem trawl survey bottom temperature anomalies and long-term statistics.

	Annual Anomaly		1991-2020 Climatology	
NAFO Zone	**Observed (℃)**	**Normalized (SD)**	**Mean (℃)**	**SD**
4Vn	+0.9	+1.1	+3.88	+0.83
4Vs	-0.1	-0.1	+3.43	+0.89
4W	-0.0	-0.0	+6.76	+0.99
4X	+0.3	+0.3	+7.84	+0.93
4XSS	+0.4	+0.4	+7.06	+1.06
4XeGoM BoF	-0.1	-0.1	+8.22	+0.92

17 FIGURES

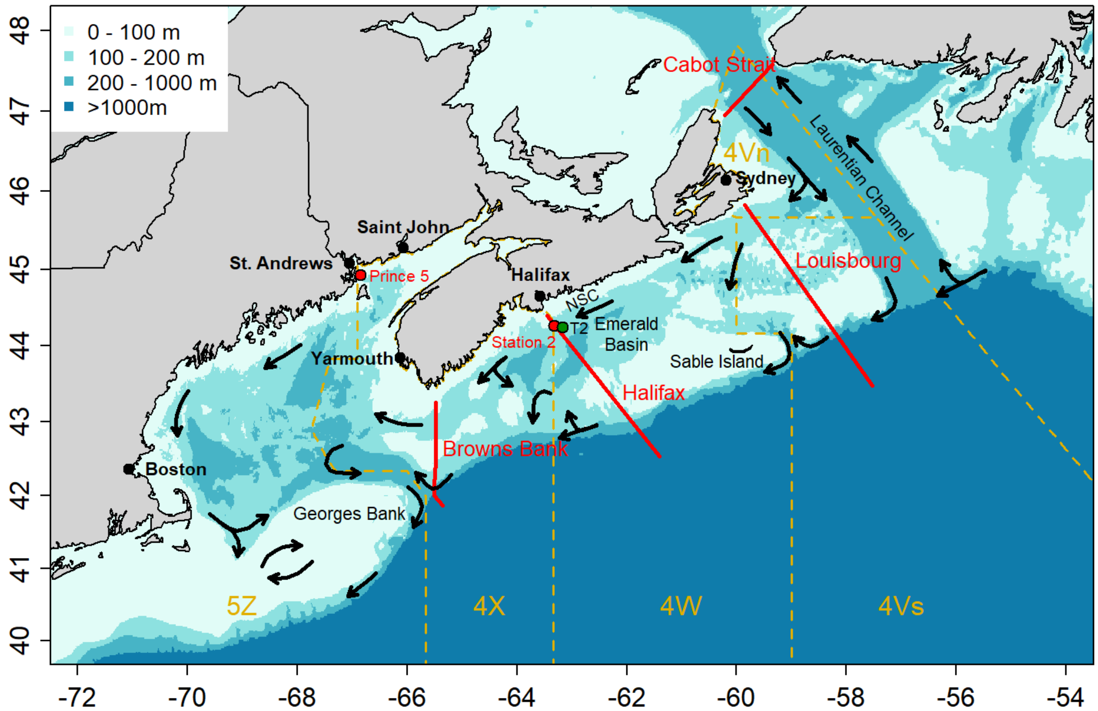

Figure 1. Map of the Scotian Shelf and the Gulf of Maine showing high frequency sampled hydrographic stations (red circles) near Halifax and St.Andrews, core AZMP lines (red lines), Nova Scotia Current mooring, T2, (green dot) near Halifax, weather stations (black dots) and topographic features. The Nova Scotia Current (NSC) is shown. The dotted yellow lines indicate the boundaries of the Northwest Atlantic Fisheries Organization Divisions.

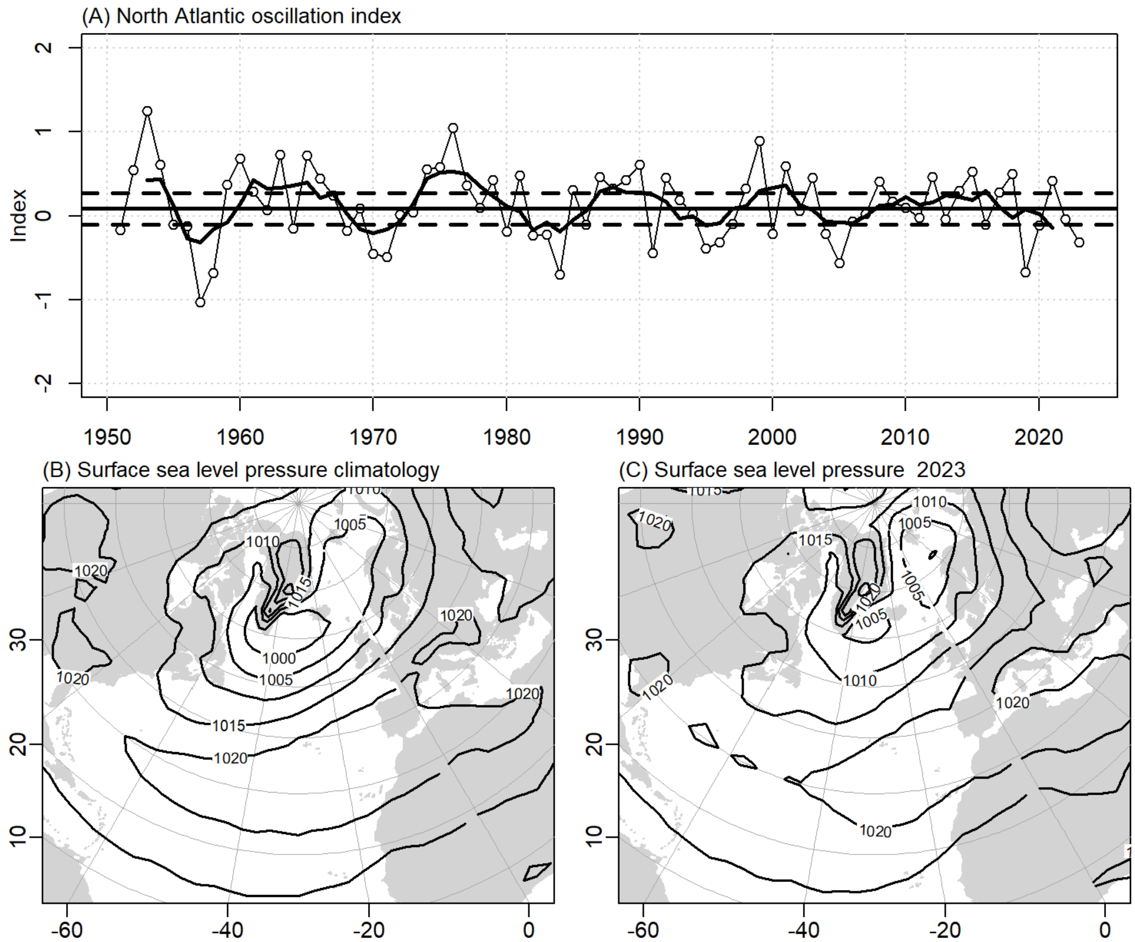

Figure 2. (A) The North Atlantic Oscillation (NAO) index, defined as the winter (December, January, February, March) 500 mb pressure Principal Component Analysis which is representative of the difference between the Icelandic low and Azores high. Thick line is a 5-year moving average. Climatological mean is shown as the solid line. Dashed lines are ±0.5 standard deviation (SD). (B) The 1991-2020 December – March mean and (C) December 2022 – March 2023 mean sea-level atmospheric pressure over the North Atlantic. (Data provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado.)

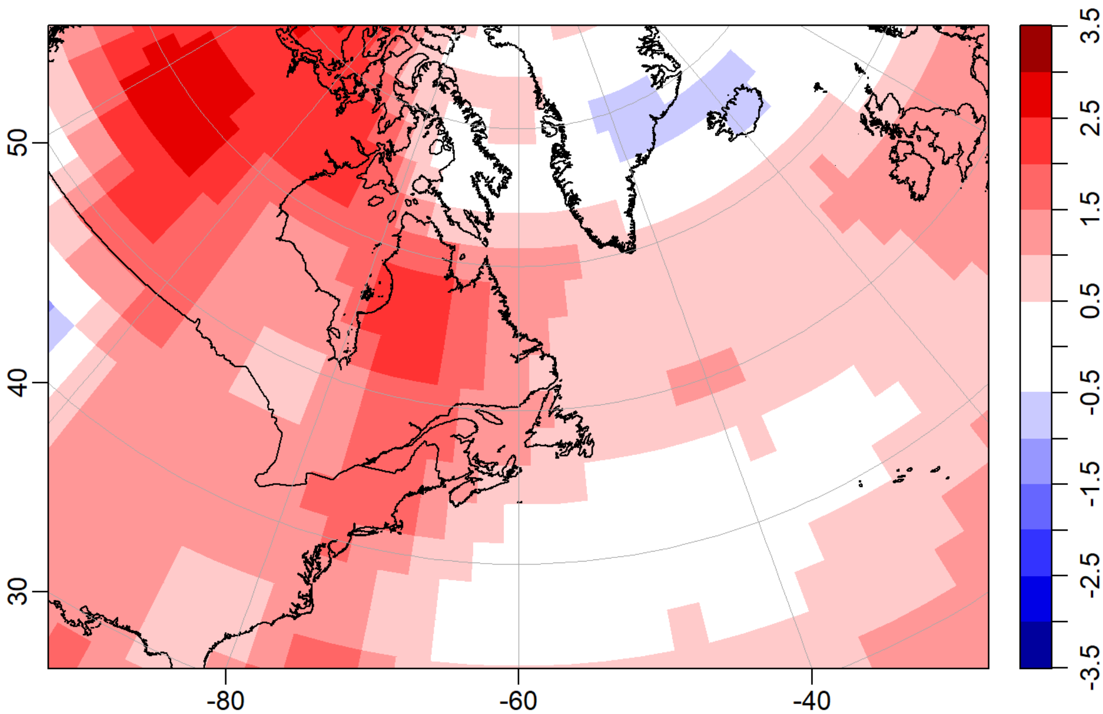

Figure 3. Annual air temperature anomalies (°C) over the Northwest Atlantic relative to the 1991-2020 mean; data were obtained from NOAA Internet site (accessed 31 January 2024).

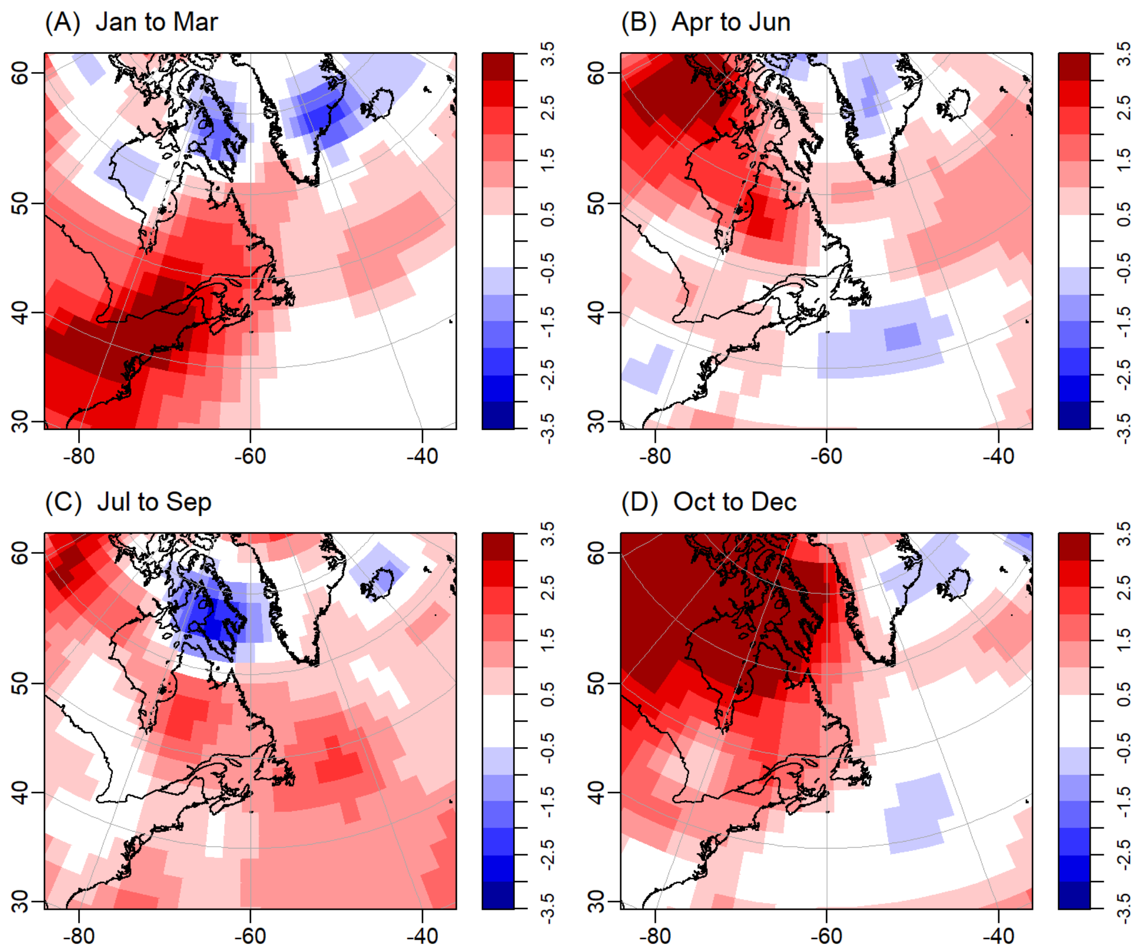

Figure 4. Seasonal air temperature anomalies (°C) over the Northwest Atlantic relative to the 1991-2020 means; data were obtained from NOAA Internet site (accessed 31 January 2024).

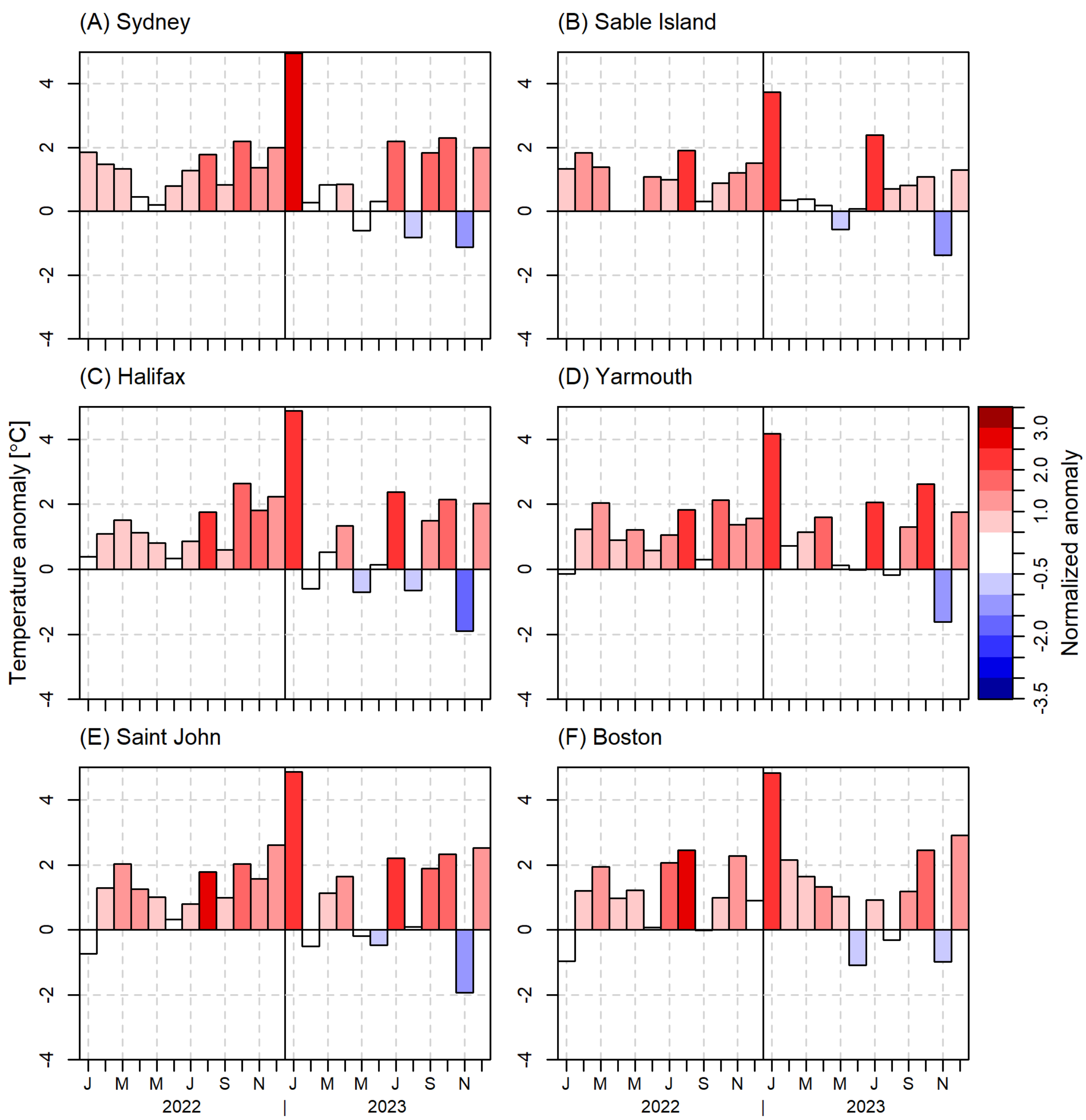

Figure 5. Monthly air temperature anomalies (°C) at several sites in Scotian Shelf/Gulf of Maine region for 2022 and 2023. See Figure 1 for locations. JMMJSN on x-axis represent January, March, May, June, September, and November. Anomalies are colour coded in terms of the number of SD above or below normal relative to monthly statistics.

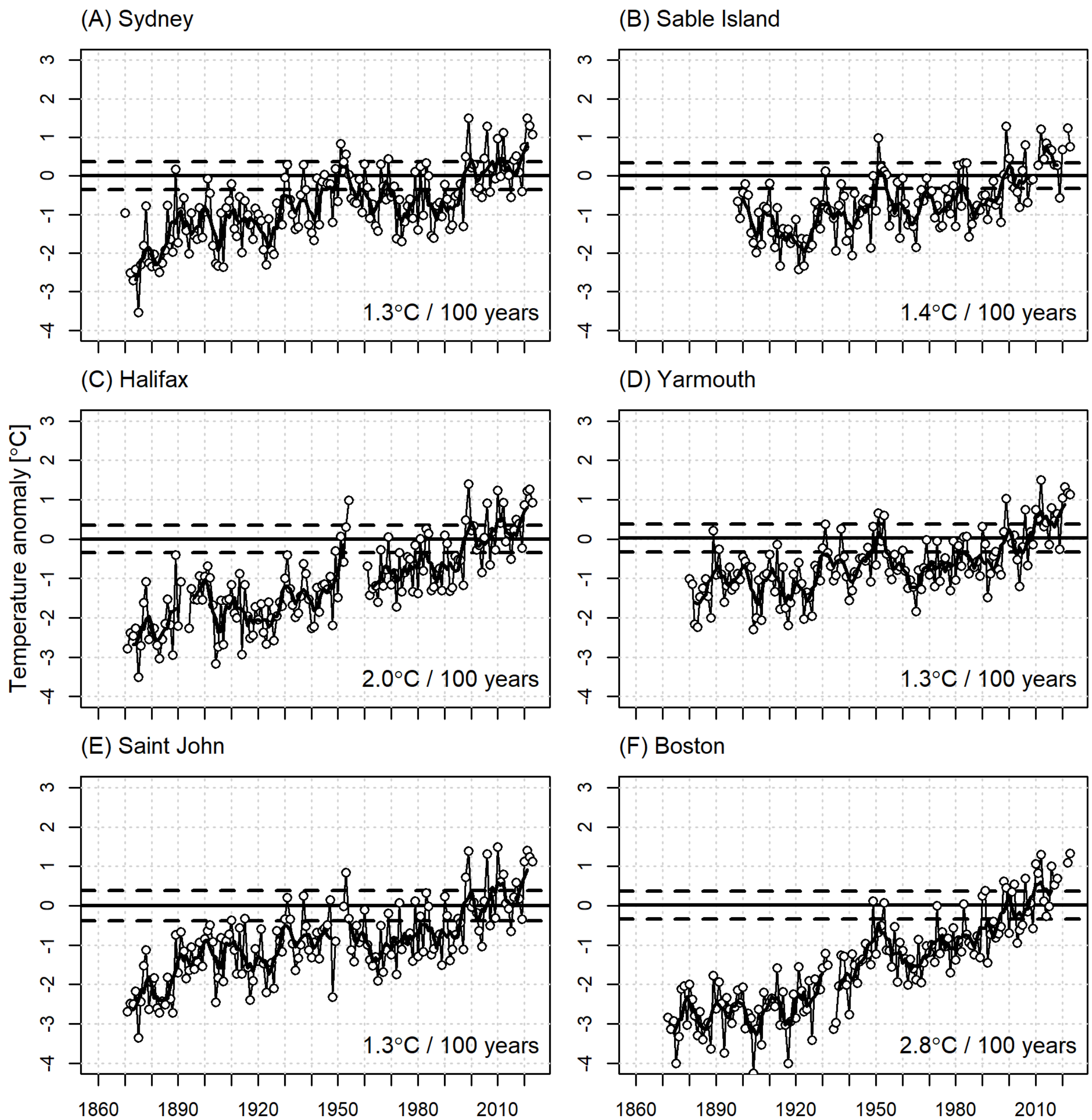

Figure 6. Annual air temperature anomalies in °C (dashed line) and five-year running means (solid line) at selected sites (Sydney, Sable Island, Halifax (Shearwater), Yarmouth, Saint John, and Boston) in Scotian Shelf/Gulf of Maine region (years 1870 to 2023). Horizontal dashed lines represent plus or minus 0.5 SD for the 1991-2020 period. Linear trends for 1900–present are shown.

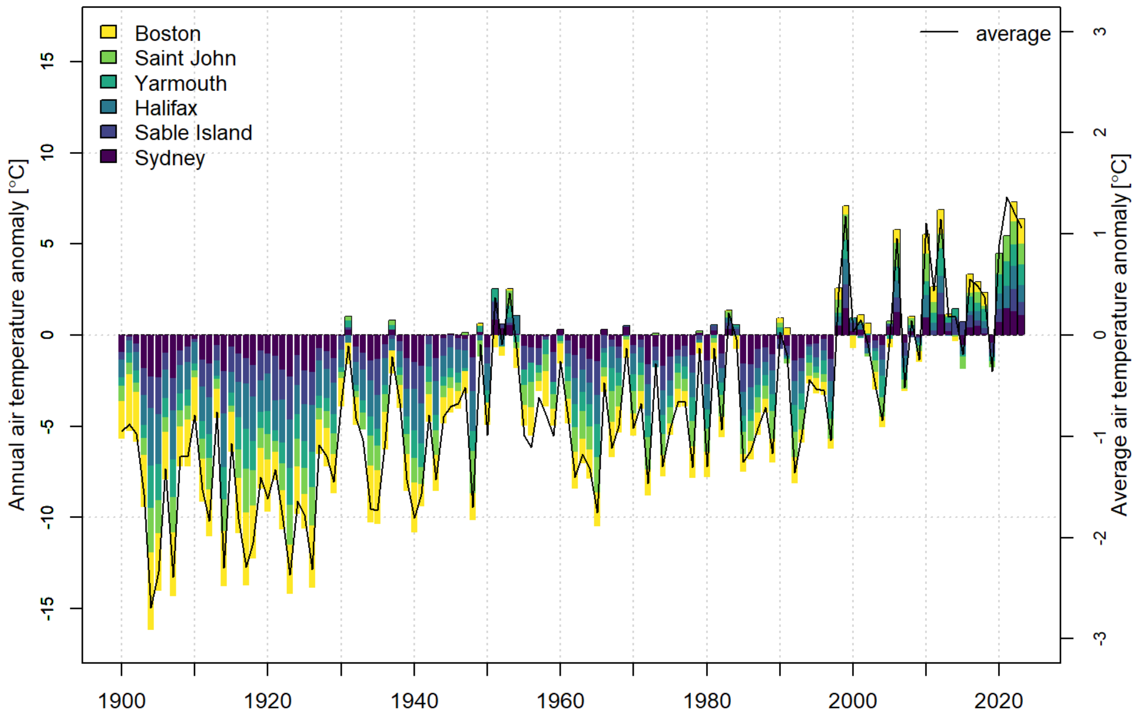

Figure 7. The contributions of each of the annual air temperature anomalies for six Scotian Shelf/Gulf of Maine sites (Boston, Saint John, Yarmouth, Halifax (Shearwater), Sable Island, and Sydney) are shown as a stacked bar chart. Anomalies referenced to 1991-2020.

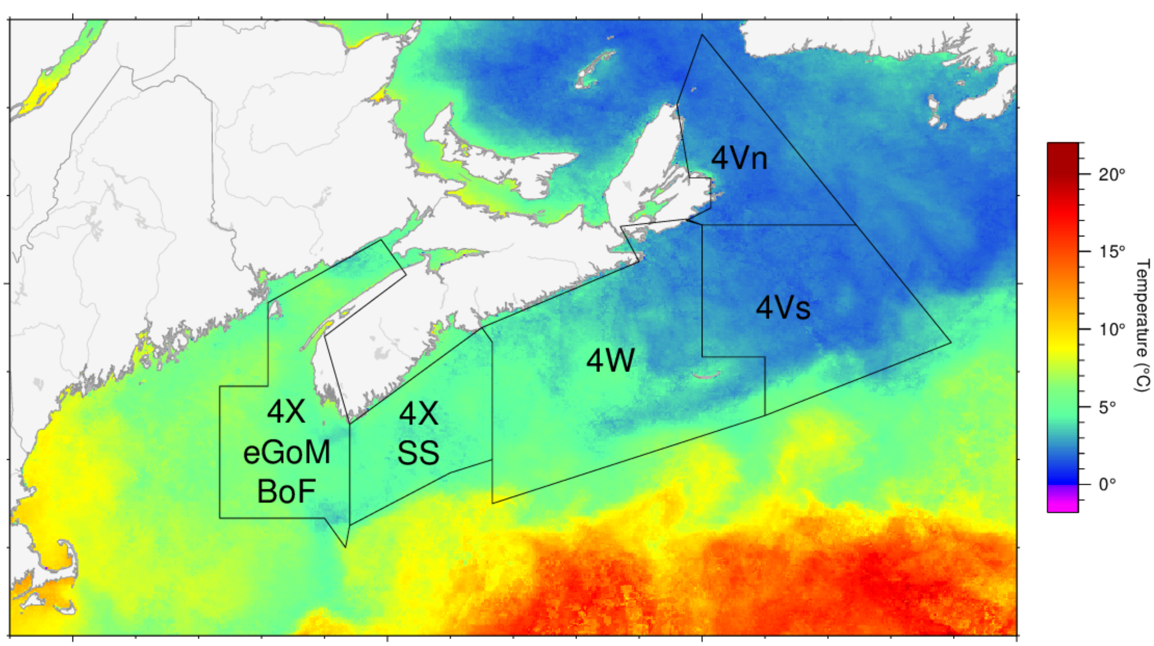

Figure 8. Scotian Shelf/Gulf of Maine areas (4Vn, 4Vs, 4W, 4X SS, and 4X eGoM-BoF) used for extraction of sea surface temperature.

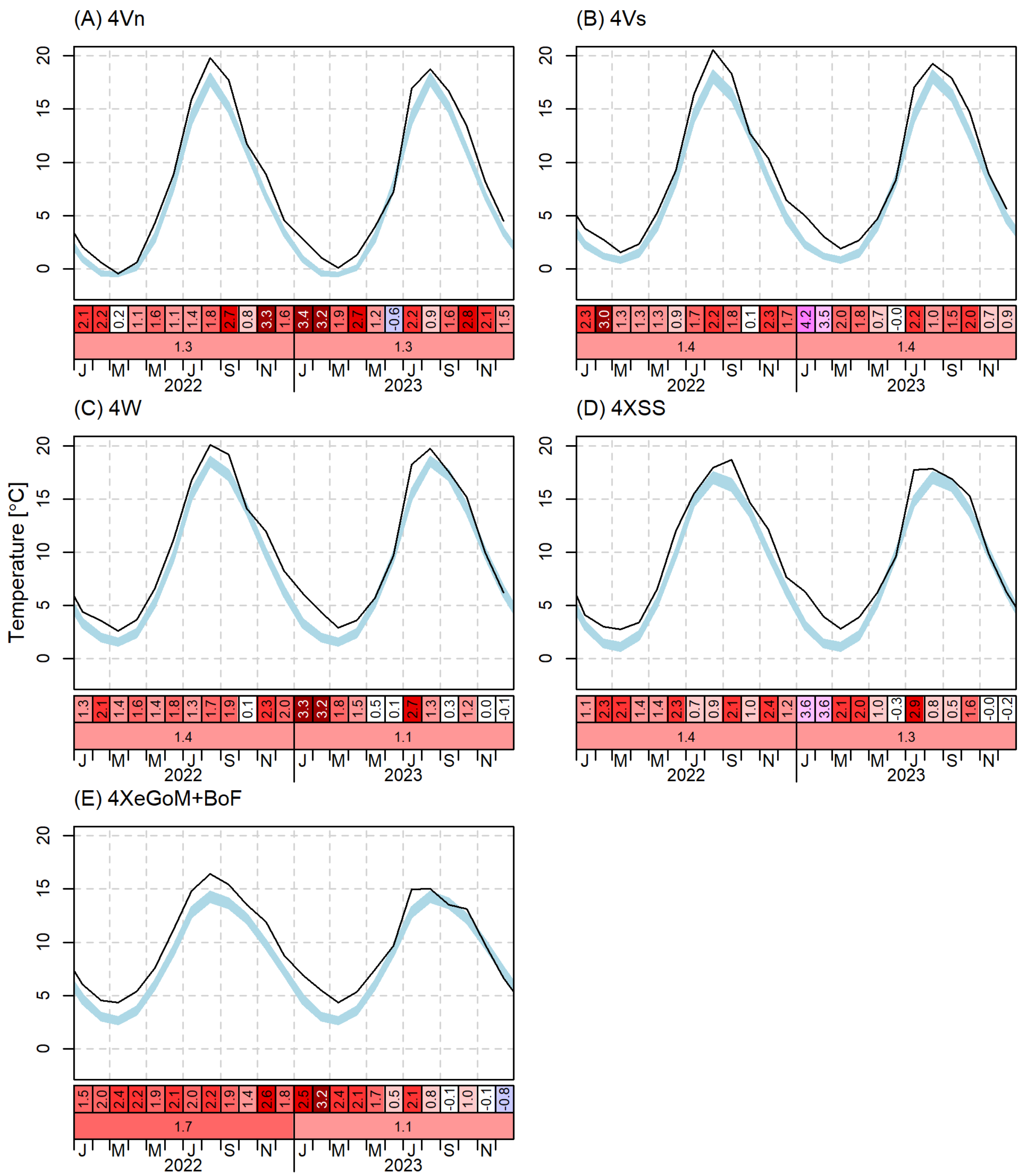

Figure 9. AVHRR SST monthly and annual averages over the five regions of the Scotian Shelf and Gulf of Maine. The blue area represents the 1991-2020 climatological monthly mean ± 0.5 SD. The scorecards are colour-coded according to the normalized anomalies based on the 1991-2020 climatologies for each month (top row) or for the year (bottom row).

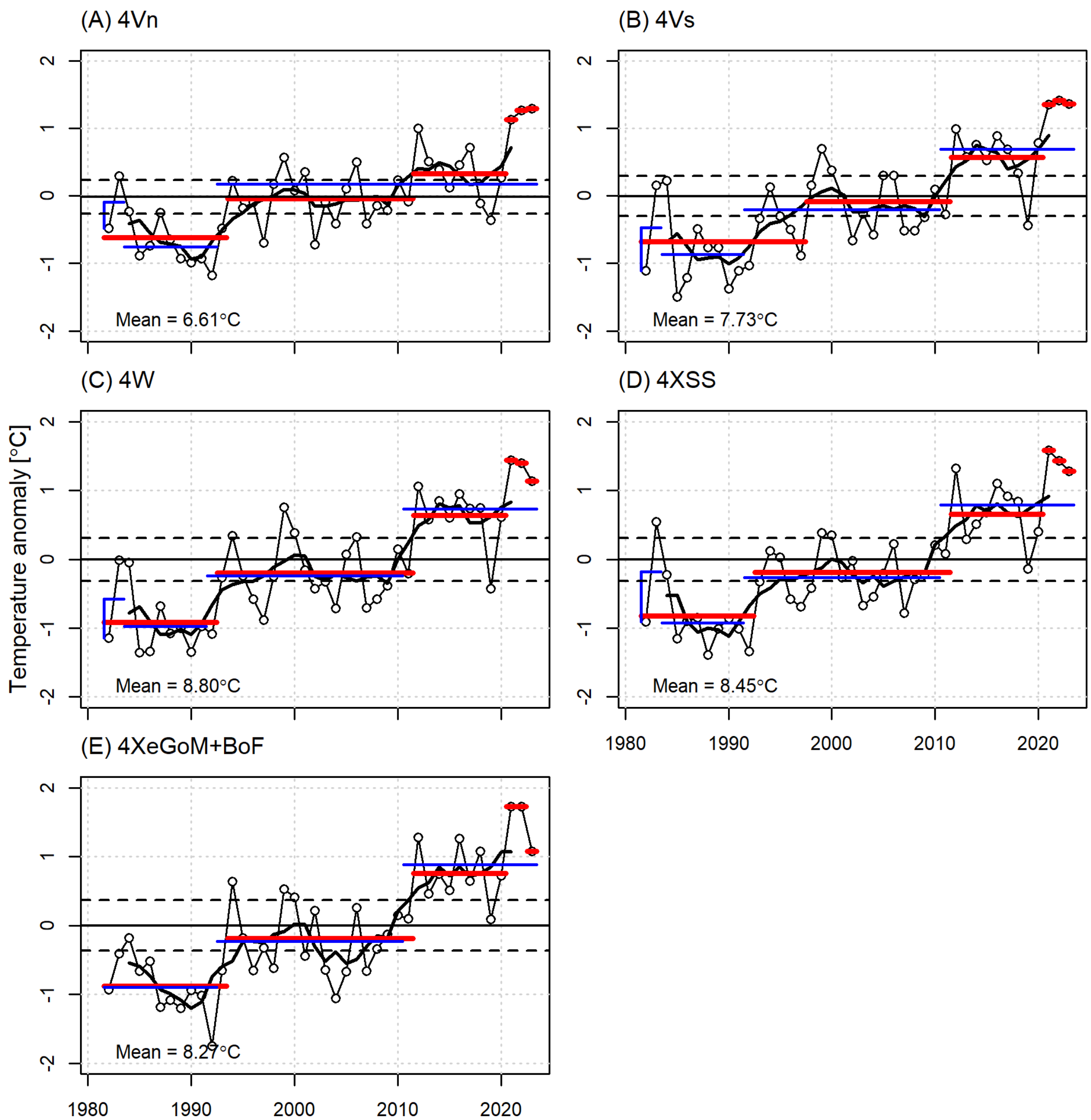

Figure 10. The annual sea-surface-temperature normalized anomalies derived from satellite imagery compared to their long-term monthly means (five Scotian Shelf and Gulf of Maine regions–4Vn, 4Vs, 4W, 4X Scotian Shelf, and 4X eastern Gulf of Maine/Bay of Fundy (Figure 8)). Horizontal dashed lines represent plus or minus 0.5 SD for the 1991-2020 period. Regime shift analysis results from running the method forwards and backwards on the time series depicted by the blue and red horizontal lines, respectively.

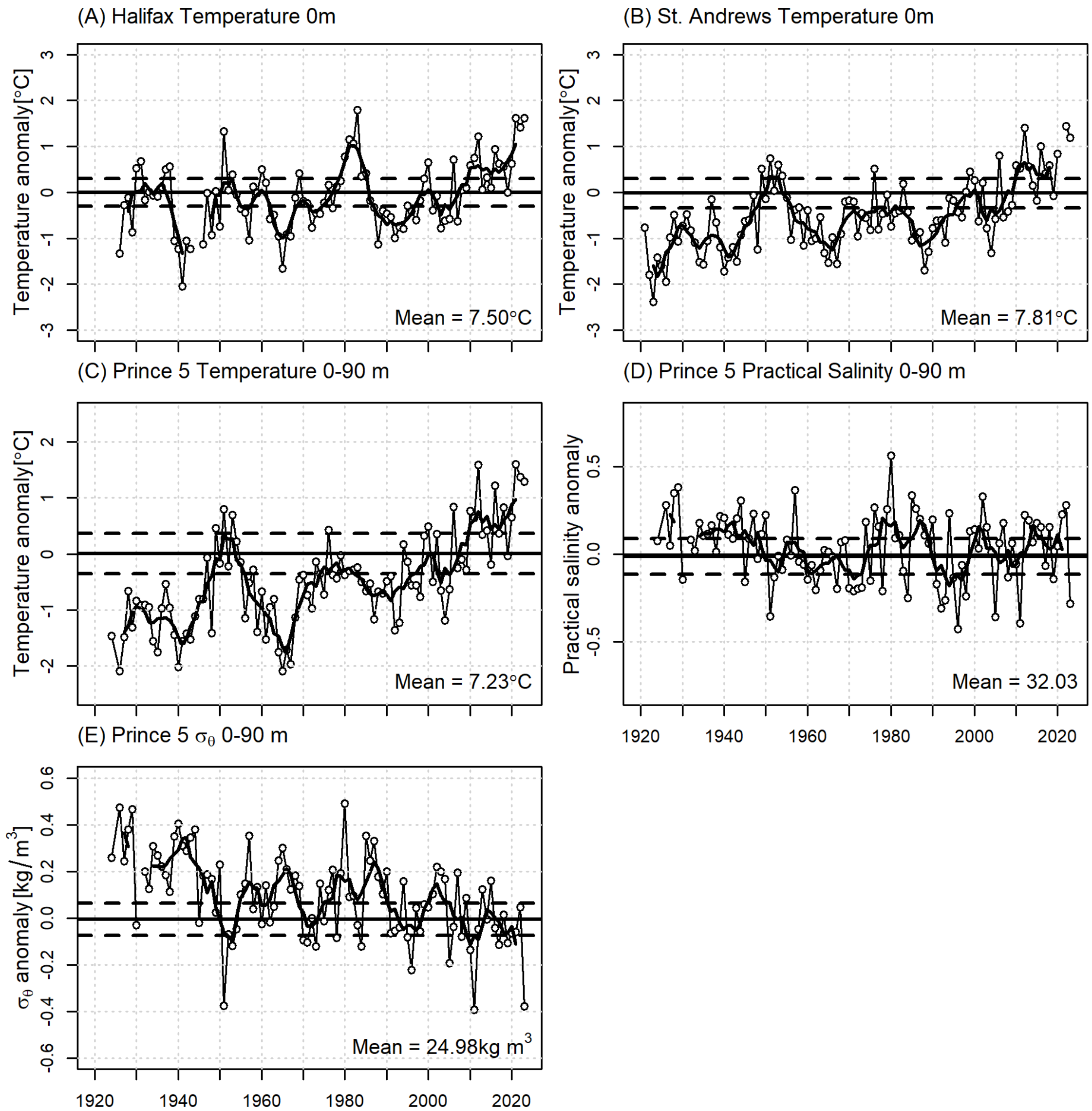

Figure 11. The annual surface-temperature anomalies with respect to the 1991–2020 climatology (thin solid line with circles) and their five-year running means (thick black line) for (A) Halifax Harbour and (B) St. Andrews; and annual depth-averaged (0–90 m) temperature (C), salinity (D), and density (E) anomalies for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Horizontal dashed lines represent the mean ±0.5 SD.

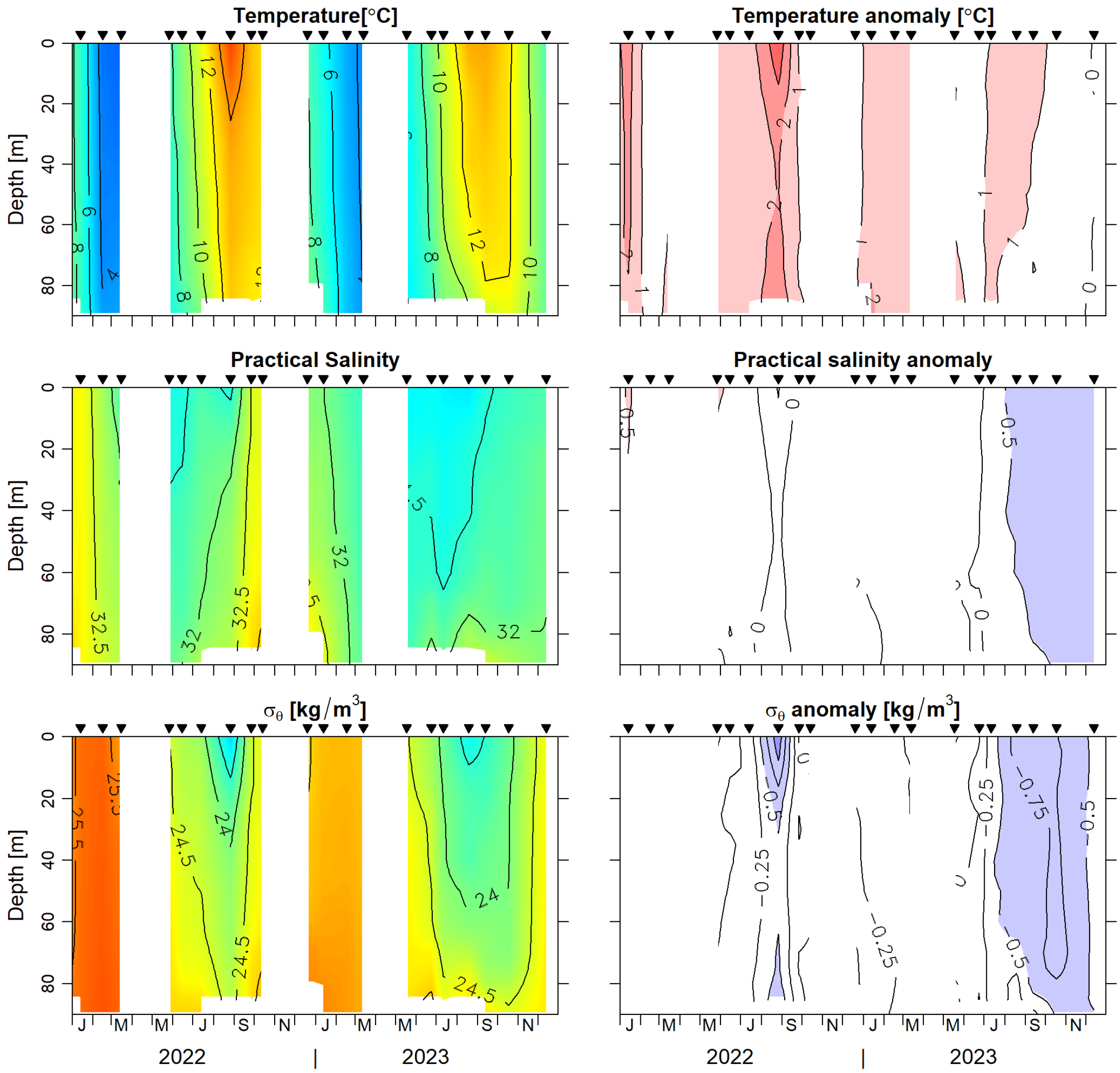

Figure 12. The 2022-2023 annual cycle of temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to 1991–2020 climatology (right panels) for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Triangles indicate periods of sampling.

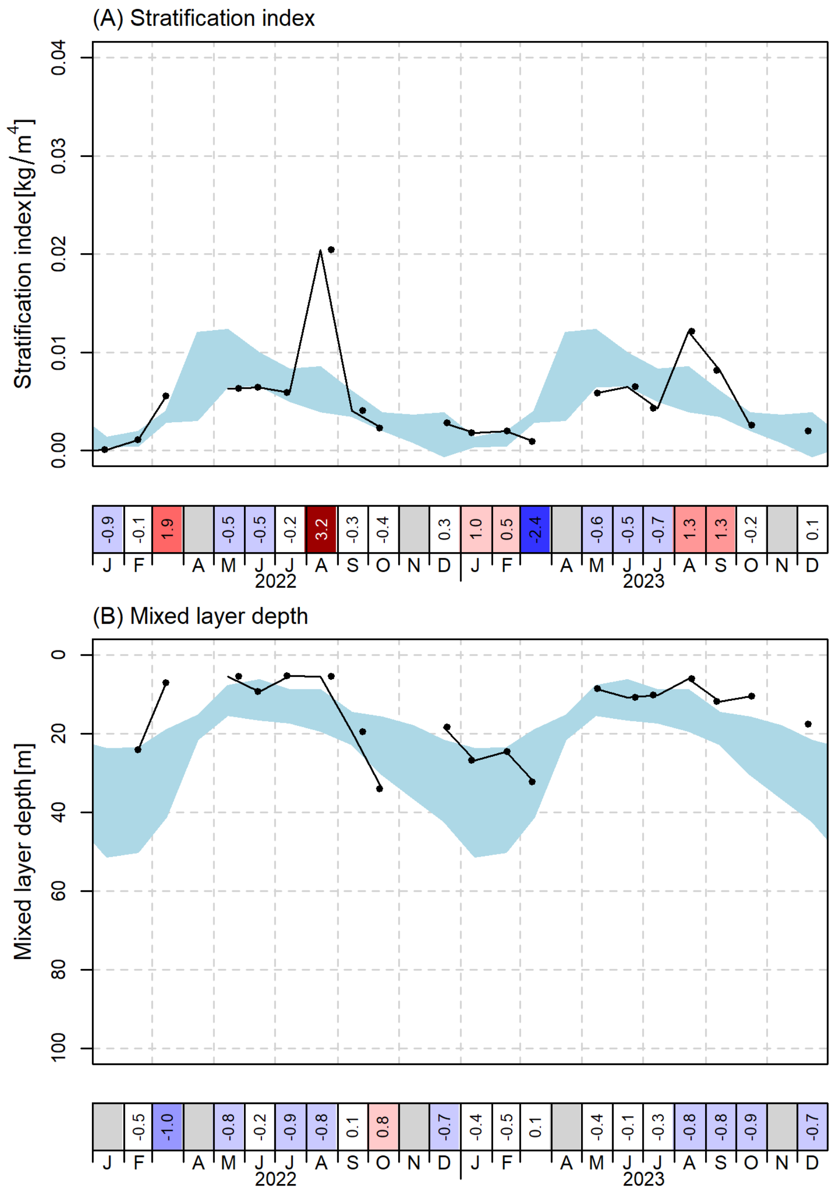

Figure 13. The 2022– 2023 annual cycle of stratification index (top panel) and mixed layer depth (lower panel) for Prince 5. The shaded area is the 1991–2020 climatological mean +/- 0.5 standard deviations. The dots represent actual measurements and solid line is the monthly average value plotted at mid-month. Their anomalies with respect to 1991–2020 monthly means are shown below each figure.

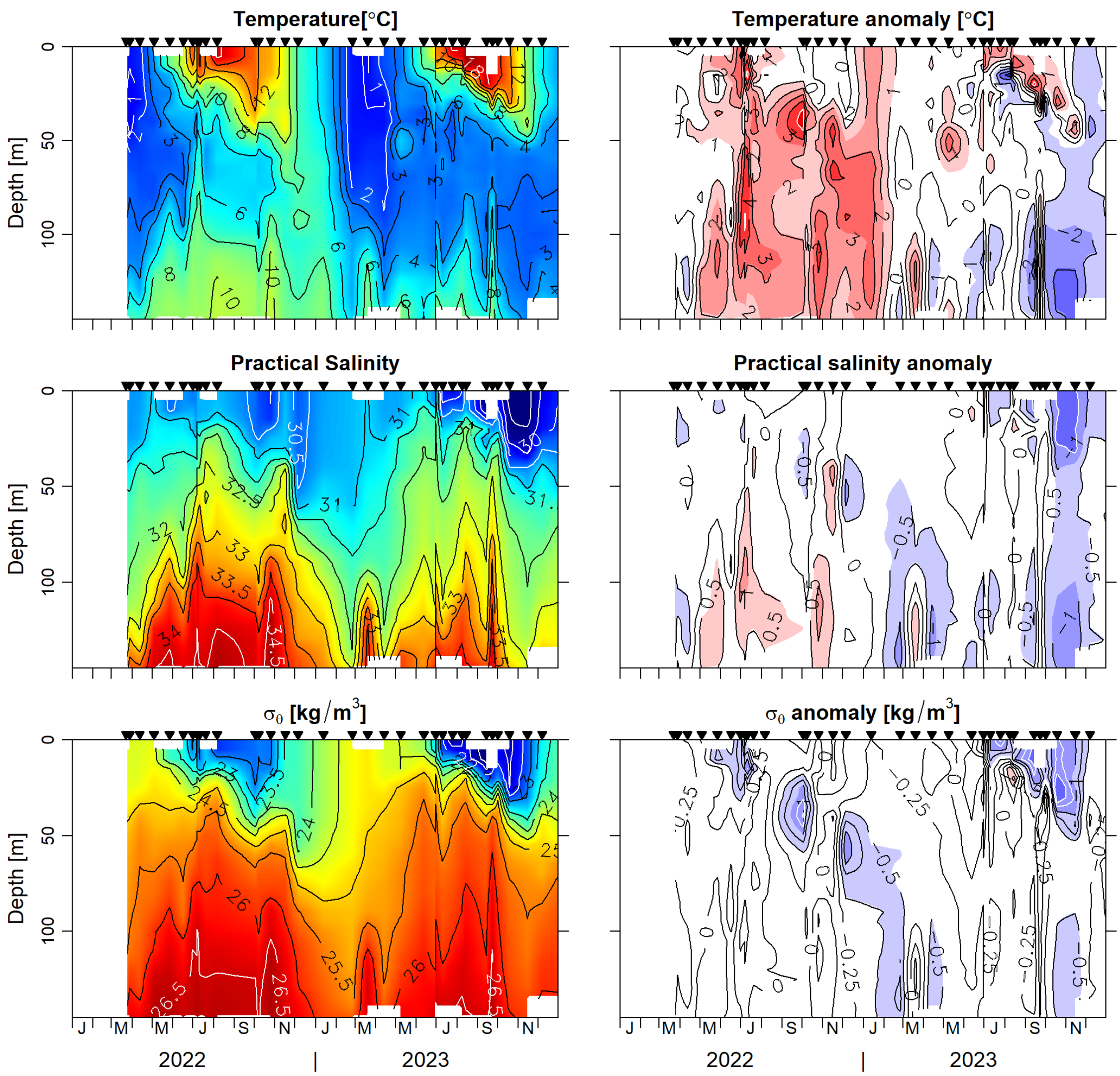

Figure 14. The 2022-2023 annual cycles of temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to 1991–2020 climatology (right panels) for Halifax station 2. Triangles indicate periods of sampling.

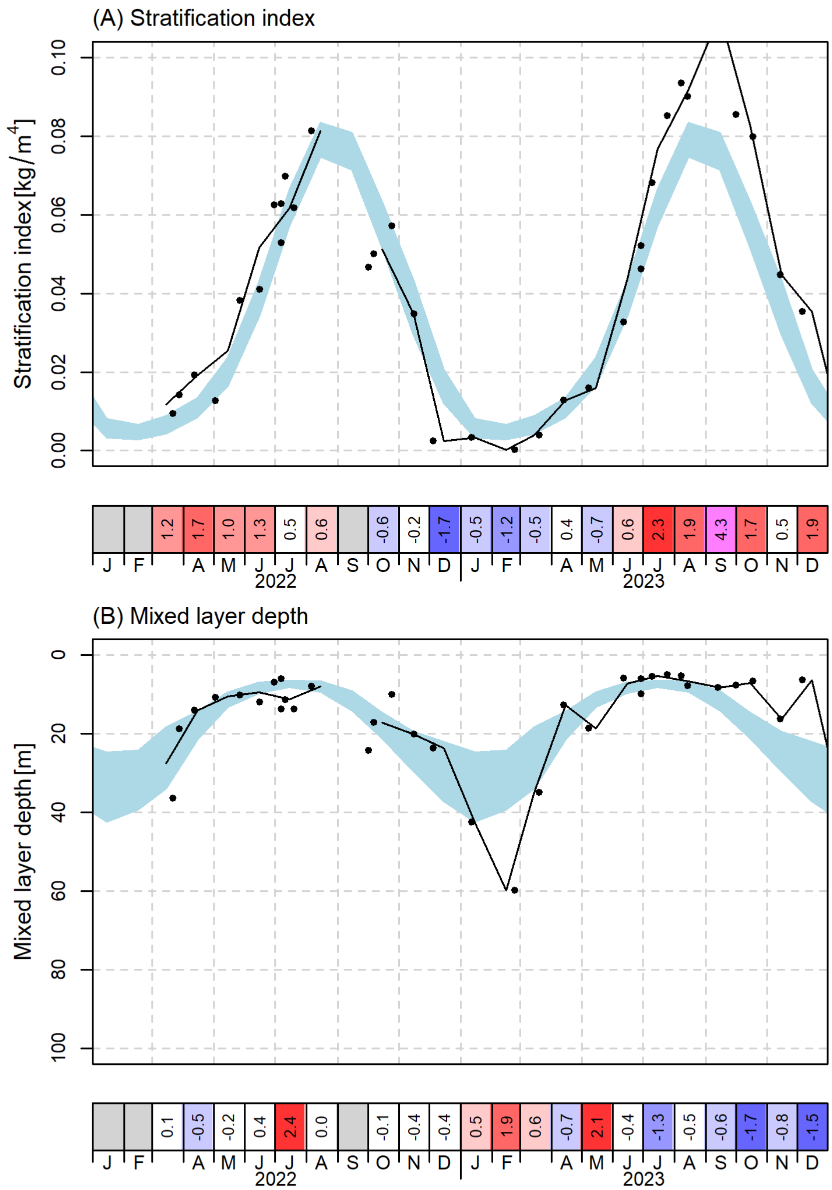

Figure 15. The 2022– 2023 annual cycle of stratification index (top panel) and mixed layer depth (lower panel) for Halifax station 2. The shaded area is the 1991–2020 climatological mean +/- 0.5 standard deviations. The dots represent actual measurements and solid line is the monthly average value plotted at mid-month. Their anomalies with respect to 1991–2020 monthly means are shown below each figure.

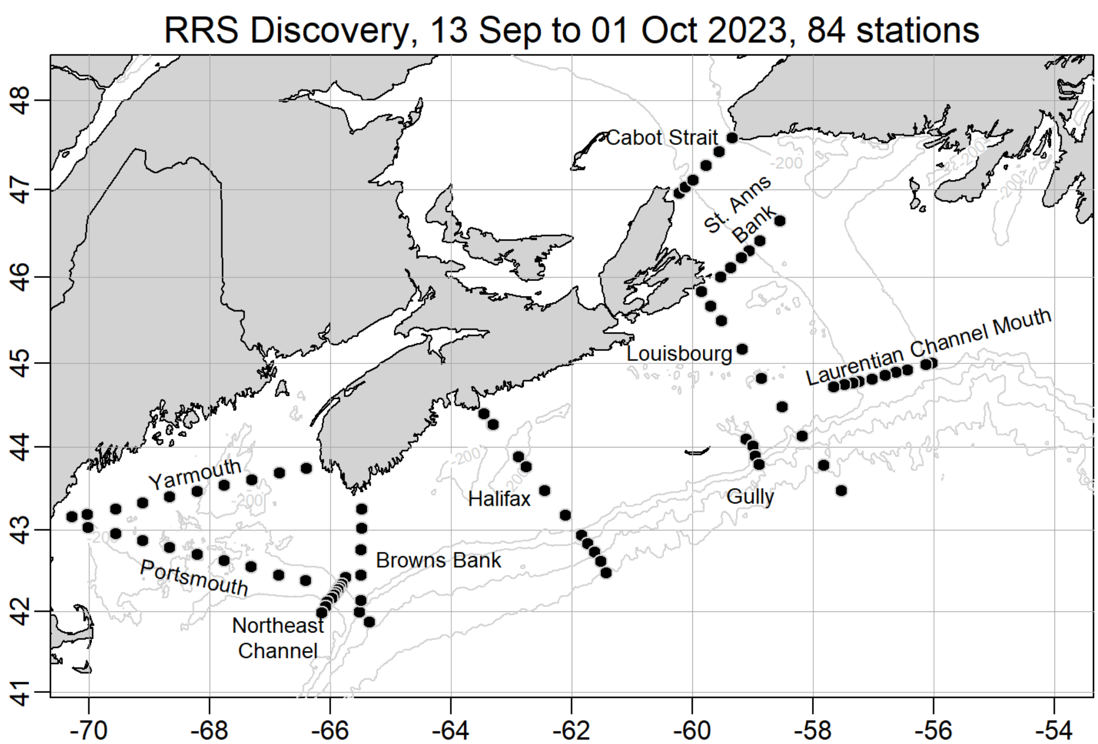

Figure 16. The 2023 sampling of the Scotian Shelf/Gulf of Maine for the fall survey.

Cabot Strait: 16 Sep to 17 Sep 2023

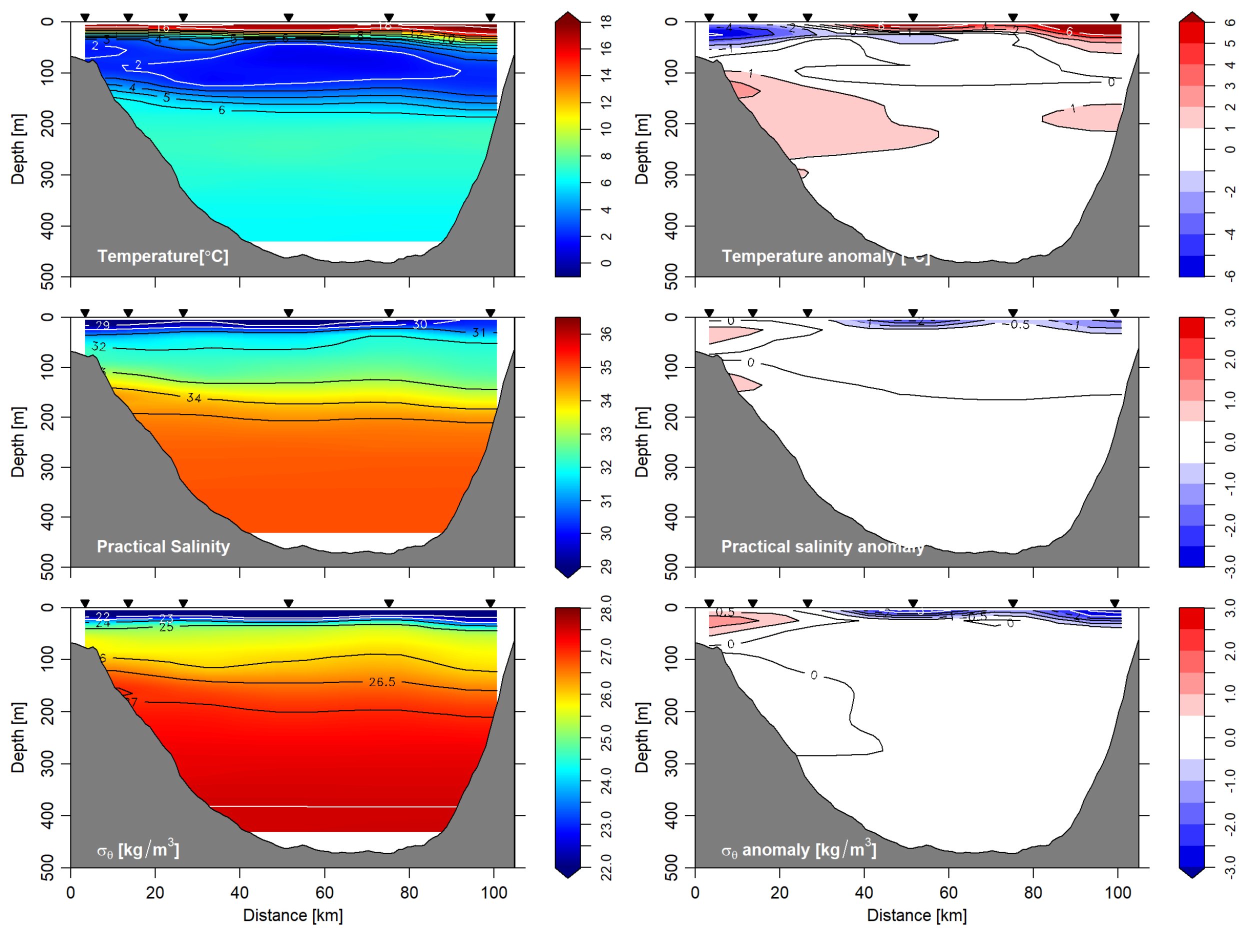

Figure 17. The 2023 sampling of the Cabot Strait line for fall. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to the 1991–2020 climatology (right panels). Triangles indicate locations of sampling.

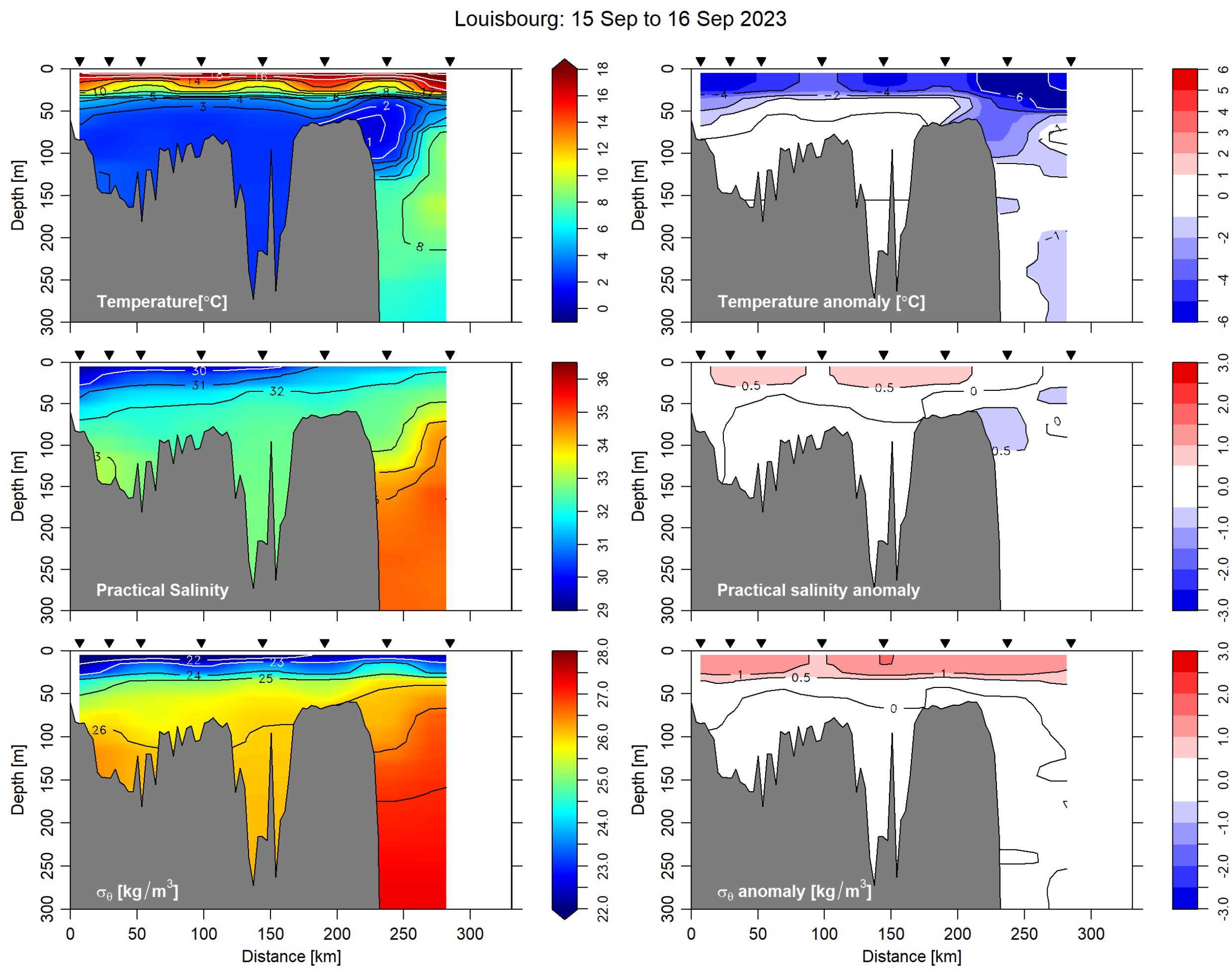

Figure 18. The 2023 sampling of the Louisbourg line for fall. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to the 1991–2020 climatology (right panels). Triangles indicate locations of sampling.

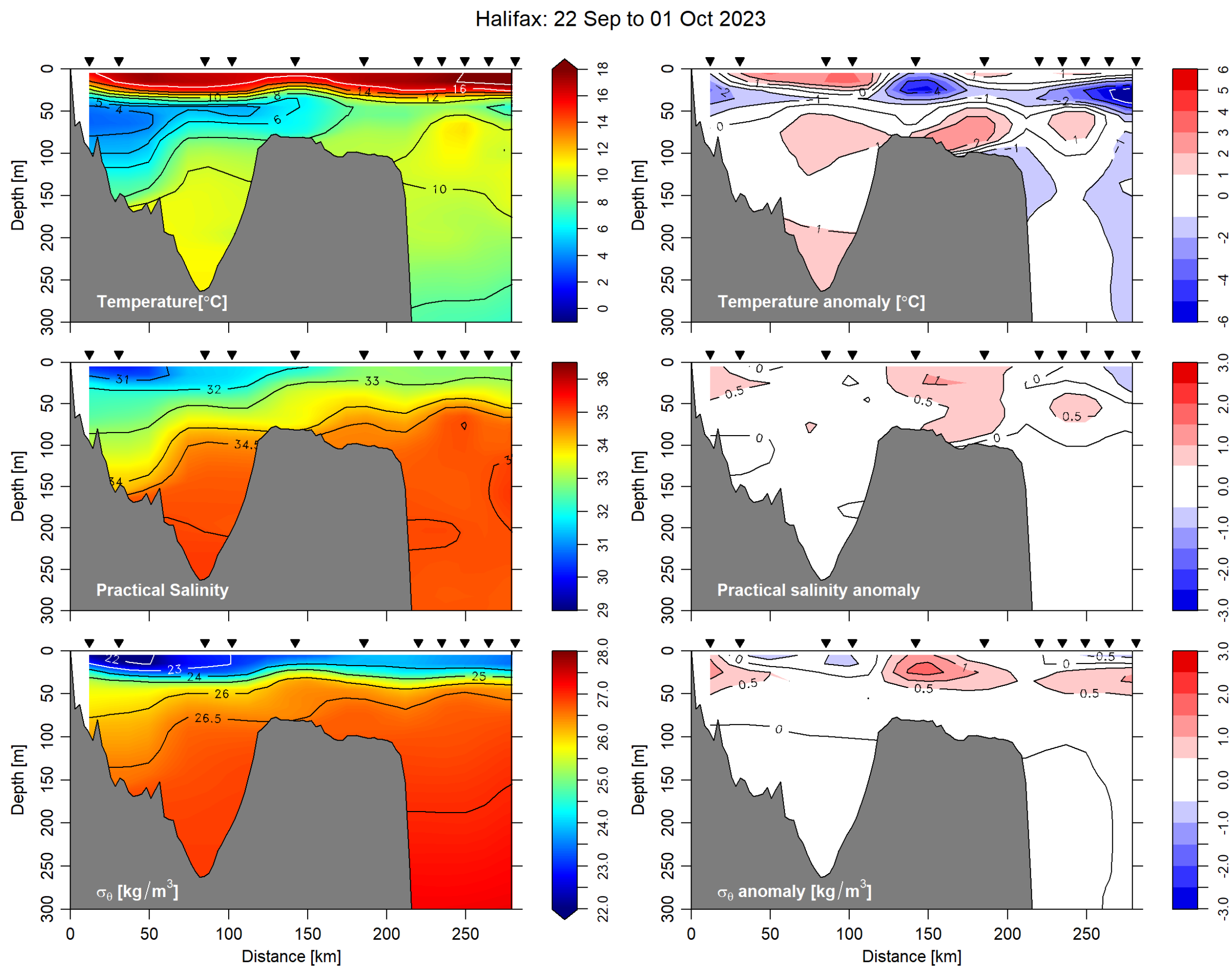

Figure 19. The 2023 sampling of the Halifax line for fall. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to the 1991–2020 climatology (right panels). Triangles indicate locations of sampling.

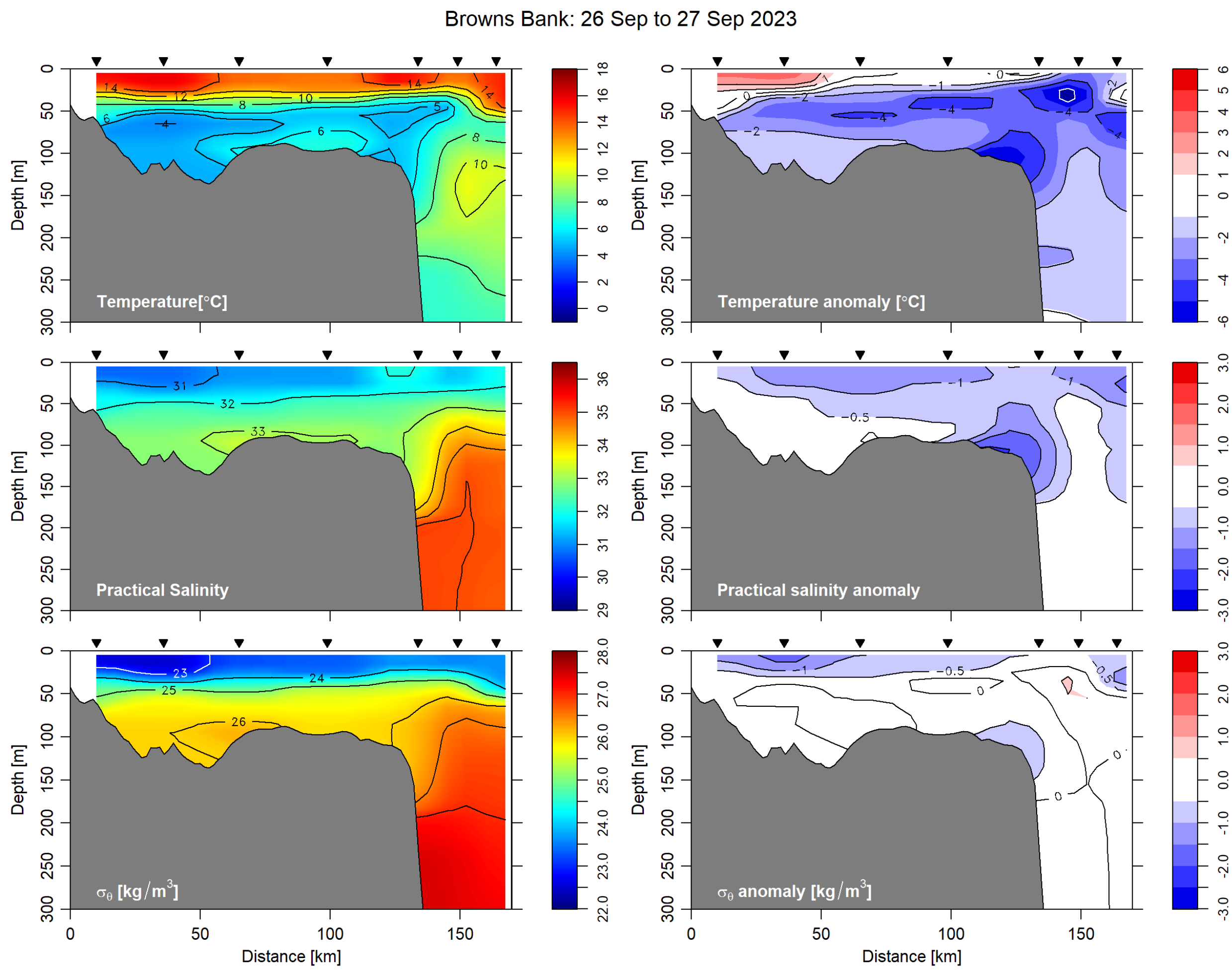

Figure 20. The 2023 sampling of the Browns Bank line for fall. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to the 1991–2020 climatology (right panels). Triangles indicate locations of sampling.

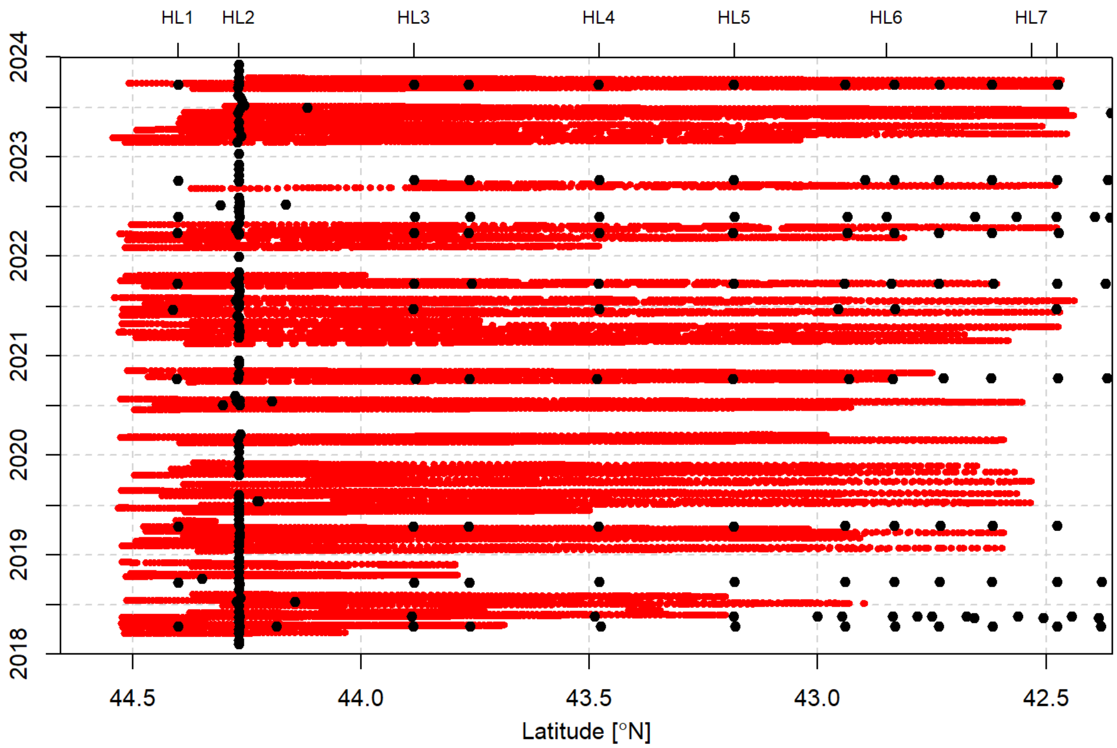

Figure 21. Hodograph of sampling on the Halifax Line for 2018-2023. Black dots represent the sampling by a vessel. Red dots represent sampling by the gliders.

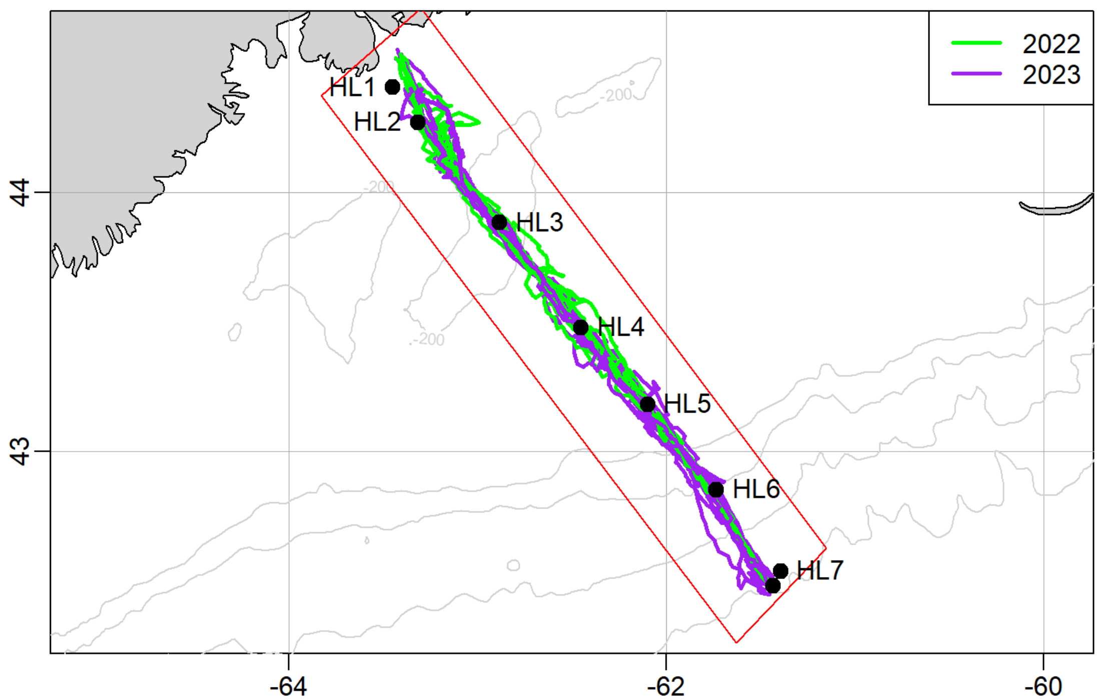

Figure 22. Glider trajectories on the Halifax Line (HL) for 2022 and 2023. Locations of the HL stations are shown by the black dots. Red box shows the limitations applied to glider data to be considered on HL.

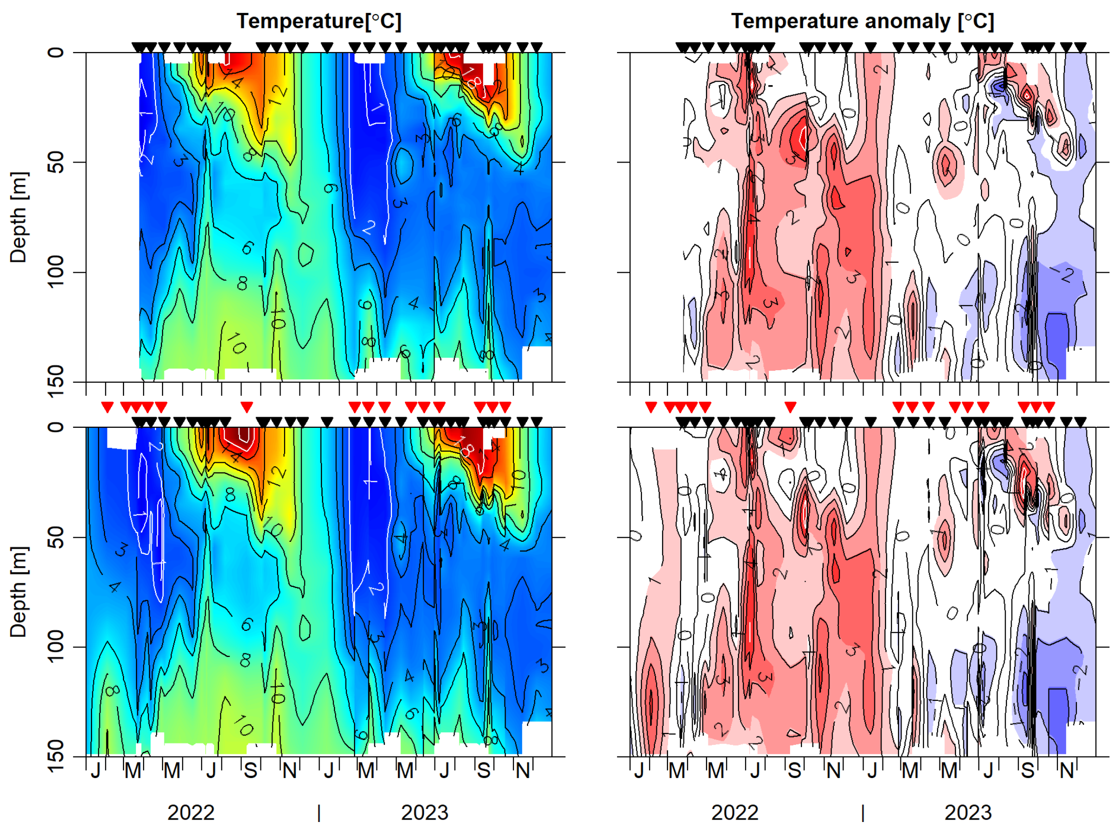

Figure 23. Top panels for temperature (left) and temperature anomaly (right) with standard vessel sampling at Station 2. Bottom panels include the additional glider data that has been averaged hourly. Times of vessel sampling (black triangles) and glider sampling (red triangles) are shown for each panel.

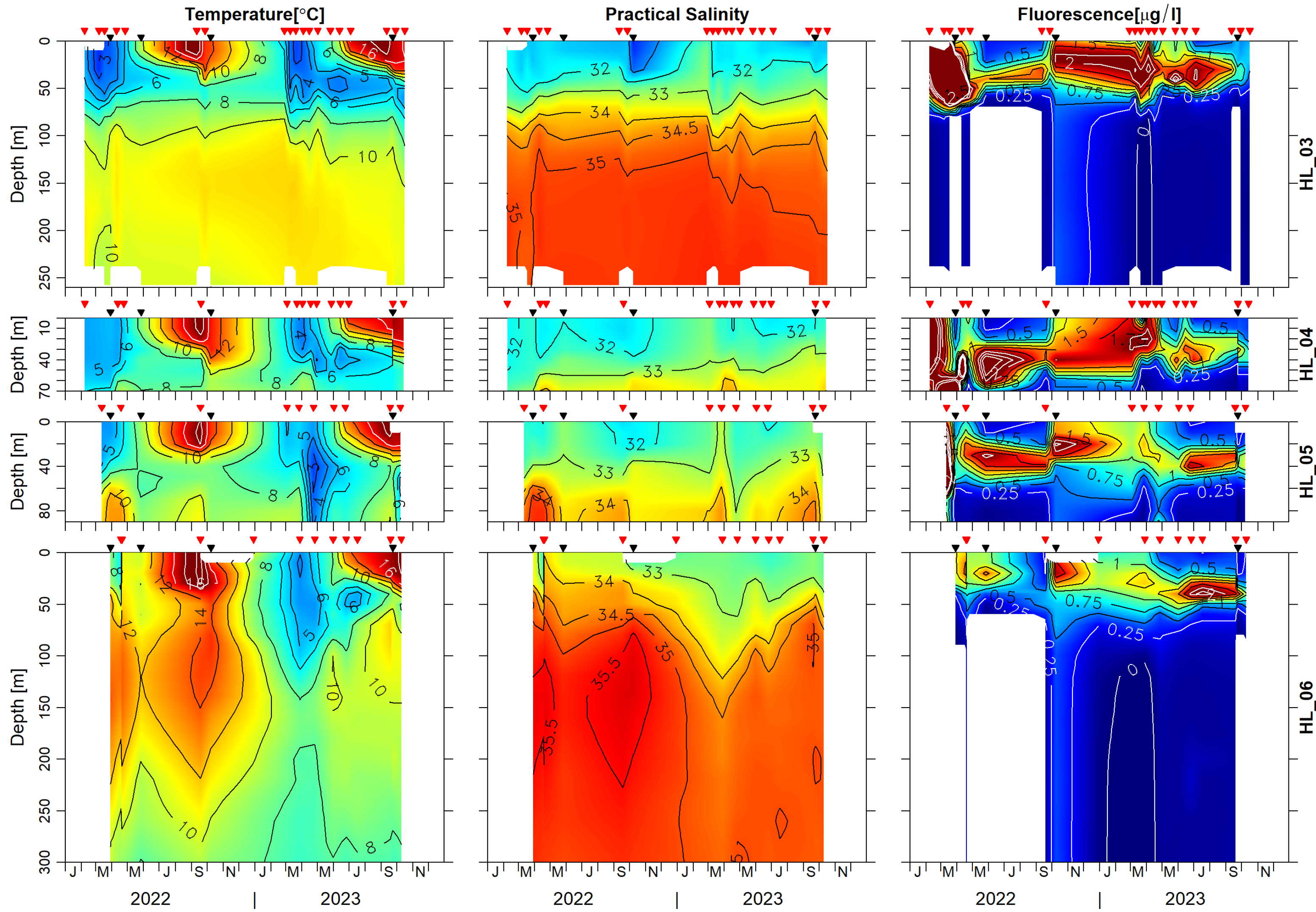

Figure 24. Temperature (left), salinity (middle), and chlorophyll fluorescence (right) for the standard hydrographic stations on the Halifax Line: HL3 (top panel), HL4 (second panel from the top), HL5 (third panel from the top), and HL6 (bottom panel). Only the top 300 m of HL data is shown. Times of vessel sampling (black triangles) and glider sampling (red triangles) are shown for each panel.

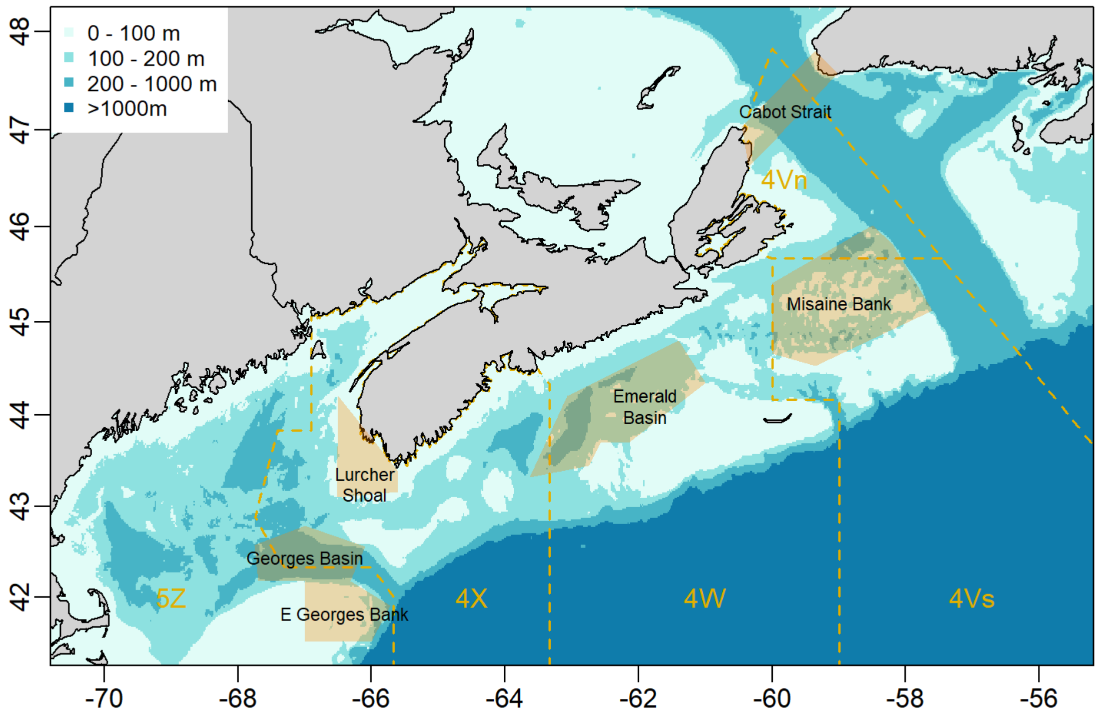

Figure 25. Areas on the Scotian Shelf and eastern Gulf of Maine depicting the different water masses: Cabot Strait; Misaine Bank; Emerald Basin; Lurcher Shoals; Georges Basin; and Eastern Georges Bank.

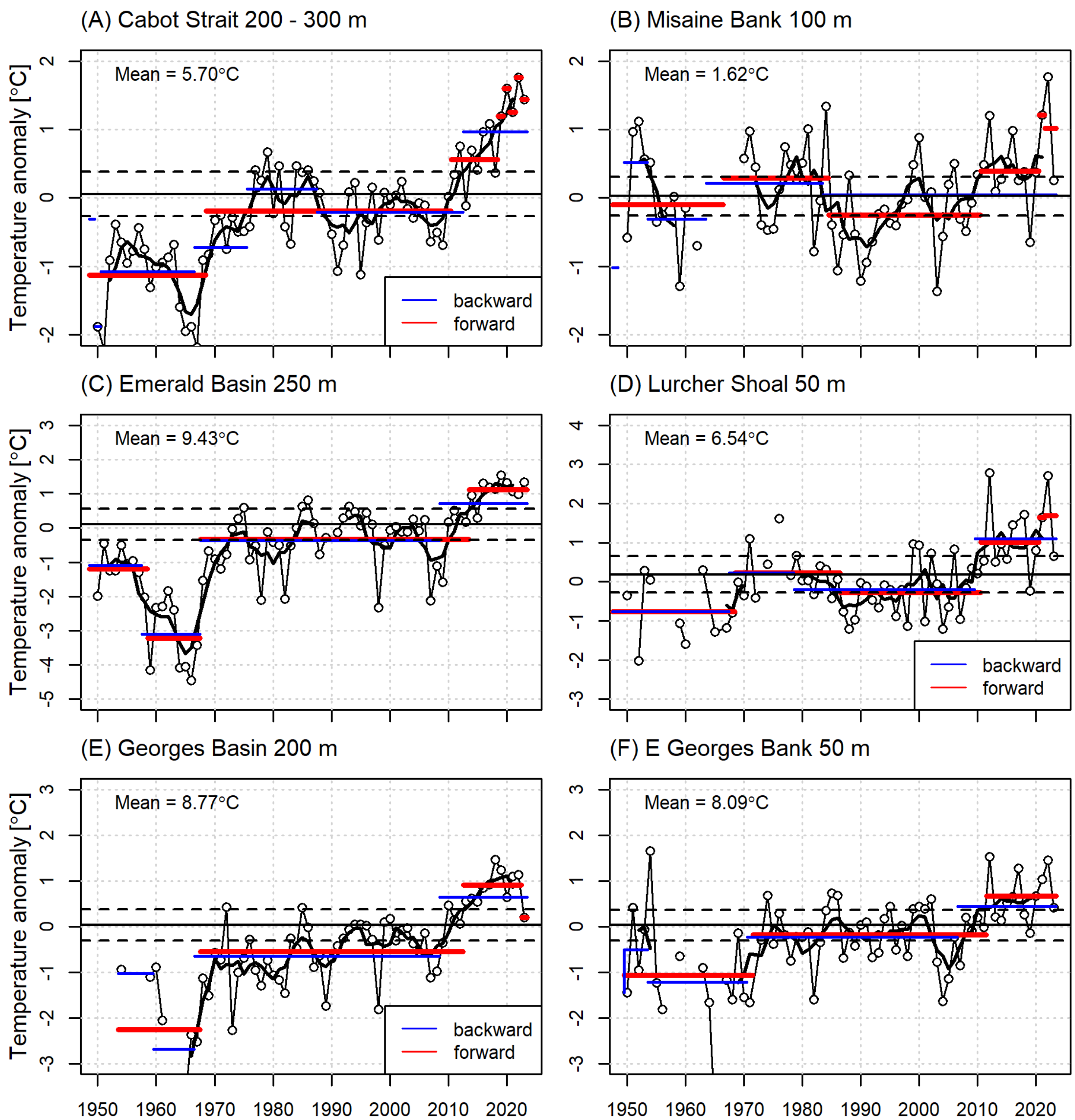

Figure 26. The annual mean temperature-anomaly time series (line with circles) and the five-year-running-mean filtered anomalies (heavy solid line) on the Scotian Shelf and in the Gulf of Maine at: (A) Cabot Strait at 200–300 m, (B) Misaine Bank at 100 m, (C) Emerald Basin at 250 m, (D) Lurcher Shoals at 50 m, (E) Georges Basin at 200 m, and (F) Eastern Georges Bank at 50 m (see Figure 23 for locations of regions). Horizontal dashed lines represent the mean ±0.5 SD for the 1991-2020 period. Regime shift analysis results from running the method forwards and backwards on the time series depicted by the blue and red horizontal lines, respectively.

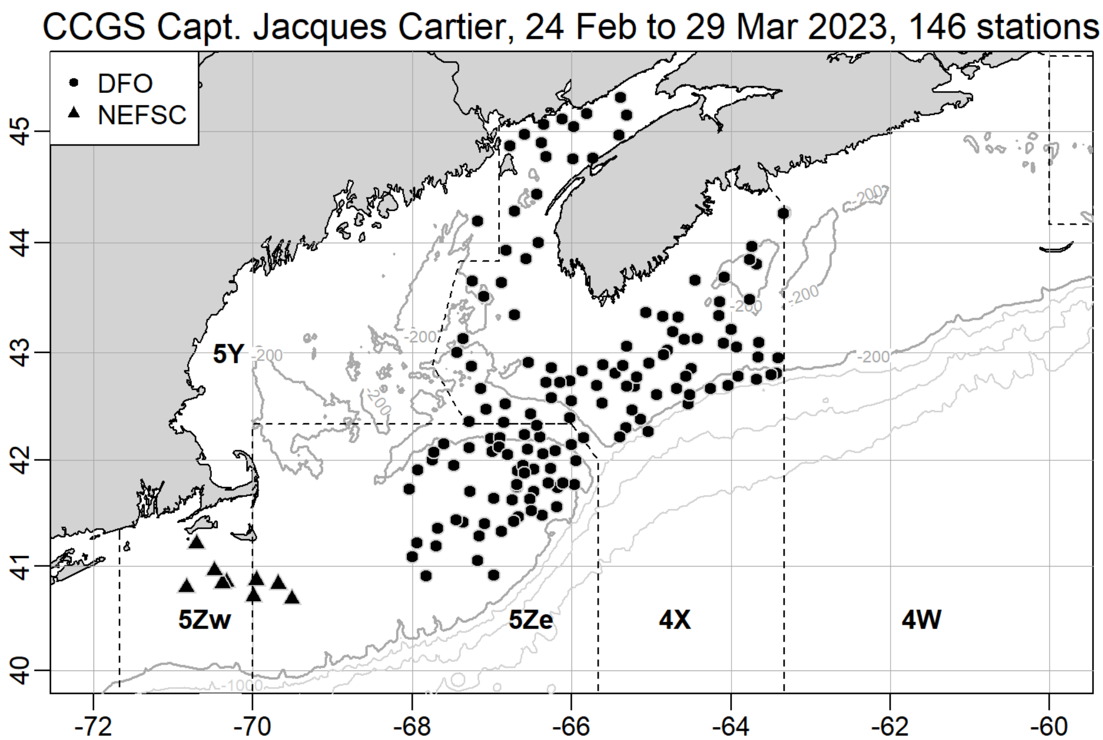

Figure 27. Locations of CTD sampling during the 2023 winter survey. The 200 m isobath is shown as a darker line. NAFO Divisions 4W, 4X, 5Ze, 5Y, and 5Zw are shown.

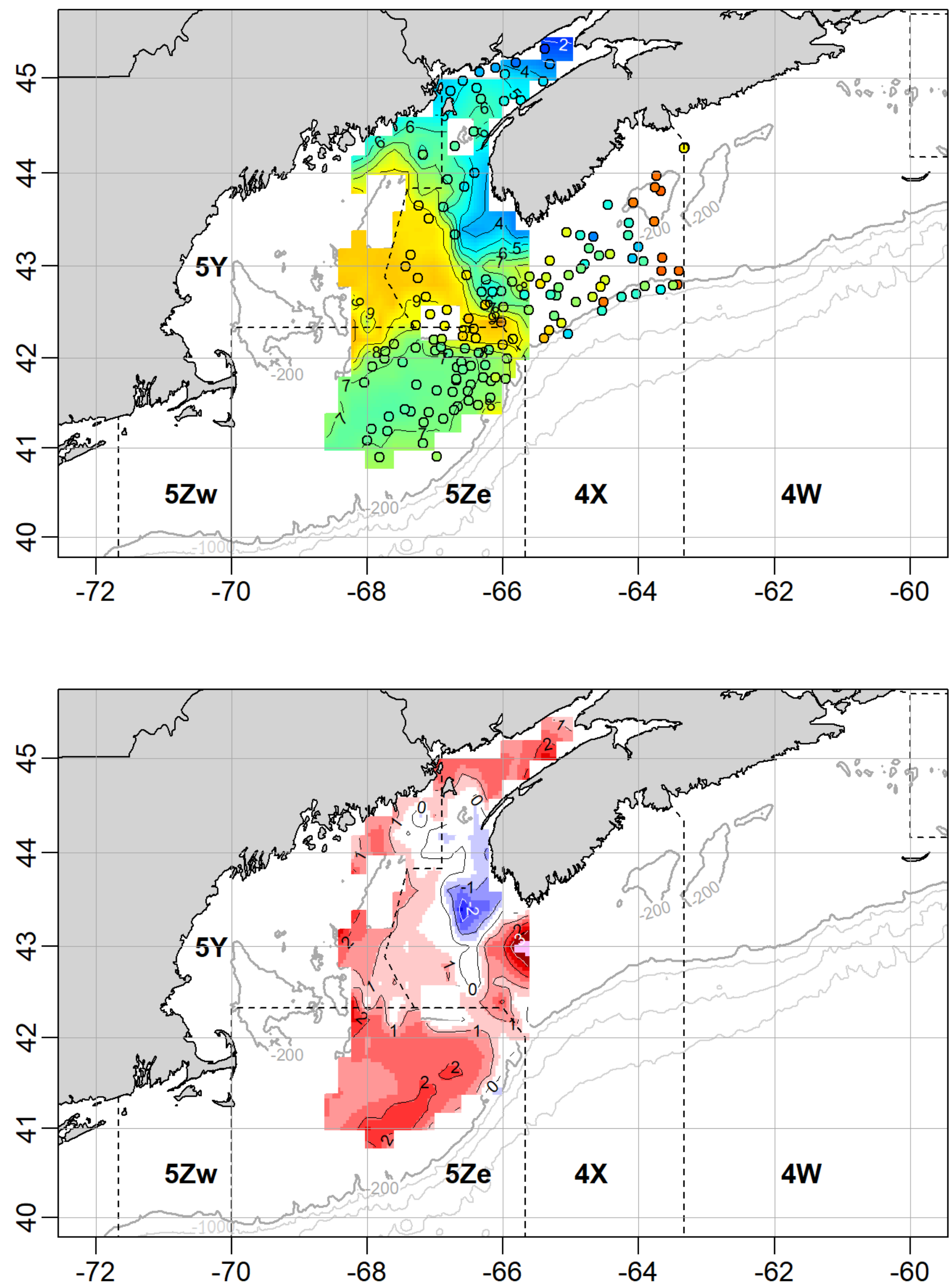

Figure 28. Winter bottom-temperature (upper panel) and anomaly (lower panel; relative to 1991–2020) maps for 2023. NAFO Divisions 4W, 4X, 5Ze, 5Y, and 5Zw are shown.

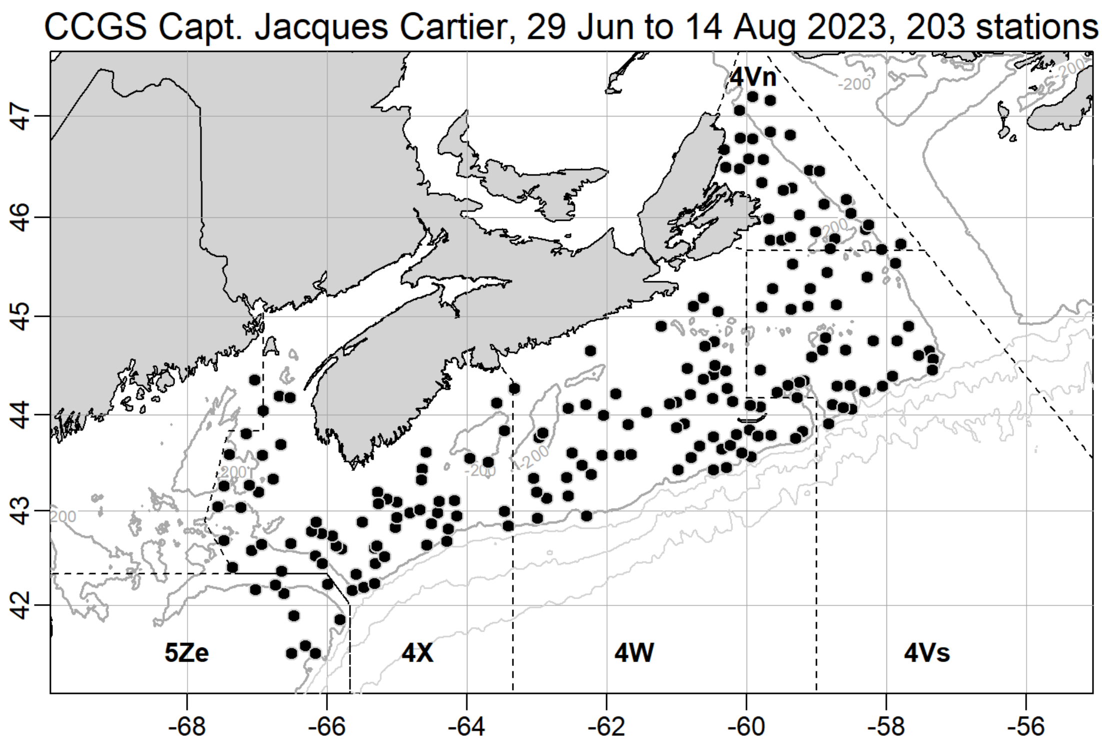

Figure 29. Locations of CTD sampling during the 2023 summer survey. The 200 m isobath is shown as a darker line. NAFO Divisions 4W, 4X, 5Ze, 5Y, and 5Zw are shown.

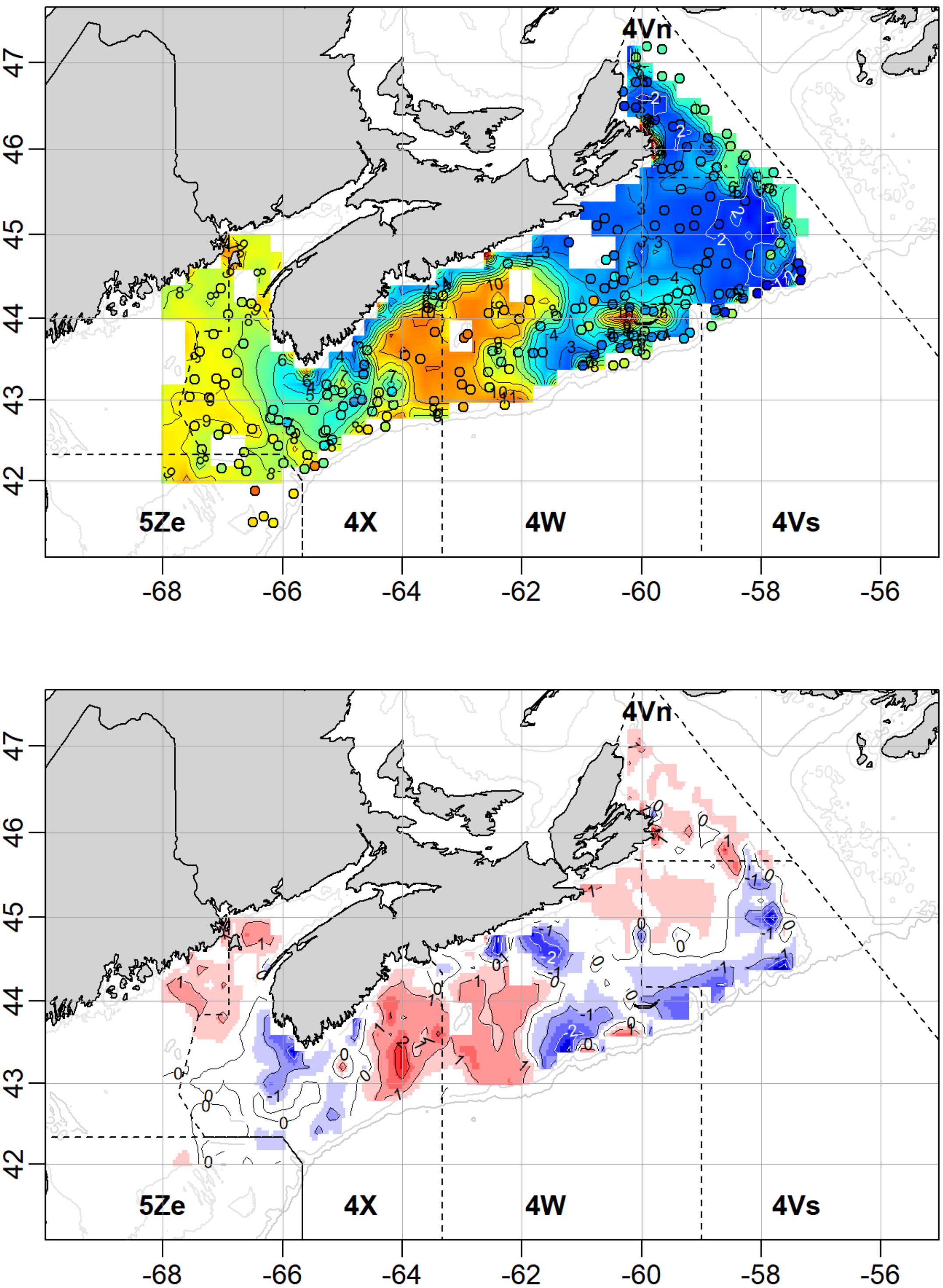

Figure 30. Summer bottom-temperature (upper panel) and anomaly (lower panel; relative to 1991–2020) maps for 2023. NAFO Divisions 4Vn, 4Vs, 4W, 4X, 5Ze, 5Y, and 5Zw are shown.

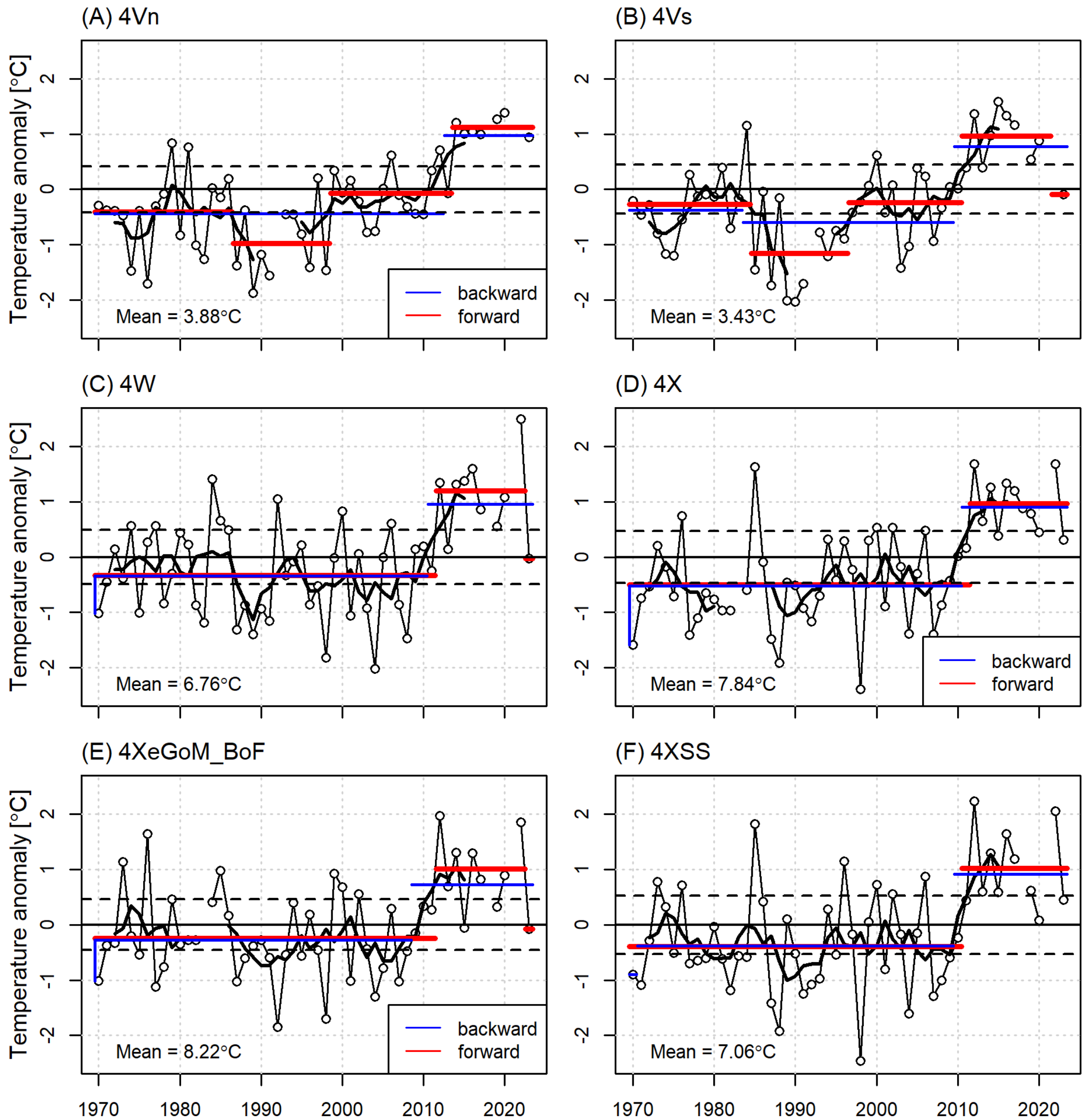

Figure 31. Time series of July bottom-temperature anomalies (thin lines with circles) and five-year-running-mean filtered series (heavy line) for NAFO Divisions: 4Vn, 4Vs, 4W, 4X, and 4X separated into two regions; the eastern Gulf of Maine/Bay of Fundy(eGoMBoF) and the Scotian Shelf (SS). The solid horizontal line is the 1991-2020 mean and dashed lines represent ±0.5 SD. Regime shift analysis results from running the method forwards and backwards on the time series depicted by the blue and red horizontal lines, respectively.

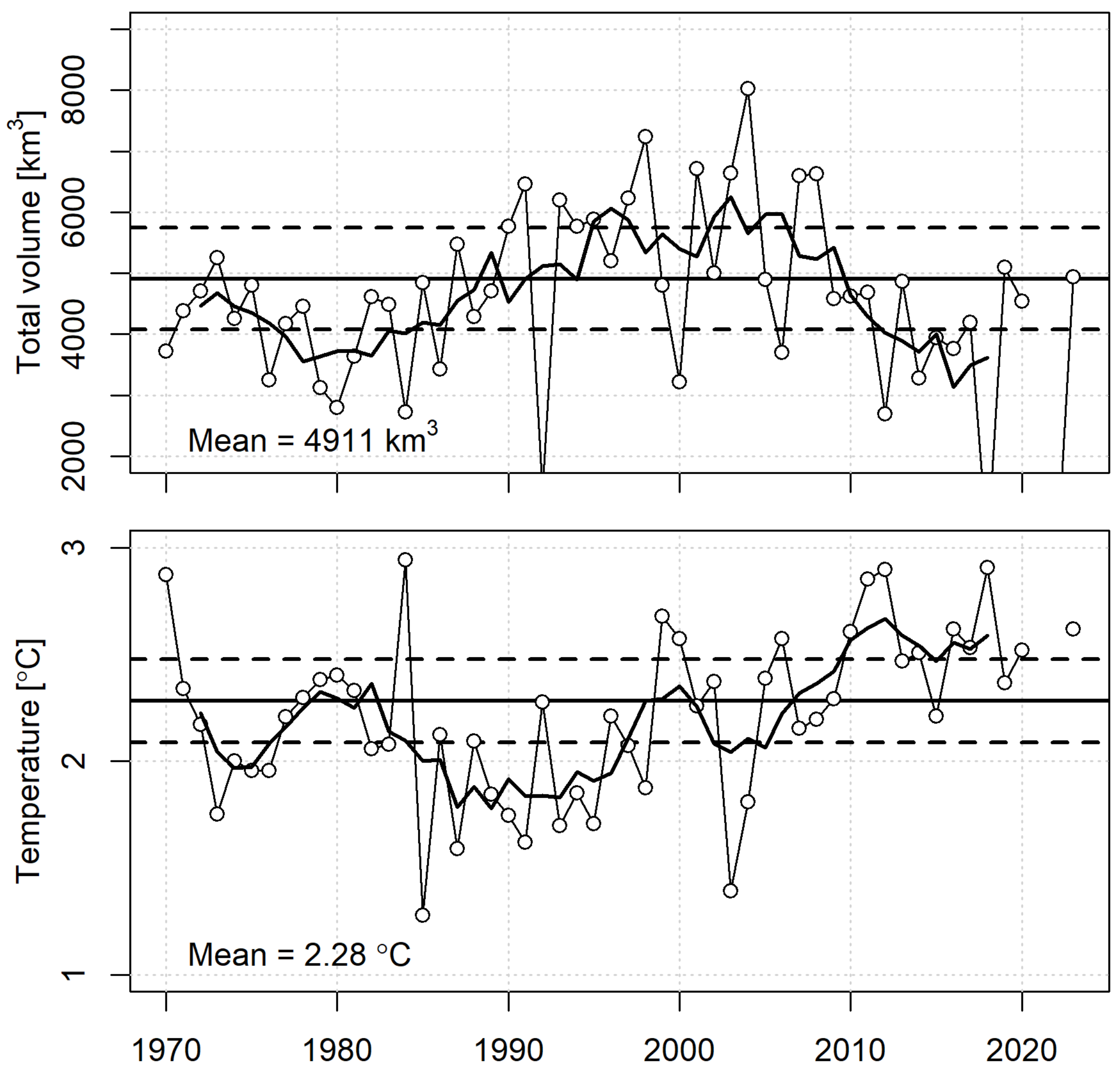

Figure 32. Time series of the Cold Intermediate Layer (CIL; defined as waters with temperature < 4°C) volume on the Scotian Shelf based on the DFO ecosystem summer trawl survey (top panel). When grid coverage is less than 70%, a blended CIL calculation is used, indicated by an asterisk. The area-weighted average minimum temperature in the CIL (bottom panel). The solid horizontal lines are the 1991–2020 means and dashed lines represent ±0.5 SD.

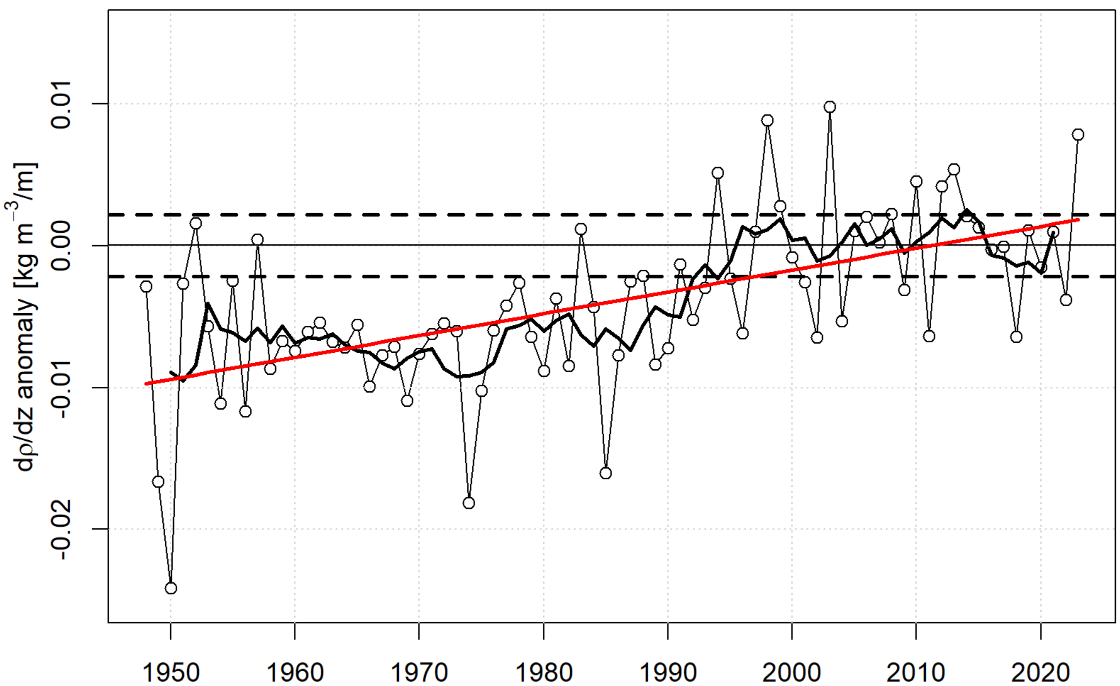

Figure 33. Stratification index (0–50 m density gradient) mean annual anomaly (black line with circles) and five-year running mean (black heavy solid line) averaged over the Scotian Shelf. The linear trend (red line) shows a change in the 0–50 m density difference of 0.38 kg m^{-3} over 50 years for the 1991-2020 period.

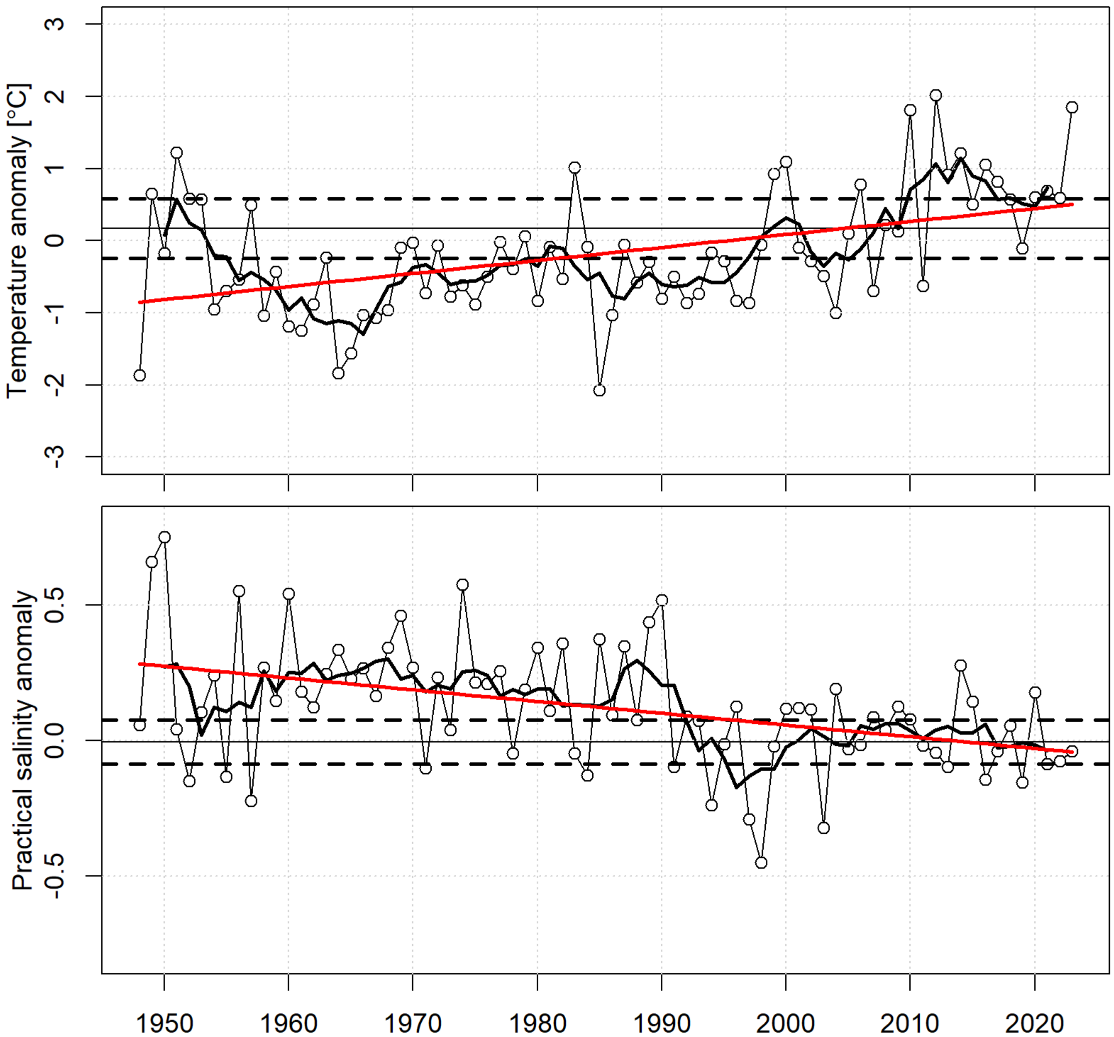

Figure 34. The mean-annual-surface-temperature (top panel) and salinity (lower panel) anomalies (black line with circles) and five-year running mean (black heavy solid line) averaged over the Scotian Shelf. Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a warming of 0.90°C and a freshening of 0.22 over a 50-year period.

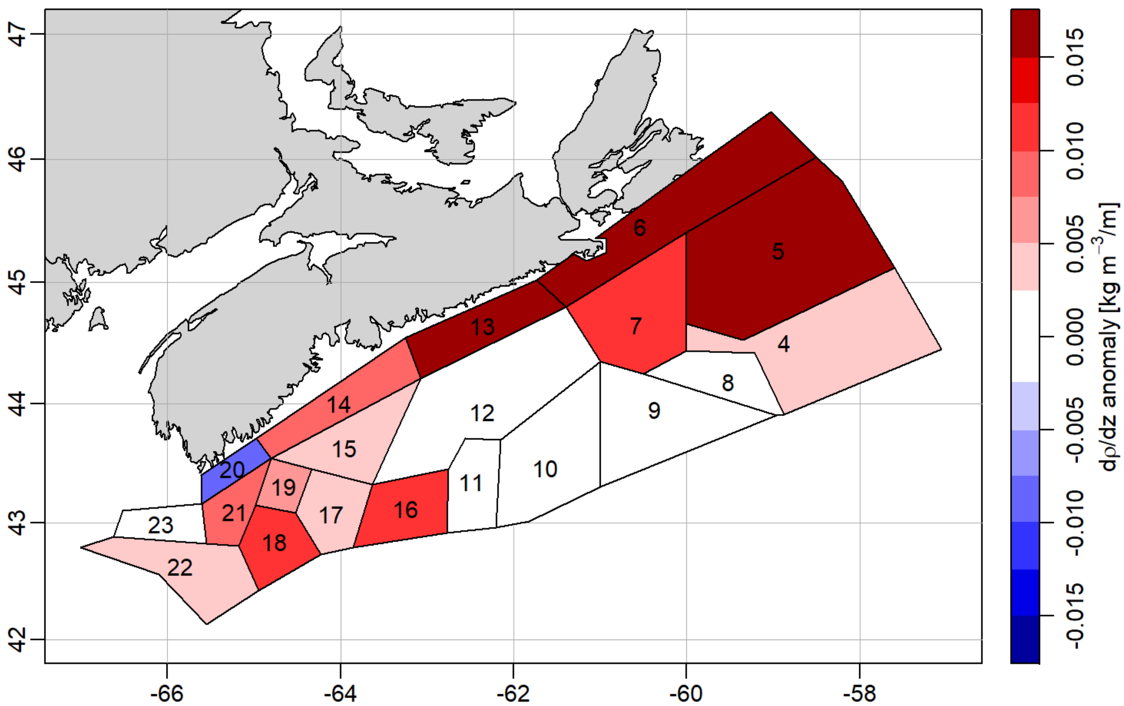

Figure 35. Stratification index (0–50 m density gradient) mean 2020 annual anomaly over the Scotian Shelf. The different areas were defined by Petrie et al. (1996).

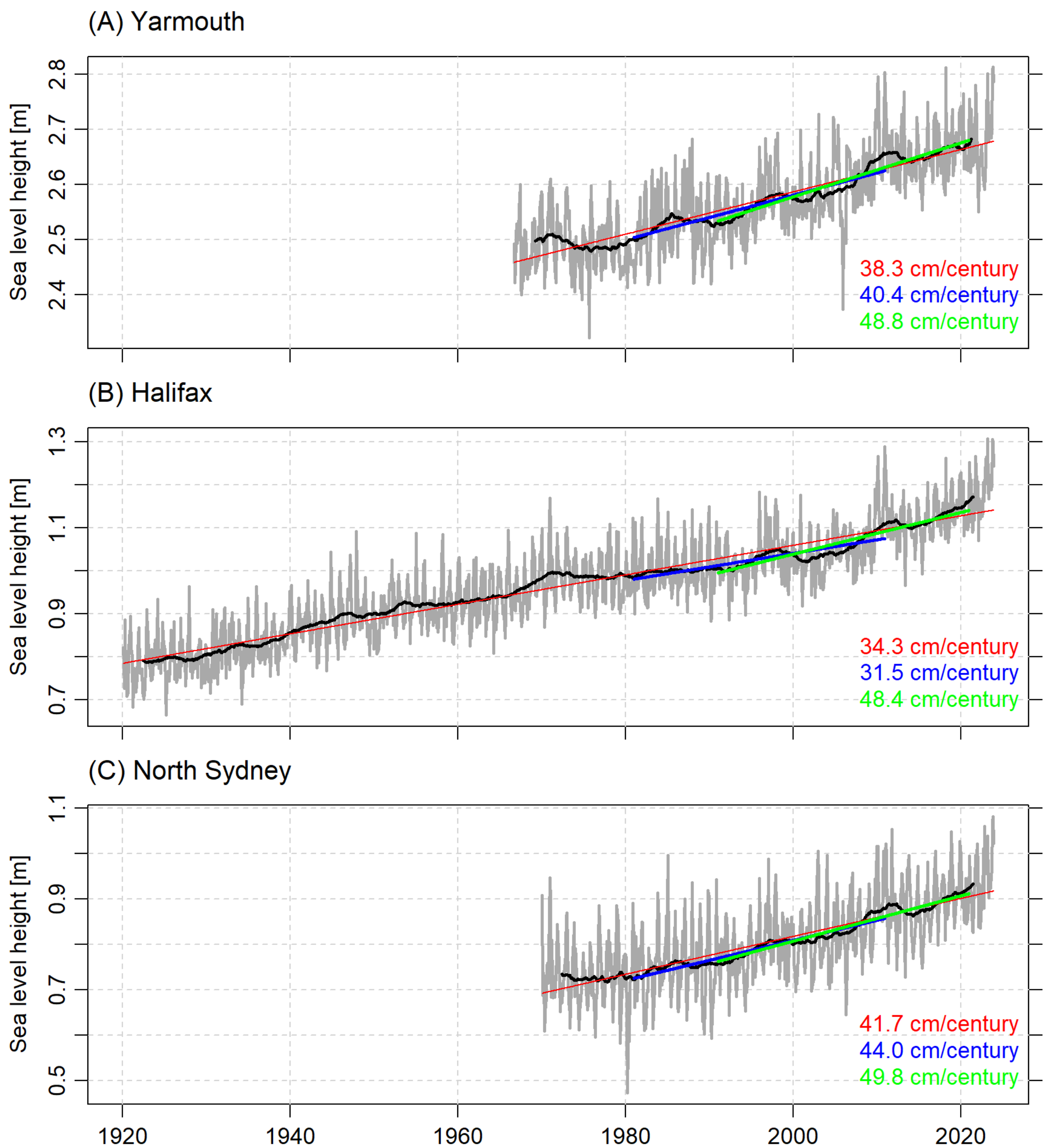

Figure 36. The time series of the monthly means (grey line) and a five-year running mean (black line) of the relative sea-level elevations at Yarmouth (top panel), Halifax (middle panel), and North Sydney (bottom panel), along with the linear trend (red line) over the observation period, over 1981–2010 (blue line) and over 1991–2020 (green line).

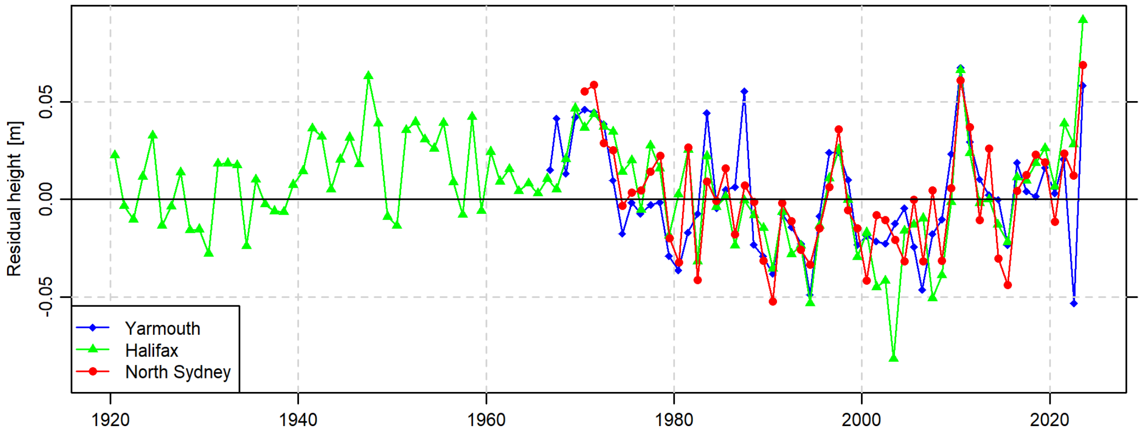

Figure 37. Residual relative sea level (annual observed values—linear trend based on the 1970— 2023 period) for Yarmouth (blue line with diamonds), Halifax (green line with triangles), and North Sydney (red line with circles).

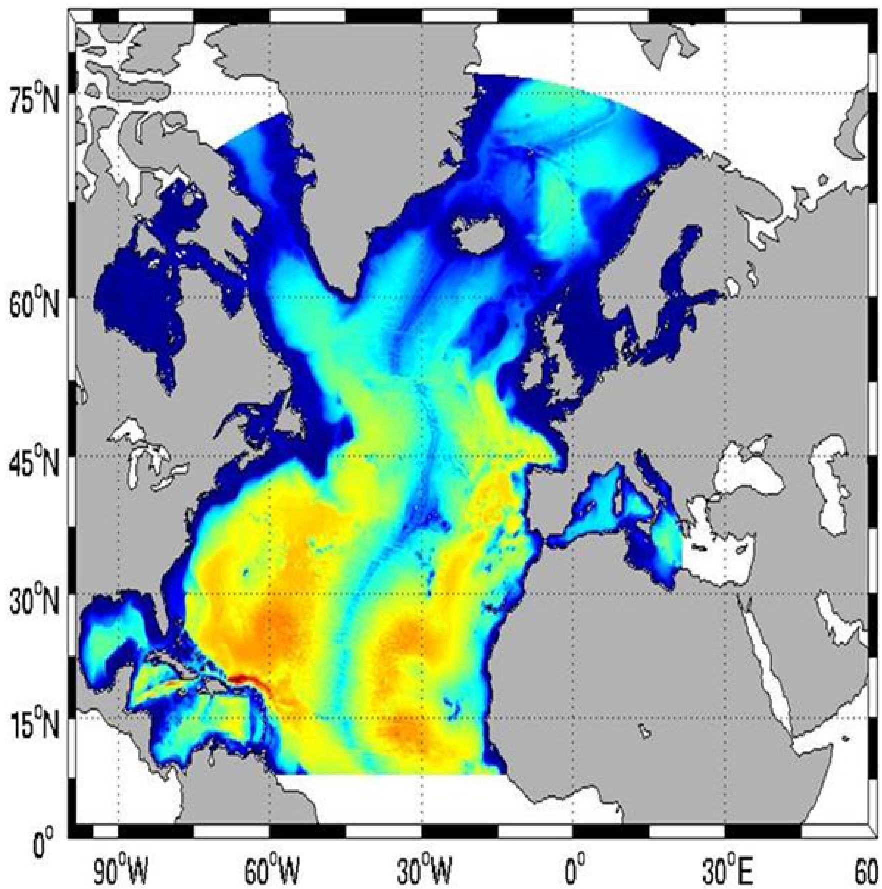

Figure 38. The BIO North Atlantic Model (BNAM) domain Bathymetry coloured from red (deep) to blue (shallow).

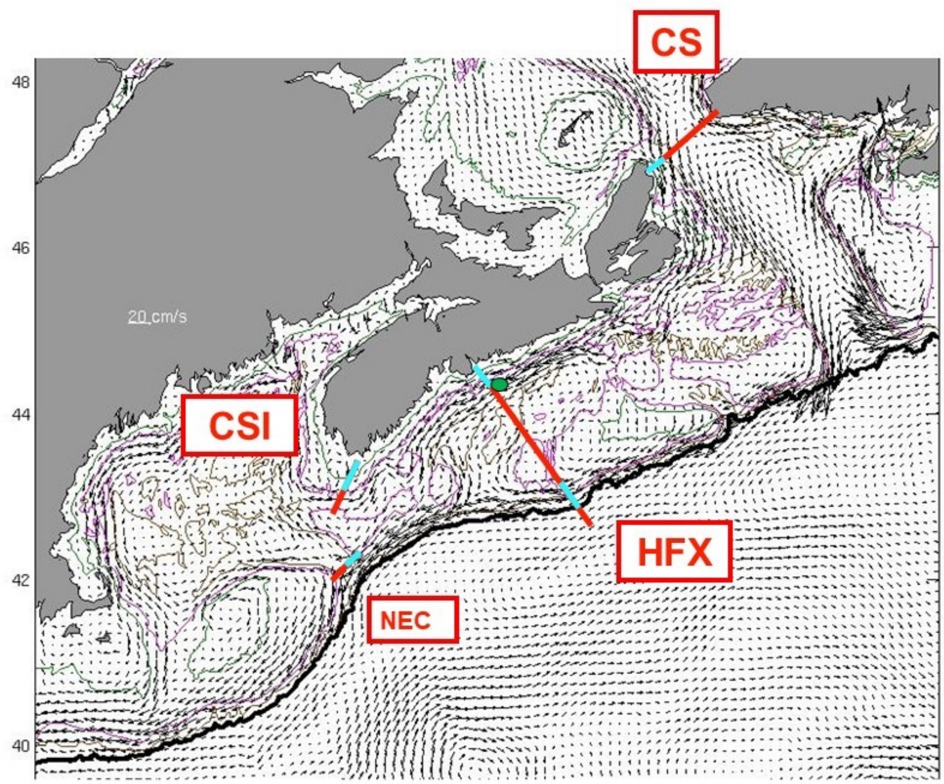

Figure 39. Climatological-annual and depth-averaged circulation illustrating the principal flow pathways from the southern Gulf of St. Lawrence to the Gulf of Maine and the subsections where transport calculations were made (cyan). CS = Cabot Strait; HFX = Halifax; CSI = Cape Sable Island/Browns Bank; NEC = Northeast Channel. Green circle shows the location off T2.

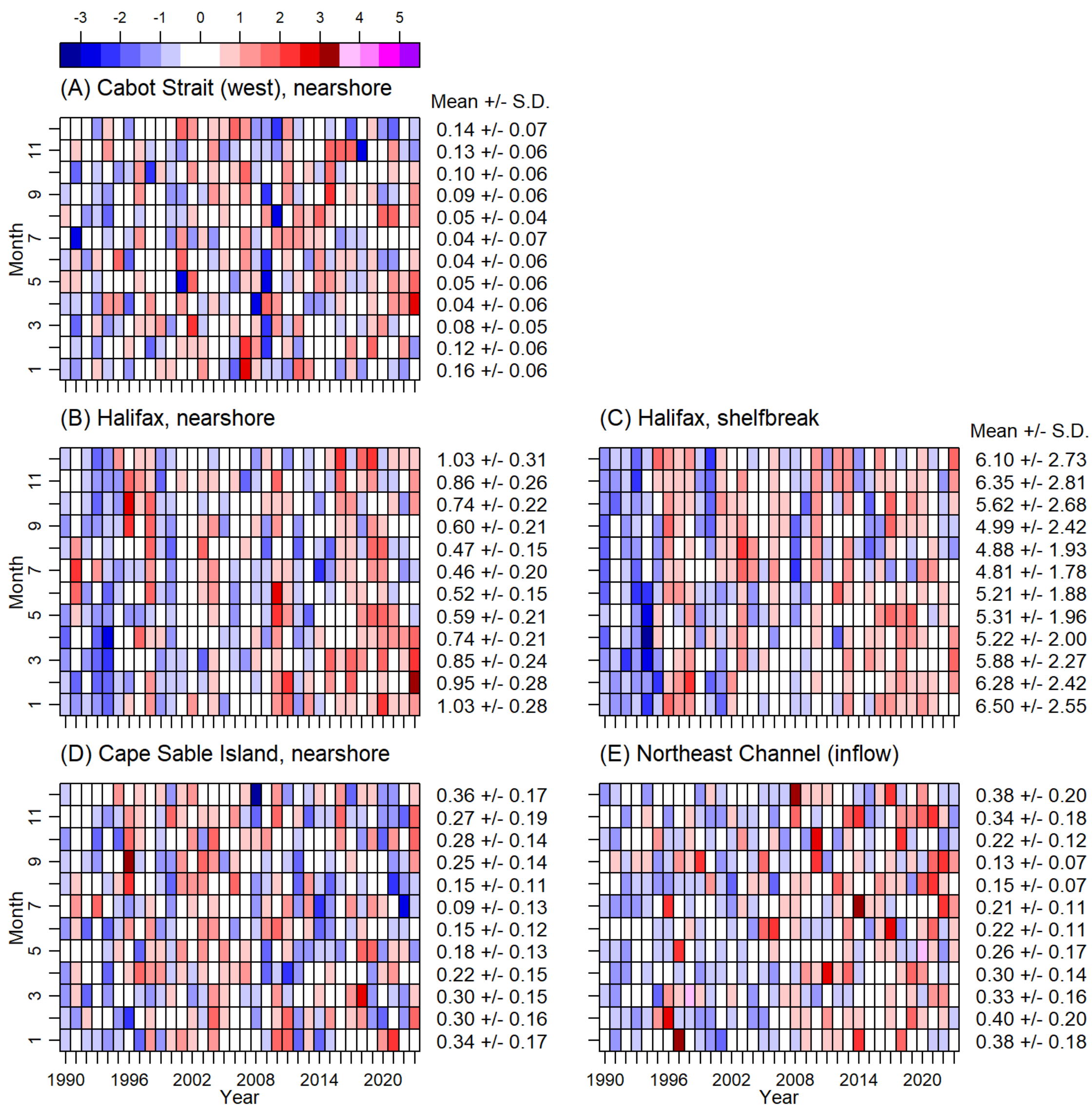

Figure 40. Standardized anomalies of the monthly transport relative to 1991-2020 for four Maritime sections: (A) Cabot Strait (CS) west nearshore; Halifax (HFX) (B) nearshore and (C) shelf break; (D) Cape Sable Island (CSI) nearshore; and (E) the Northeast Channel (NEC). Numbers to the right are monthly means and standard deviations in Sverdrups (1 Sv = $10^6 m^3 s^{-1}$).

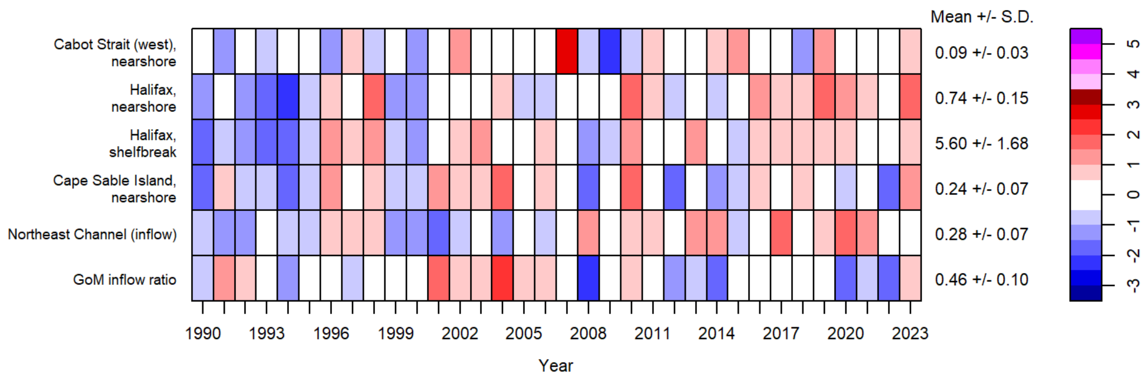

Figure 41. Annual transport anomalies scaled by the standard deviation for the monthly values shown in Figure 40 and Figure 43. Numbers to the right are climatological (1991-2020) annual means and standard deviations (in Sverdrups).

	2008		2010		2012		2014		2016		2018		2020		2022		Mean +/- S.D.
Dec	-0.46	-0.59	-0.58	-0.33	-0.5	-0.83	-0.42	-0.53	-0.82	-0.4	-0.89	-0.76	-0.46	-0.87	-0.57		-0.60 +/- 0.19
Nov	-0.22	-0.34	-0.52	-0.49	-0.43	-0.3	-0.5	-0.38	-0.57	-0.21	-0.85	-0.28	-0.23	-0.36	-0.34		-0.40 +/- 0.17
Oct	-0.22	-0.51	-0.36	-0.3	-0.32	-0.22	-0.21	-0.17	-0.4	-0.33	-0.36	-0.24	-0.17	-0.45	-0.26		-0.30 +/- 0.10
Sep	-0.43	-0.21	-0.3	-0.12	-0.14	-0.03	-0.17	-0.13	-0.2	-0.28	-0.28	-0.22	-0.35	-0.21	-0.25		-0.22 +/- 0.10
Aug	-0.4	-0.26	-0.32	-0.23	-0.13	-0.08	-0.12	-0.18	-0.27	-0.05	-0.22	-0.26	-0.31	-0.27	-0.15	-0.42	-0.23 +/- 0.11
Jul	-0.04	-0.29	-0.39	-0.37	-0.11	-0.15	-0.07	-0.22	-0.31	-0.23	-0.34	-0.32	-0.3	-0.31	-0.24	-0.49	-0.26 +/- 0.12
Jun	-0.11	-0.31	-0.54	-0.4	-0.09	-0.16	-0.28	-0.35	0.05	-0.28	-0.23	-0.16	-0.17	-0.23	-0.2	-0.56	-0.25 +/- 0.16
May		-0.33	-0.52	-0.43	-0.22	-0.12	-0.26	0.04	-0.23	-0.35	-0.32	-0.34	-0.47	-0.43	-0.31	-0.47	-0.32 +/- 0.15
Apr		-0.34	-0.33	-0.48	-0.23	-0.37	-0.39	-0.32	-0.31	-0.33	-0.35	-0.39	-0.38	-0.32	-0.63	-0.49	-0.38 +/- 0.10
Mar		-0.48	-0.47	-0.55	-0.64		-0.53	-0.63	-0.4	-0.79	-0.31	-0.47	-0.58	-0.5	-0.6	-0.45	-0.53 +/- 0.12
Feb		-0.66	-0.68	-0.85	-0.59	-0.64	-0.44	-0.62	-0.46	-0.88	-0.66	-0.7	-0.42	-0.73	-0.47	-0.78	-0.64 +/- 0.14
Jan		-0.8	-0.65	-0.67	-0.38	-0.6	-0.45	-0.74	-0.6	-0.71	-0.78	-0.64	-0.75	-0.63	-0.79	-0.59	-0.65 +/- 0.12
Annual	-0.27	-0.43	-0.47	-0.43	-0.32	-0.32	-0.32	-0.35	-0.38	-0.4	-0.46	-0.4	-0.38	-0.43	-0.4	-0.53	-0.39 +/- 0.07

Figure 42. Monthly transport (Sv) for the Nova Scotia Current south of Halifax from ADCP measurements. Negative transports are to the southwest. The monthly transports are colour-coded for whether they are above, less southwestward (blue), or below, stronger southwestward (red), than the monthly average for the observation period (numbers to the right) by more than one-half standard deviation.

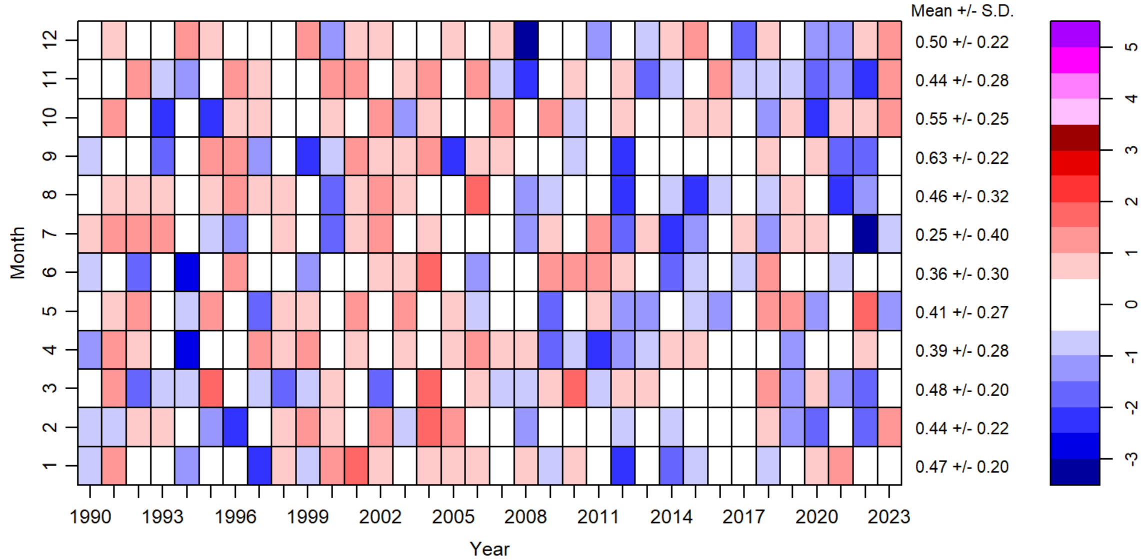

Figure 43. Standardized anomalies of the Gulf of Maine inflow ratio. Numbers to the right are 1991-2020 climatological monthly means and standard deviations.

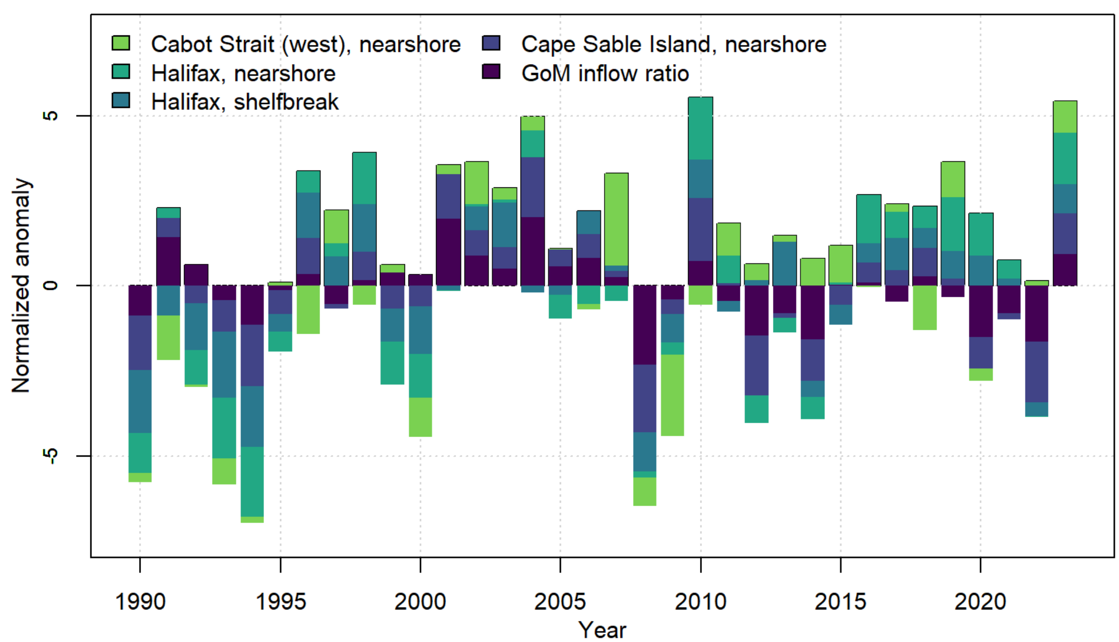

Figure 44. Sum of standardized transport anomalies for the variables in Figure 41.

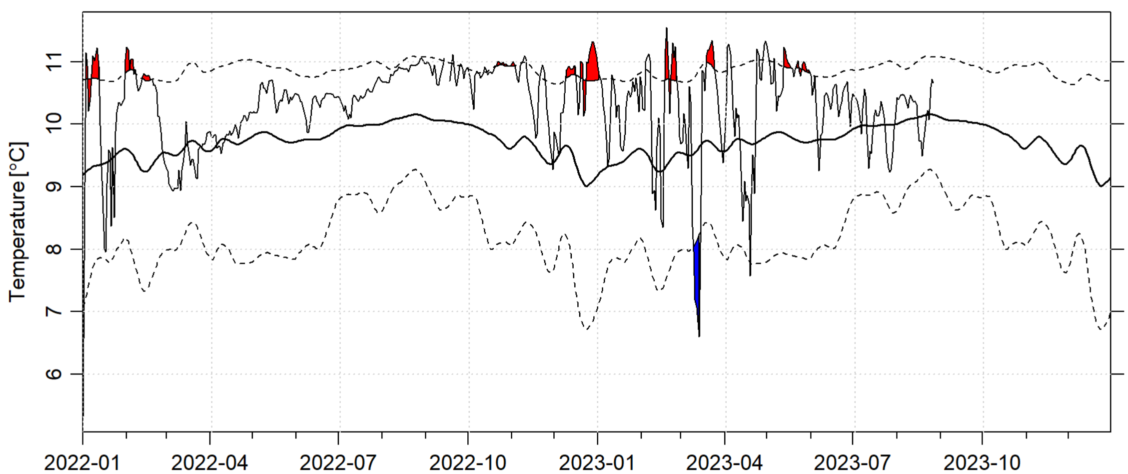

Figure 45. Timeseries of bottom temperature (thin line) from the T2 mooring location near Station 2 with the 11-day running mean 2008 to 2023 climatology (thick line). The 10th percentile (dashed line) to detect cold spells and the 90th percentile (dashed line) to detect heat waves are shown. Time periods where a cold spell is detected is indicated by a filled blue area and a heat wave with a filled red area.

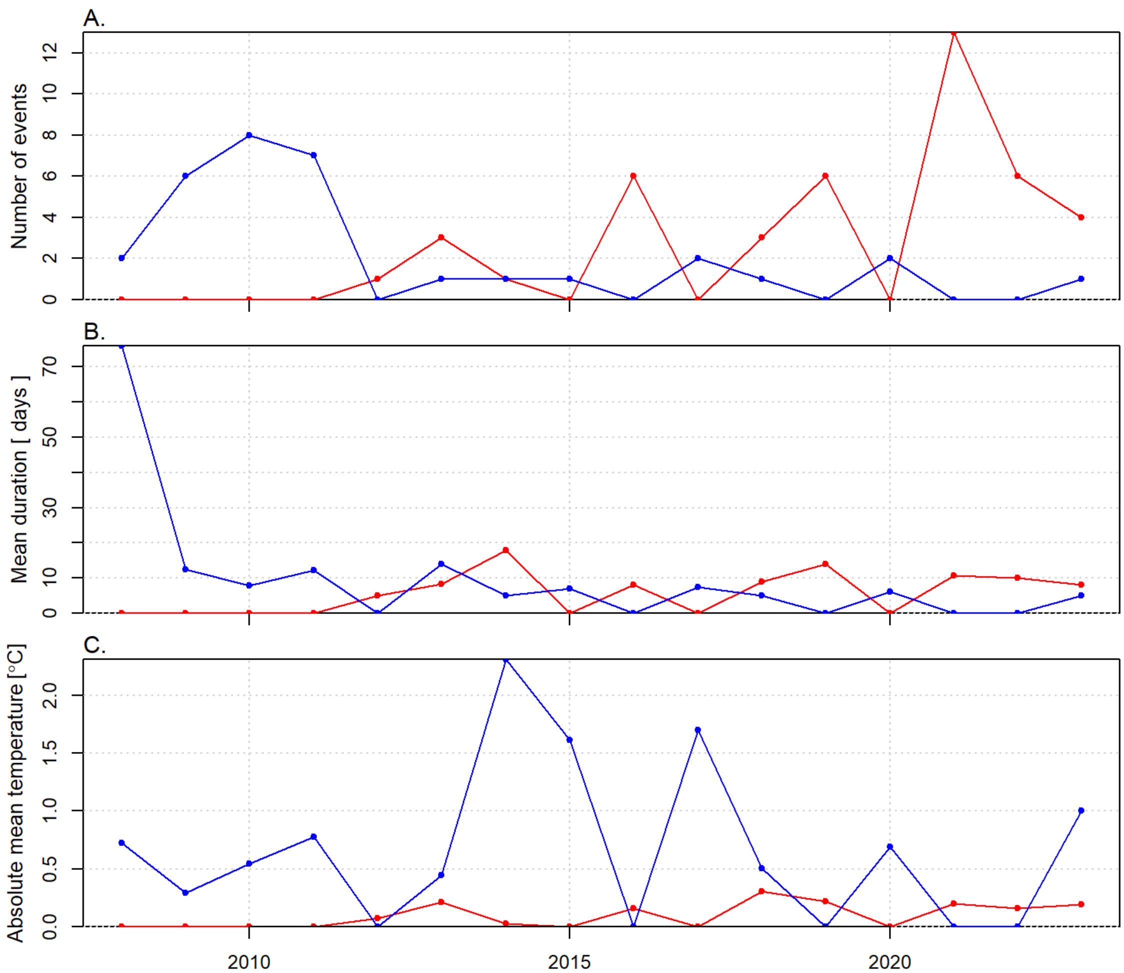

Figure 46. Annual heat wave (red dots connected by a red line) and cold spell (blue dots connected by a blue line) metrics derived from the T2 mooring, located near Station 2, bottom temperature. The total number of events (A), the mean duration of the events (B), and the absolute mean temperature of the events (C).

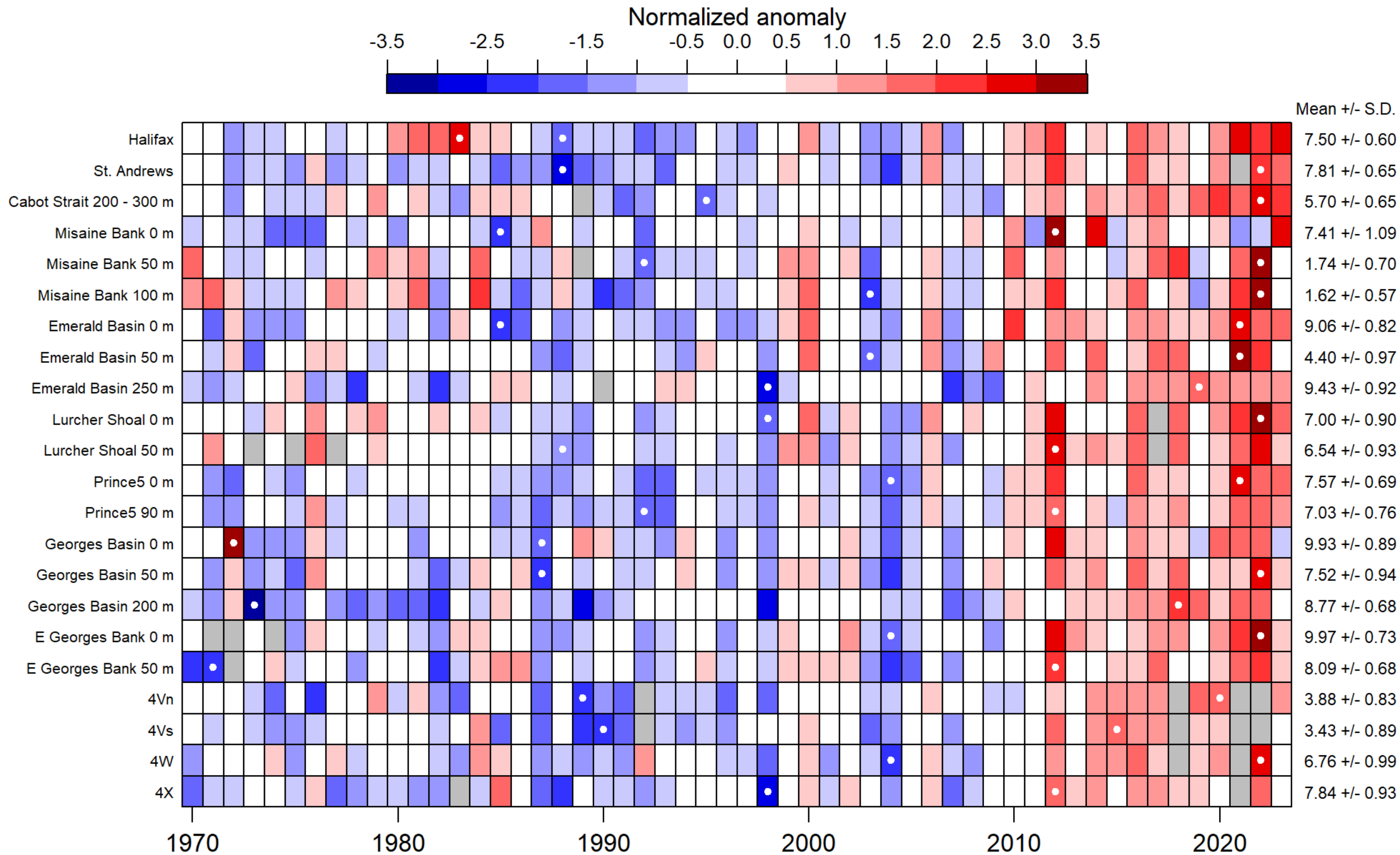

Figure 47. Normalized annual anomalies of temperatures at the bottom and discrete depths for the Scotian Shelf/Gulf of Maine region. These anomalies are based on the 1991–2020 means divided by the standard deviation. Blue colours indicate below-normal anomalies. Red colours indicate above-normal anomalies. White dots represent record minimum and maximum years for each parameter. Gray represents lack of data.

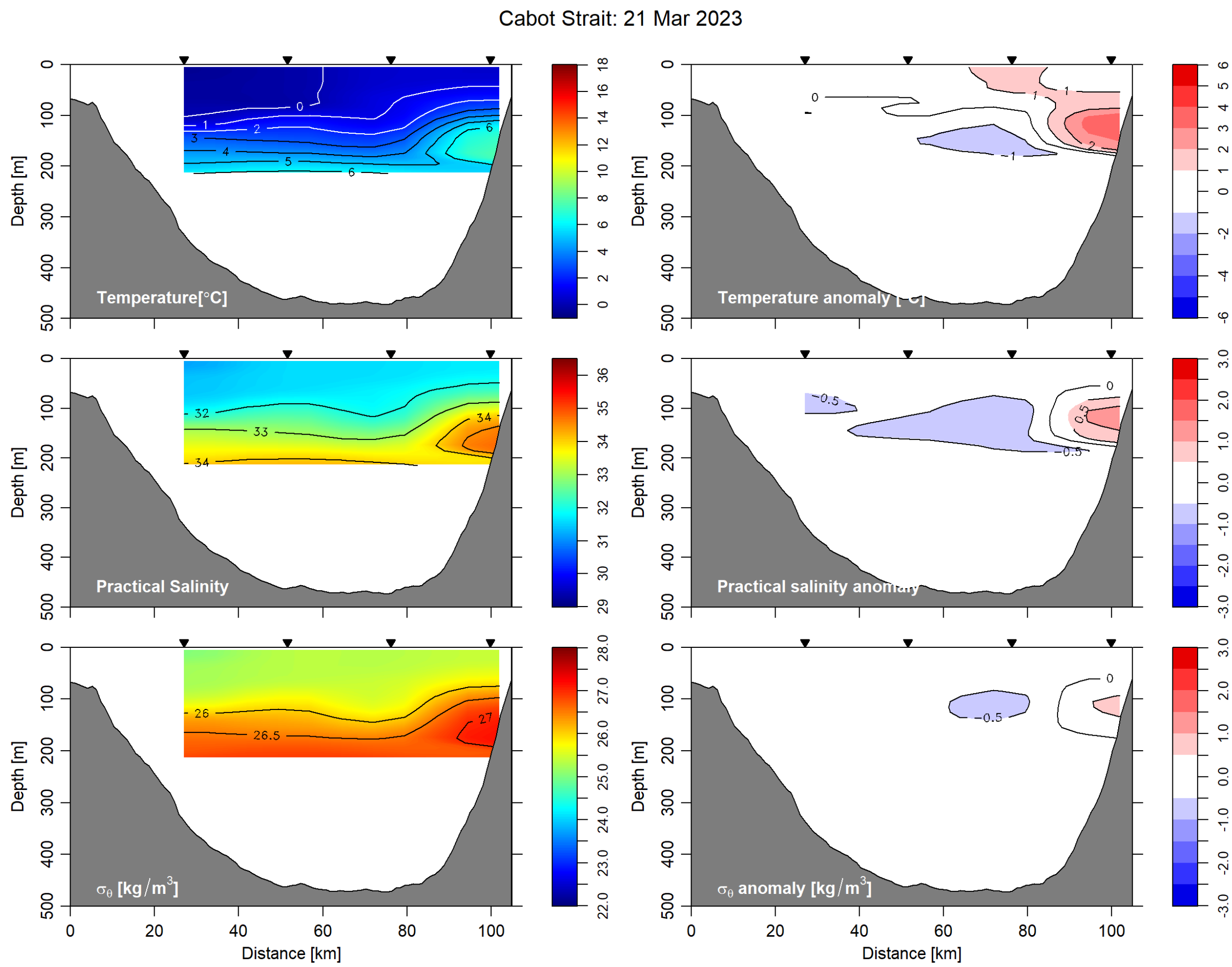

Figure A.1. The 2023 sampling of the Cabot Strait line for spring collected by Quebec Region AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to 1991–2020 monthly means (right panels). Triangles indicate locations of sampling.

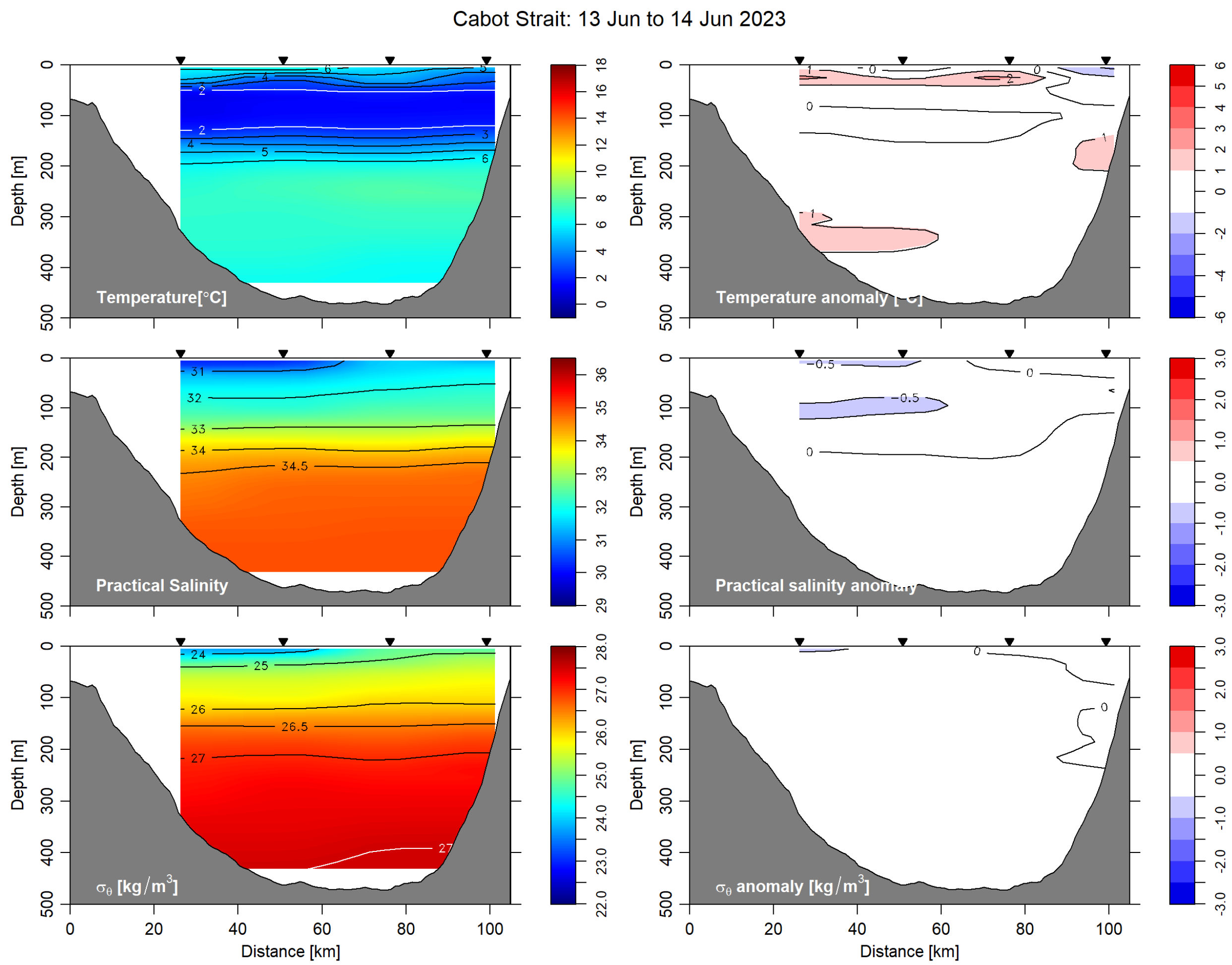

Figure A.2. The 2023 sampling of the Cabot Strait line for summer collected by Quebec Region AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to 1991–2020 monthly means (right panels). Triangles indicate locations of sampling.

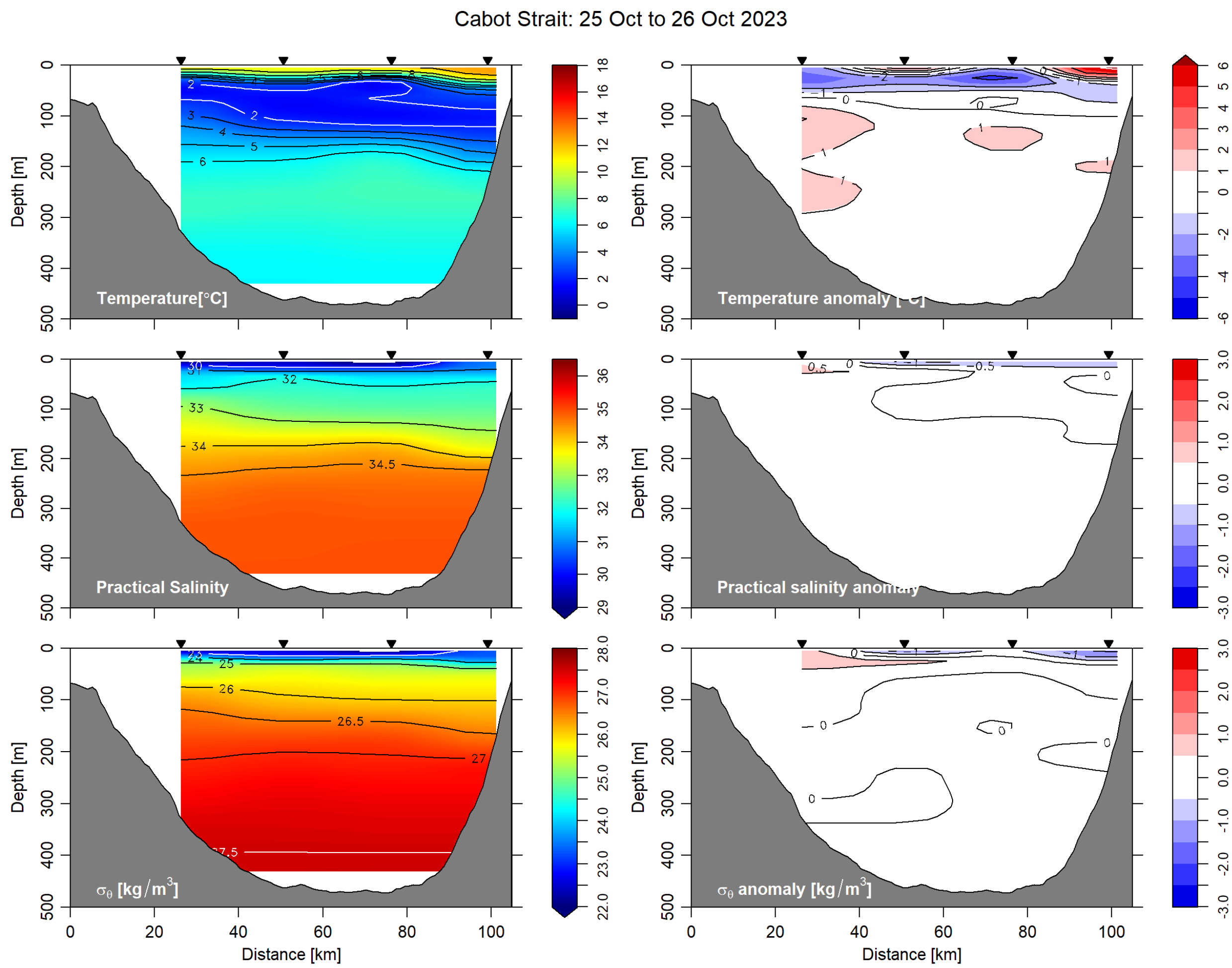

Figure A.3. The 2023 sampling of the Cabot Strait line for fall collected by Quebec Region AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to 1991–2020 monthly means (right panels). Triangles indicate locations of sampling.

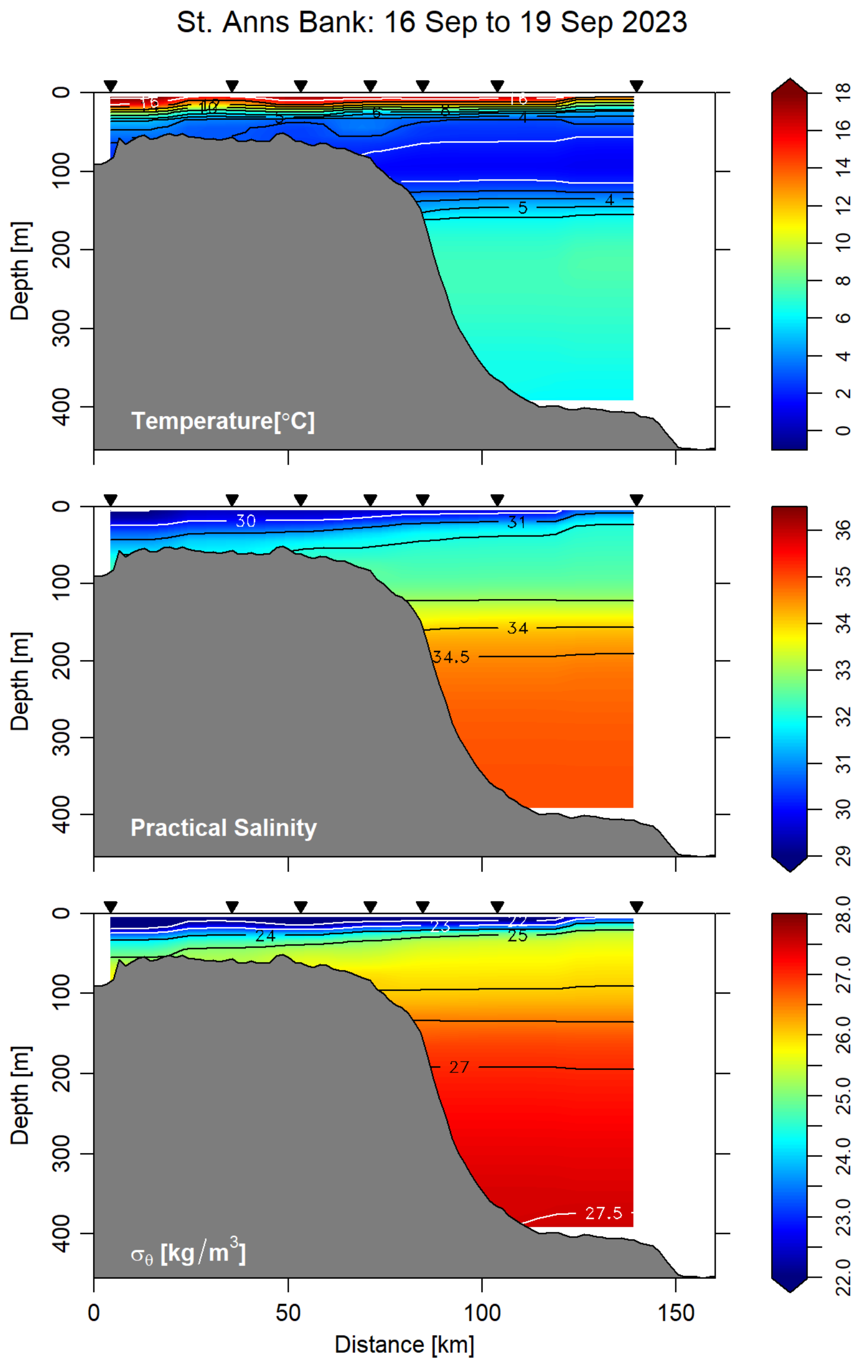

Figure A.4. The 2023 sampling of the St. Anns Bank section for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

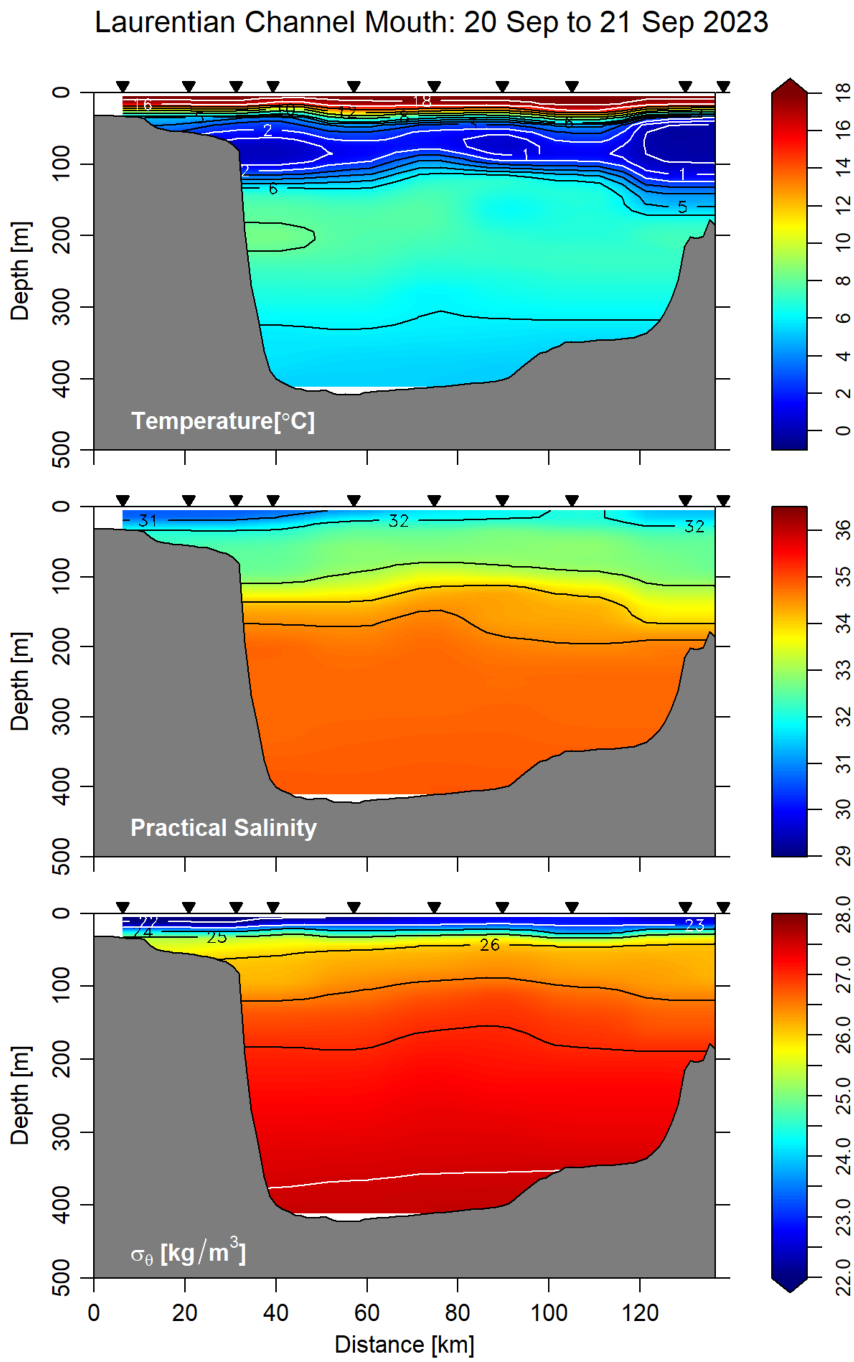

Figure A.5. The 2023 sampling of the Laurentian Channel Mouth section for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

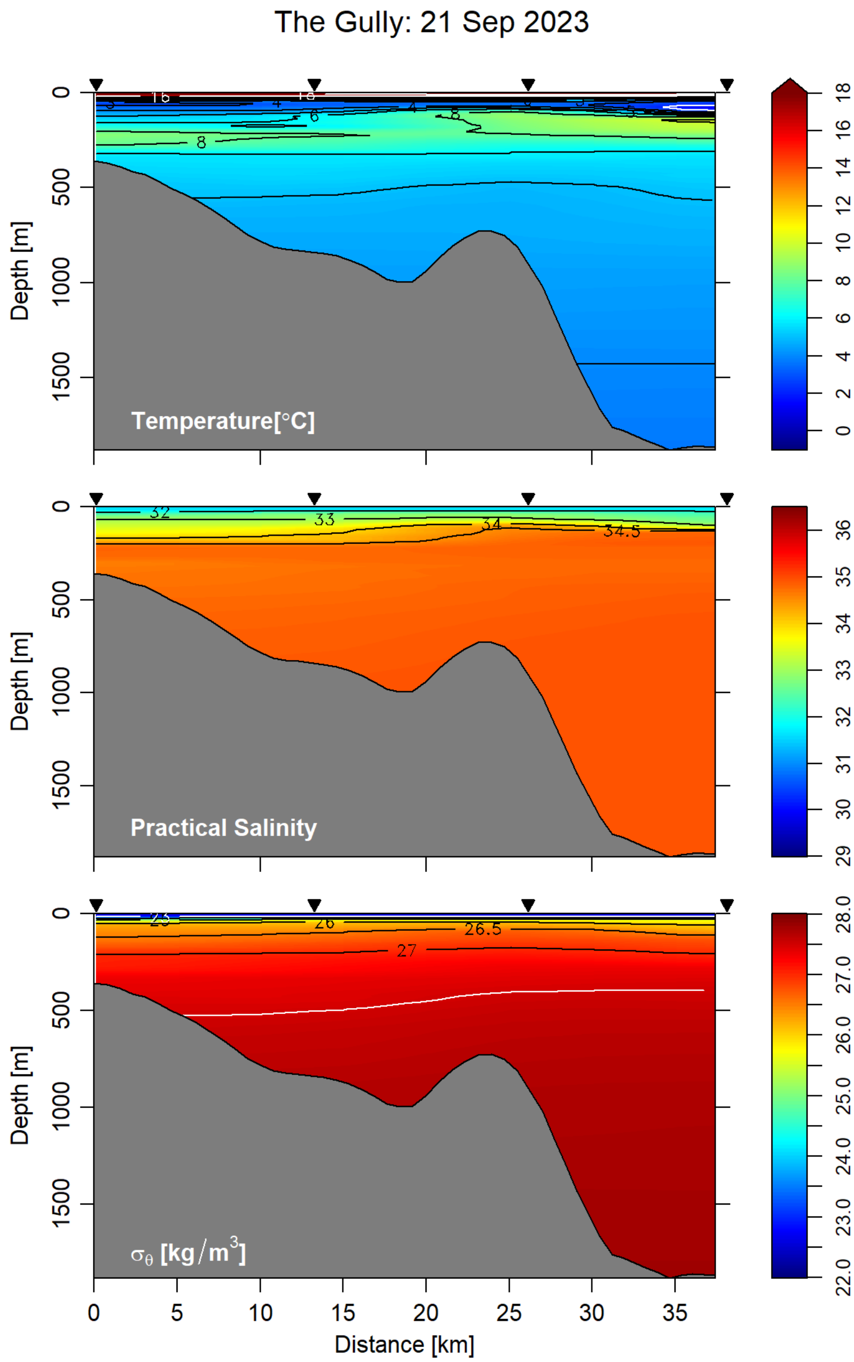

Figure A.6. The 2023 sampling of The Gully line for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

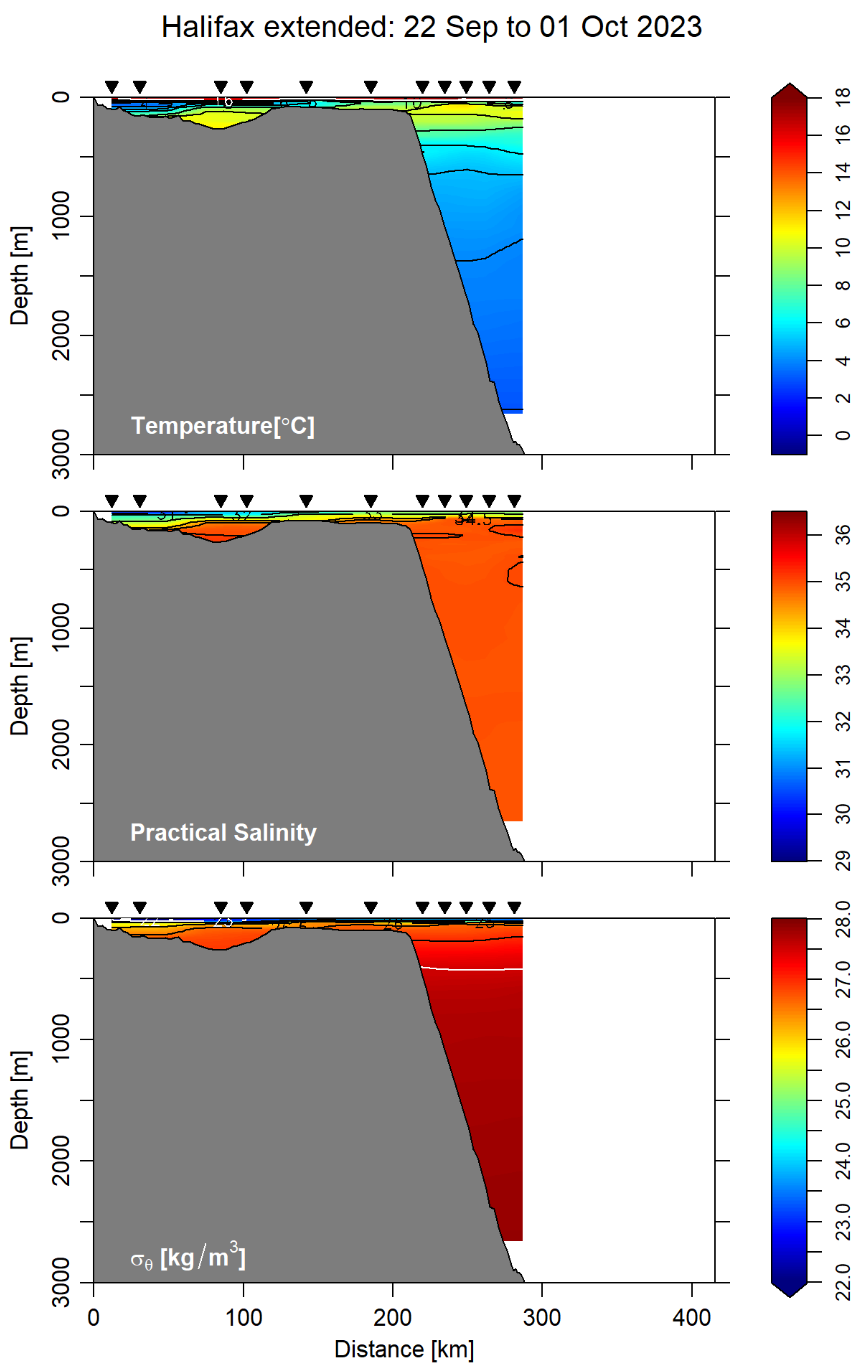

Figure A.7. The 2023 sampling of the Halifax extended line for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

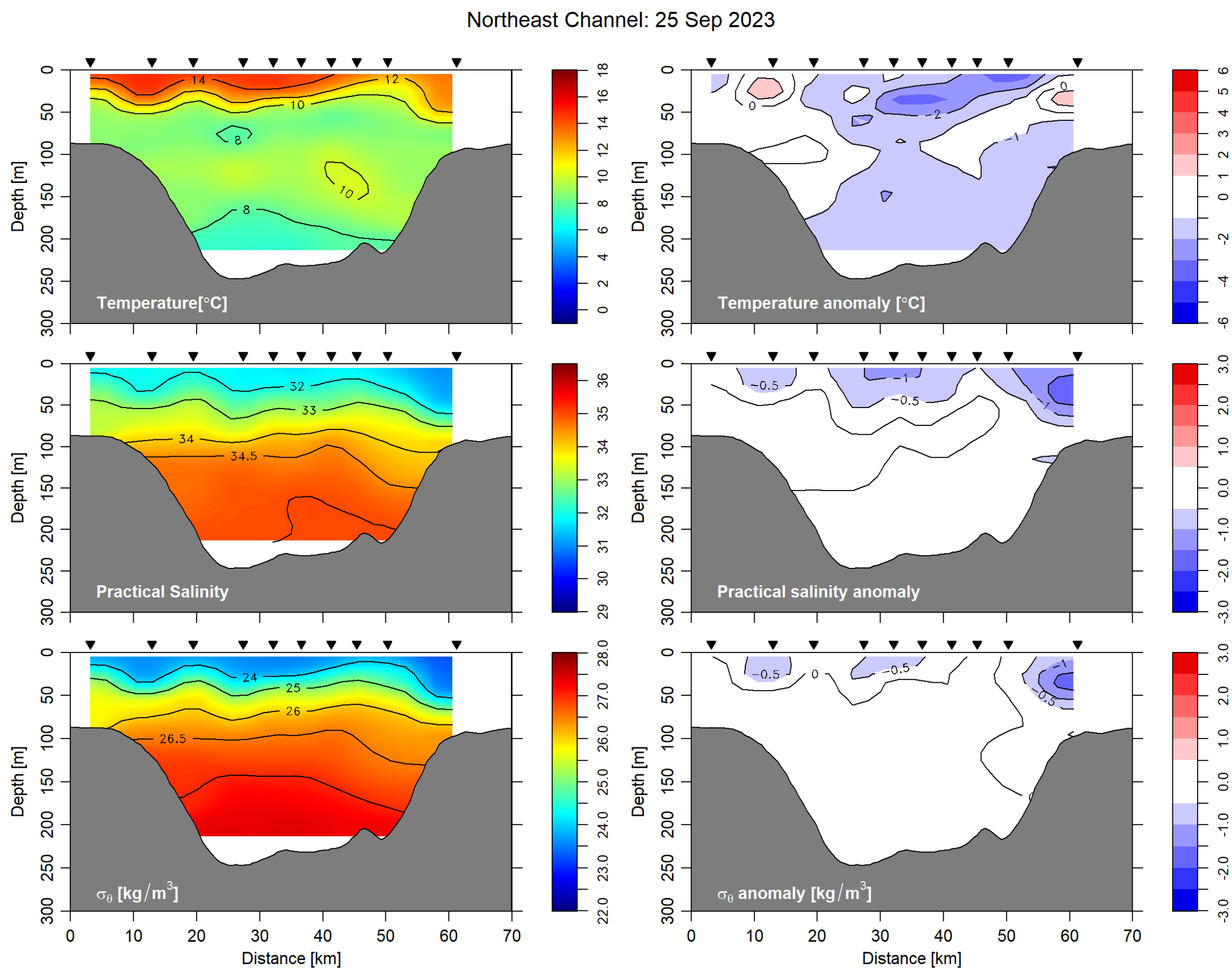

Figure A.8. The 2023 sampling of Northeast Channel for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel)and their anomalies with respect to 1991–2020 monthly means (right panels). Triangles indicate locations of sampling.

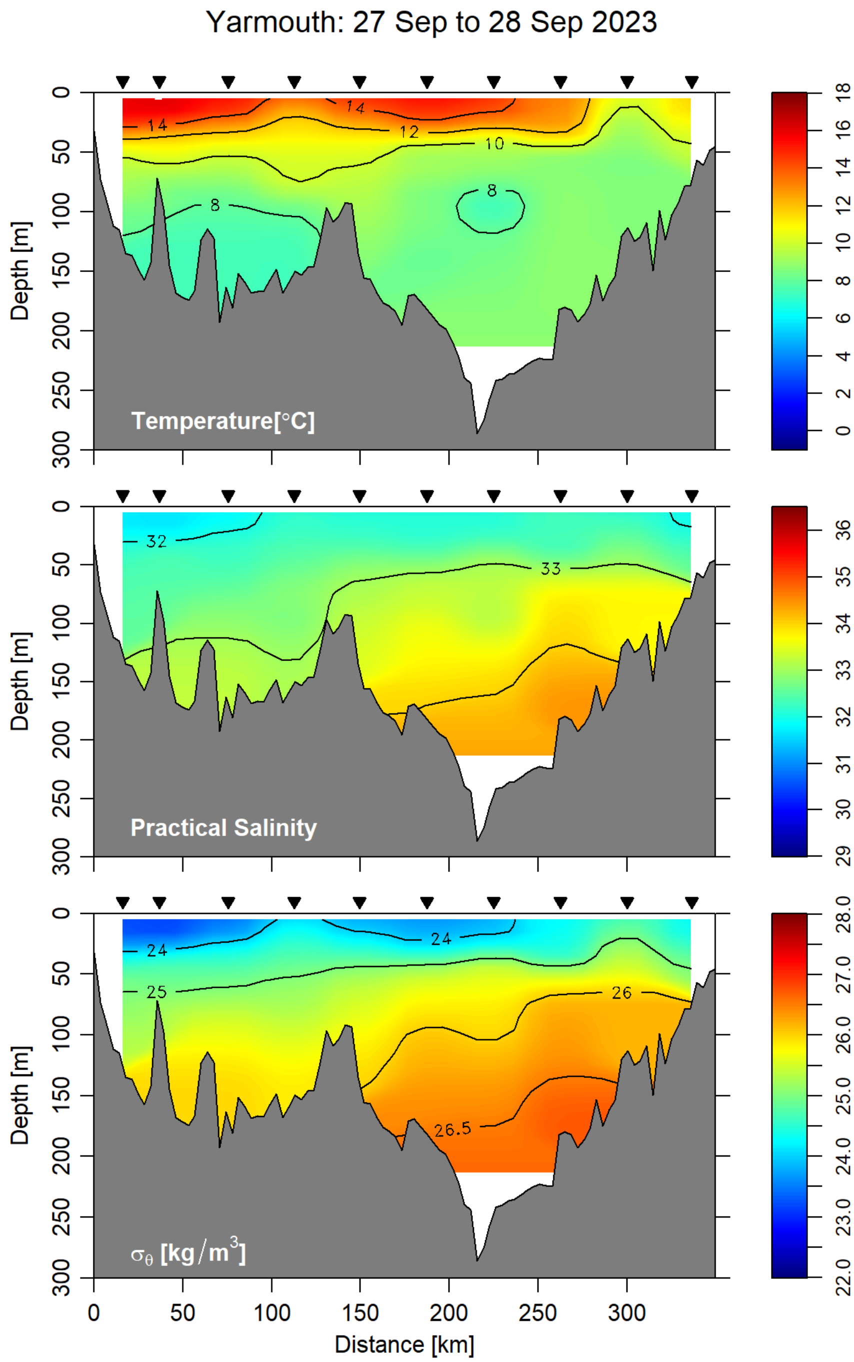

Figure A.9. The 2023 sampling of the Yarmouth line for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

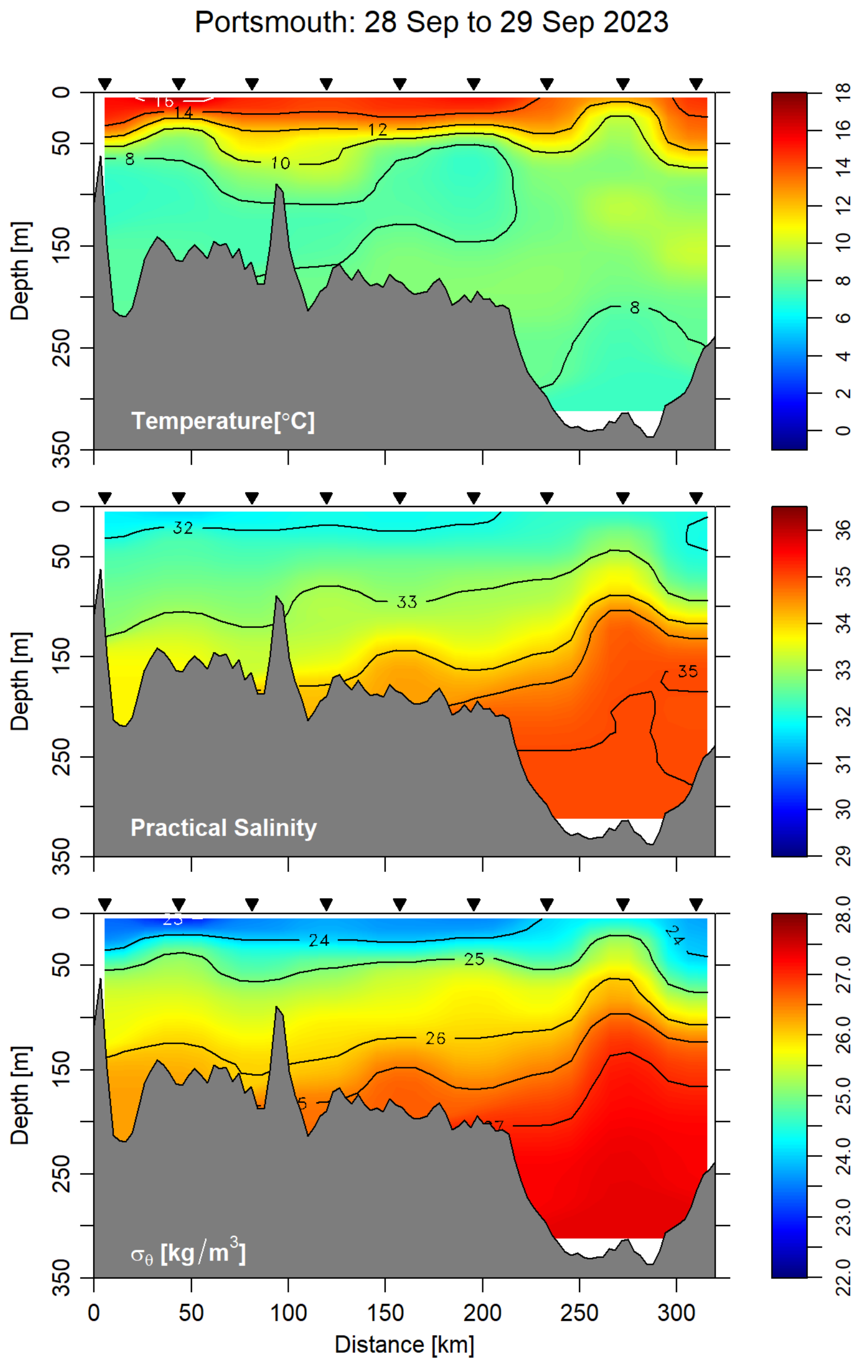

Figure A.10. The 2023 sampling of the Portsmouth line for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.