Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2022

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PHYSICAL OCEANOGRAPHIC CONDITIONS ON THE SCOTIAN SHELF AND IN THE GULF OF MAINE DURING 2022

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 sites (1991–2020 average temperature). The last two years were the two warmest years in all regions. Long-term coastal monitoring at Halifax (Nova Scotia) recorded the third highest value annual SST and at St. Andrews (New Brunswick) the warmest temperature in the record. At other selected sites across the region, annual water temperature anomalies were above normal. Cabot Strait at 200-300 m depth was the warmest temperature in the record (the last four years were the warmest). Emerald Basin at 250 m was the seventh warmest temperature in the record (the last seven years were the warmest; 2019 was the record high). Georges Basin at 200 m was the third warmest temperature in the record (the last ten years were the warmest; 2018 was the record high). A composite index, consisting of 22 ocean temperature time series from surface to bottom across the region, indicated that, of the 20 measurable metrics, 2022 was well above normal with 10 of the time series greater than two standard deviations.

RÉSUMÉ

Hebert, D., Layton, C., Brickman, D., and Galbraith, P.S. 2023. Physical Oceanographic Conditions on the Scotian Shelf and in the Gulf of Maine during 2022. Can. Tech. Rep. Hydrogr. Ocean Sci. 359: vi + 81 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) enregistrées par satellite étaient supérieures à la normale (température moyenne de 1991 à 2020). Les deux dernières années ont été les deux années les plus chaudes dans toutes les régions. La station de monitorage côtière à long terme située à Halifax (Nouvelle-Écosse) a enregistré la troisième température annuelle la plus chaude de la SST et à la station de St Andrews (Nouveau-Brunswick) la température la plus chaude jamais enregistrée. À d'autres stations dans la région, les anomalies annuelles de la température de l'eau étaient supérieures à la normale. L'anomalie de température dans le détroit de Cabot aux profondeurs de 200 à 300 m était la plus élevée de la série chronologique (les quatre dernières années ont été les plus chaudes). Le bassin d'Émeraude à 250 m a eu sa septième anomalie la plus chaude (les sept dernières années ont été les plus chaudes jamais enregistrées, 2019 étant le record de série). Le bassin Georges à 200 m a connu sa troisième année la plus chaude (les dix dernières années ont été les plus chaudes, avec 2018 la plus chaude). Un indice composite, composé de 22 séries chronologiques de températures océaniques de la surface jusqu'au fond à travers de la région, a indiqué que, des 20 métriques mesurables, 2022 était bien au-dessus de la normale avec 10 des séries chronologiques plus élevées d'au moins deux écarts-types.

1 INTRODUCTION

This document discusses air temperature trends, Sea Surface Temperatures (SST), and physical oceanographic variability during 2022 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.

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 2022, the winter (December–March) NAO index was above the 1991 – 2020 mean, +0.96 (+1.42SD), after one year of below normal and seven earlier years of above normal values (Figure 2A). The lower panels of Figure 2 show the sea-level atmospheric pressure conditions during the winter of 2022 compared to the 1991 – 2020 mean. The Icelandic low and Azores high were higher and lower, respectively, to the long-term 1991–2020 average.

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 2022, the annual anomalies were above normal over the Scotian Shelf and the Gulf of Maine (Figure 3). The seasonal anomaly of these regions was normal during the spring, and above normal during winter, summer, and fall (Figure 4). The fall anomaly was the greatest.

Monthly air temperature anomalies for 2021 and 2022 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. In general, all sites show that 2022 has above- or near-normal temperatures for most of the year, with January being below normal for Saint John and Boston.

In 2022, the mean annual air temperature anomalies relative to 1991–2020 climatology were positive for all sites, with anomalies ranging from +1.1°C (+1.6 SD) for Boston to +1.3°C (+1.8 SD) for Sydney (Table 1). Valid data for Sable Island and Boston sites varied for 2021. 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 (+1.0°C, +1.7°C), +2.0°C (+1.7°C, +2.3°C), +1.2°C (+0.9°C, +1.6°C), +1.3°C (+0.9°C, +1.6°C), and +2.4°C (+2.1°C, +2.7°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 two 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 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). Sea surface temperatures were above normal for most of 2022; only October had near normal temperatures for most of the region (Figure 9). Annual anomalies were calculated from monthly-averaged temperatures for the five subareas (Table 2 and Figure 10). The annual anomalies during 2022 ranged from +1.3°C (+2.6 SD) in 4Vn to +1.7°C (+2.4 SD) in eastern Gulf of Maine/Bay of Fundy. The last two years were the two warmest years in all regions since the start of observations. Over the lengths of the records, all areas show increasing temperature trends (Figure 10), based on a linear-least-squares fit, ranging from the lowest value of +0.3°C/decade in 4Vn to a highest value of +0.5°C/decade in eastern Gulf of Maine/Bay of Fundy. A similar trend in SST from AVHRR measurements was found in the Gulf of St. Lawrence (Galbraith et al. 2012).

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 2022, the SST anomalies relative to the 1991

– 2020 for Halifax was +1.4°C (+2.3 SD)(the third highest value; the last three years were the warmest on record), a decrease of -0.2°C from 2021, and for St. Andrews was +1.4°C (+2.2 SD)(the largest anomaly of the time series).

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 and equipment issues affected the sampling of the station during 2022. The depth-averaged (0–90 m) temperature, salinity, and density time series are shown in Figure 11. In 2022, the annual temperature anomaly was +1.4°C (+1.9 SD) (the third highest value; 2021 was the record high) and the salinity anomaly was +0.3 (+1.3 SD) (the eighth highest value). These represent changes of -0.2°C and +0.1 from the 2021 values.

The 2022 annual cycle at Prince 5 shows above-normal temperatures throughout the year with not much depth dependence in the anomaly (Figure 12) when sampling was undertaken. 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 shallowest depth where the gradient in density stratification is greater than 0.01 kg/m^4.

In 2022, for Prince 5, the stratification index shows that the fall is higher than normal (Figure 13). The MLD in the spring and fall are shallower than normal.

The 2022 annual temperature, salinity, and density cycles at Halifax 2, located at the mouth of Halifax harbour (Figure 1), are shown in Figure 14. The temperature anomaly is above normal for most of the year except at the beginning of the year and near the surface for the last half of the year. The SI and MLD are near normal for most of 2022 (Figure 15).

5 STANDARD SECTIONS

The sections across the Cabot Strait, St. Anns Bank, Louisbourg line, The Gully, on Sable Island Bank, Halifax line, Browns Banke line, across the Northeast Channel, Portsmouth line, and Yarmouth line (Figure 1) were sampled during the early spring of 2022 (Figure 16). Since the sampling of these sections were earlier than the normal AZMP spring sampling for most of the region, anomalies of temperature, salinity and density are not shown for those sections.

During the spring of 2022, the Cabot Strait section showed above normal April temperatures and salinity around 100 m to 300 m with the largest anomalies on the eastern side (Figure 17). Temperatures were slightly above normal at depth on the shelf portion of the Louisbourg section and warmer, saltier at the shelfbreak (Figure 18). The Halifax section shows warm waters in Emerald Basin and outer shelf and shelfbreak (Figure 19). During the early spring, the Browns Bank section, which was also sampled earlier than normal, showed cool water over the shelf (Figure 20).

During the fall of 2022, the mission was completed at the normal historic time of the year which included sampling across the Cabot Strait, St. Anns Bank, across the mouth of Laurentian Channe, Louisbourg line, The Gully, Halifax line, Browns Bank line, and across the Northeast Channel (Figure 21). The Cabot Strait section showed above-normal temperatures over most of the strait but fresher water at the surface (Figure 22). In the fall of 2022, there was anomalously warm, fresh water on the shelf of the Louisbourg section (Figure 23). The offshore was warm and saltier —evidence of warm Slope water returning. The Halifax section shows anomalously warm waters near the bottom over most of section (Figure 24). In Emerald Basin and slope region, the water was slightly above normal in temperature and salinity. During the fall of 2022, the Browns Bank section showed slightly anomalous warm water over most of the shelf (Figure 25).

The Appendix contains sections in the region conducted by IML for Cabot Strait in winter (Figure A.1), summer (Figure A.2) and fall (Figure A.3). For the AZMP missions, additional regions were sampled: St. Anns Bank Marine Protected Area in spring (Figure A.4) and fall (Figure A.5), the Laurentian Channel Mouth in the fall (Figure A.6), the Gully Marine Protected Area in early spring (Figure A.7) and fall (Figure A.8), near Sable Island in early spring (Figures A.9 and A.10), the extended Halifax Line during the spring AZMP mission (Figure A.11), during the AZOMP mission (Figure A.12) and fall AZMP missions (Figure A.13), across the Northeast Channel in early spring (Figure A.14) and fall (Figure A.15). Two sections across the Gulf of Maine, Yarmouth Line (Figure A.16) and Portsmouth Line (Figure A.17) were completed during the early spring. 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 this document, the data are used in the analysis presented here.

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 26). 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 27). Thus, only glider data collected within 15 nm of the Halifax Line are considered, which explains some of the gaps in Figure 26. Station 2 (HL2) is sampled throughout the year from a small vessel and provides the highest temporal resolution of our stations (Figure 28). 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 2021–2022 period (Figure 29). 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 29). An improved battery allowed better coverage in 2021 and 2022 for HL7. Due to battery limits and weather, the glider cannot reach HL7 consistently, especially in winter (Figure 26).

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 30) is presented (Figure 31). 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 31C, 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 2022 annual anomalies are based on observations from three, two, six, one, four, and five month, respectively.

In 2022, the annual anomaly was +1.8°C (+2.7 SD) for Cabot Strait at 200-300 m (the largest anomaly of the time series; the last four years were the warmest on record). For the shallow Misaine Bank on the eastern Scotian Shelf, the annual anomaly was +1.8°C (+3.1 SD) at 100 m (the largest anomaly of the time series). For the deep basins on the central Scotian Shelf and Gulf of Maine, the 2022 anomalies were +1.0°C (+1.1 SD) for Emerald Basin at 250 m (the seventh highest value; the last seven years were the warmest on record; 2019 was the record high) and +1.2°C (+1.7 SD) for Georges Basin at 200 m (the third highest value; the last ten years were the warmest on record; 2018 was the record high). For the shallow banks in western Nova Scotia, the anomalies were +1.5°C (+2.2 SD) for Eastern Georges Bank at 50 m (the third highest value) and +2.7°C (+2.9 SD) for Lurcher Shoals at 50 m (the second highest value; the last two years were the warmest on record; 2012 was the record high). These values correspond to changes of +0.5°C, +0.5°C, -0.1°C, +0.0°C, +0.4°C and +1.1°C, respectively, from the 2021 values. The 2010 and 2011 NAO 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 on the Scotian Shelf in 2012 (Petrie 2007). Anomalies were highly positive for that year and started to return to normal in 2013, but increased to record or near-record values in 2014 and continued to remain high in 2022. The transport of colder shelf break current of Labrador origin has been negative since 2014 (Cyr et al. 2023). Deep-water temperature anomalies continued to increase due to intrusions from offshore slope water. The correlation between the NAO and deep-water temperatures appears to have changed.

8 TEMPERATURES DURING THE ECOSYSTEM TRAWL SURVEYS

8.1 WINTER SURVEY

The winter survey took place from 28 March to 12 April 2022. A total of 53 Conductivity-Temperature-Depth (CTD) stations were sampled (Figure 32). Sampling was mainly on Georges Bank (NAFO Division 5Ze) and Georges Basin (part of NAFO Division 4X). For most of the areas, bottom temperatures were above normal (Figure 33).

8.2 SUMMER SURVEY

The summer survey took place from 07 July to 06 August 2022. A total of 150 Conductivity-Temperature-Depth (CTD) stations were sampled (Figure 34). The survey covered the Bay of Fundy, Eastern George Bank, and east on the Scotian Shelf to west of Sable Island (western half of NAFO Division of 4W). The near-bottom temperature anomalies for 2022 were positive for most of the sampled region (Figure 35). The anomaly was positive for the NAFO Divisions sampled on the Scotian Shelf in 2022: +2.5°C (+2.5 SD) for 4W (the largest anomaly of the time series) and +1.7°C (+1.8 SD) for 4X (the largest anomaly of the time series) (Figure 36). All regions, including 4X, show a steadily increasing temperature from approximately 2010.

The volume of the Cold Intermediate Layer (CIL), defined as waters with temperatures less than 4°C, was estimated from objectively mapped data using the full depth CTD profiles for the region, from Cabot Strait to Cape Sable (Figure 37). There is considerable variation in the volume of the CIL from 1998 until 2009 (Figure 37). In 2022 , the CIL volume could not be determined since the region sampled on the Scotian Shelf (Figure 37) had no temperature below 4°C. The low-frequency variability of the area-weighted average minimum temperature mirrors the CIL volume.

In an attempt to determine whether there could be CIL water east of the survey area, the 1991 – 2020 climatology was used as the basis of shelf-wide conditions. First, the minimum temperature was examined for the 2022 year compared the climatology data for the surveyed area (Figure 38). Thus, the 2022 average difference was 1.9°C. In Figure 39, the coverage of the whole gridded for the Scotian Shelf had varied over the whole record with 1992 and 2018 having poorer coverage but the average minimum temperature difference was not as large as found in 2022. To see whether the climatological temperature can be used to estimate the CIL volume, the measured CIL volume was compared to using the climatological temperature for the survey region each year increased by the mean difference in minimum temperature at each location for that year and climatological minimum temperature. This is referred to as the adjusted climatology CIL volume (Figure 39). There was general agreement between the two timeseries. Finally, a third estimate of the CIL, the blended CIL volume, uses the measured CIL for the region where data was collected and used the climatological data with the temperature adjustment for the regions not sampled. For 1992 and 2018, this improved the CIL volume to similar to adjacent years. For 2022, the CIL volume was estimated to be 1716 km^3 which is still significantly below climatological average (Figure 39).

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 42) 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 40). 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 0.37 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 41). Stratification in 2022 was lower than in 2021 due to the surface becoming slightly cooler and saltier. Examining the 2022 stratification anomaly for areas 4–23 on the Scotian Shelf shows that the slightly below normal anomaly for the Scotian Shelf (Figure 40) is due to an area-average of positive and negative on the Scotian Shelf (Figure 42).

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 (1966-2022), Halifax [1] (1920-2022), and North Sydney (1970-2022) are plotted as monthly means and as a filtered series using a five-year-running-mean filter (Figure 43). The linear trend of the monthly mean data has a positive slope of +37.1 cm/century (Yarmouth), +33.7 cm/century (Halifax), and +40.2 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 +26.8 cm/century, +19.0 cm/century, and +23.4 cm/century, respectively. An interesting feature of the data is the long-term variation that has occurred since the 1920s (Figure 44). The residual sea-level data for the common period 1970-2022 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).

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 45.

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

[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.

Cabot Strait, and along the Scotian Shelf toward the Gulf of Maine (Figure 46). 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 1990–2022 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 46). 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 47. 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 48). 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 47, 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 46) 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 49). 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 the timeseries, with the exception of a strong increase in transport in April, 2022. 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 47).

The fraction of transport into the Gulf of Maine through the Cable Sable Island section (GoM inflow ratio of Figure 50) 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 48) the GoM inflow ratio was near neutral from 1990–2007 (with only 2001 and 2004 above normal), mostly negative from 2008–2014 (with near-neutral values from 2015–2019), and strongly negative from 2020 onwards. 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 51) by summing the standardized anomalies (Figures 47 and 48) for five of the six transport variables (the inflow 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.

12 SUMMARY

In 2022, the North Atlantic Oscillation index was above normal (+0.96, +1.42SD). The analysis of satellite data indicates that sea-surface temperatures were above normal at regions with the last two years being the warmest and record values at 4Vn and 4Vs. 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 2010–2022 were warmer than normal (Figure 52). In 2022, 19 of 20 variables that were able to be measured were more than 1 SD above their normal values. Of these, 10 were more than 2 SD above normal and 4 were more than 3 SD above normal. Interestingly, Misaine Bank at 0 m was the only series below normal. Nine of the series were record highs in 2022. Three other series were the second highest and 6 series the third highest.

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

13 ACKNOWLEDGEMENTS

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15 TABLES

Table 1. The 2022 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 (°C)**	**Normalized (SD)**	**Mean (°C)**	**SD**
Sydney	+1.3	+1.8	+6.45	+0.72
Sable Island	+1.2	+1.8	+8.35	+0.67
Halifax	+1.3	+1.8	+7.16	+0.70
Yarmouth	+1.2	+1.7	+7.69	+0.71
Saint John	+1.2	+1.6	+5.71	+0.77
Boston	+1.1	+1.6	+10.90	+0.68

Table 2. 2022 SST anomalies and long-term SST statistics including 1991-2020 temperature change based on the linear trend.

	Annual Anomaly		1991-2020 Climatology		
Site	**Observed (°C)**	**Normalized (SD)**	**Mean (°C)**	**SD**	**Slope (°C/decade)**
4Vn	+1.3	+2.6	+6.61	+0.50	+0.30
4Vs	+1.4	+2.4	+7.73	+0.60	+0.40
4W	+1.4	+2.2	+8.80	+0.63	+0.50
4XSS	+1.4	+2.3	+8.45	+0.63	+0.50
4XeGoM+BoF	+1.7	+2.4	+8.27	+0.73	+0.50

16 FIGURES

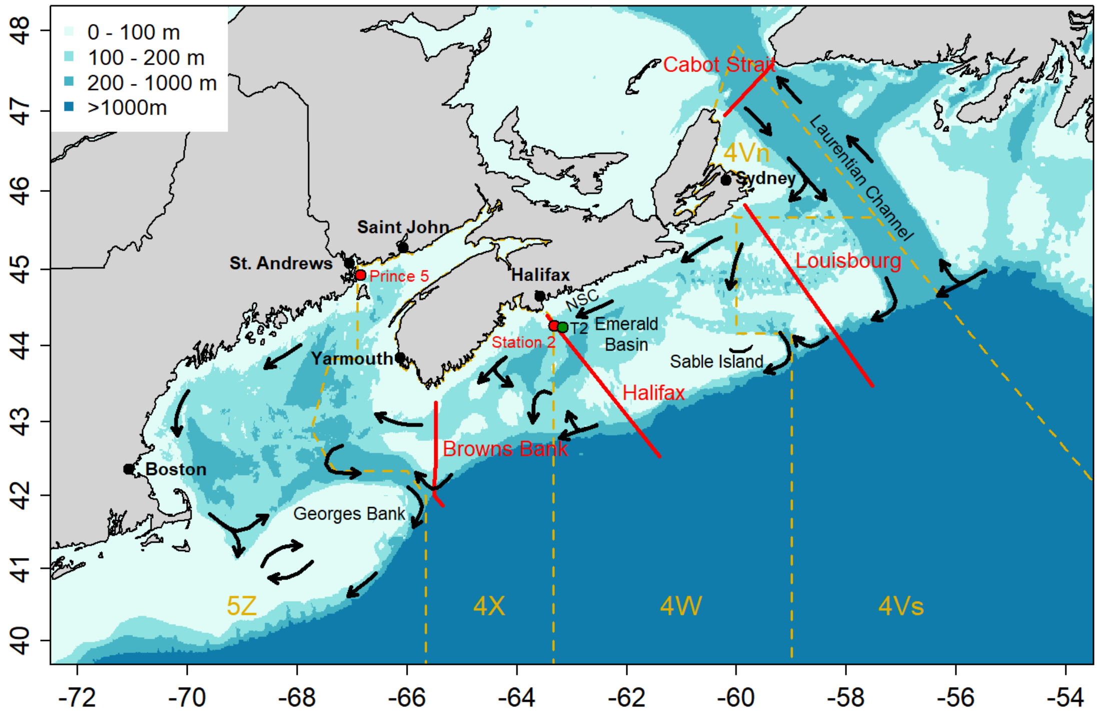

Figure 1. Map of the Scotian Shelf and the Gulf of Maine showing hydrographic stations (red circles), standard sections (red lines), current meter mooring (green), and topographic features. The Nova Scotia Current (NSC) is shown. The dotted lines indicate the boundaries of the Northwest Atlantic Fisheries Organization Divisions

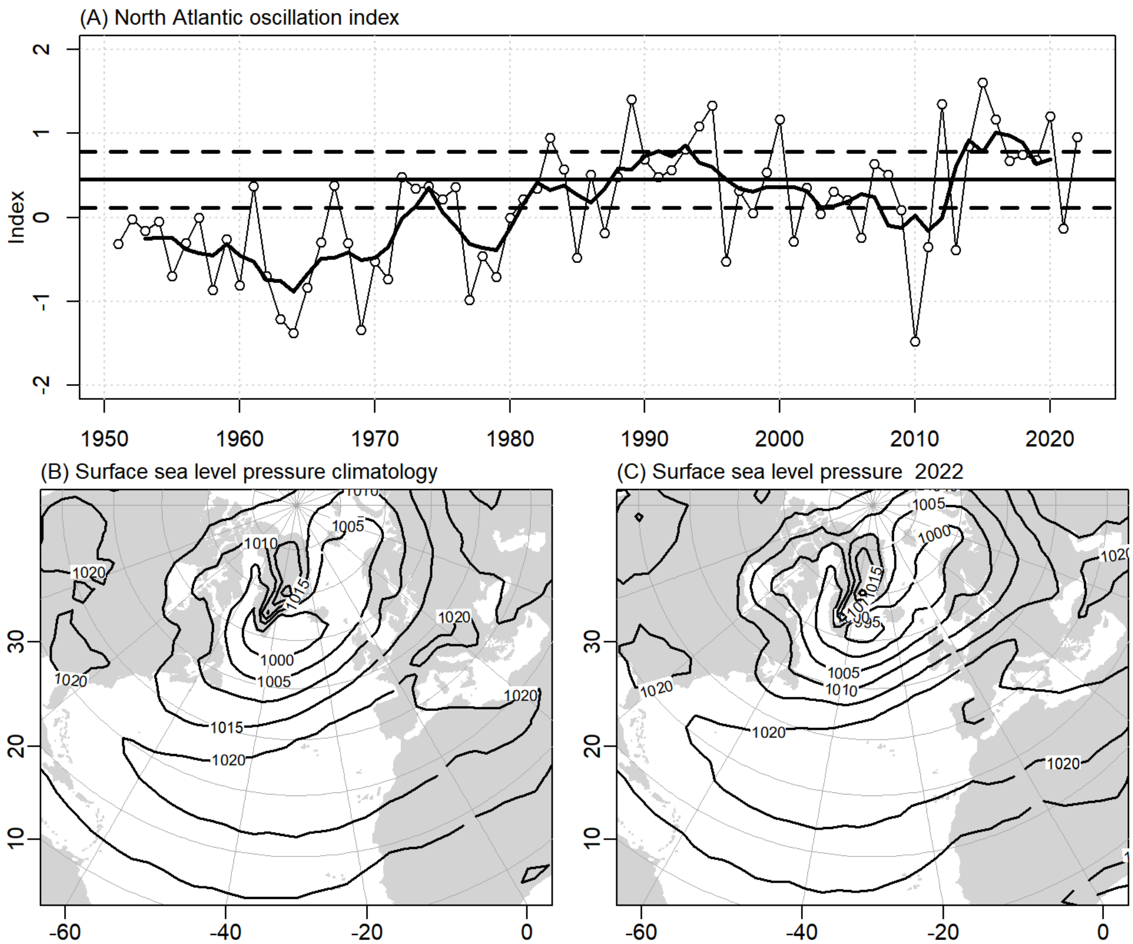

Figure 2. (A) The North Atlantic Oscillation (NAO) index, defined as the winter (December, January, February, March) 500 mb pressure Principal Component Analysis which is representative of the difference between the Icelandic low and Azores high. Thick line is a 5-year moving average. Climatological 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 2021 – March 2022 mean sea-level atmospheric pressure over the North Atlantic. (Data provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado.)

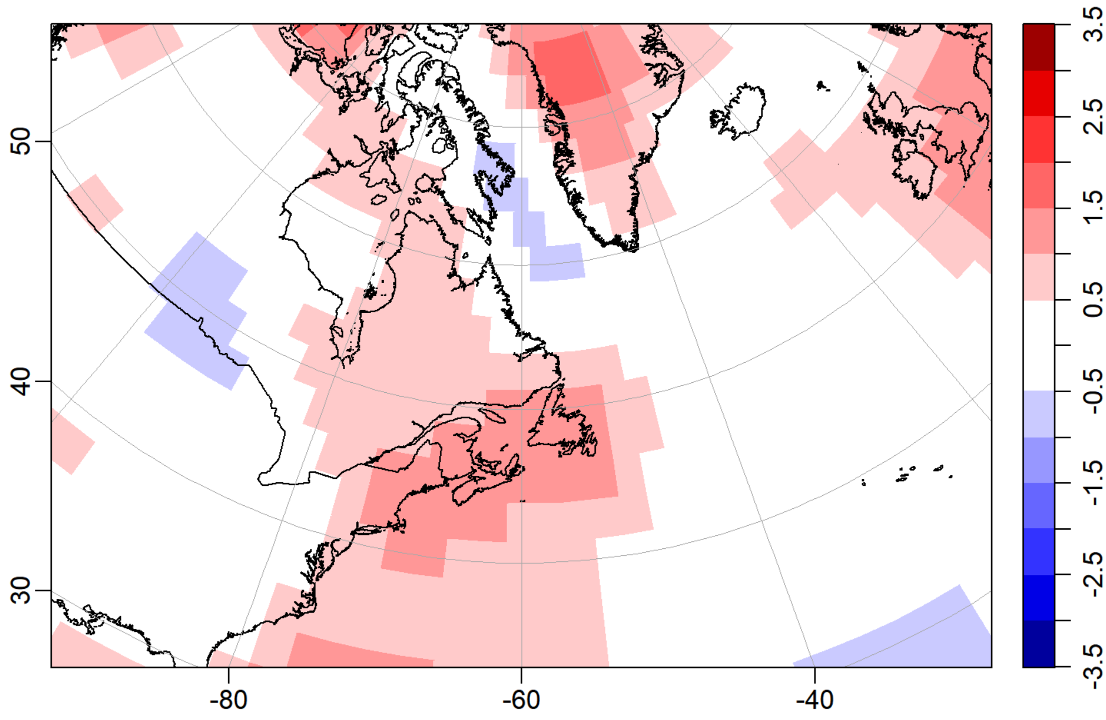

Figure 3. Annual air temperature anomalies (°C) over the Northwest Atlantic relative to the 1991-2020 means; data were obtained from NOAA Internet site (accessed 6 February 2023).

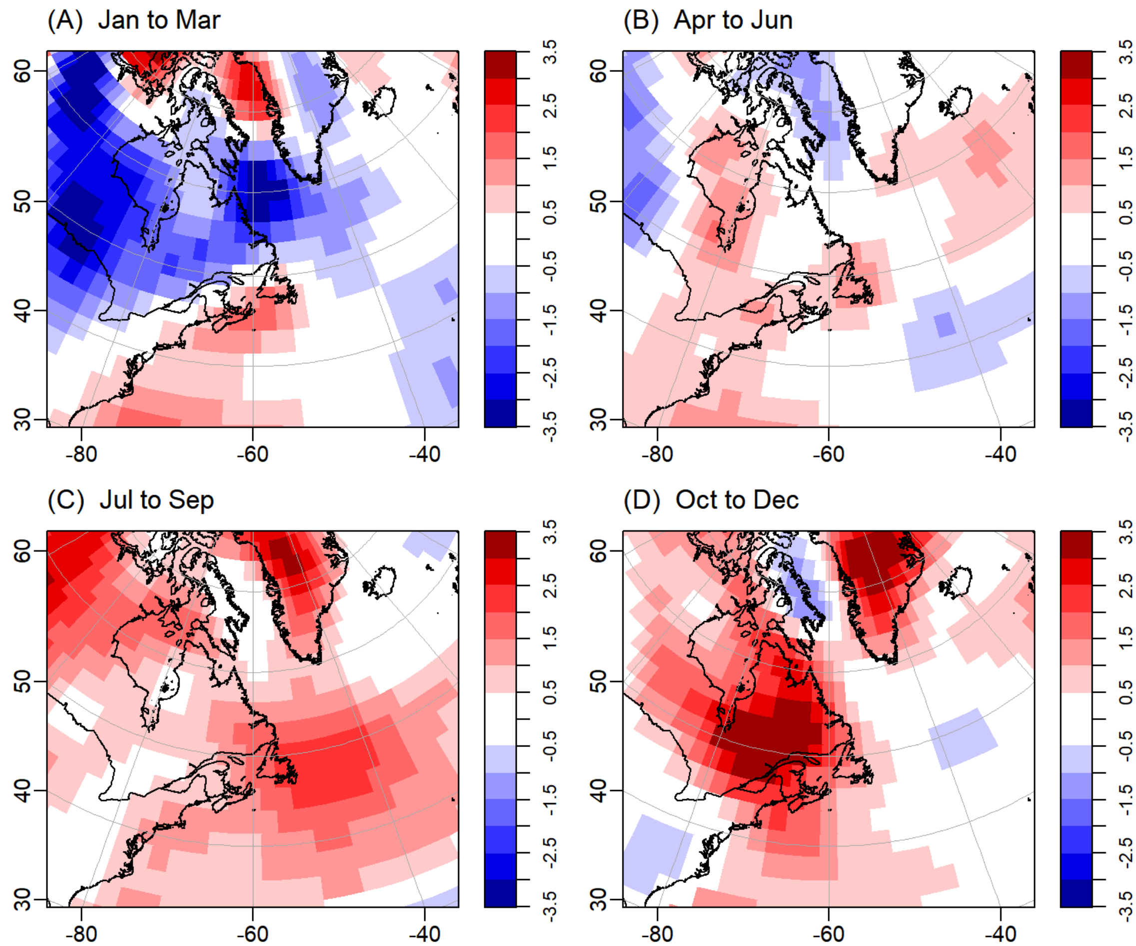

Figure 4. Seasonal air temperature anomalies (°C) over the Northwest Atlantic relative to the 1991-2020 means; data were obtained from NOAA Internet site (accessed 6 February 2023).

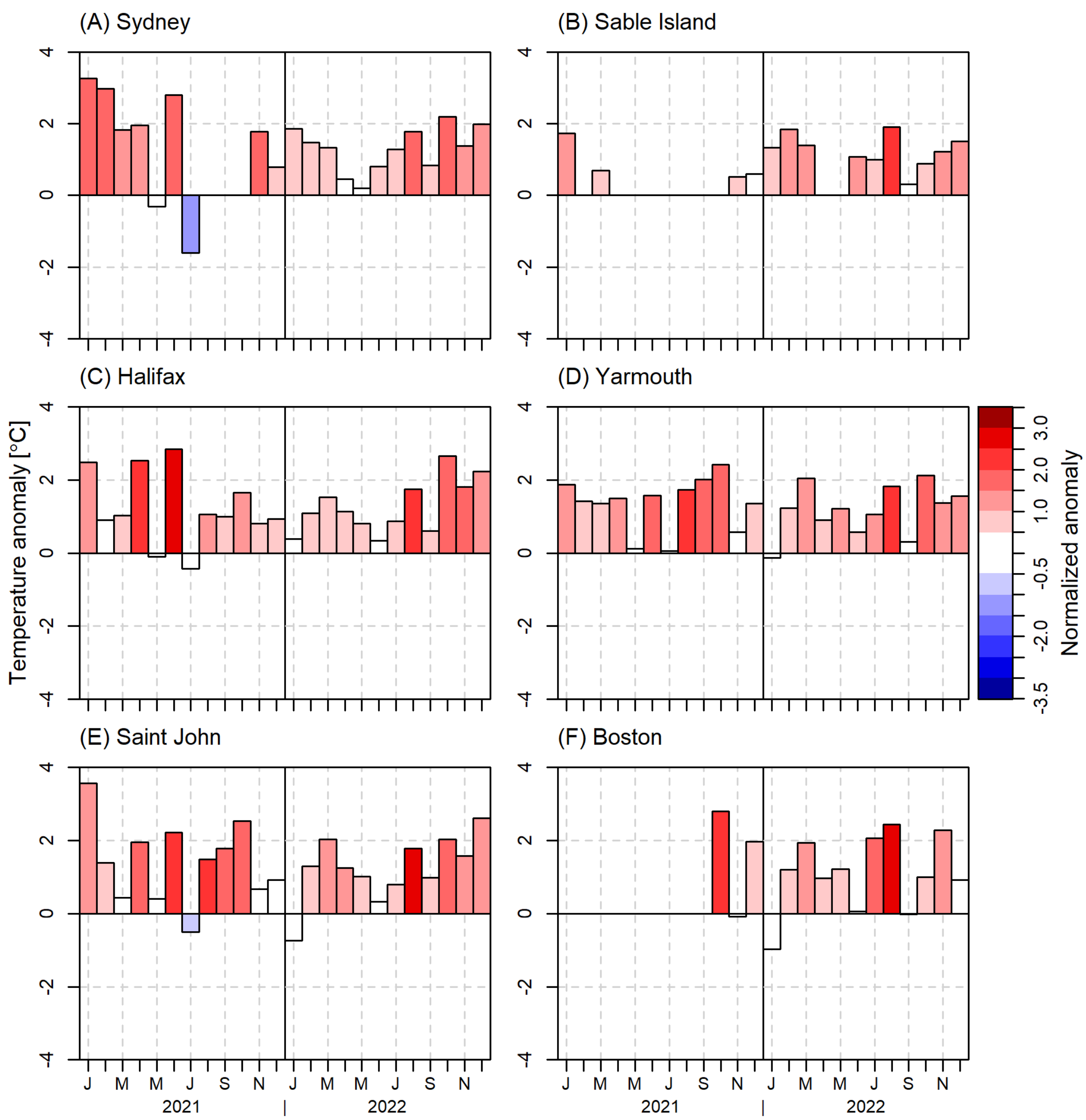

Figure 5. Monthly air temperature anomalies (°C) at several sites in Scotian Shelf/Gulf of Maine region for 2021 and 2022. See Figure 1 for locations. JMMJSN on x-axis represent January, March, May, June, September, and November. Anomalies are colour coded in terms of the numbers of SD above or below normal relative to monthly statistics.

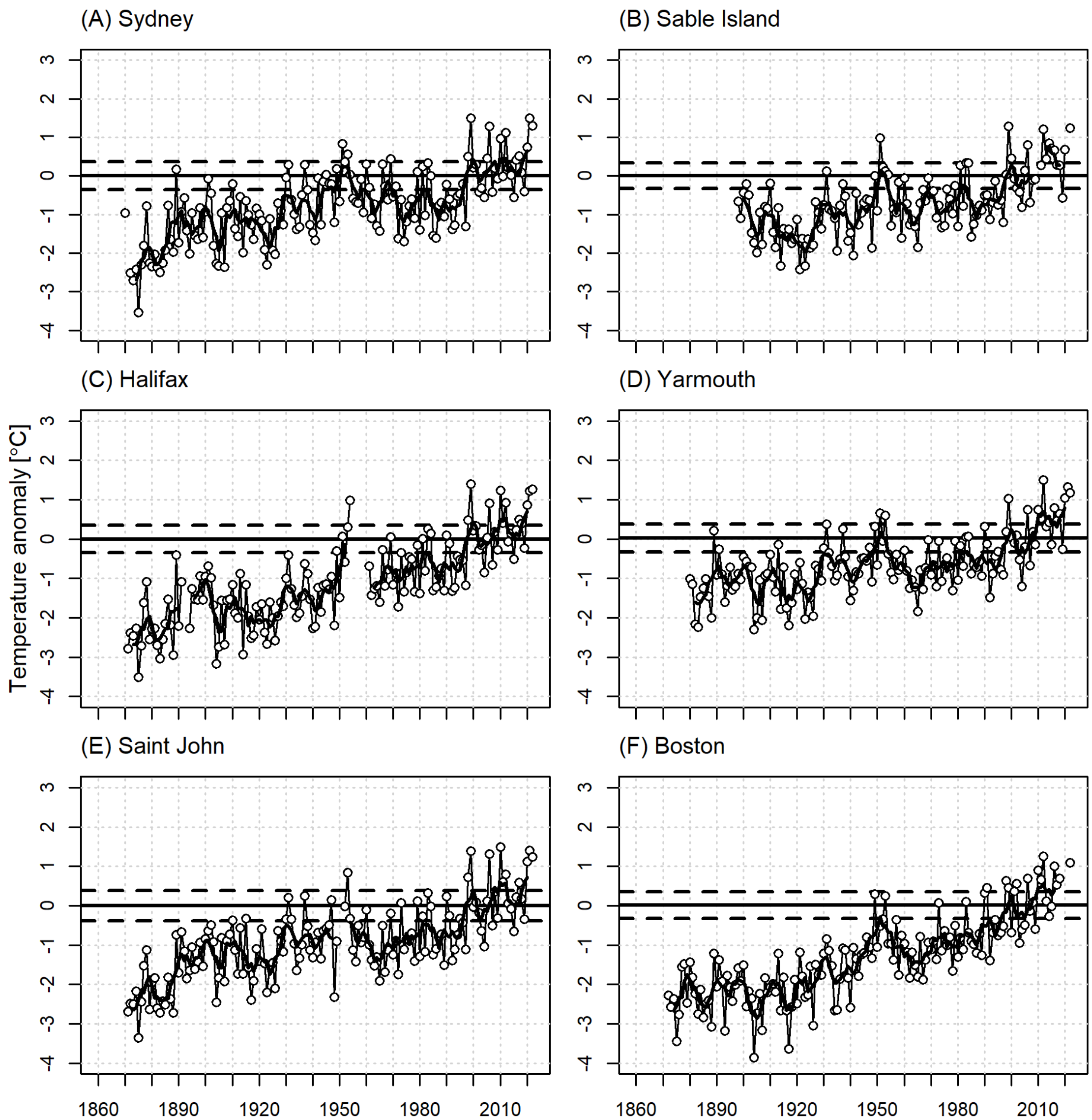

Figure 6. Annual air temperature anomalies in °C (dashed line) and five-year running means (solid line) at selected sites (Sydney, Sable Island, Halifax (Shearwater), Yarmouth, Saint John, and Boston) in Scotian Shelf/Gulf of Maine region (years 1870 to 2022). Horizontal dashed lines represent plus or minus 0.5 SD for the 1991-2020 period. Linear trends for 1900–present are shown.

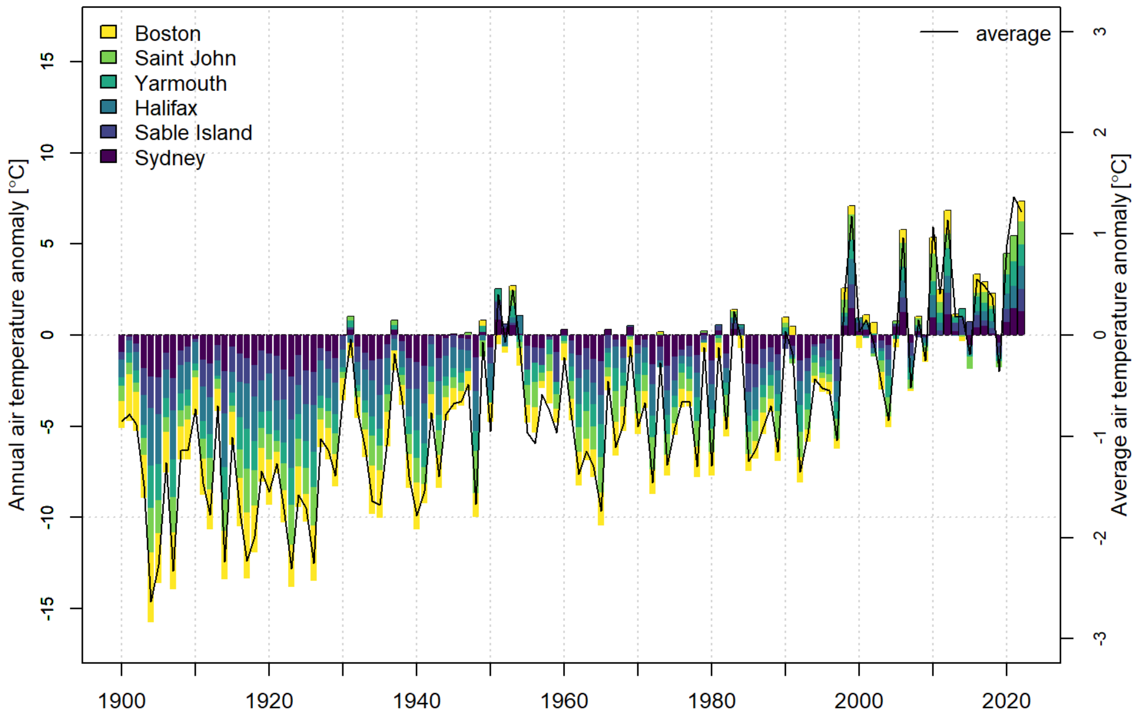

Figure 7. The contributions of each of the annual air temperature anomalies for six Scotian Shelf/Gulf of Maine sites (Boston, Saint John, Yarmouth, Halifax (Shearwater), Sable Island, and Sydney) are shown as a stacked bar chart. Anomalies referenced to 1991-2020.

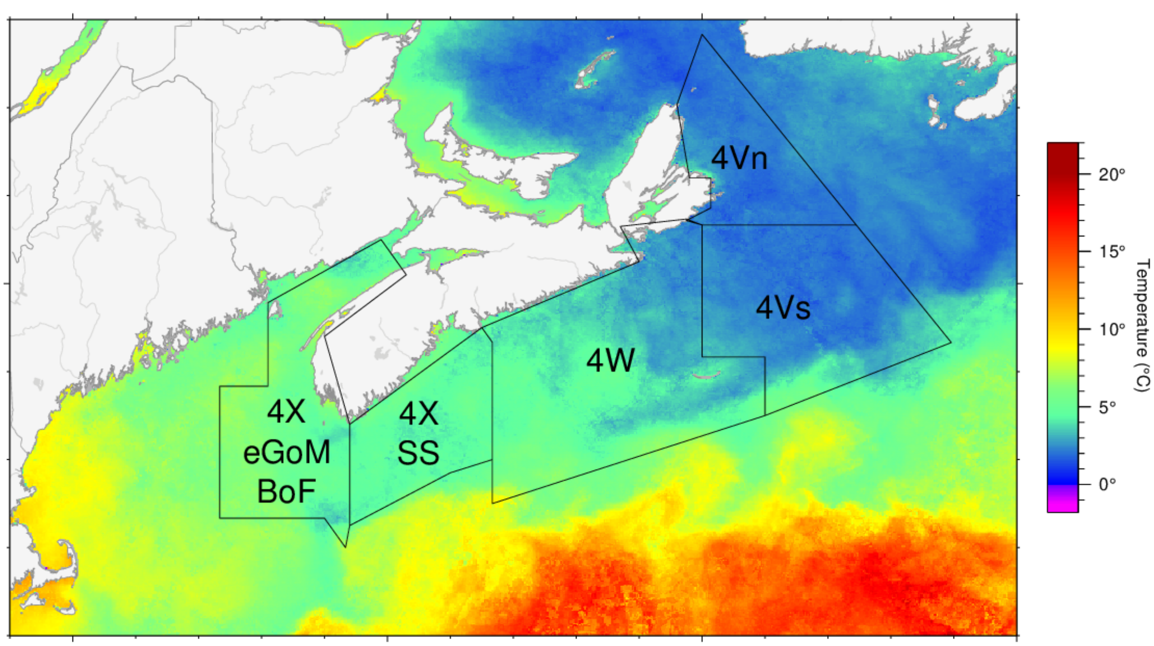

Figure 8. Scotian Shelf/Gulf of Maine areas (4Vn, 4Vs, 4W, 4X SS, and 4X eGoM-BoF) used for extraction of sea surface temperature.

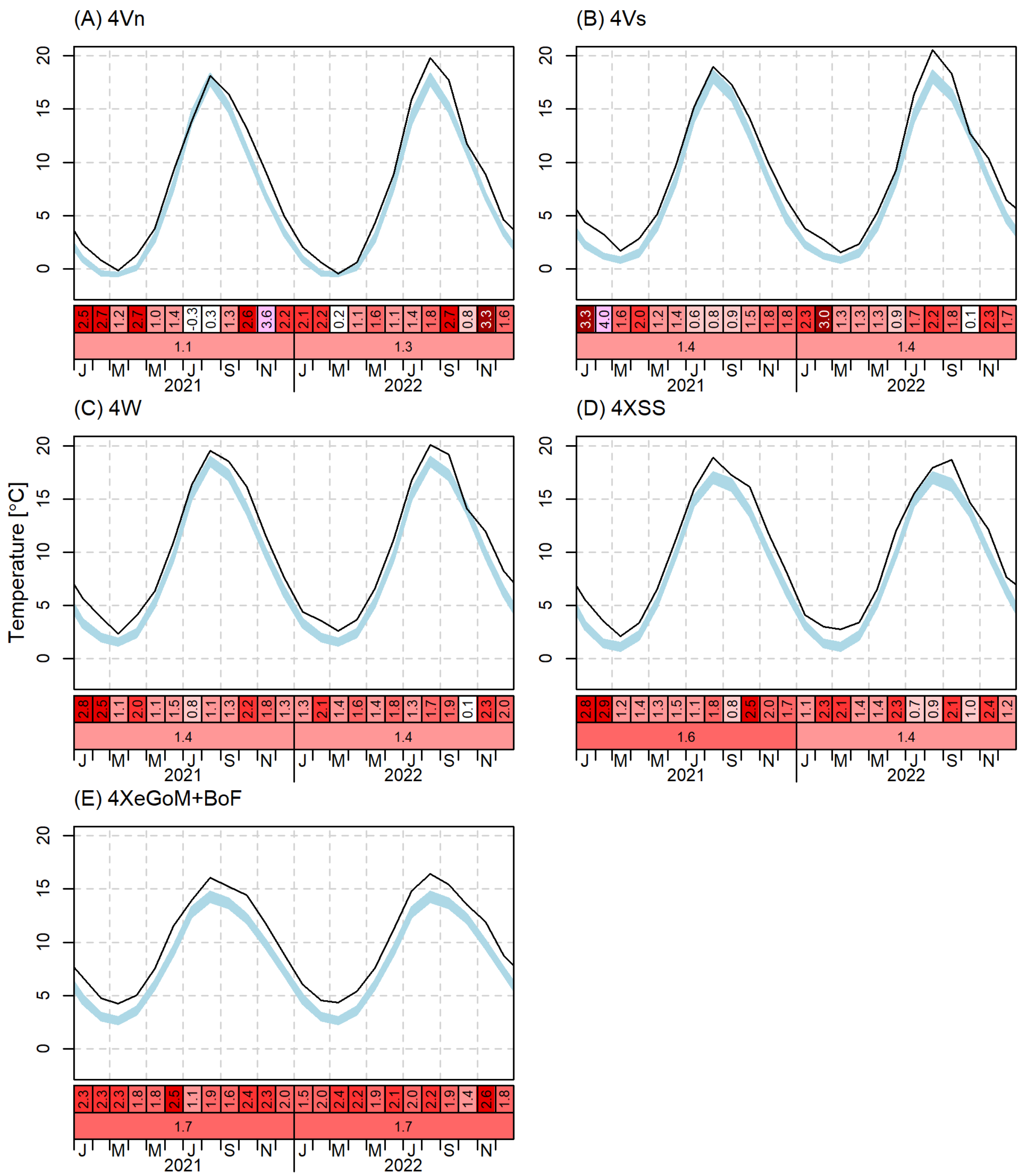

Figure 9. AVHRR SST monthly and annual averages over the five regions of the Scotian Shelf and Gulf of Maine. The blue area represents the 1991-2020 climatological monthly mean ± 0.5 SD. The scorecards are colour-coded according to the normalized anomalies based on the 1991-2020 climatologies for each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

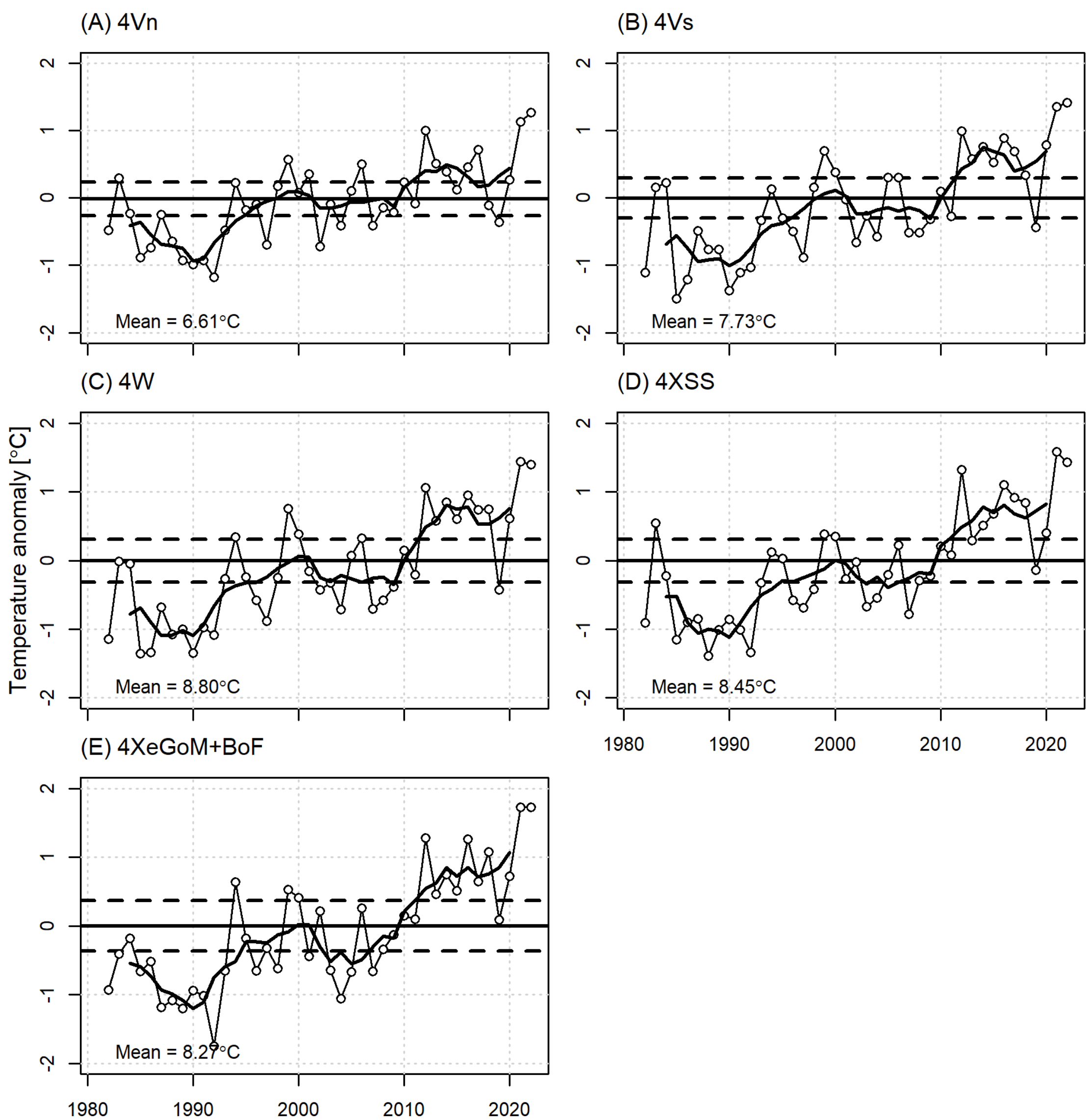

Figure 10. The annual sea-surface-temperature normalized anomalies derived from satellite imagery compared to their long-term monthly means (five Scotian Shelf and Gulf of Maine regions–4Vn, 4Vs, 4W, 4X Scotian Shelf, and 4X eastern Gulf of Maine/Bay of Fundy (Figure 8). Horizontal dashed lines represent plus or minus 0.5 SD for the 1991-2020 period.

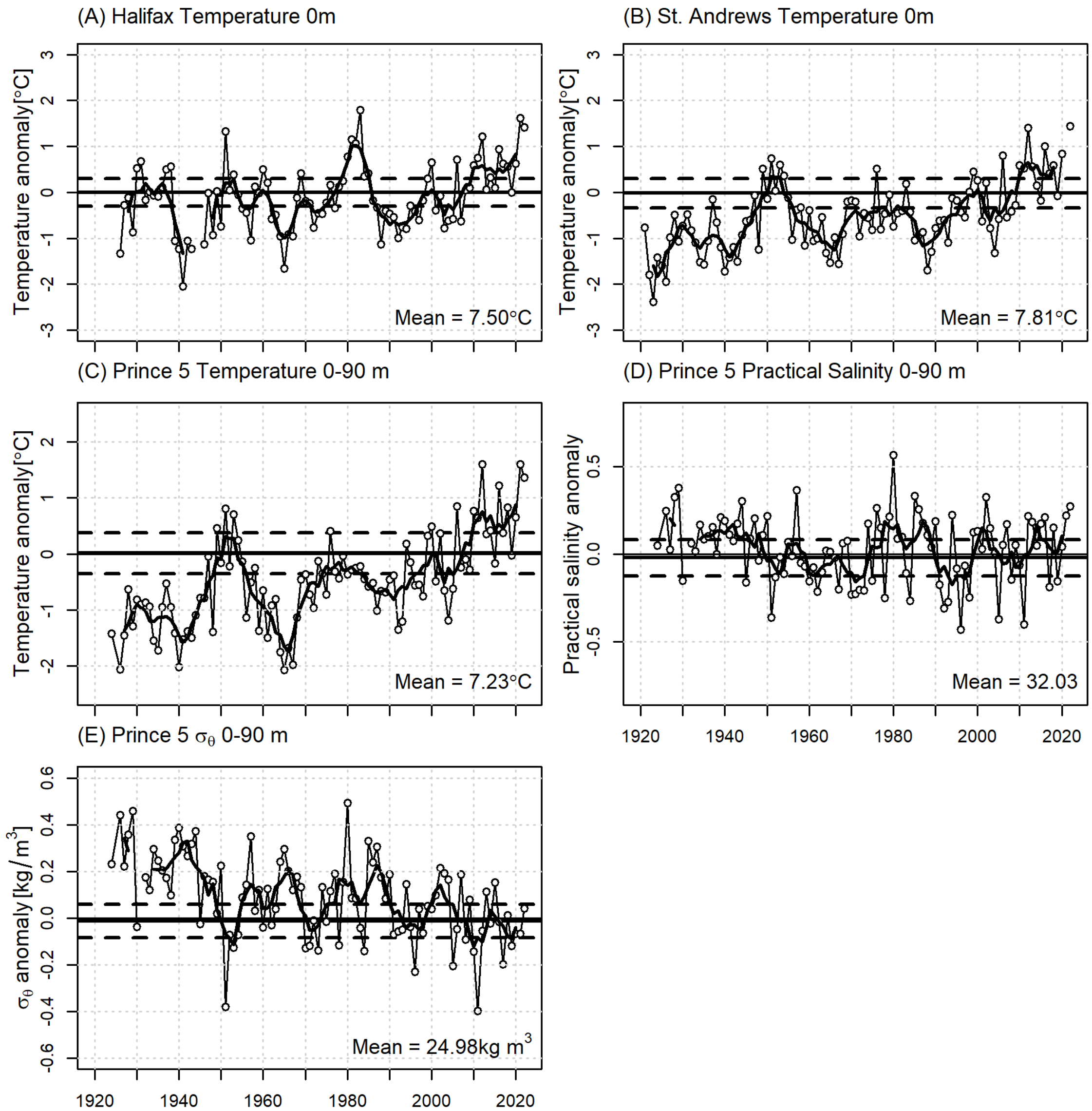

Figure 11. The annual surface-temperature anomalies (thin solid line with circles) and their five-year running means (thick black line) for (A) Halifax Harbour and (B) St. Andrews; and annual depth-averaged (0–90 m) temperature (C), salinity (D), and density (E) anomalies for the Prince 5 monitoring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

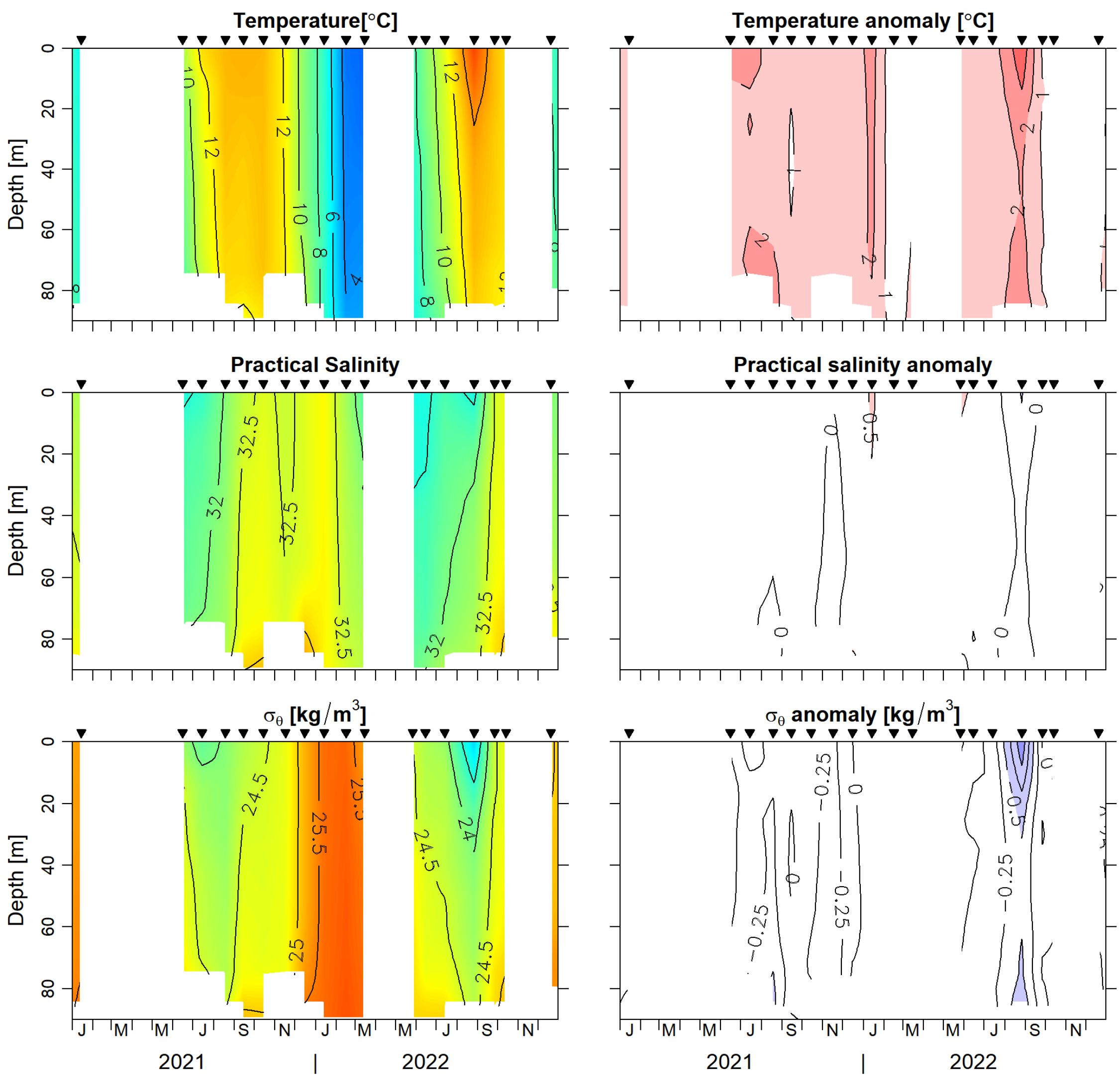

Figure 12. The 2021-2022 annual cycle of temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to 1991–2020 climatology (right panels) for the Prince 5 monitoring station at the mouth of the Bay of Fundy. Triangles indicate periods of sampling.

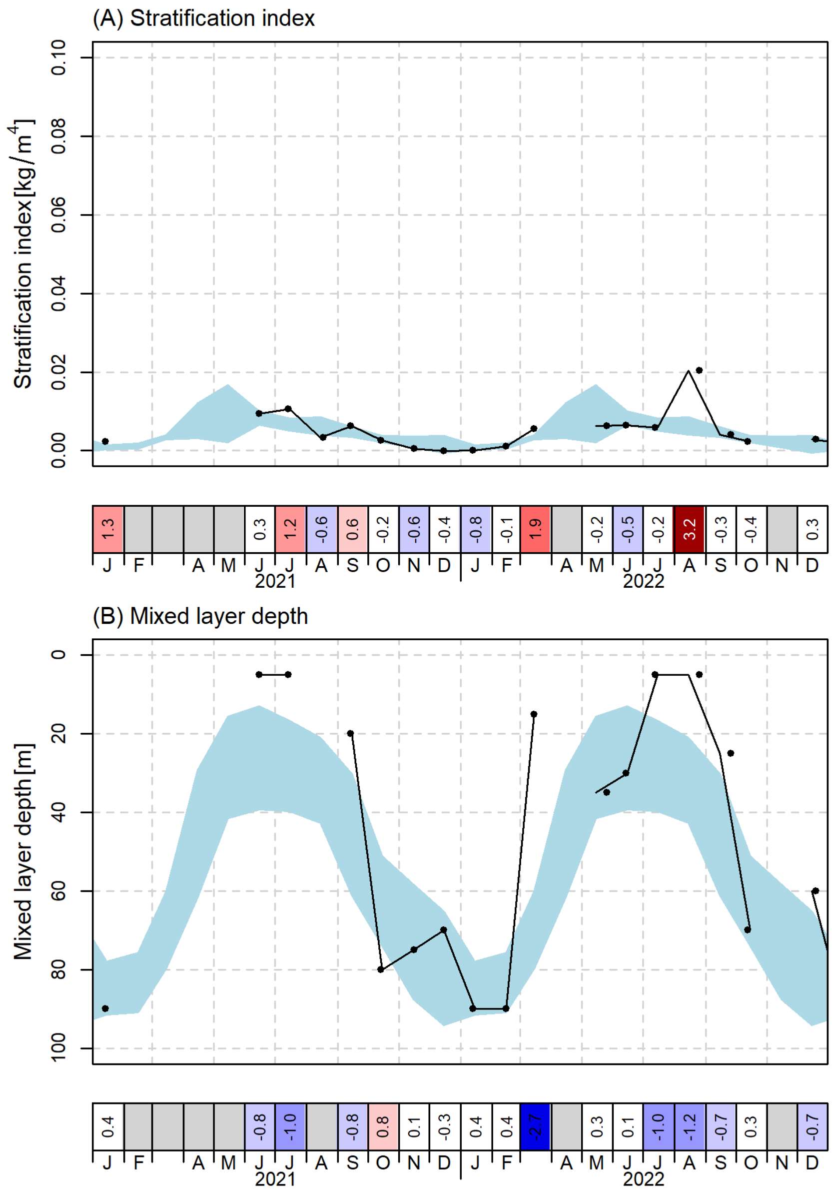

Figure 13. The 2021– 2022 annual cycle of stratification index (top panel) and mixed layer depth (lower panel) for Prince 5. The shaded area is the 1991–2020 climatological mean +/- 0.5 standard deviations. The dots represent actual measurements and solid line is the monthly averaged value. Their anomalies with respect to 1991–2020 monthly means are shown below each figure.

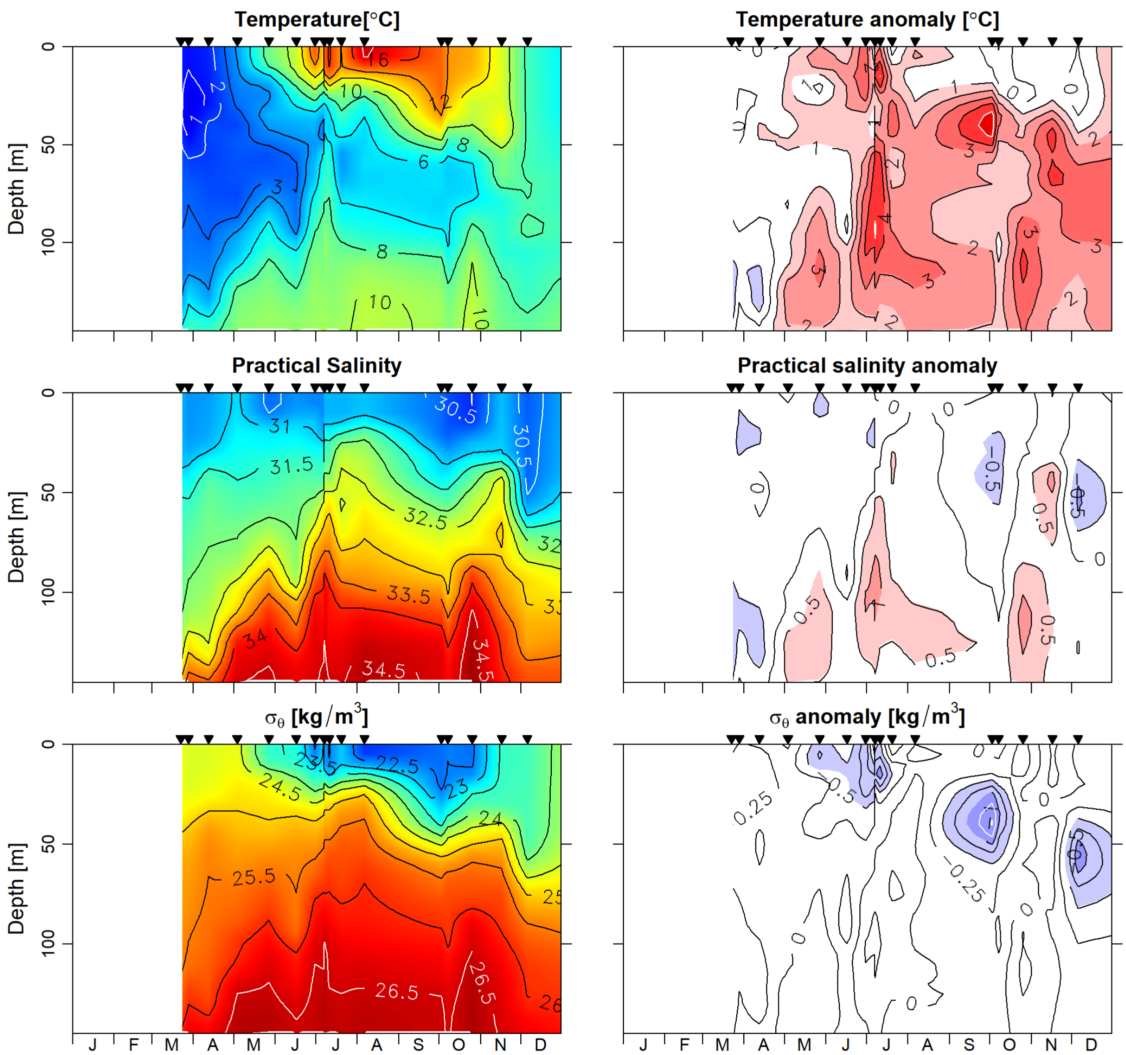

Figure 14. The 2021-2022 annual cycles of temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to 1991–2021 climatology (right panels) for Halifax station 2. Triangles indicate periods of sampling.

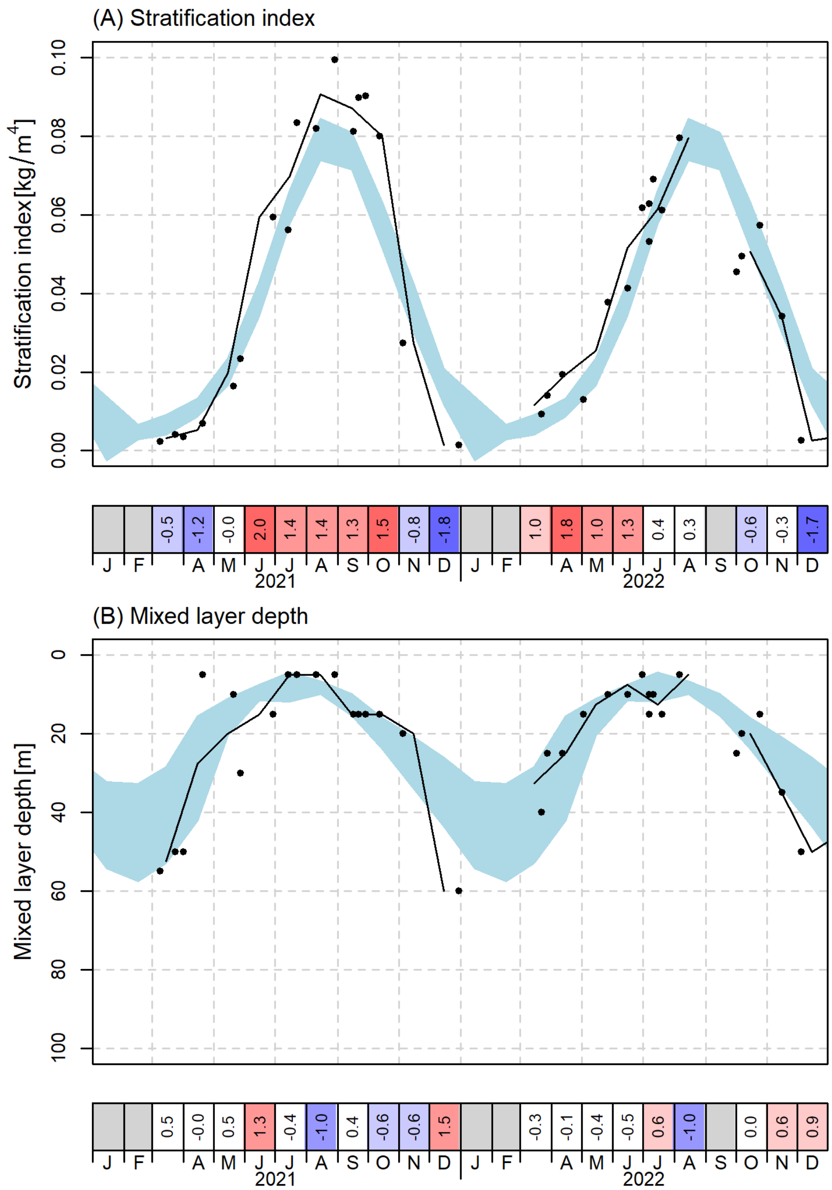

Figure 15. The 2021– 2022 annual cycle of stratification index (top panel) and mixed layer depth (lower panel) for Halifax station 2. The shaded area is the 1991–2021 climatological mean +/- 0.5 standard deviations. The dots represent actual measurements and solid line is the monthly averaged value. Their anomalies with respect to 1991–2021 monthly means are shown below each figure.

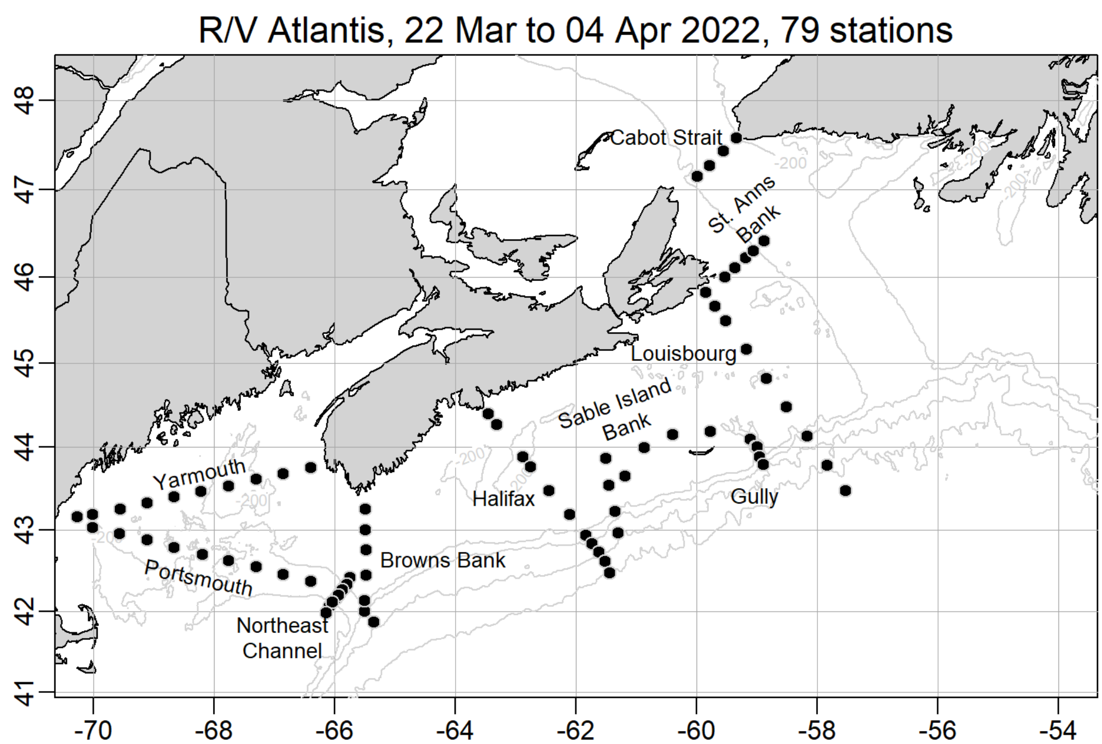

Figure 16. The 2022 sampling of the Scotian Shelf/Gulf of Maine for the spring survey.

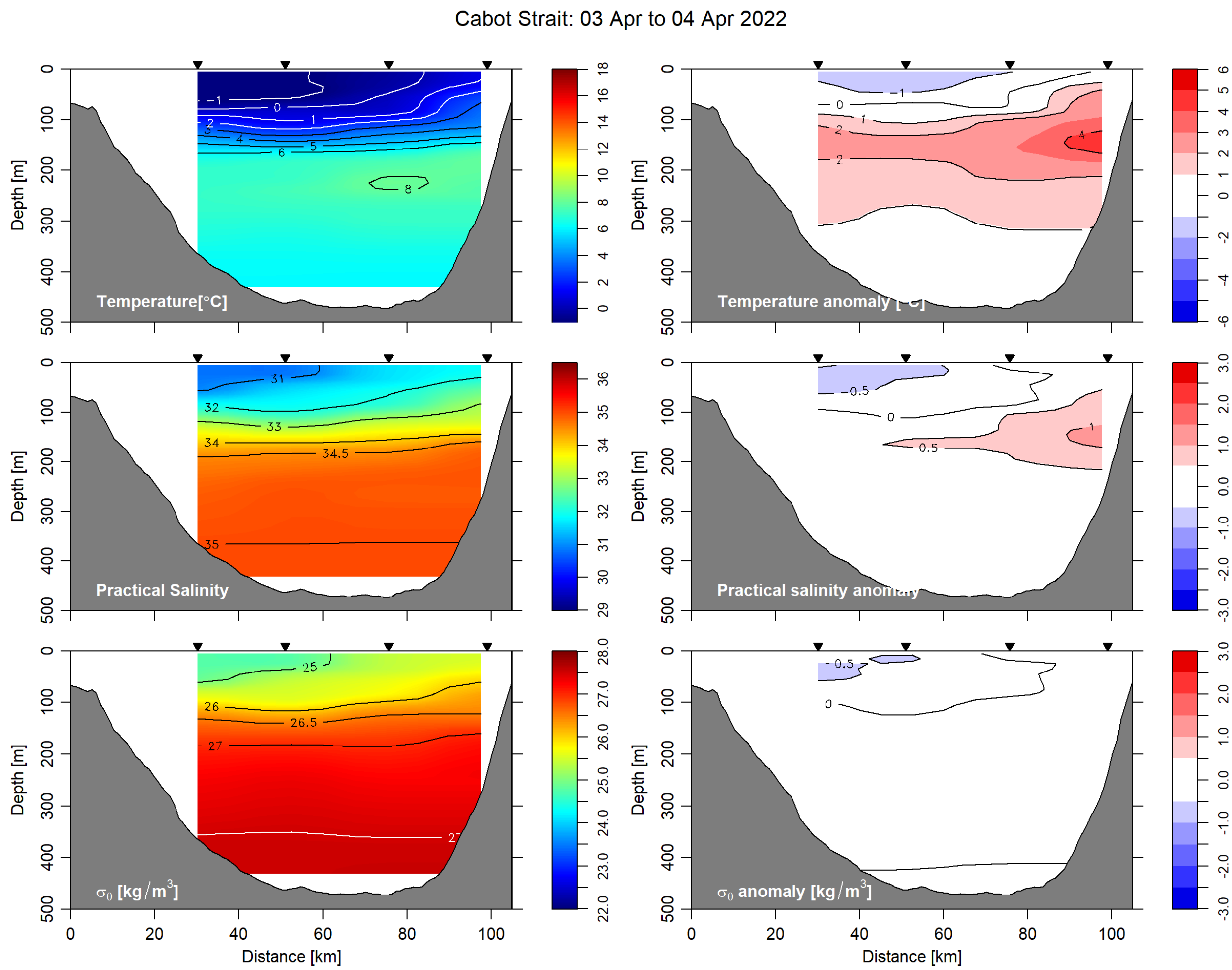

Figure 17. The 2022 sampling of the Cabot Strait Section for spring. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to the 1991–2020 climatology (right panels). Triangles indicate locations of sampling.

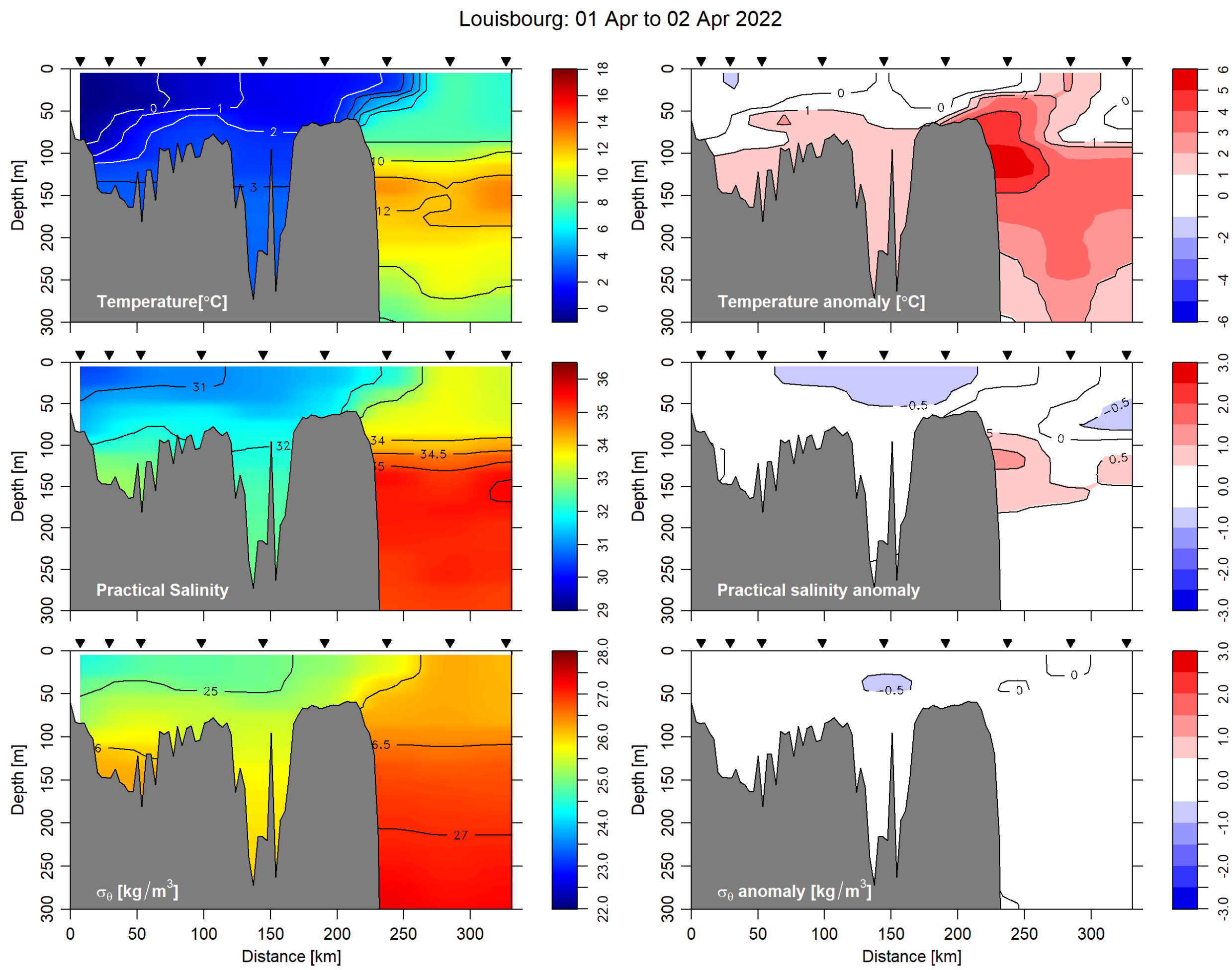

Figure 18. The 2022 sampling of the Louisbourg Section for spring. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to the 1991–2020 climatology (right panels). Triangles indicate locations of sampling.

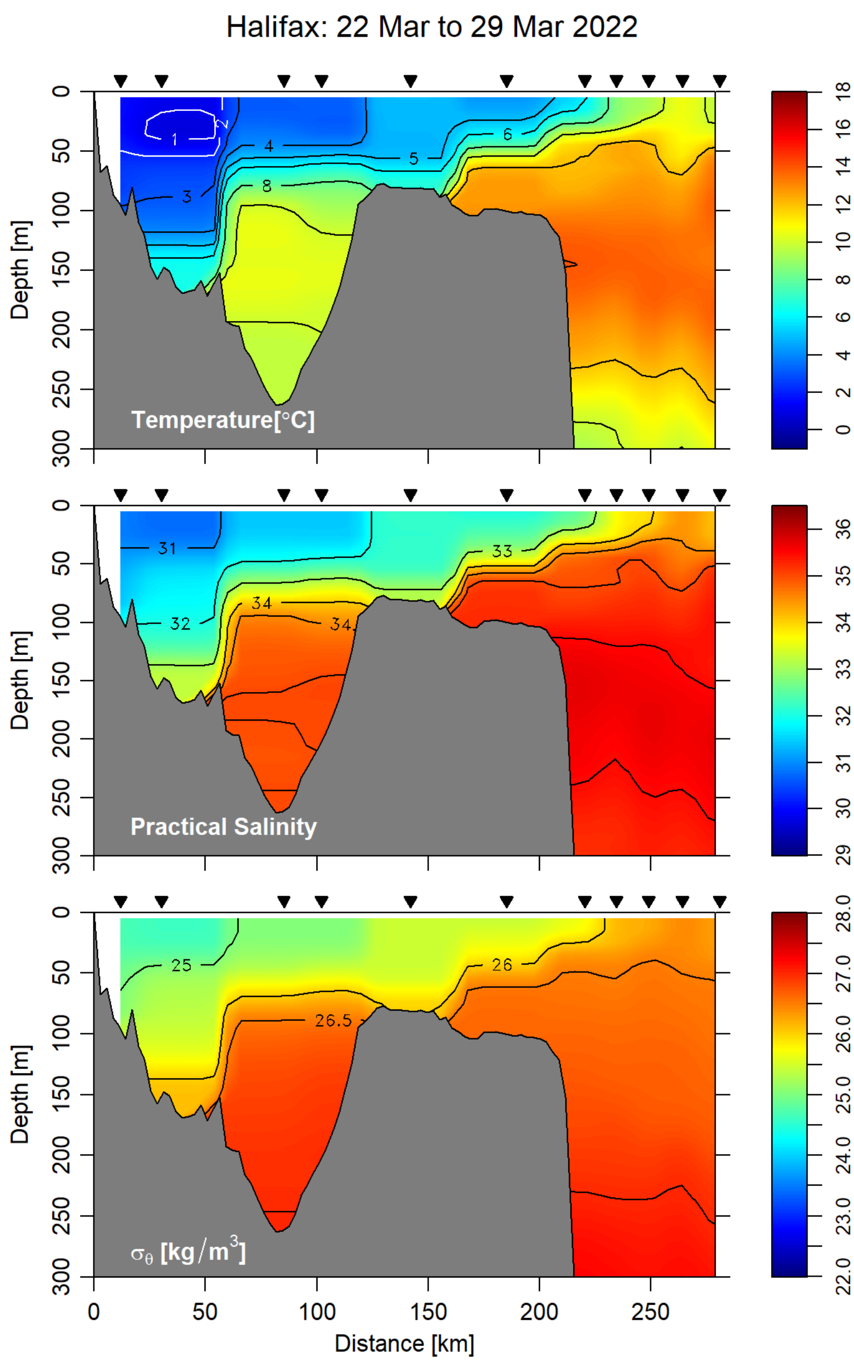

Figure 19. The 2022 sampling of the Halifax Section for spring. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

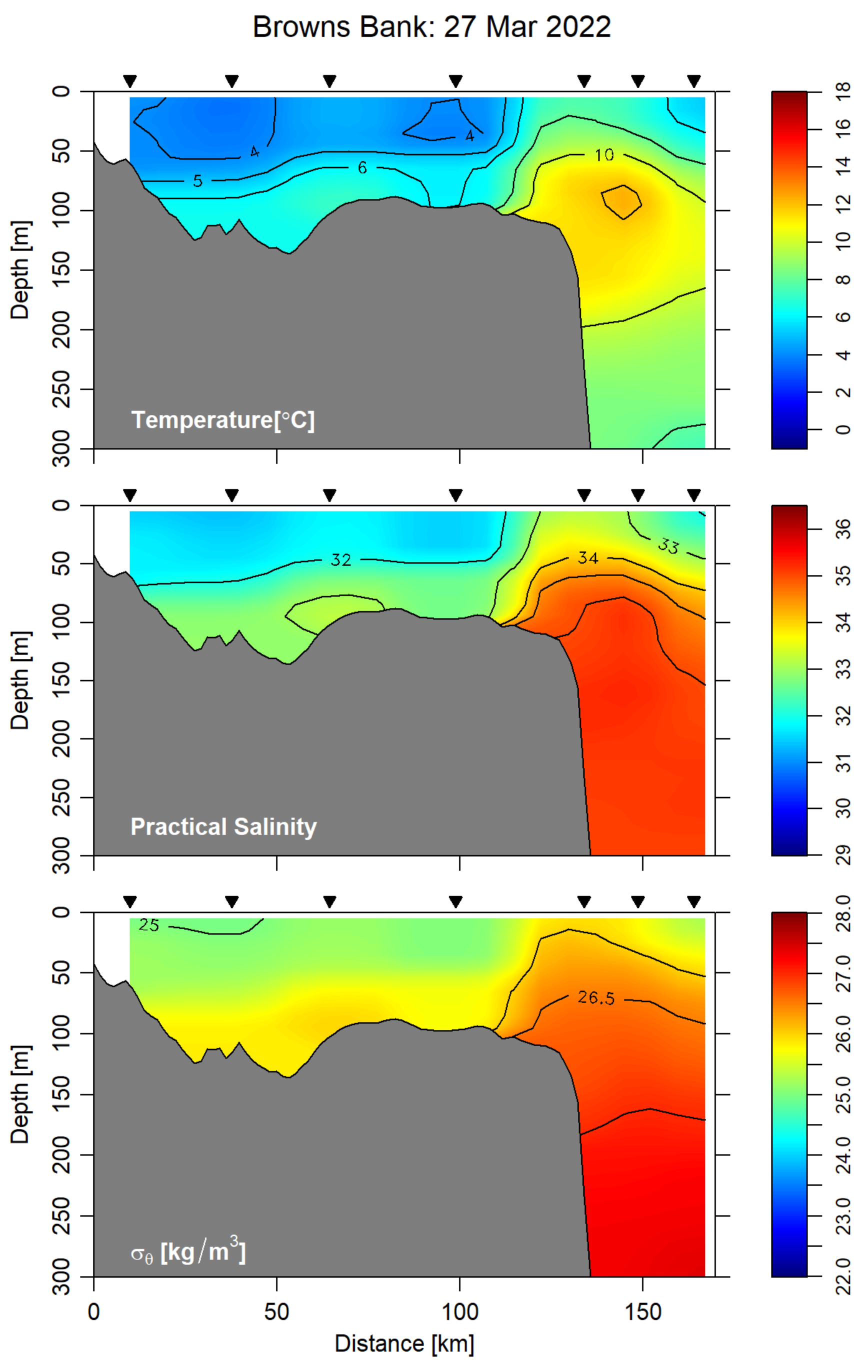

Figure 20. The 2022 sampling of the Browns Bank Section for spring. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

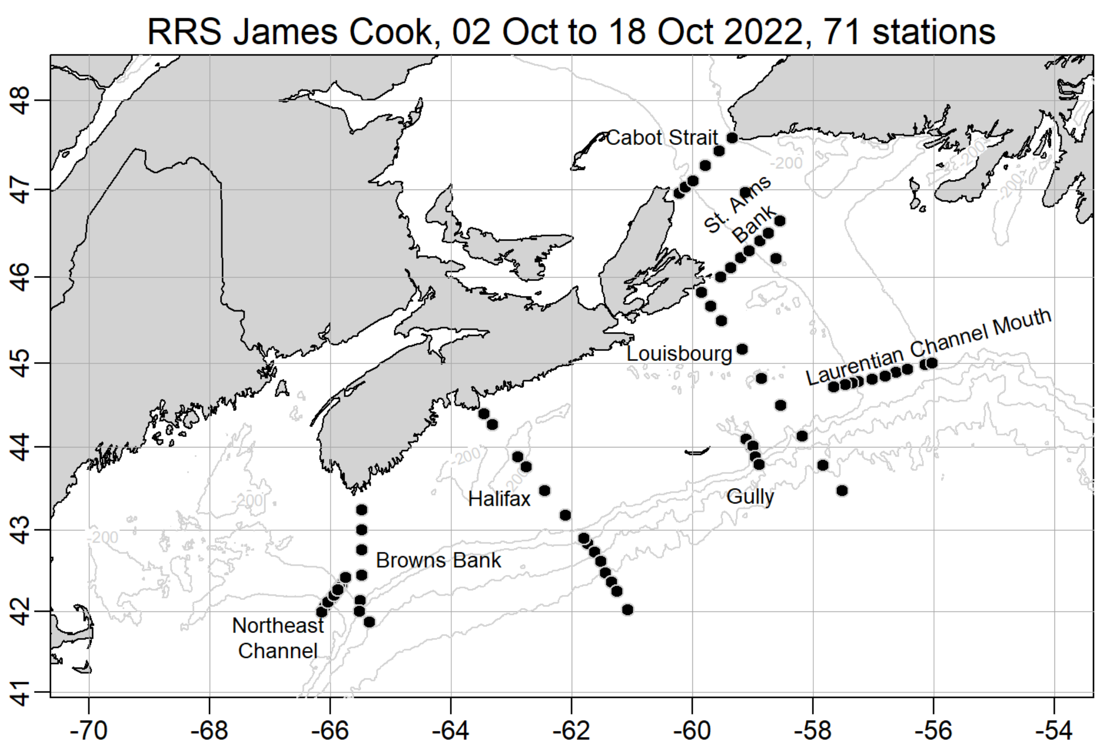

Figure 21. The 2022 sampling of the Scotian Shelf/Gulf of Maine for the fall survey.

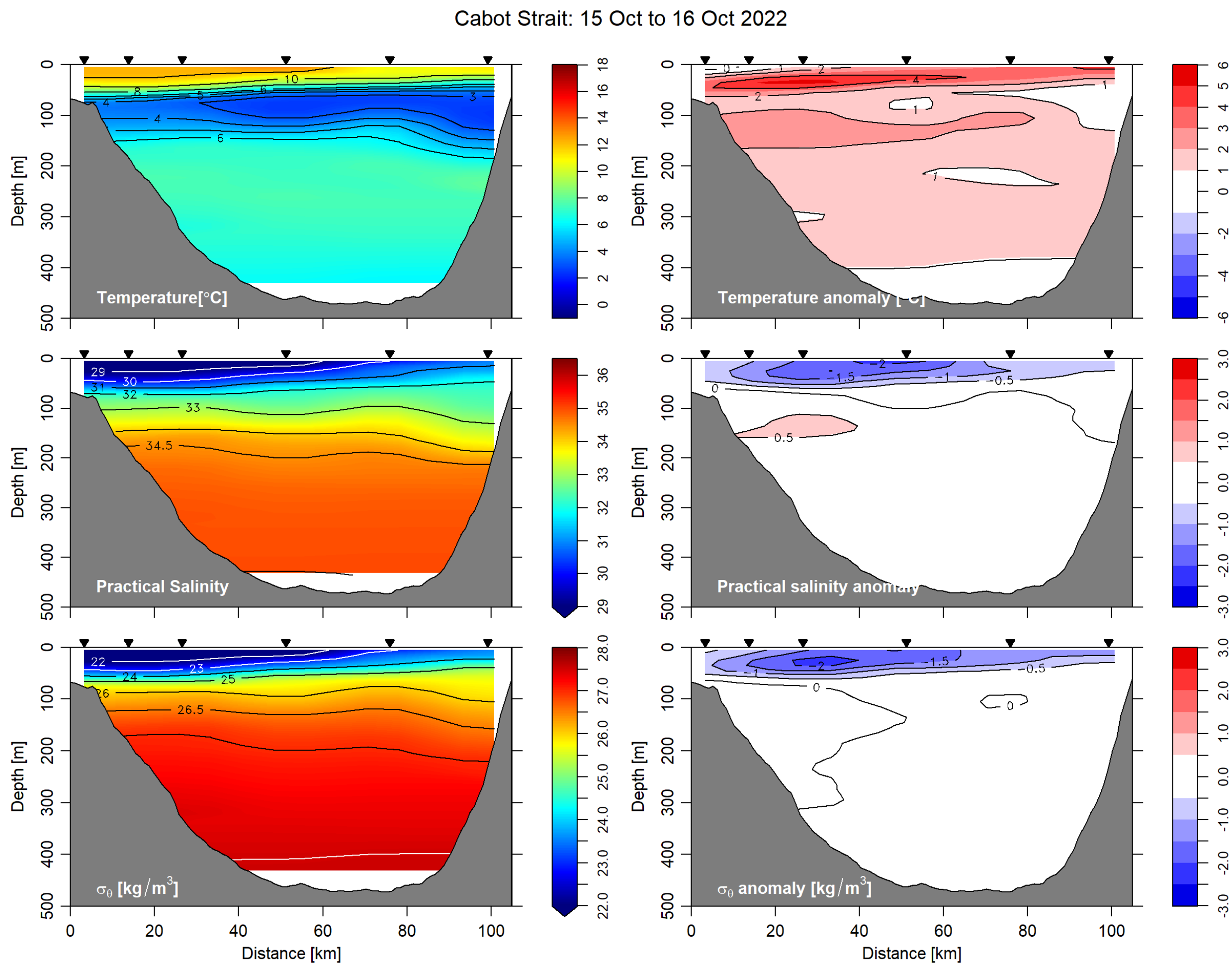

Figure 22. The 2022 sampling of the Cabot Strait Section for fall. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to the 1991–2020 climatology (right panels). Triangles indicate locations of sampling.

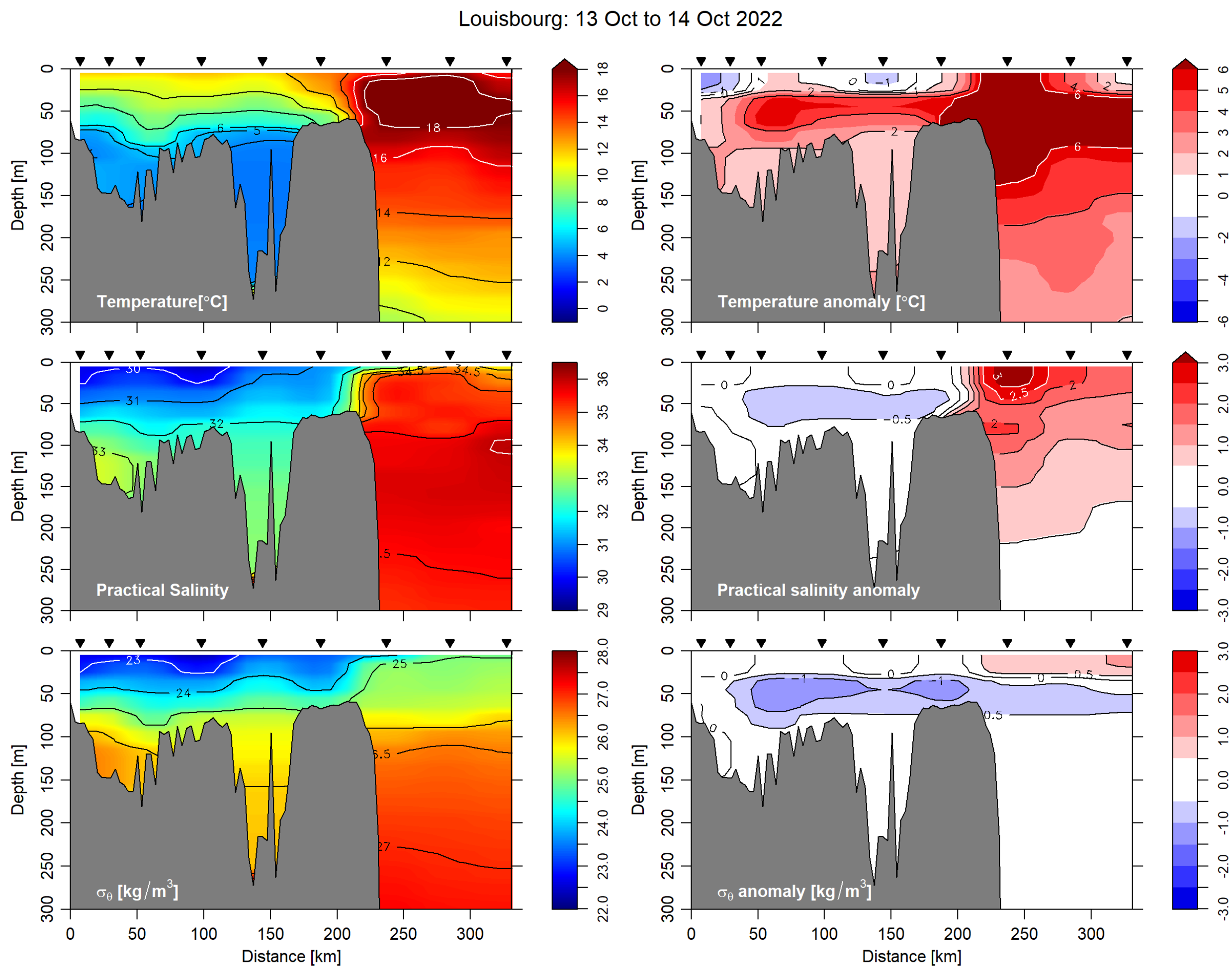

Figure 23. The 2022 sampling of the Louisbourg Section for fall. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to the 1991–2020 climatology (right panels). Triangles indicate locations of sampling.

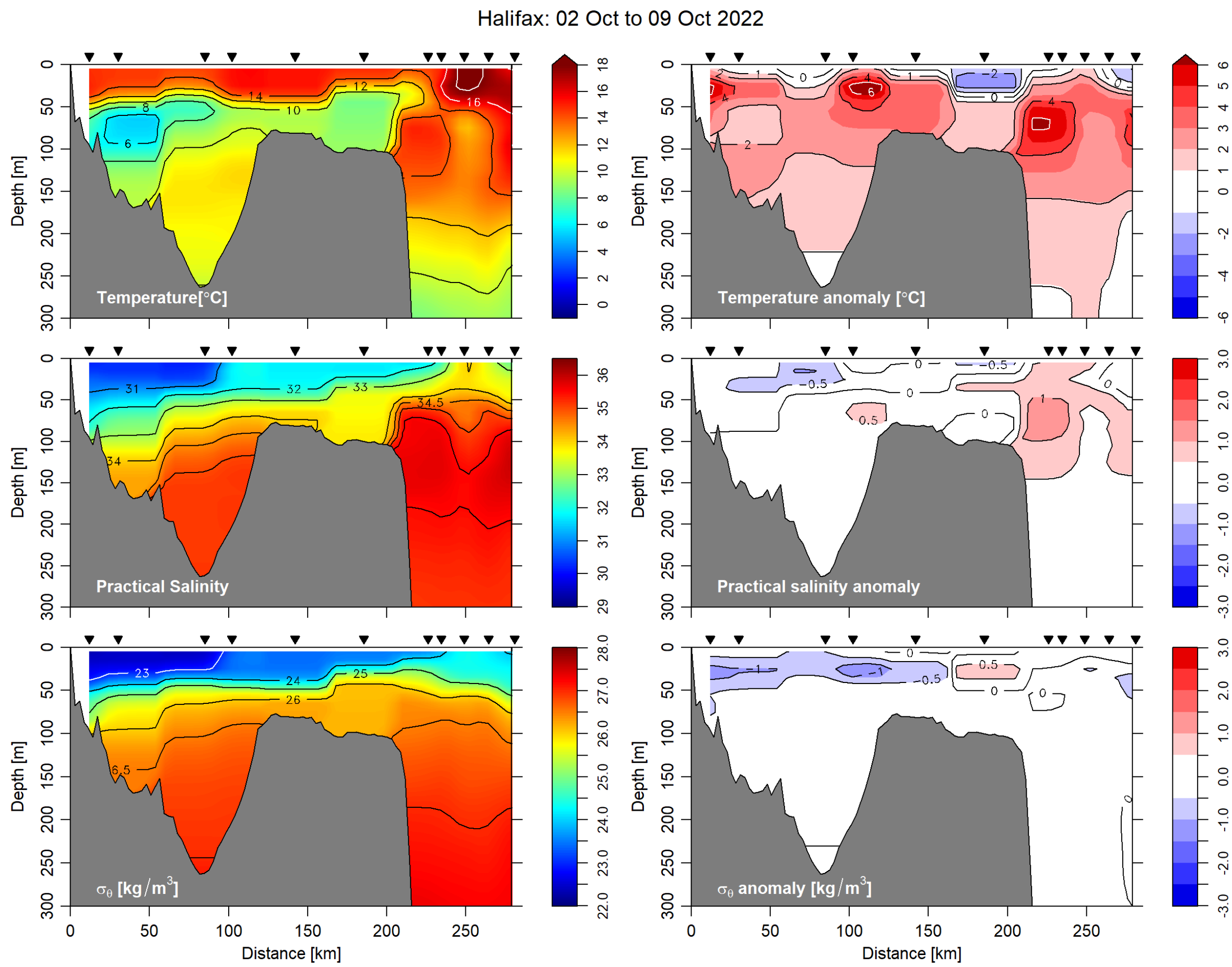

Figure 24. The 2022 sampling of the Halifax Section for fall. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to the 1991–2020 climatology (right panels). Triangles indicate locations of sampling.

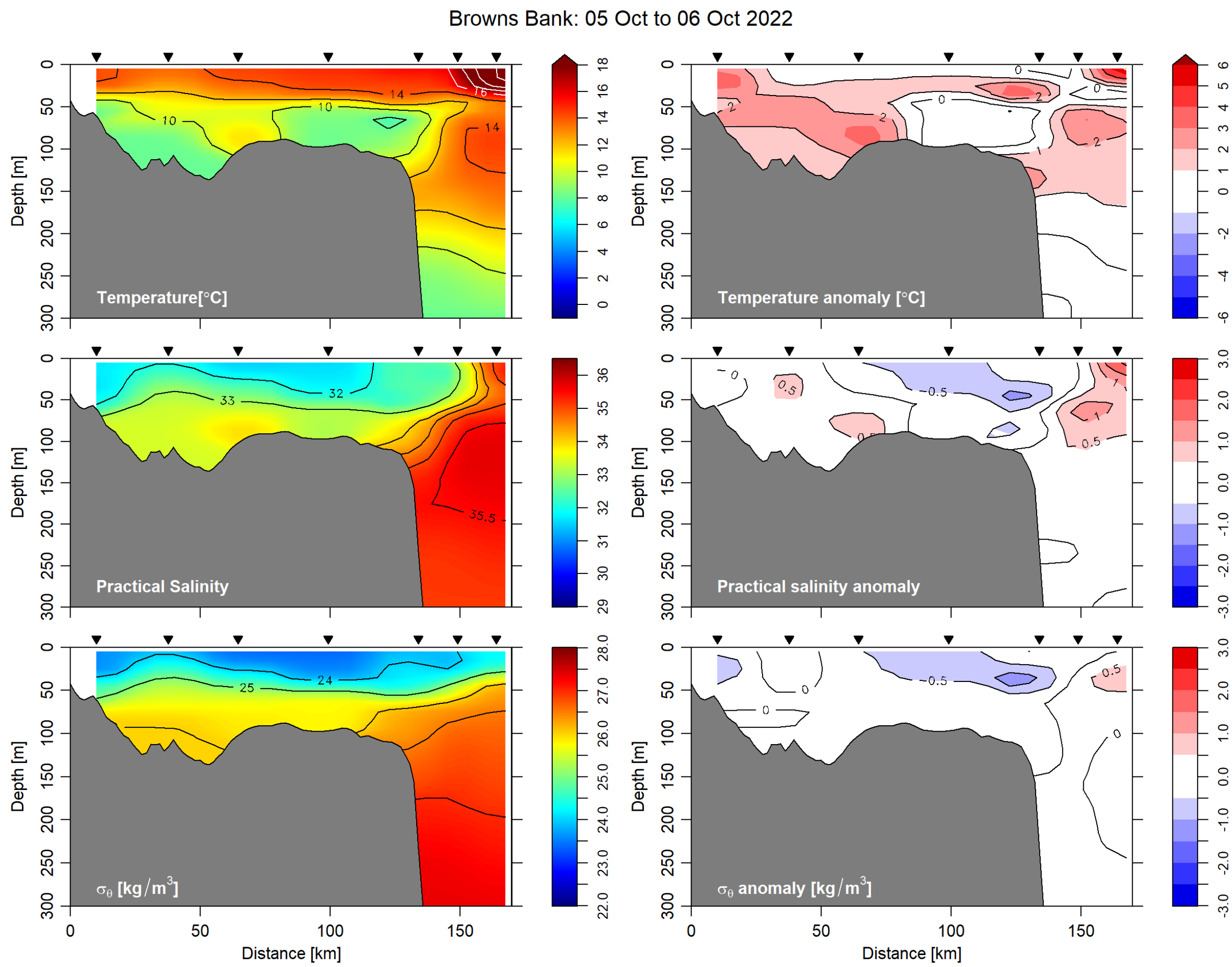

Figure 25. The 2022 sampling of the Browns Bank Section for fall. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to the 1991–2020 climatology (right panels). Triangles indicate locations of sampling.

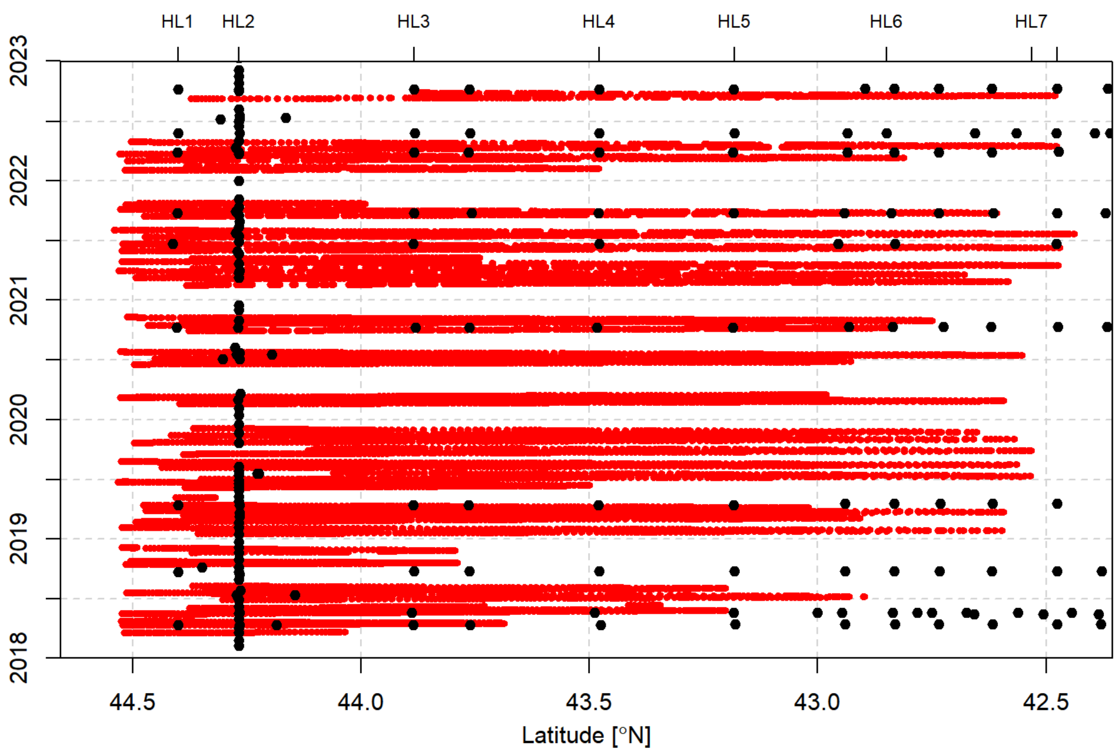

Figure 26. Hodograph of sampling on the Halifax Line for 2018-2022. Black dots represent the sampling by a vessel. Red dots represent sampling by the gliders.

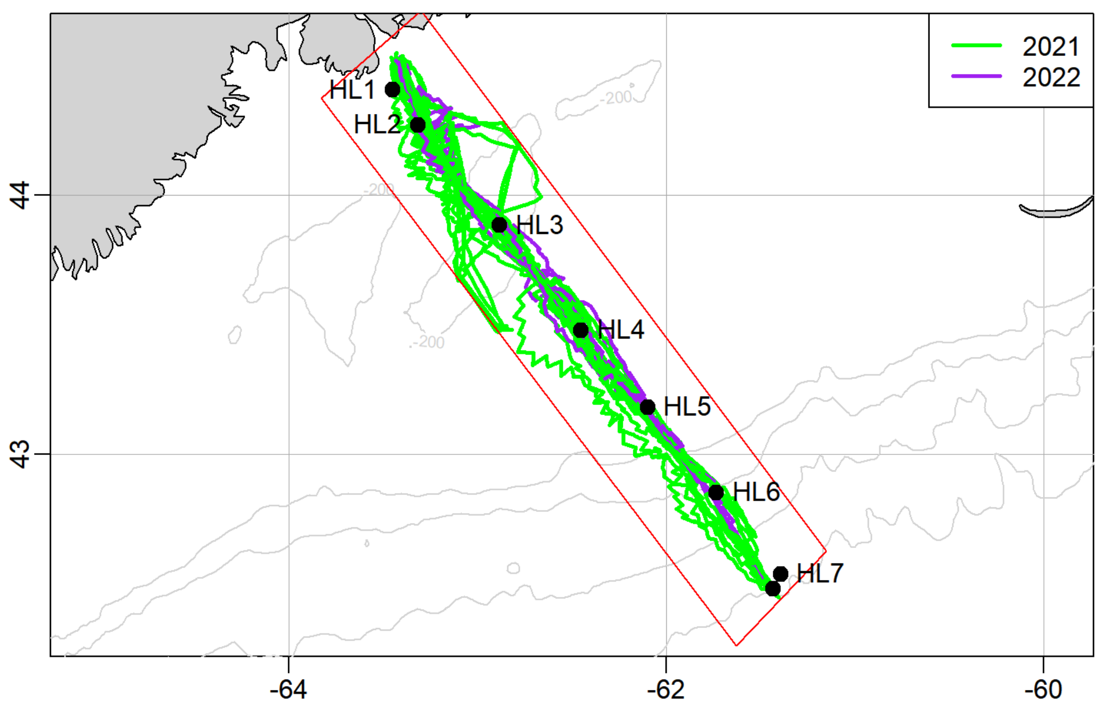

Figure 27. Glider trajectories on the Halifax Line (HL) for 2021 and 2022. Locations of the HL stations are shown by the black dots. Red box shows the limitations applied to glider data to be considered on HL.

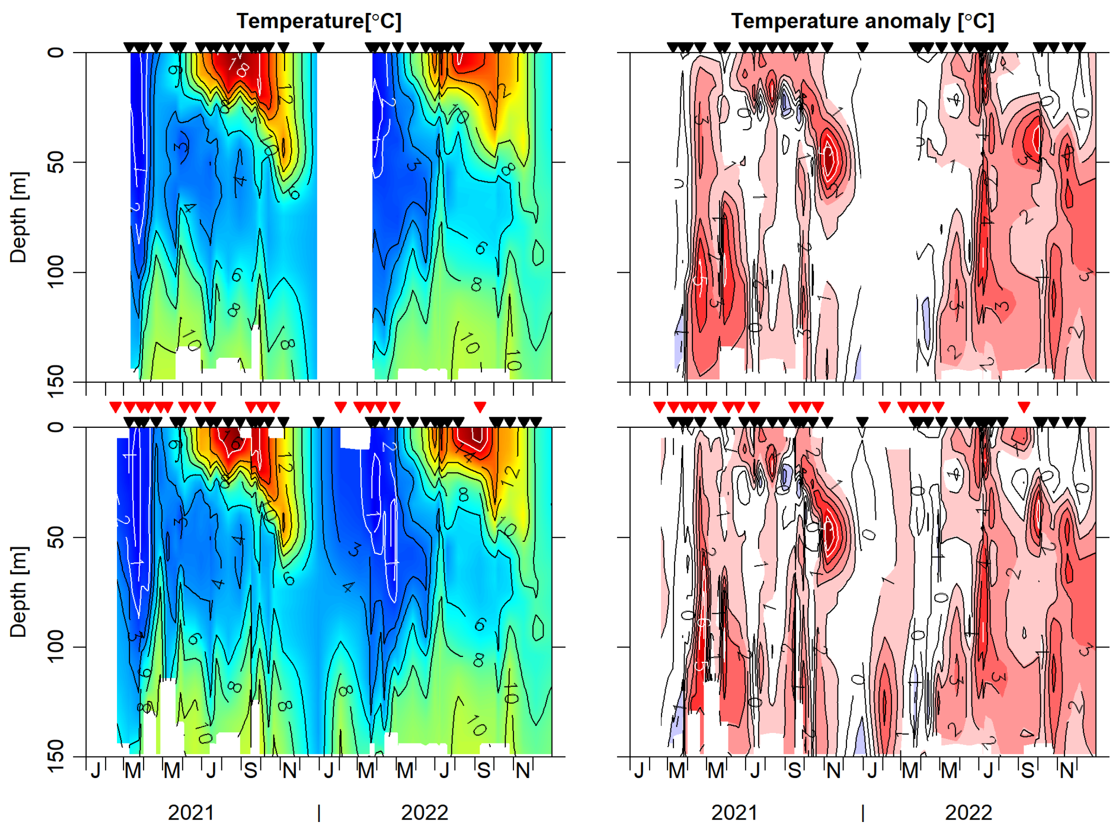

Figure 28. Top panels for temperature (left) and temperature anomaly (right) with standard vessel sampling at Station 2. Bottom panels include the additional glider data that has been averaged hourly. Times of vessel sampling (black triangles) and glider sampling (red triangles) are shown for each panel.

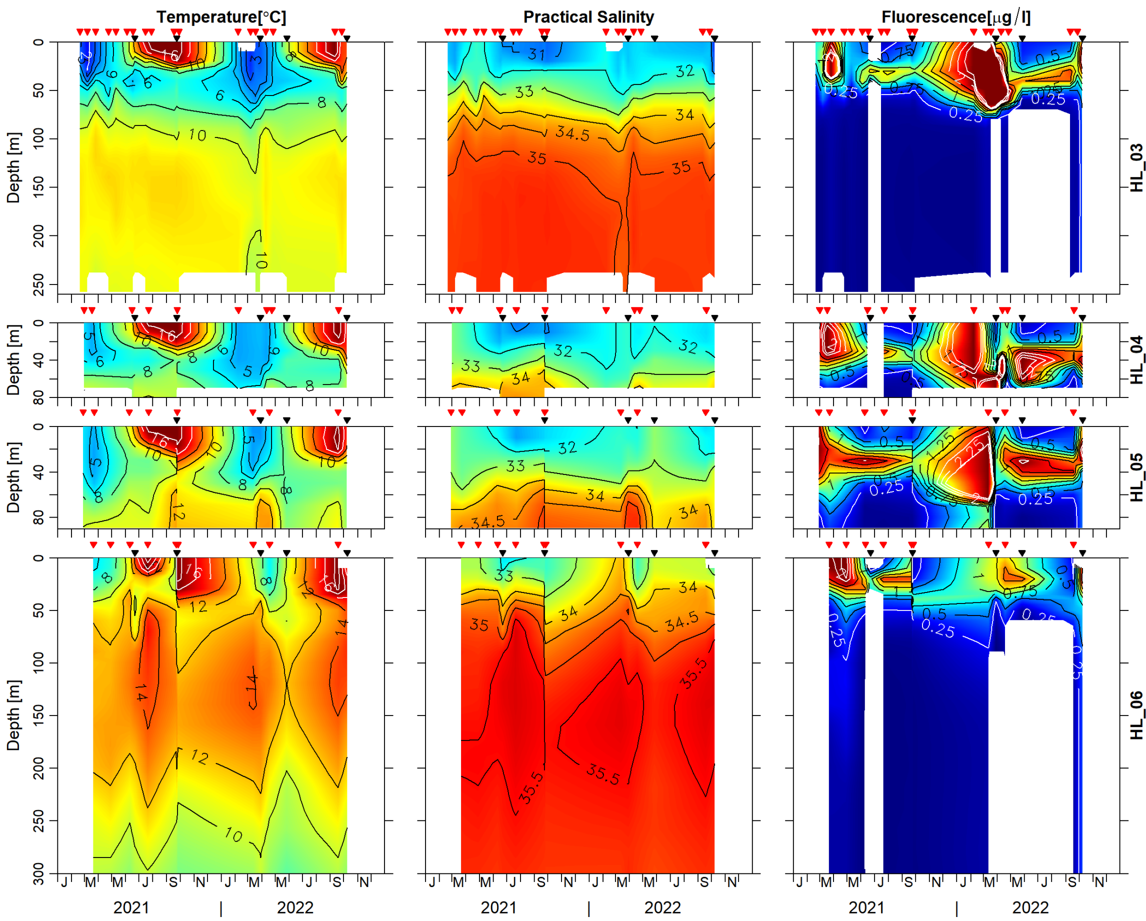

Figure 29. Temperature (left), salinity (middle), and chlorophyll fluorescence (right) for the standard hydrographic stations on the Halifax Line: HL3 (top panel), HL4 (second panel from the top), HL5 (third panel from the top), and HL6 (bottom panel). Only the top 300 m of HL data is shown. Times of vessel sampling (black triangles) and glider sampling (red triangles) are shown for each panel.

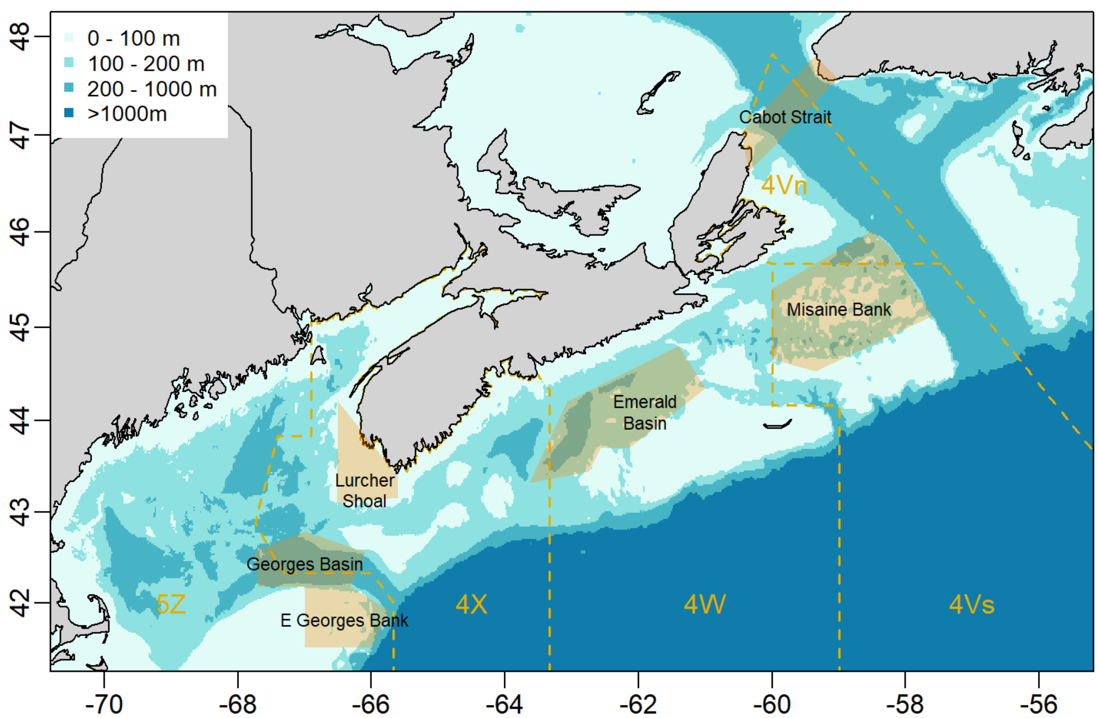

Figure 30. Areas on the Scotian Shelf and eastern Gulf of Maine depicting the different water masses: Cabot Strait; Misaine Bank; Emerald Basin; Lurcher Shoals; Georges Basin; and Eastern Georges Bank.

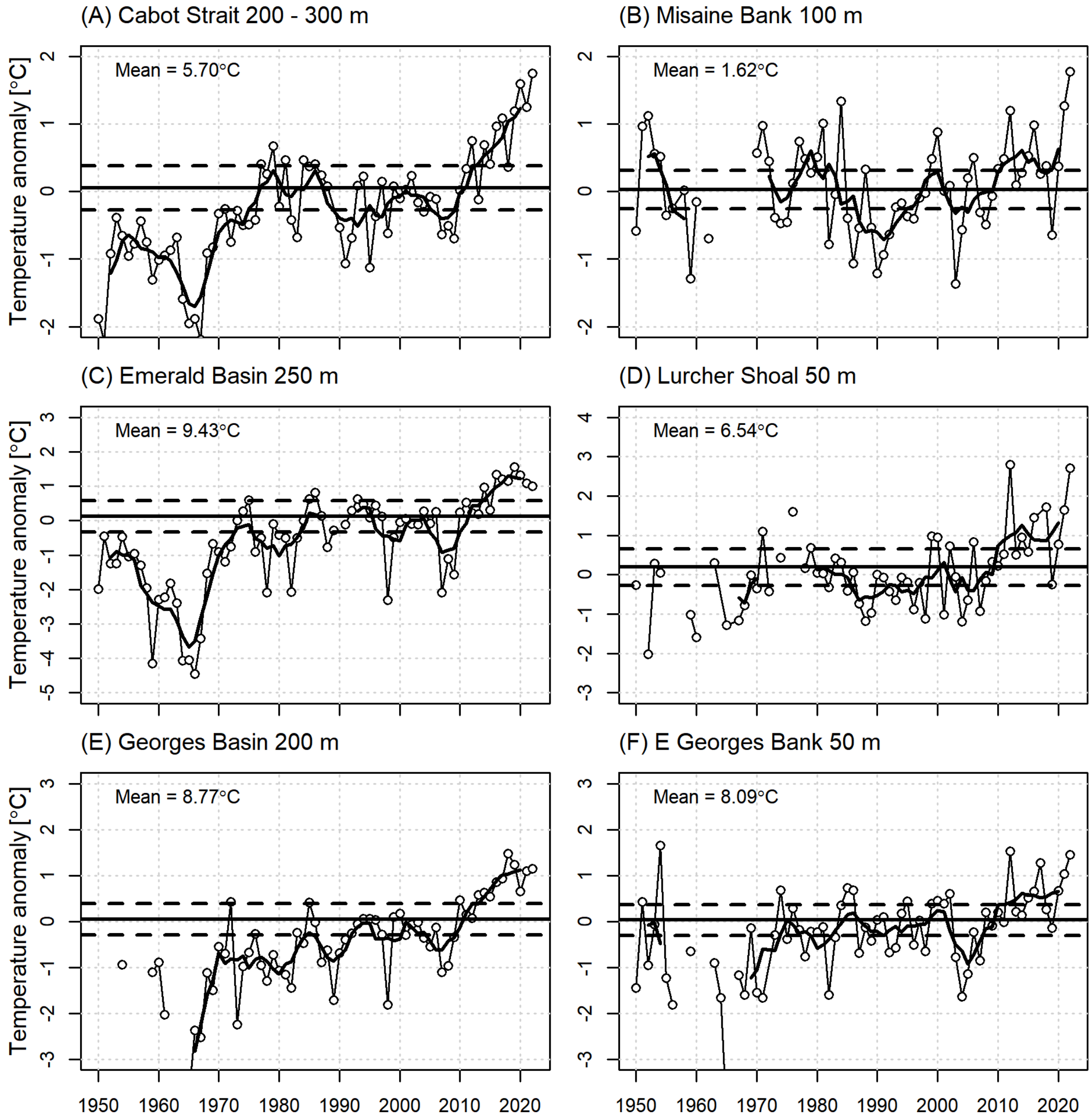

Figure 31. The annual mean temperature-anomaly time series (line with circles) and the five-year-running-mean filtered anomalies (heavy solid line) on the Scotian Shelf and in the Gulf of Maine at: (A) Cabot Strait at 200–300 m, (B) Misaine Bank at 100 m, (C) Emerald Basin at 250 m, (D) Lurcher Shoals 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.

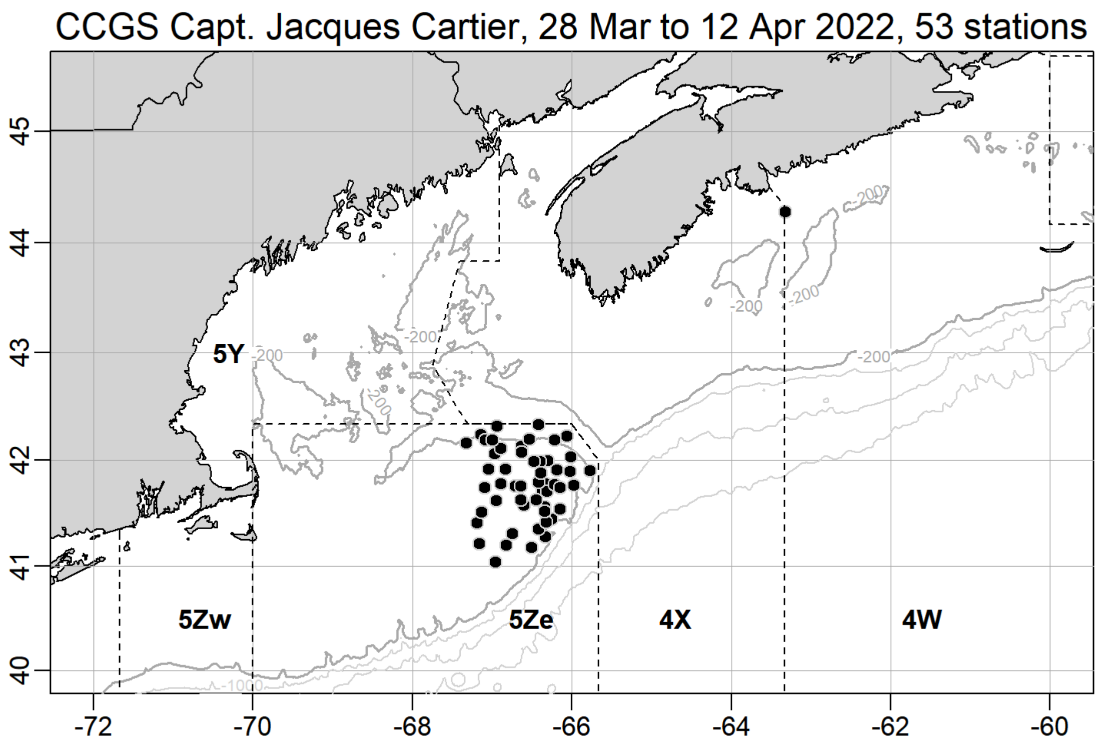

Figure 32. Locations of CTD sampling during the 2022 winter survey. The 200 m isobath is shown as a darker line. NAFO Divisions 4W, 4X, 5Ze, 5Y, and 5Zw are shown.

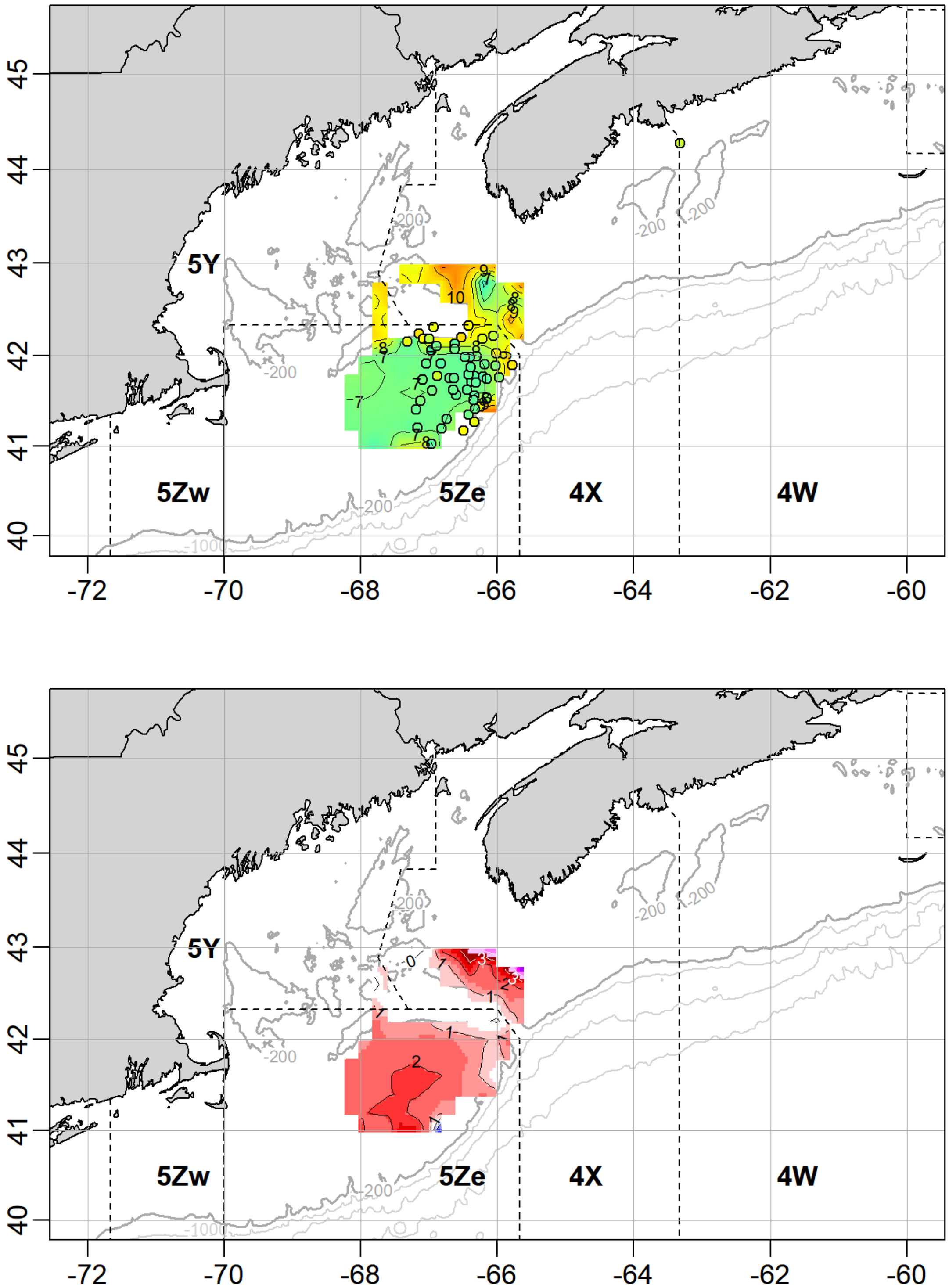

Figure 33. Winter bottom-temperature (upper panel) and anomaly (lower panel; relative to 1991–2020) maps for 2022. NAFO Divisions 4W, 4X, 5Ze, 5Y, and 5Zw are shown.

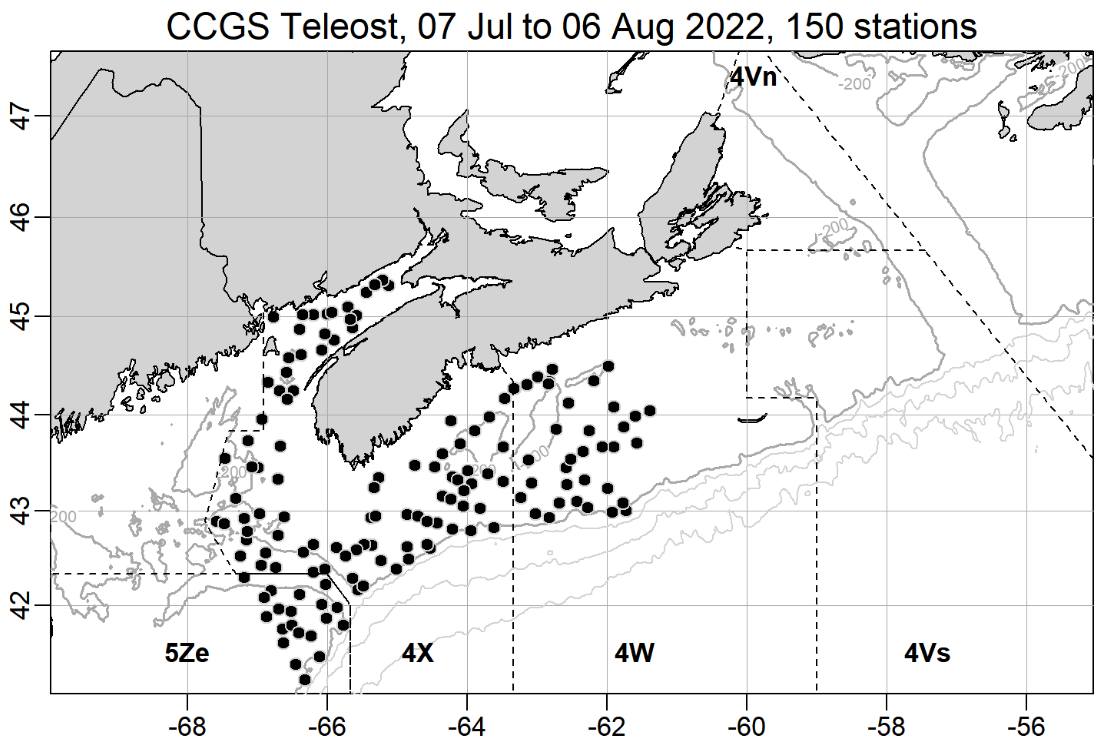

Figure 34. Locations of CTD sampling during the 2022 summer survey. The 200 m isobath is shown as a darker line. NAFO Divisions 4W, 4X, 5Ze, 5Y, and 5Zw are shown.

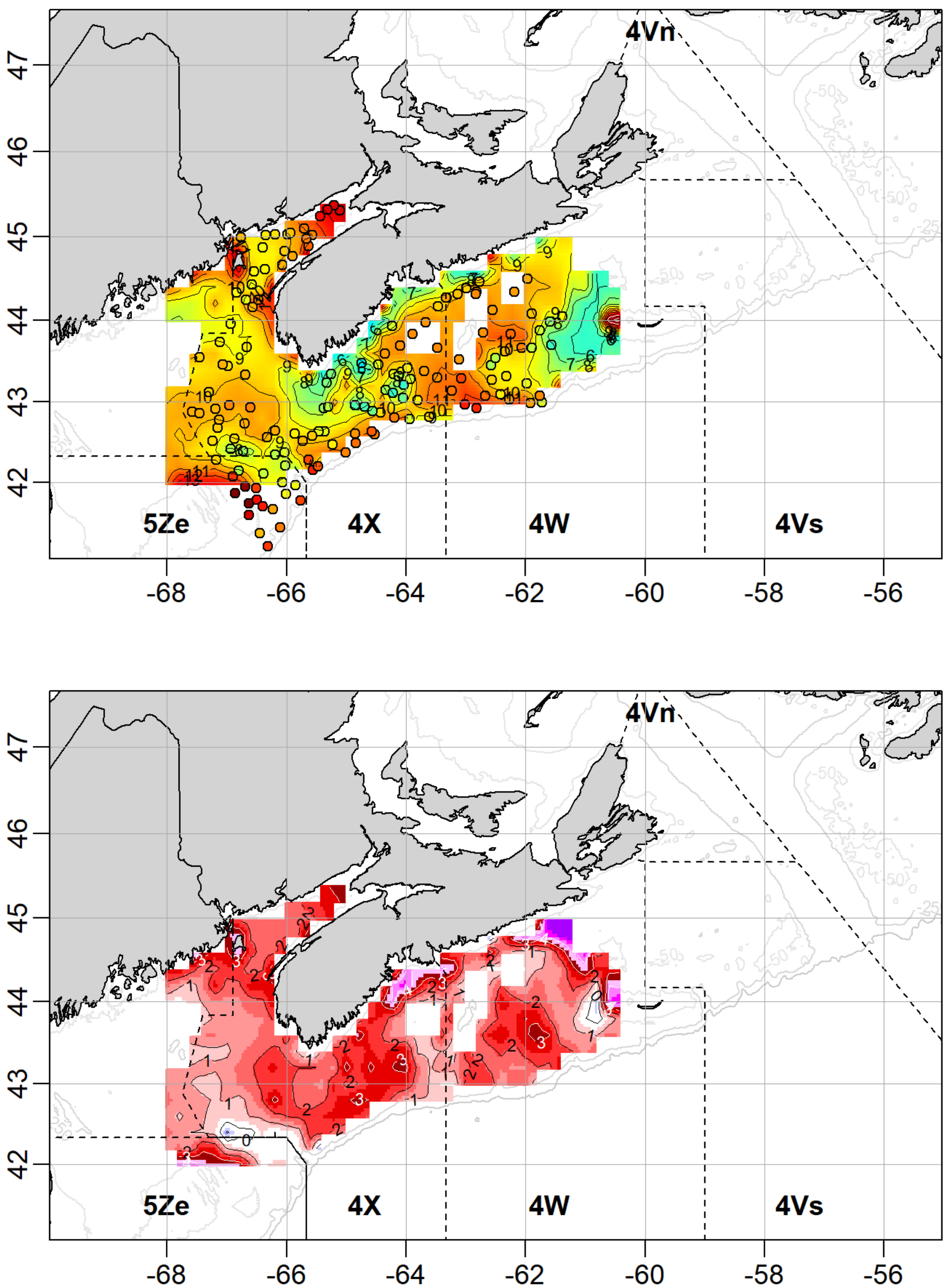

Figure 35. Summer bottom-temperature (upper panel) and anomaly (lower panel; relative to 1991–2020) maps for 2022. NAFO Divisions 4Vn, 4Vs, 4W, 4X, 5Ze, 5Y, and 5Zw are shown.

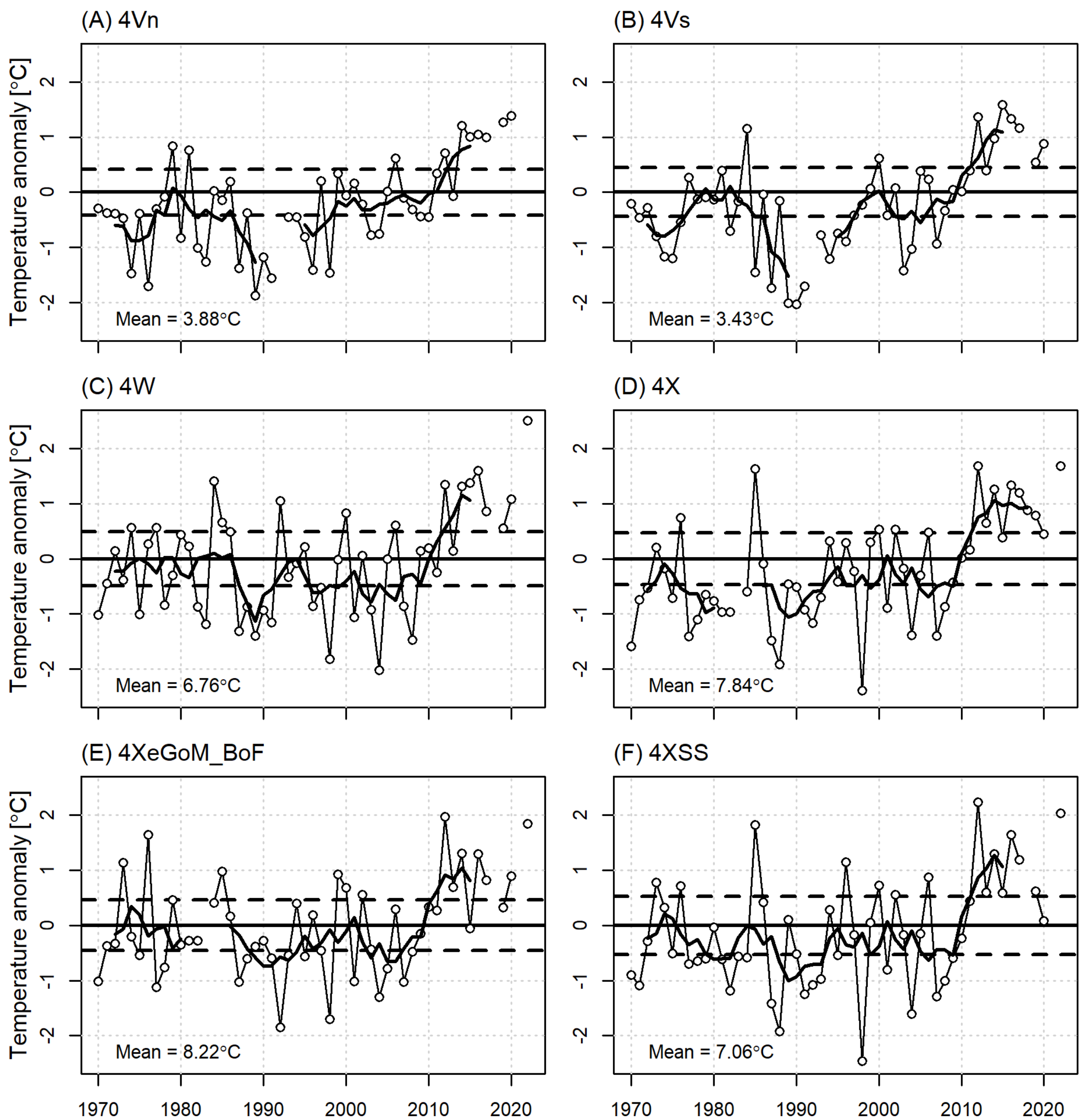

Figure 36. Time series of July bottom-temperature anomalies (thin lines with circles) and five-year-running-mean filtered series (heavy line) for NAFO Divisions: 4Vn, 4Vs, 4W, 4X, and 4X separated into two regions; the eastern Gulf of Maine/Bay of Fundy(eGoMBoF) and the Scotian Shelf (SS). In 2022, only 4W and 4X were sampled sufficiently to calculate bottom temperatures. The solid horizontal line is the 1991-2020 mean and dashed lines represent ±0.5 SD.

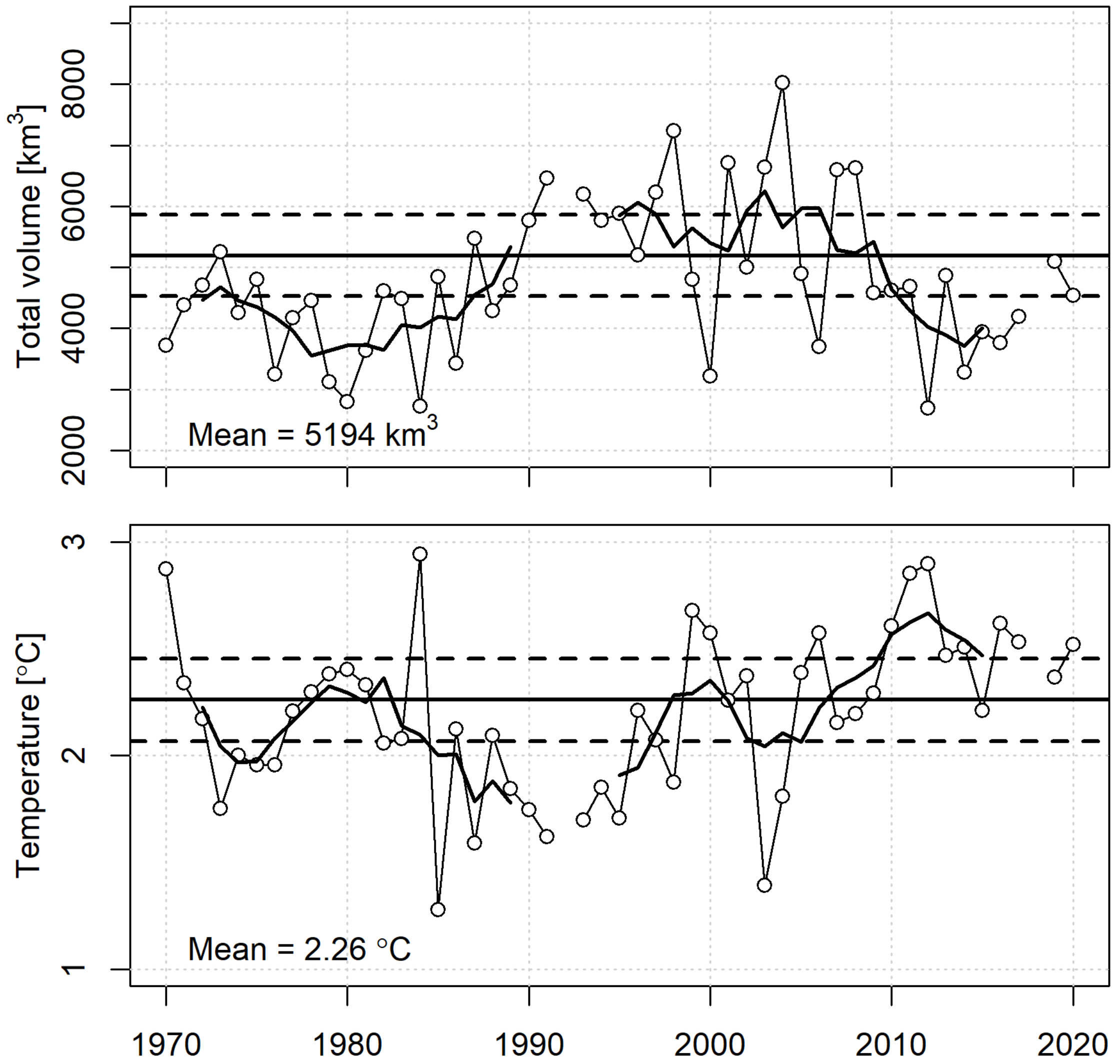

Figure 37. Time series of the Cold Intermediate Layer (CIL; defined as waters with temperature < 4°C) volume on the Scotian Shelf based on the DFO ecosystem summer trawl survey (top panel). The area-weighted average minimum temperature in the CIL (bottom panel). The solid horizontal lines are the 1991–2020 means and dashed lines represent ±0.5 SD.

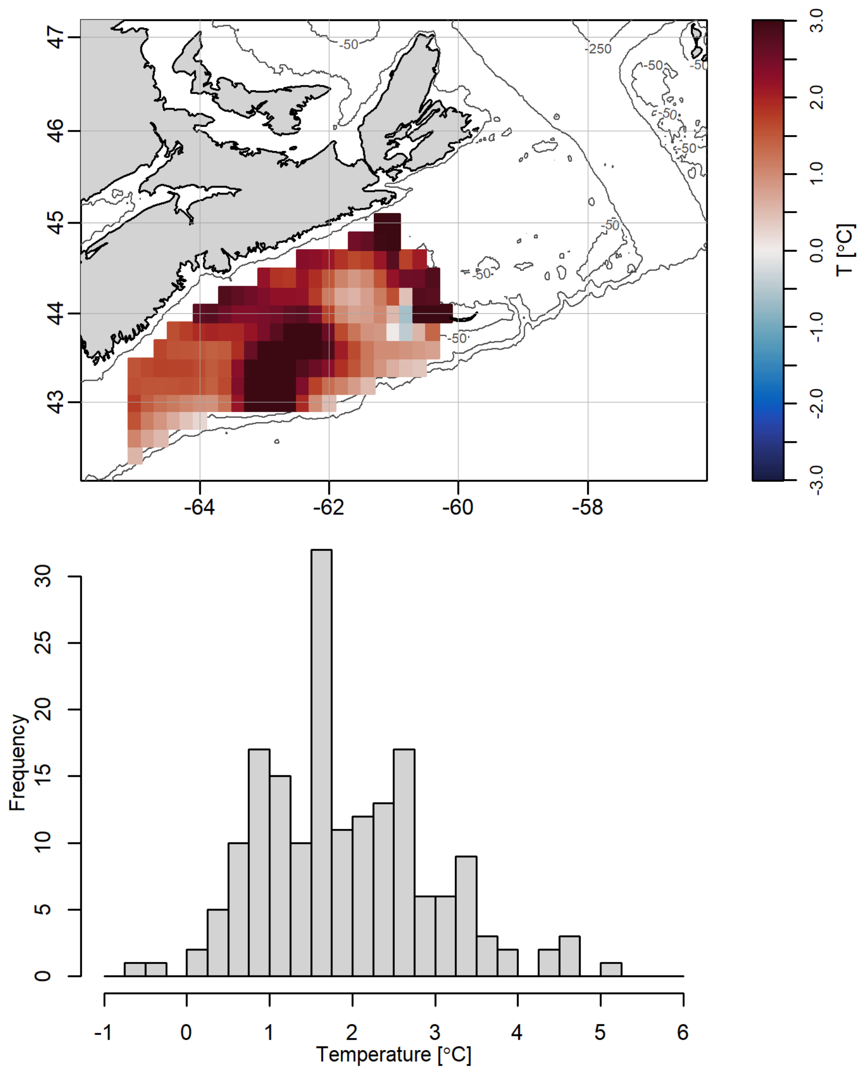

Figure 38. The difference in minimum temperature in the 2022 survey region and the climatological minimum temperature (top panel) and a histogram of the difference (lower panel).

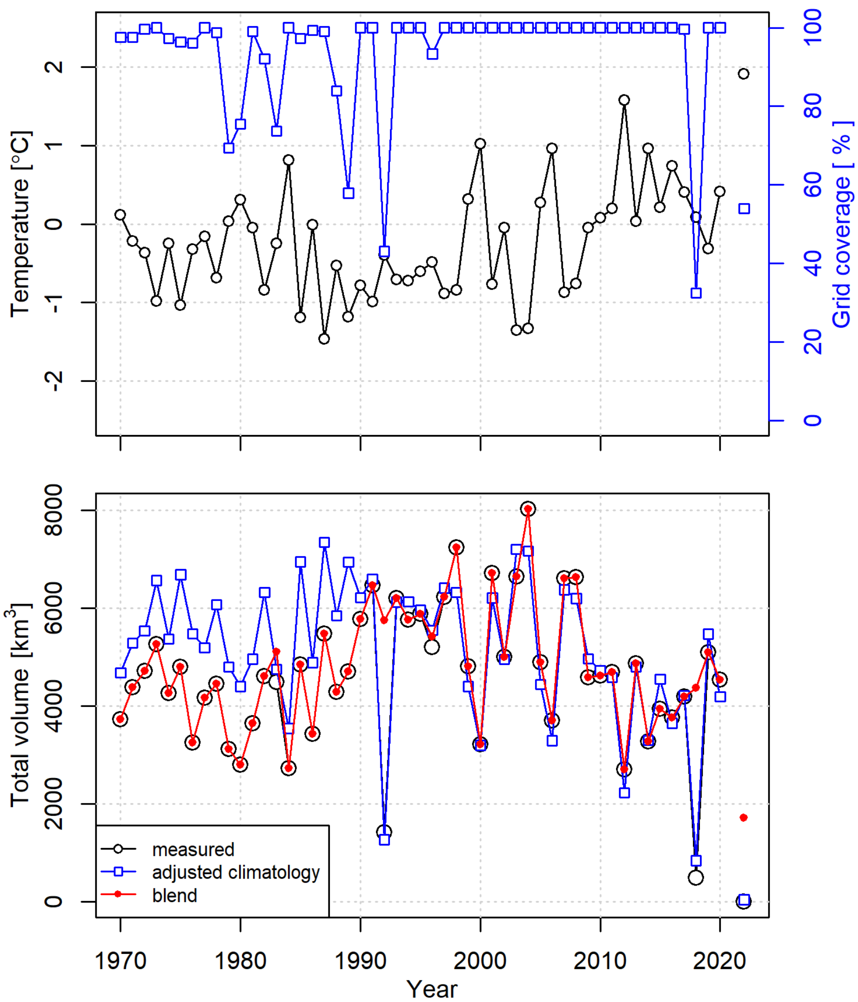

Figure 39. The percentage of the mapped gridded Scotian Shelf for each year and the average of minimum temperature of the survey area relative to the climatology (top panel). The CIL volume based over the survey region, the volume if the climatology temperature was adjusted by the mean observed temperature for the survey region and the volume using the observed data for the survey region and adjusting the climatological data for the area not covered by the survey in that year (lower panel).

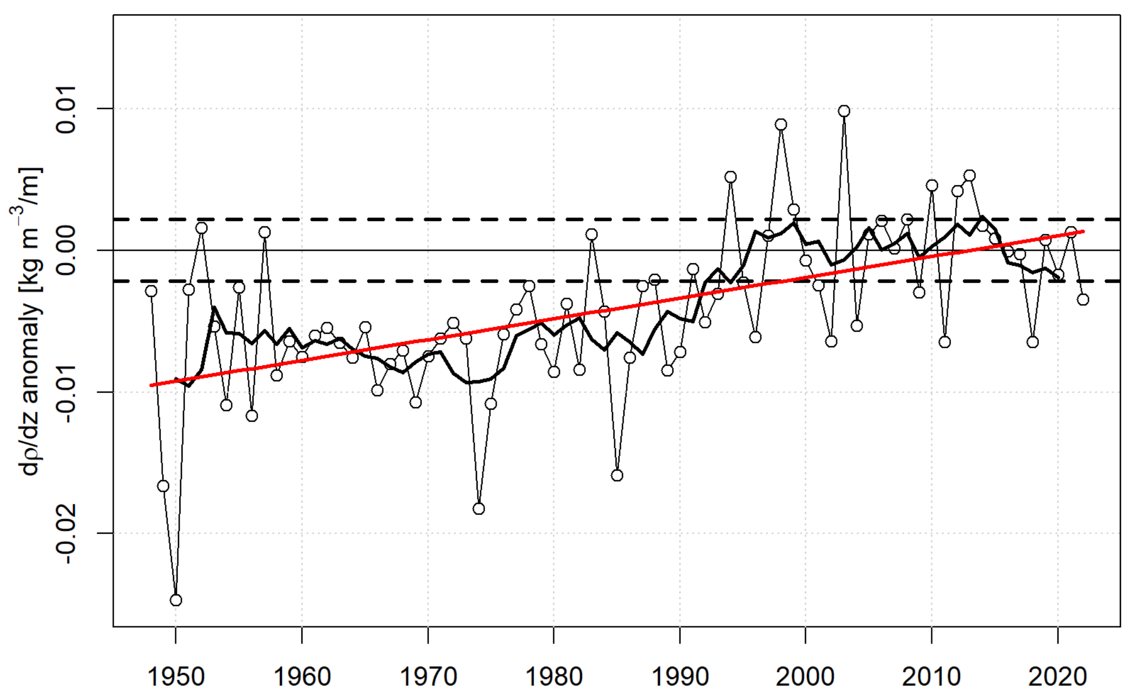

Figure 40. Stratification index (0–50 m density gradient) mean annual anomaly (black line with circles) and five-year running mean (black heavy solid line) averaged over the Scotian Shelf. The linear trend (red line) shows a change in the 0–50 m density difference of 0.37 kg m^{-3} over 50 years for the 1991-2020 period.

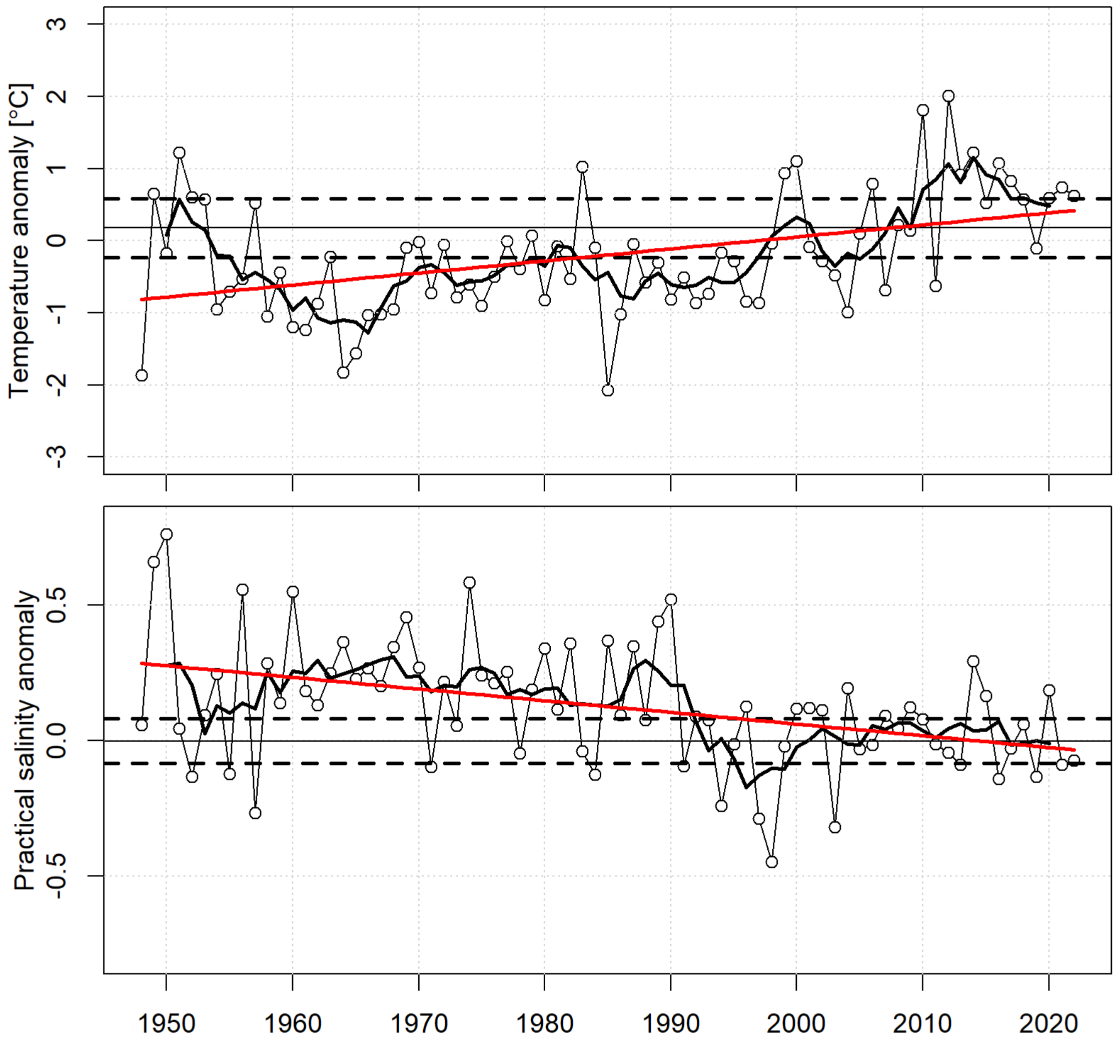

Figure 41. The mean-annual-surface-temperature (top panel) and salinity (lower panel) anomalies (black line with circles) and five-year running mean (black heavy solid line) averaged over the Scotian Shelf. Standard error estimates for each annual anomaly value are also shown. The linear trend (red line) shows a warming of 0.83°C and a freshening of 0.22 over a 50 year period.

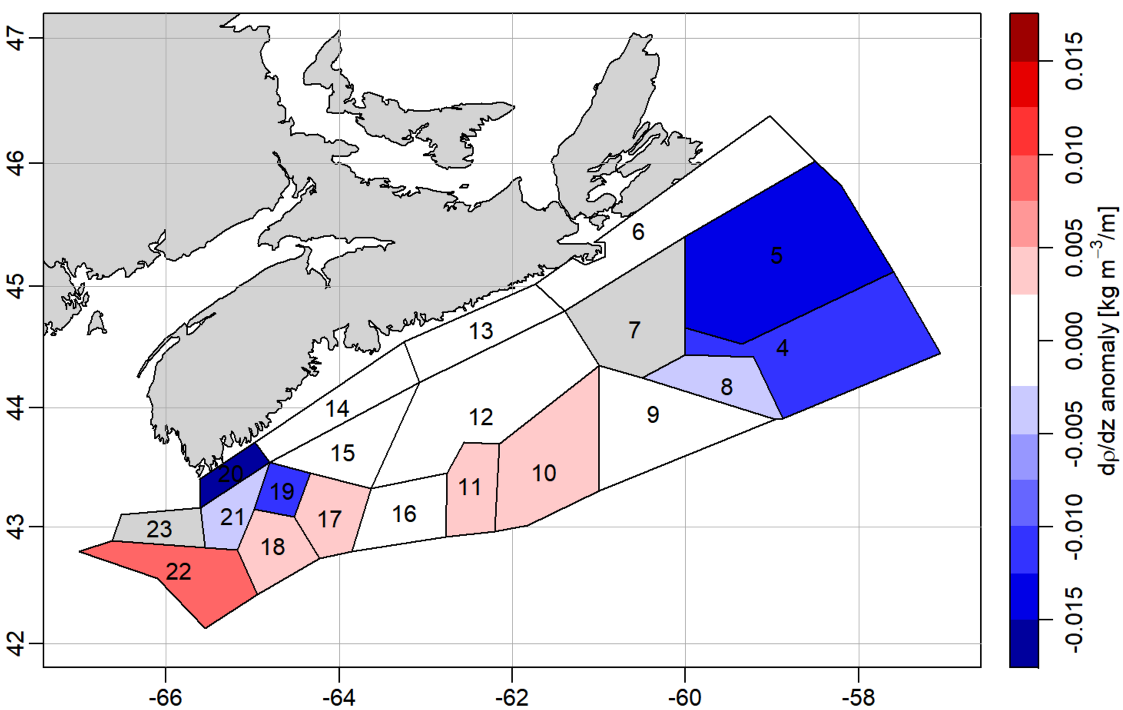

Figure 42. Stratification index (0–50 m density gradient) mean 2020 annual anomaly over the Scotian Shelf. The different areas were defined by Petrie et al. (1996).

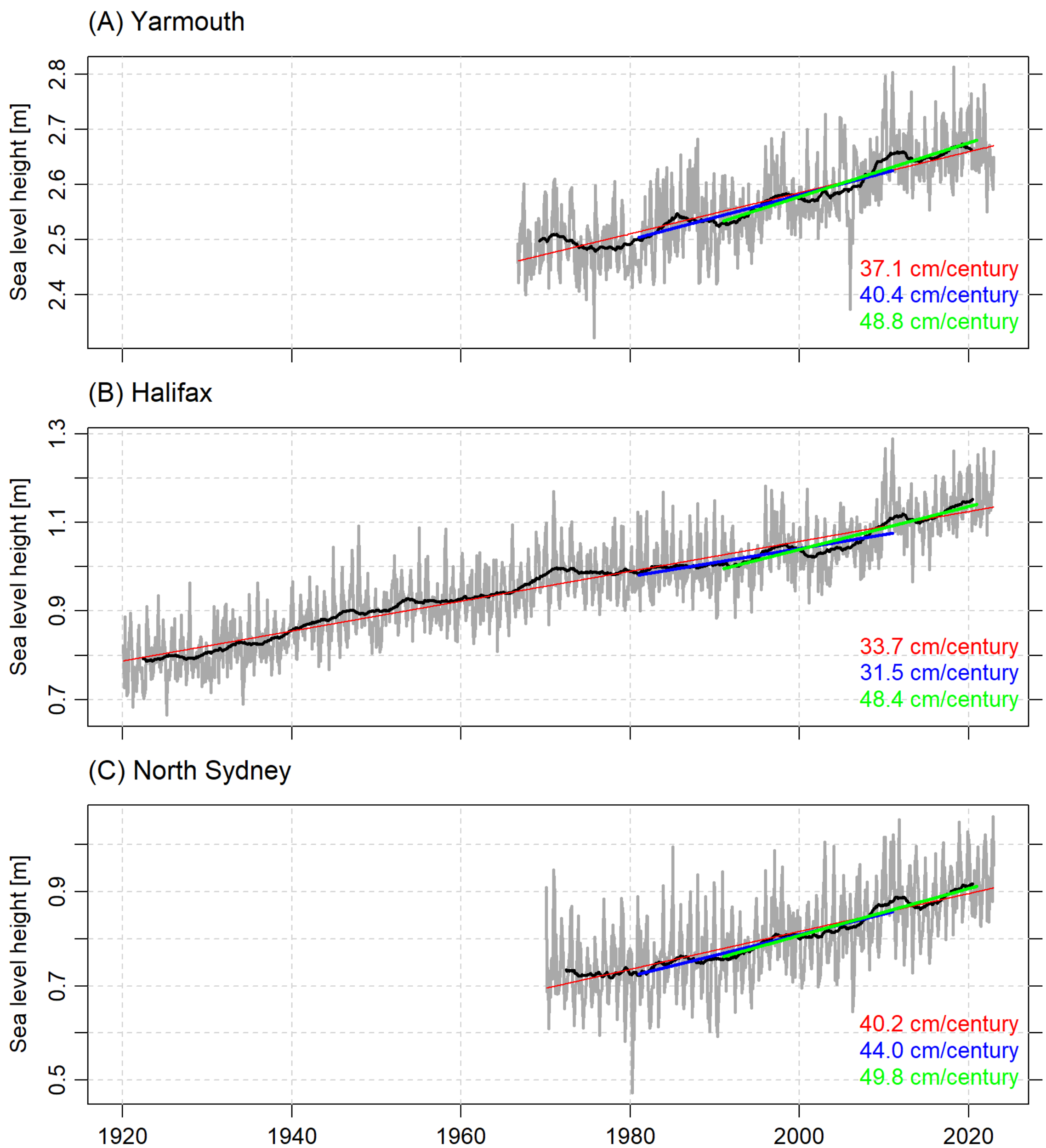

Figure 43. The time series of the monthly means (grey line) and a five-year running mean (black line) of the relative sea-level elevations at Yarmouth (top panel), Halifax (middle panel), and North Sydney (bottom panel), along with the linear trend (red line) over the observation period, over 1981–2010 (blue line) and over 1991–2020 (green line).

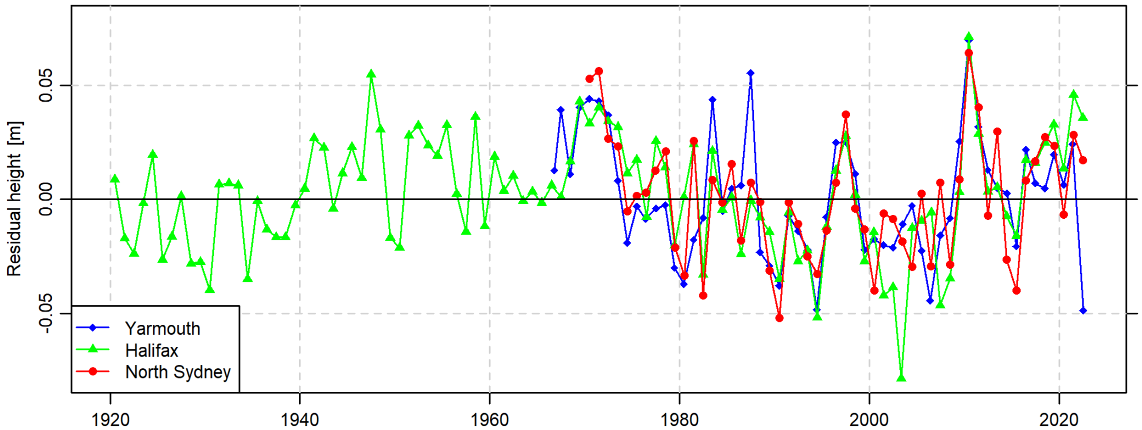

Figure 44. Residual relative sea level (annual observed values—linear trend based on the 1970— 2022 period) for Yarmouth (blue line with diamonds), Halifax (green line with triangles), and North Sydney (red line with circles).

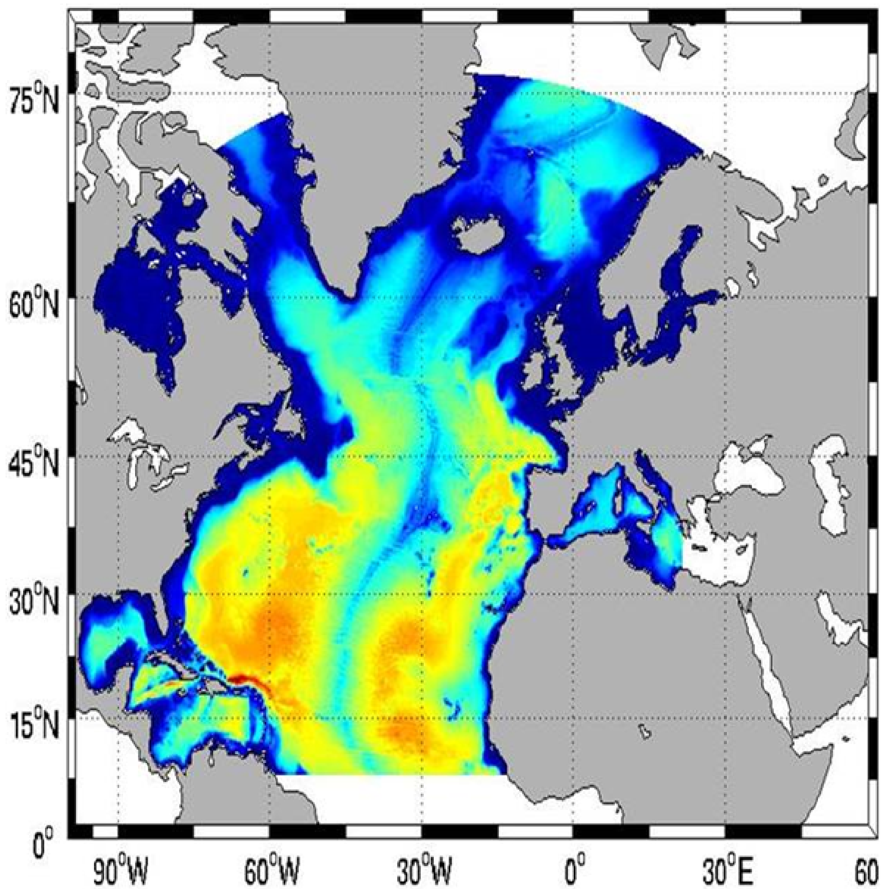

Figure 45. The BIO North Atlantic Model (BNAM) domain Bathymetry coloured from red (deep) to blue (shallow).

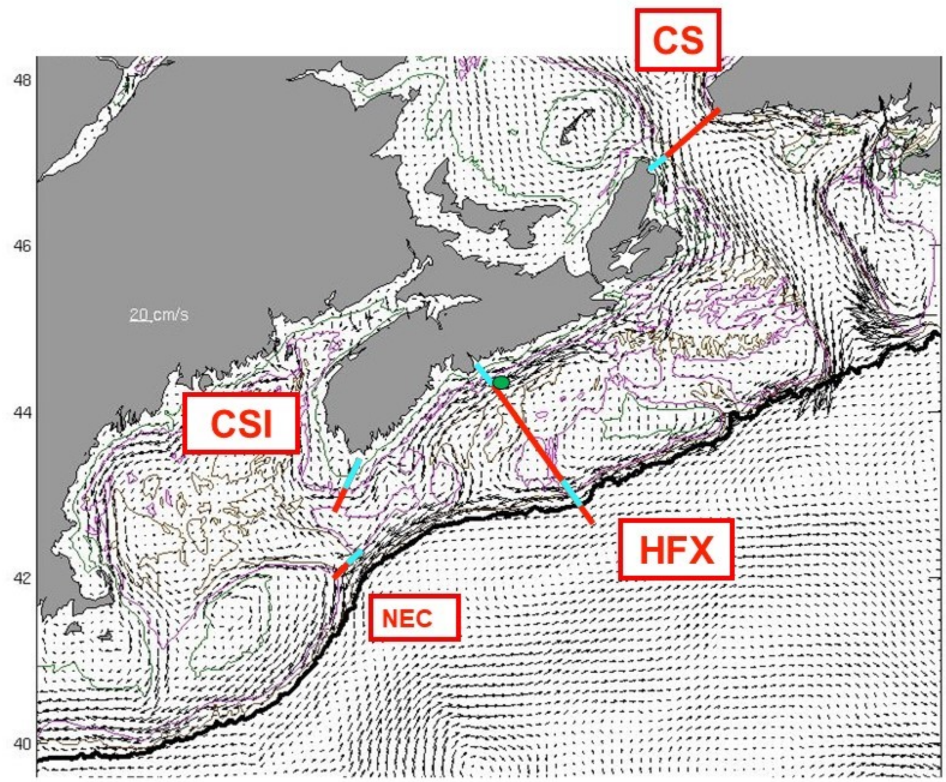

Figure 46. Climatological-annual and depth-averaged circulation illustrating the principal flow pathways from the southern Gulf of St. Lawrence to the Gulf of Maine and the subsections where transport calculations were made (cyan). CS = Cabot Strait; HFX = Halifax; CSI = Cape Sable Island/Browns Bank; NEC = Northeast Channel. Green circle shows the location off T2.

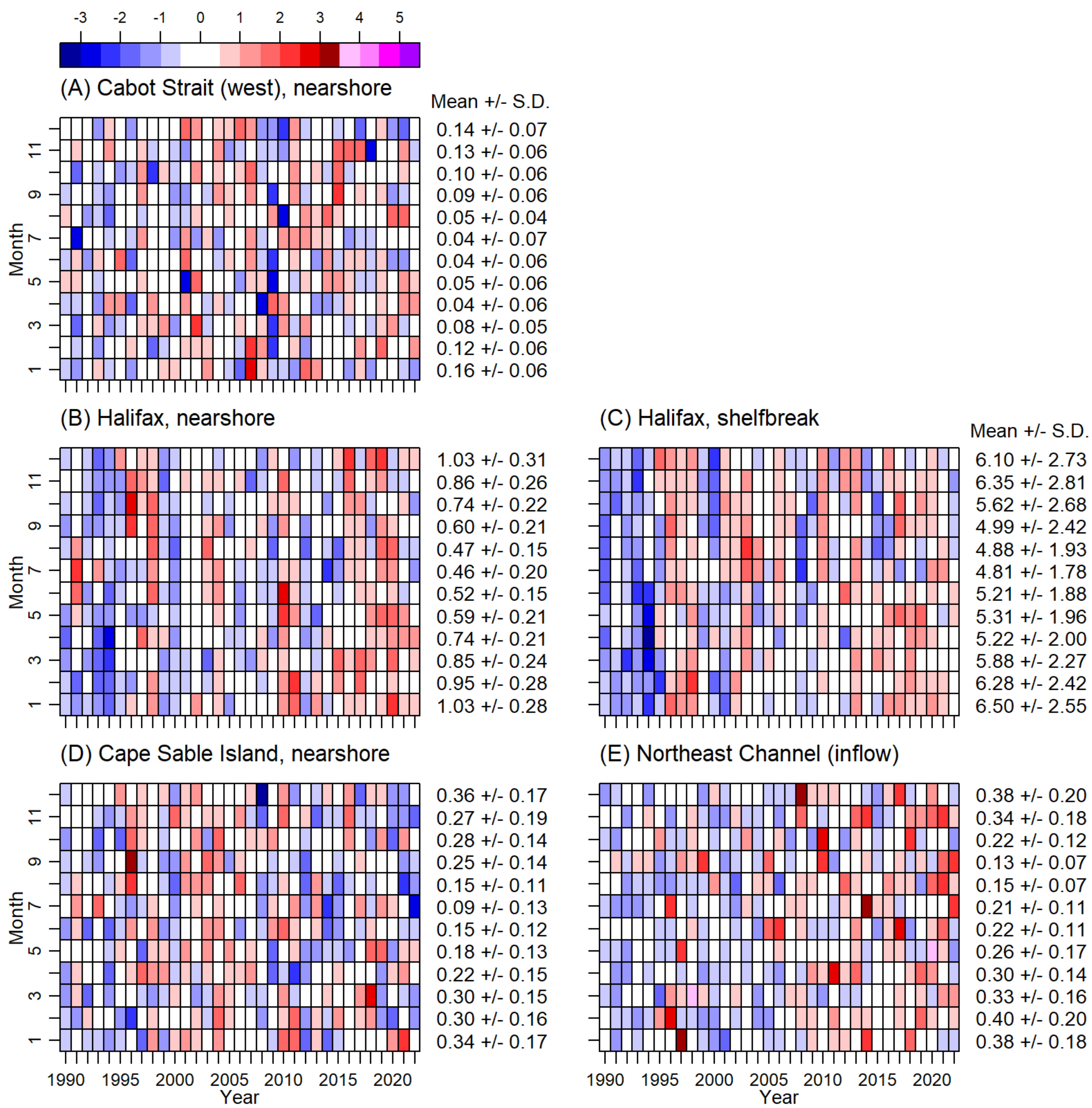

Figure 47. Standardized anomalies of the monthly transport relative to 1991-2020 for four Maritime sections: (A) Cabot Strait (CS) west nearshore; Halifax (HFX) (B) nearshore and (C) shelf break; (D) Cape Sable Island (CSI) nearshore; and (E) the Northeast Channel (NEC). Numbers to the right are monthly means and standard deviations in Sverdrups (1 Sv = $10^6 m^3 s^{-1}$).

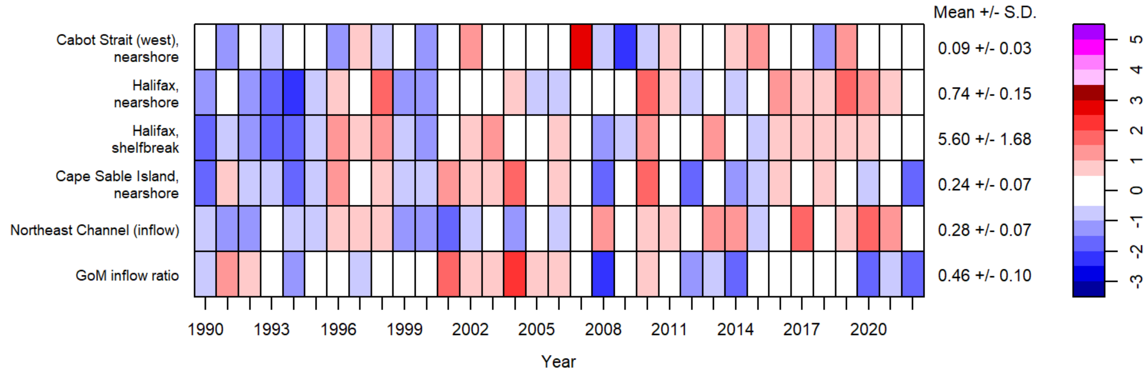

Figure 48. Annual transport anomalies scaled by the standard deviation for the monthly values shown in Figure 47 and Figure 50. Numbers to the right are climatological (1991-2020) annual means and standard deviations (in Sverdrups).

	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		-0.60 +/- 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		-0.41 +/- 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		-0.30 +/- 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	-0.22 +/- 0.10
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	-0.25 +/- 0.11
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	-0.23 +/- 0.14
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	-0.31 +/- 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	-0.37 +/- 0.09
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	-0.54 +/- 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	-0.63 +/- 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	-0.66 +/- 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	-0.41	-0.38 +/- 0.06

Figure 49. 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.

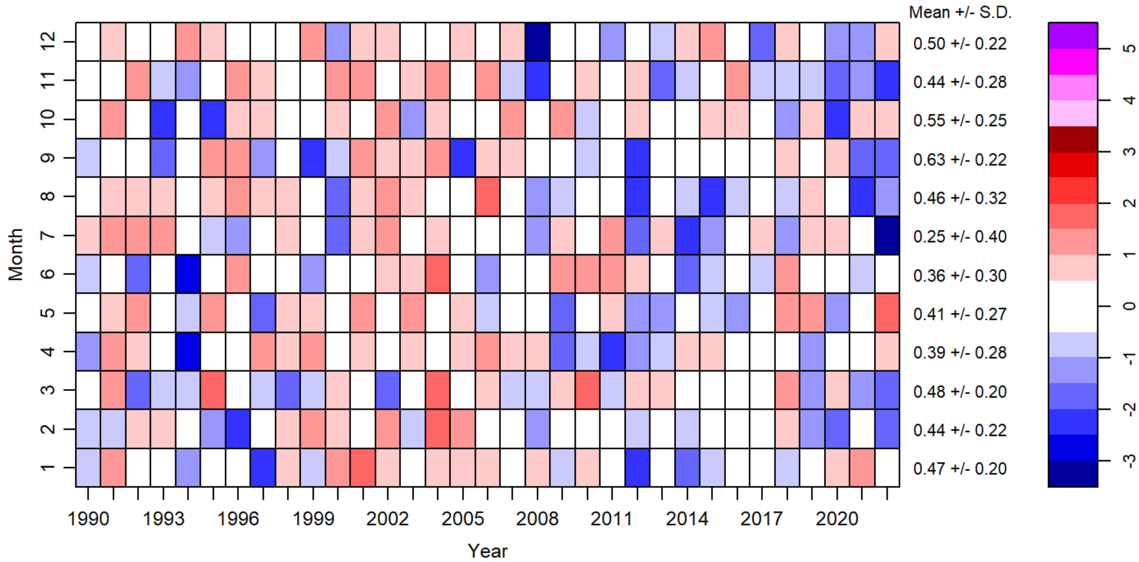

Figure 50. Standardized anomalies of the Gulf of Maine inflow ratio. Numbers to the right are 1991-2020 climatological monthly means and standard deviations.

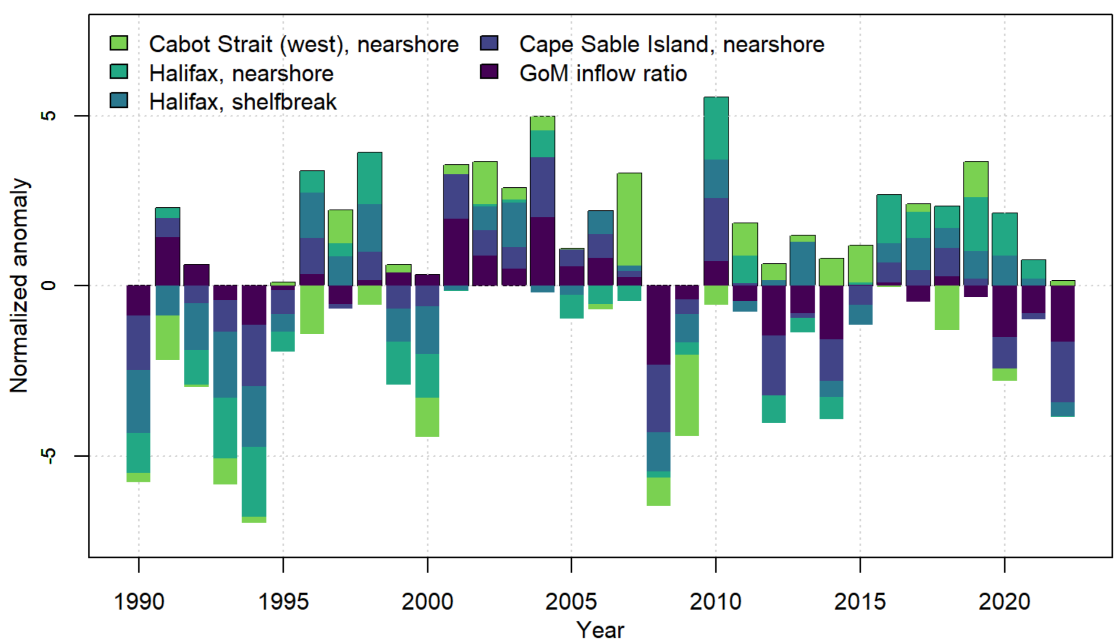

Figure 51. Sum of standardized transport anomalies for the variables in Figure 48.

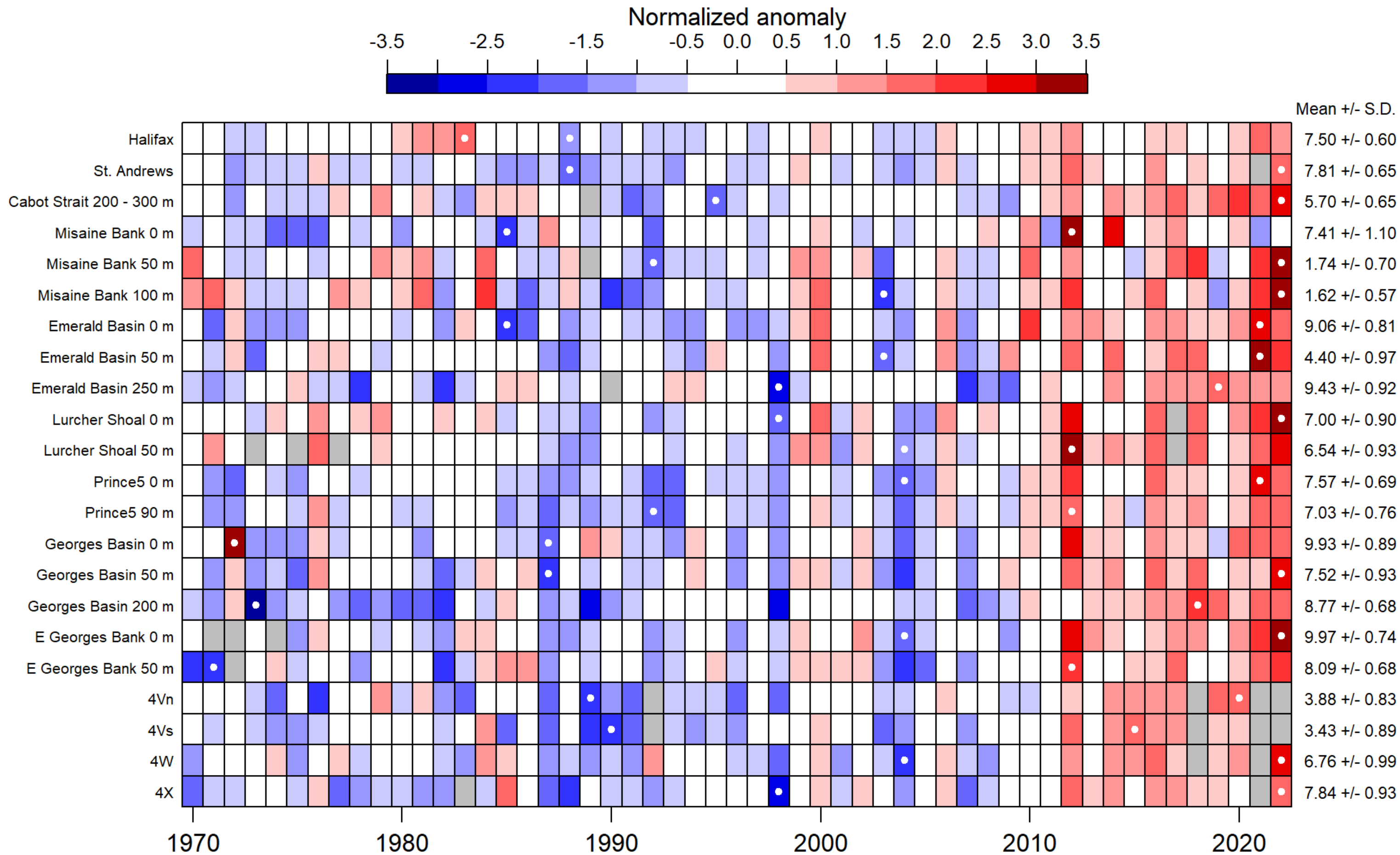

Figure 52. Normalized annual anomalies of temperatures at the bottom and discrete depths for the Scotian Shelf/Gulf of Maine region. These anomalies are based on the 1991–2020 means divided by the standard deviation. Blue colours indicate below-normal anomalies. Red colours indicate above-normal anomalies. White dots represent record minimum and maximum years for each parameter. Gray represents lack of data.

APPENDIX A APPENDIX

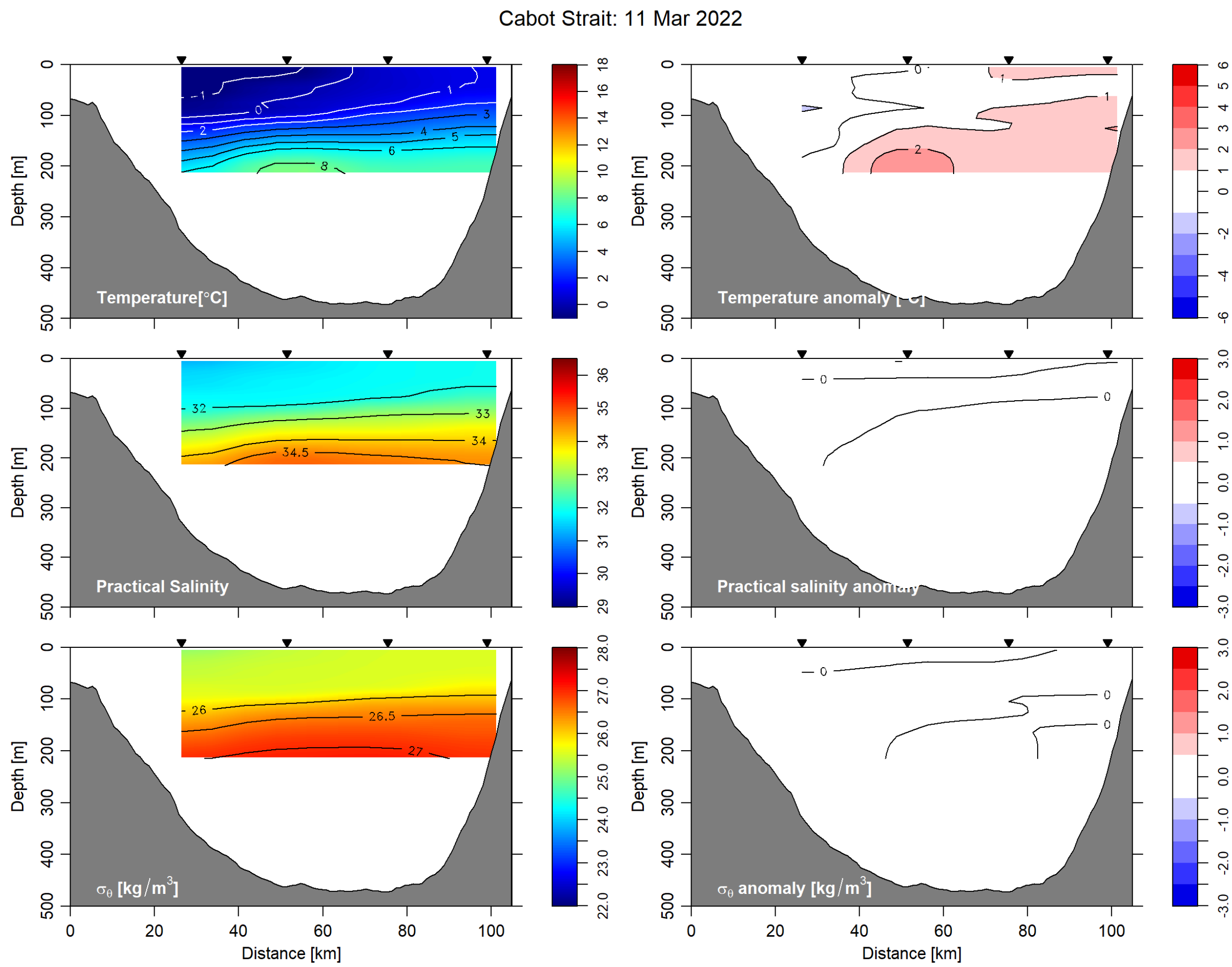

Figure A.1. The 2022 sampling of the Cabot Strait Section for Spring collected by Quebec Region AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to 1991–2020 monthly means (right panels). Triangles indicate locations of sampling.

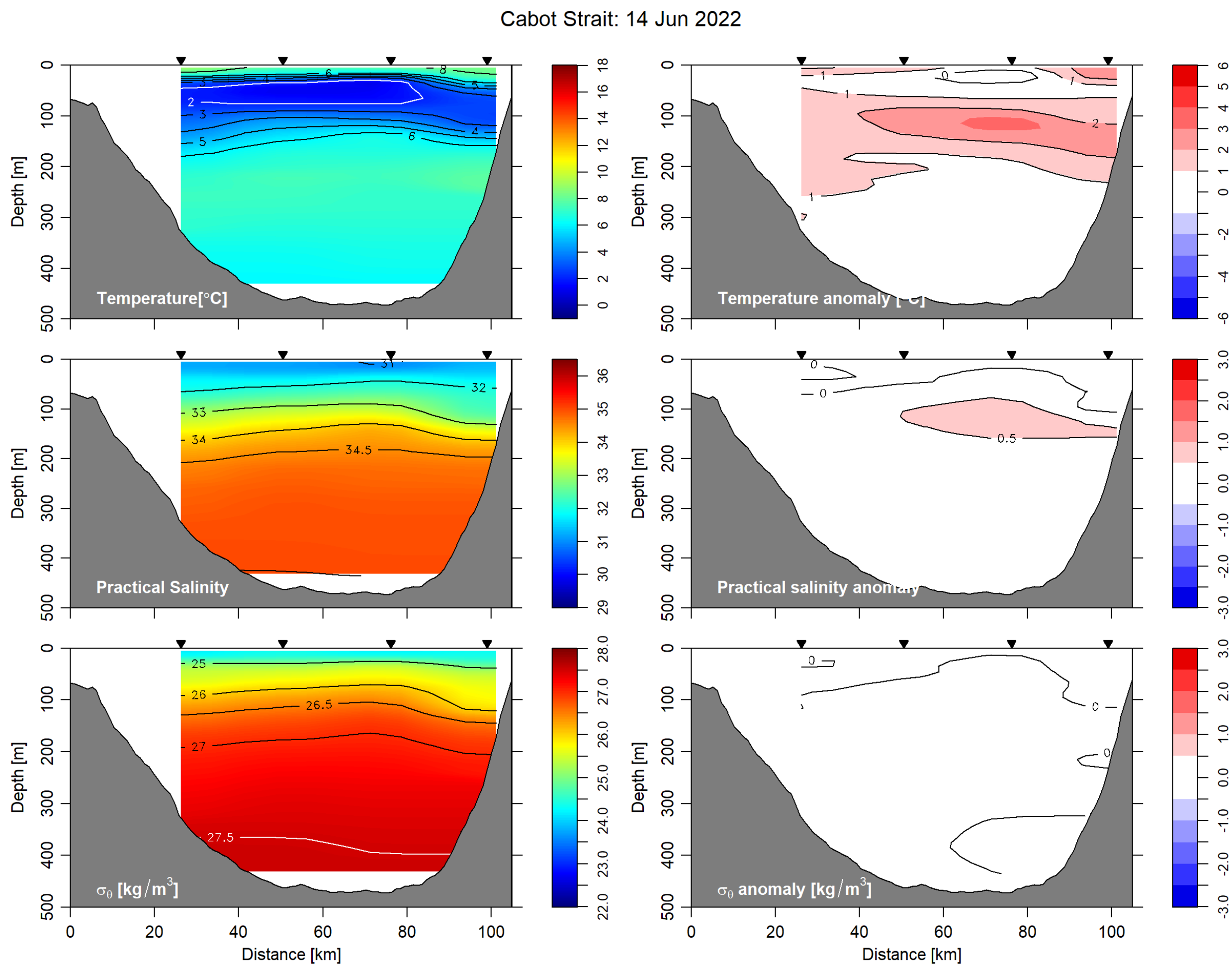

Figure A.2. The 2022 sampling of the Cabot Strait Section for Summer collected by Quebec Region AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to 1991–2020 monthly means (right panels). Triangles indicate locations of sampling.

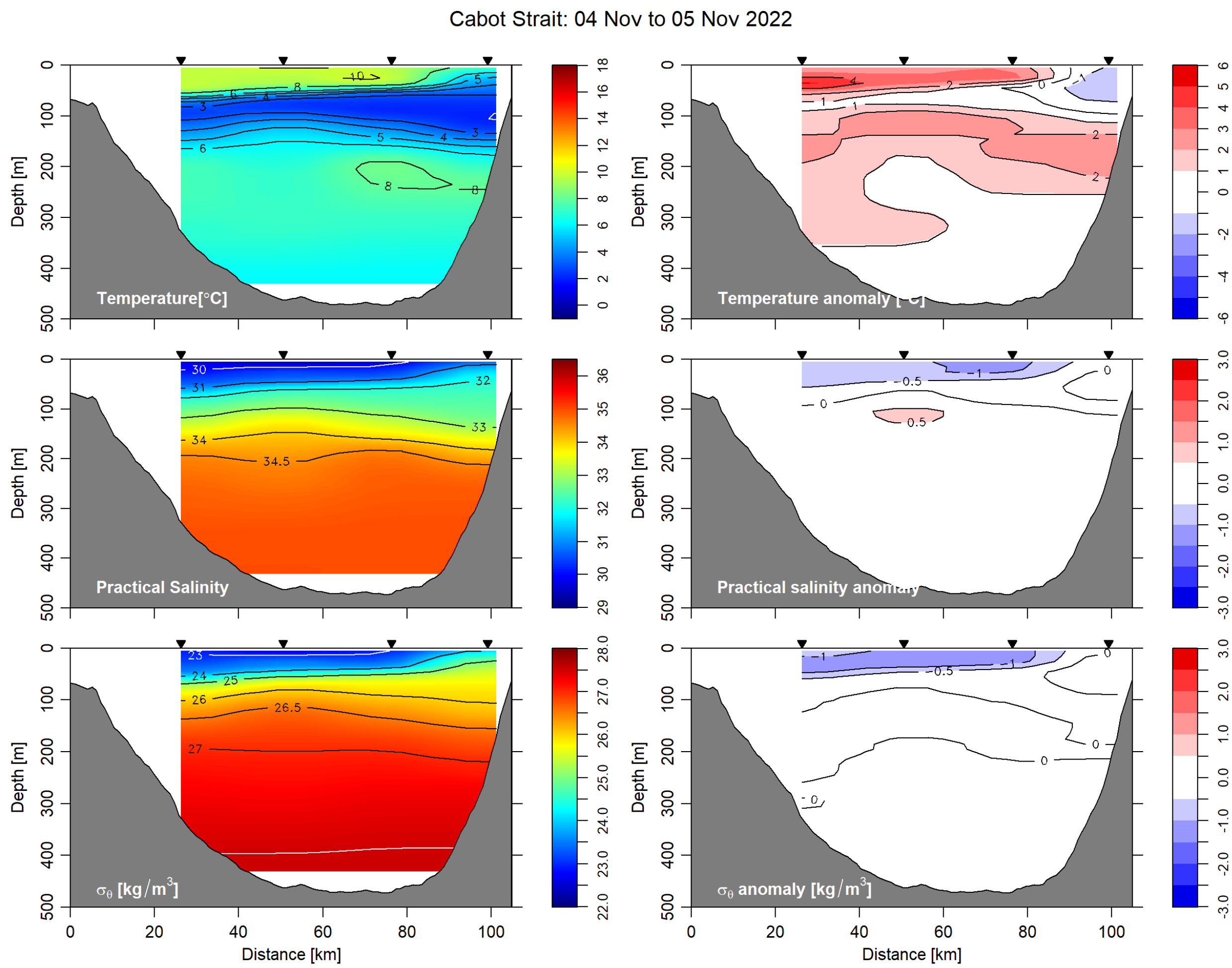

Figure A.3. The 2022 sampling of the Cabot Strait Section for Fall collected by Quebec Region AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel) and their anomalies with respect to 1991–2020 monthly means (right panels). Triangles indicate locations of sampling.

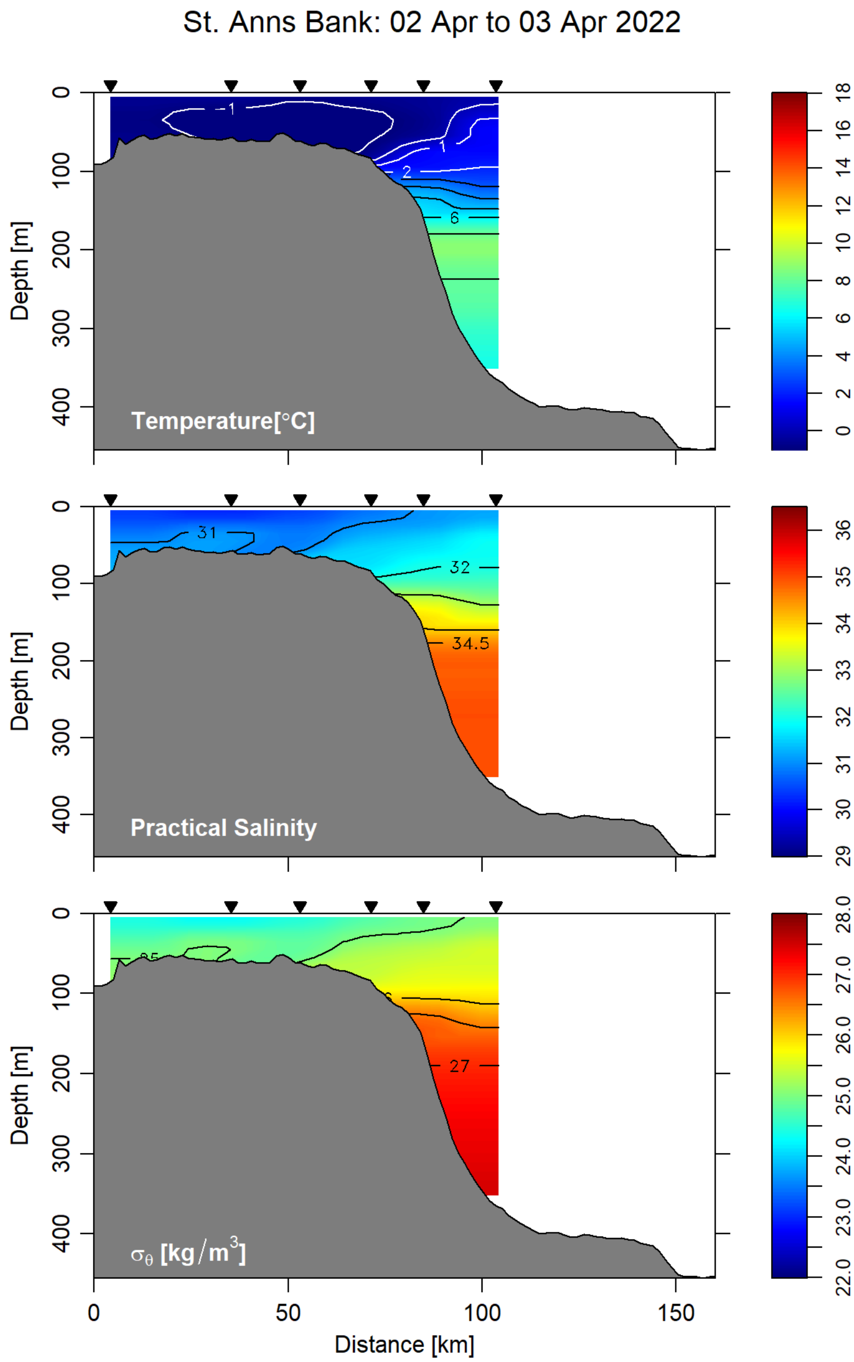

Figure A.4. The 2022 sampling of the St. Anns Bank Section for spring collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

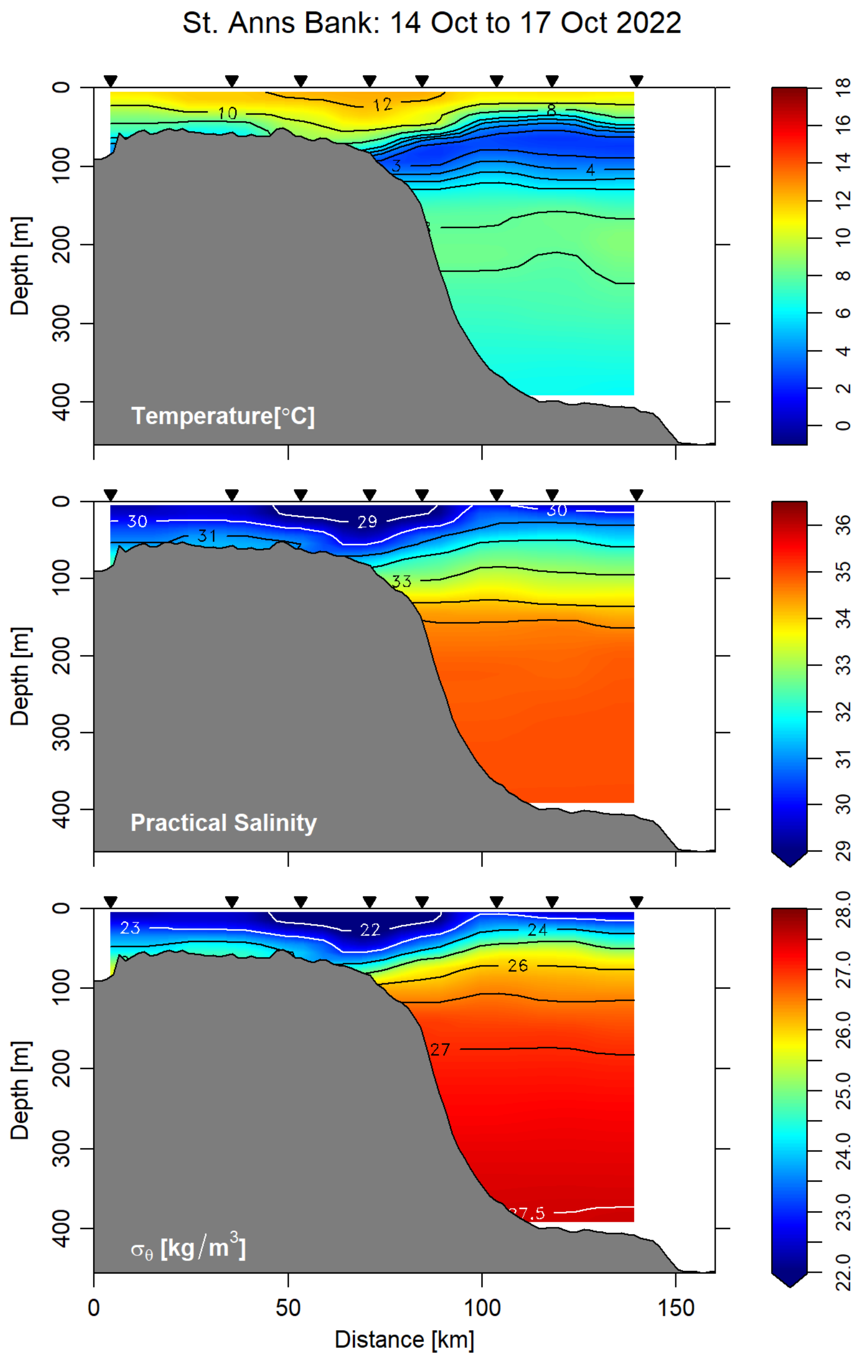

Figure A.5. The 2022 sampling of the St. Anns Bank section for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

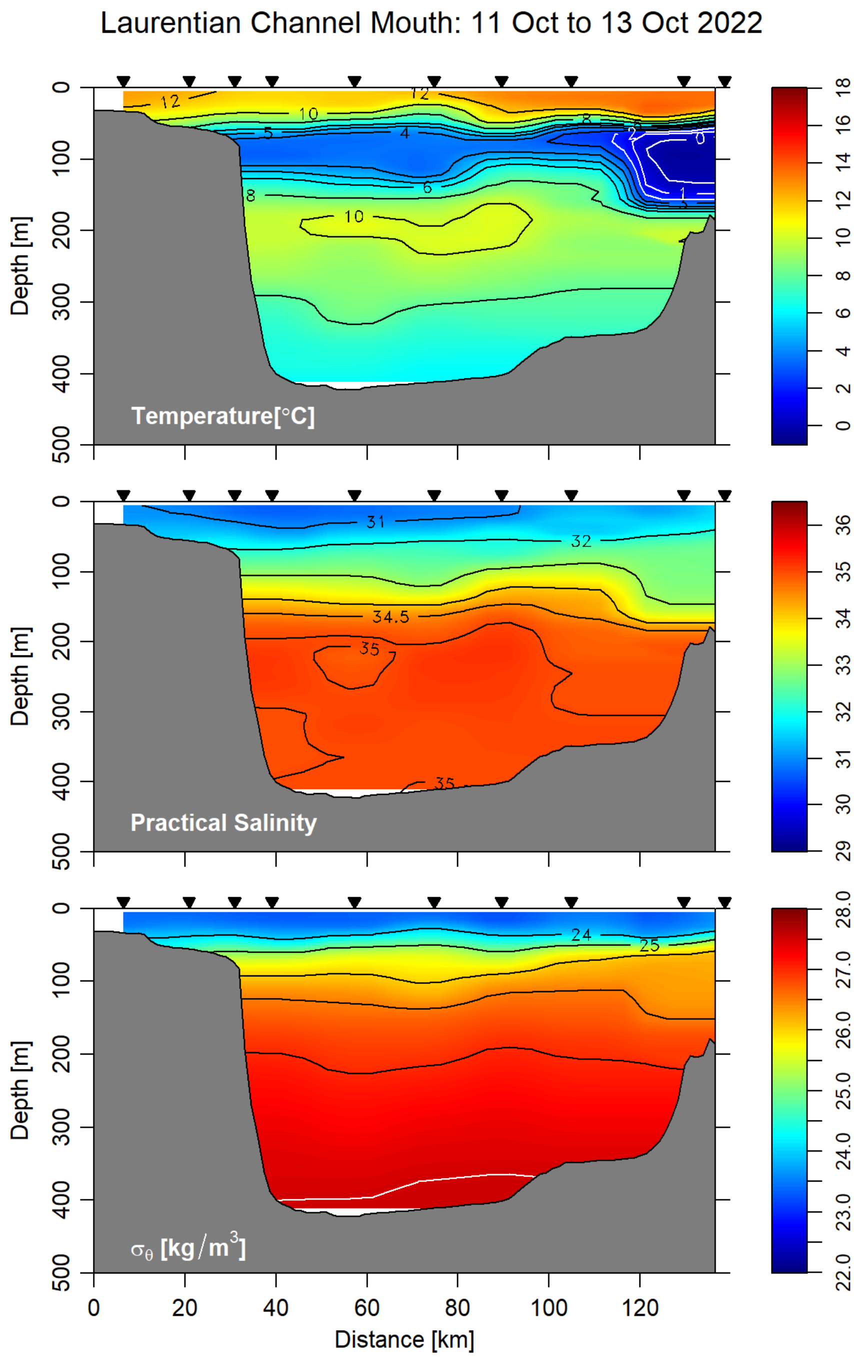

Figure A.6. The 2022 sampling of the Laurentian Channel Mouth section for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

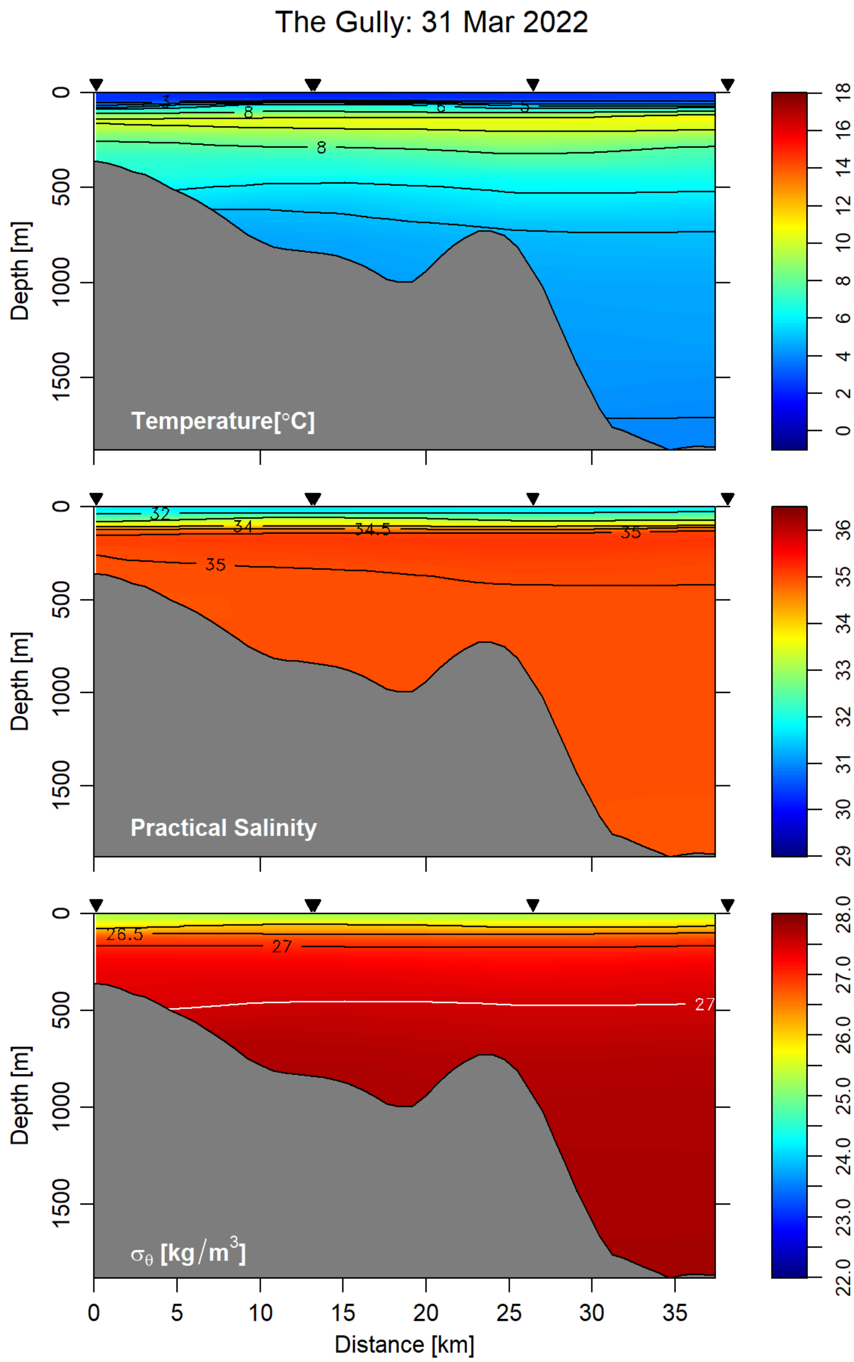

Figure A.7. The 2022 sampling of The Gully Section for spring collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

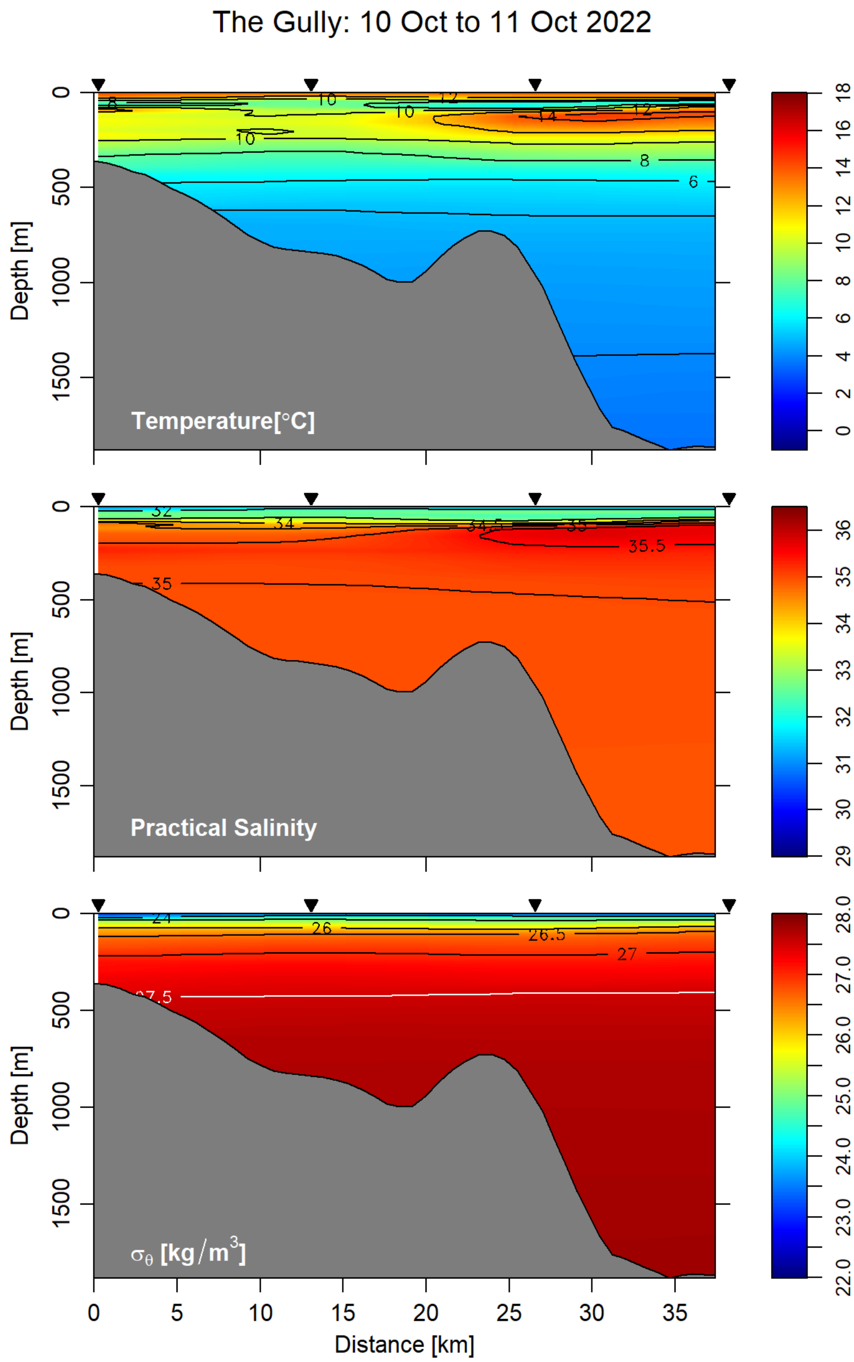

Figure A.8. The 2022 sampling of The Gully section for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

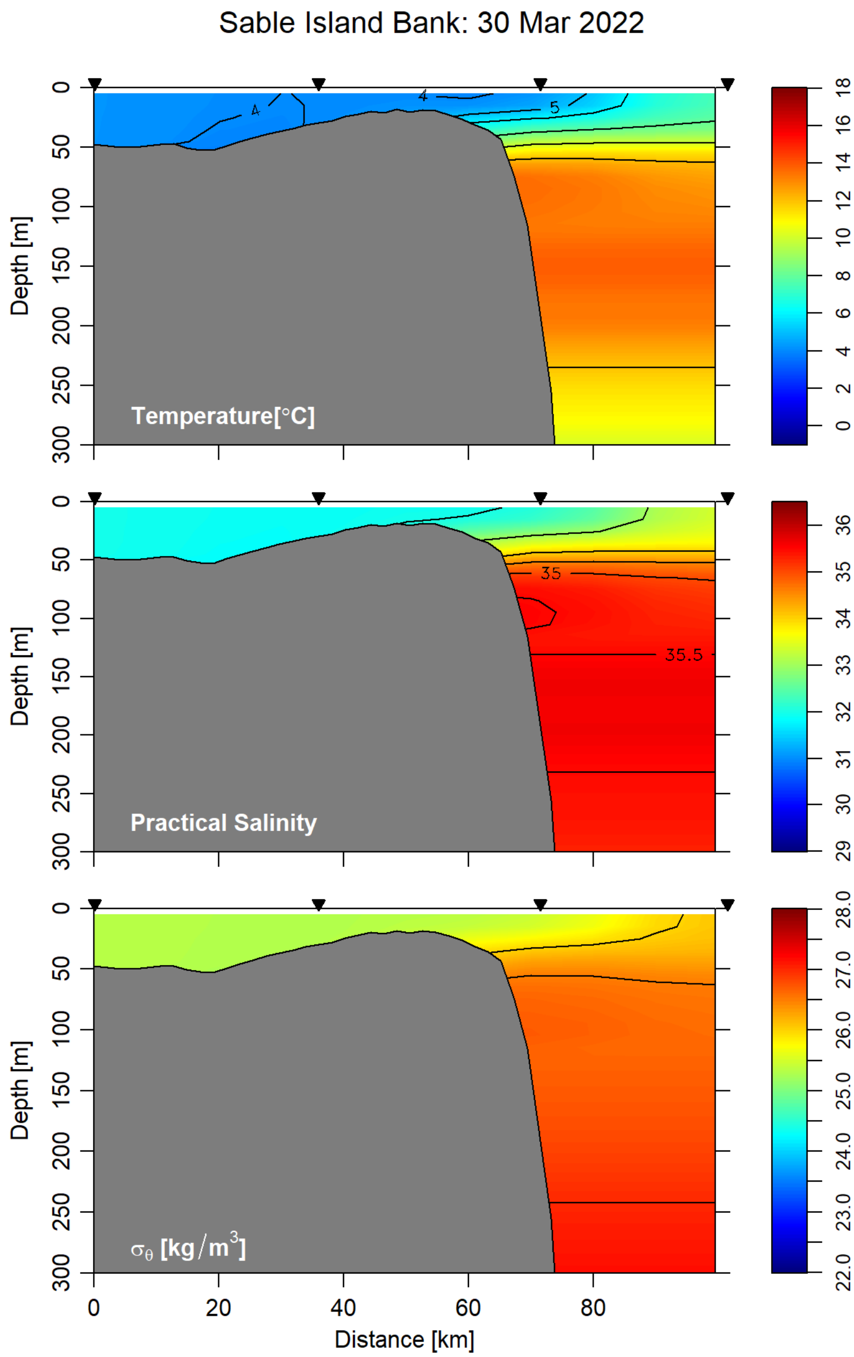

Figure A.9. The 2022 sampling of Sable Island Bank (north-south) for spring collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

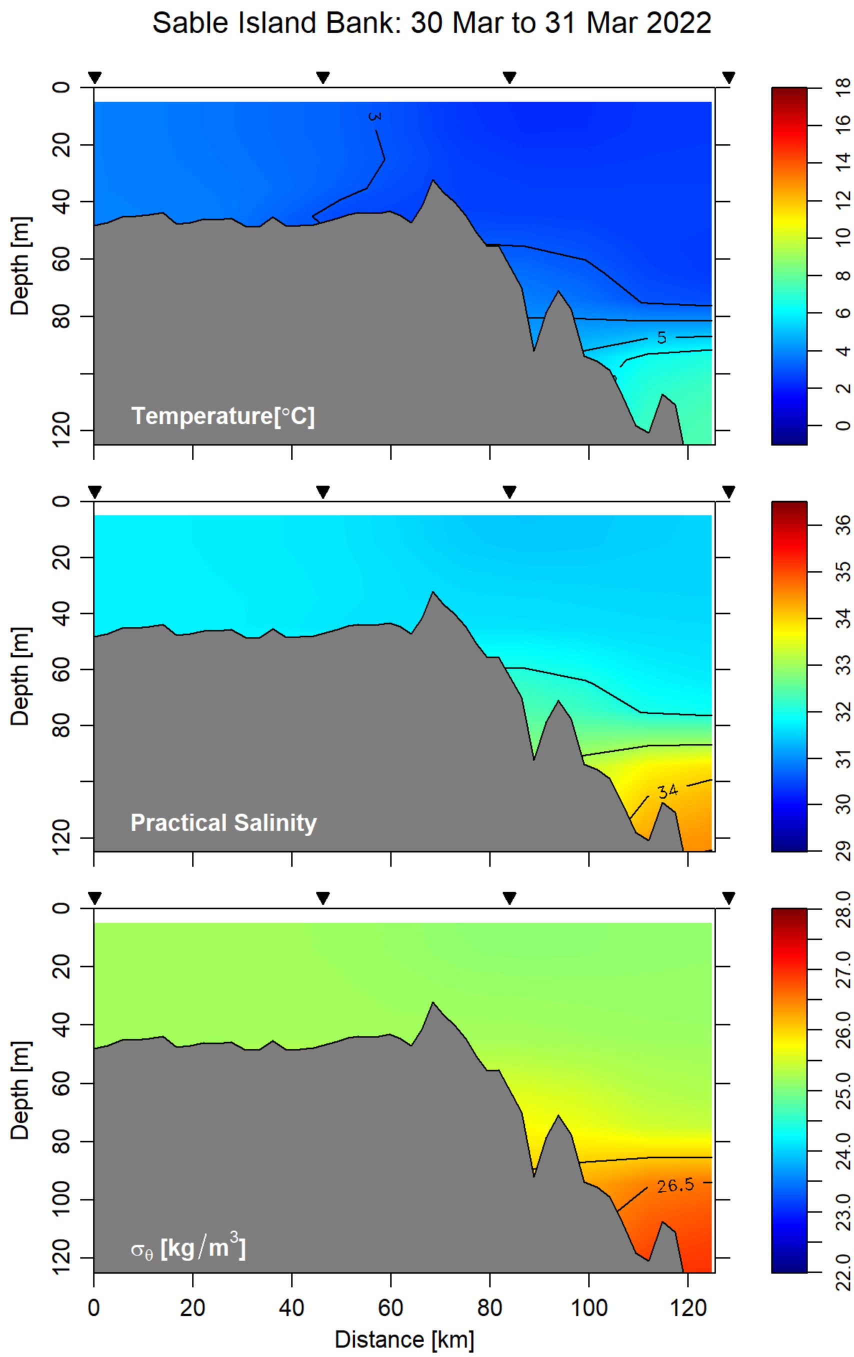

Figure A.10. The 2022 sampling of Sable Island Bank (west-east) for spring collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

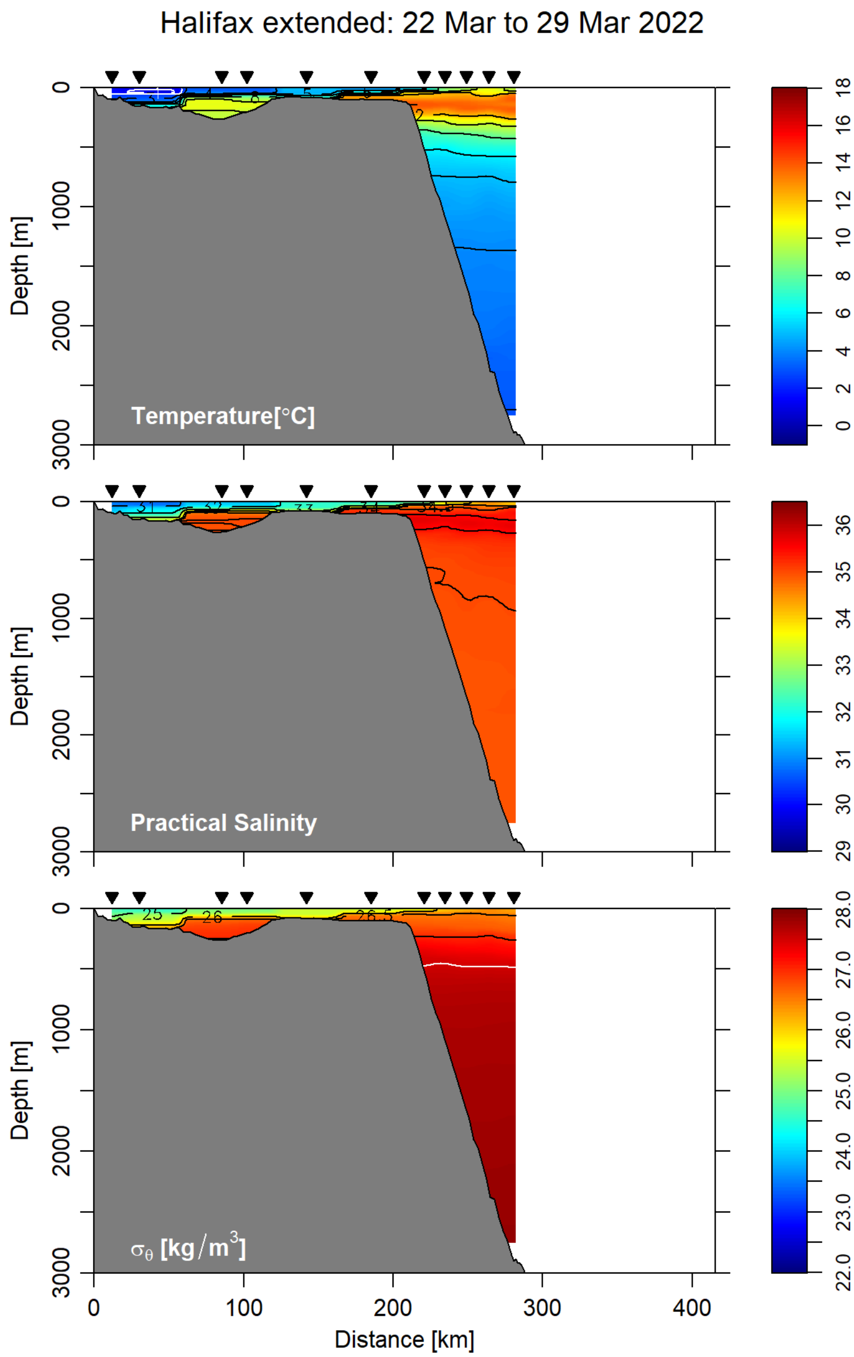

Figure A.11. The 2022 sampling of the Halifax extended line for spring collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

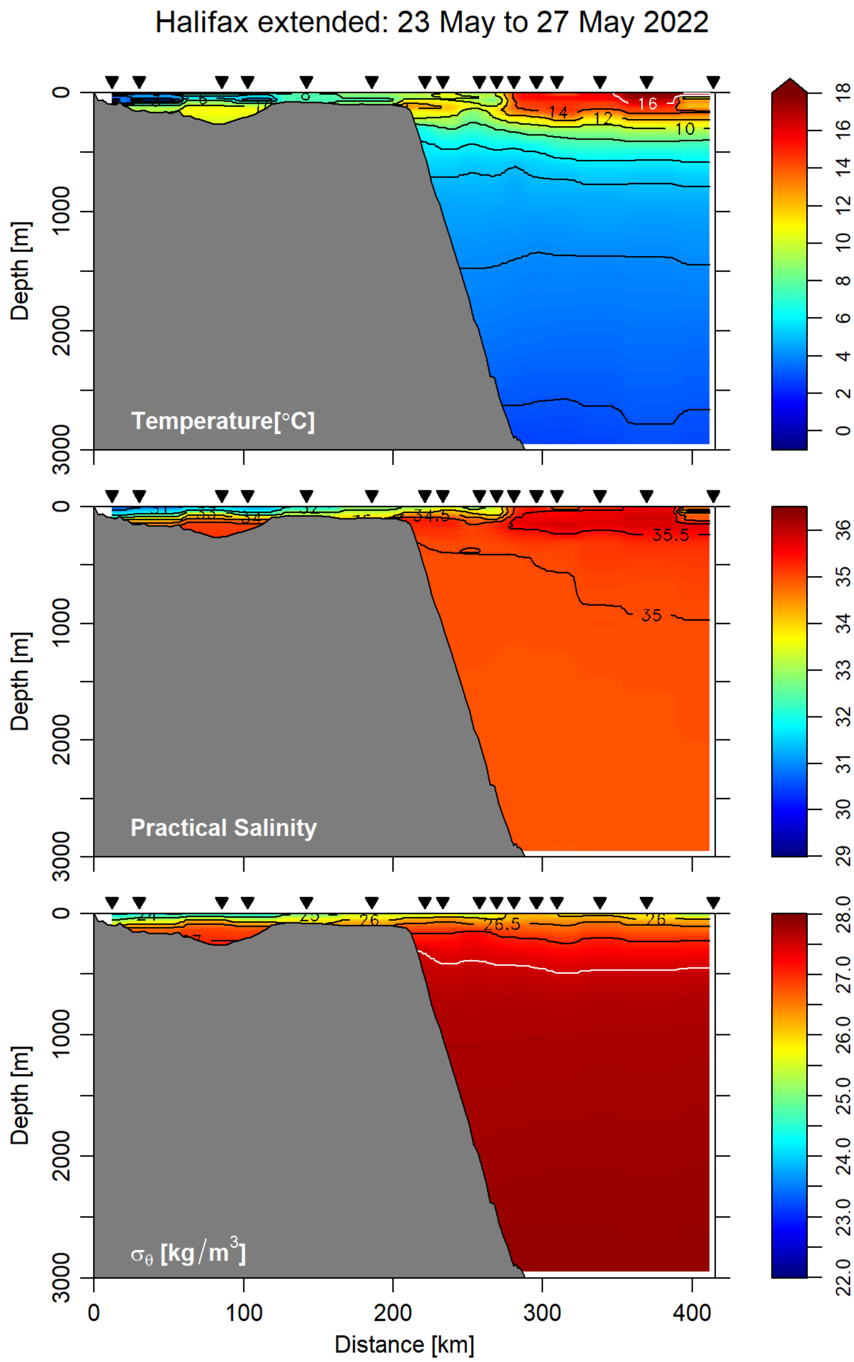

Figure A.12. The 2022 sampling of the Halifax extended line for spring collected by Maritimes AZOMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

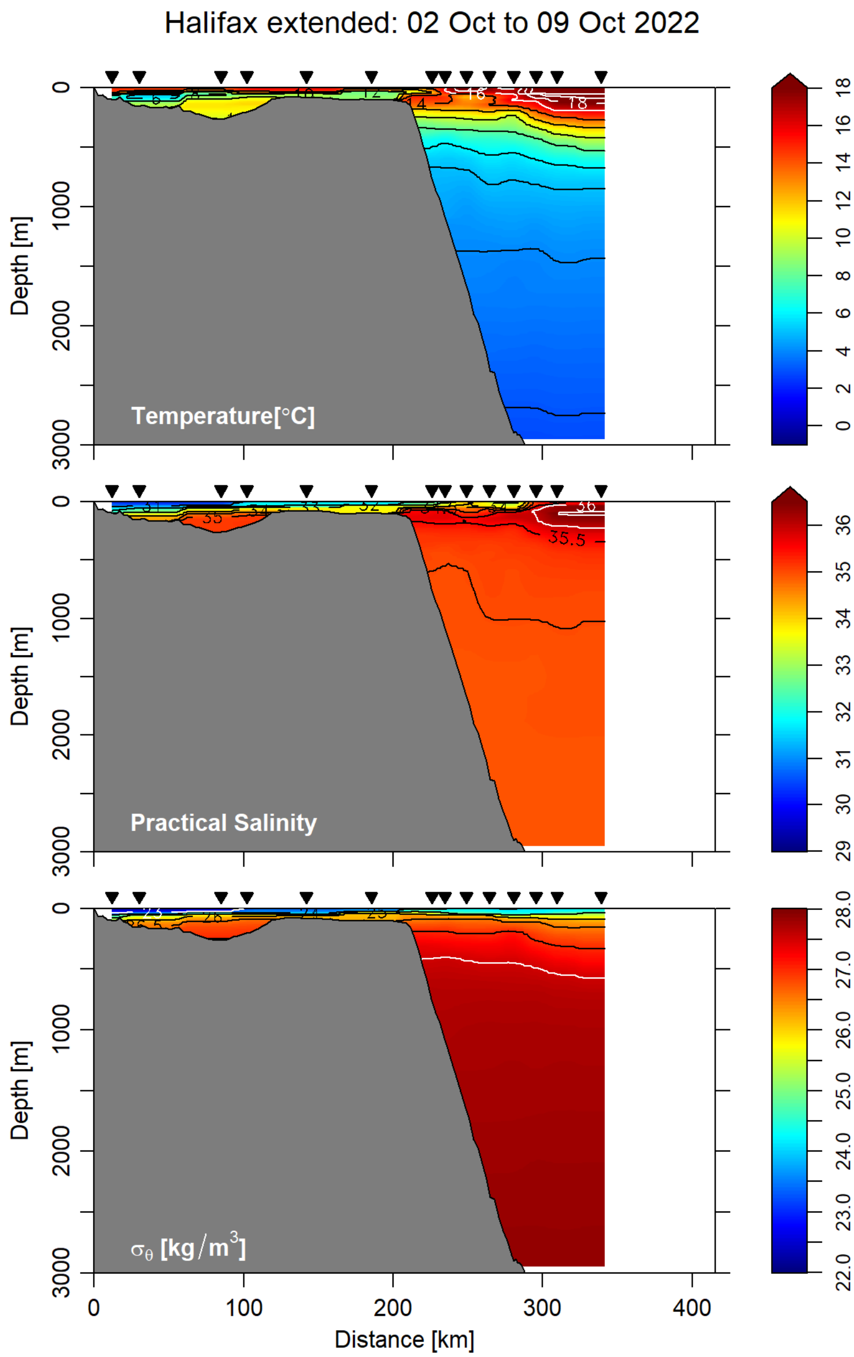

Figure A.13. The 2022 sampling of the Halifax extended line for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

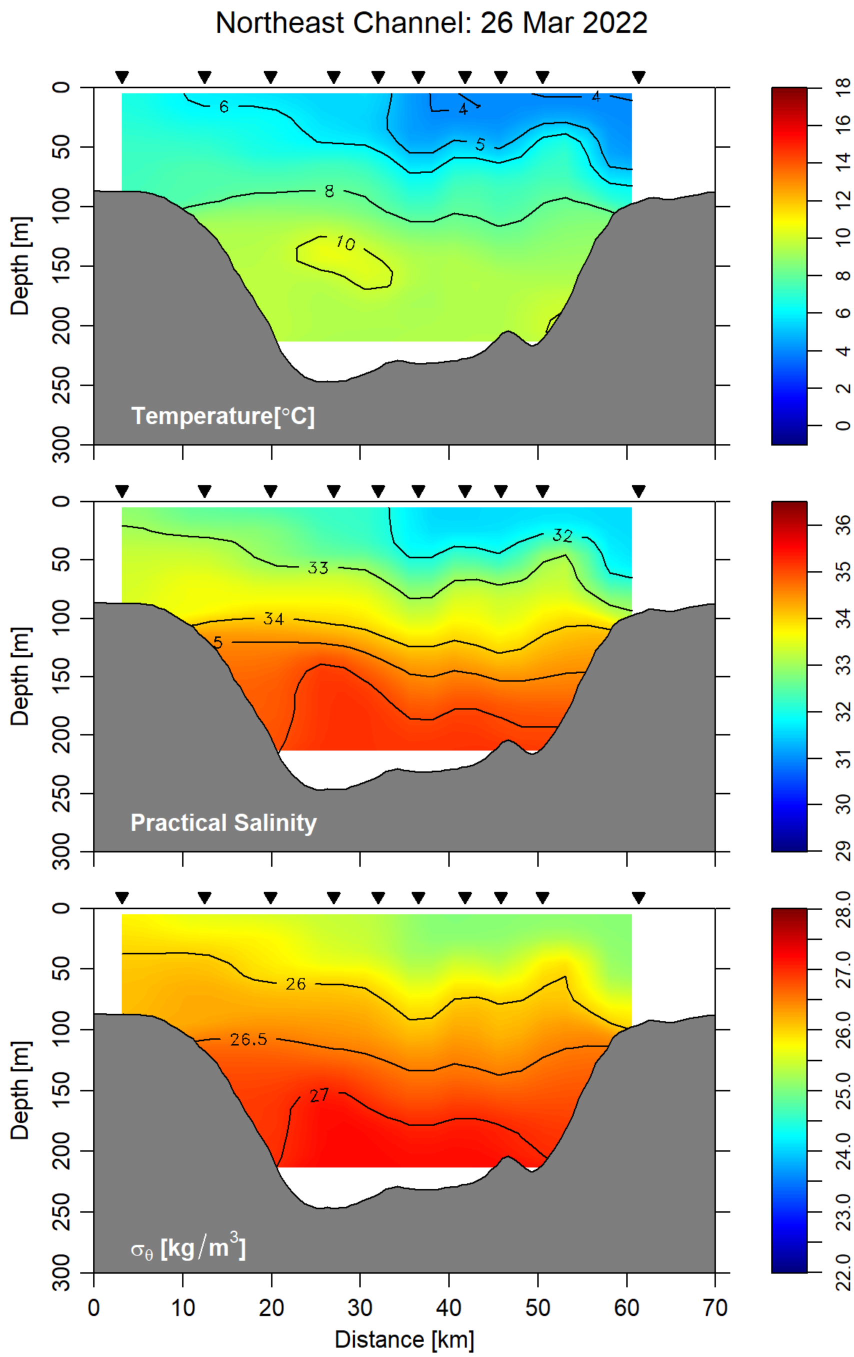

Figure A.14. The 2022 sampling of Northeast Channel for spring collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

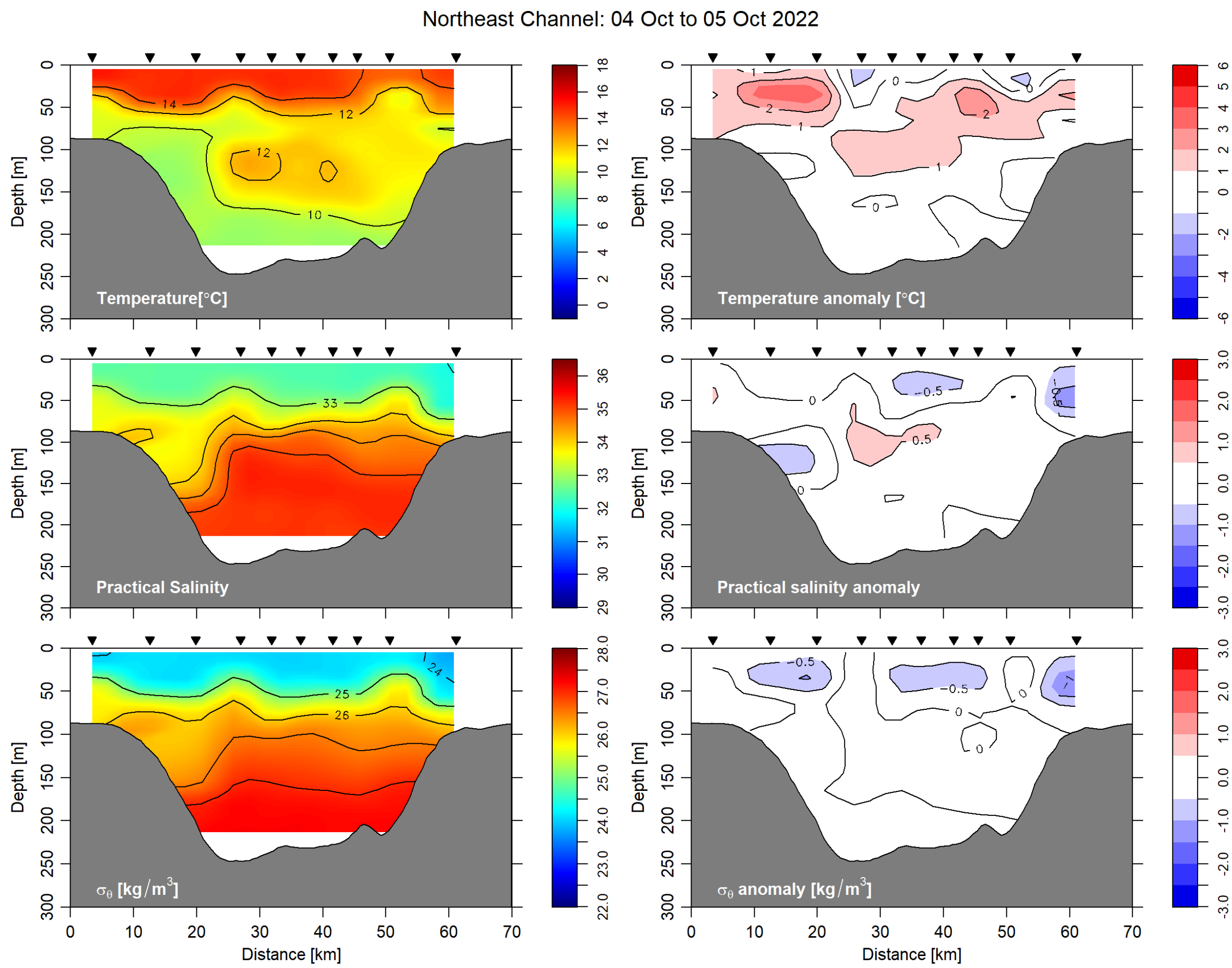

Figure A.15. The 2022 sampling of Northeast Channel for fall collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel)and their anomalies with respect to 1991–2020 monthly means (right panels). Triangles indicate locations of sampling.

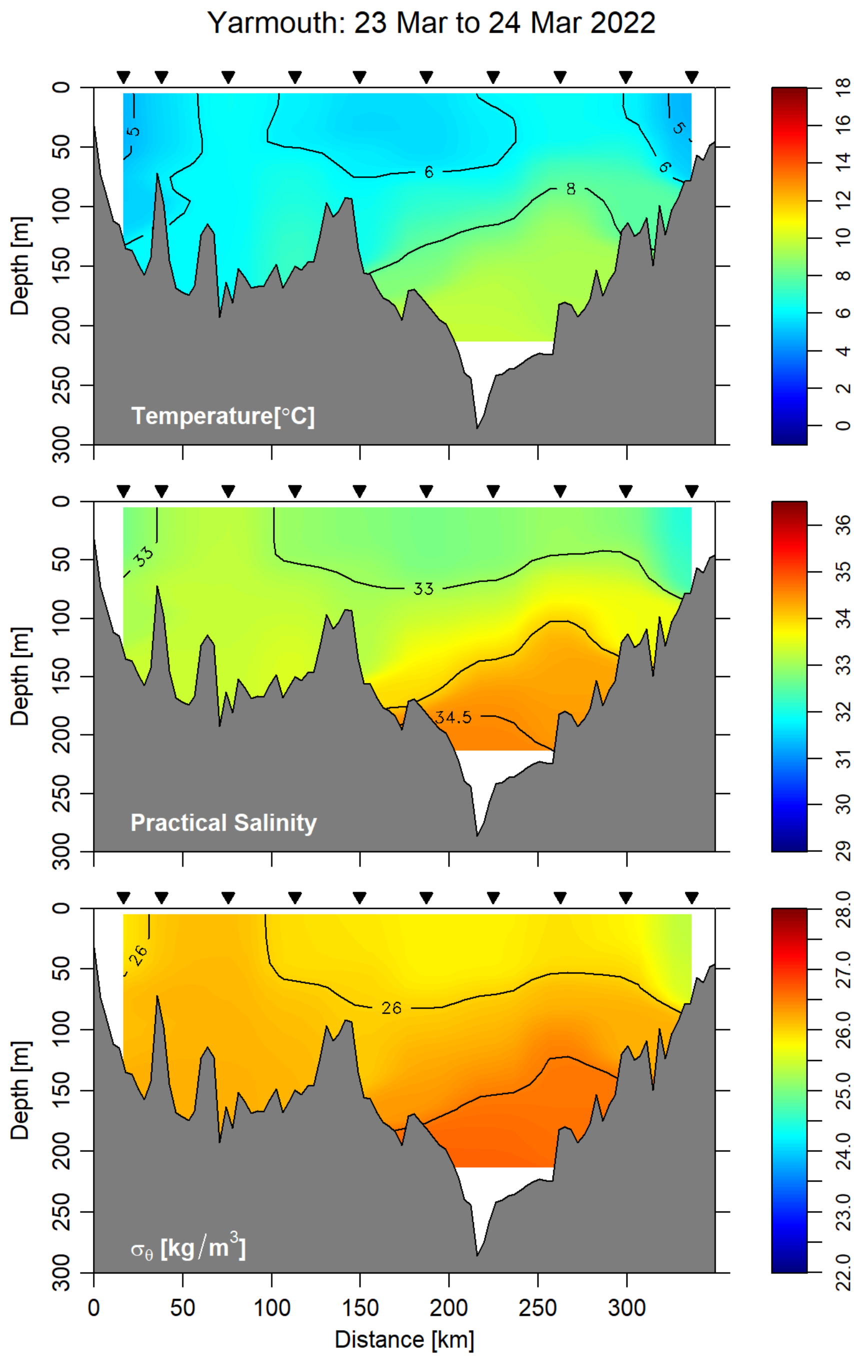

Figure A.16. The 2022 sampling of the Yarmouth section for spring collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.

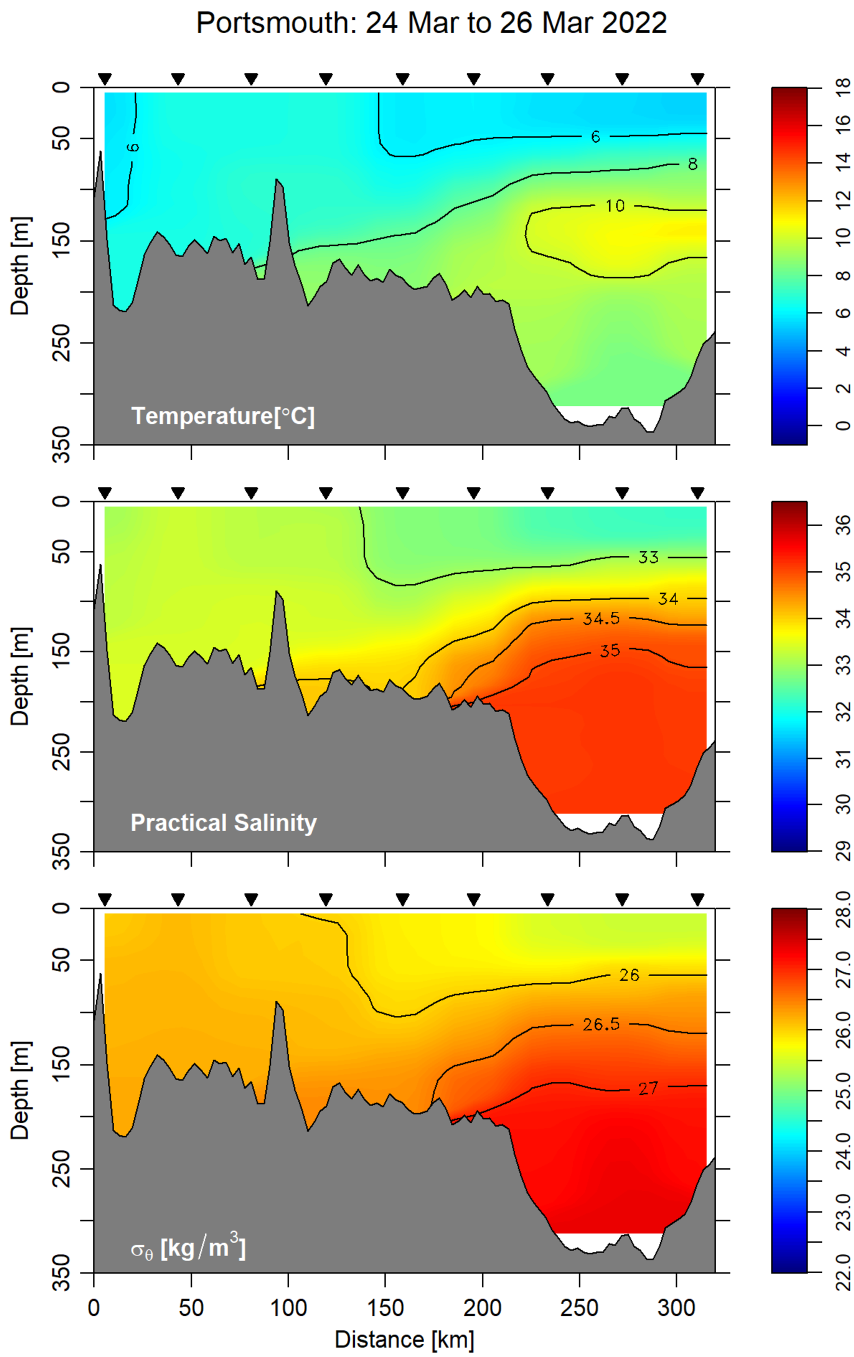

Figure A.17. The 2022 sampling of the Portsmouth section for spring collected by Maritimes AZMP. Temperature (top panel), salinity (middle panel), and density (lower panel). Triangles indicate locations of sampling.