Oceanographic conditions in the Atlantic zone in 2023

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ABSTRACT

Galbraith, P.S., Blais, M., Lizotte, M., Cyr, F., Bélanger, D., Casault, B., Clay, S., Layton, C., Starr, M., Chassé, J., Azetsu-Scott, K., Coyne, J., Devred, E., Gabriel, C.-E., Johnson, C.L., Maillet, G., Pepin, P., Plourde, S., Ringuette, M., Shaw, J.-L. 2024. Oceanographic conditions in the Atlantic zone in 2023. Can. Tech. Rep. Hydrogr. Ocean Sci. 379: v + 38 p.

This summarizes oceanographic conditions for 2023 detailed in Atlantic Zone Monitoring Program (AZMP) reports. Sea surface temperatures were overall second highest since records began in 1982. Summer cold intermediate layer conditions in the Gulf of St. Lawrence were fourth warmest and thinnest in the time series, but near normal elsewhere in the zone. Bottom temperatures remained high in the Gulf but reached normal temperatures almost everywhere else. In recent years a shift in the zooplankton community occurred, with lower abundances of *C. finmarchicus* and higher abundances of *Pseudocalanus* spp., causing a decline in overall zooplankton biomass. A zone-wide record high abundance of *C. finmarchicus* in 2023 moderated this pattern. The deep waters of the St. Lawrence Gulf and Estuary have experienced a decrease in the inflow of cold, oxygen-rich Labrador Current Water, accompanied by an increase in the influx of warm, oxygen-poor North Atlantic Central Water since 2009. This has led to unprecedentedly low pH levels in the St. Lawrence Estuary in 2023, as well as record-low oxygen saturation values in 2022. The increase in transport along the Scotian Shelf break observed in 2023 for the first time in a decade may be indicative of the stabilization of these trends.

RÉSUMÉ

Galbraith, P.S., Blais, M., Lizotte, M., Cyr, F., Bélanger, D., Casault, B., Clay, S., Layton, C., Starr, M., Chassé, J., Azetsu-Scott, K., Coyne, J., Devred, E., Gabriel, C.-E., Johnson, C.L., Maillet, G., Pepin, P., Plourde, S., Ringuette, M., Shaw, J.-L. 2024. Oceanographic conditions in the Atlantic zone in 2023. Can. Tech. Rep. Hydrogr. Ocean Sci. 379: v + 38 p.

Ceci résume les conditions océanographiques pour 2023 détaillées dans les rapports du Programme de monitorage de la zone atlantique (PMZA). Les températures à la surface de la mer étaient dans l'ensemble les deuxièmes plus élevées depuis le début des données en 1982. Les conditions estivales de la couche intermédiaire froide dans le golfe du Saint-Laurent étaient les quatrièmes plus chaudes et les plus minces de la série chronologique, mais près de la normale ailleurs dans la zone. Les températures au fond sont restées élevées dans le Golfe, mais ont atteint des températures normales presque partout ailleurs. Ces dernières années un changement dans la communauté zooplanctonique s'est produit, avec des abondances plus faibles de *C. finmarchicus* et des abondances plus élevées de *Pseudocalanus* spp., causant un déclin de la biomasse totale du zooplancton. L'abondance record au travers de la zone de *C. finmarchicus* en 2023 a atténué cette tendance. Les eaux profondes du golfe et de l'estuaire du Saint-Laurent ont connu depuis 2009 une diminution de l'apport d'eau froide et riche en oxygène du courant du Labrador, accompagnée d'une augmentation en apport d'eau chaude pauvre en oxygène qu'est l'eau centrale de l'Atlantique Nord. Ceci a conduit à des niveaux faibles de pH sans précédent dans l'estuaire du Saint-Laurent en 2023, ainsi qu'à des faibles valeurs record de saturation en oxygène en 2022. L'augmentation du transport océanique au talus du plateau néo-écossais, observée en 2023 pour la première fois depuis une décennie, pourrait cependant être le signe d'une stabilisation de ces tendances.

1. INTRODUCTION

The Atlantic Zonal Monitoring Program (AZMP) was implemented in 1998 (Therriault et al. 1998) with the aim of:

1. Increasing Fisheries and Oceans Canada's (DFO's) capacity to understand, describe, and forecast the state of the marine ecosystem; and
2. Quantifying the changes in ocean physical, chemical, and biological properties.

A critical element of the AZMP is an annual assessment of the physical oceanographic properties and of the distribution and variability of nutrients, phytoplankton and zooplankton.

A description of the distribution in time and space of nutrients and gases dissolved in seawater (nitrate, silicate, phosphate, oxygen) provides important information on water-mass movements and on the locations, timing, and magnitude of biological production cycles. A description of the distribution of phytoplankton and zooplankton provides important information on the organisms forming the base of the marine food web. An understanding of the production cycles of plankton is an essential part of an ecosystem approach to stock assessment and fisheries management.

The AZMP derives its information on the state of the marine ecosystem from data collected at a network of sampling locations (high-frequency sampling stations, cross-shelf sections and ecosystem surveys) in each of DFO's administrative regions in Eastern Canada (Quebec, Maritimes, Gulf, Newfoundland and Labrador) sampled at frequencies between weekly and annually (Figure 1).

The sampling design provides information on the natural variability in physical, chemical, and biological properties of the Northwest Atlantic continental shelf. Multispecies trawl surveys and cross-shelf sections provide detailed geographic information but are limited in their seasonal coverage. Strategically placed high-frequency sampling stations complement the broad scale sampling by providing more detailed information on temporal (seasonal) changes in pelagic ecosystem properties (Therriault et al. 1998). Sampling procedures are standardized across the zone and described in Mitchell et al. (2002). In addition, in 2023, 7 glider missions consisting of 14,272 profiles of temperature, salinity, oxygen, optical backscatter, chlorophyll and CDOM fluorescence were conducted on the Halifax Line. For the Bonavista Line, one mission collected 1,290 profiles. This glider mission also had a Minifluo sensor which measures fluorescent dissolved organic matter (FDOM) such as amino acids and polycyclic aromatic hydrocarbons (PAHs). Viking oceanographic buoys collected 947 vertical profiles throughout the zone.

This annual assessment of the State of the Atlantic Zone has included Labrador Sea observations collected by the Atlantic Zone Off-Shelf Monitoring Program (AZOMP) since the report on 2015 conditions. Information on ocean acidification was first presented in the report on 2018 conditions.

Environmental conditions are usually expressed as anomalies, i.e., deviations from their long-term mean. The long-term mean or normal conditions are calculated when possible for the 1991–2020 reference period for physical parameters, and for 1999–2020 for biogeochemical parameters. Furthermore, because these series have different units (°C, km^3, km^2, etc.), each anomaly time series is normalized by dividing by its standard deviation (SD), which is also calculated using data from the reference period. This allows direct comparison of the various series. Missing data are represented by grey cells, and near-normal conditions are designated by white cells. These are values within ± 0.5 SD of the average for physical parameters while a threshold of ± 1/3 SD is used for biological parameters. Conditions corresponding to warmer than normal (higher temperatures, reduced ice volumes, reduced cold-water volumes or areas) are shown as red cells, with more intense reds corresponding to increasingly warmer conditions or greater levels of biogeochemical variables. Similarly, blue represents colder than normal conditions or lower levels of biogeochemical variables. Higher than normal freshwater inflow, salinity or stratification are shown as red, but do not necessarily correspond to warmer than normal conditions. While we often describe the environment in terms of anomalies relative to the climatological period, it remains important to look at the long-term trends. We also often speak in terms of rank and series records which help to paint a broader picture.

2. PHYSICAL OCEANOGRAPHIC CONDITIONS

Peter S. Galbraith, Frédéric Cyr, Chantelle Layton, David Hebert, Joël Chassé, Jonathan Coyne, Jean-Luc Shaw

This is a summary of physical oceanographic conditions during 2023 for eastern Canadian oceanic waters (Figures 1 and 2) as reported annually by the AZMP in technical reports (e.g., Galbraith et al. 2024, Cyr et al. 2024 and Hebert et al. 2024 for conditions in 2023). Unless otherwise noted, the methodologies documented in these past reports are used here. Detailed descriptions of conditions in 2023 will be published in similar reports.

2.1 ANNUAL TEMPERATURE CYCLE

Ocean Temperature varies vertically through the seasons in the Atlantic Zone (Figure 3). The summertime temperature (T) structure consists of three distinct layers: the summertime warm surface layer, the cold intermediate layer (CIL), and the deeper water layer. During fall and winter, the surface layer deepens and cools mostly from wind-driven mixing and heat loss to the atmosphere prior to ice formation, but also partly because of reduced runoff and brine rejection associated with sea ice formation where it occurs. The surface winter layer extends to an average depth of about 50 m on the Scotian Shelf, 75 m in the Gulf of St. Lawrence (GSL) by March, and can extend to the bottom (>150 m) on the Labrador and Newfoundland Shelves. It reaches near-freezing temperatures in the latter two areas. During spring, surface warming, sea ice melt waters, and continental runoff lead to a lower salinity and higher temperature surface layer, below which cold waters from the previous winter are partly isolated from the atmosphere and form the summer CIL. This layer persists until the next winter, gradually warming and deepening during summer (Gilbert and Pettigrew 1997, Cyr et al. 2011). The CIL is, for the most part, locally formed in winter in separate areas around the zone (Galbraith 2006, Umoh and Thompson 1994, Umoh et al. 1995). For example, the temperature minimum of the winter mixed layer occurs at about the same time in March both on the Scotian Shelf and in the GSL, reaching different minimum temperatures; an indication of local formation rather than advection from one region to the other. However, transport occurs later in the year from the Labrador Shelf to the GSL (Galbraith 2006) and Newfoundland Shelf (Umoh et al. 1995) and from the GSL to the St. Lawrence Estuary (Galbraith 2006) and the Scotian Shelf (Umoh and Thompson 1994). The temperature minimum in southern parts of the Newfoundland Shelf (e.g., at Station 27) can occur well after winter; for example, in 2021 it was observed in June-July. Deep waters are defined here as those below the CIL that have only weak seasonal cycles.

2.2 SEA SURFACE TEMPERATURE

The satellite-based sea surface temperature product used here blends data from Pathfinder version 5.3 (1982–2021), Maurice Lamontagne Institute (1985–2013) and the GHRSST NOAA/STAR L3S-LEO-Daily “super-collated” product (0.02 degree resolution for 2007 to current; NOAA/STAR 2021). We download the day and night composites for each day and create a daily composite as the average of both values if available for a pixel, or using the available day or night pixel value minus or plus half of the average diurnal variation in the Atlantic Zone (0.22 °C). Daily pixel values were then calibrated against the daily range of observations at four offshore thermograph stations as well as all oceanographic Viking buoys (6,691 days of observations) by linear regression against the NOAA/LEO daily composite values at corresponding pixels and used as a calibration (SST = 1.01 LEO – 0.41). This calibration cools the NOAA/LEO daily composite values by 0.41 °C at 0 °C and by 0.19 °C at 20 °C.

Monthly temperature composites are calculated from averaged daily anomalies to which monthly climatological average temperatures are added (Galbraith et al. 2021). Figures 4 and 5 show monthly temperature composites and anomalies, and Figures 6 and 7 show area-averaged values by month and for the ice-free season.

Averaged over ice-free periods of the year as short as June to November on the Labrador Shelf, May to November in the Gulf, to the entire year on the Scotian Shelf, air temperature has been found to be a good proxy of sea surface temperature, and the warming trend observed in air temperature since the 1870s of about 1 °C per century is also expected to have occurred in surface water temperatures across Atlantic Canada (Galbraith et al. 2021).

Marine heatwaves are occurring more frequently as ocean temperatures increase. Following Hobday et al. (2016), we define a moderate marine heatwave as an event having temperatures above the 90th percentile lasting for a minimum of 5 days. The 90th percentile corresponds to a temperature anomaly threshold that changes seasonally and spatially. As proposed by Hobday et al. (2018), marine heatwave categories are defined by temperature anomalies exceeding multiples of this threshold, from moderate (1x), through strong (2x) and severe (3x) to extreme (4x).

In 2023, monthly average sea surface temperatures were generally normal to above normal in ice-free areas. Of the 143 regional monthly averages reported in Figure 6, a total of 105 were above normal, including 35 series records. Only 11 were below normal, 6 of them occurring in June when only two regional monthly averages were above normal. This cool period was followed by record highs in July in all regions except the Estuary, reflecting a month-long large-scale marine heatwave affecting the western North Atlantic. Of the 15 July record highs, the monthly average anomaly at four of the regions (2J, 3K, 3L and 3M) were at or more than +3.0 SD, with the area over Flemish Cap (3M) reaching +5.1 °C (+3.7 SD). Temperatures were also at record highs in winter on the Scotian Shelf, in August on the Labrador and northern Newfoundland Shelf, in September in 3P and in the Lower St. Lawrence Estuary, and in October in the Estuary, Gulf of St. Lawrence, and 3P/4V regions.

Another marine heatwave occurred in the Estuary; it was rated severe in September and extreme in October, when monthly anomalies reached +4.8 °C and +5.0 °C respectively. The average temperature at the end of September was higher than the climatological summer peak. The heatwave was 110 days long with an intensity peak on November 15.

Sea surface temperature seasonal averages were above normal across the zone (Figure 7), reaching record highs in the regions of the Labrador Shelf (2H, 2J), the northern Newfoundland Shelf (3K), Flemish Cap (3M), the northern Gulf of St. Lawrence and the Estuary. The spatially weighted zonal average was second highest of the time series.

2.3 THE NORTH ATLANTIC OSCILLATION

The North Atlantic Oscillation (NAO) index (Figure 7) is based on the sea-level atmospheric pressure difference between the sub-equatorial high and subpolar low and quantifies the dominant winter atmospheric forcing over the North Atlantic Ocean. The winter index used here is the December-March average of the monthly time series from the National Oceanic and Atmospheric Administration (NOAA). It affects winds, air temperature, precipitation, and hydrographic properties on the eastern Canadian seaboard either directly or through advection. Strong northwest winds, cold air and sea temperatures, and heavy ice in the Labrador Sea area have usually been associated with a high positive NAO index, with opposite effects occurring with a negative NAO index. The minimum value on record was reached in 2010 at -1.5, coinciding with warmer than normal conditions. The recent positive streak has, however, not coincided with winter conditions as cold as in the previous positive streak of the late-1980's/early-1990s. In 2023, the winter NAO index was near normal at +0.2.

2.4 COLD INTERMEDIATE LAYER

For the Newfoundland and Labrador Shelf, the CIL indices shown in Figure 7 are the cross-sectional areas of waters with T <0 °C during summer along the Seal Island, White Bay, Bonavista and Flemish Cap AZMP sections (Cyr et al. 2024). The time series for the Newfoundland and Labrador Shelf differ slightly from previous reports because a new calculation method was introduced (see upcoming report for documentation). For the Gulf, the CIL volume with T <1 °C observed in August-September is used (Galbraith et al. 2024). Because the CIL reaches to the bottom on the Magdalen Shallows in the Southern Gulf, the area of the bottom occupied by waters colder than 1 °C during the September survey is also used as a CIL index specific to that area (Galbraith et al. 2024). For the Scotian Shelf, the volume with T <4 °C observed in July is used (Hebert et al. 2024). The CIL indices reported here are taken at about the same time within their respective annual cycles, although not simultaneously.

The Gulf of St. Lawrence CIL volume was at record low in 2021, representing record warm conditions. The volume in summer 2023, while over twice as large as 2021, was fourth lowest. On the Scotian shelf, the 2022 CIL volume was not reported in last year's report because the survey did not cover the Eastern area where the CIL is usually prominent. A new analysis based on spatial anomalies has since been done that provides a volume estimate for 2022 indicating that it was a record low year (warm conditions). Conditions on the Scotian Shelf have cooled to near normal in 2023. The CIL area metric derived from the four AZMP sections on the NL shelf was at its 3rd lowest value on record in 2021, but it has returned to normal in 2023 with normal CIL areas on the White Bay and Flemish Cap sections and above normal CIL areas on the Seal Island and Bonavista sections.

2.5 SEA ICE

Because the CIL and sea ice cover are both formed in winter, it is not surprising that indices for both are well correlated with each other and with winter air temperature, and show the North-South advective nature of properties on the Newfoundland and Labrador Shelf. Seasonal average sea ice volume on the Southern Labrador Shelf is correlated with the CIL area further south along the Bonavista section (1980–2020, $R^2 = 0.70$) whereas Newfoundland Shelf sea ice metrics are correlated with December-March air temperature further north at Cartwright (1969–2022, $R^2 = 0.62$–0.78; Cyr et al. 2024). In the Gulf of St. Lawrence, the correlation between the December-March air temperature averaged over multiple coastal meteorological stations and the maximum annual ice volume reaches $R^2 = 0.74$ (1969–2022). Air temperature is similarly well correlated to sea ice cover area and duration ($R^2 = 0.75$–0.83; Galbraith et al. 2024). Sensitivity of the Gulf of St. Lawrence ice cover to climate change can be therefore estimated using past patterns of change in winter air temperature and sea ice features, which indicate losses of 18 km^3, 31,000 km^2 and 14 days of sea ice season for each 1 °C increase in winter air temperature (Galbraith et al. 2024).

Sea ice conditions on the Newfoundland and Labrador Shelf are provided by an index that encompasses duration and seasonal maximum area in three regions: Northern and Southern Labrador Shelf and Newfoundland Shelf (Cyr and Galbraith 2021). The index was second lowest in 2010, reached a record low in 2011, rebounded during 2014–2017 when heavy sea ice conditions were observed, was lower than normal in 2020 and 3rd lowest in 2021 (Figure 7). The index has been near normal for the last two years. On the Labrador Shelf, the first occurrence of sea ice was late with none in December and below normal conditions in January through March, but conditions were above normal in June leading to late last occurrence on the southern Labrador Shelf.

Sea ice conditions in the Gulf of St. Lawrence and the Scotian Shelf have been below normal since 2010 except for a rebound in 2014 and 2015. The record low seasonal maximum occurred in 2010 (Galbraith et al. 2024) but the record low seasonal average (January to March) occurred in 2021 (Figure 7). In the fourteen year period between 2010 and 2023, the seasonal average sea ice volume had ten of the fourteen lowest values of the series. In 2023, it was below normal (8 km^3; -1.1 SD), ranking 6th lowest since 1969, and almost no ice was exported onto the Scotian Shelf.

2.6 LABRADOR CURRENT AND SCOTIAN SHELF TRANSPORT INDEX

The annual-mean Labrador Current transport index (Han et al 2014, Cyr et al 2024) shows that transport along the Newfoundland and Labrador (NL) shelf break is generally out of phase with transport on the Scotian shelf break (Figure 7). Transport was strongest in the early 1990s and weakest in the mid-2000s over the NL shelf break, and opposite over the Scotian shelf break. The transport index is positively and negatively correlated with the winter NAO index over the NL and Scotian shelf, respectively. Variations in the westward transport of Labrador Slope Water from the Newfoundland region along the shelf break have been shown to have a strong effect on water masses of the Scotian Shelf deep basins, with increased transport through Flemish Pass associated with below normal deep temperatures and salinities on the Scotian Shelf and in the Gulf of Maine. The transport was above normal along the Newfoundland and Labrador Shelf break (+1.1 SD) and also along the Scotian Shelf break for the first time since 2011 (+1.4 SD). This indicates increased input of cold waters with high dissolved oxygen concentrations that may feed into the Gulf of St. Lawrence and Scotian Shelf at depth.

2.7 BOTTOM AND DEEP WATER TEMPERATURES

Interdecadal changes in temperature, salinity, and dissolved oxygen of the deep waters of the GSL, Scotian Shelf, and Gulf of Maine are related to the varying proportion of their source waters: cold—fresh/high-dissolved-oxygen Labrador Current water and warm—salty/low-dissolved oxygen Warm Slope Water (Gilbert et al. 2005). The >150 m water layer of the GSL below the CIL originates from an inflow at the entrance of the Laurentian Channel which circulates towards the heads of the Laurentian, Anticosti, and Esquiman Channels in up to roughly three to four years at 300 m after reaching Cabot Strait, with limited exchange with shallower upper layers (Gilbert et al. 2004). Deeper portions of the Scotian Shelf and Gulf of Maine are similarly connected to the slope through deep channels that cut into the shelves from the shelf break. Deep basins such as Emerald Basin undergo very large interannual and interdecadal variability of the bottom water temperature associated with deep renewal events. More regular changes associated with circulation are observed in bottom water temperature over the central and eastern Scotian Shelf (NAFO Divisions 4W and 4Vs respectively). Bathymetry in these areas is fairly evenly distributed between 30 m and 170 m, with 4Vs including some 400–450 m depths from the Laurentian Channel. Both these areas are therefore affected somewhat by CIL waters as well as the waters underneath.

In 2023, bottom temperatures have decreased in all areas of the zone, in some cases from record highs observed in 2020, 2021 or 2022 (Figure 7). They remained high in the Gulf but reached normal temperatures almost everywhere else. In the northern Gulf, bottom temperatures deeper than 200 m decreased to 2^{nd} highest of the time series, from the 2022 record that was associated with 100+ year records at 150, 200, 250 and 300 m. This is an indication that deep water temperatures are stabilizing in the Gulf. NAFO Division 3Ps had below-normal temperatures in the spring, the first such occurrence for a reported area since 2017.

2.8 RUNOFF AND STRATIFICATION

Freshwater runoff in the Gulf of St. Lawrence, particularly within the St. Lawrence Estuary, strongly influences circulation, salinity, and stratification (and hence upper-layer temperatures) in the Gulf and, via the Nova Scotia Current, on the Scotian Shelf. The runoff product is based on daily runoff estimated at Quebec City that are then lagged by 3 weeks to account for transport time to the Estuary, then combined with output from a hydrological watershed model for rivers flowing into the Estuary to form the RIVSUM II (Galbraith et al. 2024). The inter-annual variability of seasonal (May–October) stratification (0–50 m) at Rimouski Station in the Estuary is correlated with seasonally averaged RIVSUM II runoff (1991–2023; $R^2 = 0.59$, Figure 8). The 2023 annual runoff was above normal (18,800 m^3s^{-1}, +1.0 SD).

Stratification at Station 27 was normal in 2023. The time series differ from previous reports because a new calculation method was introduced (see upcoming report for documentation). Stratification on the Scotian Shelf was above normal in 2023 (+1.8 SD). 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} per 50 years (Figure 8). This change in mean stratification is due mainly to a decrease in the surface density, caused equally by warming and freshening. Stratification was above normal at Rimouski station (+0.6 SD). This was consistent with the seasonal average runoff (Figure 8). However the peak in stratification occurred much later than usual, in August instead of May.

2.9 CONDITIONS AT AZMP HIGH FREQUENCY SAMPLING STATIONS

At the high-frequency sampling sites (Figure 9), seasonal average 0–50 m temperature was at a record high at Shediac Valley and second highest at Rimouski station. It was below normal at Station 27 for the first time since 2009. Bottom temperatures at all sites were all near or above normal, second highest of the series at Rimouski and Shediac Valley. Near-surface salinity (0–50 m) was lower than normal at all sites except at Station 27, and second lowest at Rimouski. Stratification was normal to above normal, and second highest at Halifax 2.

2.10 SUMMARY

Surface oceanic waters in the Atlantic zone during ice-free months have been mostly tracking the climate-change driven warming trends observed in the atmosphere. Sea surface temperatures averaged over the 2023 ice-free months were all above normal across the zone, with seasonal series records set in six areas. The last three years have been the warmest on record.

Warming winters have also led to less sea ice cover and warmer/thinner cold intermediate layers, more notably on the western half of the Zone. The 2010–2021 period was characterized by record lows in 2021 and 2022 for CIL volumes in the Gulf of St. Lawrence and Scotian Shelf respectively, representing record warm conditions. In the fourteen-year period between 2010 and 2023, the seasonal average sea ice volume had ten of the fourteen lowest values of the 55-

year series. However, while the 2018–2021 period had been characterized by warm/thin CIL conditions on the Newfoundland and Labrador Shelf, conditions were generally near normal in 2023.

Deep water temperatures on the Scotian Shelf and Gulf of St. Lawrence have been greatly influenced by an increasing proportion of Gulf Stream Water relative to Labrador Water in recent years. However, the transport along the Scotian Shelf break was above normal in 2023 for the first time since 2011, indicating possible increased input of cold waters with high dissolved oxygen concentrations that may feed into the Gulf of St. Lawrence and Scotian Shelf at depth. Bottom temperatures have decreased in all areas of the zone, in some cases from record highs observed in 2020, 2021 or 2022. They remained high in the Gulf but reached normal temperatures almost everywhere else. In the northern Gulf, bottom temperatures deeper than 200 m decreased to 2nd highest of the time series, an indication that deep water temperatures are stabilizing. NAFO Division 3Ps had below-normal temperatures in the spring, the first such occurrence for a reported area since 2017.

Four annual composite index time series were constructed as the average of anomalies shown earlier and represent the state of different components of the system with each time series contribution shown as stacked bars (Figure 10). The components describe sea surface and bottom temperatures, as well as the cold intermediate layer and sea ice volume, which are both formed in winter. Two bottom temperature indices group areas with colder waters affected by CIL conditions and waters that are below the influence of the CIL. These four composite indices measure the overall state of the climate system with positive values representing warm conditions and negative representing cold conditions (e.g., less sea ice and CIL areas and volumes are translated into positive anomalies). Cumulated indices also give a sense of the degree of coherence between the various metrics of the environmental conditions and different regions across the zone. Sea surface anomalies are weighted to their spatial area (although not by the numbers of months in the season) and all four panels are weighted for missing values. On average over the zone, conditions in 2023 were second highest for surface temperatures, and above normal for CIL and sea ice anomalies as well as for bottom temperatures influenced by the CIL. Bottom temperatures below the influence of the CIL were above normal but decreased sharply from the 2022 record high. A total of 49 indices listed in Figures 7 and 9 describe ocean conditions related to temperature within the AZMP area in 2023 (SST; ice; summer CIL areas, volumes, and minimum temperature; deep and bottom temperature; 0–50 m average temperature). Of these, only two presented colder than normal conditions, 13 were within normal values (± 0.5 SD) and 34 were above normal, including 7 series records. This indicates a continuation of warmer than normal oceanographic conditions in 2023 across much of the Atlantic Zone, but with decreased intensity compared to 2022.

3. BIOGEOCHEMICAL ENVIRONMENT

Blais, M., Bélanger, D., Casault, B., Clay, S., Devred, E., Johnson, C.L., Maillet, G., Pepin, P., Plourde, S., and M. Ringuette

Lower trophic level organisms include phytoplankton and zooplankton. Together, they form the component of marine food webs that channel the sun’s energy to higher trophic level animals such as shellfish (e.g., crabs, lobsters, scallops, and mussels), finfish (e.g., capelin, cod, herring, and halibut), marine mammals (e.g., seals and whales), reptiles (e.g., leatherback and loggerhead turtles) and seabirds. Phytoplankton are microscopic algae that form the base of the aquatic food web and occupy a position in the marine food web similar to that of plants on land. There is a wide variation in the size of phytoplankton, from the small flagellates (< 5 μm) to the large diatoms (5–50 μm), with each taxon fulfilling a different ecological function. Phytoplankton are the primary food source for zooplankton, which are the critical link between phytoplankton and larger organisms. The zooplankton sampled are a broad variety of small animals ranging from 0.2 to 20 mm in length that drift with ocean currents. The zooplankton community includes animals such as copepods, gelatinous filter feeders and predators, and ephemeral larval stages of bottom-dwelling and planktonic invertebrates (i.e., meroplankton). As with phytoplankton, there is a broad range of sizes of zooplankton. Smaller zooplankton species and developmental stages are the principal prey of larval fish, and larger copepods are consumed predominantly by juvenile and adult fishes that feed in the water column.

The productivity of marine ecosystems depends primarily on photosynthesis, the synthesis of organic matter from carbon dioxide and dissolved nutrients by phytoplankton. Light provides the energy necessary for the transformation of inorganic elements into organic matter. The growth rate of phytoplankton is dependent on the availability of light and nutrients in the form of nitrogen (nitrate, nitrite, and ammonium), phosphorous (phosphate), and silica (silicate), with the latter being essential for the production of diatoms. During springtime, phytoplankton biomass increases rapidly, reaching a period of maximum biomass known as the spring bloom. The spring bloom occurs primarily in near-surface waters where light and nutrient conditions are optimal. In fall, a secondary bloom, usually less intense (i.e., lower biomass/shorter duration) than the spring bloom, also contributes to the functioning of the marine ecosystem. We report on the amount of nutrients available for phytoplankton, the concentration of chlorophyll-*a* (a proxy for phytoplankton biomass), important features of the spring bloom, and the biomass and abundance of key zooplankton taxa based on the data available from 1999 to 2023. In addition, this year's report includes information on fall bloom timing and intensity, which seems to have changed in recent years across the Atlantic zone (Casault et al. 2024, Blais et al. 2023, Maillet et al. 2022).

Indices of nitrate inventories, phytoplankton biomass, features of the spring and fall phytoplankton bloom derived from satellite observations, and zooplankton abundance and biomass from the Labrador Sea (Ringuette et al. 2022), Newfoundland Shelf (Maillet et al. 2022), Gulf of St. Lawrence (Blais et al. 2023) and Scotian Shelf (Casault et al. 2024) are summarized as time series of annual values in matrix form in Figures 11–14. Unless otherwise noted, the regional citations provided above include the methodologies used in this current assessment. Descriptions of the aforementioned indices in 2023 will be published in similar regional reports. Anomalies were calculated using a climatological reference period of 1999–2020 for the biogeochemical parameters derived from *in situ* observations during seasonal oceanographic surveys. The climatological reference period for the spring and fall bloom parameters derived from satellite observations of ocean colour is 2003–2020 since they are collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) "Aqua" sensor launched by National Aeronautics and Space Administration (NASA) in July 2002.

The relatively short time series of biogeochemical variables highlight the high degree of interannual variability of the lower trophic levels as compared to the physical variables. Even without long-term trends, distinct shifts for several biological variables are evident in recent years with the sign of anomalies persisting for several years. Moreover, a high degree of synchrony in biological index patterns of variation at adjacent locations can also be observed, although spatial variability may also be considerable in some instances.

3.1 NUTRIENTS

In continental shelf waters, nitrate, the dominant form of nitrogen, is usually the limiting nutrient for phytoplankton growth. The amount of nitrate contained in waters below the surface mixed layer is called the "subsurface nitrate inventory" (depths of 50–150 m for Labrador and Newfoundland Shelf, Gulf of St. Lawrence and Scotian Shelf, and depths deeper than 100 m for the Labrador Sea). Generally, this inventory is not greatly influenced by the growth of phytoplankton, so it provides a good indicator of resources that can be mixed into the surface mixed layer during winter, or by upwelling during summer and fall, to become available for phytoplankton growth. Subsurface nitrate inventories, and the relative abundances of other nutrients, are mostly dependent on the source waters that make up the deep water (> 150 m) on continental shelves, which can vary from year to year. Subsurface nitrate inventories in 2023 showed lower-than-normal inventories in most regions including the Labrador Sea, the St. Lawrence Estuary (Rimouski) and most of the Scotian Shelf, but higher-than-normal inventories on the Newfoundland Shelf and the Grand Bank, resulting in a slightly negative zonal index (Figure 11). Nitrate inventories for the Gulf of St. Lawrence were not available at the time of writing this report. In 2023, the Bonavista section exhibited a record-high subsurface water nitrate inventory for a second consecutive year, while the Bay of Fundy (station Prince 5) had a record-low inventory. Subsurface nitrate inventories have generally been above normal over the past five years along the Newfoundland Shelf while low nitrate inventories have been observed most years on the Scotian Shelf since 2016.

3.2 PHYTOPLANKTON

Chlorophyll *a* inventories in the upper ocean (0–100 m) are used as a proxy for the overall phytoplankton biomass. They exhibited a high degree of year-to-year variability (Figure 11). Part of this variation is explained by the timing of the program's oceanographic surveys throughout the zone relative to the timing of phytoplankton production, which varies according to environmental conditions.

Annual chlorophyll *a* inventories in 2023 were generally near or below normal on the Newfoundland Shelf and in the Gulf of St. Lawrence. In contrast, in the Labrador Sea and on the Scotian Shelf, annual chlorophyll *a* inventories ranged from near to above normal. The zonal annual chlorophyll *a* index was near-normal (Figure 11). The lower-than-normal chlorophyll *a* inventories in the Gulf of St. Lawrence ends an almost decade-long period of mainly positive anomalies. Although subsurface nutrient inventories provide some threshold to limit seasonal production dynamics across the zone, additional factors are likely to influence local nutrient-phytoplankton dynamics, such as the variability of the nutrient transfer from the subsurface layer to the surface waters where phytoplankton production occurs. The balance of these factors is likely to differ when considered at the very large spatial scale from the Gulf of Maine to the Labrador Sea, which includes estuarine to oceanic environments.

The timing and intensity of the spring and fall phytoplankton blooms provide important information about regional variations in ecosystem productivity and are linked to the production of organisms that depend directly on lower trophic levels. Bloom intensity (i.e., chlorophyll biomass production) partly depends on the amount of nutrients that are mixed into surface waters over the course of the winter for the spring bloom, or through episodic upwellings or water column mixing events such as windstorms during fall. Maximum production and bloom duration are also influenced by the amount of zooplankton grazing. Characteristics of the phytoplankton blooms were derived from daily composite concentration of chlorophyll *a* at the ocean surface based on satellite observations of ocean colour (MODIS 2003–2023; Figure 12). Intensity of the spring and fall blooms is inferred from the daily surface chlorophyll *a* concentration averaged over spring and fall seasons, respectively. These seasons are defined by the timing (start and end) of their respective bloom over the climatology, encompassing 80% of all climatology bloom starts and ends. Spring bloom timings were derived using a symmetric shifted Gaussian function of time (Zhai et al. 2011) while fall bloom timings are defined from the threshold method (Layton et al. 2022) due to the scarcity of data during late fall.

The timing of the 2023 spring phytoplankton bloom was normal to later than normal across the Atlantic zone, with particularly strong positive (i.e., late) anomalies throughout the Scotian Shelf (Figure 12). Record-late timing was also observed on the Greenland Shelf, Magdalen Shallows and eastern Scotian Shelf. The intensity of the spring bloom was highly variable across the Atlantic zone. While most anomalies suggest a weak spring bloom, some intense spring blooms also occurred on Lurcher Shoal, in the Northeast Gulf and in most of the northern Atlantic zone from northeast Newfoundland up to Greenland Shelf. The fall bloom timing showed considerable interannual and regional variability in the Atlantic zone over the time series (Figure 12). In 2023, the Scotian Shelf had earlier-than-normal fall bloom timing including record low (i.e., early) anomalies on Georges Bank and the central Scotian Shelf. In contrast, late fall bloom timing was widespread on the Newfoundland Shelf. Timing was normal in the Labrador Sea, except for a time series record early fall bloom on Hamilton Bank. In contrast to the strong variability in fall bloom timing, its intensity, measured by the mean fall surface chlorophyll *a* concentration, exhibited more regional coherence. Anomalies were positive in most parts of the Scotian Shelf, Gulf of St. Lawrence and northern Newfoundland Shelf. Anomalies were either neutral or slightly negative in the Labrador Sea and on Newfoundland Shelf south of Flemish Pass. Record-high fall chlorophyll *a* averages were found on the western Scotian Shelf, in most of the Gulf of St. Lawrence and in the Avalon Channel.

3.3 ZOOPLANKTON

Zooplankton community structure is strongly influenced by depth, temperature and season, and the community's composition differs greatly among the Northwest Atlantic bioregions. Despite regional composition and diversity differences, four indices of abundance provide good indicators of the state of the zooplankton community. Zooplankton abundance indices exhibited a high degree of large-scale coherence in their signal across different parts of the Atlantic zone (Figure 13). Copepods are by far the most abundant group, but non-copepods also significantly contribute to total zooplankton abundance. Two copepod taxa are used to characterize trends in different groups with similar life histories: *Calanus finmarchicus* and *Pseudocalanus* spp. *Calanus finmarchicus* is a large, ubiquitous copepod that dominates zooplankton biomass throughout most of the zone. It develops large energy reserves in later developmental stages and is therefore a rich source of food for pelagic fish. *Pseudocalanus* spp. are small copepods that are widespread throughout the Atlantic zone and have smaller energy reserves relative to *C. finmarchicus*. Their life history features are generally representative of smaller taxa in the copepod community. We also report on the dry biomass of the zooplankton in the 0.2–10 mm size fraction, which is typically dominated by copepods (Figure 14).

A shift in the size structure of the zooplankton community characterized by lower abundances of the large copepod *C. finmarchicus,* and higher abundances of small copepods and non-copepods occurred between 2014 and 2018. This trend has moderated between 2019 and 2022, with increases in *C. finmarchicus* and declines in *Pseudocalanus* spp., although the overall abundance of small copepod taxa and non-copepod zooplankton remained elevated (Figure 13). Over the Atlantic Zone, 2023 represents a return to pre-shift (i.e., pre-2014) conditions for some of the zooplankton indices. Indeed, *C. finmarchicus* showed widespread positive anomalies with a zonal record high and the first overall positive anomaly since 2010. There was high regional variability in non-copepod abundance anomalies: they were generally positive on the Newfoundland Shelf where they continued a decade-long pattern, negative in the Gulf of St. Lawrence and near normal along the Scotian Shelf. Mean non-copepod abundance for the zone declined to near-normal for the first time since 2012. Total copepod abundance also exhibited high spatial variability with a slightly negative zonal index, reflecting record low abundances in centre Gulf, Cabot Strait and Louisbourg section. *Pseudocalanus* spp.

abundances remained above normal levels across the zone with new record high abundance anomalies at the Shediac Valley station and on the Halifax and Browns Bank sections, except for Cabot Strait and most of the Gulf of St. Lawrence where a record low was registered in central Gulf.

Despite the general increase in *C. finmarchicus* abundances, zooplankton biomass was mainly normal or slightly below normal on the Newfoundland Shelf and below normal in the rest of the zone, except for the southern Gulf, Browns Bank section and Bay of Fundy (station Prince 5). New biomass record lows were set in the centre Gulf and Cabot Strait (Figure 14). In the Gulf of St. Lawrence, the low zooplankton biomass in 2023 is largely due to low *Calanus hyperboreus* abundance (not shown). Overall, the zonal index indicates lower-than-normal biomass for the second year in a row, similar to the 2015–2017 period that was marked by very low zooplankton biomass throughout most of the Atlantic zone. Recent findings in zooplankton community structure suggest that changes are taking place in the marine food web energy flow of the Atlantic Canadian waters (Blais et al. 2023, Casault et al. 2024, Maillet et al. 2022). These changes are associated with shifts in the distribution of North Atlantic right whales in their northwest Atlantic shelf foraging areas (Brennan et al. 2021) and may be associated with declines in herring (Brosset et al. 2019) in the Atlantic zone. However, the broader consequences to the marine ecosystem are not yet fully characterized.

4. OCEAN ACIDIFICATION AND DEOXYGENATION

Martine Lizotte, Frédéric Cyr, Michel Starr, Kumiko Azetsu-Scott, Marjolaine Blais, Joël Chassé, Carrie-Ellen Gabriel, Gary Maillet

Ocean acidification (OA) and deoxygenation represent significant oceanic stressors arising from anthropogenic climate and environmental changes (Pörtner et al. 2019). Ocean acidification is primarily driven by the absorption of atmospheric carbon dioxide (CO_2) by the oceans, leading to widespread alterations in oceanic chemistry, including declines in carbonate ion concentrations and pH (*i.e.*, increased concentration of hydrogen ions leading to an increase in acidity). Nearshore ocean acidification, characterized by a decrease in pH over decades or longer periods, arises not only from atmospheric CO_2 uptake but also from shifts in coastal and estuarine hydrographic and biogeochemical processes (Cai et al. 2021; Doney, 2010). Heightened acidity renders the water more corrosive to organisms that depend on calcium carbonate for their skeletons and shells. This includes mollusks, crustaceans, corals and shellfish. While historical data on acidification parameters exist in the Atlantic Zone (*e.g.*, Mucci et al. 2011), systematic measurements of OA parameters have been conducted by DFO since fall 2014 as part of the AZMP and the Aquatic Climate Change Adaptation Services Program (Gibb et al. 2023).

Deoxygenation results from a decrease in the oceans dissolved oxygen inventories primarily driven by increased ocean warming and stratification, as well as changes in ocean circulation and biogeochemistry (*e.g.*, eutrophication and organic matter remineralization, particularly in coastal areas) (Oschlies et al. 2018). Oxygen plays a pivotal role in governing biological and biogeochemical dynamics within the ocean. Reductions in oxygen levels can cause significant alterations in the range of habitats for marine organisms, as well as modifications in oceanic productivity, biodiversity, and biogeochemical cycling (Breitburg et al. 2018). Deoxygenation through microbial respiration can exacerbate ocean acidification, a phenomenon frequently observed in deep waters. DFO has been systematically measuring dissolved oxygen levels as part of the AZMP since 1998. Both ocean deoxygenation and acidification can heighten physiological stress in a wide range of marine organisms.

4.1 OCEAN ACIDIFICATION

In addition to pH, the calcium carbonate saturation states with respect to calcite and aragonite (Ω_{cal} and Ω_{arg}) serve as indicators of ocean acidification, reflecting the propensity for calcium carbonate to dissolve. Below a threshold of 1, the environment is considered undersaturated with respect to calcium carbonate and potentially corrosive to biogenic carbonate shells. Ω typically decreases with depth, and thus deep slope waters tend to have lower Ω than the shallower shelf bottom regions. In 2023, bottom water Ω_{arg} was slightly undersaturated in the Avalon channel, on the Grand Banks, in the deepest parts of the Newfoundland Shelf slope and the eastern Scotian Shelf (Figure 15, top row). Most of the bottom waters within the Gulf of St. Lawrence, encompassing even the shallower southern region, exhibited undersaturation with respect to aragonite. The only exceptions were observed in inflowing waters within the Strait of Belle Isle and the Cabot Strait, and in the Northumberland Strait where Ω_{arg} in the bottom waters were >1. Saturation states for calcite in the Atlantic Zone were >1 in the bottom waters of the Scotian Shelf and Newfoundland Shelf (Figure 15, bottom row). In most bottom waters of the Gulf of St. Lawrence, values of Ω_{cal} were above the threshold of 1, except for certain stations in the southern and northwest Gulf of St. Lawrence, as well as in the lower St. Lawrence Estuary, where undersaturation with respect to calcite was observed. This represents an expansion of Ω_{cal} undersaturation in bottom waters of the lower St. Lawrence Estuary compared to 2018 (Figure 15, bottom row). Such an expansion was projected by numerical models on Ω_{cal} undersaturation time of emergence (Lavoie et al. 2020).

The Gulf of St. Lawrence has experienced the fastest decrease in pH of the Atlantic Zone, at a rate of about 0.04 units per decade since 1934 (Bernier et al., 2023). From 2018 to 2023, values of near-bottom pH in the Gulf of St. Lawrence have shown a general decline. In 2023, the lowest pH values occurred in the deep Laurentian channel (Figure 16, top row), particularly notable in the St. Lawrence Estuary, where most of the deep layer (>300 m) also exhibited undersaturation with respect to aragonite and calcite. Levels of pH remained consistently below 7.6 throughout the Estuary, indicating increased acidification compared to conditions observed in 2022 (DFO, 2023). At Station Rimouski, a monthly average low of 7.47 (new record) was reached in the bottom 50 m of the water column in 2023 (Figure 17). Overall, the rates of pH decrease in Atlantic Canadian waters (0.03–0.04 per decade) are generally faster than the global average for surface pH (0.017–0.027 per decade) are generally higher than in other parts of the world ocean (Bernier et al., 2023). Bottom water pH values on the Scotian, Newfoundland, and Labrador shelves ranged from 7.8 to above 8 during summer, demonstrating considerable spatial variability (Figure 16, top row). A slight decrease in bottom water pH on the Newfoundland Shelf (Station 27), has been observed since pH measurements began in 2014 within the AZMP (Figure 17). This signal is, however, marked by strong interannual variability. Conversely, the surface waters at Station 27 do not show a similar decline, and display greater interannual variability than bottom waters (Figure 17). In 2023, surface pH and Ω_{arg} were lower on the Newfoundland and Labrador Shelf compared to the Scotian Shelf (data not shown), highlighting the natural disparity that exists between sub-regions of the North Atlantic in terms of their OA sensitivities (Cai et al. 2020).

4.2 DISSOLVED OXYGEN SATURATION

Dissolved oxygen saturation was generally high across the zone, except for the bottom waters of the deep channels of the Gulf of St. Lawrence (Figure 16, bottom row). As deep waters slowly flow from the mouth of the Laurentian Channel to its head in the St. Lawrence Estuary, the dissolved oxygen content gradually decreases due to microbial respiration and oxidation of sinking organic material. Consequently, the deepest waters of the estuary, particularly at the head of the Laurentian Channel, exhibit the lowest levels of dissolved oxygen. In the early

1970s, dissolved oxygen saturation ranged between 30 and 40% and have consistently been hypoxic (below 30%) since 1984 (Gilbert et al. 2005).

Various factors may have driven the decadal alterations in dissolved oxygen concentration and saturation within the deep waters of the Gulf of St. Lawrence. While part of the oxygen depletion may have stemmed from enhanced oxygen utilization in response to elevated temperatures and eutrophication in the St. Lawrence Estuary, the fluctuating ratio of oxygen-rich Labrador Current Water (LCW) and oxygen-poor North Atlantic Central Waters (NACW) entering the Laurentian Channel has likely exerted a predominant influence (Gilbert et al., 2005). Sudden swift reductions in oxygen levels observed since 2008 in the deep waters of the Gulf of St. Lawrence could have arisen from a diminished influx of highly oxygenated LCW into the deep waters of the system, favouring pulses of low-oxygenated NACW (Jutras et al. 2020). These circulation alterations also likely accounted for the rapid rise in deep bottom temperatures in the St. Lawrence Gulf and Estuary (Chapter 2). Recent findings suggest that temperature fluctuations within the deep St. Lawrence Estuary explain up to 74% of the variations in dissolved oxygen (Galbraith et al. 2017), reinforcing the presumed influence of circulation dynamics on oxygen levels in this area of the Atlantic zone.

In 2023, oxygen saturation at many sampling locations in the deep waters of the Estuary and northwest Gulf was well below 20% (Figure 16, bottom row), dropping to <12% at some stations. This represents a significant decline compared to 2018, when saturation levels <20% were only observed at the head of the Laurentian Channel. The historical lowest monthly average of oxygen saturation in the bottom waters was recorded in 2022 at Rimouski station, dropping below 9% (Figure 18, top panel). Monthly mean oxygen saturation in the bottom waters at Station 27 in 2023 (Figure 18, bottom panel) remained within the bounds of the historical series range (from 75% to near 100%).

5. CONCLUSION

While a shift to warmer ocean conditions occurred prior to the implementation of the AZMP, the period since 2010 has seen further warming with sea surface temperatures reaching record values across the zone in summer 2022 and second highest in 2023. Winter average sea ice volume was below normal in the Gulf of St. Lawrence and sea ice conditions were near normal on the Newfoundland and Labrador shelf. The summer cold intermediate layer conditions were fourth warmest and thinnest in the Gulf of St. Lawrence, but near normal elsewhere in the zone. Bottom temperatures remained high in the Gulf but reached normal temperatures almost everywhere else. In the northern Gulf, bottom temperatures deeper than 200 m decreased to 2nd highest of the time series, an indication that deep water temperatures are stabilizing.

Patterns of variation in biogeochemical variables appear dominated by short-term fluctuations over the course of the twenty-five-year time series. However, there is evidence of multi-year shifts in recent years. The current state of the biogeochemical environment demonstrates some spatial structuring across the Atlantic Zone. Overall, there appears to have been changes in the productivity of lower trophic levels in recent years, especially highlighted by changes in the zooplankton community. Following a period of general decline in overall zooplankton biomass associated with lower abundances of *C. finmarchicus* and higher abundances of *Pseudocalanus* spp. that suggested lower ecosystem production potential over the past decade or so, high levels of phytoplankton biomass during fall and zonal record high abundance of *C. finmarchicus* in 2023 moderated this pattern and might suggest changes in the seasonality of lower trophic level production. However, zooplankton biomass in 2023 was highly similar to the 2015–2017 low production potential period.

The accumulation of anthropogenic CO_2 in the atmosphere and its uptake by the surface ocean have led to an increase in CO_2 in the ocean and a decrease in pH. This acidification has likely been further exacerbated by biogeochemical and hydrographic processes particularly in nearshore regions of the Atlantic zone. The rates of pH decrease in Atlantic Canadian waters are generally higher than in other parts of the world ocean. The deoxygenation and decreasing pH in the deep waters of the St. Lawrence Gulf and Estuary are consistent with the increasing influence of oxygen-poor North Atlantic Central Water (NACW) and decreasing fraction of oxygen-rich Labrador Current Water (LCW) water in the region. This persistent pattern, observed since approximately 2008, has led to unprecedentedly low pH levels in the St. Lawrence Estuary in 2023, as well as record-low oxygen saturation values in 2022, highlighting the need for continued studies on the impacts of deoxygenation and ocean acidification on the vulnerability of aquatic species and their associated biological and ecological processes. The increase in LCW transport along the Scotian Shelf break observed in 2023 for the first time in a decade (see physical oceanography chapter) may, however, be indicative of a stabilization of these trends in the short term.

5.1 SUMMARY

- Monthly average sea surface temperatures were at record highs in July in all NAFO and other averaging regions (Figure 2, top panel) except the St. Lawrence Estuary, where records were reached later in September and October, when monthly anomalies reached +4.8 °C and +5.0 °C respectively. Of the 15 July record highs, the monthly averaged anomaly at four of the regions (2J, 3K, 3L, 3M) were at or more than +3.0 SD, with the area over Flemish Cap (3M) reaching +5.1 °C. Temperatures were also at record highs in winter on the Scotian Shelf, in August on the Labrador and northern Newfoundland Shelf, in September in 3P and in the Lower St. Lawrence Estuary, and in October in the Estuary, Gulf of St. Lawrence, and 3P/4V regions.
- The July SST records reflect a month-long large-scale marine heatwave affecting the western North Atlantic. The fall anomalies in the St. Lawrence Estuary were a separate marine heatwave that lasted 110 days. It was rated severe in September and extreme in October. Estuary surface temperatures at the end of September were higher than the climatological summer peak.
- Sea surface temperature seasonal averages were above normal across the zone, reaching record highs in regions of the Labrador Shelf (2H, 2J), the northern Newfoundland Shelf (3K), Flemish Cap (3M), the northern Gulf of St. Lawrence and the Estuary. The spatially weighted zonal average was second highest of the time series.
- The Labrador Current transport was above normal along the Newfoundland and Labrador Shelf break. The transport along the Scotian Shelf break was also above normal for the first time since 2011. This indicates possible increased input of cold waters with high dissolved oxygen concentrations that may feed into the Gulf of St. Lawrence and Scotian Shelf at depth.
- Winter average sea ice conditions were below normal in the Gulf of St. Lawrence and near normal on the Newfoundland and Labrador Shelf as well as in the Northern Labrador Sea. First and last occurrences were late on the Labrador Shelf. In the 14-year period between 2010 and 2023, the Gulf of St. Lawrence seasonal average sea ice volume had 10 of the 14 lowest values in the 55-year time series.
- The cold intermediate layer (CIL) indices were lower than normal in the Gulf of St. Lawrence, normal to lower-than-normal on the Newfoundland and Labrador Shelf, and

normal on the Scotian Shelf. All regions show cooling since the records of 2021 in the Gulf and on the Newfoundland and Labrador Shelf, and of 2022 on the Scotian Shelf.

- Bottom temperatures have decreased in all areas, in some cases from record highs observed in 2020, 2021 or 2022. They remained high in the Gulf but reached normal temperatures almost everywhere else. NAFO Division 3Ps had below-normal temperatures in the spring, the first such occurrence for a reported area since 2017.
- At the high-frequency sampling stations (Figure 1):
  - Seasonal average 0–50 m temperature was at a record high at Shediac Valley and second highest at Rimouski station. It was below normal at Station 27 for the first time since 2009.
  - Bottom temperatures at all sites were all near or above normal, second highest at Rimouski and Shediac Valley.
  - Near-surface salinity (0–50 m) was lower than normal at all sites except at Station 27, second lowest at Rimouski.
  - Stratification was normal to above normal, second highest at Halifax 2. It was also third highest averaged annually over the Scotian Shelf.
- Subsurface nitrate inventories were above normal across the Newfoundland and southern Labrador Shelf for the second consecutive year. In contrast, the Labrador Sea, the St. Lawrence Estuary (Rimouski) and the Scotian Shelf exhibited near or below normal levels, including a record low in the Bay of Fundy (Prince 5). On the western Scotian Shelf, deep nitrate inventories have remained below average since 2016.
- Chlorophyll *a* inventories were near normal or below normal on the Newfoundland and southern Labrador Shelf and most of the Gulf of St. Lawrence, and near or above normal on the Scotian Shelf and in the Labrador Sea. It has been above normal in the northwest Gulf of St. Lawrence since 2018.
- The timing of the spring phytoplankton bloom peak was near or later-than normal throughout the Atlantic Zone, with record late timing occurring on the Greenland Shelf, Magdalen Shallows and Eastern Scotian Shelf. This contrasts with earlier-than-normal blooms in recent years.
- The mean spring surface chlorophyll *a* concentration, a measure of the bloom intensity, showed a north to south gradient. Anomalies were mostly positive in the Labrador Sea, including Hamilton Bank where there was a record high, and on the northern Newfoundland Shelf. They were mostly negative on the Grand Banks, the Scotian Shelf and the Gulf of St. Lawrence, with the exception of record highs in the northeast Gulf and on Lurcher Shoal.
- The timing of the fall bloom onset showed high variability. Record early onsets were recorded on Hamilton Bank, central Scotian Shelf and Georges Bank. Timing was generally late on the Newfoundland Shelf and early on the Scotian Shelf.
- The mean fall surface chlorophyll *a* concentration was particularly high in the Gulf of St. Lawrence including three record highs in its four subregions, and on the Scotian Shelf with a record high on the western Scotian Shelf. There were positive anomalies on the northern Newfoundland Shelf and a record high in the Avalon Channel.
- Copepod abundances were highly variable across the Atlantic Zone in 2023 with the zonal index being slightly below normal as a result of record-low abundances registered in centre Gulf, Cabot Strait and on Louisbourg sections.

- The abundance of non-copepods was above normal on most of the Newfoundland and Labrador Shelf, continuing a decade-long pattern, generally below normal in the Gulf of St. Lawrence and relatively close to normal on the Scotian Shelf.
- *Pseudocalanus* spp. abundance was above normal on the Newfoundland and Labrador Shelf, continuing a trend that started in 2013, and over most of the Scotian Shelf and southern Gulf. Shediac Valley station, Halifax and Browns Bank sections exhibited record highs. The northern and centre Gulf exhibited below normal abundances, including a record low in the latter.
- The abundance of *Calanus finmarchicus* was above normal in most of the Atlantic Zone, with four record highs spread over the Zone, leading to a zonal record. Such widespread positive anomalies have not been observed since 2008.
- Zooplankton biomass was mostly near or below normal across most of the Atlantic Zone, with record lows in centre Gulf and Cabot Strait. The southern Gulf and Browns Bank had noteworthy positive biomass anomalies associated with record high *Calanus finmarchicus* abundance.
- The rates of pH decrease in Atlantic Canadian waters are generally higher than in other parts of the world.
- From 2018 to 2023, values of near-bottom pH in the Gulf of St. Lawrence have shown a general decline. The lowest pH and calcium carbonate saturation states (Ω) values were observed along the deep Laurentian channel, especially in the hypoxic waters of the Lower St. Lawrence Estuary, where the deep layer (>300 m) was undersaturated with respect to aragonite and calcite, and where pH values were below 7.6 throughout the Estuary (monthly mean record low of 7.47 in 2023 at Station Rimouski).
- The bottom waters of the St. Lawrence Estuary remained in a state of severe dissolved oxygen undersaturation (<20%), and values at Rimouski station in 2023 were close to the 2022 record low levels.

ACKNOWLEDGMENTS

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FIGURES

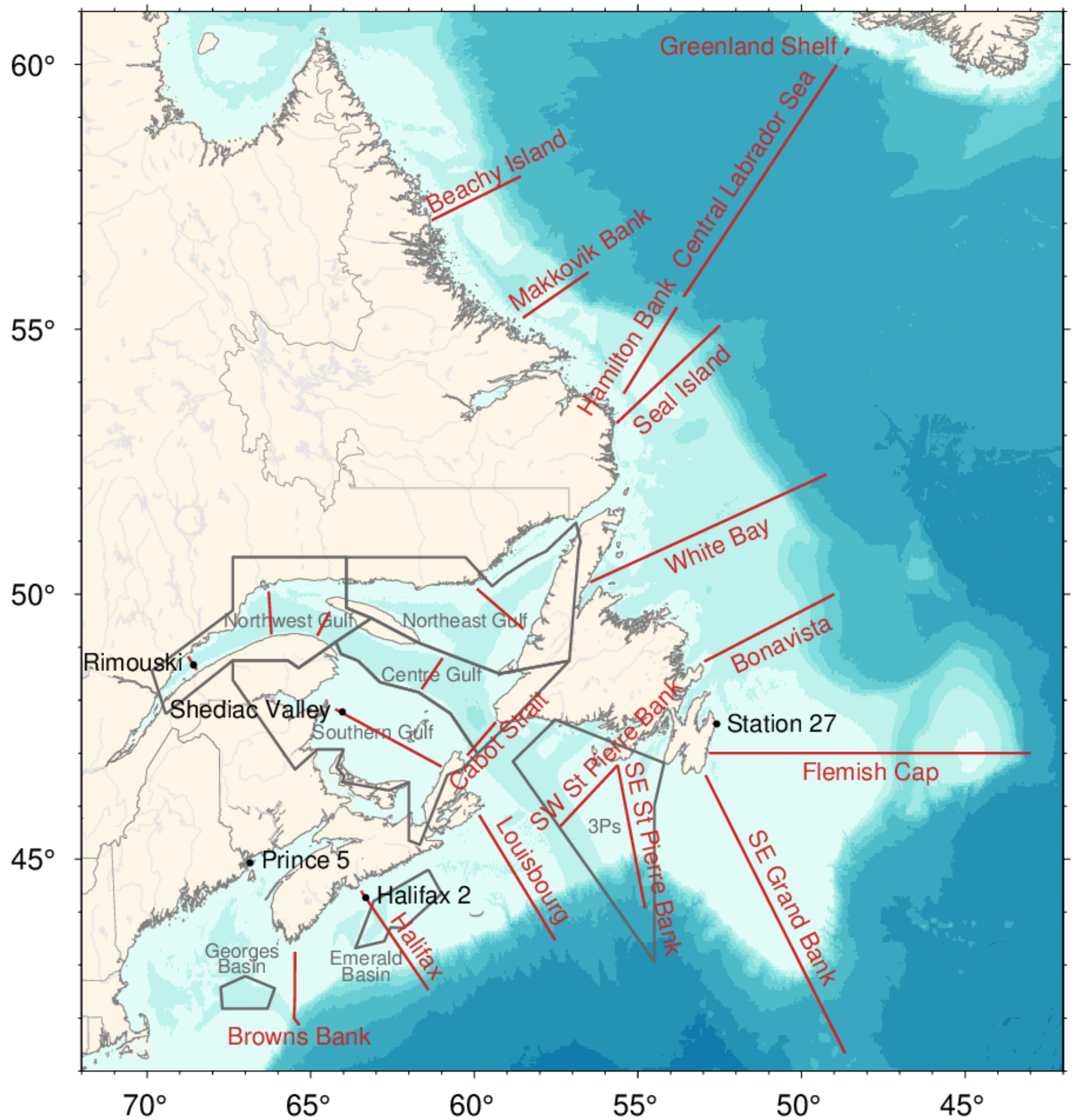

Figure 1. Atlantic Zone Monitoring Program high-frequency sampling stations (black), selected section lines (red) and averaging areas (gray).

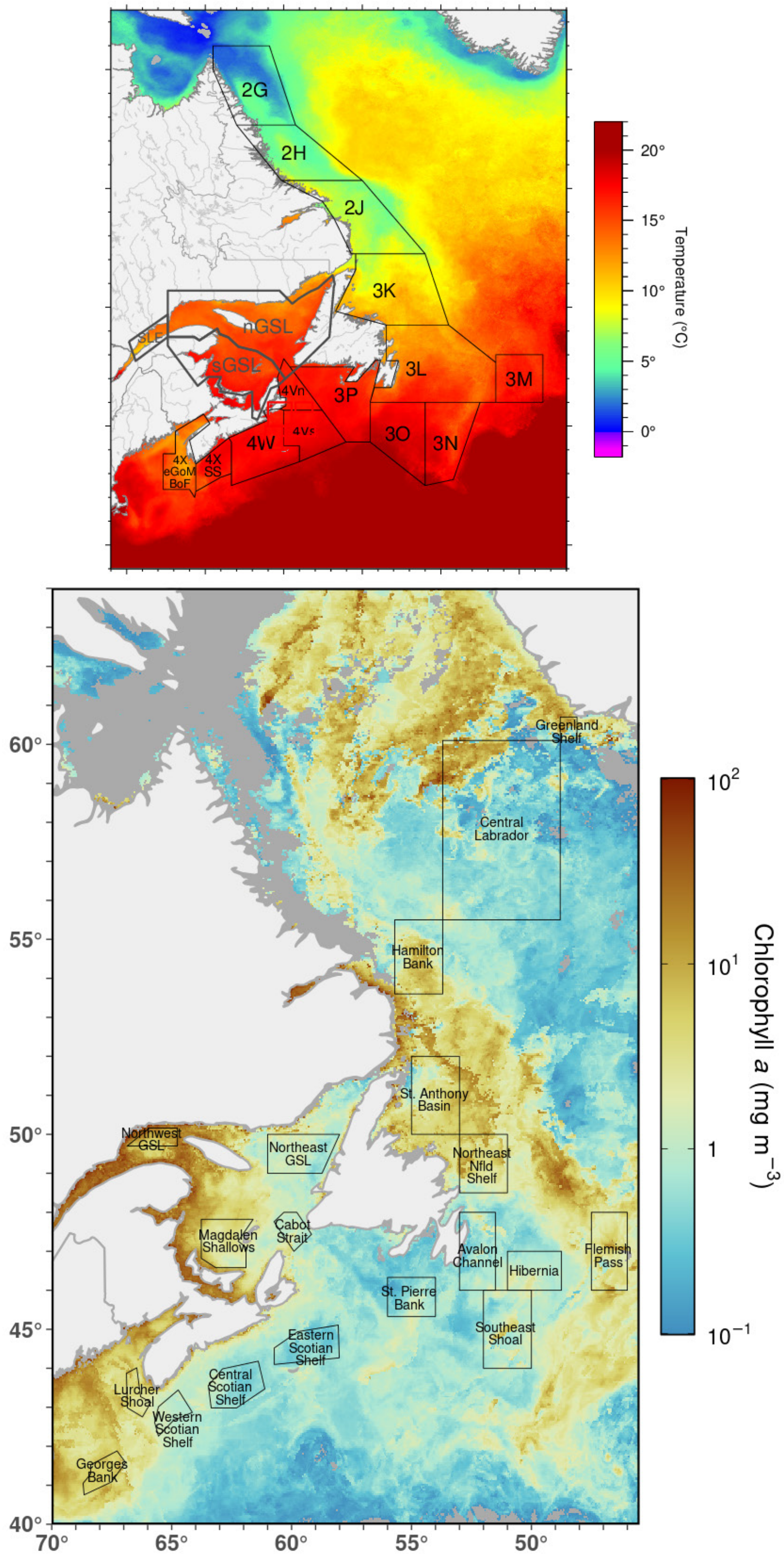

Figure 2. Areas used for (top) temperature and (bottom) ocean colour averages. (Top) North Atlantic Fisheries Organization Divisions are cut off at the shelf break. The acronyms GSL and SLE are Gulf of St. Lawrence and St. Lawrence Estuary respectively. Sea surface temperatures are shown for September 2023 and ocean colour chlorophyll *a* concentrations are for May 2023.

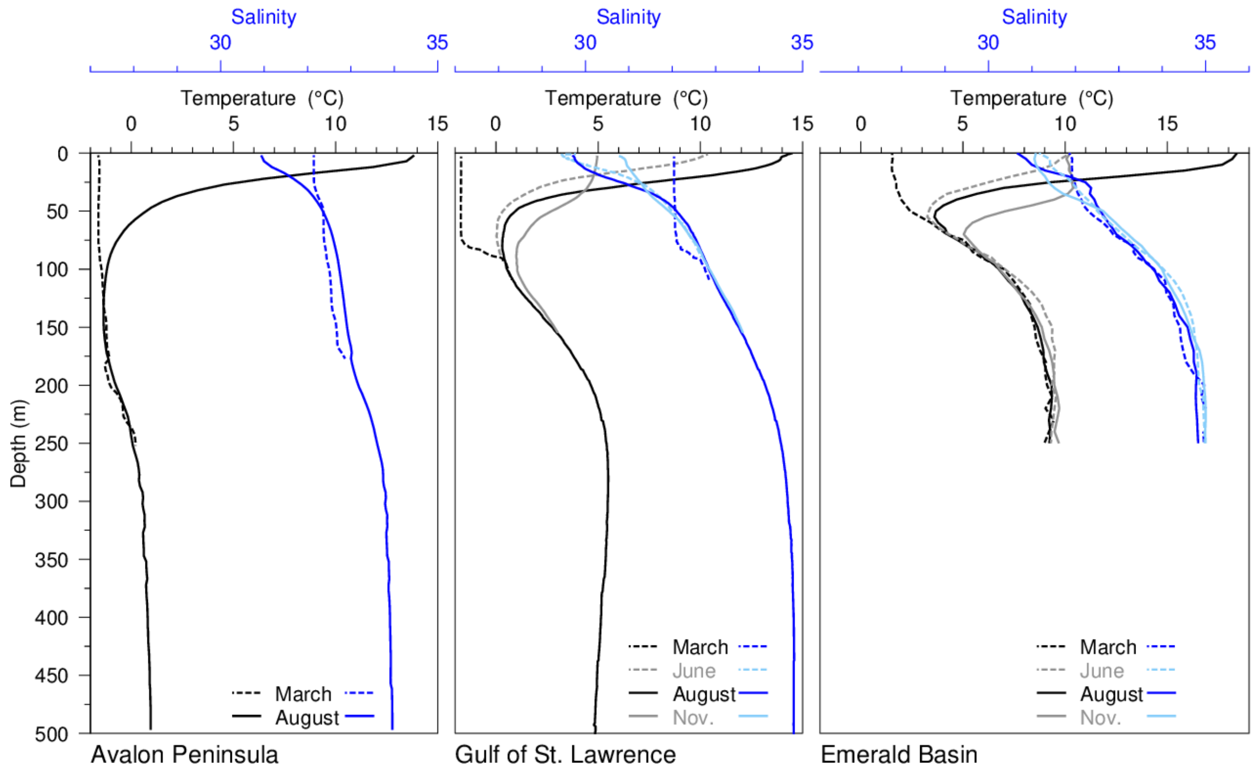

Figure 3. Typical seasonal progression of the depth profile of temperature and salinity observed in three representative regions across the zone. The Avalon Peninsula region is delimited by 45–50°N and 50–55°W and shown are the averages of profiles for March and August between 2015 and 2017, calculated from 5 and 302 profiles respectively. The Gulf of St. Lawrence profiles are averages of observations in June, August and November 2007 in the northern Gulf, while the March profile shows a single winter temperature profile (March 2008), with near-freezing temperatures in the top 75 m. The Emerald Basin profiles are monthly climatological averages for 1981–2010.

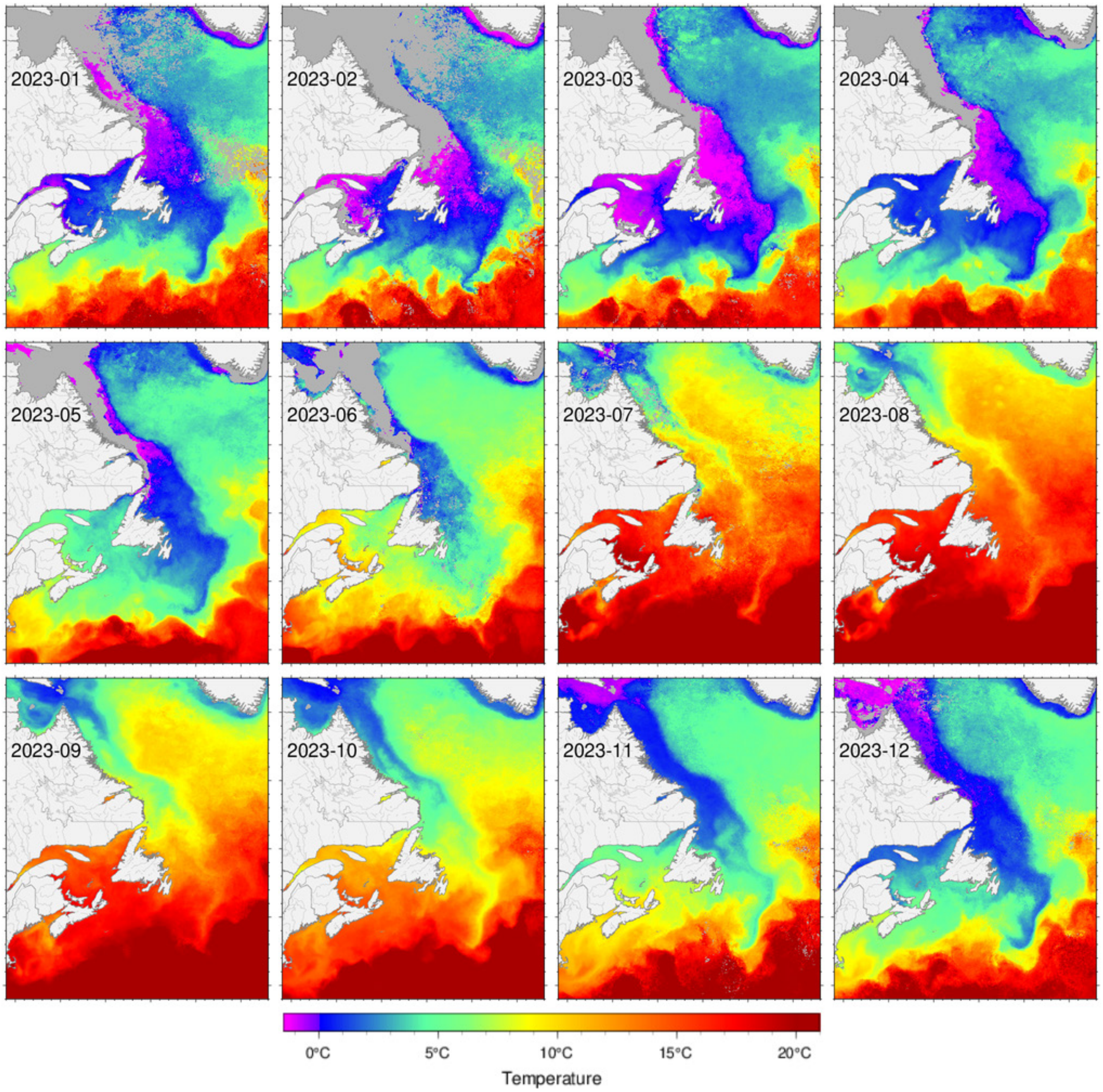

Figure 4. Sea surface temperature monthly averages for 2023 in the Atlantic zone.

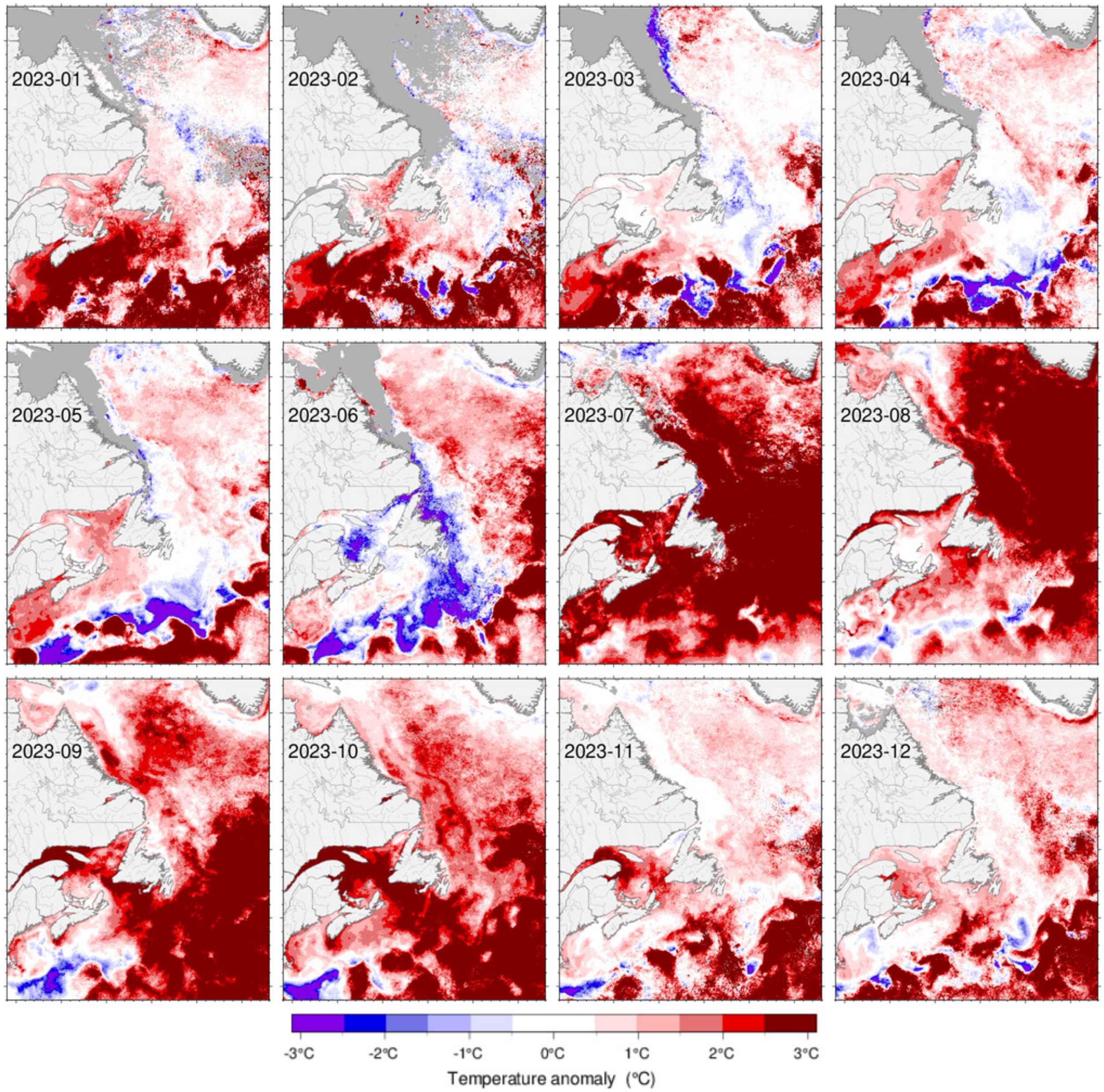

Figure 5. Sea surface temperature monthly anomalies for 2023 in the Atlantic zone. Temperature anomalies are based on a 1985–2010 climatology and not the 1991–2020 used elsewhere in this document.

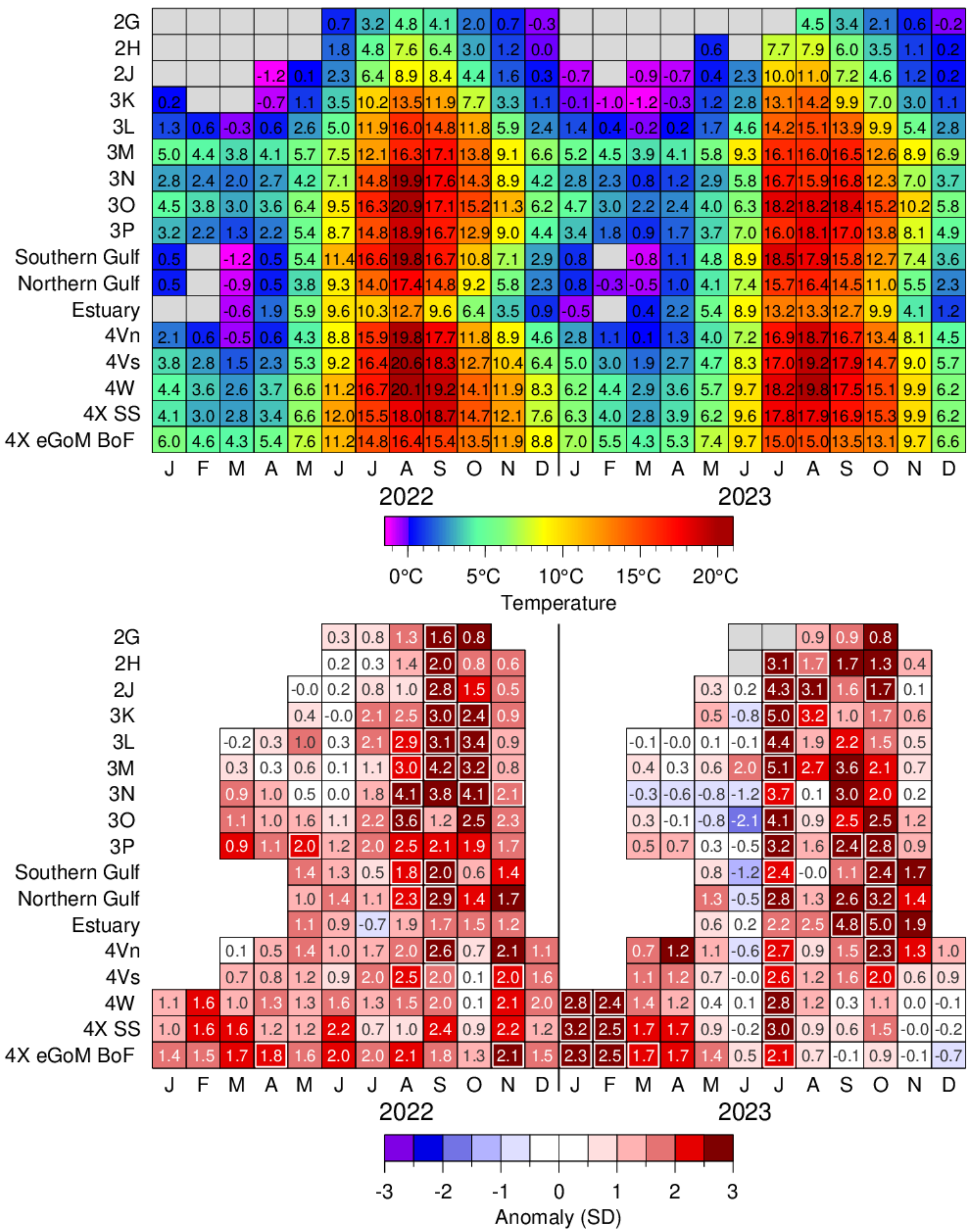

Figure 6. Monthly sea surface temperatures (top) and anomalies in °C (bottom) for ice-free months of 2022–2023, averaged over the 17 regions shown in the top panel of Figure 2. Regions and months for which the average temperature was at a record high or low are indicated by white outlines. Grey squares have insufficient data coverage to yield a monthly average anomaly (<7%).

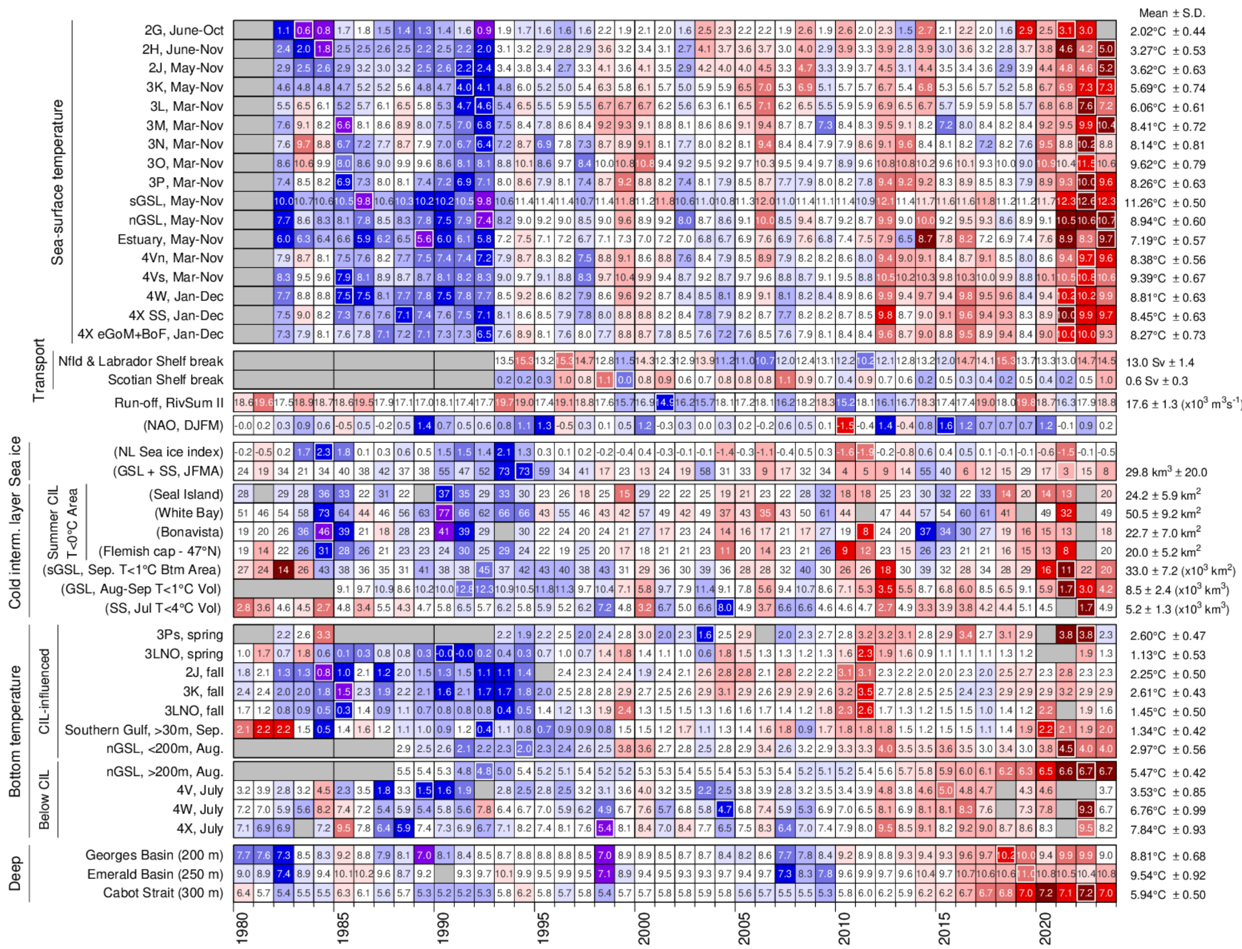

Figure 7. Time series of oceanographic variables, 1980–2023. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1991 to 2020 when possible; a red cell indicates above normal conditions, and a blue cell below normal. Variables whose names appear in parentheses have reversed colour coding, whereby reds are lower than normal values that correspond to warm conditions. More intense colours indicate larger anomalies. Series minimums and maximums are indicated by a white outline when they occur in the displayed time span. Long-term means and standard deviations are shown on the right-hand side of the figure. (RIVSUM II is the combined runoff flowing into the St. Lawrence Estuary. North Atlantic Oscillation [NAO], GSL [Gulf of St. Lawrence], SS [Scotian Shelf], sGSL [southern Gulf of St. Lawrence], nGSL [northern Gulf of St. Lawrence], cold intermediate layer [CIL]).

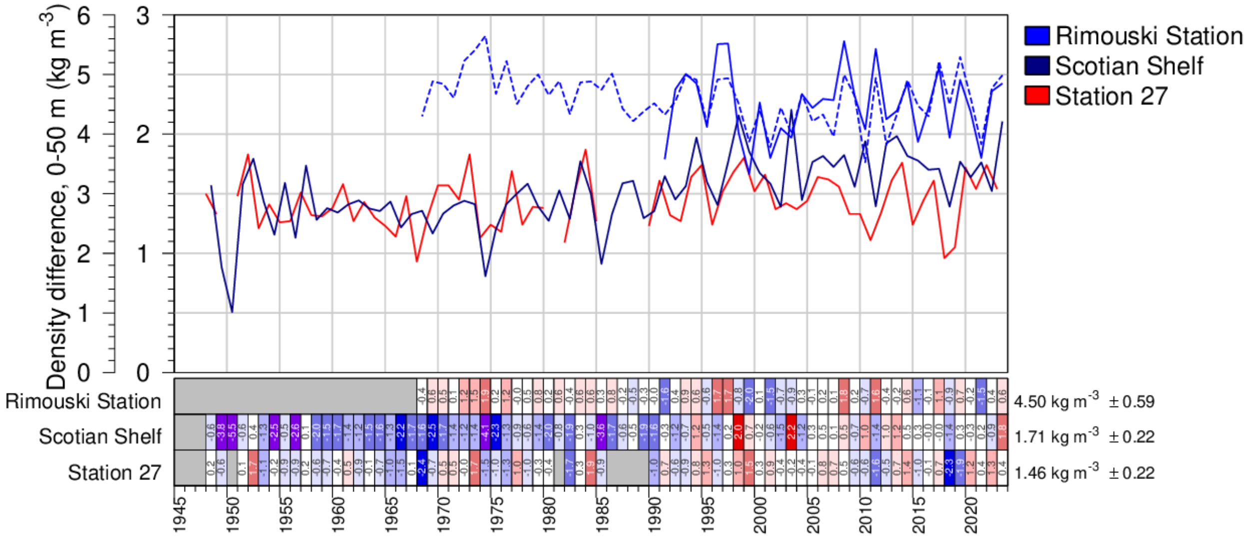

Figure 8. Stratification trends on the southern Newfoundland-Labrador Shelf (May-Nov average at Station 27), Scotian Shelf and St. Lawrence Estuary (May–Oct average at Rimouski Station). The inner y-axis is for Station 27 and Scotian shelf, while the outer y-axis is for Rimouski Station. The dashed line for Rimouski Station is a proxy based on May–October RIVSUM II freshwater runoff. The three bottom lines show normalized anomalies based on the 1991–2020 period. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean, a red cell indicates above normal conditions, and a blue cell below normal.

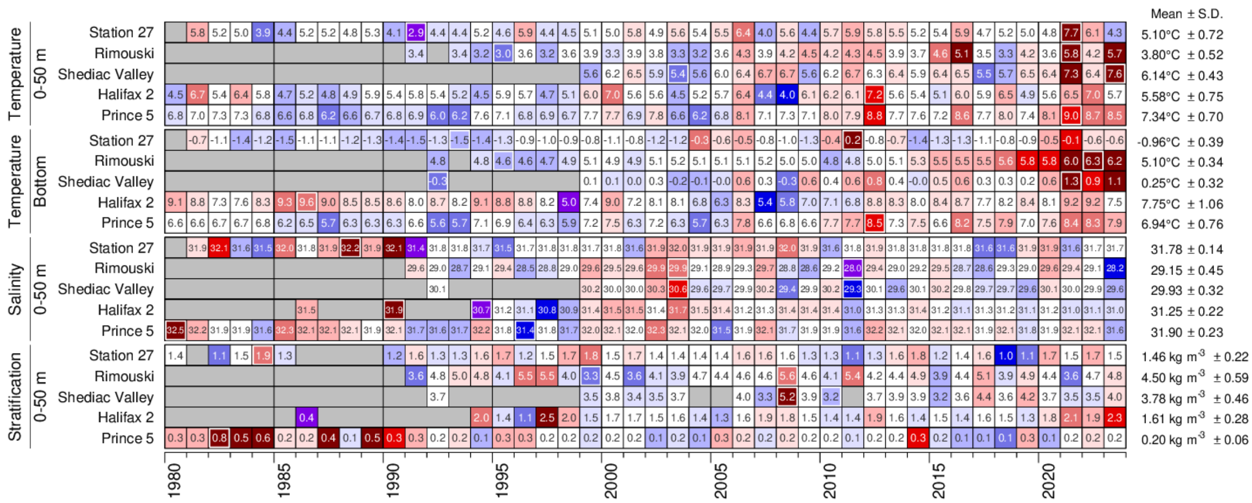

Figure 9. Time series of oceanographic variables at AZMP high-frequency sampling stations, 1980–2023. Values are annual averages at Halifax 2 and Prince 5, May–November at station 27 and May-October at Rimouski station. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1991 to 2020 when possible; for high-frequency station depth-averaged temperature, a red cell indicates warmer than normal conditions, a blue cell colder than normal. More intense colours indicate larger anomalies. For salinity and stratification, red corresponds to above normal conditions. Series minimums and maximums are indicated by a white outline when they occur in the displayed time span. Climatological means and standard deviations are shown on the right-hand side of the figure. Palette as in Figures 6 and 7.

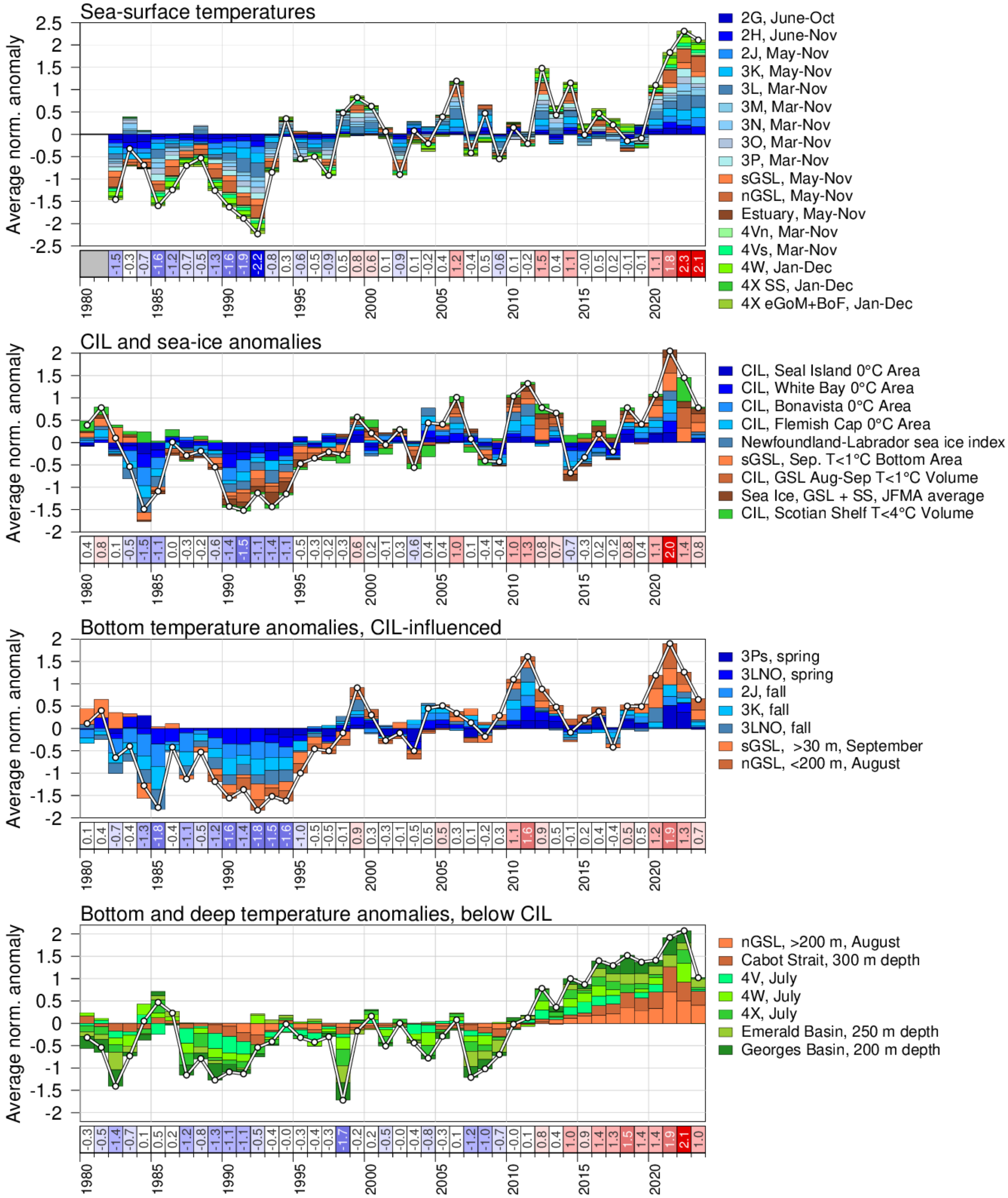

Figure 10. Composite climate indices (white lines and dots) derived by averaging various normalized anomalies from different parts of the environment (coloured boxes stacked above the abscissa are positive anomalies, and below are negative). Top panel shows average sea surface temperature anomalies weighted by area, second panel averages cold intermediate layer and sea ice anomalies with areas and volumes in reversed scale (positive anomalies are warm conditions) and bottom panels average bottom temperature anomalies for cold, CIL-influenced waters and for warmer waters found below the CIL.

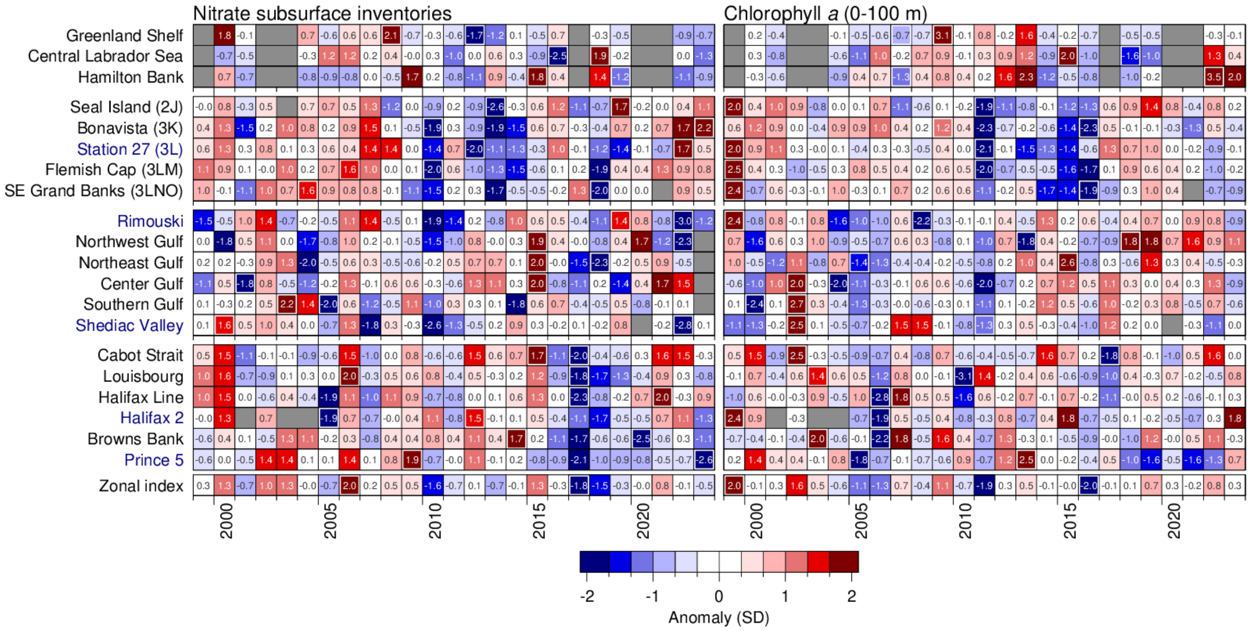

Figure 11. Time series of subsurface nitrate inventories (100 m – bottom in Labrador Sea; 50–150 m in other regions) and phytoplankton biomass (expressed as chlorophyll a 0–100 m inventory) in the Labrador Sea, at AZMP sections, in the Gulf averaging areas and at high-frequency sampling stations (labelled in blue), 1999–2023. A grey cell indicates missing data. A white cell is a value within 1/3 SD of the long-term mean based on data from 1999–2020; a red cell indicates above normal inventories, a blue cell below normal. More intense colours indicate larger anomalies; anomaly values are indicated in each cell. Series minimums and maximums are framed in white. The "zonal index" is created as the average of all normalized anomalies, and that result is again normalized. See Figure 1 for section, averaging area and station positions.

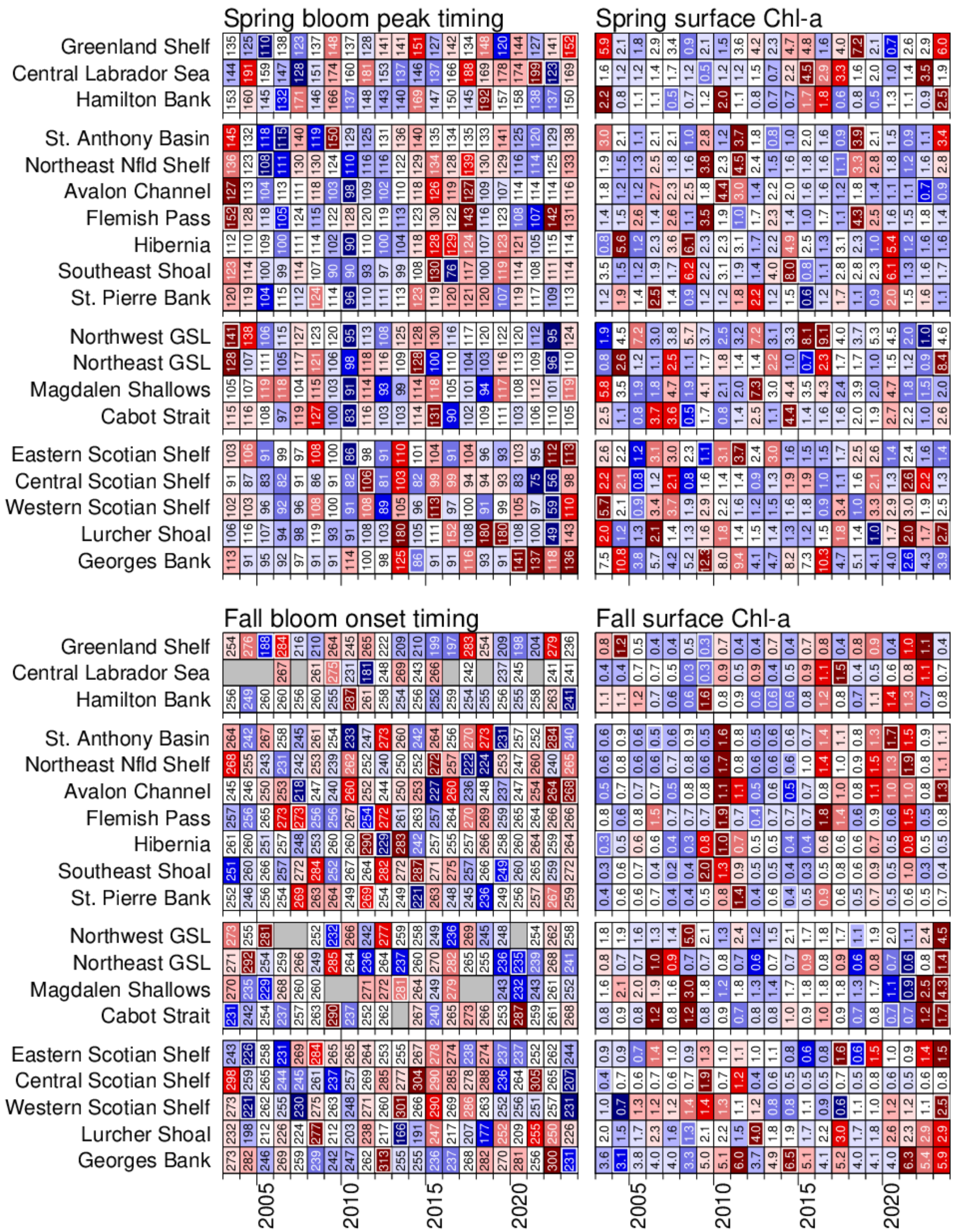

Figure 12. Time series of remotely sensed bloom parameter anomalies (spring bloom peak timing, fall bloom onset timing, spring and fall chlorophyll *a*), 2003–2023. Seasonal anomalies are calculated from the daily surface chlorophyll *a* concentration averaged over spring and fall. Data are from MODIS. A grey cell indicates missing data, a white cell is a value within 1/3 SD of the long-term mean based on data from 2003 to 2020; a red cell indicates late timing, or above normal inventories, and a blue cell early timing/below normal. More intense colours indicate larger anomalies. Values in cells are days of the year for bloom timing indices and surface chlorophyll *a* concentration (mg m^{-3}) for seasonal averages. Series minimum and maximums are framed in white. See Figure 2 for ocean colour subregion definitions.

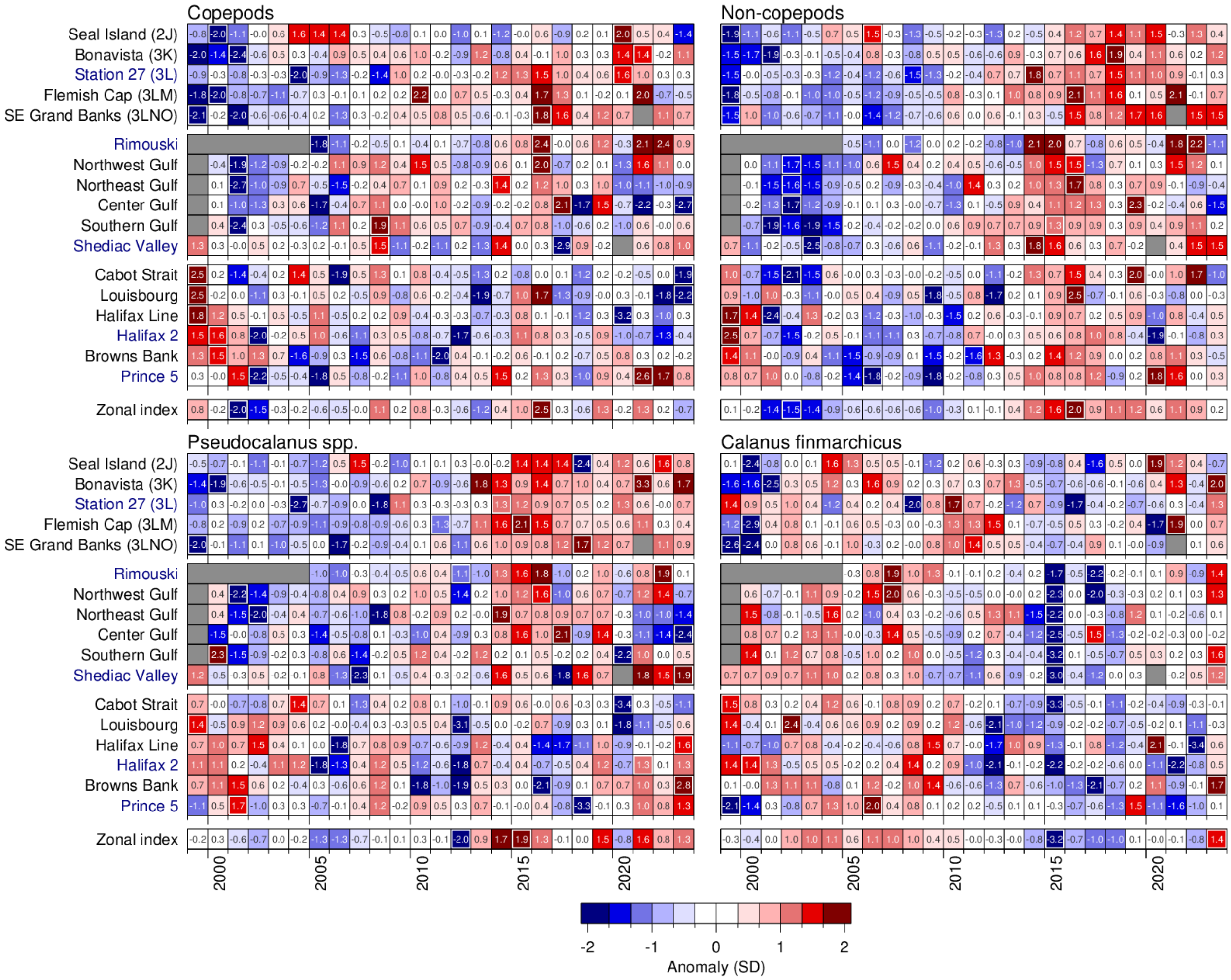

Figure 13. Time series of the (log-transformed) standing stocks of total copepods, *Calanus finmarchicus*, *Pseudocalanus* spp., and non-copepod zooplankton at AZMP sections, in the Gulf averaging areas and at high-frequency sampling stations (labelled in blue), 1999–2023. A grey cell indicates missing data, a white cell is a value within 1/3 SD of the long-term mean based on data from 1999 to 2020; a red cell indicates above normal inventories, a blue cell below normal. More intense colours indicate larger anomalies. Series minimum and maximums are framed in white. The “zonal index” is created as the average of all normalized anomalies, and that result is again normalized. See Figure 1 for section, averaging area and station positions.

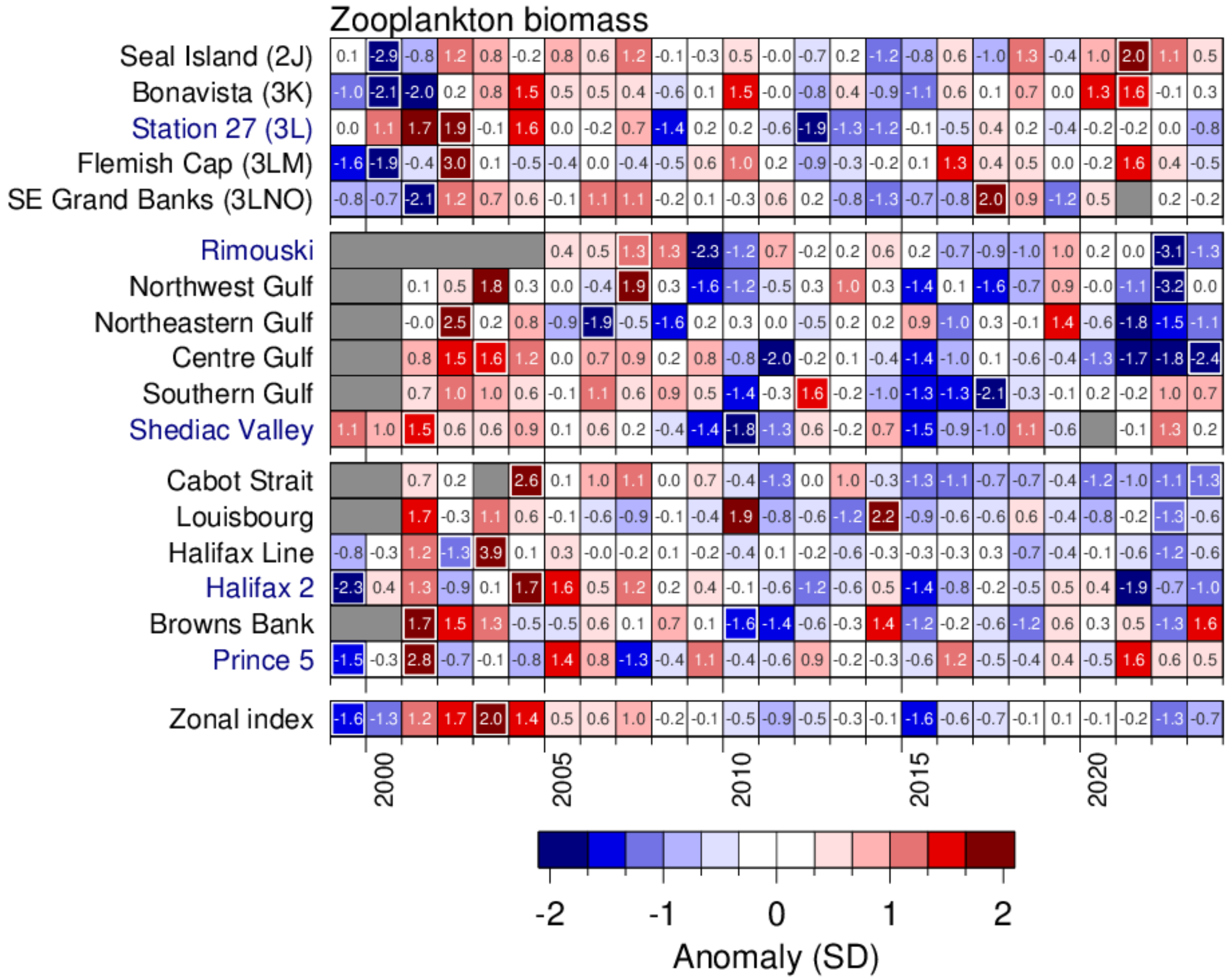

Figure 14. Time series of zooplankton biomass (dry weight, log-transformed) at AZMP sections, in the Gulf averaging areas and at high-frequency sampling stations (labelled in blue), 1999 to 2023. Biomass is measured on the 0.2–10 mm size fraction which is usually dominated by copepods. A grey cell indicates missing data, a white cell is a value within 1/3 SD of the long-term mean based on data from 1999 to 2020; a red cell indicates above normal inventories, a blue cell below normal. More intense colours indicate larger anomalies. Series minimums and maximums are framed in white. The “zonal index” is created as the average of all normalized anomalies, and that result is again normalized. See Figure 1 for section, averaging area and station positions.

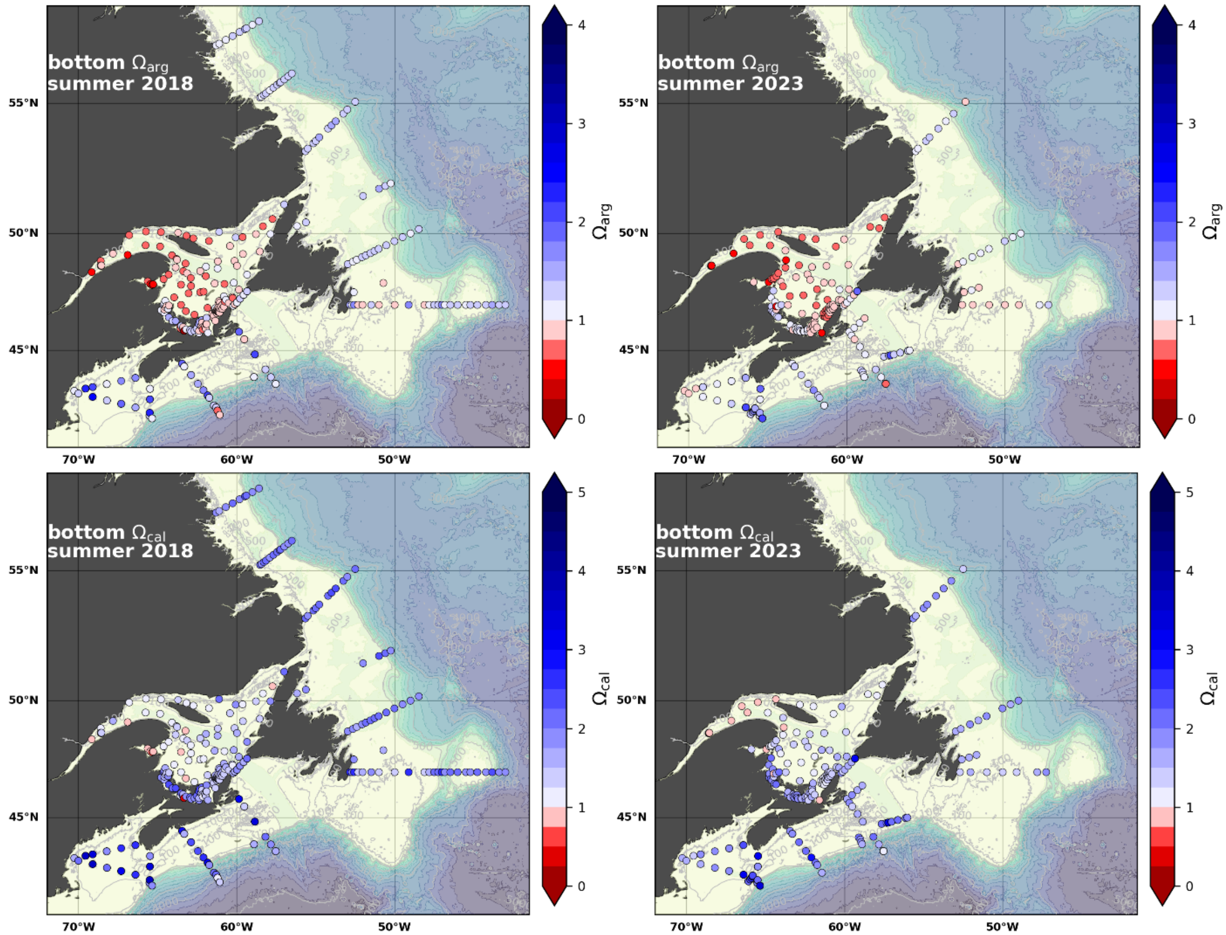

Figure 15. Bottom water aragonite saturation state (Ω arg; top row) and calcite saturation state (Ω cal; bottom row) during summer 2018 (left) and 2023 (right) for the Gulf of St. Lawrence, Scotian Shelf and Newfoundland Shelf. Undersaturated conditions (<1) relative to aragonite and calcite are shown in the pink to red scale. Summer observations encompass measurements conducted from early July to mid-September. The bottom summer conditions of 2023 are compared to those of 2018, as the sampling efforts in both years were similar.

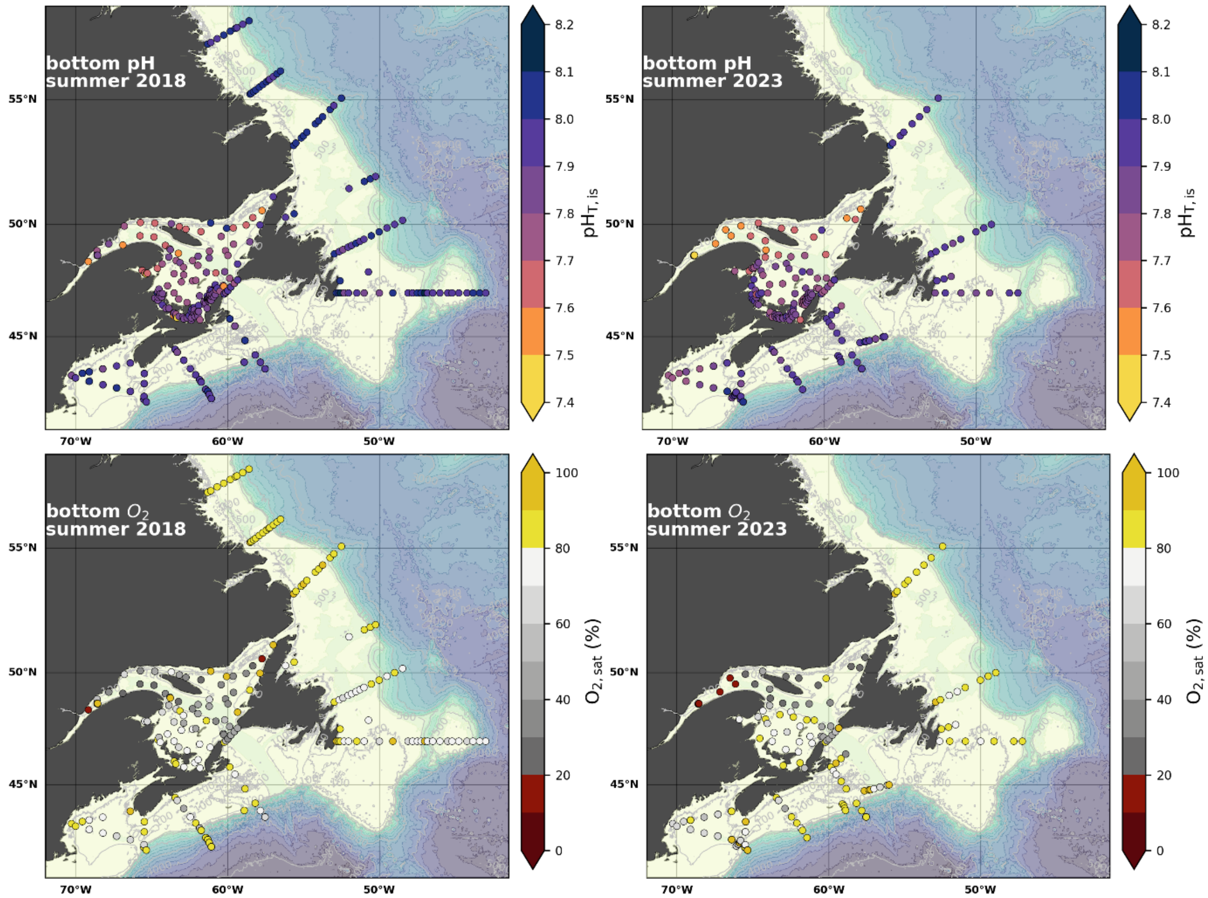

Figure 16. Bottom water in situ pH (total scale, top row) and dissolved oxygen saturation (%, lower row) during summer 2018 (left) and 2023 (right) for the Gulf of St. Lawrence, Scotian Shelf and Newfoundland Shelf. Hypoxic oxygen conditions (<20%) are plotted in red colours in the bottom panels. Summer observations encompass measurements conducted from early July to mid-September. The bottom summer conditions of 2023 are compared to those of 2018, as the sampling efforts in both years were similar.

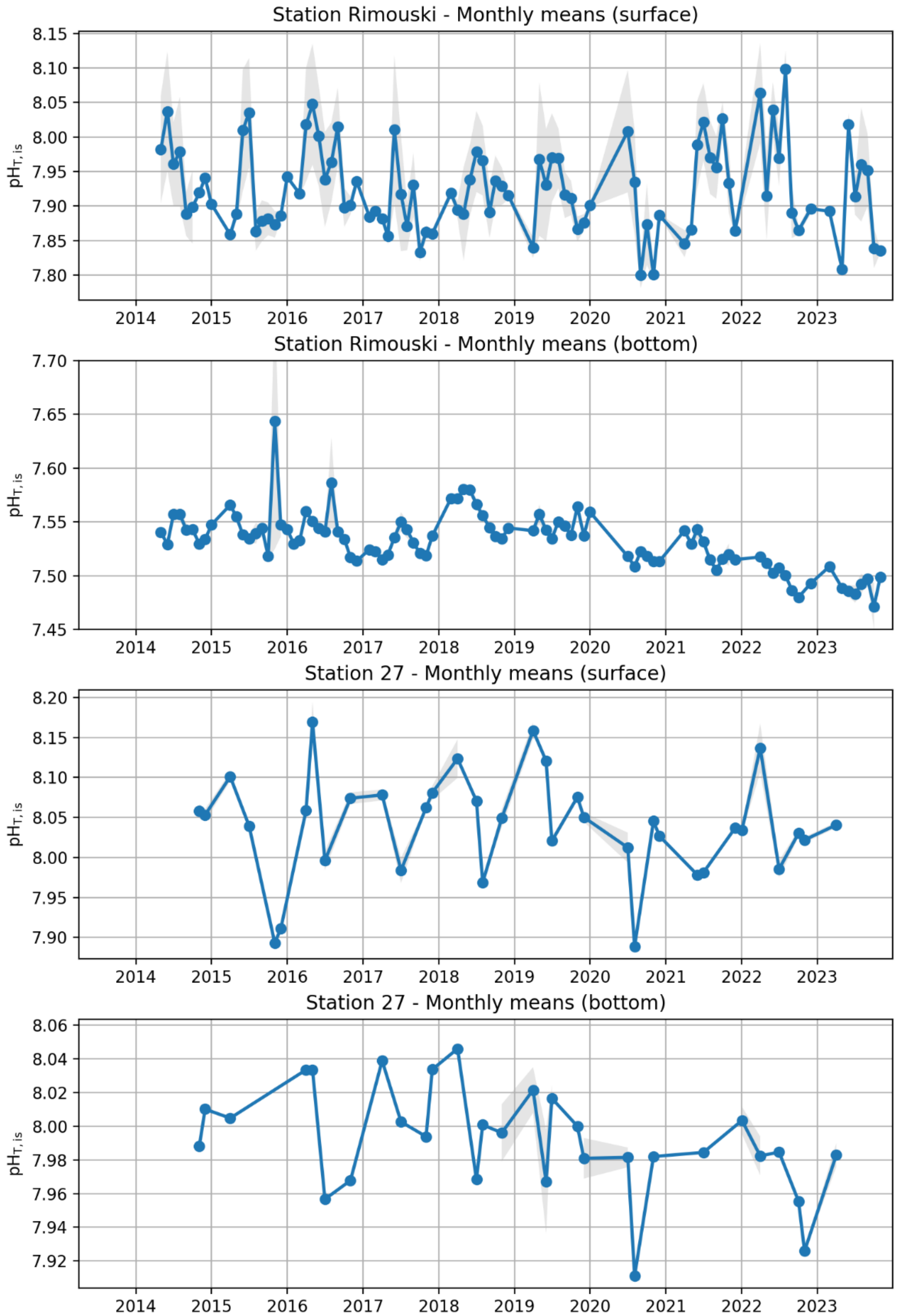

Figure 17. Monthly means of in situ pH (total scale) data at Station Rimouski for surface waters (first panel) and bottom waters (second panel), and monthly means of in situ pH (total scale) data at Station 27 for surface waters (third panel) and bottom waters (fourth panel). Surface and bottom water values represent the averages in the top 15 m and in the bottom 50 m of the water column, respectively. The shaded areas represent ±0.5 SD of the monthly distribution (when more than one observation per month was available). The tick marks on the horizontal axis correspond to the beginning of each year.

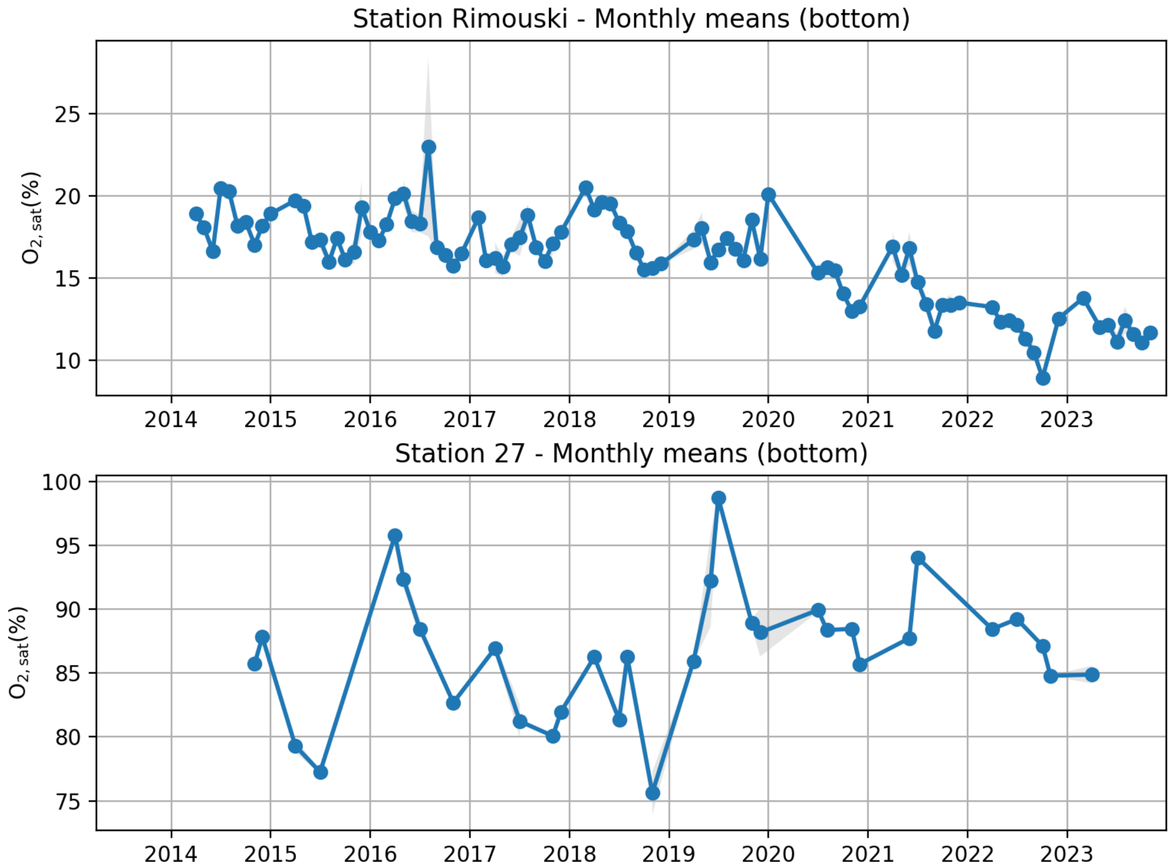

Figure 18. Monthly means of dissolved oxygen saturation (%) in the bottom waters at Station Rimouski (top panel) and Station 27 (bottom panel). Bottom water values represent averages in the bottom 50 m of the water column. The shaded areas represent ±0.5 SD of the monthly distribution (when more than one observation per month was available). The tick marks on the horizontal axis correspond to the beginning of each year.