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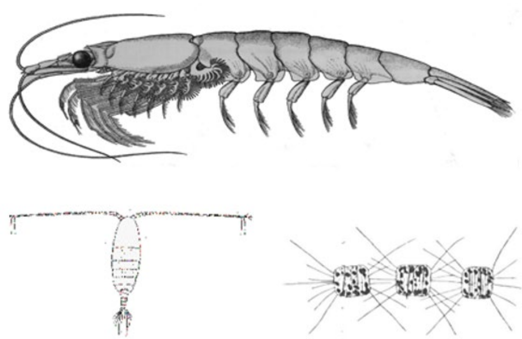
OCEANOGRAPHIC CONDITIONS IN THE ATLANTIC ZONE IN 2022



Key taxa of the pelagic food web: euphausiids (top), phytoplankton (bottom right), and copepods (bottom left).
Images: Fisheries and Oceans Canada

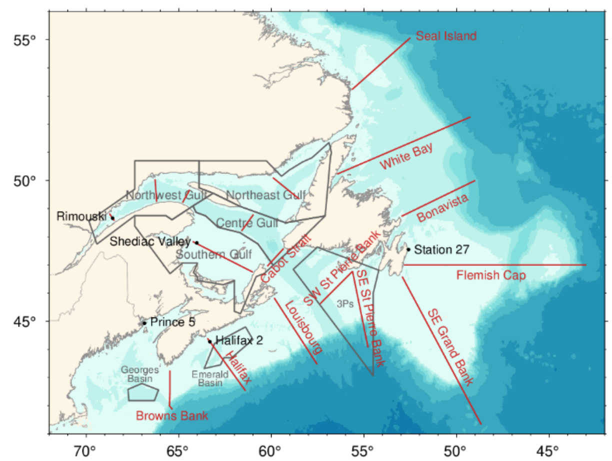


Figure 1. Atlantic Zone Monitoring Program high-frequency sampling stations (black), selected section lines (red) and averaging areas (gray).

Context:

The Atlantic Zone Monitoring Program (AZMP) was implemented in 1998 with the aim of increasing Fisheries and Oceans Canada (DFO) capacity to understand, describe, and forecast the state of the marine ecosystem and to quantify the changes in the ocean's physical, chemical and biological properties.

A description of the seasonal patterns in the distribution of phytoplankton (microscopic plants) and zooplankton (microscopic animals) in relation to the physical environment provides important information about organisms that form the base of the marine food web. An understanding of the production cycles of plankton and their interannual variability is an essential part of an ecosystem approach to stock assessment and marine resource management.

This Science Advisory Report is from the zonal peer review of March 27–29, 2023 on the Twenty-Fifth Annual Meeting of the Atlantic Zone Monitoring Program (AZMP). Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule] as they become available.

June 2023

SUMMARY

- Monthly and seasonal average sea surface temperatures were normal to above normal in ice-free areas, with a single monthly exception in the Estuary. Many regional monthly and seasonal records were set. The spatially weighted zonal average was at a record high.
- The Labrador Current transport was above normal along the Newfoundland and Labrador Shelf break. The transport along the Scotian Shelf break was near normal and has not been above normal since 2011.
- 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.
- The winter surface cooling in the central Labrador Sea was the highest since 2015, while the resulting convection depth of 1 600 m was near normal.
- The cold intermediate layer (CIL) was anomalously warm and of limited extent in the Gulf of St. Lawrence; its August-September volume was second lowest of the time series. However, no CIL metrics can be reported for the rest of the Zone.
- Bottom temperatures were substantially above normal across the zone, including record highs in the deep waters of the northern Gulf of St. Lawrence, off southern Newfoundland and on the Scotian Shelf. The zonal average index for CIL-influenced bottom temperatures was third highest of the time series and the zonal average index for warmer, below-CIL deep waters was at a record high.
- At the high-frequency sampling sites, seasonal average 0-50 m and bottom temperatures were all above normal, including a series record in bottom temperature at Rimouski station. Stratification was at a record high at Station 27, offshore of St. John’s.
- Deep nitrate inventories were above normal off Newfoundland, in the central Gulf of St. Lawrence and Cabot Strait, below normal in the northern Gulf of St. Lawrence and Shediac Valley, and slightly above normal or normal in the southern Gulf of St. Lawrence and on the Scotian Shelf, except for the Bay of Fundy.
- Surface chlorophyll inventories were highly variable throughout the Atlantic Zone. Above normal inventories occurred on the Newfoundland Shelf, most of the Gulf of St. Lawrence including Cabot Strait, and on the central and western Scotian Shelf. Below normal inventories occurred in the Grand Banks and Flemish Cap, Shediac Valley and the Bay of Fundy.
- The onset of the spring phytoplankton bloom was normal to late throughout most of the Atlantic Zone, with exceptions in the northern Gulf of St. Lawrence and central and western Scotian Shelf where the time series earliest timing of the spring bloom were observed.
- The magnitude of the bloom was generally below normal across the zone, but reached record highs on Hamilton Bank, St. Pierre Bank and central Scotian Shelf.
- The duration of the bloom was mainly shorter than normal, with exceptions of longer than normal values in northern Gulf of St. Lawrence and western Scotian Shelf.
- The Eastern Scotian Shelf exhibited its latest onset, lowest magnitude and shortest duration on record.

- Copepod abundance was generally above normal on the Newfoundland Shelf, northwest Gulf, Shediac Valley and Bay of Fundy, and normal or below normal in the rest of the Atlantic Zone.
- The abundance of non-copepods was close to normal on most of the Newfoundland Shelf, the eastern Scotian Shelf and Bay of Fundy, and above normal off Labrador, the southern Grand Banks and throughout most of the Gulf of St. Lawrence.
- The abundance of *Calanus finmarchicus* was below normal on the Scotian Shelf with a record low on the Halifax Line, generally normal in the rest of the Atlantic Zone, and above normal at Station 27.
- *Pseudocalanus* spp. abundance was mainly above normal on the Newfoundland Shelf, northwestern Gulf of St. Lawrence, Shediac Valley and Bay of Fundy, below normal in the eastern and central Gulf of St. Lawrence, and mainly normal on the Scotian Shelf.
- Zooplankton biomass was mostly near normal on the Newfoundland Shelf, above normal in the southern Gulf of St. Lawrence and in the Bay of Fundy, and below normal across the rest of the Gulf of St. Lawrence and most of the Scotian Shelf, reaching a record low in the northwest Gulf of St. Lawrence and Louisbourg section.
- Dissolved oxygen concentration generally declined in the deep waters of the Gulf of St. Lawrence and was at a record low in the Estuary.
- The bottom waters at some stations on the Grand Banks, in the Avalon channel and near Cape Breton were undersaturated with respect to Aragonite in the fall.
- The bottom waters of the St. Lawrence Estuary also reached new record low pH (more acidic conditions).
- The Central Labrador Sea exhibited record high *Pseudocalanus* spp. abundance and record low abundance of amphipods.

BACKGROUND

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

1. Increasing Department of Fisheries and Oceans' (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 in the observation program of 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 for basic 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. In addition, 4 glider missions consisting of 4 515 profiles of temperature, salinity, oxygen, optical backscatter, chlorophyll and CDOM fluorescence were conducted on the Halifax Line. For the Bonavista Line, one mission collected 1 056 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 795 vertical profiles throughout the zone.

This annual assessment of the State of the Atlantic Zone has included Labrador Sea observations resulting from the Atlantic Zone Off-Shelf Monitoring Program (AZOMP) since the report on 2015 conditions and information on ocean acidification since 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.

ASSESSMENT

Physical Oceanographic Conditions

This is a summary of physical oceanographic conditions during 2022 for eastern Canadian oceanic waters (Figures 1 and 2) as reported annually by the AZMP in research documents (e.g. Galbraith et al. 2023 for conditions in 2022, Cyr et al. 2022 for conditions in 2021 and Hebert et al. 2021 for conditions in 2020). Other conditions in 2022 will be published as Technical Reports.

The North Atlantic Oscillation

The North Atlantic Oscillation (NAO) index is based on the sea-level atmospheric pressure difference between the sub-equatorial high and sub-polar 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. In 2022, the winter NAO index was +1.0, returning positive after a brief interruption in 2021. 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.

Annual Temperature Cycle

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 prior to ice formation, but also partly because of cooling, reduced runoff and from 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. The CIL is, for the most part, locally formed in winter in separate areas around the zone. 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 and Newfoundland Shelf and from the GSL to the St. Lawrence Estuary and to the Scotian Shelf. 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.

Sea Surface Temperature

The satellite-based sea surface temperature product used in the previous two years' reports blends data from Pathfinder version 5.3 (1982–2021), Maurice Lamontagne Institute (1985–2013) and Bedford Institute of Oceanography (1997–2021). The BIO data stopped being produced in June 2022 and was replaced with 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. This new product slightly alters previously reported results; for example last year was reported as third warmest of the time series for the zone but would have ranked warmest using this product.

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).

In 2022, monthly average sea surface temperatures were generally normal to above normal in ice-free areas. Of the 147 regional monthly averages reported in Figure 6, only one was below normal: the St. Lawrence Estuary in June. Fourteen regional monthly averages were near normal, mostly during the first half of the year on the Newfoundland and Labrador Shelf. The remaining 132 were above normal, including 33 series records, most widespread in September on the Newfoundland and Labrador Shelf, the Gulf of St. Lawrence and Eastern Scotian Shelf. Sea surface temperatures averaged over the ice-free months (Figure 7) were above normal across the zone, with seasonal series records set in ten regions from Eastern Scotian Shelf, the Gulf of St. Lawrence and all regions of the Newfoundland Shelf.

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. 2022). For the Gulf, the CIL volume with T<1 °C observed in August-September is used (Galbraith et al. 2022). 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. 2022). For the Scotian Shelf, the volume with T<4 °C observed in July is used (Hebert et al. 2021). 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 2022, while almost twice as large, was second lowest. In 2021, the CIL area metric derived from the four AZMP sections on the NL shelf was at its 3rd lowest on record. Unfortunately, there are no summer measurements in 2022 along these sections. However, using CIL metrics derived from Station 27 the CIL on the NL shelf appears to have remained warmer than normal in 2022, albeit not as warm as in 2021 (not shown).

On the Scotian shelf, surveys did not cover the Eastern area where the CIL is usually prominent. For the western area of the Scotian Shelf that was covered by the survey, no water colder than the 4 °C threshold usually used to delineate the CIL was found.

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 (1969–2021, $R^2 = 0.64$–0.80; Cyr et al. 2022). In the Gulf of St. Lawrence, the correlation between the December-March air temperature averaged over multiple coastal meteorological stations and the annual maximum ice volume reaches R^2 = 0.73 (1969–2021). Air temperature is similarly well correlated to sea ice cover area and duration (R^2 = 0.80–0.83; Galbraith et al. 2022). 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. 2022).

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).

Since 2010, ice conditions on the Newfoundland and Labrador Shelf, the Gulf of St. Lawrence and the Scotian Shelf have generally been weaker than normal (except for a rebound during 2014–2017 on the Newfoundland and Labrador shelf when heavy sea ice conditions were observed) reaching a record low value seasonally averaged volume in the Gulf of St. Lawrence in 2021 and the lowest index on the Newfoundland and Labrador Shelf in 2011 (Figure 7). In the thirteen year period between 2010 and 2022, the Gulf seasonal average sea ice volume had nine of the thirteen lowest values of the series, while the Newfoundland and Labrador shelf had five of the thirteen lowest indices (including 2020 and 2021). In 2022, the Newfoundland and Labrador sea ice index was near normal (-0.1 SD). The seasonally averaged sea ice volume in the Gulf of St. Lawrence was below normal (15 km^3; -0.7 SD), and the volume of ice exported onto the Scotian Shelf was just below normal (3 km^3; -0.5 SD).

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. 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. 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. 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. 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 2022, bottom temperatures were substantially above normal across the zone, including a series record in the area deeper than 200 m of the northern Gulf in August, in 3Ps in the spring off southern Newfoundland and on 4W and 4X on the Scotian Shelf (Figure 7). There were new 100+ year high-temperature records for the GSL at 150, 200, 250 and 300 m that are reflected in the average bottom temperature of the northern Gulf deeper than 200 m. The recent warming of the Gulf deep waters began as a warm anomaly first observed in Cabot Strait in 2010 has propagated towards the heads of the channels, sustained by later warm water inflows.

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. 2022). The inter-annual variability of seasonal (May–October) stratification (0–50 m) at Rimouski Station in the Estuary is correlated with seasonally averaged runoff of the St. Lawrence river (1991–2022; $R^2 = 0.59$, Figure 8). The 2022 annual runoff was near normal (17 900 m^3s^{-1}, +0.3 SD).

Stratification on the Scotian Shelf was below normal in 2022 (-0.8 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 near normal at Rimouski station (+0.4 SD), consistent with the runoff (Figure 8).

Conditions at AZMP High Frequency Sampling Stations

At the high-frequency sampling sites, seasonal average 0–50 m and bottom temperatures were all above normal (except for 0-50 m temperature at Shediac Valley, but this station was poorly sampled in 2022), including a series record in bottom temperature at Rimouski station (Figure 9). Stratification was at a record high at Station 27.

Labrador Current Transport Index

The annual-mean Labrador Current transport index shows that transport along the Newfoundland and Labrador (NL) shelf break is generally out of phase with that 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. Labrador Current transport was above normal on the NL shelf break (+1.2 SD) and the transport of slope waters has not been above normal on the Scotian shelf break since 2011 (-0.2 SD in 2022).

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 2022 ice-free months were all above normal across the zone, with seasonal series records set in ten areas. Warming winters have also led to less sea ice cover and weaker/warmer cold intermediate layers. The 2010–21 period was characterized by record lows in 2021 and 2012 for CIL volumes in the Gulf of St. Lawrence and Scotian Shelf respectively, representing record warm conditions. For the past decade, ice volumes on the Newfoundland and Labrador Shelf, the Gulf of St. Lawrence and the Scotian Shelf have generally been lower than normal reaching a record-low value in the Gulf of St. Lawrence in 2021 and on the Newfoundland and Labrador Shelf in 2011.

Deep water temperatures on the Scotian Shelf and Gulf of St. Lawrence were greatly influenced by an increasing proportion of Gulf Stream Water relative to Labrador Water. While the

Newfoundland Shelf and Labrador Shelf were characterized by normal to above normal bottom temperatures in the early and late period of 2011–21 with some below normal temperatures in 2014–17, nearly all anomalies were above normal on the Scotian Shelf and the northern Gulf of St. Lawrence during this period. Series records were observed in all areas of the zone during this period.

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 to 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 2022 were at a record high for surface temperatures, third warmest for CIL and sea ice anomalies (however this index is missing several components for 2022) as well as for bottom temperatures influenced by the CIL. Bottom temperatures below the influence of the CIL were also at a record high. A total of 45 indices listed in Figures 7 and 9 describe ocean conditions related to temperature within the AZMP area in 2022 (SST; ice; summer CIL areas, volumes, and minimum temperature; deep and bottom temperature; 0–50 m average temperature). Of these, none presented colder than normal conditions, 2 were within normal values (± 0.5 SD) and 43 were above normal, including 16 series records. This indicates a continuation of warmer than normal oceanographic conditions in 2022 across much of the Atlantic Zone.

Biogeochemical Environment

Lower trophic levels are the components 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. Lower trophic level organisms include phytoplankton and zooplankton. Phytoplankton are microscopic plants 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. The zooplankton sampled are a broad variety of small animals ranging from 0.2 to 20 mm in length that drift with ocean currents. There is a wide variation in the size of phytoplankton, from the large diatoms to the smaller flagellates, 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 community includes animals such as copepods, gelatinous filter feeders and predators, and ephemeral larval stages of bottom-dwelling and planktonic invertebrates. As with phytoplankton, there is a broad range of sizes of zooplankton. Smaller stages and species are the principal prey of young stages of fish and larger copepods are eaten predominantly by juvenile and adult fishes that forage near the surface.

Productivity of marine ecosystems depends 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 (nitrates, nitrites, and ammonium), phosphorous (phosphate), and silica (silicate), with the latter being essential for production of diatoms. During springtime, phytoplankton undergoes an explosion in abundance known as the spring bloom. The spring bloom occurs principally in near-surface waters. In fall, a secondary bloom, less intense than the spring bloom, also contributes to the functioning of the marine ecosystem. We report on the amount of nutrients available for phytoplankton, the overall biomass of phytoplankton and important features of the spring bloom, and the abundance of key zooplankton taxa based on the data available from 1999 to present.

Indices representing nitrate inventories, phytoplankton standing stock, features of the spring phytoplankton bloom derived from satellite observations, and zooplankton abundance and biomass from the Newfoundland Shelf (Maillet et al. 2022), Gulf of St. Lawrence (GSL) (Blais et al. 2021) and Scotian Shelf (Casault et al. 2023) are summarized as time series of annual values in matrix form in Figures 11–14. Anomalies were calculated using a climatological reference period of 1999–2020 for the biogeochemical parameters derived from *in situ* observations during seasonal oceanographic surveys, and 2003–2020 for the spring bloom parameters derived from satellite observations of ocean colour.

Although the relatively short time series of biogeochemical variables from the program tend to highlight the high degree of interannual variability in the information rather than the long-term trends that are apparent for the physical environment, there have been distinct shifts across several variables in recent years. There is a degree of synchrony in the patterns of variation of individual biogeochemical variables at adjacent locations, and the sign of anomalies tends to persist for several years, although in some instances there may be considerable variability among locations within a region.

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 at depths of 50–150 m is called the “deep water nitrate inventory”. 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 water column during winter or summer and fall through upwelling to become available for phytoplankton growth. Nitrate inventories, and the relative abundances of other nutrients, are mostly dependent on the source waters that make up the deep water on continental shelves, which can vary from year to year. Deep nitrate inventories (50–150 m) in 2022 were highly variable across the Atlantic Zone, with high inventories on the Newfoundland Shelf, the Grand Banks, and most of Scotian Shelf, and low inventories in most of the Gulf of St. Lawrence where high nitrate inventory were only measured in the Center Gulf (Figure 11). While Bonavista section, Station 27 and Cabot Strait showed record-high deep water nitrate inventory in 2022, northwest Gulf of St. Lawrence, Rimouski and Shediac Valley stations had record-low inventory. Deep nitrate inventories were above normal for a second consecutive year on the Scotian Shelf a reversal from the mainly low nitrate inventories observed since 2016.

Phytoplankton

Chlorophyll inventories in the upper ocean (0–100 m) represent phytoplankton biomass. They demonstrated a high degree of year-to-year variability (Figure 11) and part of this variation is explained by the relatively fixed timing of the program’s oceanographic surveys throughout the zone while the phytoplankton production cycle timing varies according to environmental conditions.

Annual chlorophyll *a* inventories in 2022 were generally above normal on the Newfoundland Shelf, but below normal on the Grand Bank and the Flemish Cap. Above-normal chlorophyll *a* inventories in most of the Gulf of St. Lawrence show a similar pattern to the 2018–2021 period. The anomalies are highly variable across the Scotian Shelf with positive anomalies at Cabot Strait, Halifax 2 station and on Browns Bank, and negative anomalies on the western Scotian Shelf and in the Bay of Fundy. Because of the reliance of phytoplankton on nutrient availability the variation in nutrient inventories appears to be associated with general trends in phytoplankton biomass at regional scales. Although nutrient inventories provide some threshold to limit seasonal production dynamics across the zone, additional factors are likely to be influencing local nutrient-phytoplankton dynamics and the balance of these factors is likely to differ when considered at the very large spatial scale from the Gulf of Maine to southern Labrador, which includes estuarine to oceanic environments.

The characteristics of the bloom (onset, duration, and magnitude) provide important information about regional variations in ecosystem productivity and are linked to the productivity of organisms that depend on lower trophic levels. The magnitude (total production) of the spring bloom is partly dependent on the amount of nutrients that are mixed into surface waters over the course of the winter. Characteristics of the spring phytoplankton bloom were derived from daily composite observations of the concentration of chlorophyll at the ocean surface based on satellite observations (Moderate Resolution Imaging Spectroradiometer [MODIS] 2003–2022; Figure 12). The onset of the spring phytoplankton bloom was highly variable across the Atlantic zone. In the northernmost sections (Center Labrador Sea and southern Labrador Shelf), the spring bloom occurred earlier than normal whereas it was generally later than normal on the northeast Newfoundland Shelf and the Grand Banks. The Gulf of St. Lawrence also showed a similar latitudinal gradient with the earliest bloom onset on records in the northern Gulf, and normal or slightly late blooms on the Magdalen Shallows and in Cabot Strait. Spring bloom was late on the Eastern Scotian Shelf and Georges Bank and notably early on central and western Scotian Shelf for a second consecutive year. The magnitude of the spring bloom was mostly below normal or near normal across the zone with the exception of a few strong positive anomalies on the western and central Scotian Shelf, St. Pierre and Hamilton Banks, these three latter being record highs. The duration of the bloom is somewhat linked to the start of the bloom such that early blooms tend to last longer than late blooms. The anomaly pattern of spring bloom duration in 2022 reflected this general trend in the Gulf of St. Lawrence and on the Scotian Shelf but blooms were generally shorter than normal in the Labrador Sea, Newfoundland Shelf and Grand Banks.

Bloom duration was shorter than normal in the Central Labrador Sea and on the NL Shelf, but variable in the Gulf of St. Lawrence and on the Scotian Shelf with longer-than-normal blooms in the northern Gulf, the central and western Scotian Shelf and on Georges Banks, and near or shorter than normal elsewhere. There was a clear relationship between bloom onset and duration in the Gulf and on the Scotian Shelf with early onset resulting in longer blooms, and vice versa.

Zooplankton

Zooplankton community structure is strongly influenced by depth, temperature, and season and the complexity of the community differs substantially among the three bioregions of the Northwest Atlantic. Despite its complexity and diversity in different parts of the zone, four indices of abundance provide good indicators of the state of the zooplankton community. Zooplankton abundance indices demonstrate a high degree of large spatial scale coherence in their signal across different parts of the Atlantic zone. Copepods are by far the most abundant group, but non-copepod organisms also significantly contribute to total zooplankton abundance. Two copepod taxa serve to represent different broad groups with similar life histories: *Calanus finmarchicus* and *Pseudocalanus* spp. *Calanus finmarchicus* is a large, ubiquitous copepod that develops large energy reserves in later developmental stages and is therefore a rich source of food for pelagic fish and is a dominant species by biomass throughout much of the region. *Pseudocalanus* spp. are small copepods that are widespread throughout the Atlantic zone and have much smaller energy reserves relative to *C. finmarchicus,* but their life history features are generally representative of smaller taxa in the copepod community. We also report on the biomass (dry weight) of the zooplankton in the 0.2–10 mm size fraction, which is typically dominated by copepods.

The strong zooplankton community shift observed in 2014–2018, characterized by lower abundance of the large energy-rich copepod *Calanus finmarchicus* and higher abundance of small copepods and non-copepods, moderated in 2019–2022, with increases in *Calanus finmarchicus* and declines in *Pseudocalanus* spp, although the overall abundance of small copepod taxa and non-copepod zooplankton remained elevated (Figure 13). In 2022, copepod abundance was mostly above normal on the Newfoundland Shelf and the Grand Bank and in the northwest Gulf of St. Lawrence, and normal or below normal in the rest of the Gulf of St. Lawrence and on most of Scotian Shelf. Non-copepod abundances were mostly normal or above normal across the zone, including a record high at Rimouski station. The abundance of *Calanus finmarchicus* was variable on the Newfoundland Shelf, near normal on the Grand Bank and in the Gulf of St. Lawrence, and below normal on the Scotian Shelf including a record-low value on Halifax Line. *Pseudocalanus* spp. abundance was mostly above normal on the NL Shelf and near normal on the Scotian Shelf. In the Gulf of St. Lawrence, the abundance of *Pseudocalanus* spp. was variable with above-normal levels in the Estuary (Rimouski station), in the northwest Gulf, and at Shediac Valley and below normal-levels in the eastern and center Gulf.

Zooplankton biomass was generally normal on the Newfoundland Shelf but mostly below normal in the rest of the zone, including record lows at Rimouski station, in the northwest Gulf of St. Lawrence and in western Scotian Shelf waters (Figure 14). In the Gulf of St. Lawrence, the low zooplankton biomass is largely due to low *Calanus hyperboreus* abundance (not shown). The period 2015-2017 was marked by very low zooplankton biomass throughout most of the Atlantic zone and followed by small increases in the following years. Zooplankton biomass in 2022 represents a return to 2015-2017 conditions. Overall, recent changes in zooplankton community structure continue to indicate that important shifts in the flow of energy among lower trophic levels of the marine ecosystem in Atlantic Canadian waters are taking place, but the consequences to higher trophic levels are unknown.

Ocean Acidification and deoxygenation

Ocean acidification (OA) parameters are collected as part of the AZMP since fall 2014. In addition to pH, the calcium carbonate saturation states with respect to calcite and aragonite (Ω_{cal} and Ω_{arg}) are measures of ocean acidification that indicate the potential to precipitate/dissolve carbonate. Below the threshold of 1, the environment is considered undersaturated with respect to calcium carbonate and potentially corrosive to organisms that build biogenic carbonate shells. The Ω typically decreases with depth, and thus deep slope waters tend to have lower Ω than the bottom waters of the shallower shelves. From 2017 to 2022, near-bottom pH in the Gulf of St. Lawrence has shown a general decline, especially in the St. Lawrence Estuary (Figure 15). On the Newfoundland shelf, the bottom waters at some stations on the Grand Banks and in the Avalon channel were undersaturated with respect to Aragonite in the fall (not shown). Similarly, some stations along the Louisbourg section near

Cape Breton on the Scotian shelf were also undersaturated with respect to Aragonite in the fall. For the rest of the NL and SS shelves, bottom pH values ranged from 7.8 to above 8 and demonstrated considerable spatial variability.

Most of the bottom waters of the Gulf of St. Lawrence, including the shallower southern Gulf, were undersaturated with respect to aragonite (Figure 15). The lowest pH and Ω values were observed along the deep Laurentian channel, especially in the St. Lawrence Estuary where the deep layer (>300 m) was undersaturated with respect to aragonite and calcite (pH values were below 7.6 throughout the Estuary, with a minimum of 7.42), establishing a new record low. In addition, oxygen saturation at many sampling locations is well below 20% (even below 10% at some stations; Figure 15, bottom panel) and has generally declined compared to 2021. These correspond to new low oxygen concentration records for the Lower St. Lawrence Estuary, reaching 8.9% (27.69 µM) at Station Rimouski during the summer.

At the surface, pH and Ω_{arg} (not shown) are generally lower on the Newfoundland and Labrador shelf and in the Gulf (especially in the Lower Estuary) compared to the Scotian Shelf, principally because of lower temperature and/or salinity (not shown).

Labrador Sea Environment

The Atlantic Zone Off-Shelf Monitoring Program (AZOMP) provides observations of ocean climate and plankton community structure variability affecting the Labrador Sea ecosystems off Atlantic Canada and climate systems at a regional and global scale. *In-situ,* vessel-based sampling also provides means for calibration, quality-controlled measurement, and ground truth of remote sense instrumentation. In 2022, the occupation of the Atlantic Repeat 7-West line (AR7W) occurred between the 2 and 27 May on board R/V Atlantis. The latest published reports are Yashayaev et al. 2022 for meteorological, sea Ice, and physical oceanographic conditions and Ringuette et al. 2022 for optical, chemical, and biological oceanographic conditions.

The assessments of the physical oceanographic conditions across the Labrador Sea, the factors determining the state of its water column, and the roles of the regional processes and water mass property trends in the North Atlantic and planetary climates are based on year-round temperature and salinity profiles obtained with the standard, deep and biological Argo floats, satellite-based sea-ice observations and atmospheric reanalysis data. The contribution of ship-based observations to the assessments of seasonal, annual and decadal anomalies in the key oceanographic variables has declined substantially since the Argo program came to the Labrador Sea in 2002, with the 2017 and 2021 ocean state metrics presented in Figures 16 and 17 entirely based on the Argo observations as there were no ship-based observations available for these years.

The collapse of the Polar Vortex in the early winter of 2021 led to warm winter conditions pausing winter connection in that year, which was about 800 m shallower than in 2020 (Figures 7, 16 and 17), the shallowest since 2011 and third shallow in at least 33 years. In 2022, however, with the Polar Vortex being anomalously strong, NAO index high, and westerlies strong, the winter conditions changed to the opposite. The winter air temperature was below normal, and the surface heat loss was well above normal and the highest since 2015, resulting in a Labrador Sea winter convection being as deep as 1 600 m (which was about the same as in 2020 and twice deeper than 2021), and the deep ocean became colder and denser than in the previous year (Figures 16 and 17). The annual sea ice area and extent increased significantly from 2021 conditions (Figure 7). The sea ice area from Davis Strait to the Southern Labrador Sea increased from an 11-to-12-year low observed in 2021 to a 4-to-8-year high in 2022, depending on the region.

Using Ocean colour metrics for the entire Labrador Sea (dashed outline in Figure 2), 2022 represents the largest spring bloom in intensity since 2002, just surpassing 2015 (Figure 12). These 2 years can be qualified as outliers, being well above average. The initiation of this year's production season in mid-March also occurs earlier than normal. This intense primary production is reflected by lower than normal nutrient inventories in the deep ocean and in surface waters, with the exception of the Greenland shelf, where the spring bloom was beginning during sampling. *Calanus finmarchicus* abundance remains lower than average on the Labrador shelf and higher than average within the Central Labrador Sea and Greenland Shelf. Larger abundance of Euphausiids on the Labrador Shelf and the central region breaks with lower abundance trends observed since 2016. The cold Arctic water Amphipods show a much lower abundance than normal, as in 2019, the last year of Spring sampling in the Labrador Sea. Shorter time trends (3-5 years) are difficult to assess because of the sampling gap during the Summer of 2020 and the cancelled missions of 2017 and 2021.

Sources of Uncertainty

The general spatial and seasonal patterns of physical, chemical and biological oceanographic indices in the Northwest Atlantic monitored by AZMP have remained relatively consistent since the start of the program. Although there are seasonal variations in the distribution of water masses, plants and animals, these variations show generally predictable patterns. However, there is considerable uncertainty in estimates of overall abundance of phytoplankton and zooplankton. This uncertainty is caused by the life cycle of the fauna and flora, their patchy distribution in space, and by the limited coverage of the region by the monitoring program.

Physical (temperature, salinity) and chemical (nutrients) oceanographic variables are effectively sampled, because they exhibit fairly conservative properties that are unlikely to show precipitous changes either spatially or from year-to-year. In addition, measurements of these variables are made with a good degree of precision. The only exception occurs in surface waters where rapid changes in the abundance of phytoplankton, particularly during the spring bloom, can cause rapid depletion of nutrients. The seasonal and longer-term variability of Labrador Sea physical conditions presented in Figures 7, 16 and 17 are sufficiently and accurately resolved with profiling Argo float observations.

The greatest source of uncertainty is in our estimates of phytoplankton biomass. Phytoplankton may undergo rapid changes in abundance and biomass at time scales of days to weeks. Our sampling is limited in time and occasionally suffers from gaps in coverage as a result of vessel unavailability or adverse weather conditions. As a result, spring phytoplankton bloom metrics are not sampled adequately. Also, variations in the timing of the spring phytoplankton bloom across a region and in relation to spring oceanographic surveys may limit our ability to determine inter-annual variations in maximum phytoplankton biomass. In contrast, we are better capable of describing inter-annual variations of dominant zooplankton species with seasonal cycles at time scales of weeks to months. However, zooplankton show great variability in spatial distribution. Although inter-annual variations in the abundance of dominant groups, such as copepods, can be adequately assessed, abundance of rare, patchily distributed or ephemeral species cannot be estimated . Cancellation of surveys in both 2020 (COVID) and 2021 has resulted in increased uncertainty in many oceanographic indices and may alter our assessment of interannual changes in ocean conditions, particularly biogeochemical variables.

In several areas, the occupation of high frequency sampling stations during the winter and early spring is particularly limited, sometimes missing major events in the seasonal cycle (e.g., the onset of the spring phytoplankton bloom).

CONCLUSION

While a shift to warmer ocean conditions occurred prior to 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. 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 second warmest and thinnest in the Gulf of St. Lawrence, but metrics are not available for other regions. Bottom temperatures were substantially above normal across the zone, including record highs in the northern Gulf of St. Lawrence, off southern Newfoundland and on the Scotian Shelf.

Patterns of variation in biogeochemical variables appear dominated by short-term fluctuations, given the twenty-three-year time series since 1999. 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. Following a period of general declines in nutrient and chlorophyll inventories and overall zooplankton biomass that indicated lower ecosystem production potential (2015-2017), nutrient and phytoplankton metrics were more mixed in 2022, despite record warm temperatures. However, after a few years of moderation in the shift in zooplankton community structure from large lipid-rich copepods to smaller copepods and other taxa, zooplankton indices in 2022 were highly similar to the 2015-2017 low production potential period.

In the Labrador Sea, winter convection was moderately deep, reaching the depth of 1600 m, following shallow convection the previous year. Sea ice area from Davis Straight to Southern Labrador Sea increased from an 11-to-12-year low observed in 2021 to a 4-to-8-year high in 2022, depending on the region.

LIST OF MEETING PARTICIPANTS

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SOURCES OF INFORMATION

This Science Advisory Report is from zonal peer review of March 27–29, 2023 on the Twenty-Fifth Annual Meeting of the Atlantic Zone Monitoring Program (AZMP). Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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APPENDIX—FIGURES

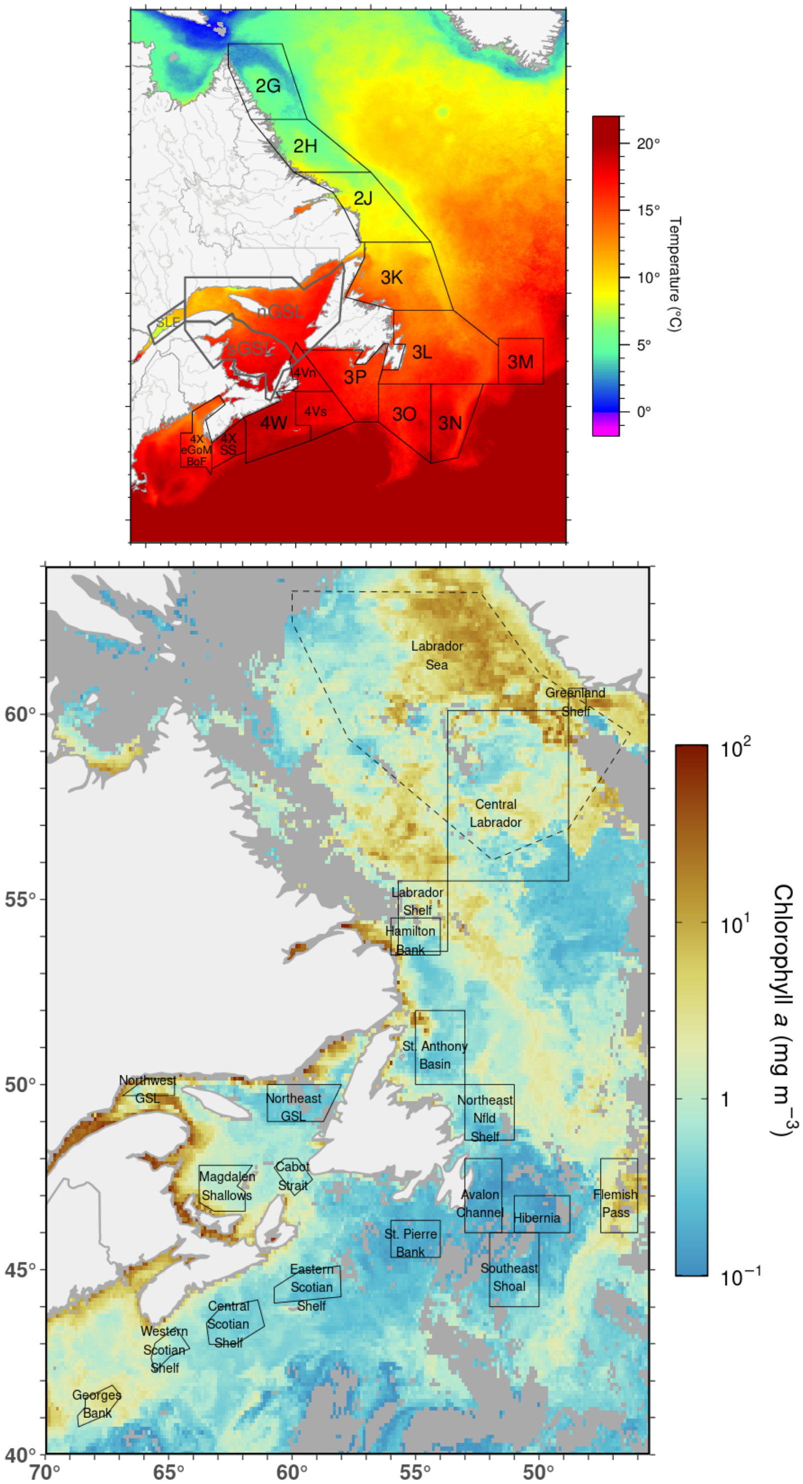

Figure 2. Areas used for (top) temperature and (bottom) ocean colour averages. (Top) North Atlantic Fisheries Organization Divisions are cut off at the shelf break. The acronyms GSL and SLE are Gulf of St. Lawrence and St. Lawrence Estuary respectively. Sea surface temperatures are shown for September 2022 and ocean colour chlorophyll a concentrations are for the day of year 145 to152.

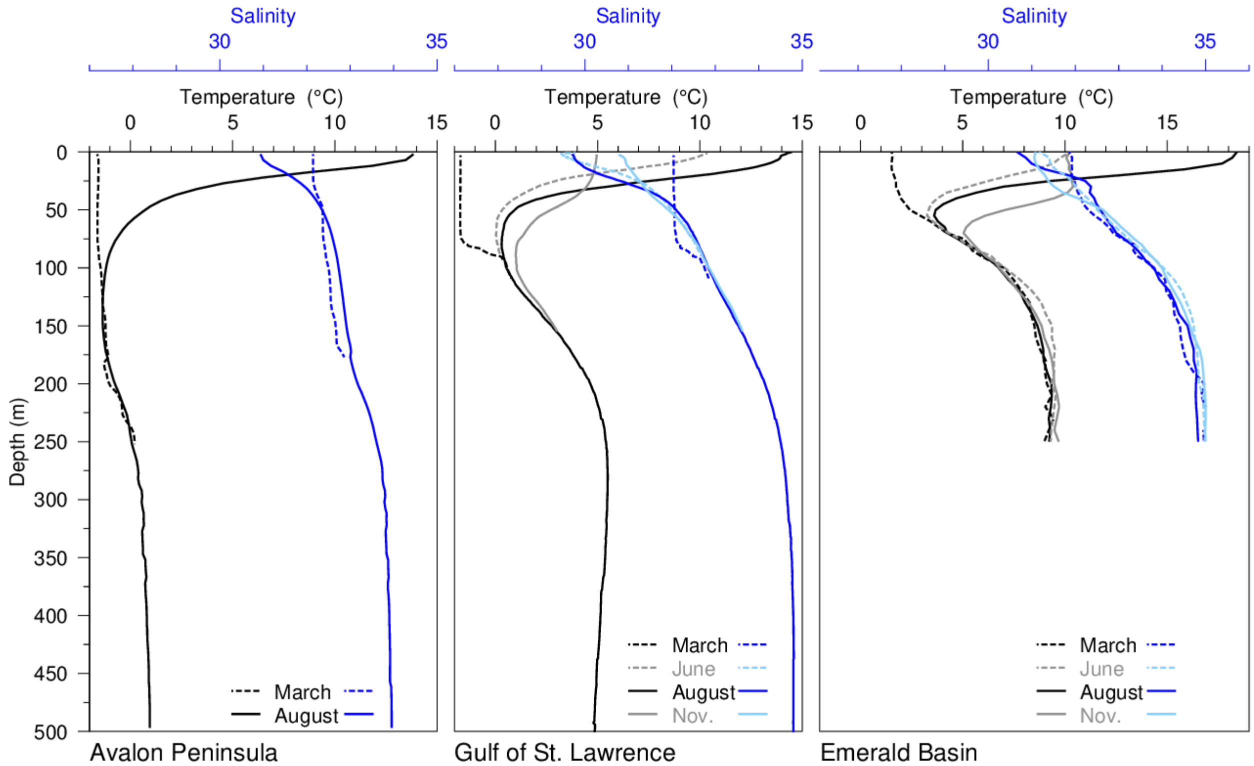

Figure 3. Typical seasonal progression of the depth profile of temperature and salinity observed in three representative regions across the zone. The Avalon Peninsula region is delimited by 45–50°N and 50–55°W and shown are the averages of profiles for March and August between 2015 and 2017, calculated 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.

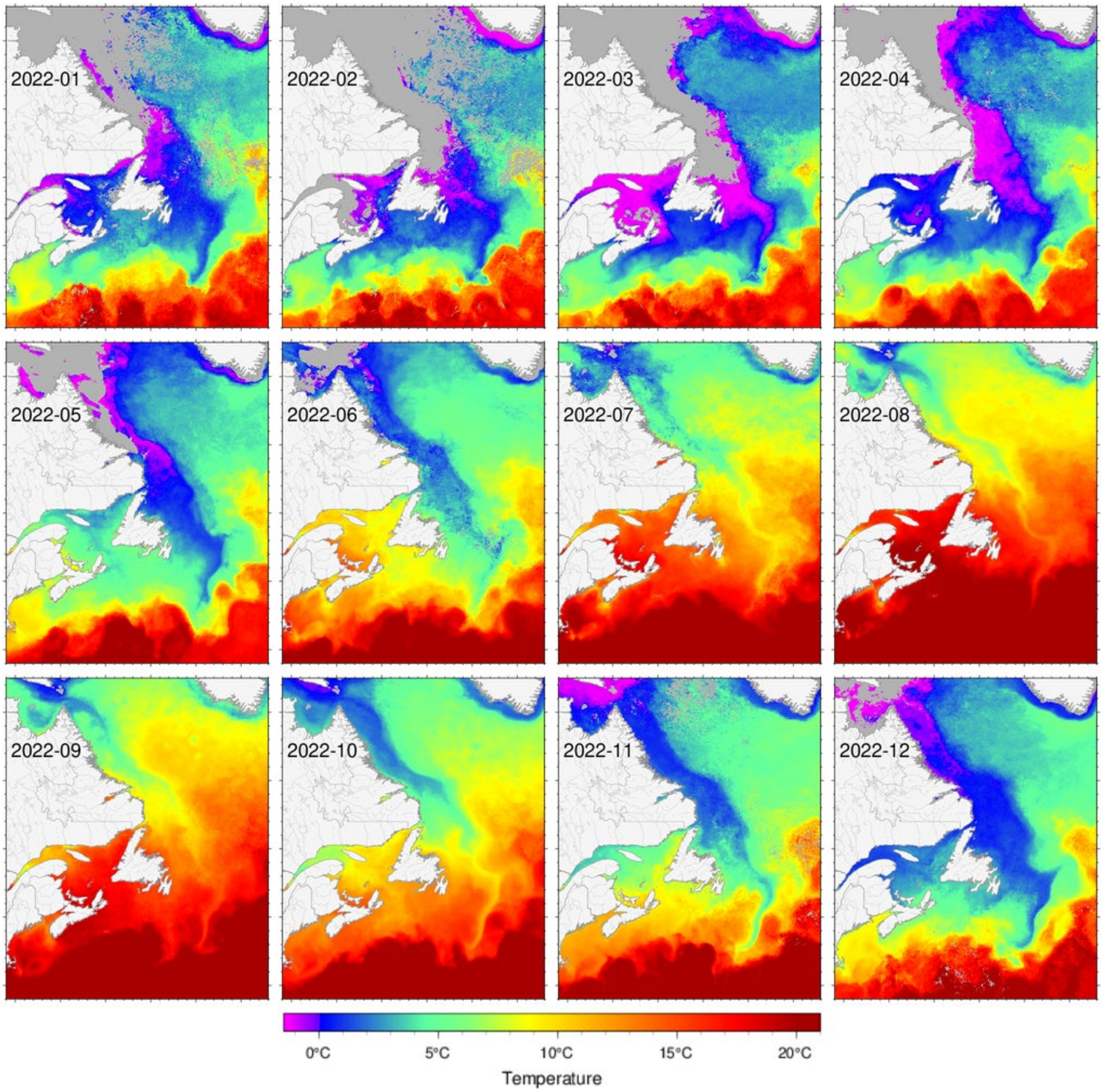

Figure 4. Sea surface temperature monthly averages for 2022 in the Atlantic zone.

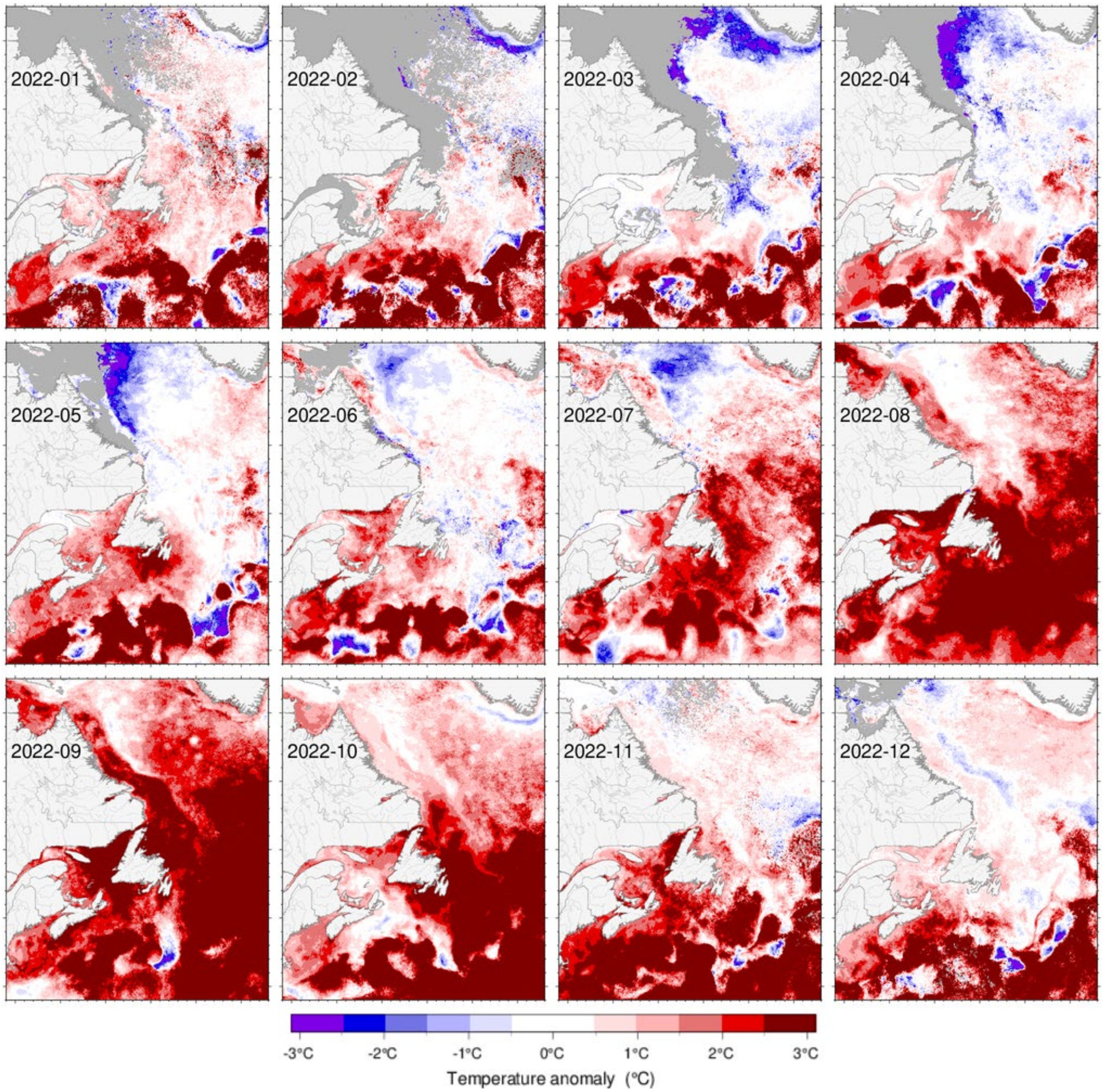

Figure 5. Sea surface temperature monthly anomalies for 2022 in the Atlantic zone. Temperature anomalies are based on a 1985–2010 climatology and not the 1991–2020 used elsewhere in this document.

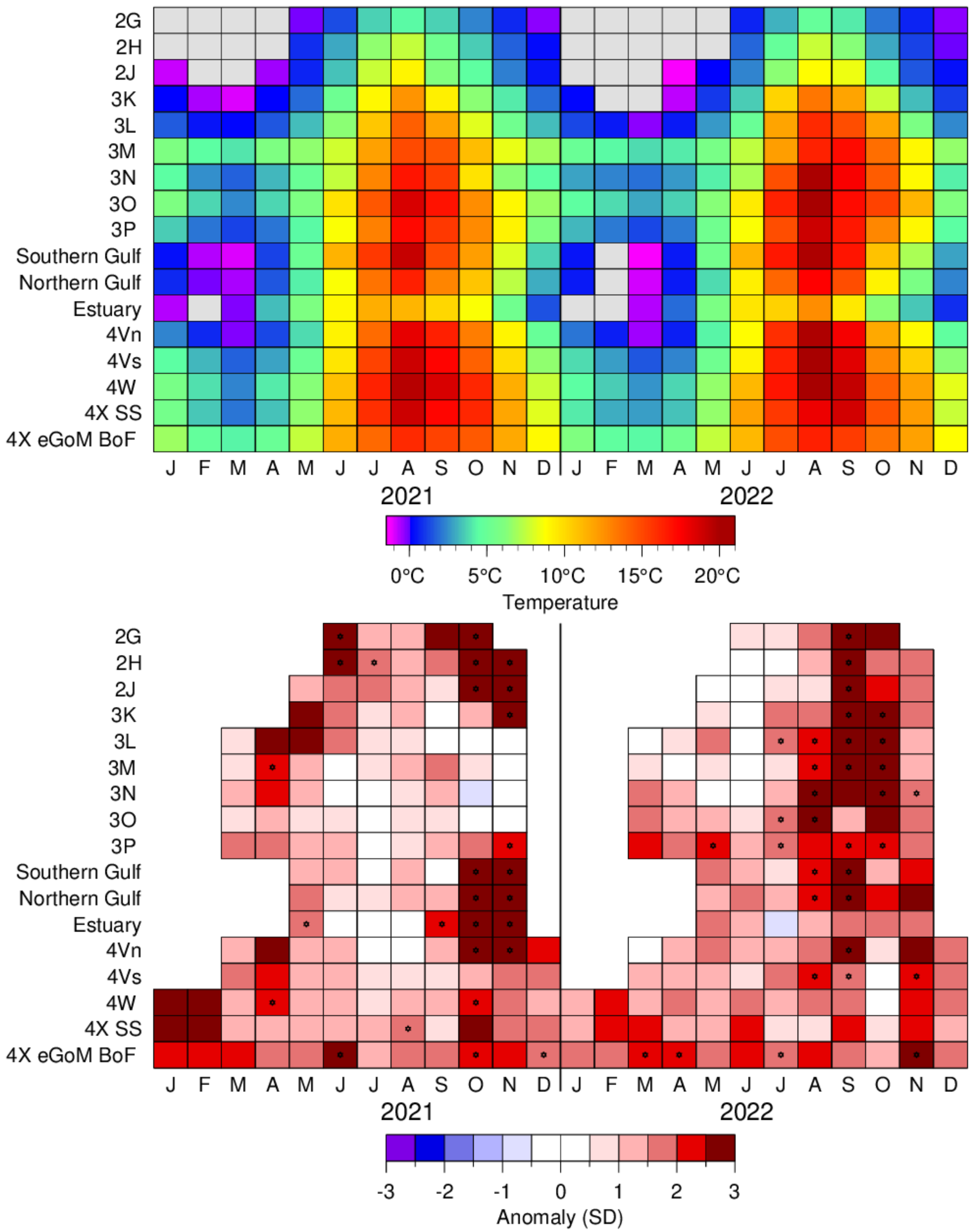

Figure 6. Monthly sea surface temperature temperatures (top) and anomalies (bottom) for ice-free months of 2021–22, averaged over the 17 regions shown in Figure 2. Regions and months for which the average temperature was at a record high or low are indicated by a star. Grey squares have insufficient data coverage to yield a monthly average anomaly (<7%).

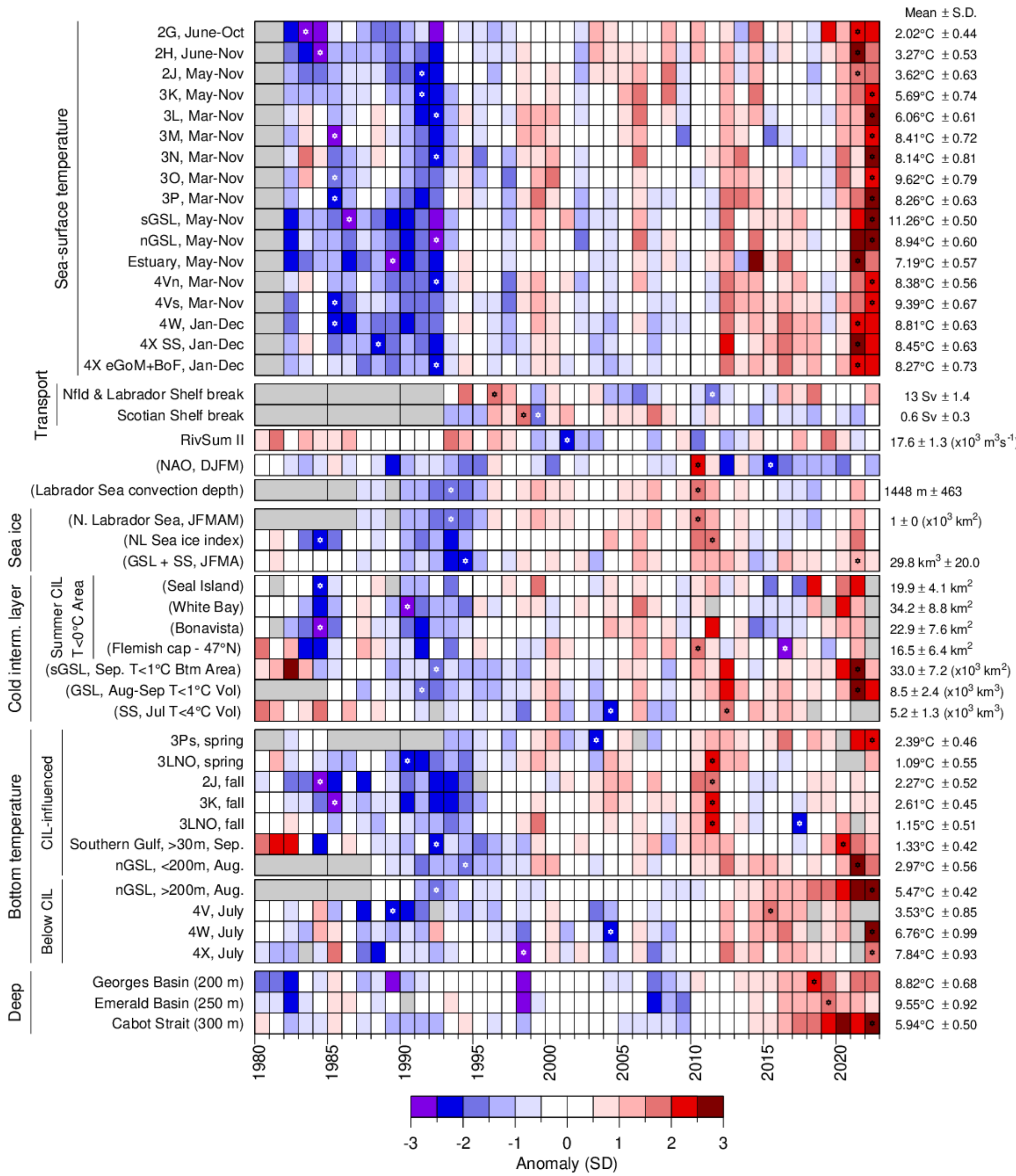

Figure 7. Time series of oceanographic variables, 1980–2022. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1991–2020 when possible; a red cell indicates above normal conditions, and a blue cell below normal. Variables whose names appear 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 minimum and maximums are indicated by a star 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]).

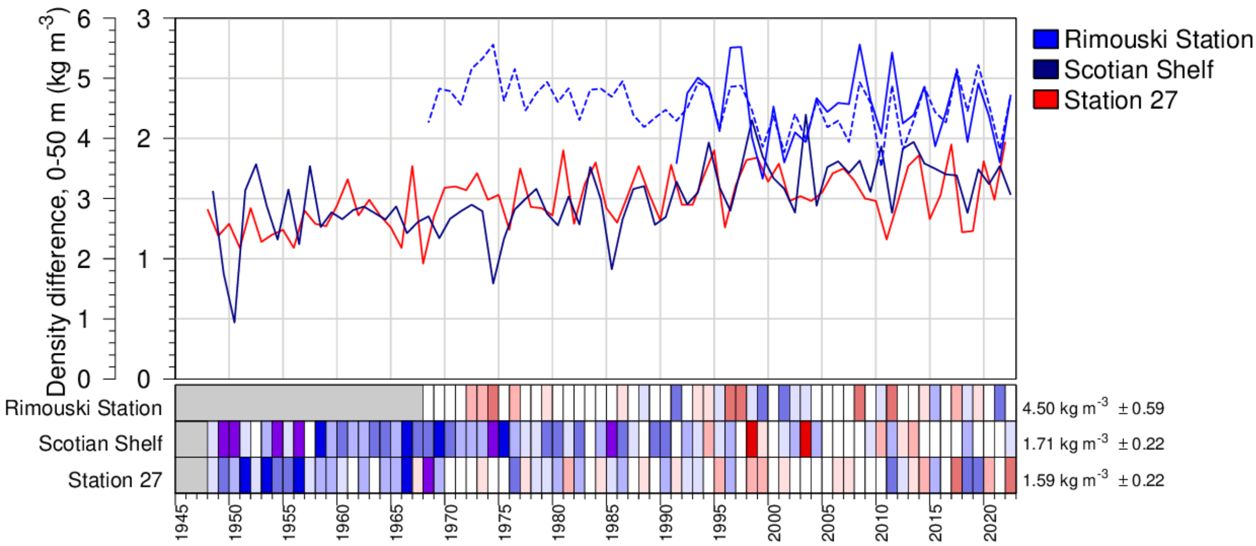

Figure 8. Stratification trends on the southern Newfoundland-Labrador Shelf (May-Nov average at Station 27), Scotian Shelf and St. Lawrence Estuary (May–Oct average at Rimouski Station). The inner y-axis is for Station 27 and Scotian shelf, while the outer y-axis is for Rimouski Station. The dashed line for Rimouski Station is a proxy based on May–October 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.

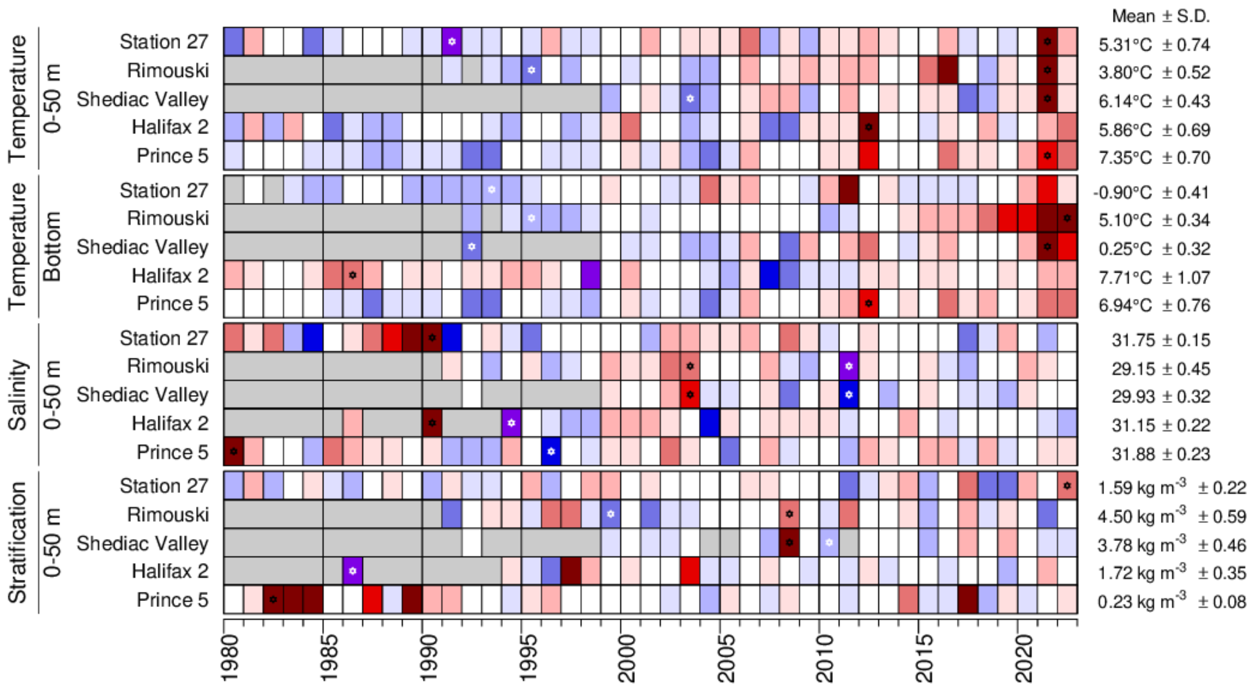

Figure 9. Time series of oceanographic variables at AZMP high-frequency sampling stations, 1980–2022. Values are annual averages at Halifax 2 and Prince 5, May–November at station 27 and May-October at Rimouski station. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1991–2020 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 minimum and maximums are indicated by a star 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.

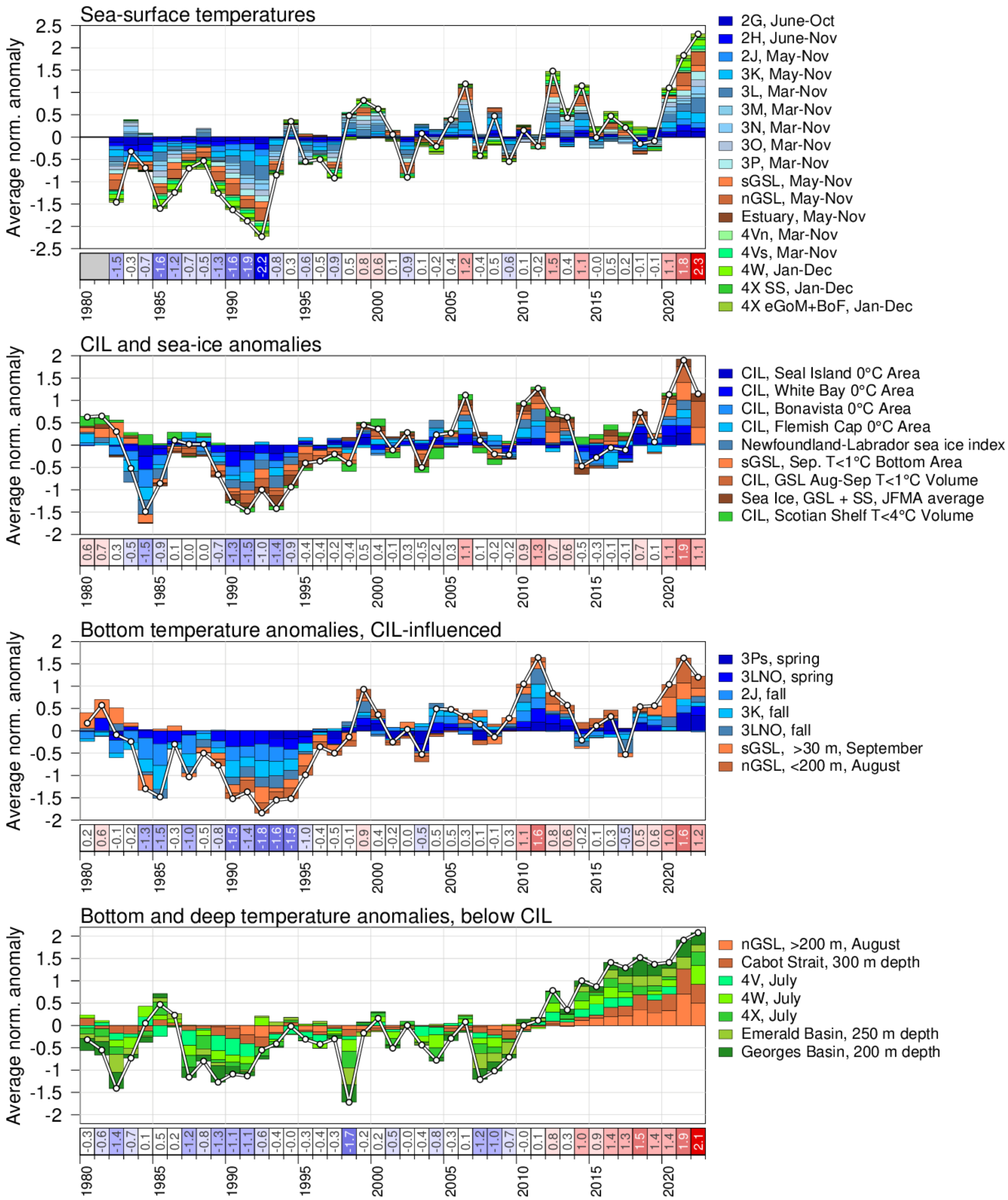

Figure 10. Composite climate indices (white lines and dots) derived by averaging various normalized anomalies from different parts of the environment (coloured boxes stacked above the abscissa are positive anomalies, and below are negative). Top panel shows average sea surface temperature anomalies weighted 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 averages bottom temperature anomalies for cold, CIL-influenced waters and for warmer waters found below the CIL.

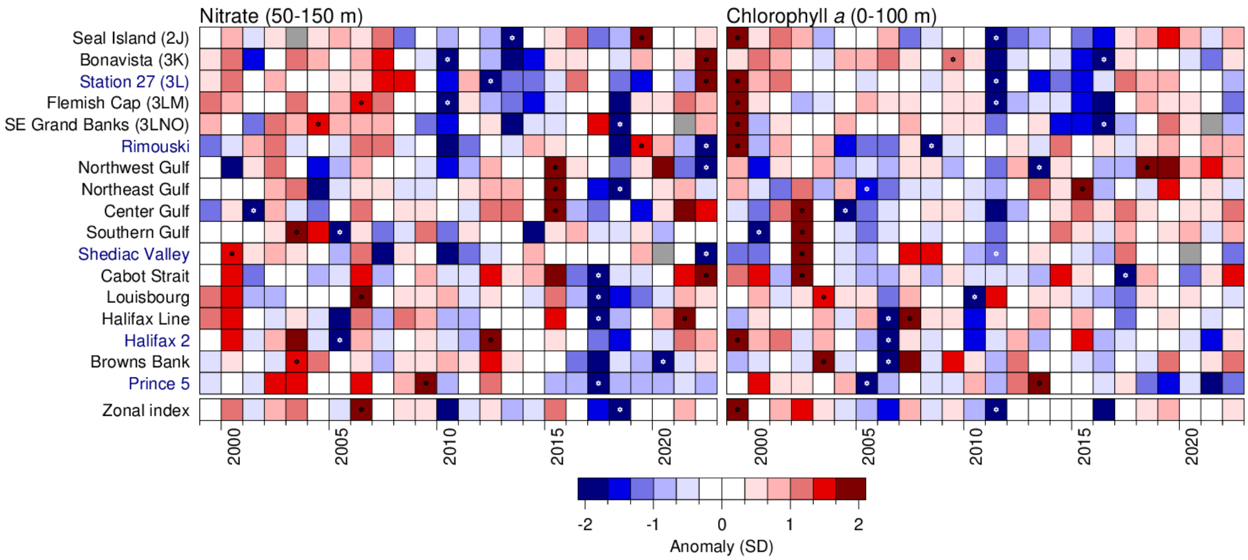

Figure 11. Time series of deep water nitrate inventories (50–150 m) and surface phytoplankton standing stocks (expressed as chlorophyll a 0–100 m mean concentration) at AZMP sections (labelled in red in Figure 1) and high-frequency sampling stations (labelled in blacks in Figure 1), 1999–2022. Chlorophyll values are log-transformed. A grey cell indicates missing data. Note change in colour palette: 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. Series minimum and maximums are indicated by a star. The "zonal index" is created as the average of all normalized anomalies, and that result is again normalized.

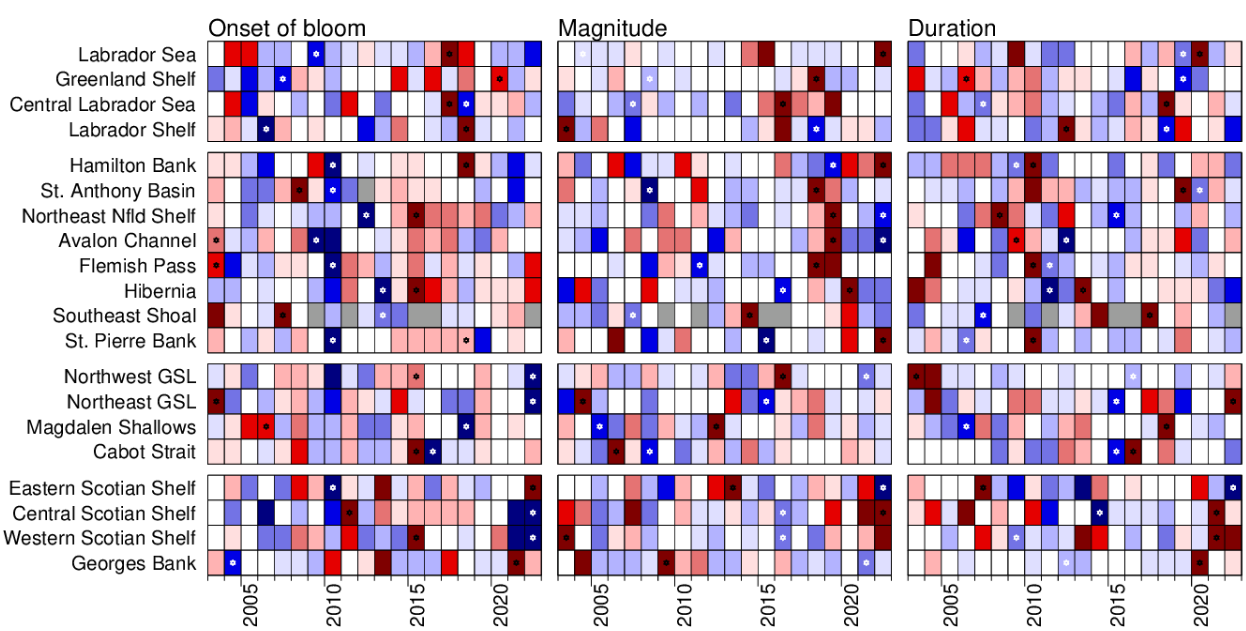

Figure 12. Time series of remotely sensed bloom parameter anomalies in various regions (onset of bloom, magnitude and duration) 2003–2022. Data are MODIS. Series minimum and maximums are indicated by a star. See Figure 2 for area definitions. Palette as in Figure 11.

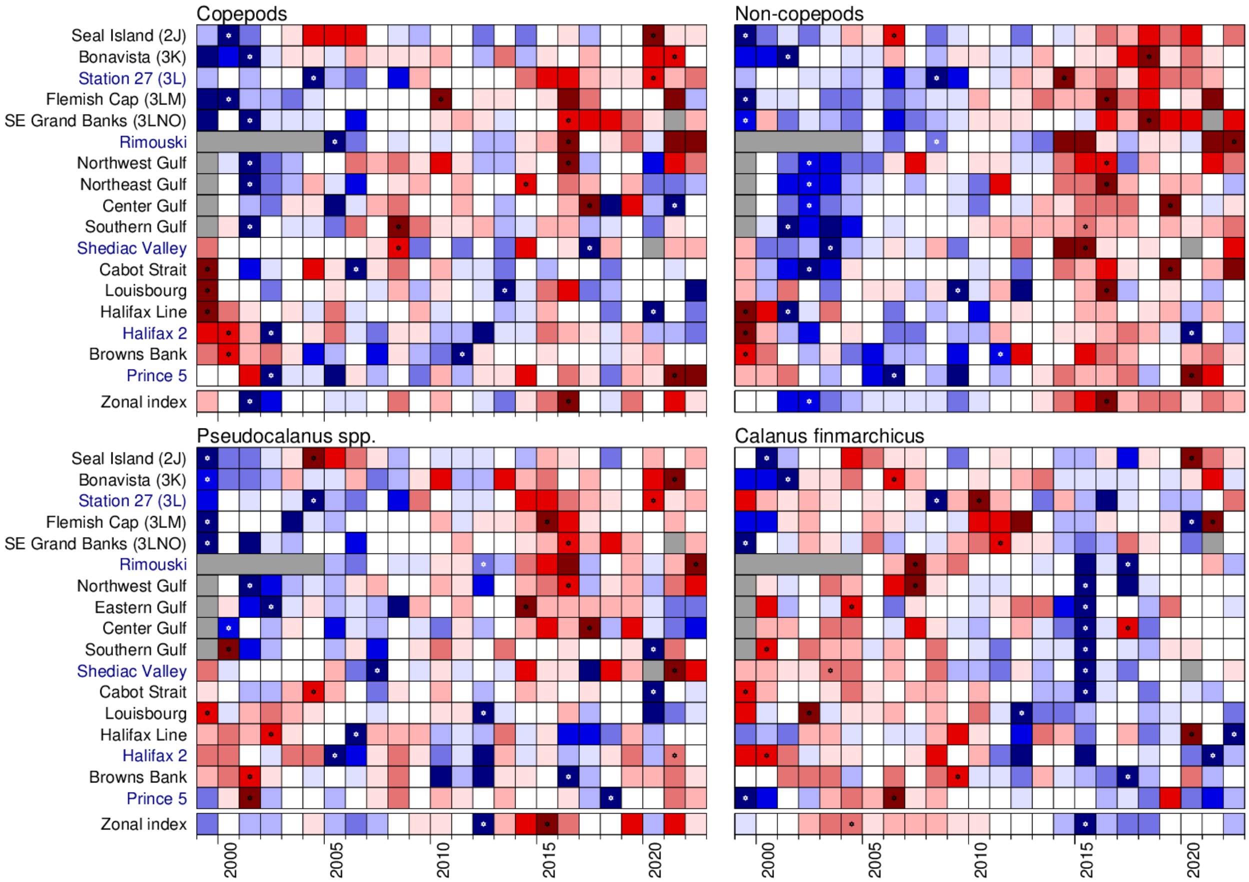

Figure 13. Time series of the (log-transformed) standing stocks of total copepods, Calanus finmarchicus*,* Pseudocalanus *spp., and non-copepod zooplankton, 1999–2022. A grey cell indicates missing data, a white cell is a value within 1/3 SD of the long-term mean based on data from 1999–2020; a red cell indicates above normal inventories, a blue cell below normal. More intense colours indicate larger anomalies. Series minimum and maximums are indicated by a star. The "zonal index" is created as the average of all normalized anomalies, and that result is again normalized.*

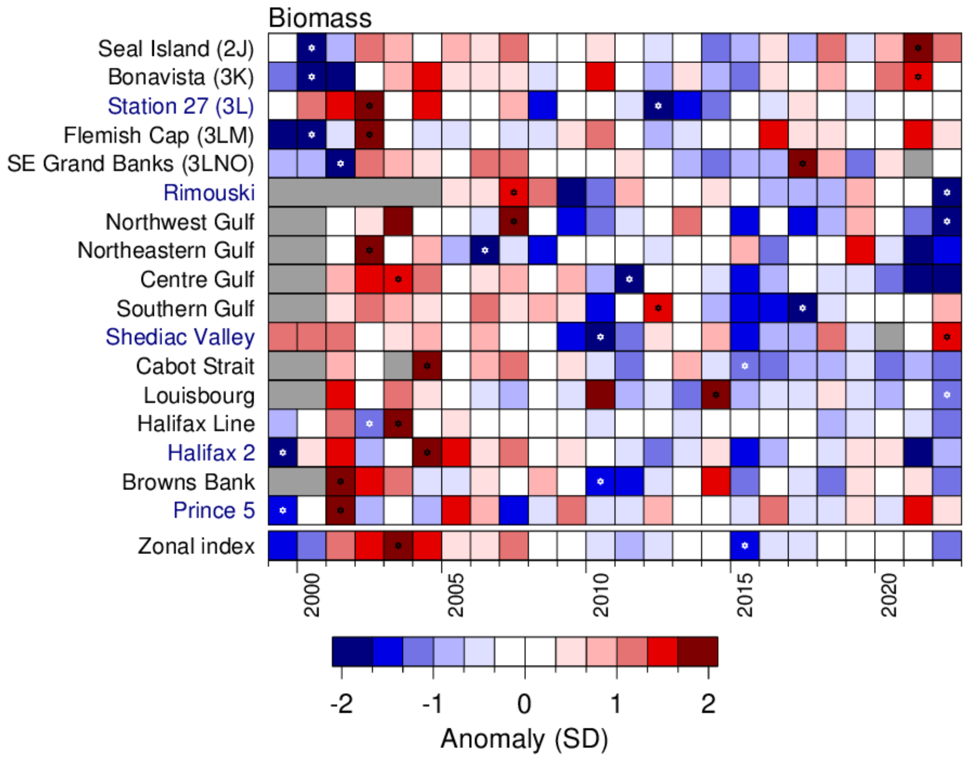

Figure 14. Time series of zooplankton biomass (dry weight, log-transformed), 1999 to 2022. Biomass is measured on the 0.2–10 mm size fraction which is usually dominated by copepods. A grey cell indicates missing data, a white cell is a value within 1/3 SD of the long-term mean based on data from 1999–2020; a red cell indicates above normal inventories, a blue cell below normal. More intense colours indicate larger anomalies. Series minimums and maximums are indicated by a star. The lowest row is the averaged (anomaly across all sections and fixed stations in a given year. The "zonal index" is created as the average of all normalized anomalies, and that result is again normalized.

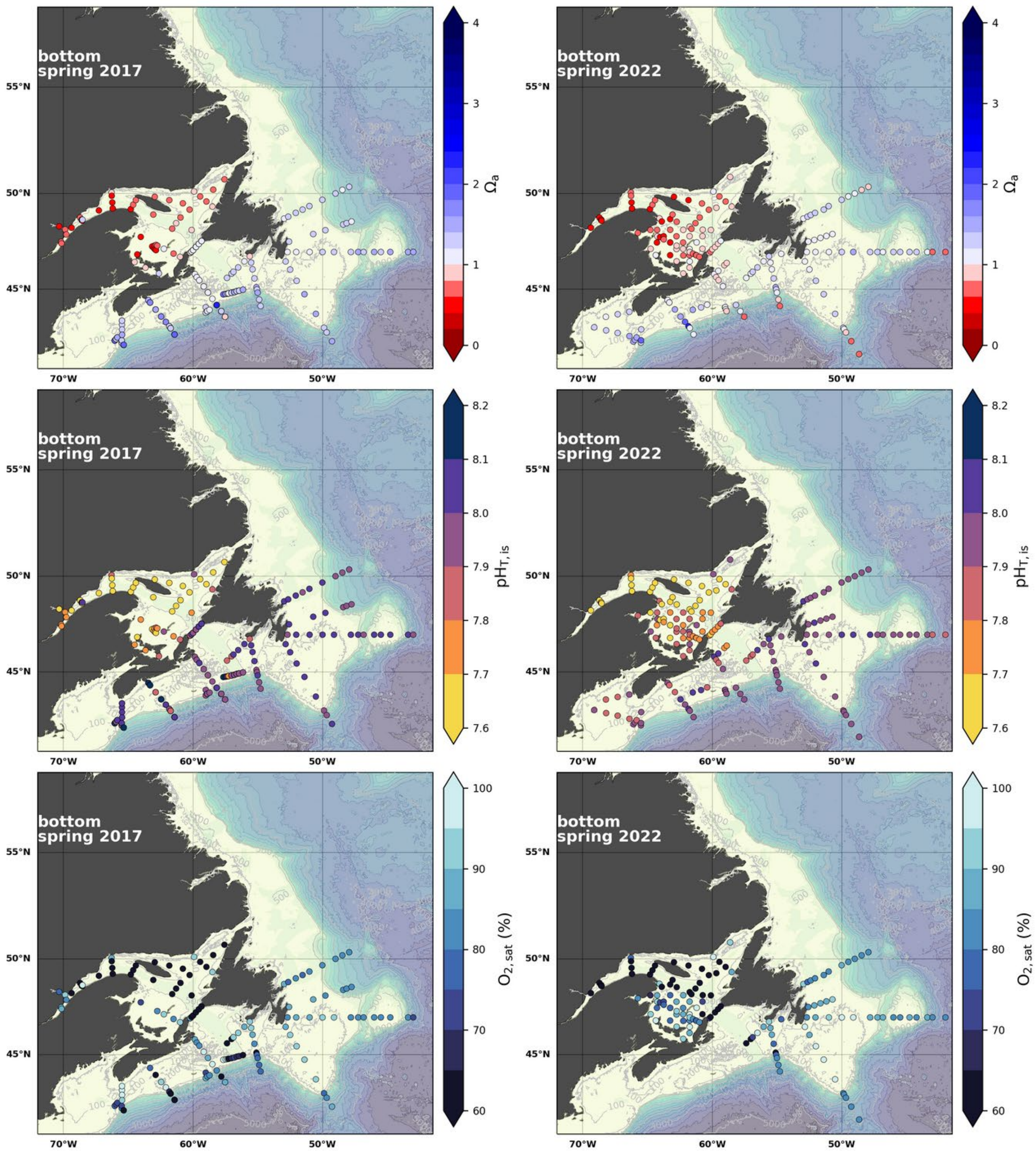

Figure 15. Bottom ocean acidification conditions during spring 2017 (left) and 2022 (right) for the Gulf of St. Lawrence, Scotian Shelf and Newfoundland Shelf: aragonite saturation state (top), in situ pH using total scale (centre) and dissolved oxygen saturation (lower). Undersaturated conditions relative to aragonite and hypoxic oxygen conditions are plotted in red colors.

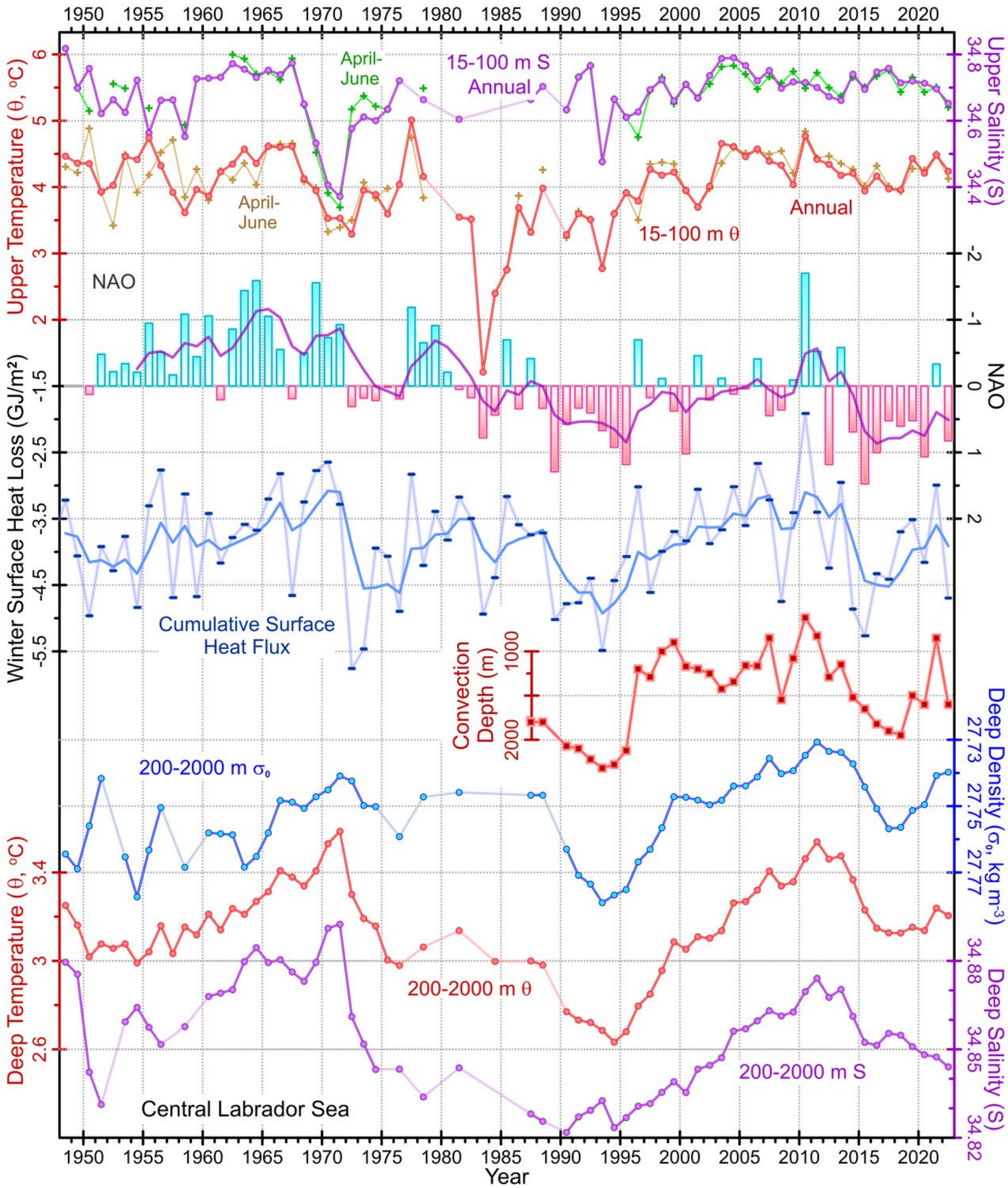

Figure 16. Key Labrador Sea environmental indices since 1948. From top to down: Annual and spring mean salinity (S) and temperature (θ) averaged over the 15–100 m depth range; The normalized winter NAO index (bar graph, inverted vertical scale); The NCEP reanalysis-based cumulative surface heat flux computed for the central Labrador Sea over individually-defined annual cooling seasons (blue); Convection depth; Annual mean seawater density (σ_0), θ and S averaged over the 200–2000 m depth range in the central Labrador Sea. The solid lines overlaying the NAO and heat flux graphs indicate five-back-point filtered series.

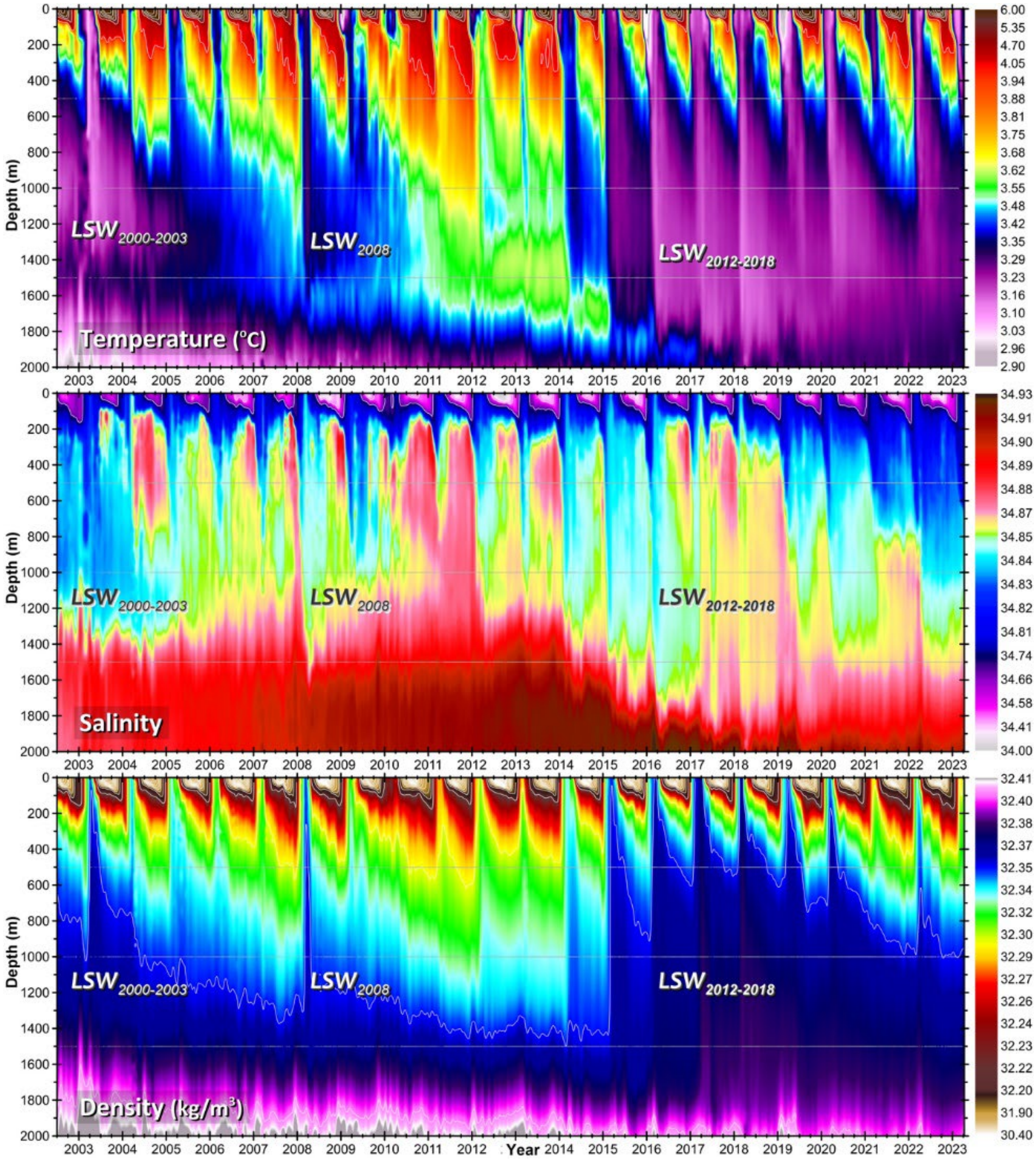

Figure 17. Temperature (upper), salinity (middle), and density (referenced to 1000 dbar; lower) over the 0–2000 m layer of the central Labrador Sea during 2002–2023, based on quality-controlled Argo float and shipboard observations that are averaged in overlapping 10-day windows, spaced 5 days apart. LSW indicates Labrador Sea Water, subscripted with respective year classes.

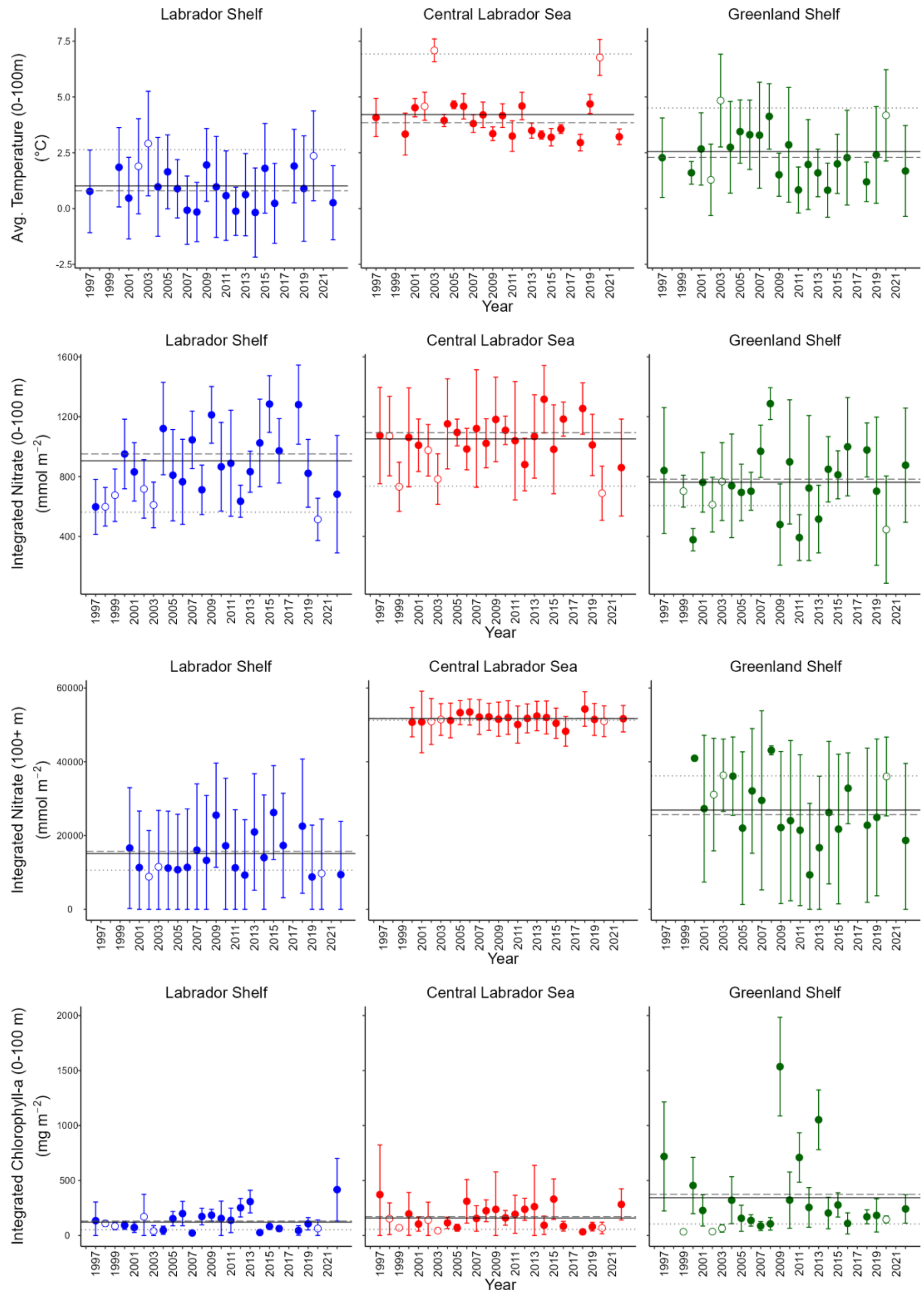

Figure 18. Labrador Sea 0–100 m averages of observations from oceanographic station data. Top to bottom panels show the average temperature from 0 to 100 m (°C), the integrated nitrate for the top 100 m, the integrated nitrate below 100 m to the bottom (mmol m^{-2}) and the integrated chlorophyll a from 0 to 100 m (mg m^{-2}). From left to right the panels are divided in 3 regions with the Labrador Shelf in Blue, the Central Labrador Sea in Red and the Greenland Shelf in green. Open symbols correspond to late surveys (after 19 June).The reference period is from 1999 to 2020 and the solid line represents the average for all years, the dashed line corresponds to the summer average and the dotted line corresponds to the spring period.

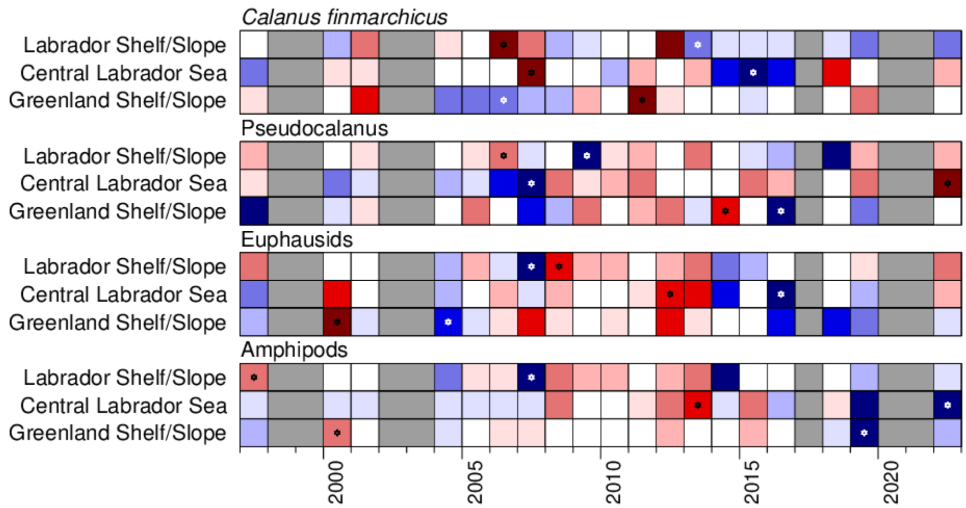

Figure 19. Normalized annual anomalies for the Labrador Sea. Zooplankton data represent anomalies of abundance estimation collected in May/June along the AR7W line between 1995 and 2019. Palette as in Figure 11.

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