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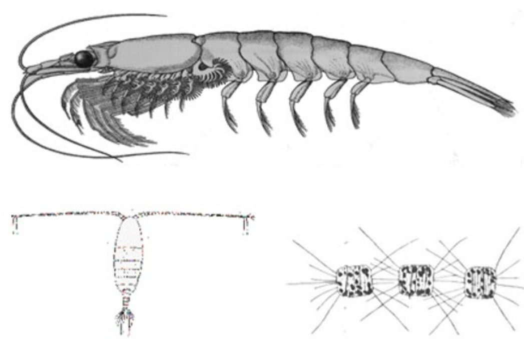
OCEANOGRAPHIC CONDITIONS IN THE ATLANTIC ZONE IN 2021



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

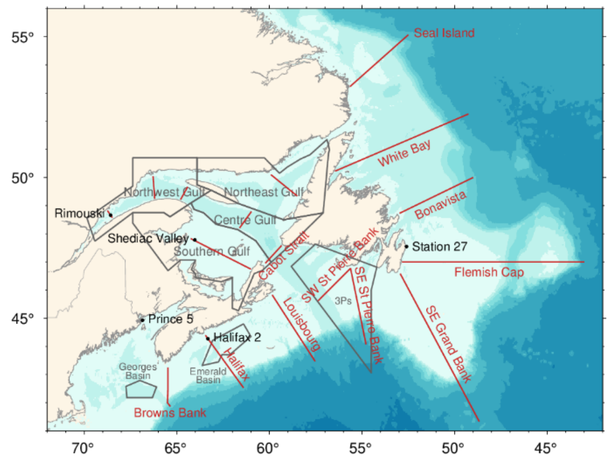


Figure 1. Atlantic Zone Monitoring Program high-frequency sampling stations (black), selected section lines (red) and averaging areas (gray).

Context:

The Atlantic Zone Monitoring Program (AZMP) was implemented in 1998 with the aim of increasing Fisheries and Oceans Canada (DFO's) 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 advisory meeting on March 21–23, 2022 Twenty-Fourth 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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SUMMARY

- Monthly and seasonal average sea surface temperatures were generally normal to above normal in ice-free areas, with many regional monthly records set in January, June, and September through December, and seasonal series records set in the northern Gulf and Estuary. Anomalies were weaker in parts of the Grand Banks. The spatially weighted zonal average was third highest of the time series.
- The Labrador Current transport remained near normal along the Newfoundland and Labrador Shelf break. The transport along the Scotian Shelf break has been weak since 2014.
- Winter average sea ice conditions were at a record low in the Gulf of St. Lawrence and third lowest of the time series on the Newfoundland and Labrador Shelf.
- The cold intermediate layer (CIL) was warm and of limited extent throughout the Zone, including series records in the Gulf of St. Lawrence. The CIL and sea ice index for the zone was the warmest of the times series, since 1980.
- Bottom temperatures were substantially above normal across the zone, including record highs in the northern Gulf of St. Lawrence and off southern Newfoundland. The zonal average index for CIL-influenced bottom temperatures tied for highest of the time series (since 1980). The zonal average index for below-CIL bottom temperatures was highest of the time series but is missing several of its components for 2021.
- At the high-frequency sampling sites, seasonal average 0–50 m and bottom temperatures were all above normal, including series records in one or both metrics at all stations except Halifax 2. Stratification was lowest since 2001 at Rimouski station and below normal to normal at other stations.
- Deep nitrate inventories were highly variable throughout the Atlantic Zone, with high inventories on the Flemish Cap, in the northeast and Central Gulf of St. Lawrence, and on the Central and eastern Scotian Shelf including a record high on the Halifax line.
- Surface chlorophyll inventories were generally below normal on the Newfoundland and Labrador Shelf and the Scotian Shelf, above normal in the Gulf of St. Lawrence. The reliability of interannual variations in this metric for 2021 from Newfoundland and Labrador and the Scotian Shelf is a concern because of limited sampling.
- The onset of the spring phytoplankton bloom was early throughout most of the Atlantic Zone, with the exception of the Grand Banks, southern Newfoundland and Georges Bank.
- The magnitude of the bloom was below normal on the Newfoundland Shelf and Gulf of St. Lawrence and above normal in the Labrador Sea, on the Labrador Shelf and the Scotian Shelf.
- The duration of the bloom followed a mainly latitudinal gradient from long in northern areas to short on the Scotian Shelf.
- Copepod abundance was below normal on the Newfoundland Shelf, the eastern Gulf of St. Lawrence and at Halifax 2, and above normal in the western and southern Gulf of St. Lawrence.
- Non-copepod abundances were close to normal on the Newfoundland Shelf, eastern Gulf of St. Lawrence and Halifax 2, and above normal in the northwestern and southern Gulf of St. Lawrence.

- The abundance of *Calanus finmarchicus* was generally normal or below normal throughout much of the Newfoundland Shelf, the Gulf of St. Lawrence, with a record low at Halifax 2.
- *Pseudocalanus* spp. abundance was below normal on the Newfoundland Shelf and eastern Gulf of St. Lawrence, and above normal in the western and southern Gulf of St. Lawrence and at Halifax 2.
- Zooplankton biomass was mostly above normal on the Newfoundland Shelf and below normal in the Gulf of St. Lawrence and at Halifax 2, reaching record or near record levels at several locations in each region.
- Zooplankton anomalies from the Scotian Shelf sections were not available as a result of limited sampling opportunities and delays in sample processing.
- Dissolved oxygen concentration generally declined in deep waters of the Gulf of St. Lawrence and was at a record low at Rimouski station, while pH remained at a near-record low value there.
- Labrador Sea convection reached 850 m, the shallowest since 2011 and 3rd shallowest in 32+ years. Sea ice area and extent were the lowest since 2011 and 2nd lowest in 42+ years.
- Biogeochemical metrics are not available for the Labrador Sea due to the cancellation of the survey in 2021.

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 the 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, ecosystem surveys) in each of DFO's administrative regions in Eastern Canada (Quebec, Maritimes, Gulf, Newfoundland and Labrador) sampled at a frequency of weekly to once 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, 11 glider missions consisting of 7895 profiles of temperature, salinity, oxygen, optical backscatter, chlorophyll and CDOM fluorescence were conducted on the Halifax Line. For the Bonavista Line, 4 missions collected 2659 profiles. Viking oceanographic buoys collected 1033 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 included 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 a more 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 0.3 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 2021 for eastern Canadian oceanic waters (Figures 1 and 2) as reported annually by the AZMP in research documents (e.g. Hebert et al. 2021 and Galbraith et al. 2021a for conditions in 2020 and Cyr et al. 2021 for conditions in 2019). Exceptionally, a primary publication describes conditions in 2020 on the Newfoundland and Labrador Shelf (Cyr and Galbraith 2021).

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 the 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 2021, the winter NAO index was -0.1, breaking a 7-year positive run. This positive streak has however not coincided with 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 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 blends data from Pathfinder version 5.3 (1982–2021), Maurice Lamontagne Institute (1985–2013) and Bedford Institute of Oceanography (1997–2021) and monthly temperature composites are calculated from averaged daily anomalies to which monthly climatological average temperatures are added (Galbraith et al. 2021b). 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. 2021b). The Zone experienced its warmest surface temperatures in 2012 when all regions had positive anomalies over ice-free months, with records reached in the Bay of Fundy-Gulf of Maine (4X eGoM+BoF), Scotian Shelf (4X SS, 4W, 4Vn, 4Vs), St. Pierre Bank (3P) and Flemish pass (3M).

In 2021, monthly average sea surface temperatures were generally normal to above normal in ice-free areas. Of the 131 regional monthly averages reported in Figure 6, only six were below normal and 22 were series records. The Scotian Shelf (4W and 4X SS), Eastern Gulf of Maine and Bay of Fundy were at record highs in January. The latter and Northern Labrador Shelf (2G) were at record highs in June. In September, there was a high temperature record in 2G and the Estuary, followed by other high record in October in many regions from Labrador Shelf (2H), Estuary, Gulf, Scotian Shelf (4Vn, 4W, 4X SS) and Eastern Gulf of Maine and Bay of Fundy.

Those high anomalies persisted onto November in multiple regions and even December in the latter region. During the same period, in October, the southern Newfoundland shelf (3LNO) was the only part of the east coast below normal.

Sea surface temperatures averaged over the ice-free months (Figure 7) were normal to above normal across the zone, with seasonal series records set in the northern Gulf and Estuary.

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. 2021). For the Gulf, the CIL volume with T <1 °C observed in August-September is used (Galbraith et al. 2021a). 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. 2021a). The CIL indices reported here are taken at about the same time within their respective annual cycles, although not simultaneously.

Prior to 2021 observations, both the Gulf of St. Lawrence and Scotian Shelf CIL volumes were at record lows in 2012, representing record warm conditions. While conditions were warmer than normal in the Newfoundland and Labrador sections in 2011 and 2013, they were followed by mostly normal to colder-than-normal conditions during 2014–17. In 2021, CIL conditions were warmer-than-normal and of limited extent where measured, by a near-record of +2.1 SD on the Seal Island section and by +3.1 SD in the southern Gulf where the September bottom area having temperatures colder than 1 °C was at a record low (since 1964) of only a third of the climatological mean. The volume of CIL waters colder than 1 °C by August/September in the Gulf of St. Lawrence was at a record low. There were no measurements of the usually reported CIL metrics on the Scotian Shelf because of limited sampling, therefore its record low volume remains in 2012.

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 (1969–2019, $R^2 = 0.65$–0.81; Cyr et al. 2021). 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 ($R^2 = 0.79$–0.82; Galbraith et al. 2021a). 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 13 days of sea ice season for each 1 °C increase in winter air temperature (Galbraith et al. 2021a).

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).

For the past decade, 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 twelve year period between 2010 and 2021, the Gulf seasonal average sea ice volume had eight of the twelve lowest values of the series, while the Newfoundland and Labrador shelf had five of the twelve lowest indices (including 2020 and 2021). In 2021, the Newfoundland and Labrador sea ice index was below normal (-1.7 SD) and 3rd lowest of the time series. The seasonally averaged sea ice volume in the Gulf of St. Lawrence was at a record low (since 1969; -1.4 SD), and the volume of ice exported onto the Scotian Shelf was close to zero (0.46 km^3; -0.8 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 2021, bottom temperatures were substantially above normal across the zone, including a series record in areas shallower than 200 m in the northern Gulf in August and a series record in 3Ps in the spring, off southern Newfoundland (Figure 7). There were however no measurements on the Scotian Shelf due to a cancelled survey. There were new 100+ year high-temperature records for the Gulf 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 the 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 runoffs 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 (Galbraith et al. 2021a). The inter-annual variability of the seasonal (May–October) stratification (0–50 m) at Rimouski Station in the

Estuary is correlated with the seasonally averaged runoff of the St. Lawrence river (1991–2021; $R^2 = 0.58$, Figure 8). The 2021 annual runoff was well below normal (16 100 m^3s^{-1}, -1.3 SD).

Stratification on the Scotian Shelf was near normal in 2021 (+0.1 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, composed equally of warming and freshening. Stratification was below normal at Rimouski station (-1.4 SD), the lowest value since 2001, consistent with the below normal 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, including series record in one or both metrics at all stations except Halifax 2 (Figure 9). All except Halifax 2 had records in 0–50 m average temperature and Rimouski and Shediac Valley stations both had records in bottom temperature. The September through November SST records in the Estuary (see above) were not limited to near-surface waters; Rimouski station recorded higher 0–50 and 0–100 m average temperatures in all three months than in August, indicating an important event in estuarine circulation. Bottom temperatures had been slowly increasing in recent years at Rimouski and was expected to gently cross the 6 °C threshold in 2021. Instead, temperature jumped suddenly to the 6.15 °C to 6.20 °C range during the winter of 2021.

Stratification was lowest since 2001 at Rimouski station and below normal to normal at other stations. There was no clear pattern in 0–50 m seasonal average salinity as it was below normal at Station 27 and Halifax 2, above normal at Prince 5, and near normal at Rimouski station where stratification was below normal.

Labrador Current Transport Index

The annual-mean Labrador Current transport index shows that the transport along the Newfoundland and Labrador (NL) shelf break is generally out of phase with that on the Scotian shelf break (Figure 7). The 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. The Labrador Current transport remained near normal on the NL shelf break and the transport of slope waters has been weak on the Scotian shelf break since 2014 (-1.4 SD in 2021).

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 2021 ice-free months were normal to above normal across the zone, with seasonal series records set in the northern Gulf and Estuary driven partly by unusually very high temperatures throughout the top 100 m. Warming winters have also led to less sea ice cover and weaker 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.

The 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 during this period in central (4W) and western (4X) Scotian Shelf, Georges Basin (200 m), Emerald Basin (250 m), southern Newfoundland (3Ps), shallow waters (<200 m) in the northern Gulf, as well as a 100+-year record in the northern Gulf of St. Lawrence deep waters (>200 m) and in Cabot Strait (300 m).

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 2021 were above normal and 3rd highest for surface temperatures, at a warm record for CIL and sea ice anomalies as well as for below CIL (warmer) bottom temperatures, however this last index is missing several components for 2021. Bottom temperatures influenced by the CIL tied for warmest with 2011. A total of 44 indices listed in Figures 7 and 9 describe ocean conditions related to temperature within the AZMP area in 2021 (SST; ice; summer CIL areas, volumes, and minimum temperature; bottom temperature; 0–50 m average temperature). Of these, none presented colder than normal conditions, 3 were within normal values (± 0.5 SD) and 41 were above normal, indicating a continuation of warmer than normal oceanographic conditions in 2021 across much of the Atlantic Zone despite a near normal NAO index.

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. Zooplankton 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. 2019), Gulf of St. Lawrence (GSL) (Blais et al. 2021) and Scotian Shelf (Casault et al. 2022) 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 nutrient inventories (50–150 m) in 2021 were highly variable across the Atlantic Zone, with high inventories on the Flemish Cap, in the northeast and central Gulf of St. Lawrence, and on the central and eastern Scotian Shelf, including a record high on the Halifax line (Figure 11). The higher deep nitrate inventories on the central and eastern Scotian Shelf are a reversal from the mainly low nitrate inventories observed on the Scotian Shelf since 2016.

Phytoplankton

Chlorophyll inventories in the upper ocean (between 0–100 m) represent phytoplankton biomass. They demonstrated a high degree of year-to-year variability including exceptional values either above or below the long-term average (Figure 11). 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 may vary annually depending on environmental conditions.

Annual chlorophyll *a* inventories in 2021 were generally below normal on the Newfoundland and Labrador Shelf. However, the reliability of interannual variations in this metric for the 2021 data from Newfoundland and Labrador Shelf is a concern because of limited sampling and restriction of field activities to the summer period when phytoplankton biomass is low. Above normal chlorophyll *a* inventories in the Gulf of St. Lawrence, particularly in the northwest Gulf, show a similar pattern to the 2018–2020 period. Mainly below normal inventories on the Scotian Shelf in 2021 are a similar pattern to the 2016–2020 period.

Because of the reliance of phytoplankton on nutrient availability, coupled with increasing length of the respective time series, 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] 2003–221; Figure 12). The onset of the spring phytoplankton bloom was early throughout most of the Atlantic Zone, with the exception of the Grand Banks, southern Newfoundland and Georges Bank. The magnitude of the bloom was below normal on the Newfoundland Shelf and Gulf of St. Lawrence and above normal in the Labrador Sea, on the Labrador Shelf and the Scotian Shelf. The duration of the bloom generally declined with decreasing latitude, with longer blooms occurring in the Labrador Sea, on the Labrador Shelf, in the northeast Gulf of St. Lawrence and western Scotian Shelf, while normal or shorter blooms occurred in other parts of the Atlantic Zone.

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 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 2019–2021, with increases in *Calanus finmarchicus* and declines in some small copepods, although the overall abundance of non-copepods remained elevated (Figure 13). In 2021, copepod abundance was below normal on the Newfoundland Shelf, the eastern Gulf of St. Lawrence and at Halifax 2, and above normal in the western and southern Gulf of St. Lawrence. Non-copepod abundances were close to normal on the Newfoundland Shelf, eastern Gulf of St. Lawrence and Halifax 2, and above normal in the northwestern and southern Gulf of St. Lawrence. The abundance of *Calanus finmarchicus* was generally normal or below normal throughout much of the Newfoundland Shelf, the Gulf of St. Lawrence and at Halifax 2. *Pseudocalanus* spp. abundance was below normal on the Newfoundland Shelf and eastern Gulf of St. Lawrence, and above normal in the western and southern Gulf of St. Lawrence and at Halifax-2. Zooplankton data from the Scotian Shelf lines were not available due to limited sampling opportunities and delays in sample processing.

Zooplankton biomass was mostly above normal on the Newfoundland Shelf and below normal in the Gulf of St. Lawrence and Halifax 2, reaching record or near record levels at several locations in each region (Figure 14). 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 will require further investigation.

Ocean Acidification

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 2020 to 2021, near-bottom pH in the Gulf of St. Lawrence has shown a general decline, especially in the St. Lawrence Estuary. On the Newfoundland shelf, while the spatial extent the undersaturated state for aragonite that occurred in 2020 on the northern part of the Grand Banks and in the Avalon channel has reduced, two stations on the northeast part of the Grand Banks show a decline in Ω_{arg} and pH in 2021 compared to 2020 (Figure 15). No data are available from the Scotian Shelf during the summer of 2021.

For the rest of the Newfoundland and Labrador shelf, 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. The only exceptions were some coastal stations in the southern Gulf and near Cabot Strait and on the West Coast of Newfoundland. 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 7.44) and represents increased acidification relative to the conditions in 2020. In addition, oxygen saturation at many sampling locations is well below 20% (even close to 13% at some stations; Figure 15, bottom panel) and has generally declined compared to 2020. These correspond to new low oxygen concentration records for the Lower St. Lawrence Estuary, reaching <1 mL/L 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.

Labrador Sea Environment

The Atlantic Zone Off-Shelf Monitoring Program (AZOMP) provides observations of variability in the ocean climate and plankton affecting ecosystems off Atlantic Canada and climate systems at a regional and global scale. In 2021, due to multiple mechanical problems on CCGS *Hudson*, the survey that began on May 19th had to be cancelled on May 27th without occupying the Atlantic Repeat 7-West (AR7W) line. Additionally, the deployments of the profiling Argo floats that provide year-round monitoring of temperature and salinity variability of the oceanographic conditions in the Labrador Sea were transferred to the Amundsen Science Program. Despite the near-normal winter NAO index in 2021, the Labrador Sea convection reached the depth of 850 m that winter—the shallowest since 2011, and third shallowest in at least 32 years (Figures 16 and 17). Consistently, the winter air temperature was above normal and surface heat loss below normal, while annual sea ice area and extent were the lowest since 2011 and third lowest in at least 42 years (Figure 7). The mild winter and weak and shallow ocean convection in 2021 owe to a collapse of the Polar Vortex, which in turn reduced the strength of the westerlies, making the winter anomalously mild. As a result, the deep ocean became slightly warmer and less dense than in the previous six years.

Biogeochemical metrics are not available for the Labrador Sea in 2021 due to the cancellation of the survey.

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 in part by the life cycle of the animals, 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 greatest source of uncertainty comes in our estimates of phytoplankton abundance because of the difficulties in determining the inter-annual variations in the timing, magnitude and duration of the spring phytoplankton bloom. Phytoplankton may undergo rapid changes in abundance, on time scales of days to weeks. Because our sampling is limited in time, and occasionally suffers from gaps in coverage as a result of vessel unavailability or adverse weather conditions, which often occurs in the sampling at our high-frequency sampling stations during the winter months, we may not sample the spring phytoplankton and other important variables 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 abundance. In contrast, we are better capable of describing inter-annual variations in the abundance of dominant zooplankton species because their seasonal cycle occurs at time scales of weeks to months as a result of their longer generation times relative to phytoplankton. However, zooplankton show greater variability in their spatial distribution. Although inter-annual variations in the abundance of dominant groups, such as copepods, can be adequately assessed, variations in the abundance of rare, patchily distributed or ephemeral species cannot be reliably estimated at this time. 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. For the Labrador Sea, the loss of the annual survey in 2017 and 2021 means an absence of *in-situ* data for these two years. Moreover, in 2019 and 2020 availability of vessels only permits the occupation of AR7W outside the regular time window, making 2018 the only valid survey for the purpose of the time series.

In several areas, the occupation of high frequency sampling stations during the winter and early spring is particularly limited, causing us to sometimes miss 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 past decade has seen further increases in water temperatures with sea surface temperatures reaching record values across the zone in summer 2012. In 2021, surface temperatures were 3rd highest of the time series that started in 1982. Winter average sea ice volume was at a record low in the Gulf of St. Lawrence and sea ice conditions were 3rd weakest (i.e., warmer) of the time series on the Newfoundland and Labrador shelf. Consistent with this, summer cold intermediate layer conditions were warmer and thinner than normal, including multiple series records in the Gulf of St. Lawrence, and a near-record on the Seal Island section. Bottom temperatures were substantially above normal across the zone, including record highs in the northern Gulf of St. Lawrence and off southern Newfoundland.

Patterns of variation in biogeochemical variables appear dominated by short-term fluctuations, given the twenty-three-year time series back initiated in 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 change 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, nutrient and phytoplankton metrics were more mixed in 2021, despite record warm temperatures. In addition, there was continued moderation in the shift in zooplankton community structure from large lipid-rich copepods to smaller taxa and non-copepods.

In the Labrador Sea, convection reached 850 m which is the shallowest since 2011 and 3rd shallowest in 32+ years. Sea ice area and extent were the lowest since 2011 and 3rd lowest in 42+ years.

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SOURCES OF INFORMATION

This Science Advisory Report is from zonal advisory meeting on March 21–23, 2022 Twenty-Fourth 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

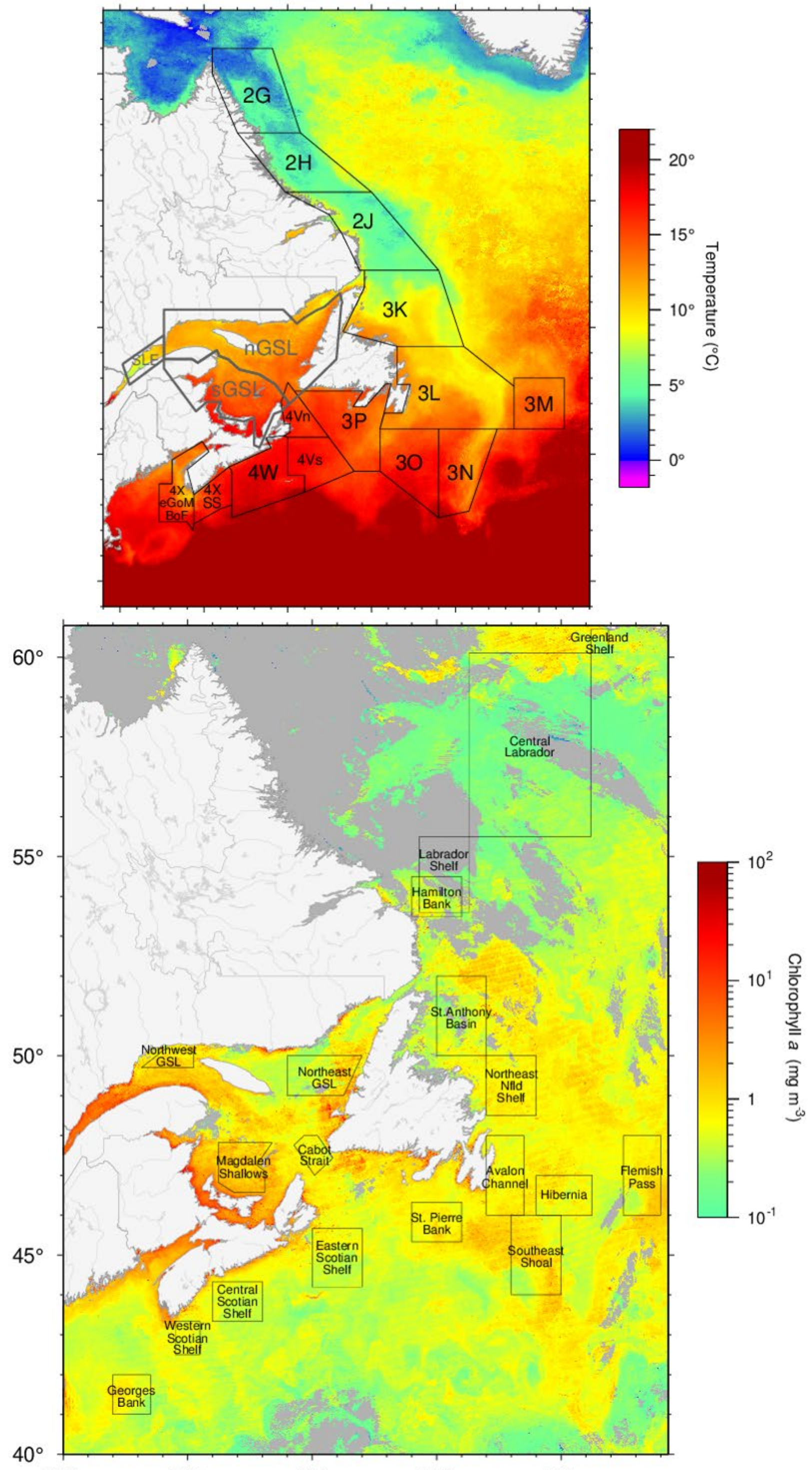

Figure 2. Areas used for (top) temperature and (bottom) ocean colour averages. (Top) North Atlantic Fisheries Organization Divisions are cut off at the shelf break. The acronyms GSL and SLE are Gulf of St. Lawrence and St. Lawrence Estuary respectively. Sea surface temperatures are shown for September 2021 and ocean colour chlorophyll a concentrations are for the second half of April 2021.

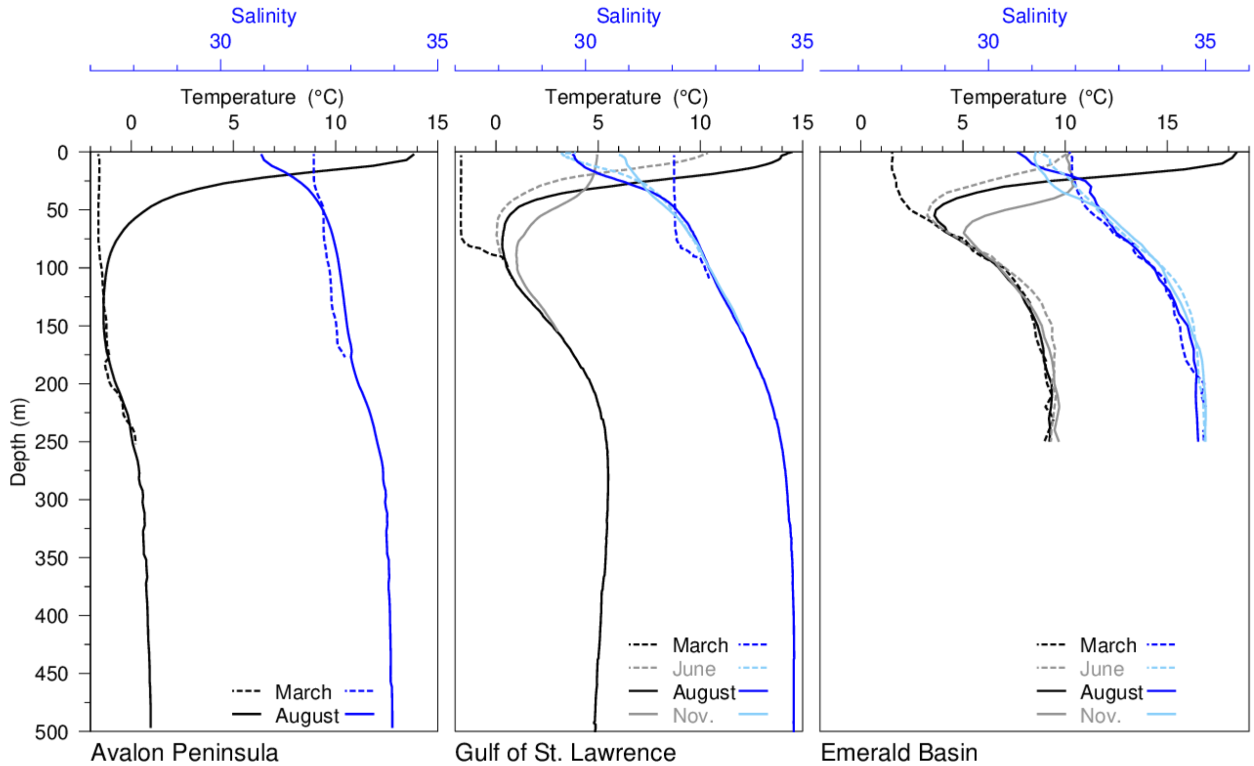

Figure 3. Typical seasonal progression of the depth profile of temperature and salinity observed in three representative regions across the zone. The Avalon Peninsula region is delimited by 45–50°N and 50–55°W and shown are the averages of profiles for March and August between 2015 and 2017, calculated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

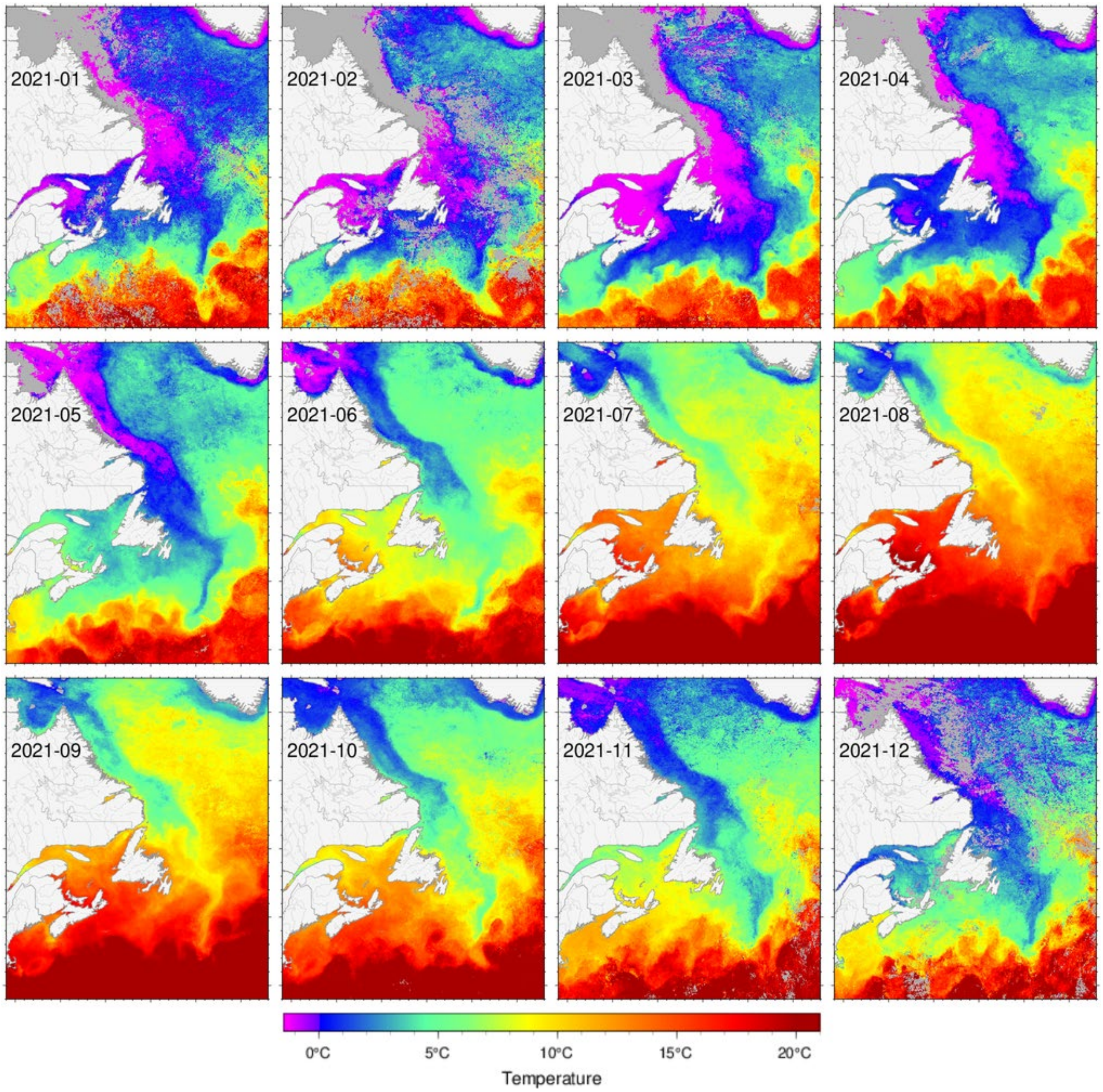

Figure 4. Sea surface temperature monthly averages for 2021 in the Atlantic zone.

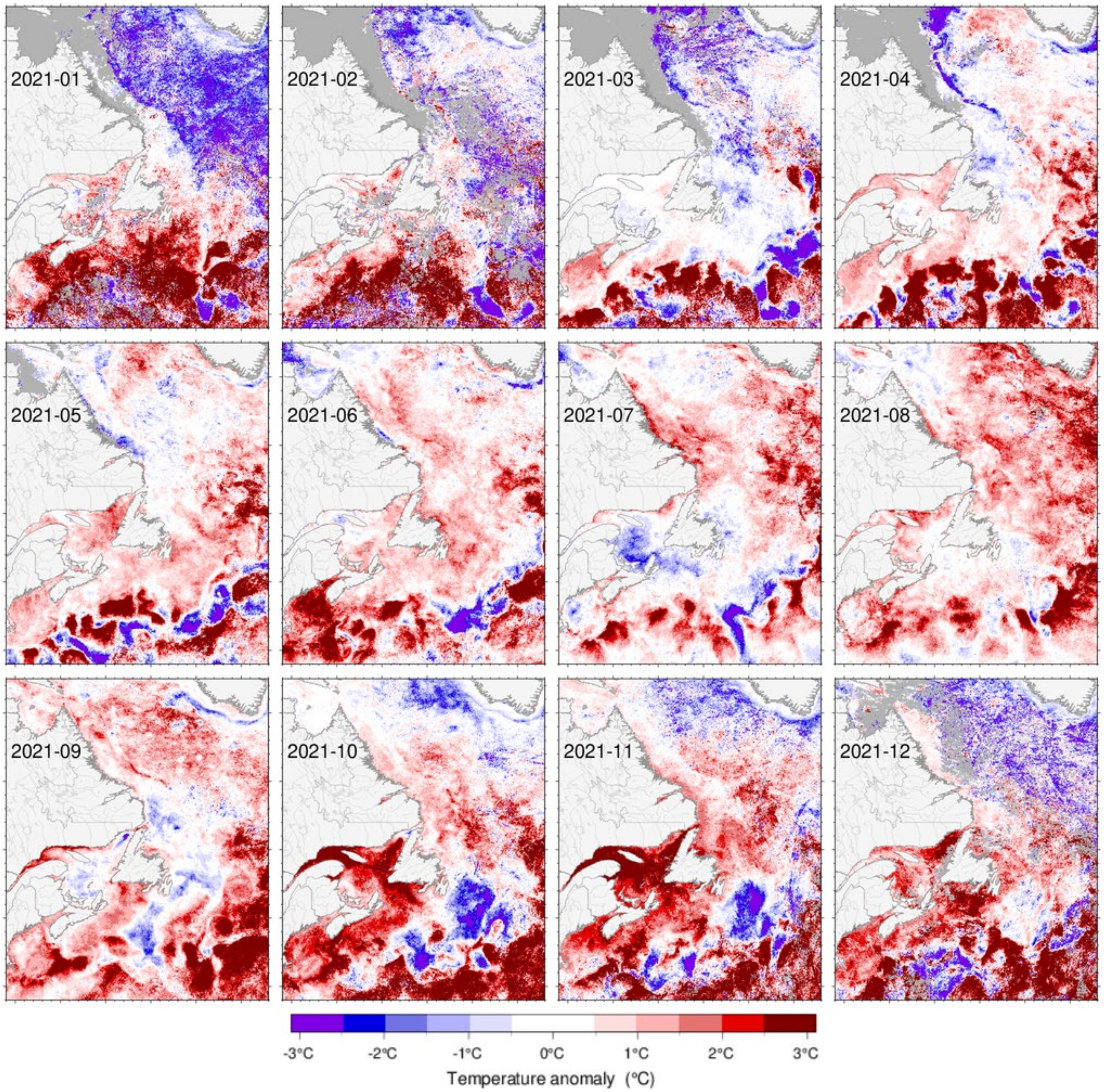

Figure 5. Sea surface temperature monthly anomalies for 2021 in the Atlantic zone. Temperature anomalies are based on a 1985–2010 climatology and not the 1991–2020 used elsewhere in this document.

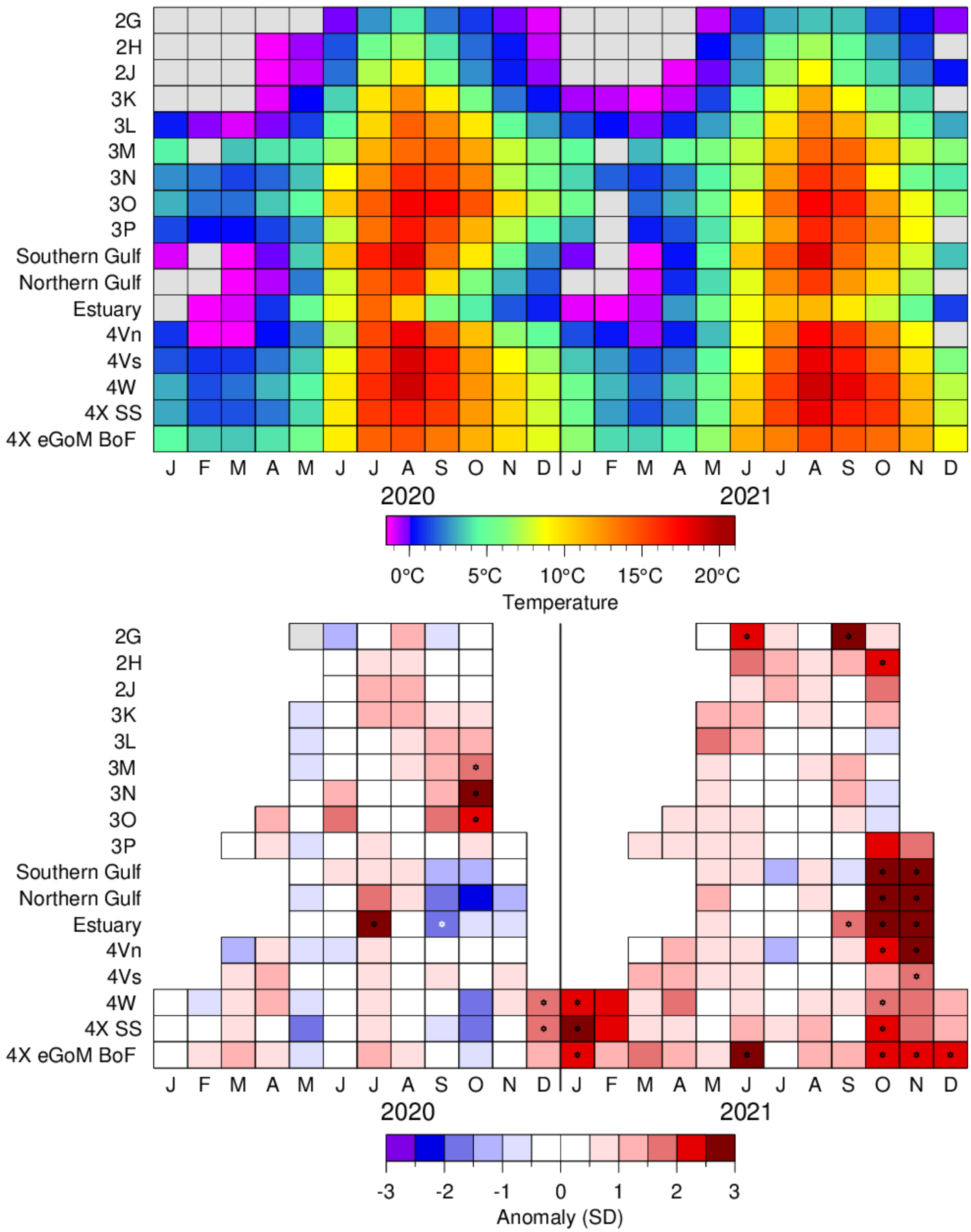

Figure 6. Monthly sea surface temperature temperatures (top) and anomalies (bottom) for ice-free months of 2020–21, averaged over the 17 regions shown in Figure 2. Regions and months for which the average temperature was at a record high or low are indicated by a star. Grey squares have insufficient data coverage to yield a monthly average anomaly (<7%).

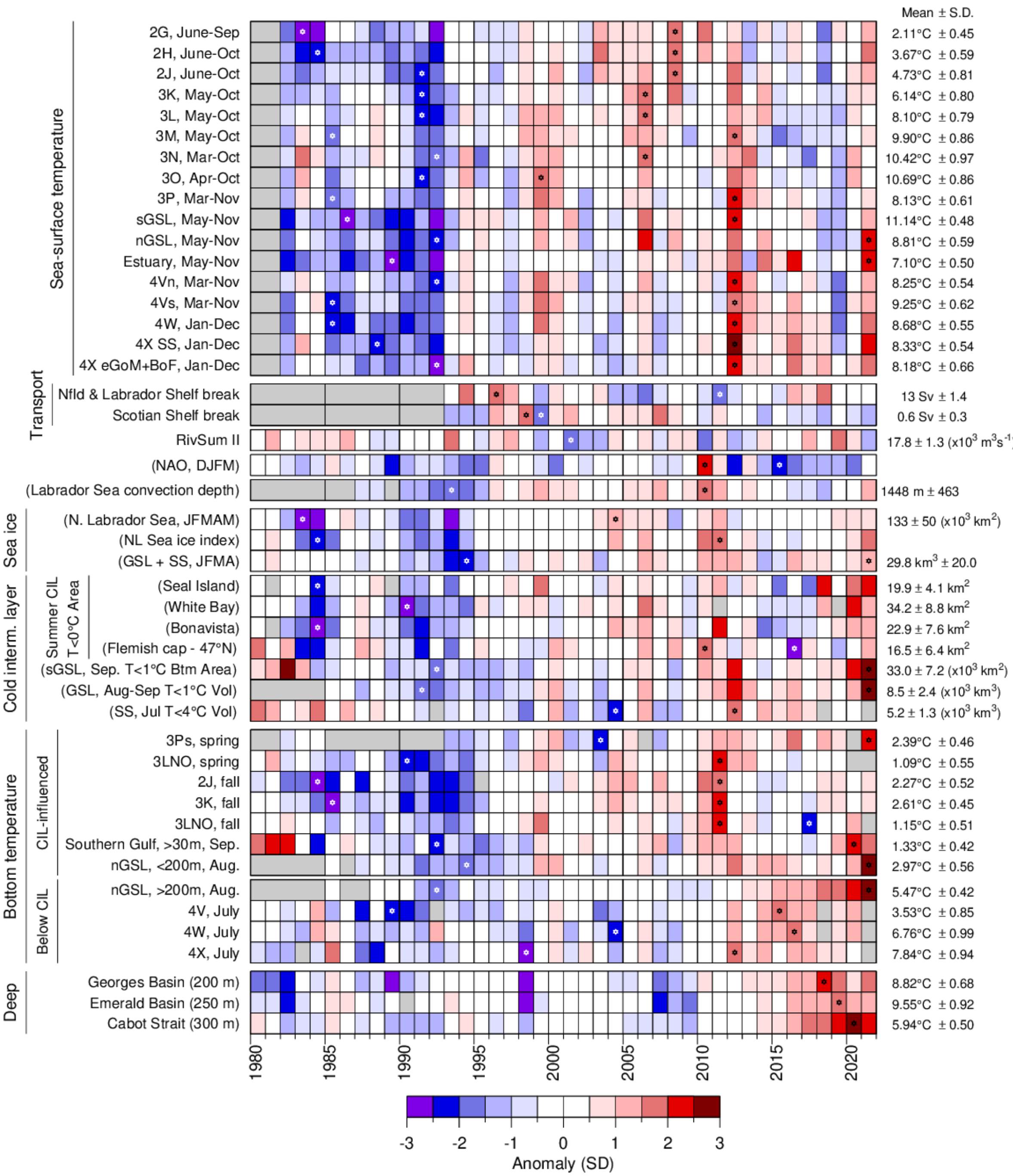

Figure 7. Time series of oceanographic variables, 1980–2021. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1991–2020 when possible; a red cell indicates above normal conditions, and a blue cell below normal. Variables whose names appear 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]).

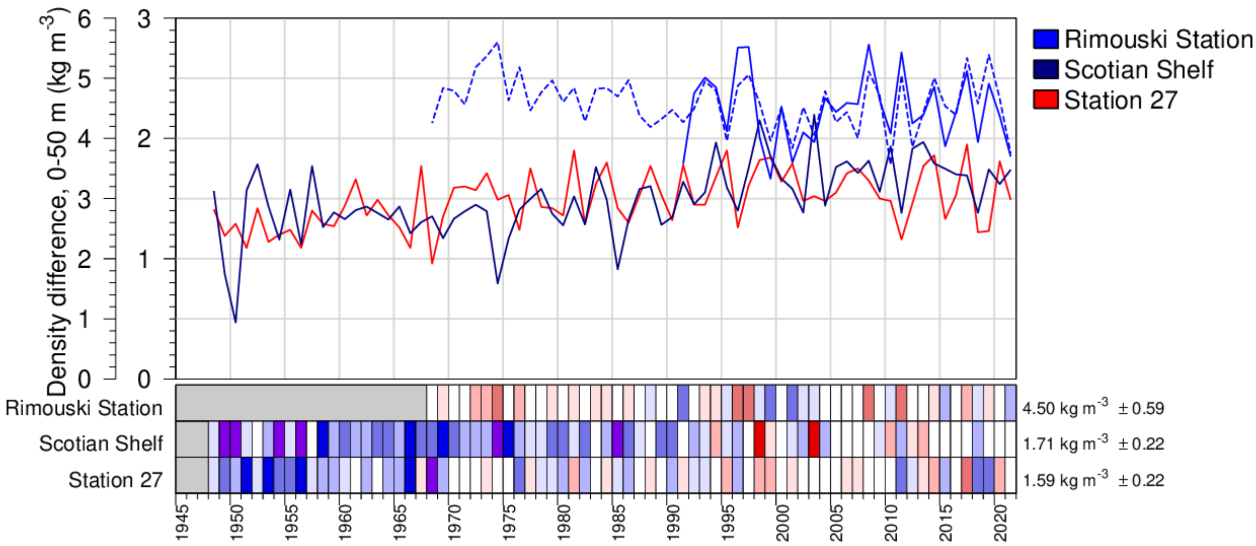

Figure 8. Stratification trends on the southern Newfoundland-Labrador Shelf (May-Nov average at Station 27), Scotian Shelf and St. Lawrence Estuary (May–Oct average at Rimouski Station). The inner y-axis is for Station 27 and Scotian shelf, while the outer y-axis is for Rimouski Station. The dashed line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

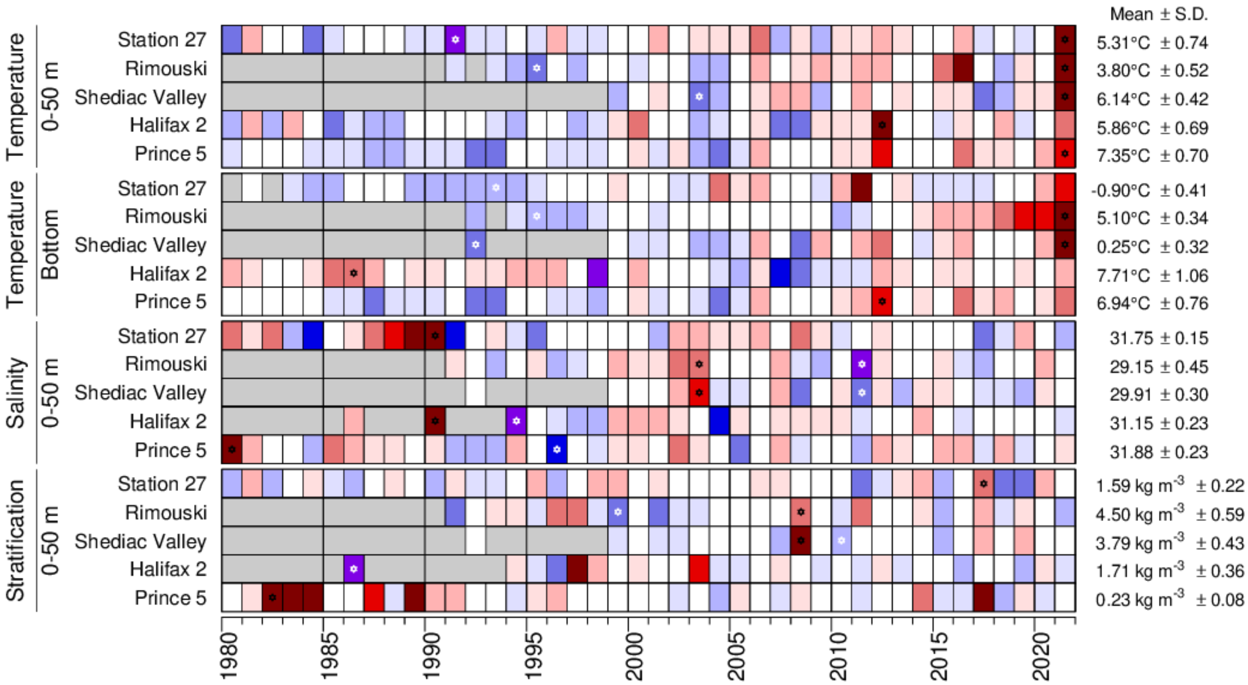

Figure 9. Time series of oceanographic variables at AZMP high-frequency sampling stations, 1980–2021. Values are annual averages at Halifax 2 and Prince 5, May–November at station 27 and May-October at Rimouski station. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the 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.

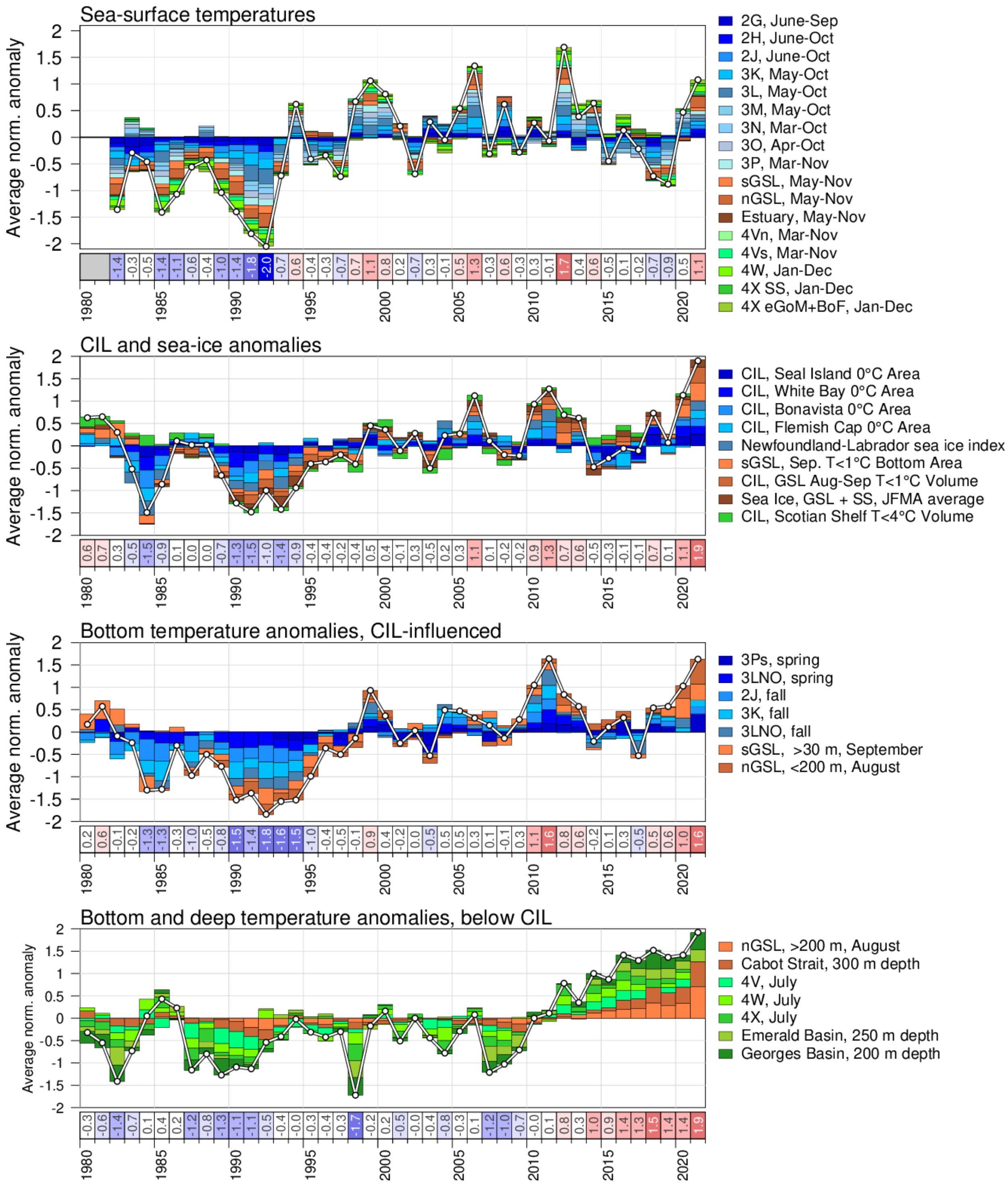

Figure 10. Composite climate indices (white lines and dots) derived by averaging various normalized anomalies from different parts of the environment (coloured boxes stacked above the abscissa are positive anomalies, and below are negative). Top panel shows average sea surface temperature anomalies weighted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

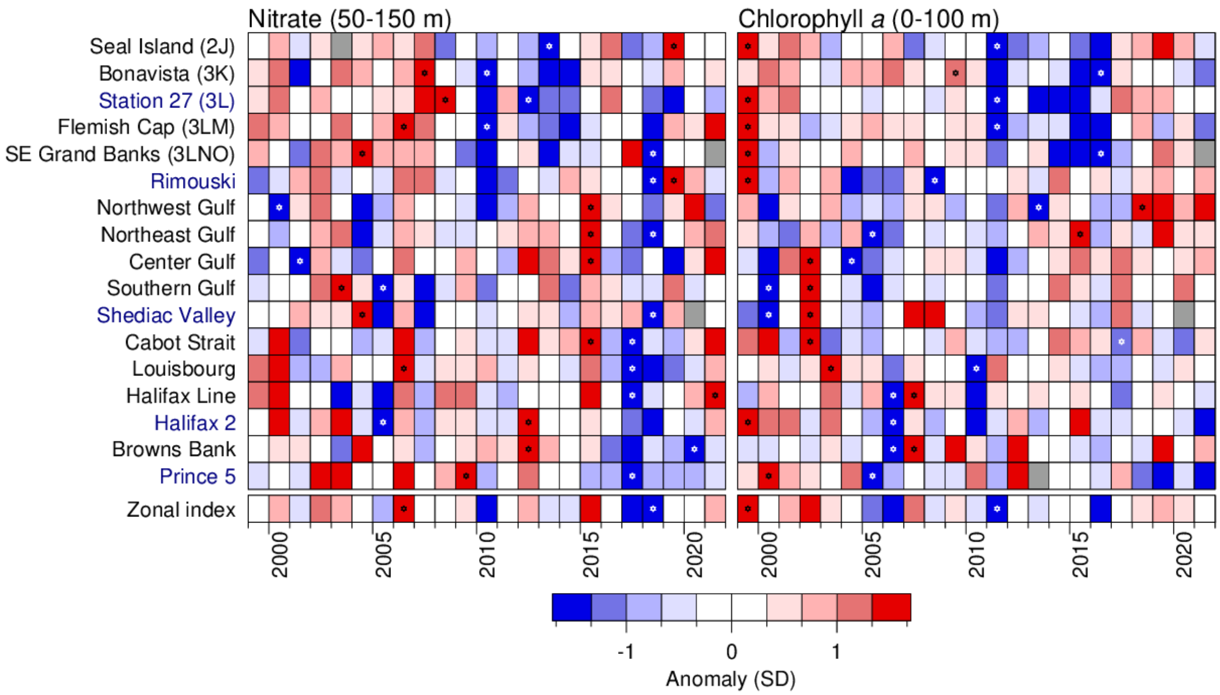

Figure 11. Time series of deep water nitrate inventories (50–150 m) and surface phytoplankton standing stocks (expressed as chlorophyll a 0–100 m mean concentration) at AZMP sections (labelled in red in Figure 1) and high-frequency sampling stations (labelled in blacks in Figure 1), 1999–2021. Chlorophyll values are log-transformed. A grey cell indicates missing data. Note change in colour palette: a white cell is a value within 0.33 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.

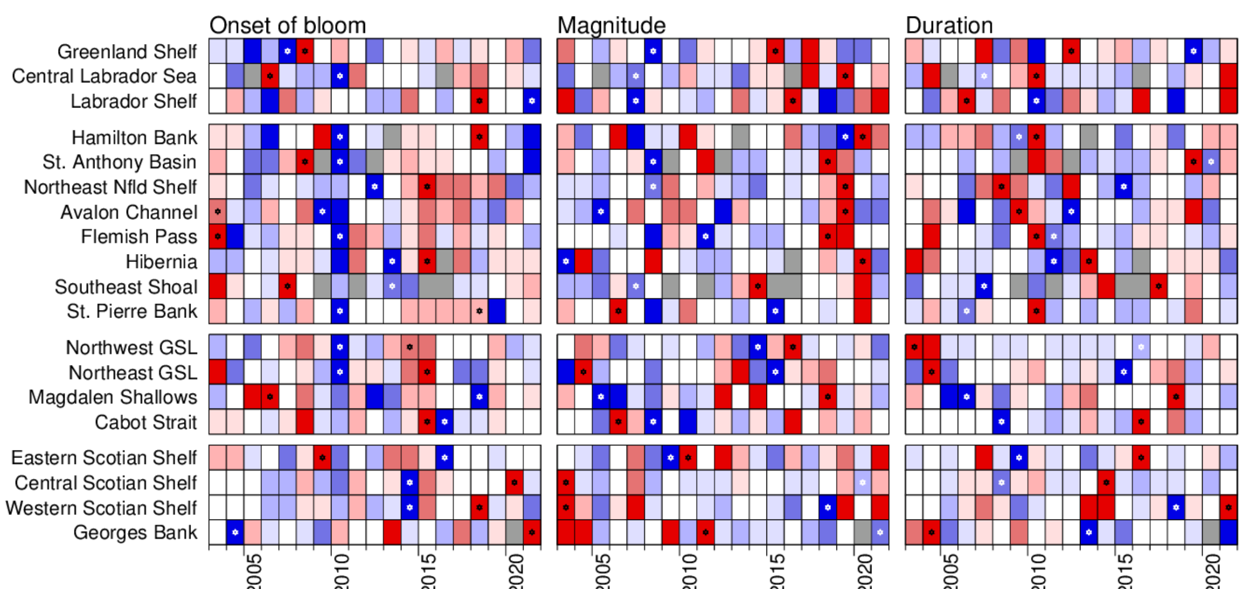

Figure 12. Time series of remotely sensed bloom parameter anomalies in various regions (onset of bloom, magnitude and duration) 2003–2021. Data are MODIS. Series minimum and maximums are indicated by a star. See Figure 2 for area definitions. Palette as in Figure 11.

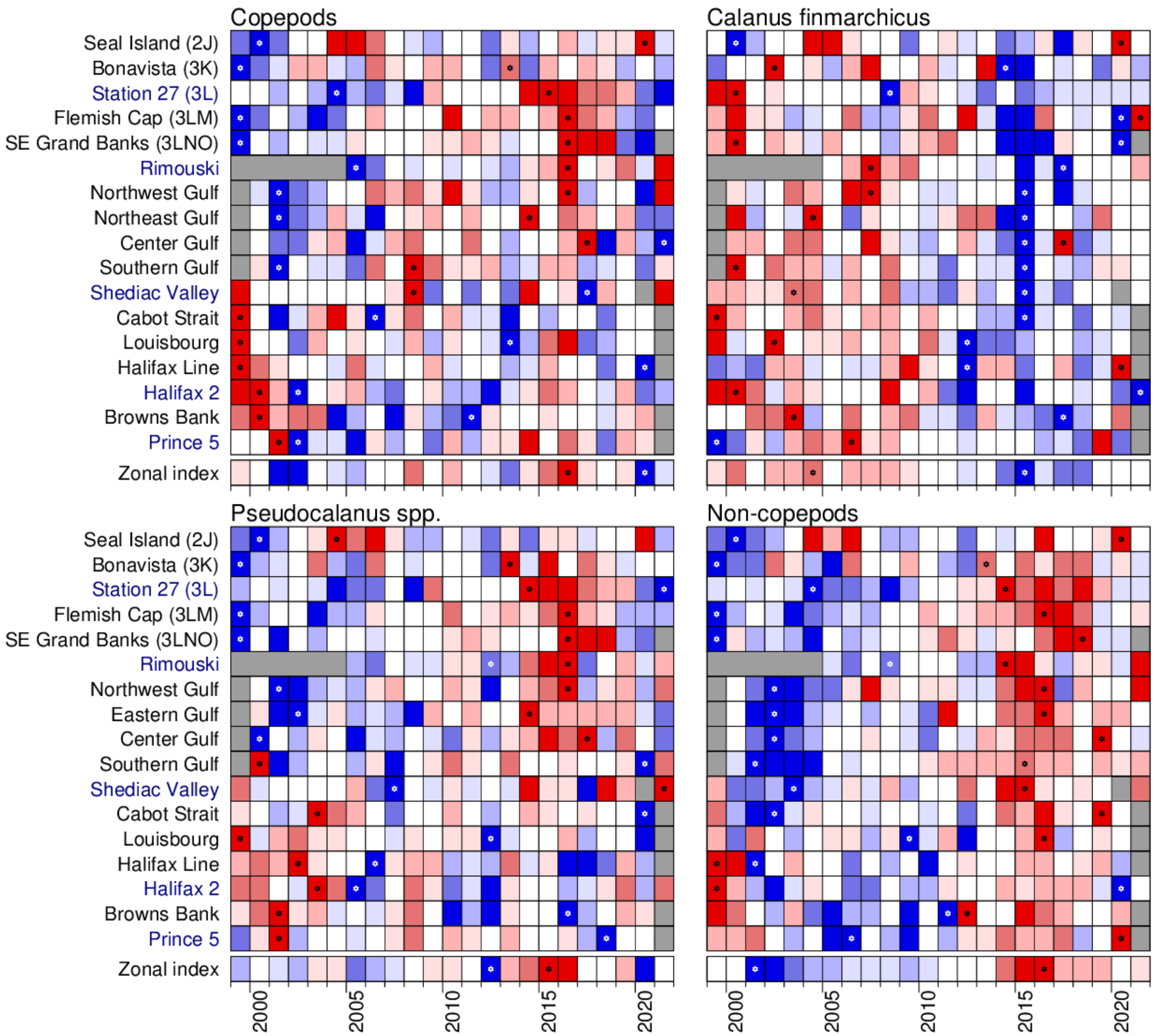

Figure 13. Time series of the (log-transformed) standing stocks of total copepods, Calanus finmarchicus, Pseudocalanus spp., and non-copepod zooplankton, 1999–2021. A grey cell indicates missing data, a white cell is a value within 1/3 SD of the long-term mean based on data from 1999–2020; a red cell 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.

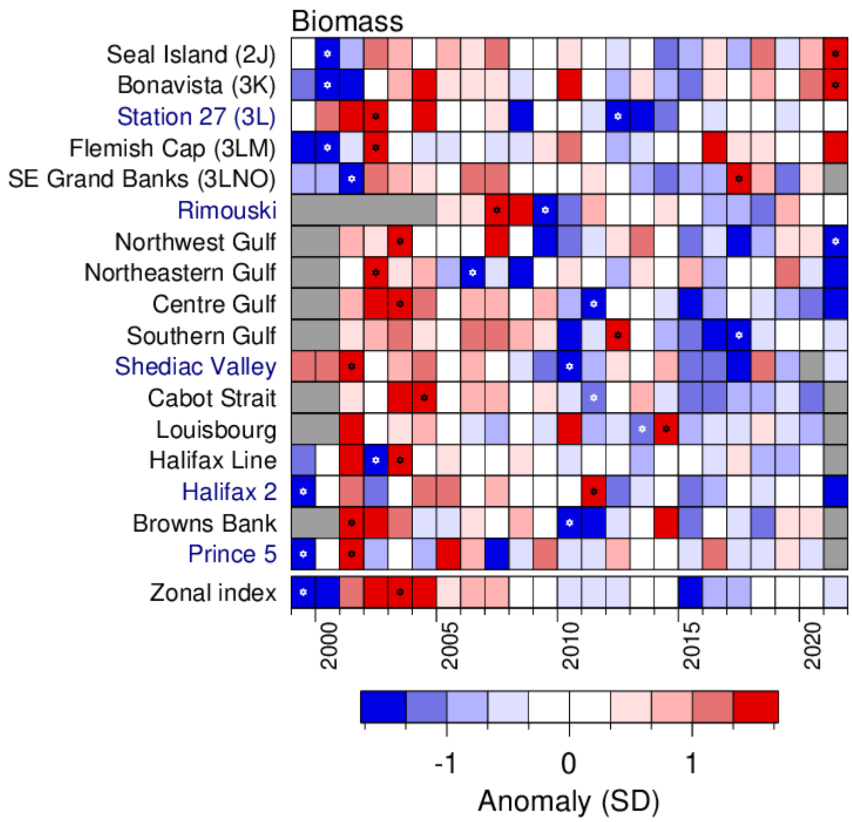

Figure 14. Time series of zooplankton biomass (dry weight, log-transformed), 1999 to 2021. Biomass is measured on the 0.2–10 mm size fraction which is usually dominated by copepods. A grey cell indicates missing data, a white cell is a value within 1/3 SD of the long-term mean based on data from 1999–2020; 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.

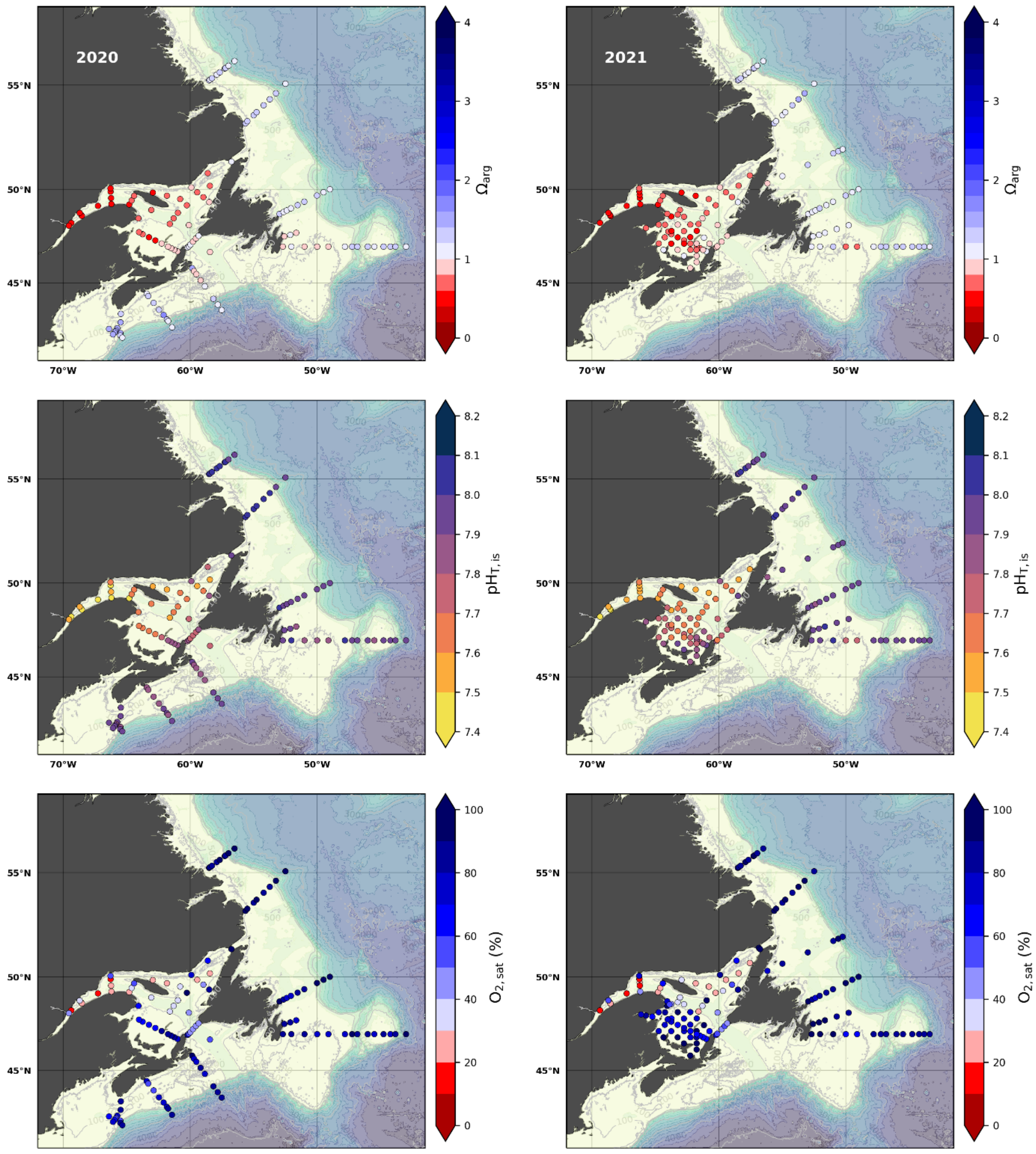

Figure 15. Bottom ocean acidification conditions during summer 2020 (left) and 2021 (right) for the Gulf of St. Lawrence, Scotian Shelf and Newfoundland Shelf: aragonite saturation state (top), in situ pH using total scale (centre) and dissolved oxygen saturation (lower). Undersaturated conditions relative to aragonite and hypoxic oxygen conditions are plotted in red colors.

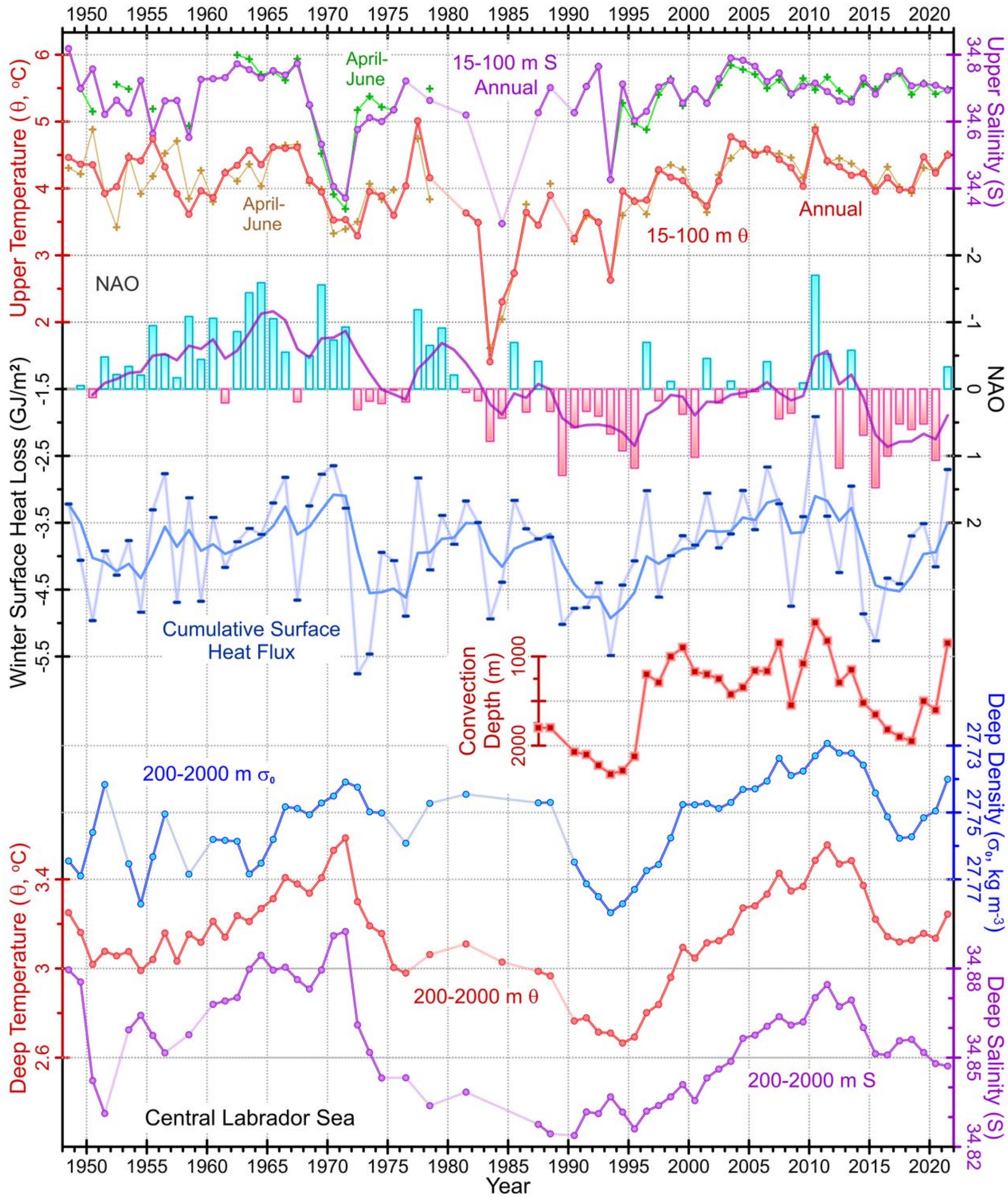

Figure 16. Key Labrador Sea environmental indices since 1948. From top to down: Annual and spring mean salinity (S) and temperature (θ) averaged over the 15–100 m depth range; The normalized winter NAO index (bar graph, inverted vertical scale); The NCEP reanalysis-based cumulative surface heat flux 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.

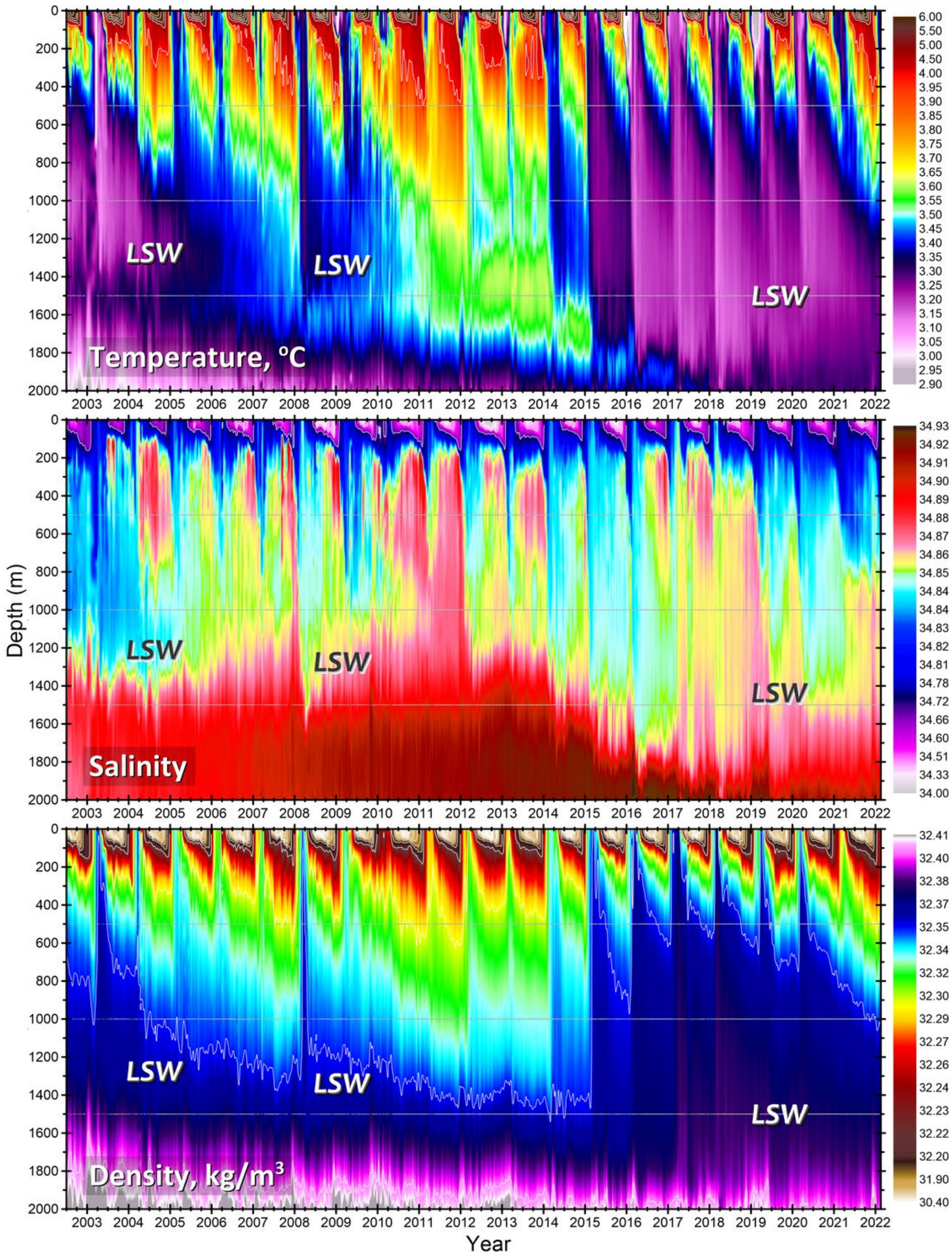

Figure 17. Temperature (upper), salinity (middle), and density (referenced to 1000 dbar; lower) over the 0–2000 m layer of the central Labrador Sea during 2002–2022, based on quality-controlled Argo float and shipboard observations that are averaged in overlapping 10-day windows, spaced 5 days apart. LSW indicates Labrador Sea Water.

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