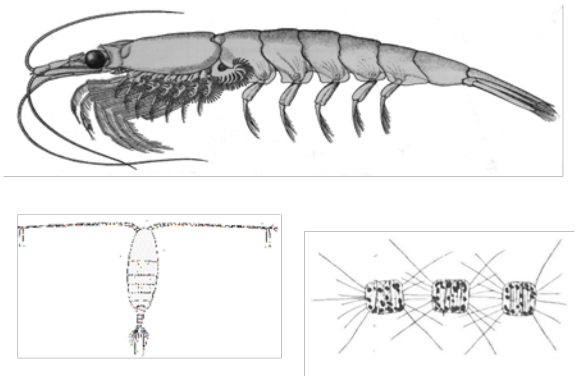
OCEANOGRAPHIC CONDITIONS IN THE ATLANTIC ZONE IN 2019



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

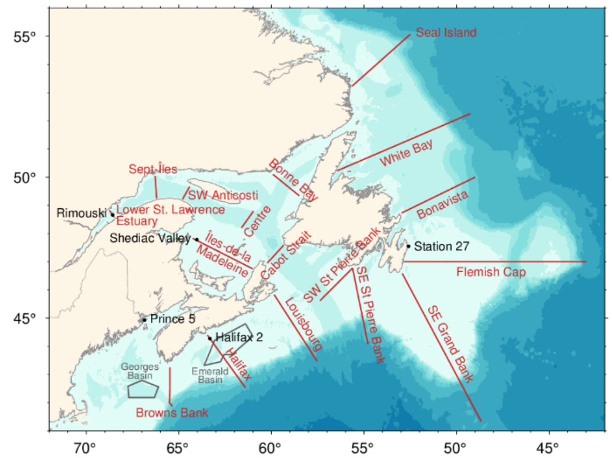


Figure 1. Atlantic Zone Monitoring Program high-frequency sampling stations (black), selected section lines (red) and averaging areas (gray).

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 Twenty-second Annual Meeting of the Atlantic Zone Monitoring Program (AZMP) held via video-conference April 20–21, 2020. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- Monthly average sea surface temperatures were generally below normal to normal in ice-free months of 2019 until July, including record lows (since 1982) in March in NAFO Divisions 3P and 4V. They were normal to above normal for the seasonal maximum reached in August, but decreased remarkably along the track of tropical storm Dorian in early September. The 100+ km/h winds mixed the water column to as deep as 45 m, decreasing surface temperatures by as much as 8°C and increasing it equally at depth. September average surface temperatures were at record lows in the Gulf of St. Lawrence and well as on St. Pierre Bank and the Scotian Shelf (NAFO Divisions 3P, 4V and 4W). Surface temperatures remained stable in the thick mixed layer until air temperatures cooled to below water temperatures. Surface temperatures were above normal in November on the Scotian Shelf and Gulf of Maine-Bay of Fundy.
- Sea surface temperatures averaged over the ice-free months were normal to above normal on the Labrador Shelf and the northern Newfoundland Shelf, and varied from below normal to normal south and east of the Newfoundland shelf. In spite of regional disparities, the zonally averaged seasonal sea surface temperature was below normal for the first time since 1992. However, this average would have been near-normal had it not been for tropical storm Dorian.
- Winter average sea ice volumes were below normal on the Newfoundland and Labrador Shelf and near normal in the Gulf of St. Lawrence. However sea ice formed much earlier than normal in the coastal areas of the western and southern Gulf, and the November first occurrence of ice in the Upper Estuary was the earliest on record.
- Summer cold intermediate layer metrics indicated normal to warmer-than-normal conditions across the zone; there were no measurements of these metrics on the White Bay line because of limited ship availability.
- Bottom temperatures were mainly above normal across the zone except in NAFO Divisions 3LNO where they were near normal. This included a 100+-year record high in the deeper waters of the northern Gulf of St. Lawrence, a record high in Emerald Basin at 250 m, and second highest at 200 m in Georges Basin.
- At the high-frequency sites Rimouski and Shediac Valley, seasonal stratification was above normal and 0–50 m seasonal average salinity was below normal. They were both associated with the highest spring freshet of the St. Lawrence since 1974. At both stations, 0–50 m seasonal average temperature was above normal (record high at Shediac Valley). Rimouski station bottom temperature was also at a record high. Station 27 and Halifax 2 had below normal stratification.
- The Labrador Current weakened relative to 2018 on the NL slope, becoming close to normal.
- Deep nitrate inventories were above or near normal on the Newfoundland and Labrador Shelf and in the Gulf of St. Lawrence but mainly below normal across the Scotian Shelf. Record highs occurred along the Seal Island section and at Station Rimouski. The record high at Station Rimouski is a marked shift from the record low that occurred in 2018.
- Annual chlorophyll *a* inventories were above normal over most of the Newfoundland and Labrador Shelf and northern Gulf of St. Lawrence, but below or near normal in the southern Gulf of St. Lawrence and Scotian Shelf.

- The onset of the spring phytoplankton bloom was highly variable across the Atlantic Zone. An early onset occurred in the St. Anthony Basin, southeast Shoal and Eastern Scotian Shelf while delayed onset occurred on the Northeast Newfoundland Shelf, northeastern Gulf of St. Lawrence and Western Bank. The magnitude of the bloom was near or below normal throughout the Atlantic Zone, with a record low on Georges Bank. Bloom duration was generally near or above normal in the Newfoundland and Labrador Shelf, reaching records in St. Anthony Basin and over Southeast Shoal. Bloom duration was also longer than normal over the Magdalen Shallows and Eastern Scotian Shelf but shorter or near normal in the other Gulf of St. Lawrence and Scotian Shelf regions.
- The zooplankton community shift observed in recent years (2014–2018), characterized by lower abundance of the large energy-rich copepod *Calanus finmarchicus*, higher abundance of small copepods and non-copepods, persisted in 2019 despite the apparent shift toward normal conditions in 2018. *Calanus finmarchicus* remained near or slightly below normal across most of the Atlantic zone with the exception of the Eastern Gulf of St. Lawrence and Prince 5. The abundance of *Pseudocalanus* spp. was above or near normal throughout the Atlantic Zone. Non-copepods were near or above normal throughout the Atlantic Zone.
- Zooplankton biomass was generally below normal across most of the Atlantic zone. Exceptions occurred on the Bonavista section, Station Rimouski, the Northwestern Gulf of St. Lawrence and Prince 5.
- Near-bottom pH and aragonite saturation are generally much lower in the Gulf of St. Lawrence than on the Grand Banks and Scotian Shelf. Near-bottom aragonite is under-saturated throughout most of the Gulf of St. Lawrence, including the shallow waters of the Southern Gulf. Undersaturated bottom conditions were also observed in the Avalon channel on the Newfoundland shelf.
- New record lows of deep dissolved oxygen concentration were measured in the Lower St. Lawrence Estuary.
- In the Labrador Sea, convection reached the depth of about 1400 m in the western part of the Labrador Basin, and only about 1000 m in the central and eastern parts, contrasting the 2014 to 2018 period during which winter convection incrementally deepened from 1600 to 2000 m. Ocean temperature in the central Labrador Sea was above-normal, reversing a cooling trend observed since 2010 in the 15–100 m layer, and since 2011 in the 200–2000 m layer.
- In general, all biological indicators in the Labrador Sea were lower than normal, including a record of Hyperiidae. Notable exceptions were the positive anomalies observed in the central Labrador Basin for Clausocalanoidea and the delayed onset of the spring phytoplankton bloom on the Labrador Shelf/slope and central Basin.

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 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 sites complement the broad scale sampling by providing more detailed information on temporal (seasonal) changes in pelagic ecosystem properties. Since 2015, the 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 last year, this evaluation also includes ocean acidification.

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 1981–2010 reference period for physical parameters, and for 1999–2015 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. 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.

ASSESSMENT

Physical Oceanographic Conditions in the Atlantic Zone in 2019

This is a summary of physical oceanographic conditions during 2019 for eastern Canadian oceanic waters (Figures 1 and 2) as reported annually by the AZMP in three reports (e.g. Hebert et al. 2020 and Cyr et al. 2020 for conditions of 2018 and Galbraith et al. 2020 for conditions of 2019).

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. 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 are usually associated with a high positive NAO index, with opposite effects occurring with a negative NAO index (Cyr et al. unpublished[1]). The winter index used here is the December-March average of the monthly time series from the National Oceanic and Atmospheric Administration (NOAA). This differs from last year's report in which a renormalized December-February average was used. In 2019, the winter NAO index was +0.68 (+1.1 SD) , positive for a 6th consecutive year (including the largest value on record of +1.6 in 2015). The minimum value on record was reached in 2010 at -1.5.

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 2016 it was observed in early August. Deep waters are defined here as those below the CIL that have only weak seasonal cycles.

Sea surface Temperature

A new satellite-based sea surface temperature product is used in this year's report. It blends data from Pathfinder version 5.3 (1982–2014), Maurice Lamontagne Institute (1985–2013) and Bedford Institute of Oceanography (1997–2019) and monthly temperature composites are calculated from averaged daily anomalies to which monthly climatological average temperatures are added (see Galbraith et al. 2020 for details). This eliminates the bias that would occur when averaging temperature data that are not evenly distributed. Coverage was extended northward and eastward to include NAFO Divisions 2G, 2H and 3M. Additionally, Division 4V was split into 4Vn and 4Vs.

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. 2020). 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 2019, monthly average sea surface temperatures were generally below normal to normal in ice-free months until July, including record lows (since 1982) in May in NAFO Divisions 3P and 4V (Figures 4 to 6). They were normal to above normal for the seasonal maximum reached in August, but decreased remarkably with the passage of tropical storm Dorian in early September. The 100+ km/h winds mixed the water column to as deep as 45 m, decreasing surface temperatures by as much as 8°C and increasing it equally at depth (Galbraith et al. 2020). September average surface temperatures were at record lows in the Gulf of St. Lawrence as well as on St. Pierre Bank and the Scotian Shelf (NAFO Divisions 3P, 4V and 4W), but not because of heat lost to the atmosphere but rather because of redistribution within the water column. Surface temperatures then remained stable in the thick mixed layer until air temperatures cooled to below water temperatures. Surface temperatures were above normal in November on the Scotian Shelf and Gulf of Maine-Bay of Fundy.

Seasonally-averaged sea surface temperature were normal to above normal on the Labrador Shelf and the northern Newfoundland Shelf, but varied from below normal to normal elsewhere (Figure 7). On average across the zone, seasonal sea surface temperatures were below normal for the first time since 1992. However, the zonal average would have been near-normal had it not been for tropical storm Dorian.

Cold Intermediate Layer

For the Newfoundland and Labrador Shelf, the CIL indices shown here (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 (based on new recalculations this year; Cyr et al unpublished[1]). For the Gulf, the CIL volume with T<1°C observed in August-September is used (Galbraith et al. 2020). 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. 2020). On the Scotian Shelf, the volume of water having T<4°C in July is used (Limited data prior to 1990 is compensated for by the use of a 5-year running mean to achieve extended temporal coverage; however, this results in a loss of high-frequency variability from that part of the time series) (Hebert et al. 2020). The CIL indices reported here are taken at about the same time within their respective annual cycles, although not simultaneously.

[1] Cyr, F., Snook, S., Bishop, C., Galbraith, P.S., Pye, B., Chen, N., and, Han, G. In prep. Physical Oceanographic Conditions on the Newfoundland and Labrador Shelf during 2019. DFO Can. Sci. Advis. Sec. Res. Doc.

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 2019, CIL conditions were normal to warmer-than-normal conditions across the zone, with warmer-than-normal values of +1.1 SD on the Bonavista section and +1.2 SD on the Magdalen Shallows. There were no measurements of the usually reported CIL metrics on the White Bay section because of limited ship availability.

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. On the Newfoundland and Labrador shelf, seasonal average sea ice volume is correlated with the CIL area along the Bonavista section (1981–2018, $R^2 = 0.56$) and Newfoundland Shelf sea ice metrics are correlated with December-March air temperature at Cartwright (1969–2019, $R^2 = 0.65–0.81$; Cyr et al. 2020). In the Gulf of St. Lawrence, the correlation between the December-March air temperature averaged over multiple meteorological stations and the annual maximum ice volume reaches $R^2 = 0.72$ (1969–2019). Air temperature is similarly well correlated to sea ice cover area and duration ($R^2 = 0.78–0.80$). 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. 2020).

For the past decade, ice volumes on the Newfoundland and Labrador (NL) 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 2010 and on the NL Shelf in 2011 (Figure 7). In the 10-year period between 2010 and 2019, the Gulf seasonal average sea ice volume had 6 of the 10 lowest values of the series (but 2019 was not among them), and the Newfoundland and Labrador shelf had 4 of the 10 lowest (including 2019). In 2019, seasonally averaged sea ice volume was below normal on the NL Shelf (-0.9 SD), 10th lowest since records began in 1969, and near normal in the Gulf of St. Lawrence, with a near normal volume of ice exported onto the Scotian Shelf (largest volume since 2015). Sea ice formed much earlier than normal in the coastal areas of the western and southern Gulf, and the November first occurrence of ice in the Upper Estuary was the earliest on record.

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 2019, bottom temperatures averaged over large areas in the Atlantic Zone ranged from normal on the Grand Banks (3LNO) to above normal elsewhere, including a new 100+ year high-temperature record for the Gulf at 250 and 300 m that is reflected in the average bottom temperature of the northern Gulf deeper than 200 m (Figure 7). The recent warming of the Gulf deep waters began as a warm anomaly first observed in Cabot Strait in 2010 that has propagated towards the heads of the channels, sustained by later warm water inflows. Temperatures at 200–300 m at the mouth of the Laurentian Channel were at record highs in 2019. Thus, the average temperature of the deep waters of the Gulf should continue to increase in the next years as estuarine circulation drives these anomalies inwards. In other areas of the zone, bottom temperature remained high in 4X in July (8.4°C, +1.6 SD) and reached second highest temperature in Georges Basin at 200 m (10.0°C, +1.7°C, +3.2 SD) and a record high in Emerald Basin at 250 m (11.0 C, +1.9 C, +2.2 SD).

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 changed in this year’s report; it is now based on daily runoffs estimated at Québec 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. The inter-annual variability of the seasonal (May–October) stratification (0–50 m) at Rimouski Station in the Estuary is strongly correlated with the seasonally average runoff of the St. Lawrence river (1991–2019; $R^2 = 0.62$, Figure 8). The 2019 annual runoff was the highest since 1976 (20,200 $m^3 s^{-1}$, +2.0 SD), with the May-June spring freshet tied for first place of the time series with 1974 at 30,900 $m^3\ s^{-1}$ (+3.1 SD).

Stratification on the Scotian Shelf increased slightly in 2019, remaining at near-normal levels. 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 0.35 kg m^{-3} over 50 years (Figure 8). This change in mean stratification is due mainly to a decrease in the surface density, composed of equally of warming and freshening. Stratification was above normal at Rimouski station (+1.2 SD), consistent with the above normal runoff (Figure 8).

Conditions at AZMP High Frequency Sampling Stations

Seasonal stratification was above normal and 0-50 m seasonal average salinity was below normal at the high-frequency sites Rimouski and Shediac Valley. They were both associated with the highest spring freshet of the St. Lawrence since 1974. The seasonal average 0-50 m temperature has been normal or above normal at all stations since 2010, except at Shediac Valley in 2017 and 2018, Rimouski Station in 2018 and now Station 27 in 2019, where it was below normal (Figure 9). A record high was reached at Shediac Valley in 2019. Bottom temperature was normal to above-normal at all stations, and at Rimouski station the last 5-year period 2015-19 had the 5 warmest averages of the time series, reaching a new record high in 2019.

Labrador Current Transport Index

The annual-mean Labrador Current transport index shows that the Labrador Current transport over the Labrador and northeastern Newfoundland Slope is generally out of phase with the shelf-break current transport over the Scotian Slope (Figure 7). The transport was strongest in the early 1990s and weakest in the mid-2000s over the Labrador and northeastern Newfoundland Slope, and opposite over the Scotian Slope. The transport index is positively and negatively correlated with the winter NAO index over the Labrador and northeastern Newfoundland Slope and over the Scotian Slope, respectively. In 2019, the annual mean transport was just above normal over the Labrador and northeastern Newfoundland Slope (+0.5 SD) and just within normal (-0.5 SD) over the Scotian Slope.

Summary

Surface oceanic waters of the Atlantic zone during ice-free months have been mostly tracking the climate-change driven warming trends observed in the atmosphere. Warming winters have also led to less sea ice cover and weaker cold intermediate layers. The 2010–19 period was characterized by record lows in 2012 for both the Gulf of St. Lawrence and Scotian Shelf CIL volumes, 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 2010 and on the NL Shelf in 2011.

The deep water temperatures on the Scotian Shelf and Gulf of St. Lawrence are greatly influenced by an increasing proportion of Gulf Stream Water relative to Labrador Water. While the Newfoundland Shelf and Labrador Shelf were characterized by above normal bottom temperatures in the early and late period of 2010–19 with some near normal temperatures in 2014–17, all anomalies were above normal on the Scotian Shelf and the northern Gulf of St. Lawrence during this time period. Series records were recorded during this period in central (4W) and western (4X) Scotian Shelf, Georges Basin (200 m), Emerald Basin (250 m) as well as a 100+-year record in the northern Gulf of St. Lawrence.

Three annual composite index time series 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. These 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. New in this report, the sea surface anomalies are weighted to their spatial area (however not by the numbers of months in the season) and all three panels are weighted for missing values. On average over the zone, conditions in 2019 were below normal for surface temperatures for the first time since 1992 (although would have been near normal except for the effect of tropical storm Dorian), and above normal for Cold Intermediate Layer and sea ice anomalies as well as for bottom temperatures. A total of 45 indices listed in Figures 7 and 10 describe ocean conditions related to temperature within the AZMP area in 2019 (SST; ice; summer CIL areas, volumes, and minimum temperature; bottom temperature; 0–50 m average temperature). Of these, 10 were colder than normal (all but one for sea surface temperature), 13 were within normal values (± 0.5 SD) and 22 were above normal, indicating a continuation but weakening of warmer than normal oceanographic conditions in 2019 across much of the Atlantic Zone. This description is however less representative of the Newfoundland and Labrador conditions where a warming trend is emerging (based on 2018 and 2019), following colder-than or close to normal conditions during the 2014–2017 period, despite a 6th consecutive year of positive winter NAO index, a situation generally leading to colder than average conditions.

Biogeochemical Environment

Lower trophic levels are the components of marine food webs that channel the sun's energy to upper trophic level animals such as shellfish (e.g., crabs, lobsters, scallops, and mussels), finfish (e.g., cod, herring, and halibut), marine mammals (e.g., seals and whales) 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. There are many types of animals in the zooplankton community, such as copepods, gelatinous filter feeders and predators, and ephemeral larval stages of bottom-dwelling 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 abundance of phytoplankton and important features of the spring bloom, and the abundance of zooplankton species based on the data available from 1999 to the present.

Indices indicative of nitrate inventories, phytoplankton standing stock, features of the spring phytoplankton bloom derived from satellite observations, and zooplankton abundance from the Newfoundland Shelf (NL) (Maillet et al. 2019), Gulf of St. Lawrence (GSL) (Blais et al. 2019) and Scotian Shelf (SS) (Johnson et al. 2018) are summarized as time series (1999–2019) of annual values in matrix form in Figures 11–14. Anomalies for biogeochemical parameters were calculated from climatologies using a 1999-2015 reference period.

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 2019 were generally above or near normal on the Newfoundland and Labrador Shelf and in the Gulf of St. Lawrence but below normal across the Scotian Shelf (Figure 11). Record highs occurred along the Seal Island section (+1.2 SD) and at Station Rimouski (+1.5 SD). The record high at Station Rimouski is a marked shift form the record low that occurred in 2018. The zonal deep nitrate index was near-normal.

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 due to the sampling program which is relatively fixed in time throughout the zone while the production cycle may vary annually depending on environmental conditions. Annual chlorophyll *a* inventories in 2019 showed a similar pattern to 2018 with anomalies mostly above normal in the northern regions (Newfoundland and Labrador Shelf, Northwest and Northeast GSL) in contrast to southern regions where they were near or below normal (Southern Gulf of St. Lawrence and Scotian Shelf). Greater positive anomalies were observed in the Northwest Gulf of St. Lawrence and on the Seal Island line, whereas the strongest negative anomaly was occurred at Prince 5 (Figure 11). 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 magnitude of the spring bloom is partly dependent on the amount of nutrients that are mixed into surface waters over the course of the winter. The characteristics of the bloom (magnitude, timing, and duration) provide important information about regional variations in ecosystem productivity and are linked to the productivity of organisms that depend on lower trophic levels. Characteristics of the spring phytoplankton bloom were derived from weekly composite observations of the concentration of chlorophyll, a commonly used index of phytoplankton biomass, at the ocean surface based on satellite observations (Sea-Viewing Wide Field-of-View Sensor [SeaWiFS] 1998-2007; Moderate Resolution Imaging Spectroradiometer [MODIS] 2008–11); Visual Infrared Imaging Radiometer Suite [VIIRS] (2012–present) (Figure 12). The onset of the spring phytoplankton bloom was highly variable across the Atlantic Zone. An early onset occurred in the St. Anthony Basin, southeast Shoal and Eastern Scotian Shelf while delayed onset occurred on the Northeast Newfoundland Shelf, northeastern Gulf of St. Lawrence and Western Bank. The magnitude of the bloom was near or below normal throughout the Atlantic Zone, with a record low on Georges Bank. Bloom duration was generally near or above normal in the Newfoundland and Labrador Shelf, reaching records in St. Anthony Basin and over Southeast Shoal. Bloom duration was longer than normal over the Magdalen Shallows and Eastern Scotian Shelf but shorter or near normal in the remainder of the Gulf of St. Lawrence and Scotian Shelf.

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. 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 region that have much smaller energy reserves relative to *C. finmarchicus* but their life history features are generally representative of smaller taxa in the copepod community. The other indices provide information on the total abundance of copepods and non-copepod taxa, and the biomass (dry weight) of the zooplankton in the 0.2–10 mm size fraction usually dominated by copepods.

The zooplankton community shift observed in recent years (2014–2018), characterized by lower abundance of the large energy-rich copepod *Calanus finmarchicus*, higher abundance of small and warm water copepods and non-copepods, persisted in 2019 to a moderate extent, following the apparent shift towards normal conditions in 2018 (Figure 13). *Calanus finmarchicus* remained near or slightly below normal across most of the Atlantic zone with the exception of the Eastern Gulf of St. Lawrence and Prince 5 where its abundance was well above normal and Station 27 where it was well below normal. The abundance of *Pseudocalanus* spp. was above normal in the Gulf of St. Lawrence, at Station 27, on Halifax section and Halifax 2 station, and near normal elsewhere across the zone. On the Scotian Shelf, this pattern was a change from low *Pseudocalanus* abundances observed in 2016–2018, and may have been influenced by sampling only in spring in 2019. Total copepod abundances were mostly above or near normal across the Atlantic zone. Non-copepods, which are mostly larval stages of benthic invertebrates, carnivorous groups that feed on other zooplankton, and small-particle feeders~~,~~ were mainly above or near normal, with a record high on the Cabot Strait section.

Zooplankton biomass was generally below normal across most of the Atlantic zone in 2019, continuing a pattern observed since 2015 (Figure 14). Exceptions occurred on the Bonavista section, at Station Rimouski, the Northwestern Gulf of St. Lawrence and Prince 5 where zooplankton biomass was above normal. 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.

Since our last report, omissions were detected in the Newfoundland and Labrador biomass database that had resulted in underestimated biomass and spurious record lows during the 2015–2017 period. This has been corrected and quality controls and assurance protocols have been revised to prevent the recurrence of this type of error.

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 shelf waters. Conditions in 2019 were similar to 2018, as well as to the 2014–2018 average (Figure 15).

For the Scotian, Newfoundland and Labrador shelves, bottom pH values ranged from 7.77 in the Gulf of Maine to above 8 on Flemish Cap section, while Ω_{arg} was slightly undersaturated on the Avalon channel (Station 27 and FC-02) and on the deepest part of the Scotian Shelf slope (station LL-09). A large part of the shallower southern Gulf was also undersaturated with respect to aragonite. The lowest pH and Ω values were however observed along the deep Laurentian channel, especially in the Lower St. Lawrence Estuary where most of the deep layer (>300 m) was undersaturated with respect to aragonite and calcite (lowest pH values were 7.53 and 7.56 at stations CH12 and Rimouski, respectively). This represents increased acidification relative to the conditions in 2018. In addition, oxygen saturation at these stations (Figure 15, bottom panel) also decreased compared to 2018 at about 17.5%, reaching new record low concentration for the Lower St. Lawrence Estuary at 1.18 ml/l.

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 June of 2019, the Atlantic Repeat 7-West (AR7W) line was occupied by the Bedford Institute of Oceanography for the 32nd time since 1990. Additionally, the network of profiling Argo floats provided temperature and salinity data to 2000 m used for monitoring of year-round variability of the oceanographic conditions in the Labrador Sea.

While the winter (Dec–Mar) NAO index in 2019 was above-normal (Figure 7), a low atmospheric pressure anomaly in the Labrador Sea resulted in above-normal winter air temperatures. Sea surface temperatures were near-normal in winter and above-normal in spring. Sea ice extent anomalies in winter and spring were generally negative, except for a near-normal winter anomaly on the central Labrador Shelf.

In the Labrador Sea, intense vertical mixing induced by high surface heat losses in winter results in the formation of a characteristic dense water mass, Labrador Sea Water, which consequently spreads across the ocean ventilating its deep layers and essentially driving the global ocean overturning circulation. The most remarkable event in the entire history of oceanographic observations in the North Atlantic was the production of a record cold dense deep gas-saturated voluminous class of Labrador Sea Water between the late 1980s and mid-1990s (Figure 16). Over about 20 years that followed this well-documented water mass development, the sea was gradually warming gaining more saline and less dense waters.

In the winter of 2015, the Labrador Sea incurred the highest heat loss in more than two decades (Figure 17). However, the four following winters showed a significant reduction in the respective net surface heat losses, remaining above-normal in 2016 and 2017, and then declining to near-normal in 2018 and 2019. Despite the persistent decline in the surface cooling since 2015, the water column preconditioned by deep convection in the previous winters eased further deepening of convective mixing in the subsequent winters. As a result, in the period from 2014 to 2018, winter convection progressively deepened from 1600 to 2000 m (Figure 7), becoming the deepest since the winter of 1994 which in turn was the deepest (2500 m) convection on the 80-year record (Figure 16). In turn, the volume of Labrador Sea Water formed by the convective mixing that deepened in each of the five winters preceding 2019 was the largest since the mid-1990s. If in the winter of 2018, convection continued to deepen despite a near-normal surface heat loss in the same winter, in the winter that followed a comparable heat loss brought a much weaker convection, reversing the multiyear trend in convection depth and implying that the effect of preconditioning of the water column by previous convections declined. Indeed, the temperature and salinity profiles collected by research vessels and profiling Argo floats in the central Labrador Sea indicate that the 2019 winter convection was shallower than in the previous five years (Figure 16). It reached the depth of about 1400 m in the western part of the Labrador Basin, and only about 1000 m in the central and eastern parts. The near-normal winter convection in the winter of 2019 further added to gas (dissolved oxygen, anthropogenic gases, and carbon dioxide) uptake and consequently respective gas concentrations in the Labrador Sea in the upper 1000 m layer, while the deeper layer showed a decrease.

The upper, 15–100 m, layer of the central Labrador Sea was the coldest since 2000 in 2018 (Figure 17). In 2019, this layer warmed by 0.5°C raising its temperature to above-normal. The intermediate, 200–2000 m, layer reached its warmest state since 1972 in 2011, and then started to cool. The cooling of the intermediate layer that followed was a direct result of persistently deepening convection during the winters from 2012 through 2018. The warming of the upper and intermediate layers of the Labrador Sea in 2019 concurs with the reduced heat loss and shallowed convection in the winter of 2019.

With respect to interdecadal variability, the Labrador Sea completed a cooling cycle, 2012–2018, similar to those observed during 1987–1994 and in the late 1950s. Each of these cooling events coincided with strengthening of winter convection and production of large volumes of Labrador Sea Water.

Temperature in the top 100m was close to normal, with slightly cooler than normal waters on the Labrador Shelf, slightly warmer than normal in the Labrador Basin. Mean chlorophyll *a* concentrations were lower than average in all three regions in 2019 (Figure 18) continuing a trend that started in 2016. The lower phytoplankton standing stock can be attributed to a lower abundance in diatoms as revealed by lower than average measurements of fucoxanthin pigments (not shown here). The same trend was observed for large centric diatom and foraminifera abundance collected from the 200µm plankton net, where a shift from positive to negative anomalies has been observed since 2014.

Presence of cloud cover in spring can make phytoplankton bloom metrics based on satellite ocean color challenging and bias the results. In 2019, the Labrador Shelf/slope and Central basin area experienced a delayed and short bloom resulting in a low amplitude and lower than average magnitude. The Greenland shelf/slope experienced the inverse trend with an early start and longer than average bloom of a larger than average magnitude.

In general, most mesozooplankton indicators were again lower than normal in 2019, a trend that coincides with the return of very deep winter convection in 2014. *Calanus finmarchicus* show regional year-to-year variations in abundance that are generally related to regional differences in the timing of the life-cycle events and environmental conditions. *Calanus finmarchicus* dominates the mesozooplankton throughout the Labrador Sea. Its abundance was higher than average on the Labrador shelves/slopes, largely caused by a higher abundance of younger life stages than normal. In the central basin only Clausocalanidea and Oithonidea showed higher than average abundances.

Sources of Uncertainty

The general spatial and seasonal patterns of physical, chemical and biological oceanographic variables 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 weather, 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.

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). Additionally, reductions in vessel scheduling within regions have also reduced the number of full observations at some sites.

CONCLUSION

While a shift to warmer ocean conditions occurred prior the implementation of the AZMP, the past decade has seen further increases in water temperatures with sea surface temperatures that reached record values across the zone in summer 2012. In 2019, they were below normal overall for the zone for the first time since 1992, yet they would have been near normal if not for tropical storm Dorian that mixed heat deep into the water column. Winter average sea ice volume was near normal in the Gulf of St. Lawrence and was 10th lowest since records began in 1969 on the NL Shelf. Consistent with this, summer cold intermediate layer conditions were near normal to warmer and thinner than normal across the zone. Bottom temperatures in the Atlantic Zone ranged from normal on the Grand Banks (3LNO) to above normal elsewhere, including a new 100+ year high-temperature record for the Gulf at 250 and 300 m, a record high in Emerald Basin at 250 m and a near record high temperature in Georges Basin.

Patterns of variation in biogeochemical variables appear dominated by short-term fluctuations, because sampling was initiated only in 1999 but there is evidence of multi-year trends in recent years. The current state of the biogeochemical environment demonstrates some spatial structuring across the Atlantic Zone. Overall, there appear to have been important changes in general patterns of productivity of lower trophic levels in recent years. General declines in nutrient and chlorophyll inventories may be indicative of lower ecosystem production potential than in the previous decade and the shift in zooplankton community structure from large lipid-rich copepods to smaller taxa may have consequences to the transfer efficiency from primary producers to upper trophic levels.

In the Labrador Sea, convection reached the depth of about 1400 m in the western part of the Labrador Basin, and only about 1000 m in the central and eastern parts, contrasting the 2014 to 2018 period during which winter convection incrementally deepened from 1600 to 2000 m.

LIST OF MEETING PARTICIPANTS

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SOURCES OF INFORMATION

This Science Advisory Report is from the Twenty-second Annual Meeting of the Atlantic Zone Monitoring Program (AZMP) held via video-conference April 20–21, 2020. 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

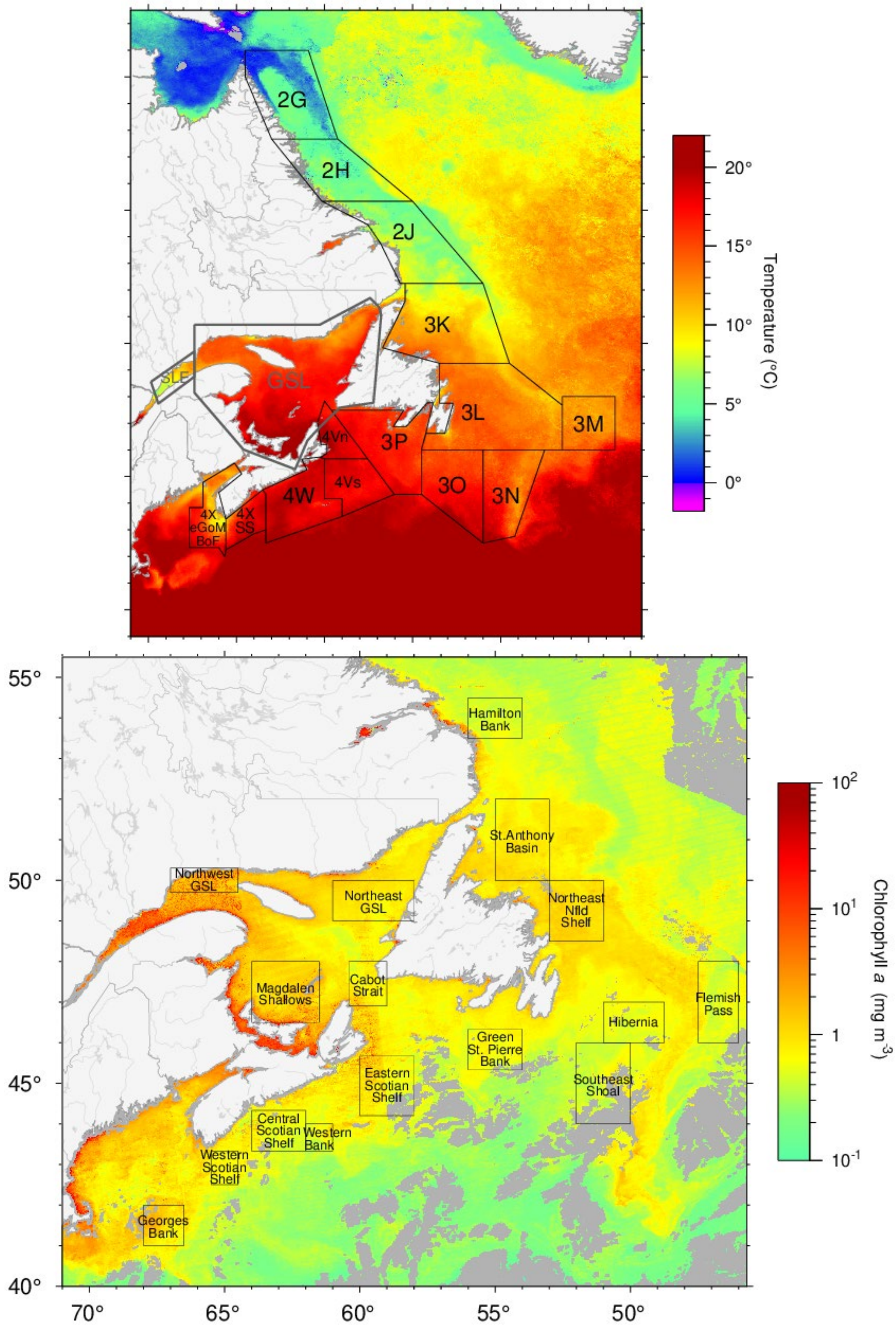

Figure 2. Areas used for (top) temperature and (bottom) ocean color averages. (Top) North Atlantic Fisheries Organization Divisions are cut off at the shelf break. The acronyms GSL and SLE are Gulf of St. Lawrence and St. Lawrence Estuary respectively. Sea surface temperatures are shown for July 2019 and ocean colour chlorophyll a concentrations are for the first half of October 2019.

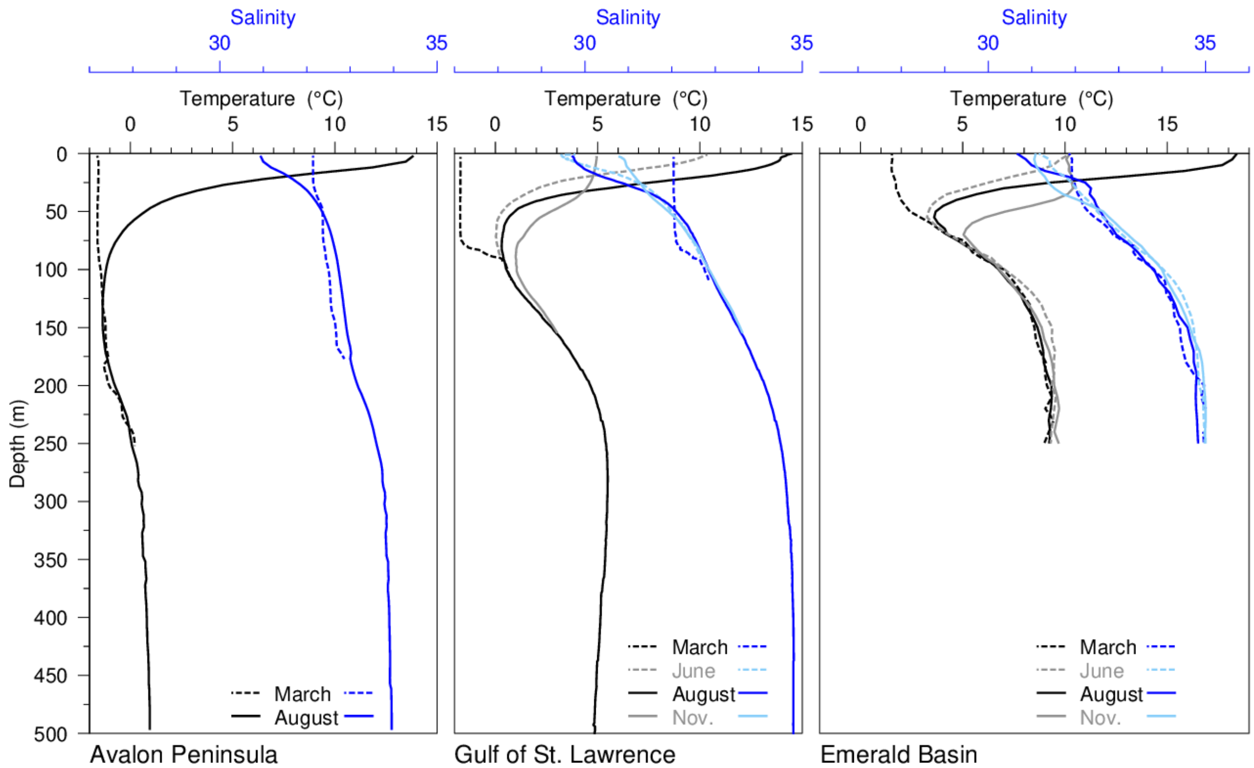

Figure 3. Typical seasonal progression of the depth profile of temperature and salinity observed in three representative regions across the zone. The Avalon Peninsula region is delimited by 45–50°N and 50–55°W and shown are the averages of profiles for March and August between 2015 and 2017, calculated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

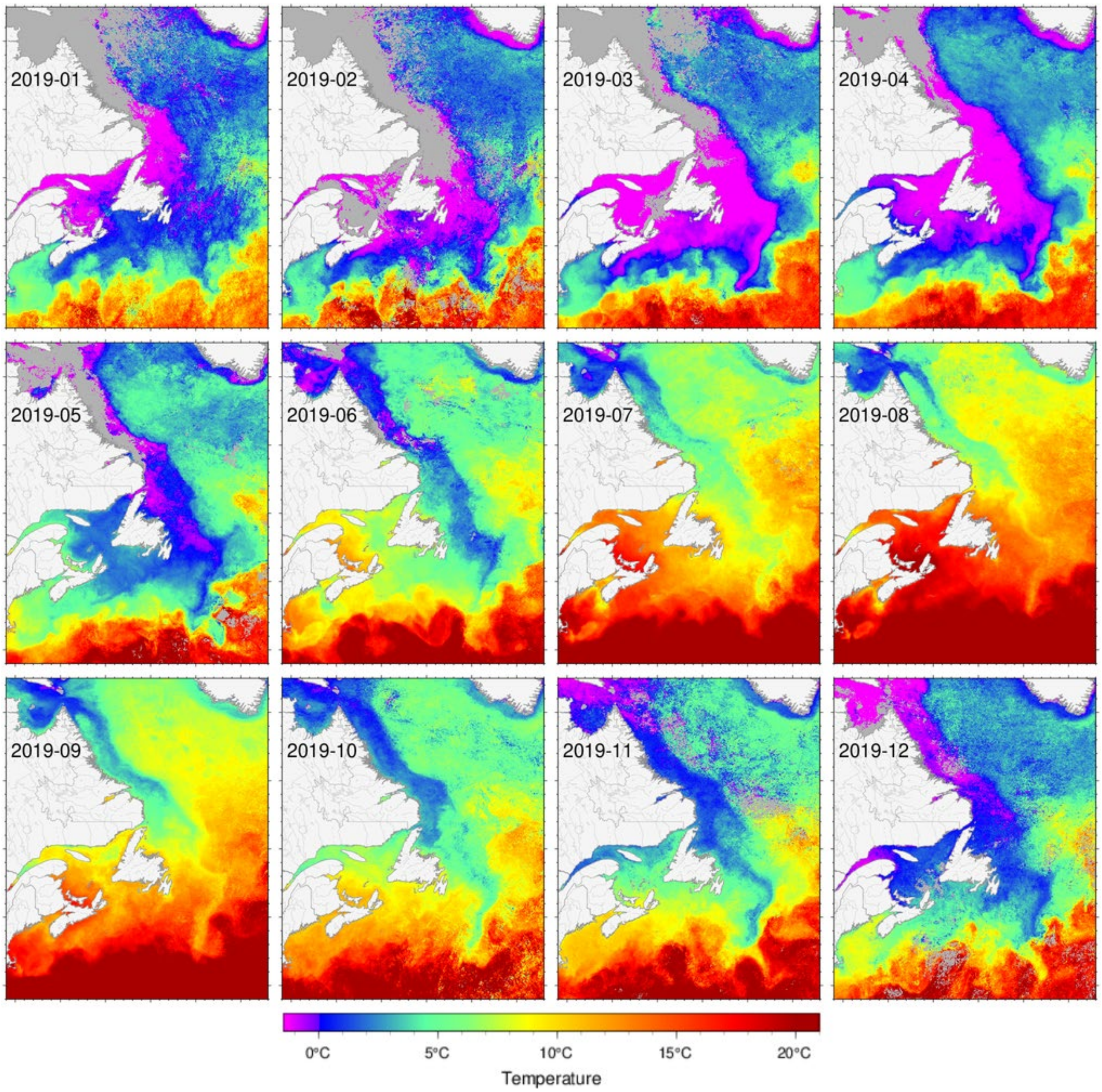

Figure 4. Sea surface temperature monthly averages for 2019 in the Atlantic zone.

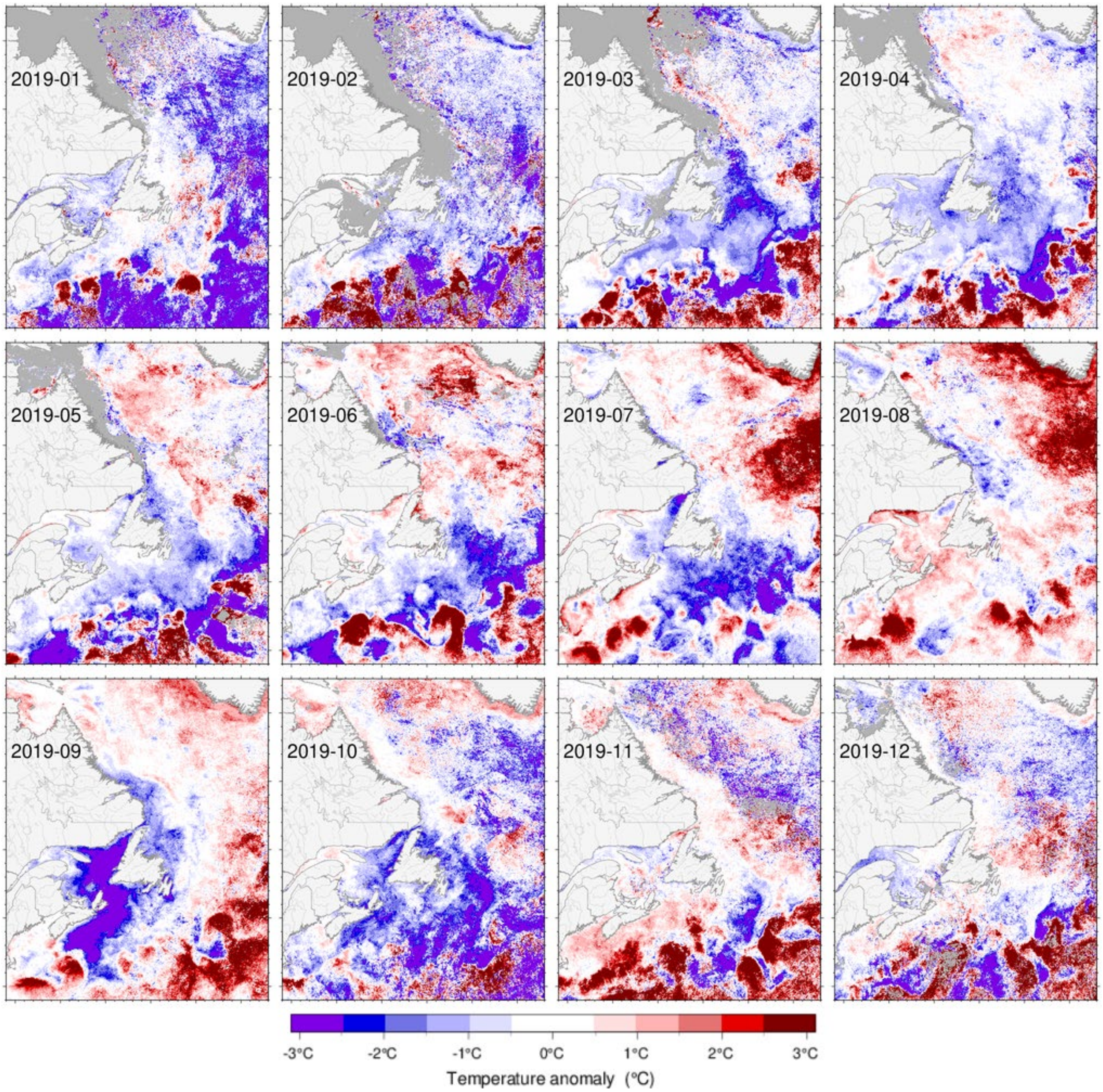

Figure 5. Sea surface temperature monthly anomalies for 2019 in the Atlantic zone. Temperature anomalies are based on a 1982–2010 climatology.

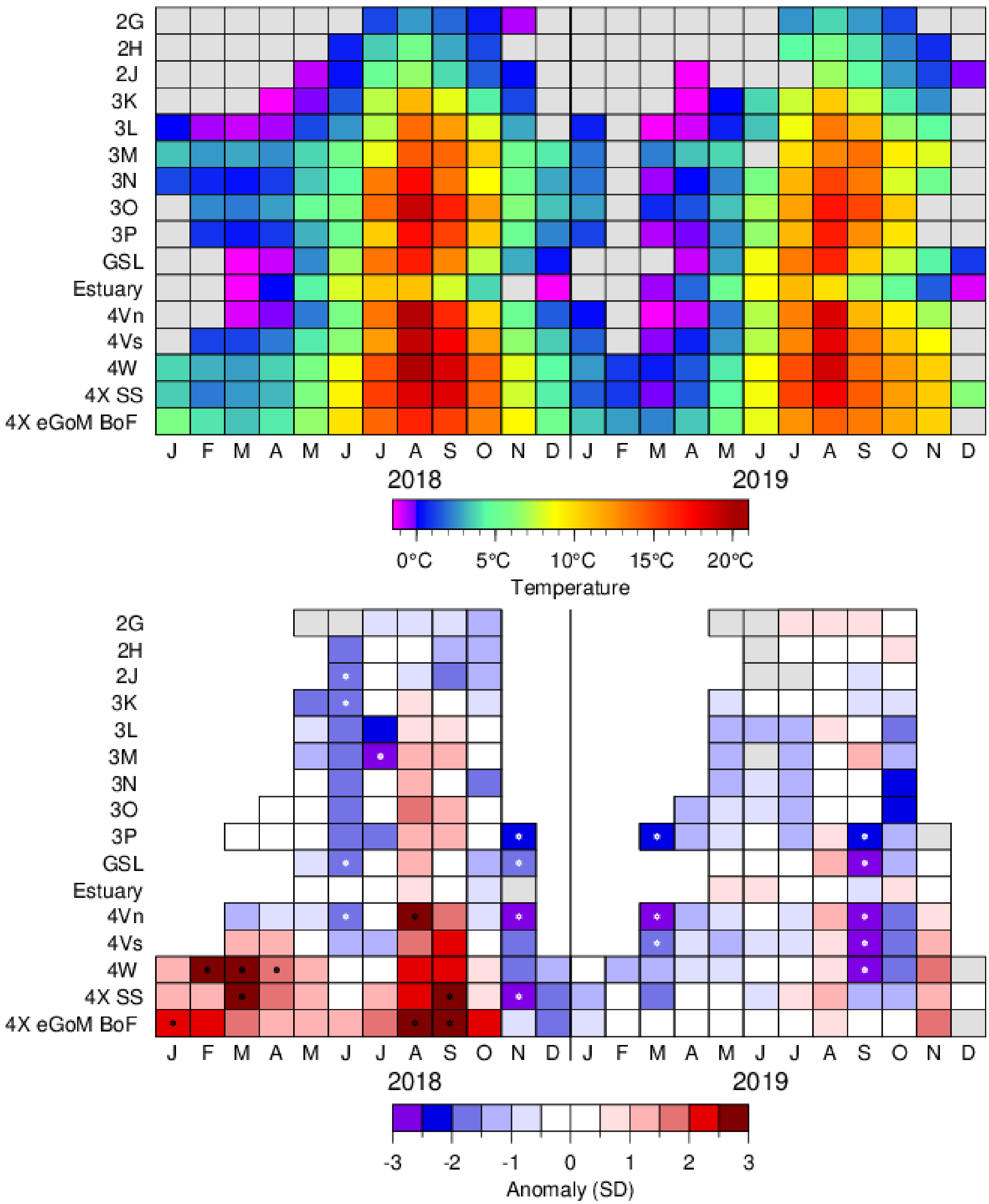

Figure 6. Monthly sea surface temperature temperatures (top) and anomalies (bottom) for ice-free months of 2018–19, averaged over the 16 regions shown in Figure 2. Regions and months for which the average temperature was at a record high or low are indicated by a star. Grey squares have insufficient data coverage to yield a monthly average anomaly (<15%).

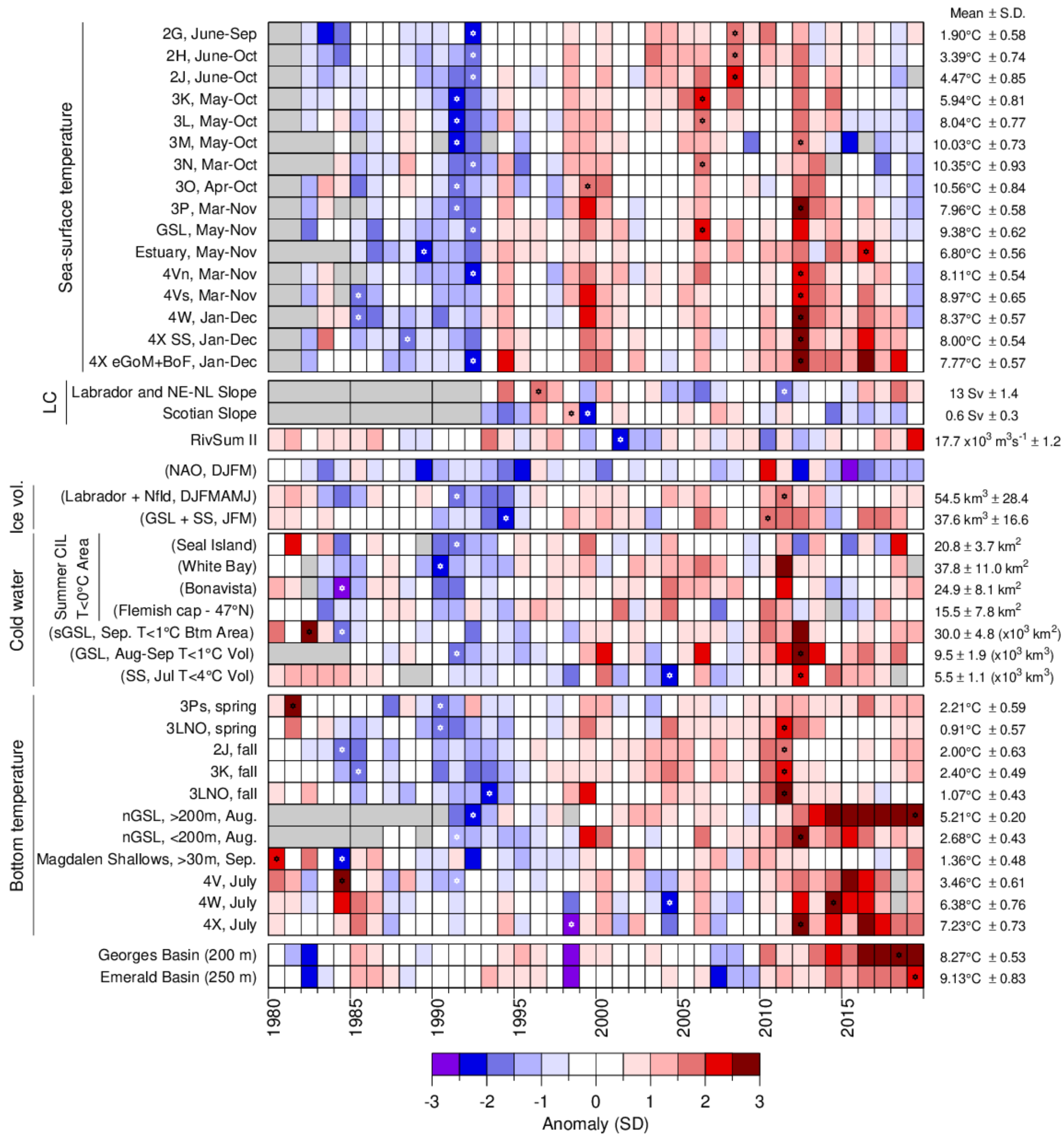

Figure 7. Time series of oceanographic variables, 1980–2019. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1981–2010 when possible; a red cell indicates above normal conditions, and a blue cell below normal. Variables whose names appear 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. (LC is Labrador Current transports. 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]).

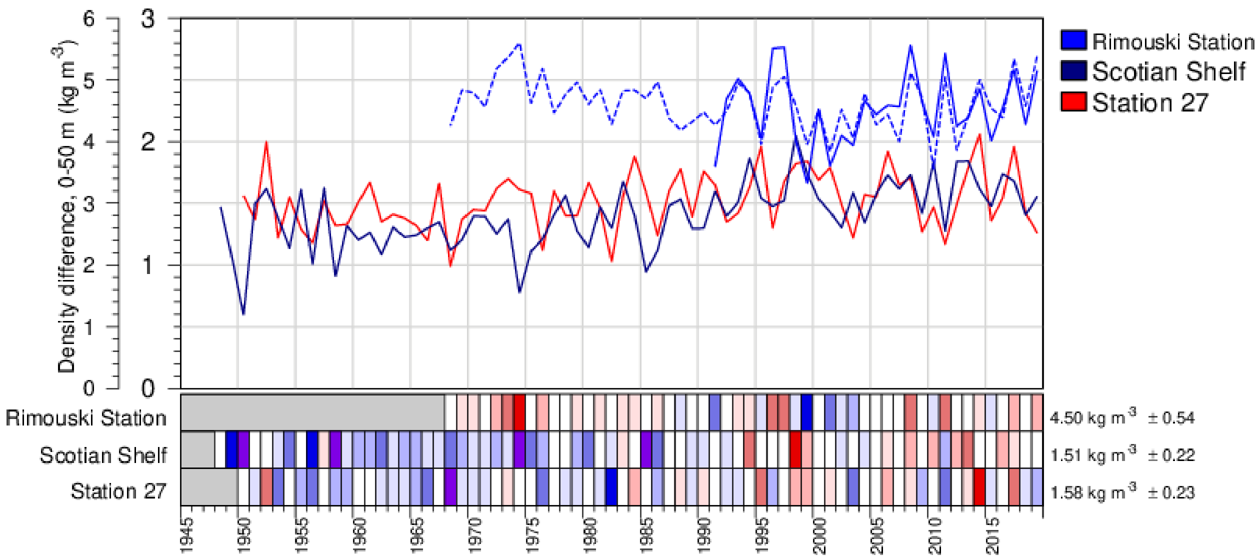

Figure 8. Stratification trends on the southern NL Shelf (May-Nov average at Station 27), Scotian Shelf and St. Lawrence Estuary (May–Oct average at Rimouski Station). The outer y-axis is for Station 27 and Scotian shelf, while the inner y-axis is for Rimouski Station. The dashed line for Rimouski Station is a proxy based on May–October fresh water runoff. The three bottom lines show normalized anomalies based on the 1981–2010 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.

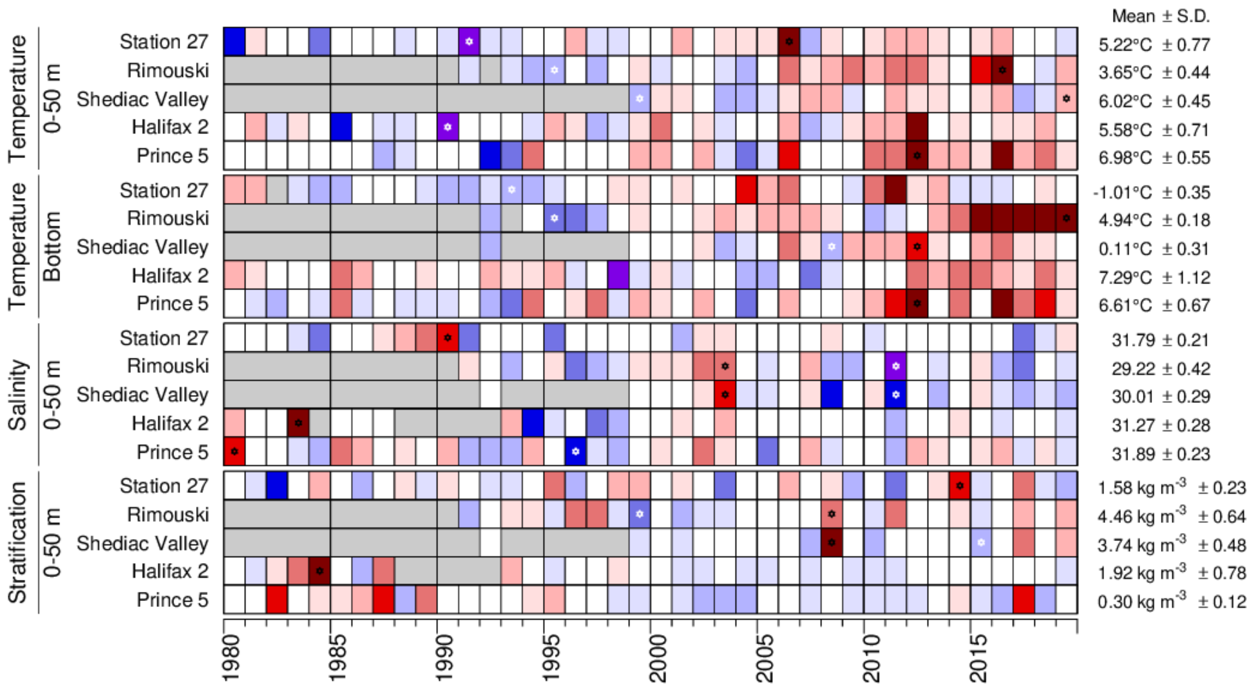

Figure 9. Time series of oceanographic variables at AZMP high-frequency sampling stations, 1980–2019. Values are annual averages at Halifax 2 and Prince 5, May–November at station 27 and May-October at Rimouski station. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1981–2010 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.

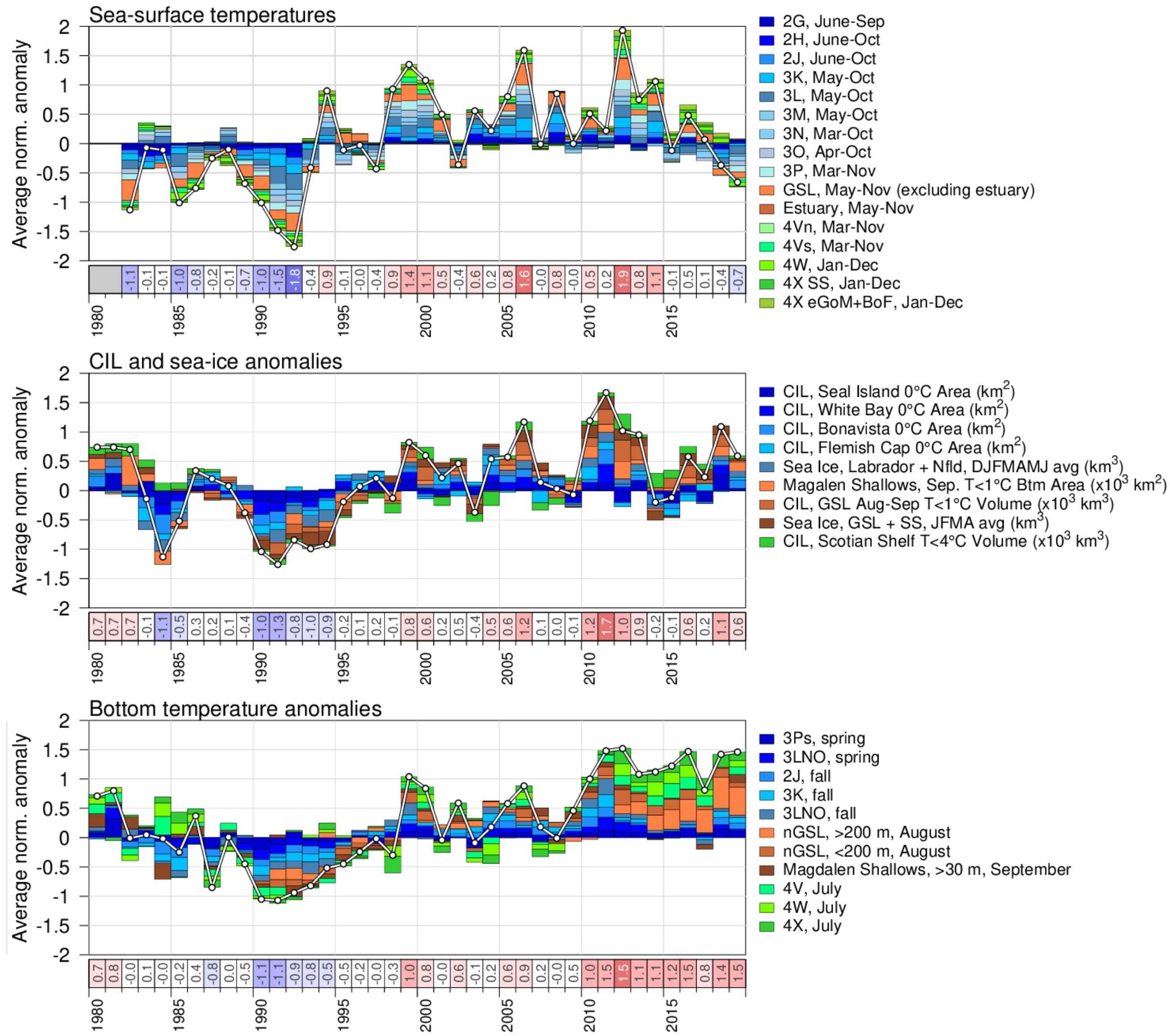

Figure 10. Composite climate indices (white lines and dots) derived by averaging various normalized anomalies from different parts of the environment (colored boxes stacked above the abscissa are positive anomalies, and below are negative). Top panel shows averages sea surface temperature anomalies weighted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

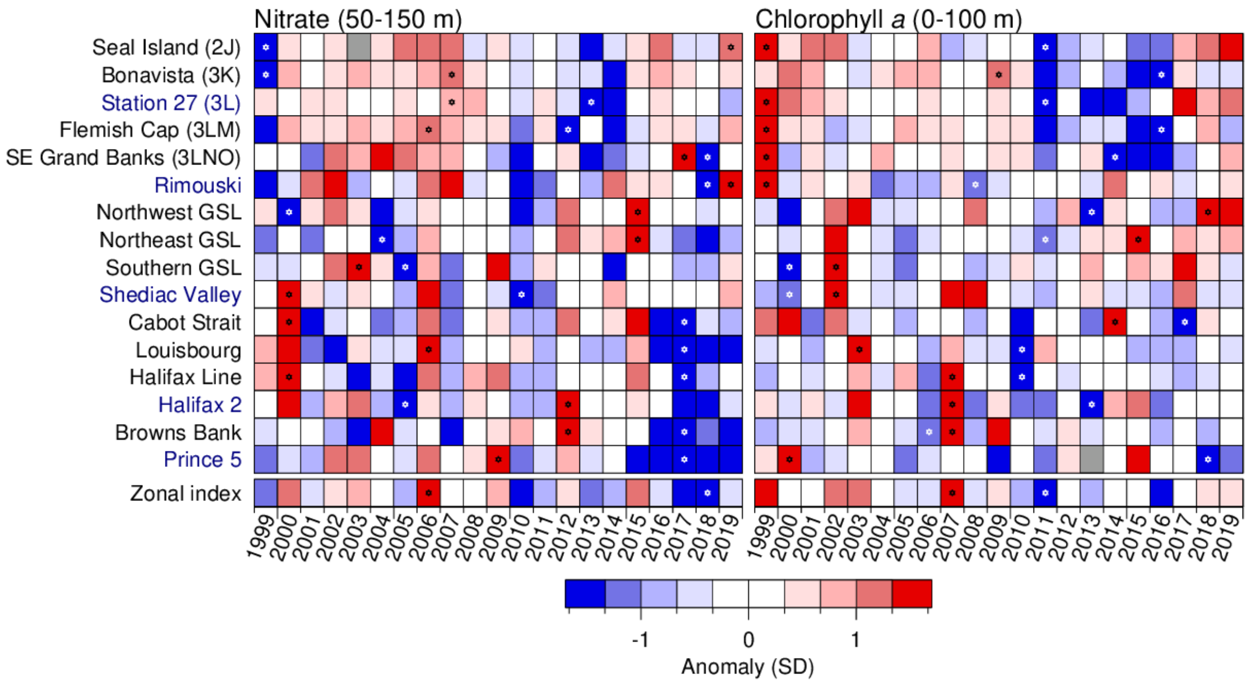

Figure 11. Time series of deep water nitrate inventories (50–150 m) and surface phytoplankton standing stocks (expressed as chlorophyll a 0–100 m mean concentration) at AZMP sections (labelled in red in Figure 1) and high-frequency sampling stations (labelled in blacks in Figure 1), 1999–2019. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1999–2015; 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. Note change in colour palette. The "zonal index" is created as the average of all normalized anomalies, and that result is again normalized.

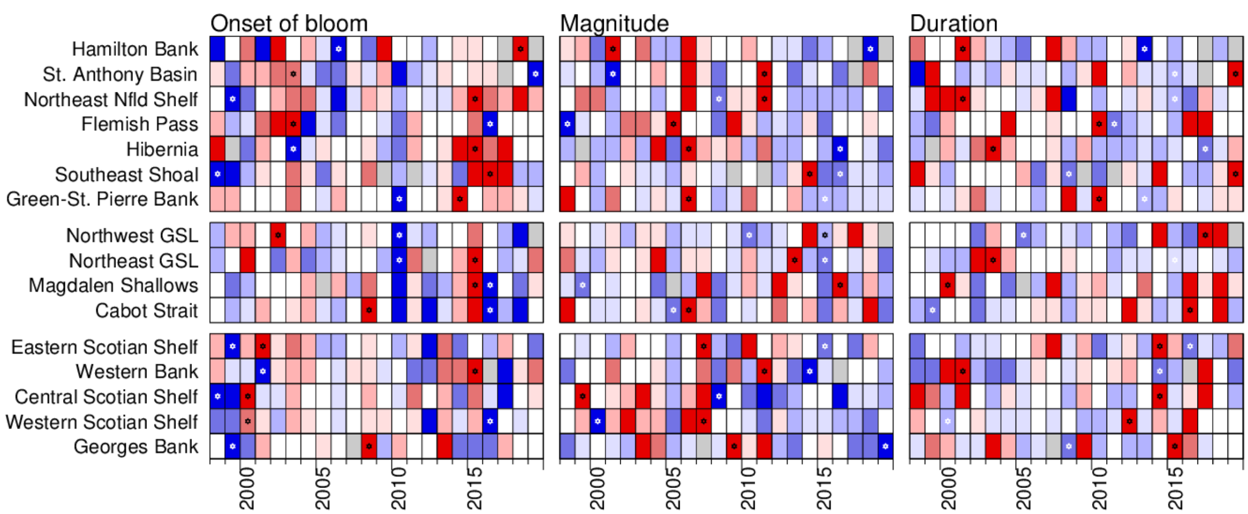

Figure 12. Time series of remotely sensed bloom parameter anomalies in various regions (onset of bloom, magnitude and duration) 1998-2019. Data are from SeaWIFS for the period 1998–2007, from MODIS for 2008–2011, and VIIRS for from 2012 to the present. Series minimum and maximums are indicated by a star. See Figure 2 for area definitions. Palette as in Figure 11.

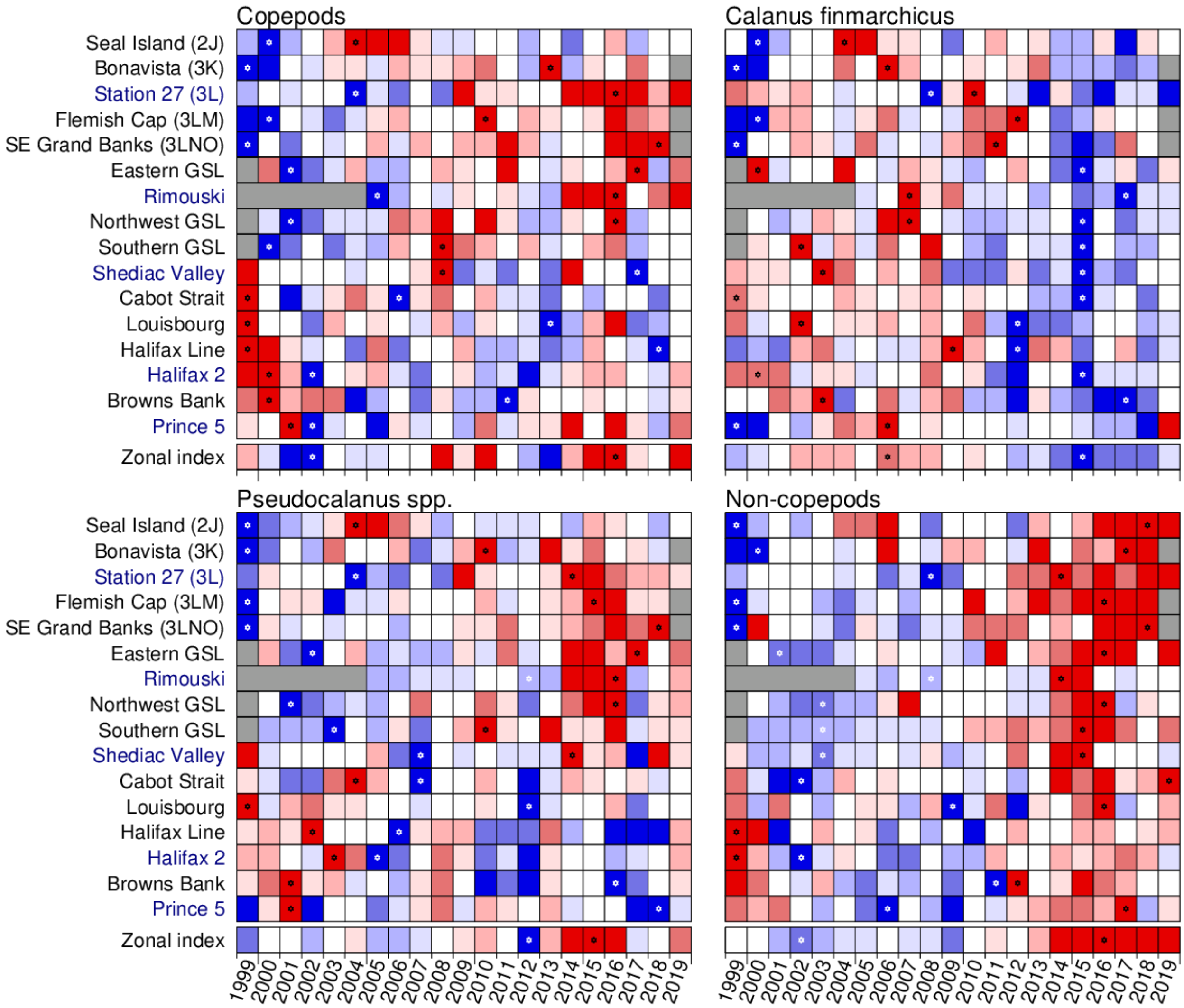

Figure 13. Time series of the standing stocks of total copepods, Calanus finmarchicus, Pseudocalanus spp., and non-copepod zooplankton, 1999–2019. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1999–2015; a red cell indicates above normal 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. Palette as in Figure 11.

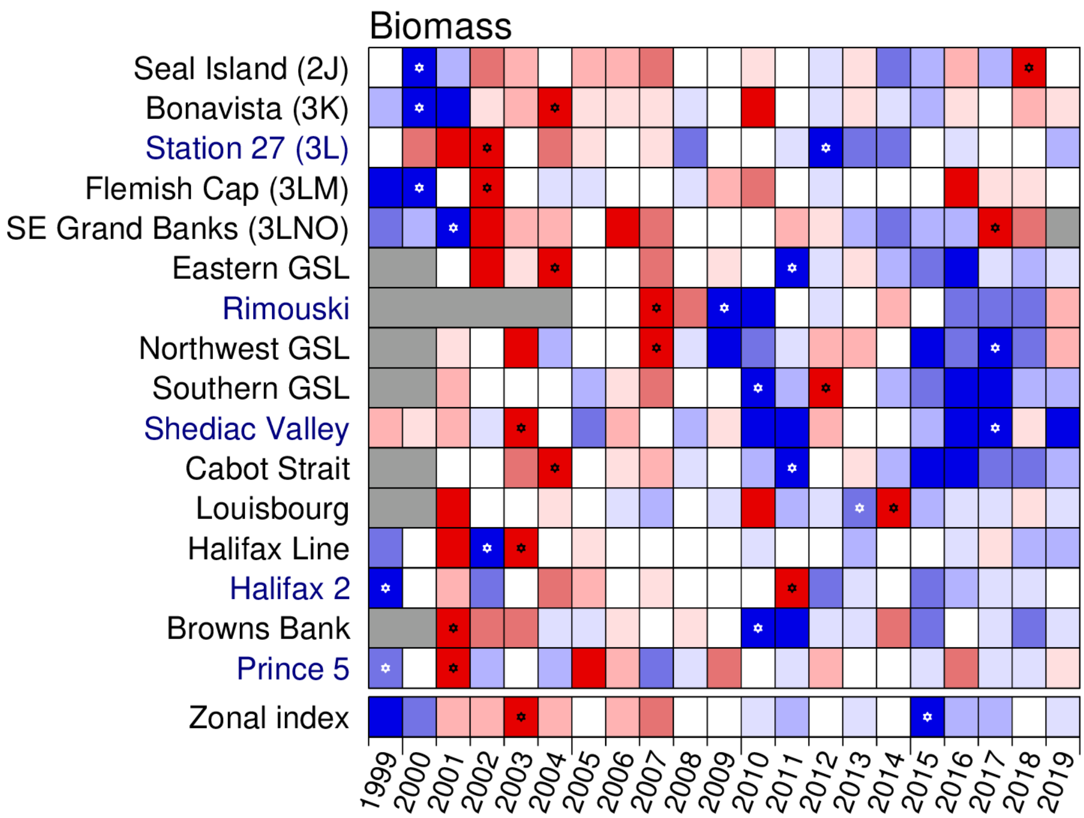

Figure 14. Time series of zooplankton biomass (dry weight), 1999 to 2019. Biomass is measured on the 0.2–10 mm size fraction which is usually dominated by copepods. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1999–2015; a red cell 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. Palette as in Figure 11.

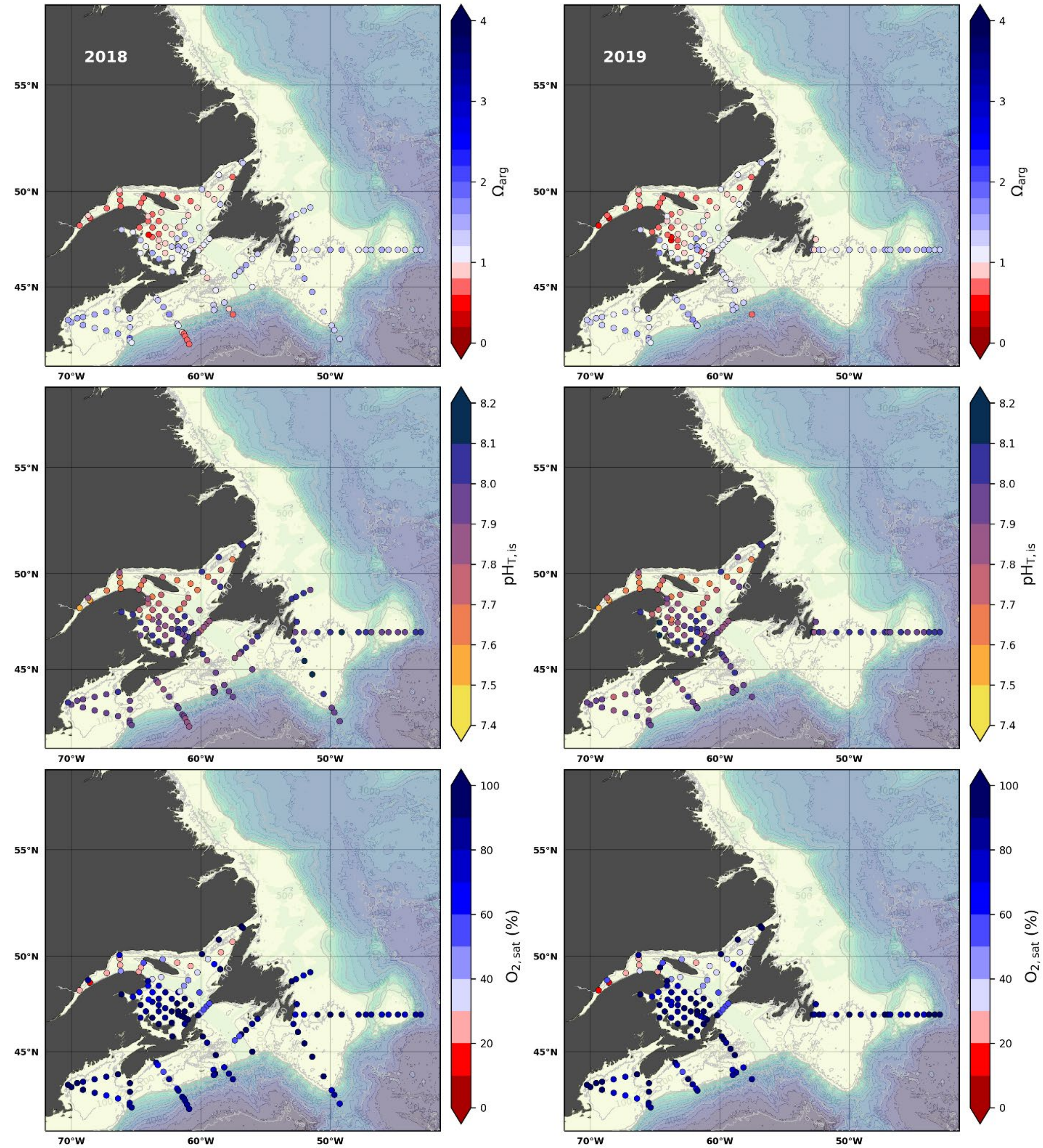

Figure 15. Bottom ocean acidification conditions during spring 2018 (left) and 2019 (right) for the Gulf of St. Lawrence, Scotian Shelf and Newfoundland Shelf: aragonite saturation state (top), in situ pH using total scale (center) and dissolved oxygen saturation (lower). Undersaturated conditions relative to aragonite and hypoxic oxygen conditions are plotted in red colors.

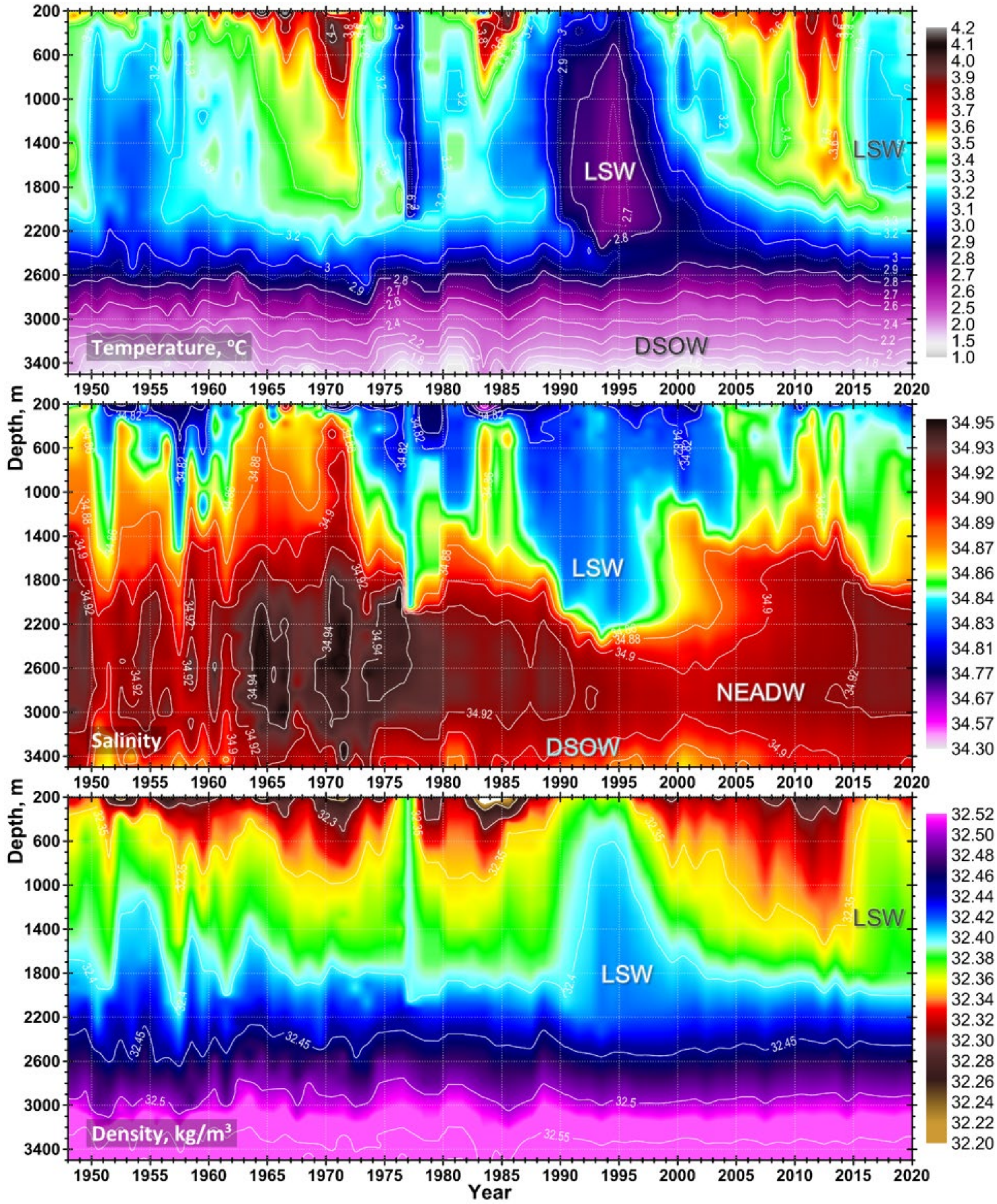

Figure 16. Annual temperature (upper panel), salinity (middle panel) and density (w.r.t. 1000 dbar, lower panel) means in the central region of the Labrador Sea between 200 and 3500 m based on profiling Argo float and shipboard observations for the time period of 1948–2019. LSW, NEADW and DSOW indicate Labrador Sea Water, Northeast Atlantic Deep Water and Denmark Strait Overflow Water, respectively.

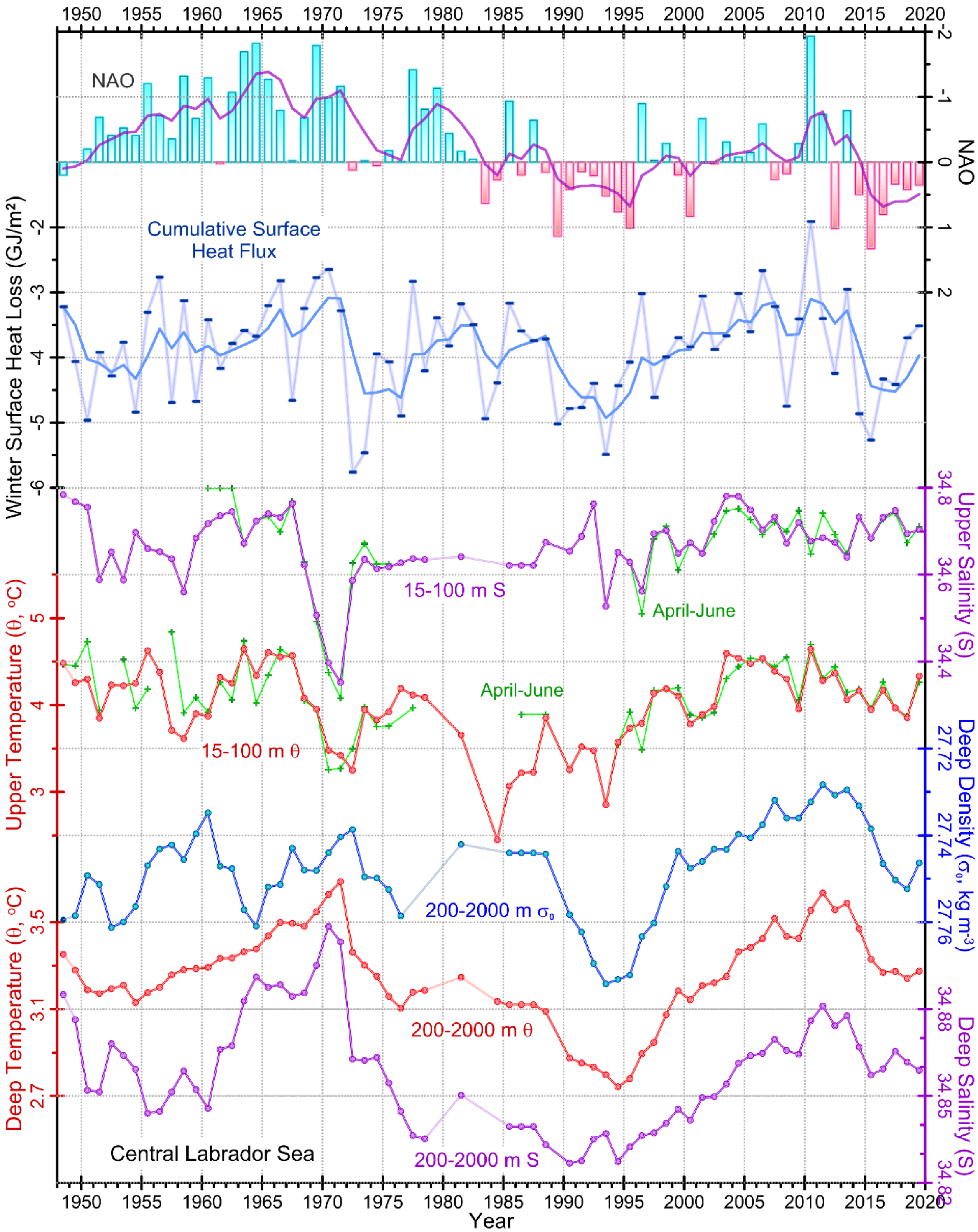

Figure 17. Key Labrador Sea environmental indices since 1948. From top to down: The normalized winter NAO index (upper bar graph, inverted scale); The NCEP-based cumulative surface heat flux computed for the central Labrador Sea over individually-defined annual cooling seasons (blue); The upper two solid lines indicate five-back-point filtered series; Annual and spring mean temperature (θ) and salinity (S) averaged over the 15-100 m depth range, and annual mean θ, S and density (σ_0) averaged over the 200–2000 m depth range in the central Labrador Sea.

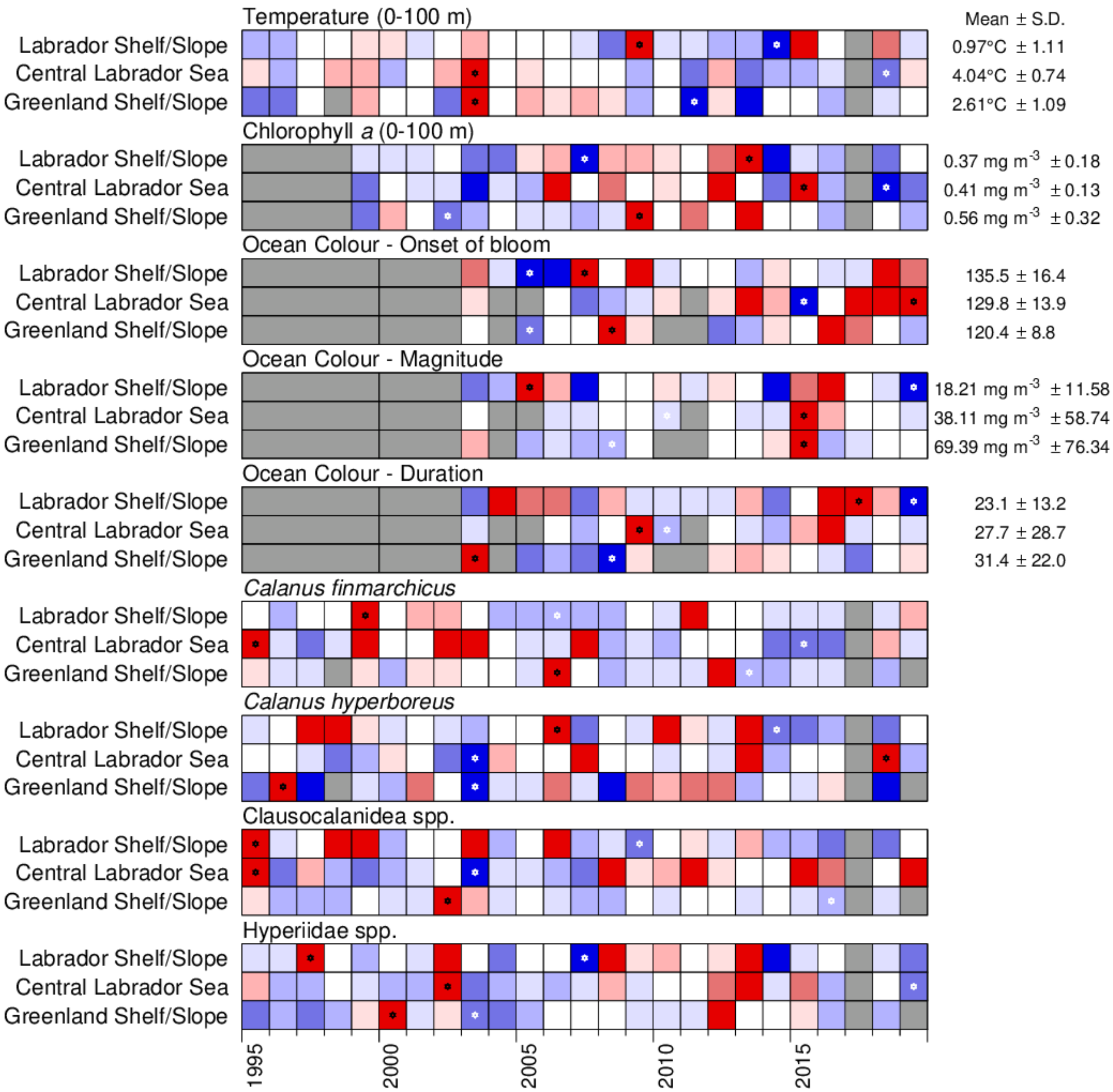

Figure 18. Normalized annual anomalies for the Labrador Sea. Temperature and chlorophyll are 0–100 m averages from oceanographic station data. Bloom parameters (onset of bloom, magnitude and duration) are derived from remote sensing observations. Zooplankton data represent anomalies of abundance estimation collected in May/June along the AR7W line between 1995 and 2019. Palette as in Figure 9.

THIS REPORT IS AVAILABLE FROM THE:

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ISSN 1919-5087

Correct Citation for this Publication:

DFO. 2020. Oceanographic Conditions in the Atlantic Zone in 2019. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/028.

Aussi disponible en français :

MPO. 2020. Conditions océanographiques dans la zone Atlantique en 2019. Secr. can. de consult. sci. du MPO, Avis sci. 2020/028.