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OCEANOGRAPHIC CONDITIONS IN THE ATLANTIC ZONE IN 2017

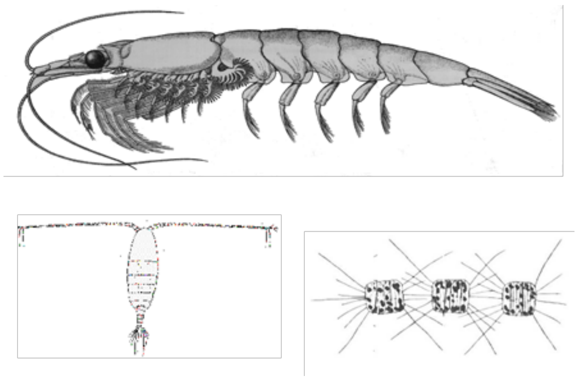

Figure 1. Key taxa of the pelagic food web: euphausids (top), phytoplankton (bottom right), and copepods (bottom left).
Images: Fisheries and Oceans Canada

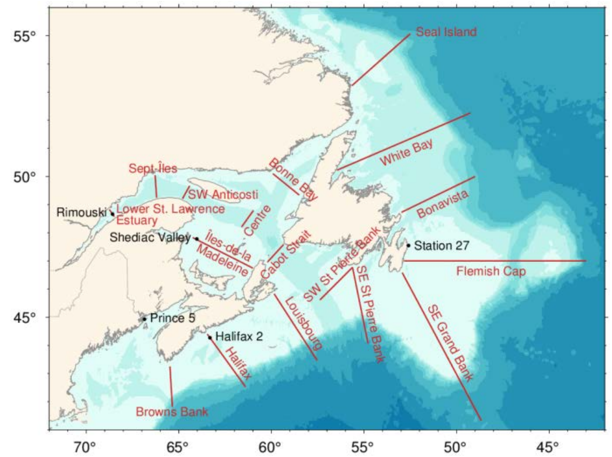

Figure 2. Atlantic Zone Monitoring Program high-frequency sampling stations (black) and selected section lines (red).

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.

SUMMARY

- Vessel breakdown and survey cancellation and delays resulted in important data gaps in the assessment of oceanographic conditions in the Atlantic Zone for 2017. Data gaps result in significant declines in the accuracy and precision of observational series and can limit our ability to detect shifts in environmental conditions in the future.
- Winter sea surface temperatures were above normal from the Scotian Shelf to the Bay of Fundy, including a record high (since 1985) on the central Scotian Shelf (4W) in February. Temperatures were also much above normal off of Nova Scotia in the fall including record highs in October and November on the Eastern Scotian Shelf (4X SS), in October and December in Eastern Gulf of Maine and Bay of Fundy and in November on the central

Canada

Scotian Shelf (4W). Temperatures were typically below normal on the Southeast Grand Banks (3N) throughout the ice-free months, including a record low in June.

- Winter average sea ice extent was near normal on the Newfoundland and Labrador Shelf but was 6th lowest since records began in 1969 in the Gulf of St. Lawrence. An unusual reappearance of very thick ice from the Labrador Shelf affected the northeastern Gulf from late May until mid-June.
- Summer cold intermediate layer conditions varied from colder than normal at the most northern sections (Seal Island and White Bay), to above normal on the Flemish Cap section and on the Scotian Shelf.
- Bottom temperatures were normal to above normal across the zone, including very high anomalies on the Scotian Shelf and in the deeper waters of the northern Gulf of St. Lawrence. Rimouski station bottom temperatures remained high but decreased from a series record high observed in 2016.
- Stratification was high at all high-frequency sites except Halifax 2. In the Estuary and Gulf of St. Lawrence, this was attributed to the highest April-May freshet on record (since 1948).
- Deep nutrient inventories declined considerably in 2017, reaching record lows across most of the Scotian Shelf. The only exceptions were the southern Grand Banks and the northern Gulf of St. Lawrence where inventories were near normal. The declines were modest across most of the Newfoundland Shelf but represent continuation of recent trends in the Gulf of St. Lawrence and the Scotian Shelf.
- Annual chlorophyll *a* inventories were below normal over the Grand Banks, Cabot Strait and eastern Scotian Shelf but normal or above normal in the Gulf of St. Lawrence.
- The onset of the spring phytoplankton bloom was delayed on the Newfoundland Shelf and normal or early in the Gulf of St. Lawrence and the Scotian Shelf; the magnitude of the bloom was generally below normal with the exception of the Northwestern Gulf of St. Lawrence which was well above normal; bloom duration was highly variable, with long blooms on the Newfoundland Shelf, Northwestern Gulf of St. Lawrence, Western Bank and Central Scotian Shelf, and near average in the remainder of the Zone.
- The zooplankton community shift observed in recent years, characterized by lower abundance of the large energy-rich copepod *Calanus finmarchicus*, higher abundance of small copepods, and higher abundance of non-copepods, persisted in 2017 although the intensity declined relative to 2016. *Calanus finmarchicus* increased on the southern Grand Banks and in the eastern Gulf of St. Lawrence while there were declines in *Pseudocalanus* sp. And non-copepods across much of the Zone.
- The biomass of zooplankton was below normal across the Zone, with the exception of the Halifax section. The strongest negative anomalies were on the Newfoundland Shelf and in the Gulf of St. Lawrence.
- The Labrador Sea continued to exhibit strong vertical mixing in the winter of 2017, exceeding 1,500 m in depth, and represents the fifth year of progressive intensification and deepening of convective mixing and production of Labrador Sea Water (LSW) since 2012. Both upper, 0-200 m, and deeper, 200-2,000 m, layers have been cooling since 2010 but the LSW formed in the winter of 2017 the densest since the mid-1990s. The Labrador Current was strong in 2016 and 2017 relative to the previous four years when it was in its near normal state. As a result of the cancellation of the spring research survey, it was not

possible to neither update the rate of decline in pH nor assess the state of *Calanus finmarchicus* population, the dominant mesozooplankton in the Labrador Sea, in 2017.

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 foodweb (Figure 1). 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 2). 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 observations from the Labrador Sea from the Atlantic Zone Off-Shelf Monitoring Program (AZOMP).

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, values within ± 0.5 SD of the average are designated as near normal and shown as white cells, and conditions corresponding to warmer than normal (higher temperatures, reduced ice volumes, reduced cold-water volumes or areas) 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 2017

This is a summary of physical oceanographic conditions during 2017 for eastern Canadian oceanic waters (Figures 2 and 3) as reported annually by the AZMP in three reports (e.g. Colbourne et al. 2017, Galbraith et al. 2017 and Hebert et al. 2018 for conditions of 2016).

The North Atlantic Oscillation

The North Atlantic Oscillation (NAO) index-computed as the sea-level pressure difference anomaly between the sub-equatorial high and sub-polar low Atlantic Ocean-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 (Colbourne et al. 2017). In 2017, the winter NAO index was near normal at +0.3 SD, decreasing for a second year from the largest value in the 120 year record (+ 2.0 SD) observed in 2015.

Annual Temperature Cycle

Temperature varies vertically through the seasons in the Atlantic Zone (Figure 4). 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 (Colborne et al. 2017). Deep waters are defined here as those below the CIL that have only weak seasonal cycles.

Sea Surface Temperature

Averaged over ice-free periods of the year as short as June to November on the Labrador Shelf to the entire year on the Scotian Shelf, sea surface temperature has been found to be well correlated with average air temperature. Therefore, 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. The Scotian Shelf, St. Pierre Bank and the Grand Bank out to the Southeast Shoal all had their warmest ice-free period of the satellite record (since 1985 in the dataset shown here) in 2012 and the St. Lawrence Estuary had its warmest ice-free period in 2016.

In 2017, winter sea surface temperatures were above normal from the Scotian Shelf to the Bay of Fundy, including a record high (since 1985) of 3.0°C (+1.3°C, +2.2 SD) on the central Scotian Shelf (4W) in February (Figures 5 to 7). Temperatures were also much above normal off of Nova Scotia in the fall, including record highs in October (16.2°C, +2.8°C, +3.1 SD) and November (12.6°C, +3.1°C, +4.8 SD) on the Eastern Scotian Shelf (4X SS), in October (13.7°C, +1.9°C, +2.5 SD) and December (8.8°C, +1.9°C, +2.4 SD) in Eastern Gulf of Maine and Bay of Fundy and in November (11.6°C, +2.1°C, +3.1 SD) on the central Scotian Shelf (4W). Temperatures were typically below normal on the Southeast Grand Banks (3N) throughout the ice-free months, including a record low in June (3.8°C, -3.1°C, -2.0 SD).

Cold Intermediate Layer

For the Newfoundland and Labrador Shelf, the CIL indices shown here (Figure 8) 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. For the Gulf, the CIL volume with T<1°C observed in August-September is used as well as an index defined as the mean of the CIL minimum core temperatures observed between 1 May and 30 September of each year, adjusted to 15 July with a region-dependant warming rate (Galbraith et al. 2017). Since 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. 2017). 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. 2016). The CIL indices reported here are taken at about the same time within their respective annual cycles, although not simultaneously.

The 2012-16 period was characterized by record lows in 2012 for both the Gulf of St. Lawrence and Scotian Shelf CIL volumes, representing record warm conditions. While conditions were warmer than normal in the Newfoundland and Labrador sections in 2013, they were followed by mostly near normal conditions from 2014-17. However, CIL conditions have remained generally warmer than normal in the Gulf and Scotian Shelf.

In a manner consistent with winter sea-ice cover, 2017 CIL conditions were mostly near normal on the Newfoundland and Labrador Shelf, except for colder than normal conditions on the Grand Banks (3LNO) in the fall, were normal to warmer than normal in the Gulf of St. Lawrence (by up to 0.6 SD) and on the Scotian Shelf (by 0.8 SD). Thus, a north-to-south gradient was observed again in CIL conditions in 2017, for the fourth consecutive year.

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 (1981-2017, $R^2 = 0.58$) and with December-March air temperature at Cartwright (1981-2017, $R^2 = 0.59$). 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 $R^2 = 0.72$ (1969-2017). Air temperature is similarly well correlated to sea-ice cover area and duration ($R^2 = 0.77$-0.78). 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 17 km^3, 31,000 km^2 and

14 days of sea-ice season for each 1°C increase in winter air temperature (Galbraith et al. 2017).

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 (Figure 8). In the 8-year period between 2010 and 2017, the Gulf average sea-ice volume had 5 of the 8 lowest values of the series, and the Newfoundland and Labrador shelf had 3 of the 8 lowest. In 2017, seasonally averaged sea ice volume was near normal on the NL Shelf but was 6th lowest since records began in 1969 in the Gulf of St. Lawrence, with very little sea-ice exported onto the Scotian Shelf. However, an unusual reappearance of very thick ice from the Labrador Shelf affected the northeastern Gulf from late May until mid-June.

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, 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 regions 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 2017, bottom temperatures in the Atlantic Zone ranged from below normal to normal when associated with cold intermediate depths such as on the NL shelf and Magdalen Shallows, to above normal for deeper waters, including a new 100-year high-temperature record for the Gulf at 300 m (Figure 8). This began as a warm anomaly first observed in Cabot Strait in 2010 that has propagated towards the heads of the channels, sustained by new warm water inflows detected in 2012 and 2014-16. Thus, the average temperature of the deep waters of the Gulf should continue to increase in the next two years as estuarine circulation drives these anomalies inwards. The bottom area covered with temperatures > 6°C has reached a series record in both Central Gulf and the northwest Gulf since at least the mid-1980s. In other areas of the zone, bottom temperature remained high in 4V (4.6°C, +1.9 SD), 4W (7.2°C, +1.1 SD) and 4X (8.8°C, +2.2 SD) in July, with record high temperature in Georges Basin (9.82°C, +1.6°C, +2.9 SD). However, colder than normal bottom temperatures have been observed in the southwestern area of the southern GSL during both 2016 and 2017.

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 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 (1991-2017; $R^2 = 0.71$, Figure 9). The annual mean run-off of 2017 was the highest since 1974 (19 200 m^3s^{-1}, +2.1 SD; Figure 8) while the average April-May freshet runoff was highest on record (+3.6 SD, since 1948).Stratification on the Scotian Shelf increased in 2016 after several years of weakening, increasing as a result of warmer, fresher near-surface waters. 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 0.36 kg m^{-3} over 50 years (Figure 9). This change in mean stratification is due mainly to a decrease in the surface density (76% of the total density difference change), composed of equally of warming and freshening. The average St. Lawrence River runoff for April-May, representing the bulk of the spring freshet, was highest of the time series (+3.6 SD, since 1948). Stratification was correspondingly above normal at Rimouski station, but not record breaking (Figure 10).

Conditions at AZMP High Frequency Sampling Stations

The seasonal average 0-50 m temperature has been normal or above normal at all stations since 2010, except at Shediac Valley in 2017 where it was below normal (Figure 10). Stratification was high at all high-frequency sites except Halifax 2, including the 4th highest value of the time series at Prince 5 (+2.7 SD; time series beginning in 1924). In the Estuary and Gulf of St. Lawrence (+1.4 SD at Rimouski station and +1.6 SD at Shediac Valley), this was attributed to the highest April-May freshet on record (since 1948). The monthly stratification was second highest of its time series at Rimouski Station in May and highest at Shediac Valley in June. At Rimouski station, the last 3 year period 2015-17 had the 3 warmest bottom temperature averages of the time series.

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 that over the Scotian Slope (Figure 8). 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 Labrador Current transport index was positively and negatively correlated with the winter NAO index over the Labrador and northeastern Newfoundland Slope and over the Scotian Slope, respectively. In 2017, the annual mean transport was above normal over the Labrador and northeastern Newfoundland Slope (+1.2 SD) and below normal (-0.9 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 2010-17 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 period of 2010-17 with some near normal temperatures in the later half, 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, a 33-year record in 3Ps as well as a 100-year record in the northern Gulf of St. Lawrence.

Figure 11 shows three annual composite index time series constructed as the sum of anomalies shown earlier, representing the state of different components of the system, with each time series contribution shown as stacked bars. 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). The plots also give a sense of the degree of coherence between the various metrics of the environmental conditions and different regions across the zone. Conditions in 2017 were above normal for surface and bottom temperatures, and near normal for Cold Intermediate Layer and sea-ice anomalies. A total of 45 indices listed in Figures 8 and 11 describe ocean conditions related to temperature within the AZMP area (SST; ice; summer CIL areas, volumes, and minimum temperature; bottom temperature; 0–50 m average temperature). Of these, 8 were colder than normal, 16 were within normal values and 21 were above normal, indicating a continuation but weakening of warmer than normal oceanographic conditions in 2017 across much of the Atlantic Zone.

Biogeochemical Environment

Lower trophic levels are the components of marine food webs that channel the sun’s energy to 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) (Pepin et al. 2018), Gulf of St. Lawrence (GSL) (Devine et al. 2017) and Scotian Shelf (SS) (Johnson et al. 2018) are summarized as time series (1999–2017) of annual values in matrix form in Figures 12-15.

Previous reports used the 1999-2010 reference period for biogeochemical parameters. Considering the non-stationary state of the Atlantic system, extending the climatology to include 1999 to 2015 changes the mean against which observations are compared, which can shift the sign or magnitude of anomalies. Thus, anomaly patterns will not be consistent with past reports. While this issue must be kept in mind, the advantage of the extended reference period is to provide more relevant depictions of current system conditions and trends.

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 has been a distinct shift 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, the 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) were below normal throughout much of the Atlantic zone in 2017 (Figure 12). Large reductions in inventories were observed throughout the Scotian Shelf with levels reaching 3 SD below normal. Conditions were mixed in the Gulf of St. Lawrence with reductions up to 1.5 SD across some sections while near normal at other sites. Inventories across the Newfoundland Shelf were mostly below normal but have showed signs of recovery from the record lows detected in 2013 throughout much of the region.

Phytoplankton

Chlorophyll inventories in the upper ocean (between 0-100 m) represent phytoplankton biomass. It demonstrated a high degree of year-to-year variability including exceptional values either above or below the long term average (Figure 12). 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 were below normal on the Grand Bank and eastern Scotian Shelf in contrast to positive anomalies throughout the Gulf of St. Lawrence and near normal on the western Scotian Shelf. Exceptional biomass levels were observed in the southern Gulf with inventories approaching 3 SD above normal in 2017. 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 that 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 (amplitude, 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 (i.e., time of onset, integrated magnitude and duration) 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 13). The onset of the spring phytoplankton bloom was delayed on the Newfoundland Shelf and earlier than normal in the Gulf of St. Lawrence and variable on the Scotian Shelf. The magnitude of the bloom was generally below normal, except in the Northwest Gulf of St. Lawrence where a record high value was observed. Bloom duration was variable, with no coherent spatial pattern. Bloom duration was highly variable, with long blooms on the Newfoundland Shelf, Northwester Gulf of St. Lawrence, Western Bank and Central scotia Shelf, and near average in the reminder of the 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 region, 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, characterized by lower abundance of the large energy-rich copepod *Calanus finmarchicus*, higher abundance of small and warm water copepods, and higher abundance of non-copepods, persisted in 2017 although the intensity declined relative to 2016 (Figure 14). The abundance of *C. finmarchicus* was lower than average overall, with record low abundances at the Rimouski station and on the Browns Bank section. However, higher than average abundances were also observed on the southern Grand Banks, in the eastern Gulf of St. Lawrence, and on the Halifax section. In 2017, *Pseudocalanus* sp. abundance declined to near-average overall across zone, with strong spatial differences between the Newfoundland and Labrador shelf, where they were more abundant than average, including record highs on the southern Grand Banks and in the eastern Gulf of St. Lawrence, and elsewhere, where they were mainly less abundant than average. Total copepod abundances were near average overall, and non-copepods, which are mostly larval stages of benthic invertebrates, carnivorous groups that feed on other zooplankton, and small-particle feeders, were above average. However, both groups showed regional differences in anomaly patterns, with higher than average abundances on the Newfoundland and Labrador shelf and eastern Gulf of St. Lawrence and at the western end of the zone, while anomalies were mainly negative in the Gulf of St. Lawrence and eastern-central Scotian Shelf. There were record high abundances of copepods on the southern Grand Banks and in the eastern Gulf of St. Lawrence and a record low at the Shediac Valley, and there were record high abundances of non-copepods on the Bonavista and Browns Bank section.

Zooplankton biomass has also been lower than average since 2015, particularly on the Newfoundland and Labrador shelf and in the Gulf of St. Lawrence, where six record low values were seen in the period 2015-17 (Figure 15). Overall, recent changes in zooplankton community structure 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.

Labrador Sea Environment

The Atlantic Zone Off-Shelf Monitoring Program (AZOMP) provides observations of variability in the ocean climate and plankton affecting regional climate and ecosystems off Atlantic Canada and the global climate system. This year posed a challenge because it was not possible to carry out a regular field campaign in the Labrador Sea, which has been conducted annually since 1990. Fortunately, the network of profiling Argo floats proved to be instrumental for monitoring year-round variability. However the number of the floats acting in the Labrador Sea in 2017 remained just marginally sufficient for resolving sub-monthly variability.

In the Labrador Sea, surface heat losses in winter result in the formation of dense waters, which drive the global ocean overturning circulation and ventilation of the deep layers. In the winter of 2016-17, as in the previous winter, the mid-high latitude North Atlantic experienced a more moderate cumulative surface (ocean-to-atmosphere) heat loss than in the winter of 2014-15. In the context of longer-term variability, the latter was associated with the highest surface heat loss in more than two decades. Despite weaker heat losses in the following two winters, the water column preconditioning caused by convective mixing in the previous years led nevertheless to the most significant, in terms of volume and depth, formation of Labrador Sea Water (LSW) since 1994. Similarly to 2016, the temperature and salinity profiles obtained by the Argo floats show that the winter mixed layer and hence convection in the central Labrador Sea reached 2000 m in 2017, exceeding the mixed layer depths of 1600 and 1700 m in 2014 and 2015, respectively (Figure 16) . Hence deep-water convection from the previous years had resulted in a kind of preconditioning that favoured this year record deep convection. A reservoir filled with this newly ventilated, cold and fairly fresh LSW is evident in Figure 16. The 2017 vintage of LSW is associated with low temperature (< 3.3°C) and salinity (< 34.86) between 1,000 and 1,700 m. The winter convection in 2015-16 and the one that followed it last year (2016-17) are arguably the deepest since the record-deep penetration of cooling of 2,400 m observed in 1994, and the resulting LSW year class is one of the largest ever observed outside of the early-1990s.

The progressive cooling of the top 2000 m, and deep and intense winter mixing during the four consecutive winters of 2013-14, 2014-15, 2015-16 and 2016-17 have interrupted the general warming and stratification-building trend that has persisted in the intermediate waters of the Labrador Sea since the mid-1990s (Figure 17).

Interannual variability in Labrador Sea ocean heat content and cumulative surface heat loss during the cooling seasons indicates that anomalously strong winter atmospheric cooling associated with the North Atlantic Oscillation is continuing to drive the recurrent convection (Figure 17). In turn, recurrent deep convection is contributing to decadal-scale variability in deep-water properties and transport across and from the subpolar North Atlantic (by the ocean's western boundary and interior pathways) and potentially in the Atlantic Meridional Overturning Circulation.

Both upper, 0-200 m, and deeper, 200-2000 m, layers have been cooling since 2010. However, the freshening trend seen in the newly-formed or newly-ventilated LSW between 2011 and 2016, reversed in 2016, making the LSW formed in the winter of 2017 the densest since the mid-1990s.

The strong winter convection in the winter of 2016-17 further added to increased gas (dissolved oxygen, anthropogenic gases, and carbon dioxide) uptakes and consequently respective gas concentrations in the Labrador Sea in the lower part of the 0-2,000 m layer, but this could not be confirmed from direct ship-based measurements.

Because of the cancellation of the spring research survey, we were not able to update the rate of decline in pH, previously reported as a mean rate of -0.002 y^{-1} 1994 to 2016. It was also not possible to assess the state of *Calanus finmarchicus*, the dominant mesozooplankton in the western and central region of the Labrador Sea, following the record lows reported in 2016. Unusually intense cloud cover in the spring also prevented an assessment of the characteristics of the spring phytoplankton bloom throughout much of the region. However, the occurrence of a fall bloom again this year seems to indicate that this feature is becoming more the norm than the exception.

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 describing 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 2017, they were above normal in fall and winter on the Scotian Shelf and Bay of Fundy, including many record levels (since 1985) in October through December. The NL Shelf however had near normal sea-surface temperatures averaged over the ice-free season. Winter average sea ice extent was near normal on the NL Shelf but was 6th lowest since records began in 1969 in the Gulf of St. Lawrence. Consistent with this, summer cold intermediate layer conditions were mostly near normal on the NL Shelf, except for colder than normal conditions on the Grand Banks (3LNO) in the fall, were normal to warmer than normal in the Gulf of St. Lawrence and on the Scotian Shelf. Thus, a north-to-south gradient was observed again in CIL conditions in 2017, for the fourth consecutive year. Bottom temperatures in the Atlantic Zone ranged from below normal to normal when associated with cold intermediate depths such as on the NL shelf and Magdalen Shallows, to above normal for deeper waters, including a new 100-year high-temperature record for the Gulf at 300 m.

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 central Labrador Sea, the winter mixed layer and convective overturning reached a maximum depth of 2,000 m, arguably the deepest since the record of 2,400 m in 1994, and the resulting Labrador Sea Water year class is one of the largest ever observed outside of the early-1990s. Deep-water convection from the previous years' has resulted in preconditions that favour deep mixing in 2017.

SOURCES OF INFORMATION

This Science Advisory Report is from the Eighteenth Annual Meeting of the Atlantic Zone Monitoring Program (AZMP) held March 20-23, 2018. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

Colbourne, E., J. Holden, S. Snook, G. Han, S Lewis, D. Senciall, W. Bailey, J. Higdon, and , N. Chen. 2017. Physical Oceanographic Conditions on the Newfoundland and Labrador Shelf during 2016. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/079. v + 50 p.

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APPENDIX

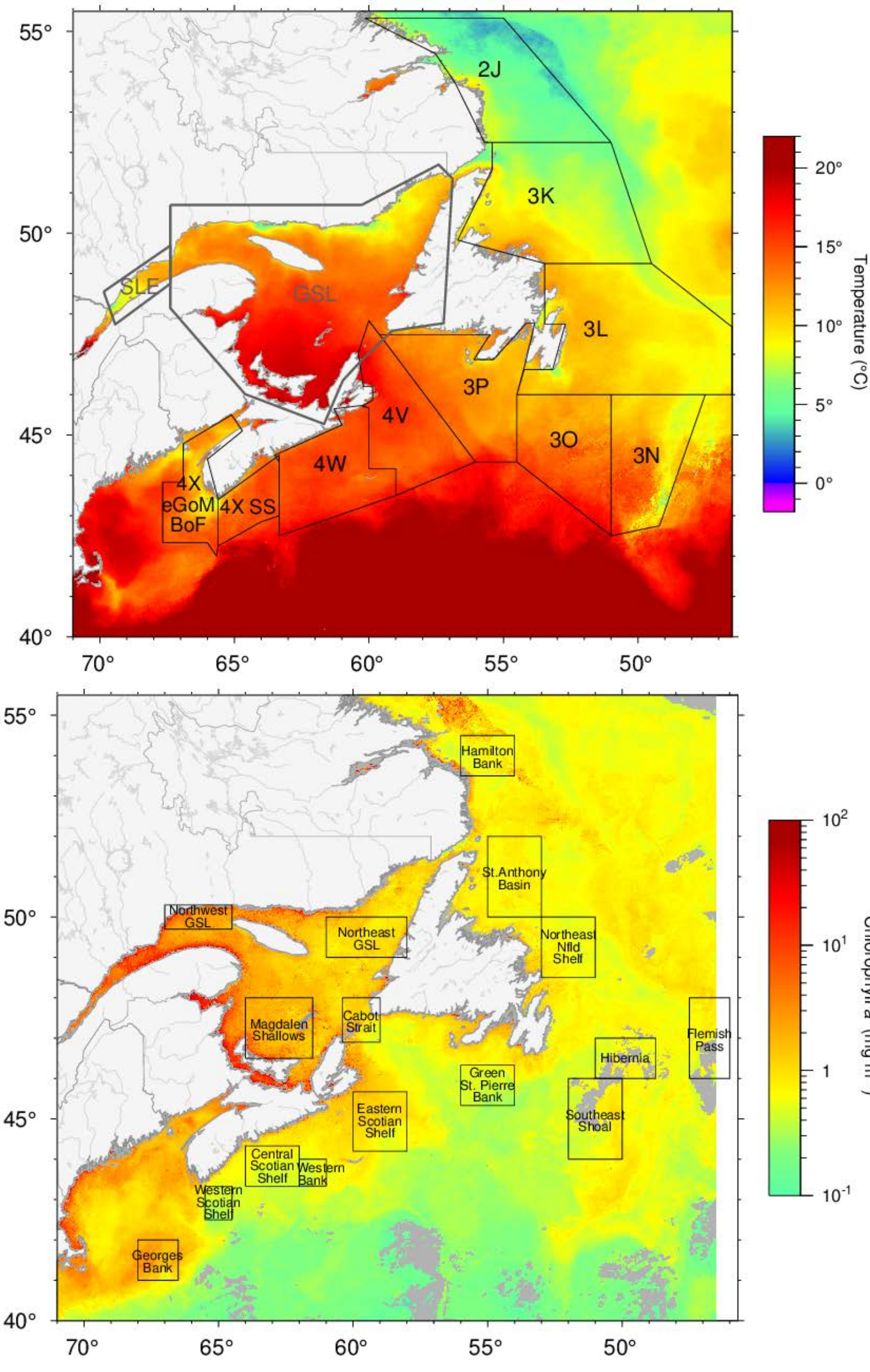

Figure 3. Areas used for (top) temperature and (bottom) ocean color averages. (Top) North Atlantic Fisheries Organization Divisions are cut off at the shelf break. The acronyms GSL and SLE are Gulf of St. Lawrence and St. Lawrence Estuary respectively. Sea-surface temperatures are shown for July 2017 and ocean colour chlorophyll a concentrations are for the second half of July 2017.

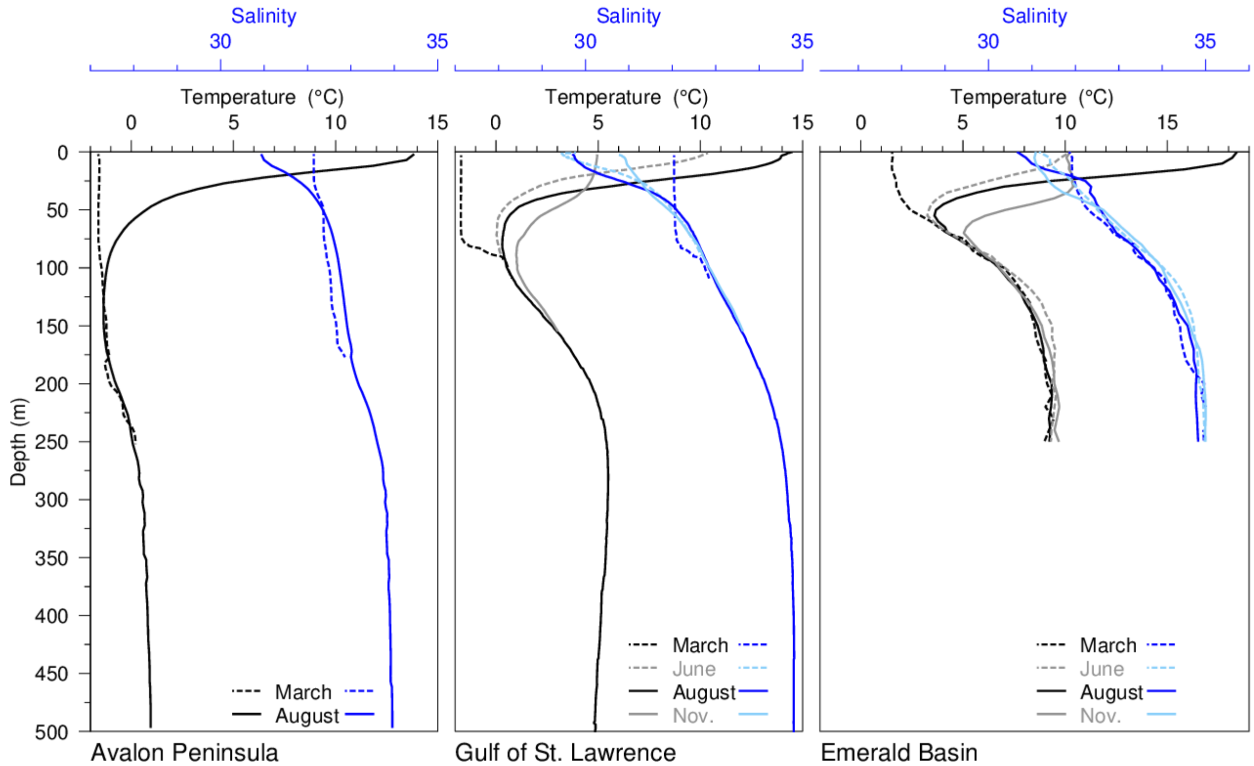

Figure 4. Typical seasonal progression of the depth profile of temperature and salinity observed in three representative regions across the zone. The Avalon Peninsula region is delimited by 45-50°N and 50-55°W and shown are the averages of profiles for March and August between 2015 and 2017, calculated 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.

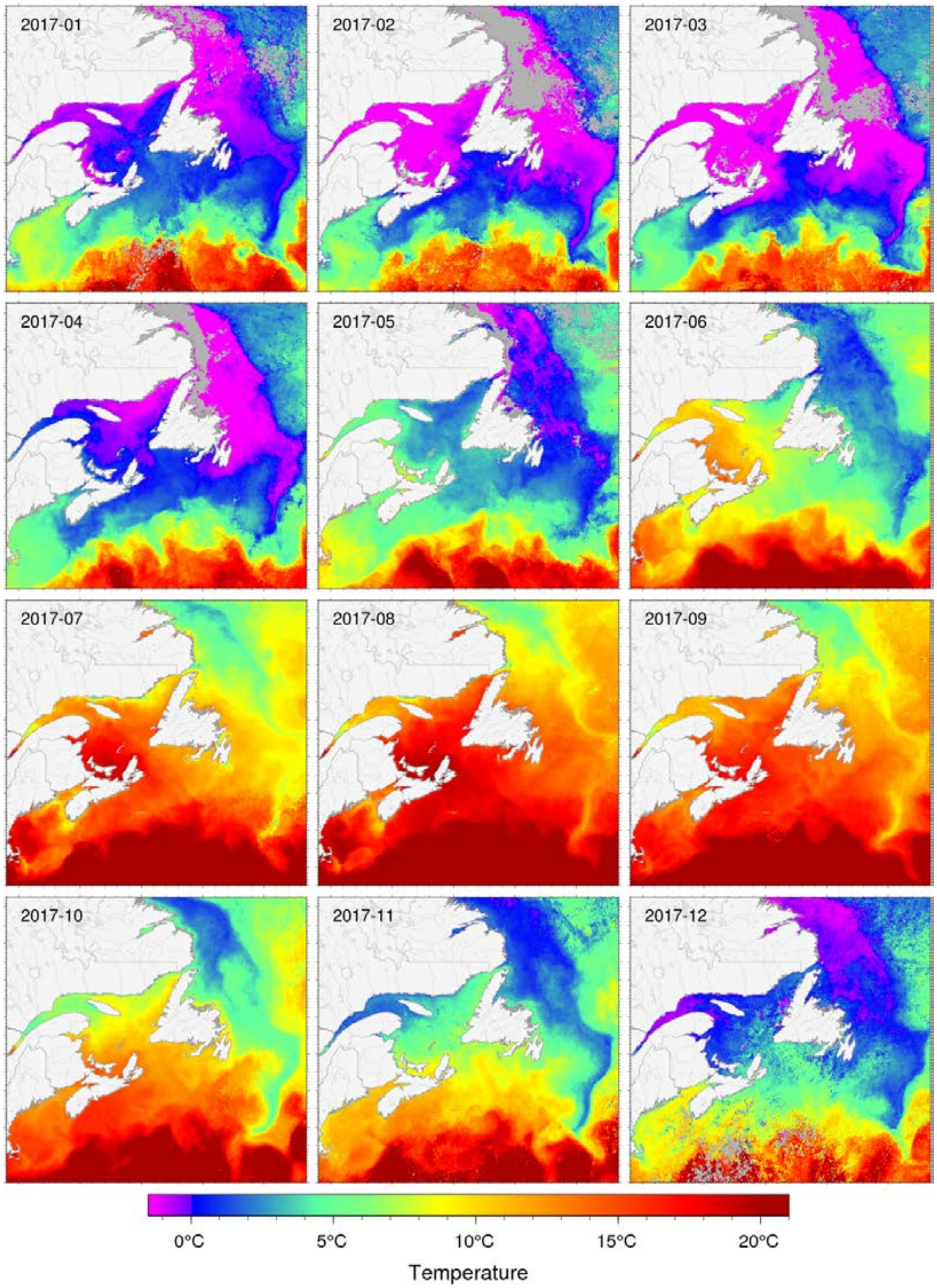

Figure 5. Sea-surface temperature monthly averages for 2017 in the Atlantic zone.

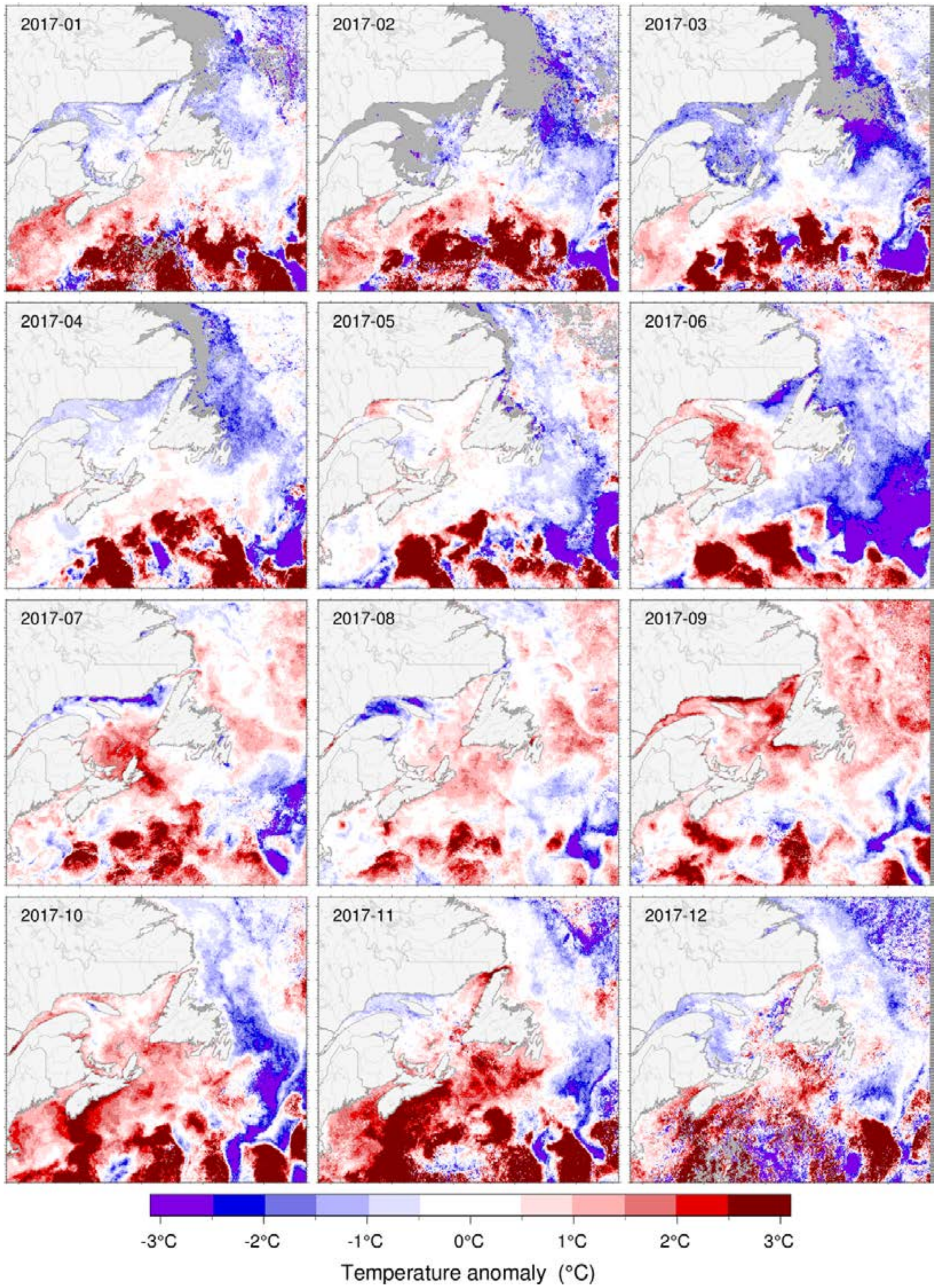

Figure 6. Sea-surface temperature monthly anomalies for 2017 in the Atlantic zone. Temperature anomalies are based on a 1985-2010 climatology.

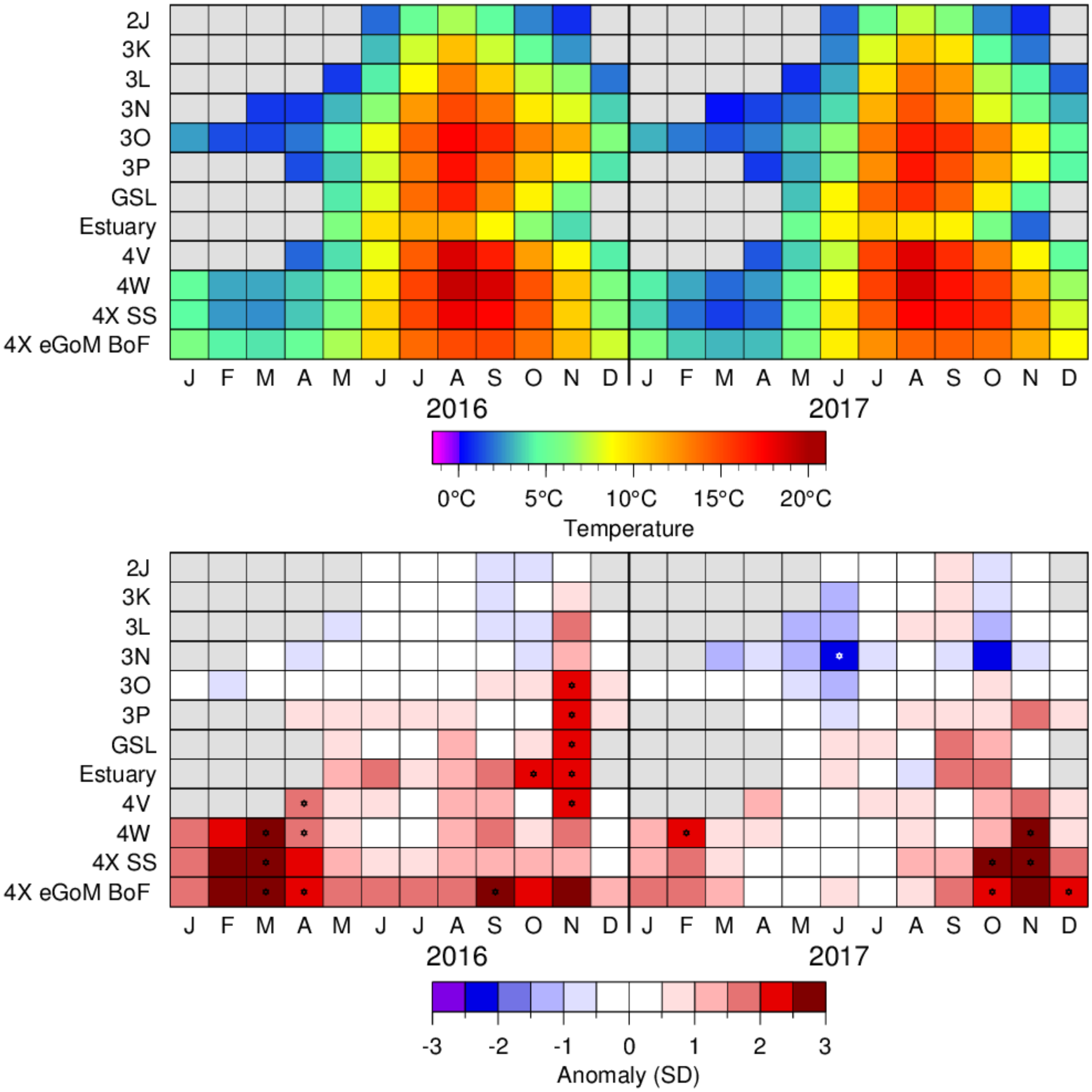

Figure 7. Monthly sea-surface temperature temperatures (top) and anomalies (bottom) for ice-free months of 2016-17, averaged over the 12 regions shown in Figure 3. Regions and months for which the average temperature was at a record high are indicated by a star.

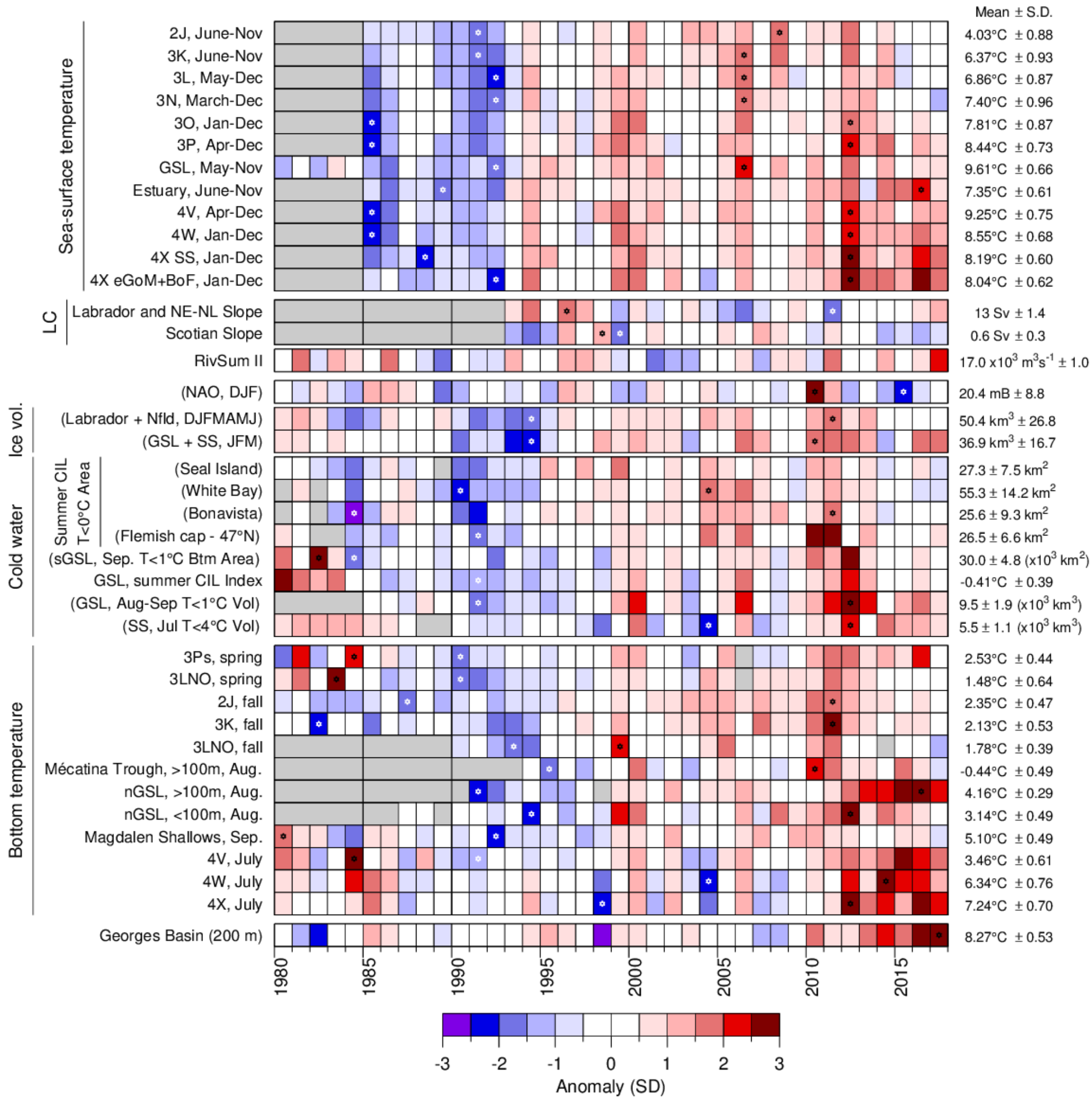

Figure 8. Time series of oceanographic variables, 1980–2017. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1981–2010 when possible; a red cell indicates above normal conditions, and a blue cell below normal. Variables whose names appear 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. Sea-surface temperature for the GSL for 1980-84 is based on an air temperature proxy. (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]).

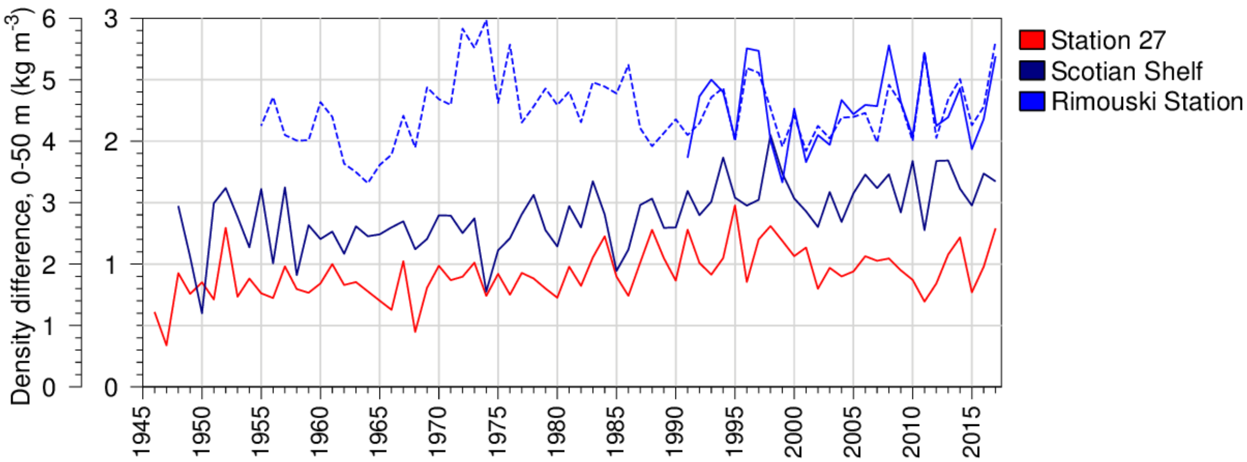

Figure 9. Stratification trends on the southern NL Shelf (at Station 27), Scotian Shelf and St. Lawrence Estuary (Rimouski Station). The dashed line for Rimouski Station is a proxy based on fresh water runoff.

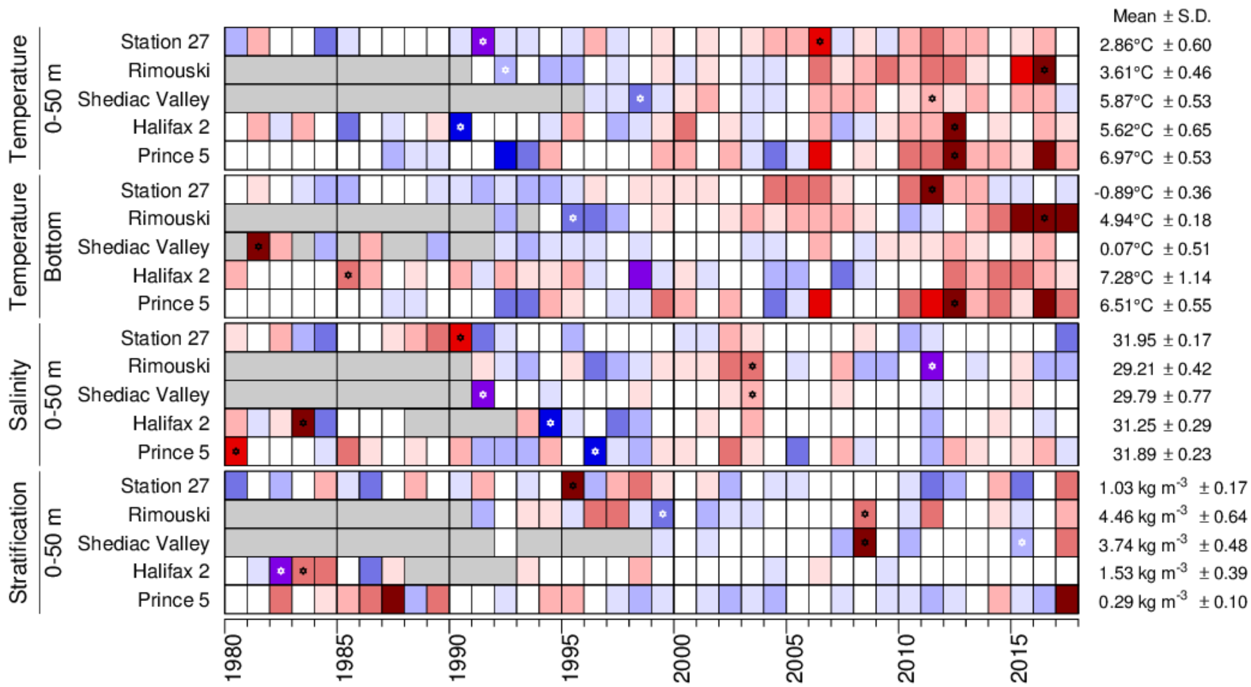

Figure 10. Time series of oceanographic variables at AZMP high-frequency sampling stations, 1980-2017. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1981–2010 when possible; for high-frequency station depth-averaged temperature, a red 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 7 and 8.

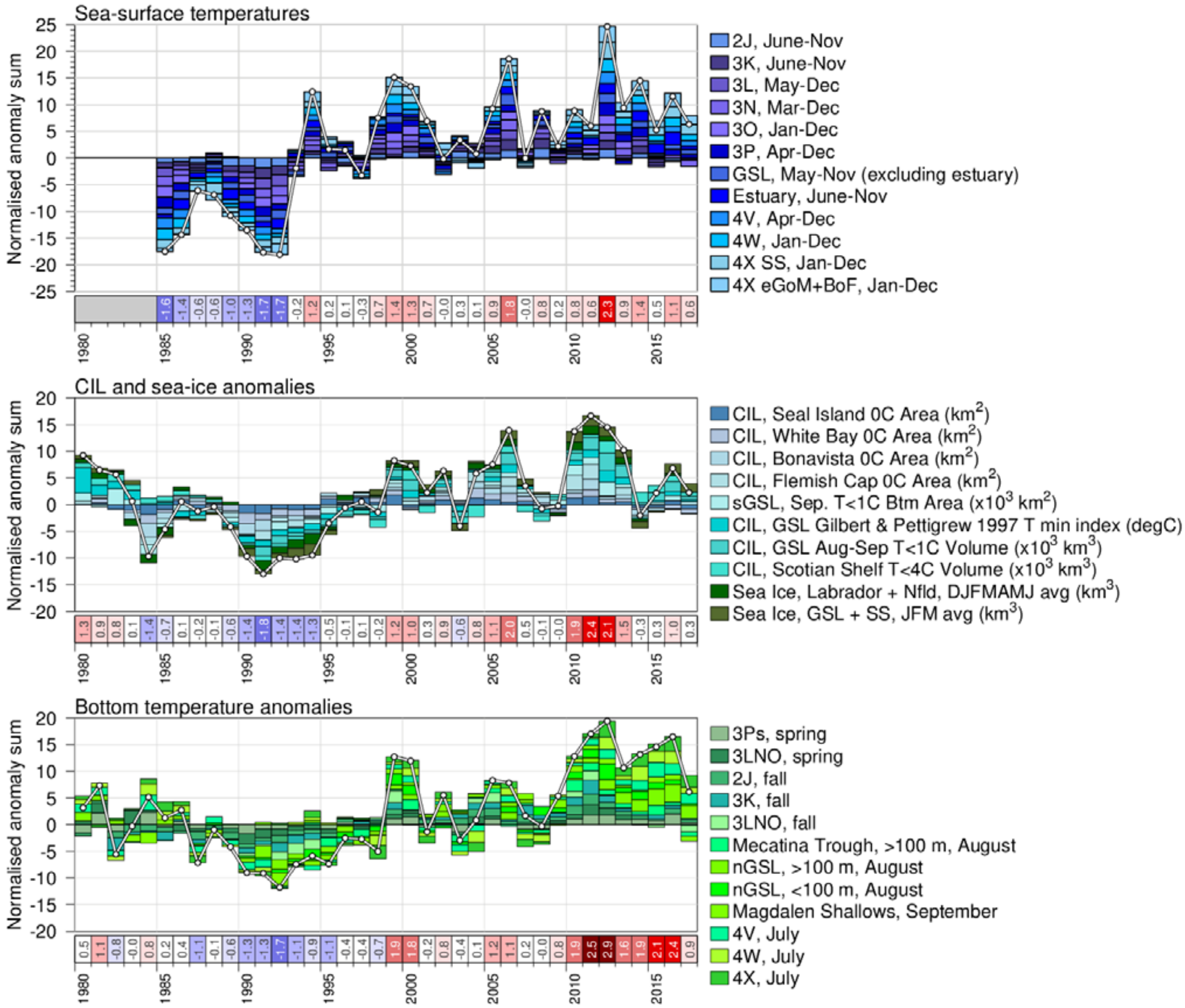

Figure 11. Composite climate indices (white lines and dots) derived by summing various standardized anomalies from different parts of the environment (colored boxes stacked above the abscissa are positive anomalies, and below are negative). Top panel sums sea-surface temperature anomalies, middle panel sums cold intermediate layer and sea-ice anomalies with areas and volumes in reversed scale (positive anomalies are warm conditions) and bottom panel sums bottom temperature anomalies.

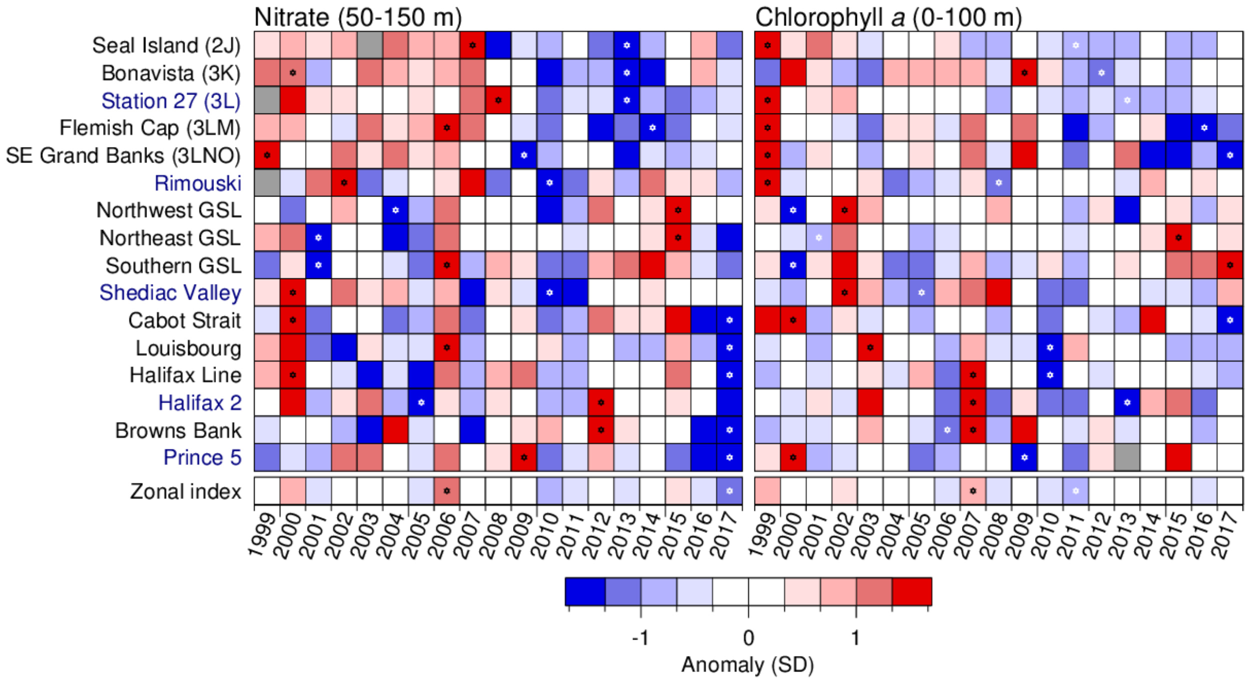

Figure 12. Time series of deep water nitrate inventories (50-150 m) and surface phytoplankton standing stocks (expressed as chlorophyll a 0-100 m mean concentration) at AZMP sections (labelled in red in Figure 2) and high-frequency sampling stations (labelled in blacks in Figure 2), 1999–2017. A grey 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 palette.

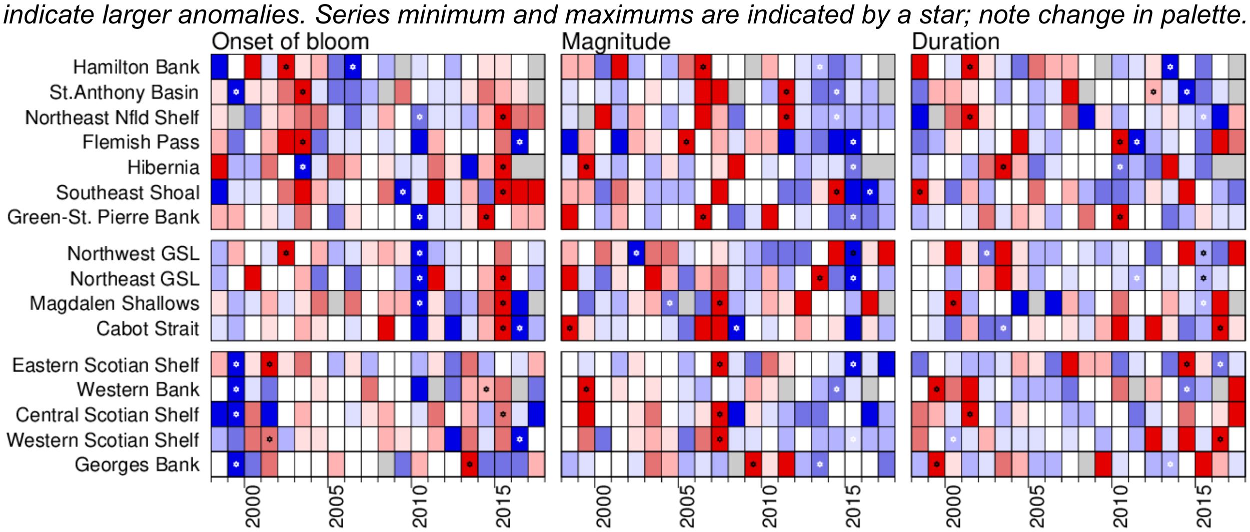

Figure 13. Time series of remotely sensed bloom parameter anomalies in various regions (onset of bloom, magnitude and duration) 1998-2017. Data are from SeaWIFS for the period 1998-2007, from MODIS for 2008-2011, and VIIRS for from 2011 to the present. Series minimum and maximums are indicated by a star. See Figure 3 for area definitions. Palette as in Figure 12.

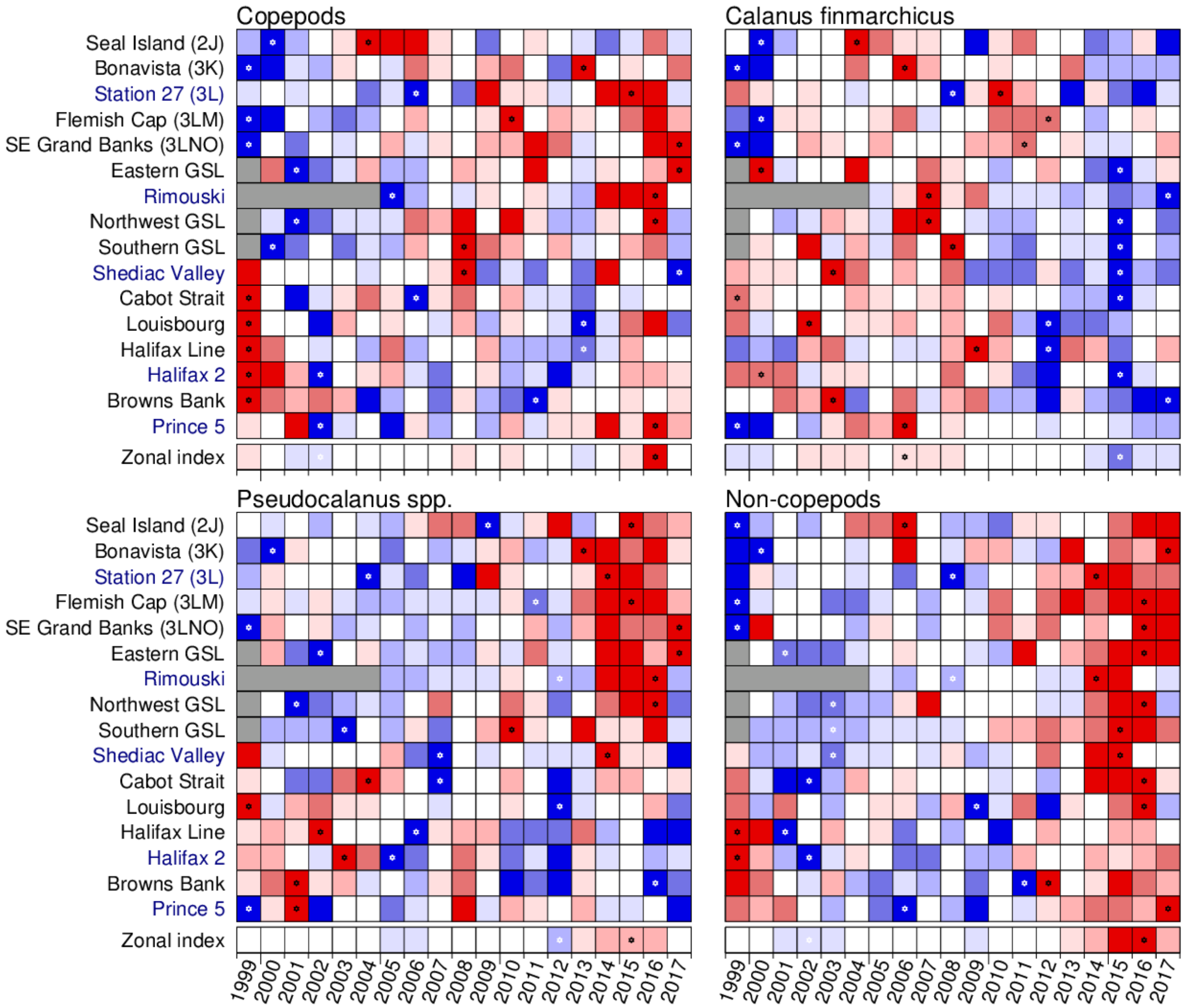

Figure 14. Time series of the standing stocks of total copepods, Calanus finmarchicus, Pseudocalanus spp., and non-copepod zooplankton, 1999–2017. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1999–2015; a red cell indicates above normal inventories, a blue cell below normal. More intense colours indicate larger anomalies. Series minimum and maximums are indicated by a star. Palette as in Figure 12.

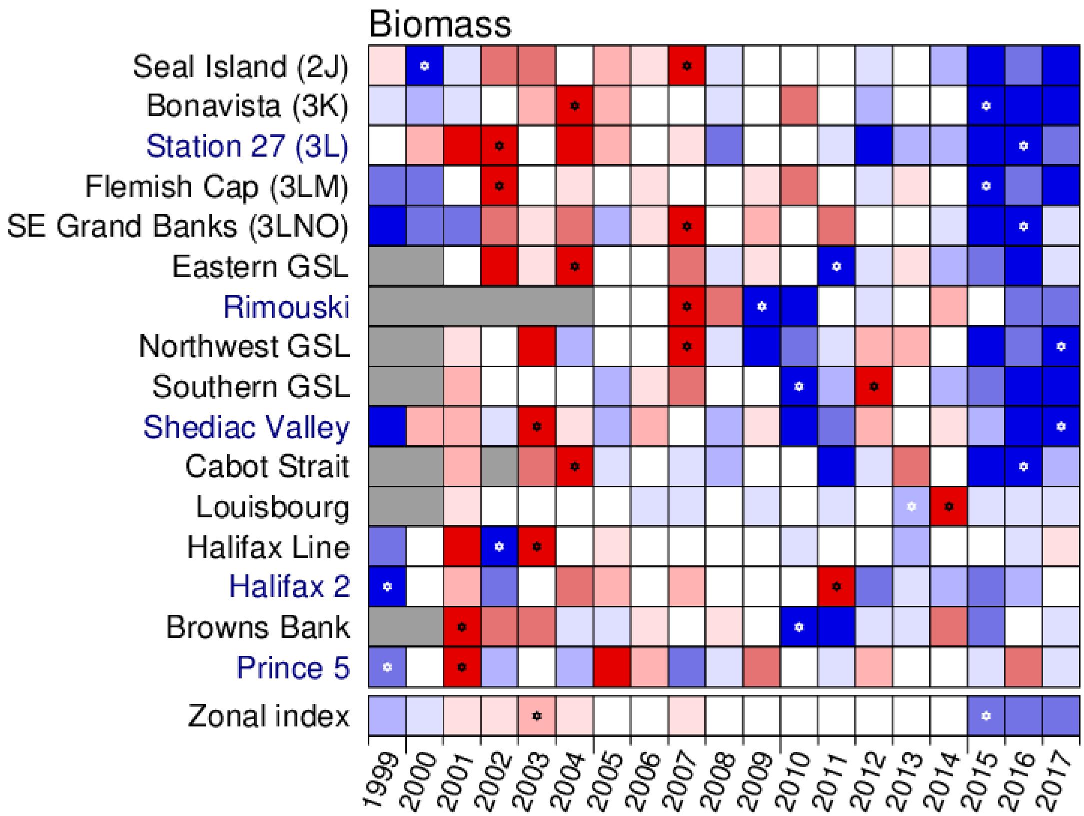

Figure 15. Time series of zooplankton biomass (dry weight), 1999 to 2017. Biomass is measured on the 0.2-10 mm size fraction which is usually dominated by copepods. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1999–2015; a red cell 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. Palette as in Figure 12.

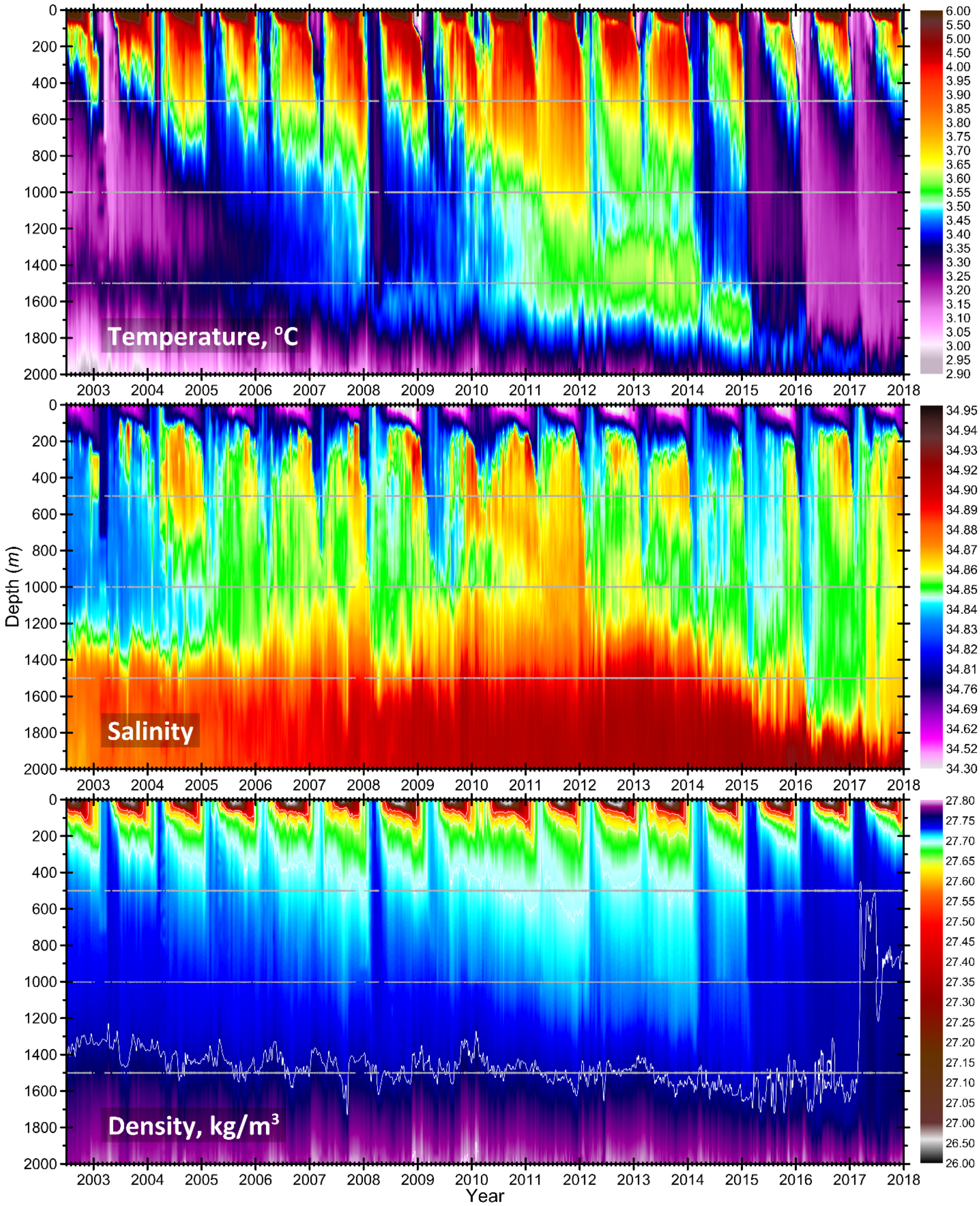

Figure 16. Temperature and salinity in the central Labrador Sea based on the measurements collected by the Argo floats and research vessels during 2002-17.

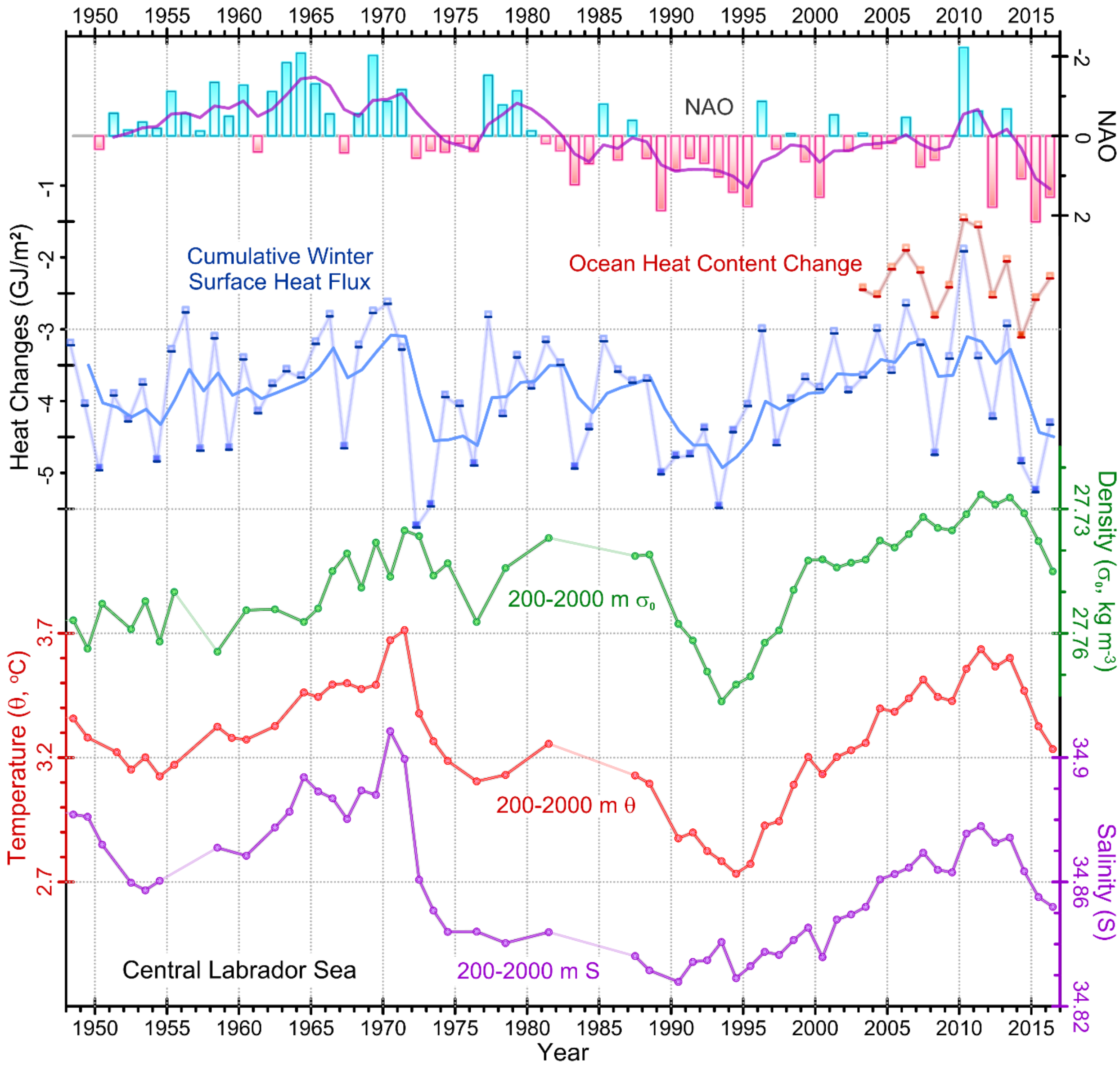

Figure 17. Key climatic indices for the central Labrador Sea since 1948. The upper bar graph shows the normalized winter NAO index (inverted scale). The next two time series represent heat changes in the central Labrador Sea during each yearly cooling season: first, the change in ocean heat content during each ocean cooling season of the Argo era (2003-present; providing all-season data coverage) based on temperature profiles (red), and, second, the change inferred from the cumulative surface heat flux computed from National Centers for Environmental Prediction (blue) and the value a five-point filter (solid line with value plotted at the last year of each period).The lower four curves are estimates of the annual density (σ_0, referenced to the surface; inverted scale), mean temperature (θ) and salinity (S) averaged over the 200–2000 m interval in the central Labrador Sea, and temperature from near-bottom current meter at about/approximately 1000 m depth east of Hamilton Bank.

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