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OCEANOGRAPHIC CONDITIONS IN THE ATLANTIC ZONE IN 2015

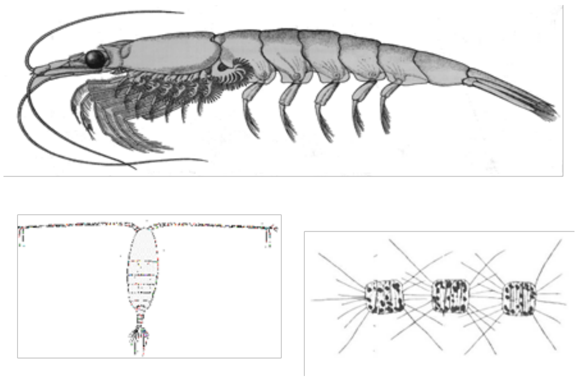

Figure 1. Key taxa of the pelagic food web: euphausids (top), phytoplankton (bottom right), and copepods (bottom left).
Images: Fisheries and Oceans Canada

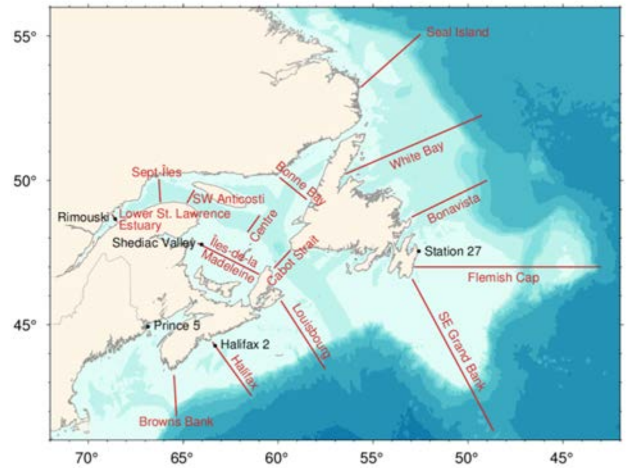

Figure 2. Atlantic Zone Monitoring Program high-frequency sampling stations (black) and selected section lines (red).

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

- Sea surface temperatures were above-normal in January and February in the ice-free southern portion of the zone, generally near-normal until June across the zone, below-normal to normal on the Labrador and Newfoundland shelf for the rest of the year but normal to above-normal elsewhere.
- Following a cold winter and late spring warming, sea surface temperatures increased to a record high in September for the satellite record (since 1985) overall in the Gulf of St. Lawrence. September series records also occurred in the St. Lawrence Estuary and western Scotian Shelf, and near-record in eastern Gulf of Maine and Bay of Fundy. Gulf of St. Lawrence fall sea surface cooling occurred two weeks later than normal. On the

Newfoundland and Labrador Shelf, sea-surface temperatures remained normal to below normal.

- Sea-ice volume was near-normal when averaged over the ice season in the Gulf of St. Lawrence and the Newfoundland and Labrador Shelf, but extent was greater than normal during March and April off eastern Newfoundland and southern Labrador and in the Southern Gulf. The ice season persisted up to five weeks later than normal, affecting the opening of the snow crab and lobster fisheries.
- Spring Cold Intermediate Layer (CIL) area was among the highest on record on the Grand Banks and remained slightly above normal in the summer but by late fall it had eroded to below normal values off eastern Newfoundland and completely eroded off southern Labrador. In the Gulf of St. Lawrence spring CIL volume was not above normal in spite of the cold winter, and was warm and thin by August. On the Scotian Shelf, its volume was the 7^{th} lowest in 42 years.
- Bottom temperatures were generally normal or above normal across the zone, including a near-record on the Scotian Shelf in 4V, and a 100-year record high in the deeper waters of the northern Gulf of St. Lawrence, where the bottom area covered with temperatures > 6°C has reached series records in Anticosti and Esquiman Channels.
- At the high-sampling frequency stations, the 0-50 m average temperature was normal or above-normal. Bottom temperatures were below-normal at Station 27, but above-normal elsewhere. Record temperatures were achieved in both layers at Rimouski station.
- Stratification was below-normal at all high-sampling frequency stations except Halifax 2, and was at a record low at Shediac Valley.
- Deep nitrate inventories on the Newfoundland Shelf remained well below normal in 2015, maintaining a pattern that started in 2008/09, while they remained above normal throughout the Gulf of St. Lawrence, with record highs in the eastern and northern parts of the Gulf. Nitrate inventories increased to above normal concentrations on the Scotian Shelf while they declined to below normal in the Bay of Fundy.
- Chlorophyll *a* inventories remained low in 2015 across the entire Newfoundland Shelf, continuing a pattern that started in 2011. Chlorophyll *a* levels were near or above normal throughout the rest of the Zone, with a record high inventory in the northeastern Gulf of St. Lawrence.
- The onset of the spring phytoplankton bloom was later than normal throughout much of the Zone, likely as a result of a prolonged winter and above normal ice extent, although earlier blooms occurred in the northwest Gulf of St. Lawrence and on Georges Bank.
- Bloom magnitude was well below normal throughout much of the Zone except in the northern portions of the Gulf of St. Lawrence, St. Anthony Basin and Georges Bank.
- The bloom duration was generally shorter than normal throughout most of the Zone; however a record long spring phytoplankton bloom occurred in the northern Gulf of St. Lawrence.
- Abundance of *Calanus finmarchicus* was well below normal across the entire Zone, with the exception of the Flemish Cap Section, reaching record lows in parts of the Gulf of St. Lawrence and Scotian Shelf.

- *Pseudocalanus* sp. copepod abundance was well above normal across the Newfoundland Shelf and the Gulf of St. Lawrence but near or below normal on the Scotian Shelf.
- Copepod abundance demonstrated modest increases from 2014 to 2015, resulting in above average concentrations throughout much of the Zone, with the exception of the eastern and northern parts of the Gulf of St. Lawrence where abundances declined to below normal levels.
- The abundance of non-copepod zooplankton was above normal throughout most of the Zone, reaching record or near record levels throughout much of the Gulf of St. Lawrence. This continues a trend that started around 2010-12.
- The Labrador Current transport index was near normal over the Labrador and northeastern Newfoundland Slope and below normal over the Scotian Slope.
- Temperature and salinity profiles show that winter convective overturning in the central Labrador Sea reached a maximum depth of 1,850 m in 2015 following a maximum of 1,700 m in 2014.
- The 2015 convection is the deepest since the 2,400 m record-deep convection observed in 1994. It produced the largest year class of Labrador Sea Water in the last two decades, containing increased concentrations of atmospheric gases (dissolved oxygen, anthropogenic gases, and carbon dioxide) which spread through the entire water mass (reaching 1,900 m in some places).
- Inter-annual variability in the cumulative surface heat loss and ocean heat content during the cooling seasons indicates that anomalously strong winter atmospheric cooling associated with the North Atlantic Oscillation is continuing to drive the recurrent convection in the Labrador Sea.
- Recurrent deep convection is contributing to decadal-scale variability in deep-water properties and transport across the subpolar North Atlantic and in the Atlantic Meridional Overturning Circulation.
- Anomalous bands of high phytoplankton abundance were observed in the eastern half of the Labrador Sea in 2015, and appeared to be aligned with horizontal gradients in seawater density across the AR7W line.

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 1999-2010 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 when possible. 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 designed 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 Environment

This is a summary of physical oceanographic conditions during 2015 for eastern Canadian oceanic waters (Figure 2) as reported annually by the AZMP in three reports (e.g. Colbourne et al. 2015, Galbraith et al. 2015 and Hebert et al. 2015 for conditions of 2014).

Air temperatures were mostly below normal across the zone in winter to early-summer, transitioned to above-normal by August in the Gulf of St. Lawrence and Scotian Shelf, where they remained above normal in the fall. Averaged over 13 meteorological stations in the Gulf of St. Lawrence, August had the second warmest air temperatures on record (since 1873, + 2.1°C, + 2.8 SD). Series record highs were set for that month at Natashquan (since 1915, + 2.9°C, + 2.9 SD), Baie-Comeau (since 1965, + 2.5°C, + 2.6 SD), and Charlottetown (since 1873, + 2.7°C, + 2.9 SD). On the Scotian Shelf, Yarmouth also had record temperatures in August (since 1879, + 2.1°C, + 2.7 SD), remaining high in September (+ 2.5°C, + 2.6 SD). In Newfoundland at St. John's, July had the coldest air temperature since 1962 (- 3.9°C, - 2.5 SD). Annual mean air temperatures were below normal at Cartwright and St. John's by - 1.6°C (- 1.2 SD) and - 0.6°C (- 0.7 SD), respectively.

Sea surface temperatures (SST) were above-normal in January and February in the ice-free southern portion of the zone, generally near-normal until June across the zone, below-normal to normal on the Labrador and Newfoundland shelf for the rest of the year but normal to above-normal elsewhere (Figures 3 to 6). Following a cold winter and spring in the Gulf of St. Lawrence, sea surface temperatures increased to a record high in September for the satellite record (since 1985, + 1.8°C, + 2.3 SD). September series records also occurred in the St. Lawrence Estuary (+ 1.9°C, + 2.3 SD) and western Scotian Shelf (+ 2.6°C, + 2.4 SD). Temperatures were also near-record in eastern Gulf of Maine and Bay of Fundy (+ 1.8°C, + 2.6 SD). Fall sea surface cooling occurred 2 weeks later than normal (+ 1.5 SD) in the Gulf of St. Lawrence. SST conditions remained near-normal to below normal in Newfoundland and Labrador waters.

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 into the St. Lawrence Estuary decreased between the early 1970s and 2001, and shows signs of increase thereafter. However the annual mean run-off of 2015 is normal (+ 0.0 SD; Figure 7) and the 2015 spring freshet was below normal (-1.1 SD).

The North Atlantic Oscillation (NAO) index 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. The tendency of the ocean currents to move from north to south eventually spreads the NAO's influence into the Gulf of St. Lawrence and onto the Scotian Shelf. In 2015, the winter NAO index was the largest value in the 120 year record (+ 2.0 SD), consistent with the low winter air temperatures on the NL Shelf and Gulf of St. Lawrence, higher-than-normal sea ice extent during March and April off eastern Newfoundland and southern Labrador, and cold intermediate layer (CIL) springtime volume at its highest level since 1985 on the Grand Bank. However, sea-ice volume was still near-normal when averaged over the season and the CIL was near-normal by summer.

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. In 2015, seasonally-averaged sea ice volume returned to near-normal conditions both on the NL Shelf (+ 0.0 SD) and in the Gulf of St. Lawrence since (+ 0.2 SD, Figure 7), but extent was greater than normal during March and April off eastern Newfoundland and southern Labrador and in the Southern Gulf. The ice season persisted up to 5 weeks later than normal, affecting the opening of the snow crab and lobster fisheries. The above-normal (+ 1.3 SD) volume of sea-ice exported to the Scotian Shelf was the largest value since 2003.

A number of indices derived from oceanographic sections and ecosystem surveys characterize the variability of cold water volumes, areas, and bottom temperatures in the AZMP area (Figure 7). For the latest 30 year period, the highest similarities are found between cold water indices from the southern Labrador and NE Newfoundland Shelf and the northern Grand Bank, followed by similarities between the Gulf of Lawrence and the Scotian Shelf. Spring CIL area was among the highest on record on the Grand Banks, was near normal in the summer and by late fall it had eroded to below normal values off eastern Newfoundland and completely eroded off southern Labrador. Similarly, the Gulf of St. Lawrence CIL was near-normal when averaged over the season, but thinner than normal by August (- 1.5 SD). This was in spite of a colder-than-normal winter. The Scotian Shelf CIL volume (T < 4°C) was seventh lowest of the 42-year time series (- 1.3 SD). Thus a north-to-south gradient was observed again in CIL conditions in 2015.

Bottom temperatures were again normal or above-normal across the zone, reaching record highs in the northern Gulf at depths over 100 m as well as in Division 4V of the Scotian Shelf (Figure 7). This is associated with 100-year high-temperature records for the Gulf at depths ranging from 150 m to 300 m, but represents a decrease on the NL Shelf in Divisions 3LNO and 3K from the record highs recorded in 2011. The series record high recorded in the northern Gulf (bottom temperature average for depths greater than 100 m, +3.1 SD) 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, 2014 and again in 2015 (indicating that the average temperature of the deep waters of the Gulf should continue to increase in the next two or three years). The bottom area covered with temperatures > 6°C has reached a series record in both Anticosti and Esquiman Channels.

Figure 8 shows three annual composite index time series constructed as the sum of anomalies from Figure 7, 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 2015 were near-normal for surface temperature and CIL conditions, and above-normal (+ 2.0 SD) for bottom water temperatures. While the bottom temperatures were third highest of the time series overall, they were lowest since the 1990s in many areas of the Newfoundland Shelf.

In 2015, annually averaged 0-50 m temperatures at high-frequency sampling stations were near-normal at Halifax 2 and above-normal at other stations (Figure 9). Bottom temperatures were below normal at Station 27 and above-normal at other stations. Record temperatures were achieved in both layers at Rimouski station. The annual 0–50 m salinity anomalies were near-normal at Station 27 and Halifax 2 and above-normal at other stations. The annual 0–50 m stratification index was near-normal at Halifax 2 and below-normal at other stations, reaching a record low at Shediac Valley. Stratification on the Scotian Shelf continued to weaken in 2015 compared to 2013 due to cooler 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. This change in mean stratification is due mainly to a decrease in the surface density (84% of the total density change), composed of two-thirds warming and one-third freshening.

A total of 44 indices listed in Figures 7 and 9 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, three were colder than normal, 18 were within normal values and 23 were above normal, indicating a continuation of warmer than normal oceanographic conditions in 2015 across much of the Atlantic Zone.

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 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 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 the past four years the Labrador Current was close to its normal strength. In 2015 its annual-mean transport was near normal over the Labrador and northeastern Newfoundland Slope and below normal by 0.7 SD over the Scotian Slope.

Biogeochemical Environment

Phytoplankton are microscopic plants that form the base of the aquatic food web, occupying a position similar to that of plants on land. There is a wide variation in the size of phytoplankton, ranging from the largest species, members of a group called diatoms, to smaller species, including members of a group called flagellates. Phytoplankton use light to produce organic matter from carbon dioxide and nutrients dissolved in marine waters. The growth rate at which new organic matter is produced depends partly on temperature and the abundance of light and nutrients. Phytoplankton constitute the primary food source of the animal component of the plankton, zooplankton. In continental shelf waters, the nutrient nitrate is usually the limiting element for phytoplankton growth in surface waters where sufficient light is available. Nitrate from subsurface waters is mixed to the surface in winter, and it is depleted in surface water during the spring phytoplankton bloom. In most marine waters, phytoplankton cells undergo a spring-summer explosion in abundance called a bloom, and some areas also have a weaker bloom in the fall in association with breakdown in stratification of the water column. The dominant zooplankton in the oceans are copepods. They represent the critical link between phytoplankton and larger organisms like fish. Young copepods (nauplii) are the principal prey of young fish while the older stages (copepodites) are eaten by larger fish, predominantly juveniles and adults of pelagic species such as capelin, sandlance and herring.

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. 2015), Gulf of St. Lawrence (GSL) (Devine et al. 2015) and Scotian Shelf (SS) (Johnson et al. 2016) are summarized as time series (1999–2015) of annual values in matrix form in Figures 10-12.

In contrast to the physical oceanographic data available to AZMP, 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. The average maximum absolute change from year-to-year across all sections and high frequency sampling sites is approximately 3.5 SD for nutrients and phytoplankton but 5.5 SD for zooplankton. Maximum variation in year-to-year changes in zooplankton abundance has increased from 3.7 SD in 1999-2010 to 5.5 SD in 1999-2015 indicating that more extreme changes in the abundance of this trophic level are being detected as the length of the observation period is extended. 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.

Deep nutrient inventories (50-150 m) on the Newfoundland Shelf remained well below normal in 2015, maintaining a pattern that started in 2008/09 (Figure 10). In contrast, deep inventories in the Gulf of St. Lawrence remained above normal, with record highs in the eastern and northern parts of the Gulf (Figure 10). Nitrate inventories increased to above normal concentrations on the Scotian Shelf, while they declined to below normal in the Bay of Fundy.

Chlorophyll inventories (0-100 m; Figure 10), a proxy for phytoplankton biomass, demonstrated a high degree of year-to-year variability including exceptional values either above or below the long term average. There has been limited consistency in the pattern of variation in chlorophyll across the entire Atlantic Zone until very recently. Chlorophyll inventories remained low in 2015 across the entire Newfoundland Shelf, continuing a pattern that started in 2011 (Figure 10). Chlorophyll levels were near or above normal throughout the rest of the Zone, with a record high inventory in the eastern Gulf of St. Lawrence. Because of the reliance of phytoplankton on nutrient availability, it is tempting to link patterns of variation in the two variables but the outcome of such a comparison across the entire Atlantic Zone indicates that there is no significant association between inventories of nitrate and phytoplankton at the annual scale. This does not imply that local variations in the seasonal production cycle are not linked to nutrient availability but rather that many 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.

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] 1998-2008; Moderate Resolution Imaging Spectroradiometer [MODIS] 2009-present) (Figure 11). The onset of the spring phytoplankton bloom was later than normal throughout much of the Zone in 2015, likely as a result of a prolonged winter and above normal ice extent. Earlier blooms occurred in the northwest Gulf of St. Lawrence and on Georges Bank. Bloom magnitude was well below normal throughout much of the Zone except in the northern portions of the Gulf of St. Lawrence, St. Anthony Basin and Georges Bank. The bloom was generally shorter than normal throughout most of the Zone; however a record long spring phytoplankton bloom occurred in the northern Gulf of St. Lawrence.

Zooplankton indices of abundance tended to demonstrate a greater degree of temporal consistency within regions than was apparent for chlorophyll. Populations of mesozooplankton (0.2-20 mm in size) sampled by the AZMP in one region potentially have a high degree of connectivity with adjacent areas because these organisms are greatly influenced by the effects of ocean currents. In 2015, zooplankton abundance indices demonstrated relatively large scale coherence (Figure 12). Copepod abundance demonstrated modest increases from 2014 to 2015, resulting in above average concentrations throughout much of the Zone, with the exception of the eastern and northern parts of the Gulf of St. Lawrence where abundances declined to below normal levels. The abundance of *Calanus finmarchicus* was well below normal across the entire Zone, with the exception of the Flemish Cap Section, and *C. finmarchicus* abundance reached record lows in parts of the Gulf of St. Lawrence and Scotian Shelf. The abundance of *C. finmarchicus* has been below normal for approximately 6 years on the Scotian Shelf and in the Gulf of St. Lawrence whereas abundance has been declining more or less steadily on the Newfoundland Shelf and Grand Banks over the same period. The abundance of *Pseudocalanus* spp*.,* an important prey for many species of young fish, was well above normal across the Newfoundland Shelf and the Gulf of St. Lawrence but near or below normal on the Scotian Shelf.

Non-copepod zooplankton consists principally of the larval stages of benthic invertebrates and many of the carnivores that feed on other zooplankton. In 2015, this group was above normal throughout most of the Zone, reaching record or near record levels throughout much of the Gulf of St. Lawrence. This continues a trend that started around 2010-12. A variety of taxonomic groups contributed to the increase in non-copepod abundance, for example pelagic gastropods on the Scotian Shelf, and tunicates, bivalves and polychaetes larvae, ostracods and cladocerans in the Gulf of St. Lawrence. Non-copepod zooplankton have shown a general trend toward increased abundance off Newfoundland and in the Gulf of St. Lawrence over the last 6 years whereas abundance anomalies on the Scotian Shelf have seen mainly positive since 2012.

Sub-dominant and uncommon zooplankton species associated with particular habitats or life-history patterns can serve as indicators of changes in the environmental and ecosystem. Examples of these indicator species include sub-tropical and cosmopolitan off-shelf copepods, cold water/arctic copepods, warm water/summer-fall shelf copepods, and deep-water copepods. In 2015 in the Gulf of St. Lawrence the abundance of summer-fall shelf copepods (*Centropages* spp. and *Paracalanus* sp.) and warm-associated deep copepods (*Metridia lucens*) were both above normal, probably reflecting the very warm conditions observed in the surface and deep water layers in the region. Conversely, cold water/arctic copepods such as *Calanus glacialis* and *Metridia longa* were generally less abundant than normal in the region in 2015. On the Scotian Shelf in 2015, the abundances of cosmopolitan (*Oithona atlantica*) and subtropical off-shelf copepods and warm water/summer-fall copepods (*Centropages* spp., *Paracalanus* sp., and *Temora longicornis*) were higher than normal, while cold water/arctic copepod abundance was lower than normal. The higher abundances of offshelf species on the Scotian Shelf suggests that shifts in the zooplankton community reflect changes in onshelf transport, in addition to local changes in ocean conditions.

The patterns of variation of copepods and non-copepods demonstrate a statistically significant association that accounts for about 25% ($r = 0.49$) of the variation. Until 2011, the patterns of variations of these two groups followed a regional progression in anomalies that originated in the northernmost reaches of the Atlantic Zone, starting at the Seal Island section off Labrador (see negative anomaly in the upper left corner of Figure 12), and moved across Newfoundland and into the upper reaches of the Gulf of St. Lawrence after which the anomalies appear to have progressed into the southern Gulf and onto the Scotian Shelf (Figure 13). Although there is considerable variability around the general trend, normal or positive anomalies have persisted throughout much of the Newfoundland and Gulf of St. Lawrence regions after low abundance levels in 1999–2001 and 1999–2004 respectively. Conditions on the Scotian Shelf have contrasted those of the Newfoundland Shelf, with high zooplankton abundance levels during 1999–2001 and generally below average until 2013 when abundances appear to be close to the 1999-2010 average.

Labrador Sea Environment

The Atlantic Zone Off-Shelf Monitoring Program provides observations of variability in the ocean climate and plankton affecting regional climate and ecosystems off Atlantic Canada and the global climate system. 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 2014-15, the mid-high latitude North Atlantic experienced the most extreme heat loss in the region since 1979; this was primarily forced by strong westerly and northerly winds. This heat loss from the ocean to the atmosphere led to the most significant formation, in terms of volume, of Labrador Sea Water (LSW) since 1994. Temperature and salinity profiles show that winter mixed layer, and hence convective overturning in the central Labrador Sea, reached a maximum depth exceeding 1800 m in 2015 following a maximum of 1,700 m in 2014 (Figure 14). The 2015 vintage of LSW is associated with low temperature (< 3.3°C) and salinity (< 34.85) below 1,000 m. The winter convection of this year is arguably the deepest since the record of 2,400 m in 1994, and the resulting LSW year class is one of the largest ever observed outside of the early 1990s. A reservoir filled with this newly ventilated, cold and fairly fresh LSW, evident in Figure 14, is also rich in carbon dioxide and other dissolved gases, suggesting that the strong winter convection in 2014-15 led to increased gas (dissolved oxygen, anthropogenic gases, and carbon dioxide) uptakes in the Labrador Sea that spread to and even below 1,800 m.

In a similar manner to the last significant renewal of LSW (winter 2007-08), the deep and intense winter mixing of two consecutive winters of 2013-14 and 2014-15 has interrupted the general warming trend that has persisted in the intermediate waters of the Labrador Sea since the mid-1990s.

Inter-annual 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 NAO is continuing to drive the recurrent convection. 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.

The extreme atmospheric and physical ocean processes in the winter and spring of 2014-15 also had profound impacts on the biological properties of the Labrador Sea. In particular, anomalous bands of high phytoplankton abundance were observed in the eastern half of the Labrador Sea in 2015, and appeared to be aligned with horizontal gradients in seawater density across the AR7W line.

A biweekly climatology of chlorophyll *a* constructed from a time series of remotely-sensed ocean colour from 2003 to 2015 indicates that the annual spring bloom of phytoplankton generally starts and ends earlier on the Labrador and Greenland Shelves (mid-April to early June) compared to the central Labrador Basin (early May to late June). However, in 2015 initiation of the spring bloom happened earlier on the Greenland Shelf and in the Central basin, beginning in the first week of May. The bloom was generally short but very intense, particularly over the Central basin. It resulted in normal or above normal annual chlorophyll abundance for 2015 in the three Labrador Sea regions (Figure 15).

Calanus finmarchicus dominates the mesozooplankton biomass throughout the central region of the Labrador Sea, while on the shelves *C. finmarchicus* abundances show regional variations that are generally consistent from year-to-year and are related to regional differences in the timing of the life-cycle events and environmental conditions. *Calanus* spp. and other copepod may have benefited from the abundance of chlorophyll during the entire growing season (Figure 15). Lower than normal abundance estimates in May throughout the Labrador Sea are probably attributable to the presence of large bloom of *Phaeocystis* spp. that likely clogged the nets at most stations along the AR7W section.

In summary, the extreme surface heat losses observed during the severe winters of 2013-14 and 2014-15 were remarkable in both their magnitude and impact on the subpolar ocean basins and their ecosystems. Furthermore, we can measure these impacts on the biological properties of the Labrador Sea, all the way up to the lower trophic level, although the mechanisms behind the biological response in 2015 may differ from those that occurred during the previous deep convection events in 2013-14 and 2007-08.

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. Also, 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. Sea-surface temperatures reached record values across the zone in summer 2012. They were above-normal after the spring in 2015 in the St. Lawrence Estuary and Scotian Shelf, with record September values in the Estuary and parts of the Scotian Shelf (4X). The Newfoundland Shelf and Labrador Shelf however had respectively near-normal and below-normal sea-surface temperatures averaged over the ice-free season. From 2010 to 2013, sea ice cover had been below normal and summertime CIL conditions uniformly warm across the zone; however the cold winter of 2014 forced CIL conditions to colder-than-normal to normal conditions on the NL Shelf and in the Gulf of St. Lawrence in 2014 and the cold winter of 2015 on the Labrador Shelf and Gulf of St. Lawrence led to overall near-normal sea-ice and CIL conditions in the summer of 2015 in these areas. The Scotian Shelf CIL volume (T < 4°C) was contrastingly small (corresponding to warm conditions) with the 7th lowest value of the time series, associated with transport of warm salty offshore waters. Thus a north-to-south gradient was observed in CIL conditions. Bottom temperatures were normal to above-normal across the entire zone with a near-record high on the Scotian Shelf (4V) and a 100-year record high recorded in the deeper waters of the northern Gulf associated with a warm anomaly first observed in Cabot Strait in 2010 that is propagating toward the heads of channels.

Patterns of variation in biogeochemical variables appear dominated by short term fluctuations, because sampling was initiated only in 1999. The current state of the biogeochemical environment appears to demonstrate some spatial structuring, with nutrient inventories being close to normal on the Scotian Shelf, generally above normal in the Gulf of St. Lawrence and well below normal throughout most of the Newfoundland Shelf. Phytoplankton abundance was normal or slightly above normal in the Gulf of St. Lawrence and Scotian Shelf and well below normal across the Newfoundland and Labrador Shelf. The abundance of different groups of zooplankton also demonstrated strong spatial structure in the patterns of variation. The abundance of the large copepod *Calanus finmarchicus* was well below normal throughout the Atlantic Zone while the abundance of the small copepod *Pseudocalanus* spp. was above normal in the Newfoundland and Labrador Shelf and the Gulf of St. Lawrence. Non-copepod taxa abundance was above normal across the entire Zone, which represents a spatial expansion of above normal conditions relative to 2014.

In the central Labrador Sea, the winter mixed layer and convective overturning reached a maximum depth of 1,700 m, arguably the deepest since the record of 2400 m in 1994, and the resulting Labrador Sea Water year class is one of the largest ever observed outside of the early 1990s. Copepod abundance throughout the Labrador Sea continues to be below normal, continuing a pattern that started in 2013.

SOURCES OF INFORMATION

This Science Advisory Report is from the Eighteenth Annual Meeting of the Atlantic Zone Monitoring Program (AZMP) held March 15--18, 2016. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

Colbourne, E., Holden, J., Senciall, D., Bailey, W., Craig, J. and Snook, S. 2015. Physical Oceanographic Conditions on the Newfoundland and Labrador Shelf during 2014. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/053. v + 37 p.

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Galbraith, P.S., Chassé, J., Nicot, P., Caverhill, C., Gilbert, D., Pettigrew, B., Lefaivre, D., Brickman, D., Devine, L., and Lafleur, C. 2015. Physical Oceanographic Conditions in the Gulf of St. Lawrence in 2014. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/032. v + 82 p.

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Johnson, C., Casault, B., Head, E., and Spry, J. 2016. Optical, Chemical, and Biological Oceanographic Conditions on the Scotian Shelf and in the Eastern Gulf of Maine in 2014. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/003. v + 51 p.

Pepin, P., Maillet, G., Fraser, S., Shears, T., and Redmond, G. 2015. Optical, chemical, and biological oceanographic conditions on the Newfoundland and Labrador Shelf during 2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/027. v + 37 p.

Therriault, J.-C., Petrie, B., Pepin, P., Gagnon, J., Gregory, D., Helbig, J., Herman, A., Lefaivre, D., Mitchell, M., Pelchat, B., Runge J. and D. Sameoto. 1998. Proposal for a northwest Atlantic zonal monitoring program. Can. Tech. Rep. Hydrogr. Ocean Sci. 194: vii+57p.

APPENDIX

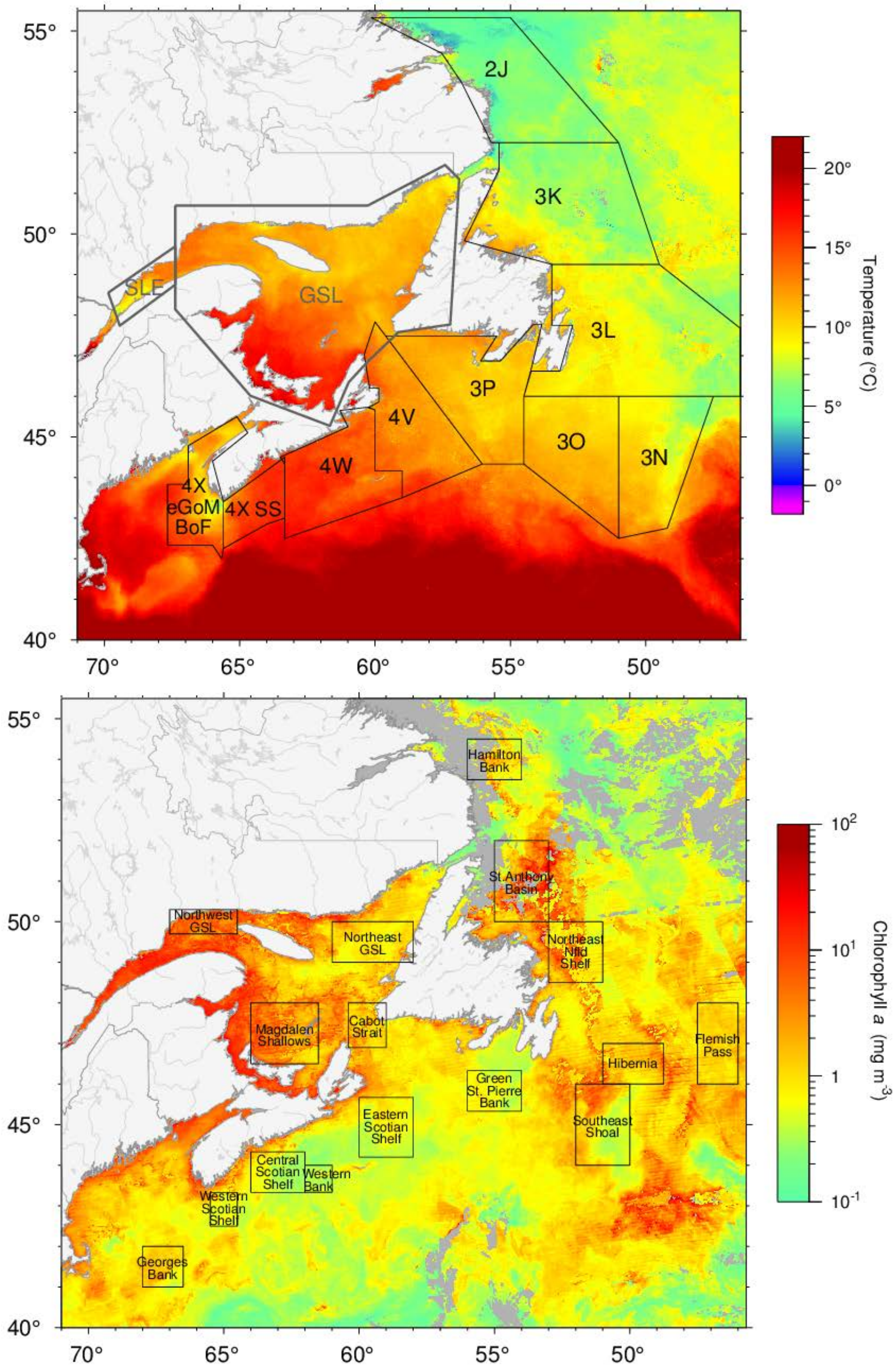

Figure 3. Areas used for (top) temperature and (bottom) ocean color averages. (Top) North Atlantic Fisheries Organization Divisions are cut off at the shelf break. The acronyms GSL and SLE are Gulf of St. Lawrence and St. Lawrence Estuary respectively. Sea-surface temperatures are shown for July 2015 and ocean colour chlorophyll a concentrations are for the first half of May 2015, emphasizing that certain areas are still ice covered when the bloom occurs in other parts of the zone.

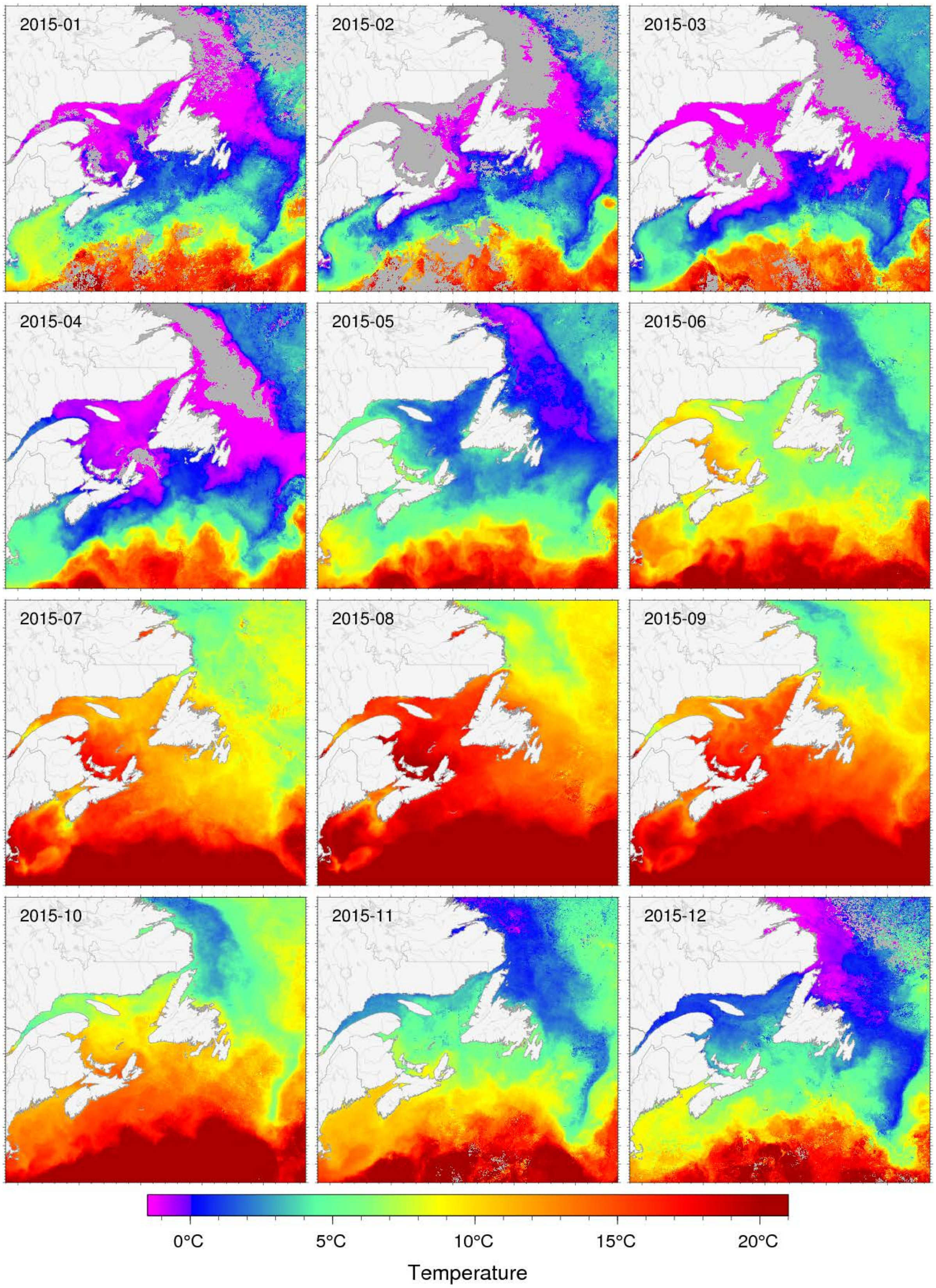

Figure 4. Sea-surface temperature monthly averages for 2015 in the Atlantic zone.

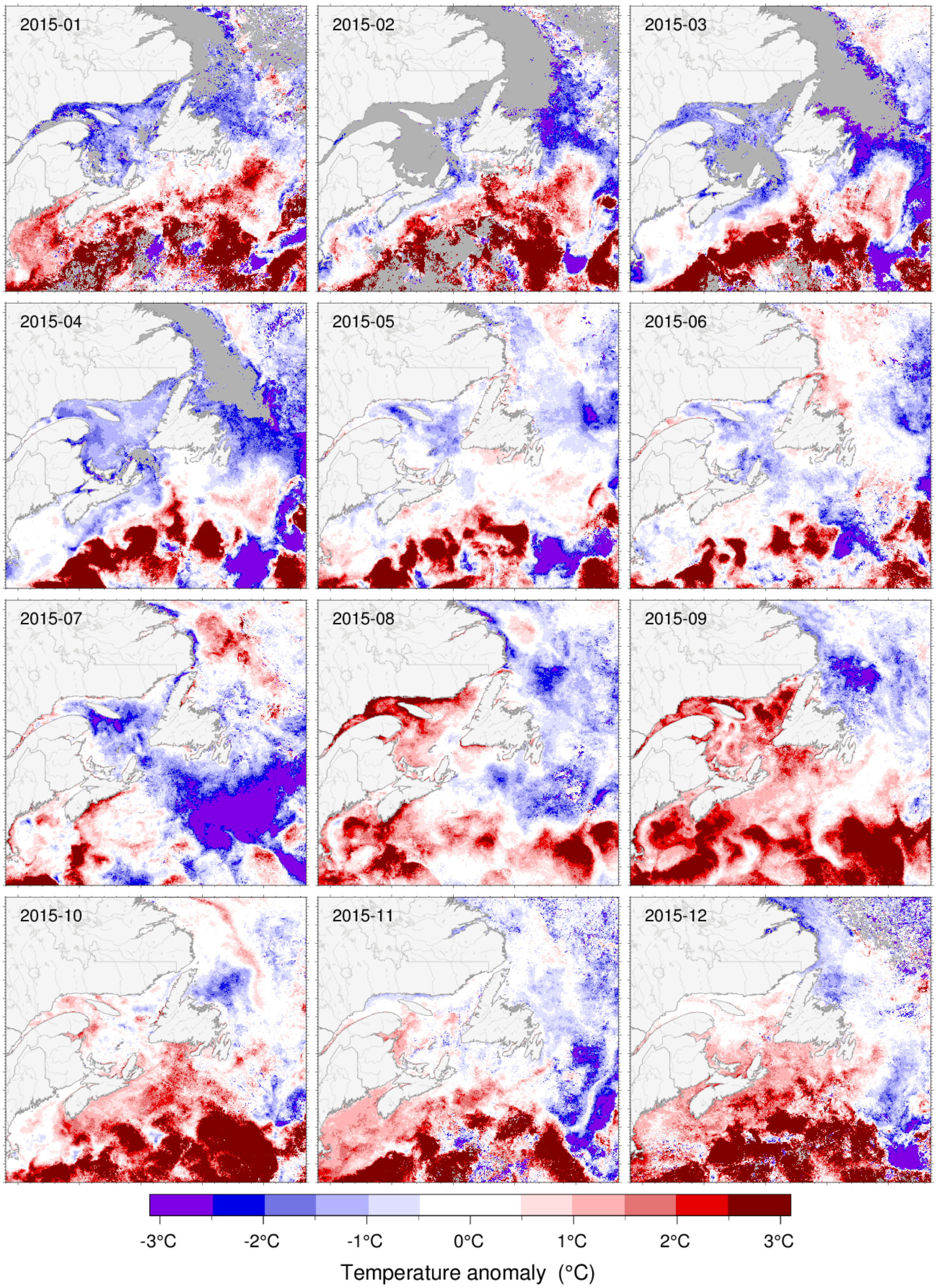

Figure 5. Sea-surface temperature monthly anomalies for 2015 in the Atlantic zone. Temperature anomalies are based on a 1985-2010 climatology.

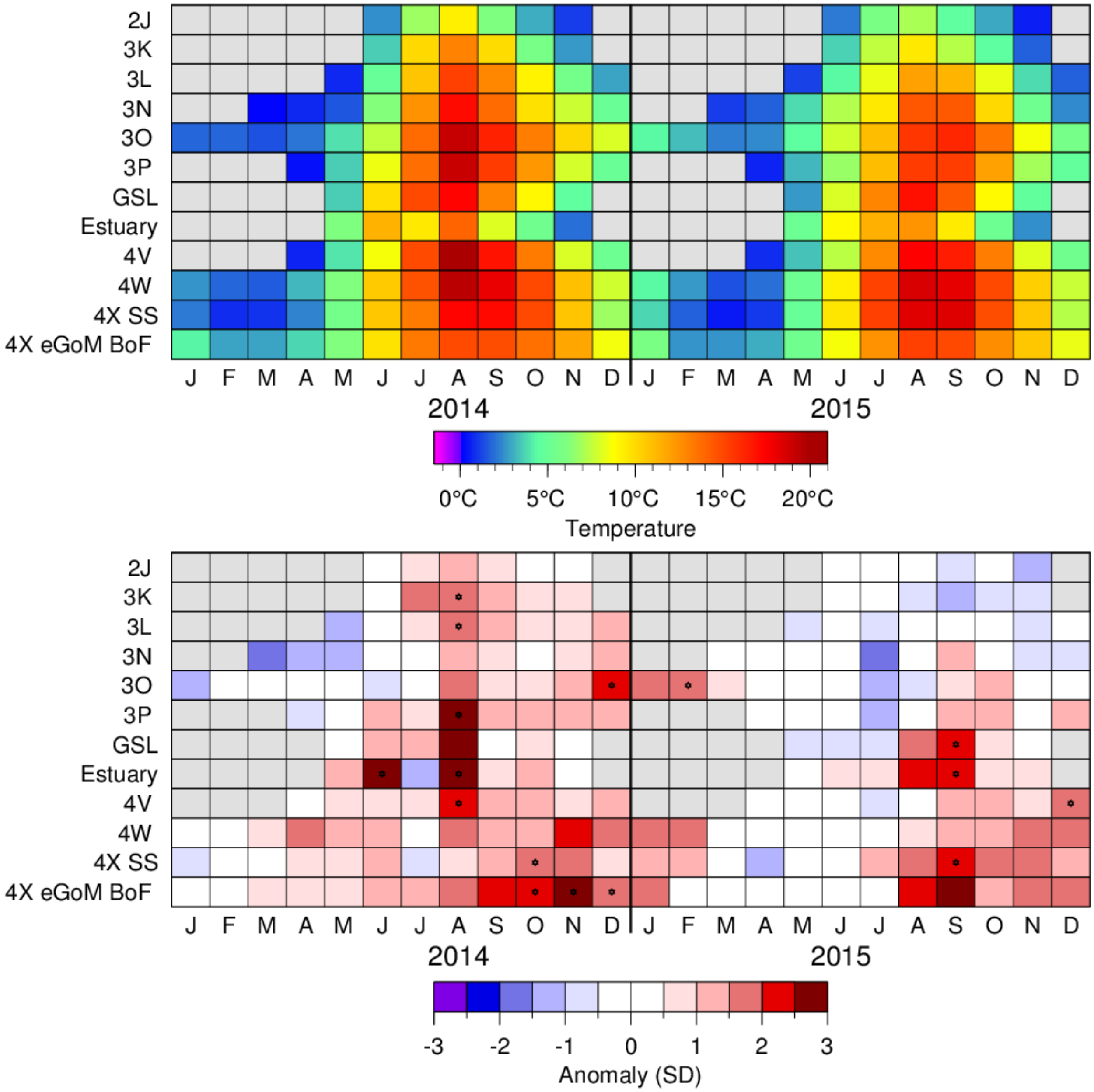

Figure 6. Monthly sea-surface temperature temperatures (top) and anomalies (bottom) for ice-free months of 2014-15, averaged over the 12 regions shown in Figure 3. Regions and months for which the average temperature was at a record high are indicated by a star.

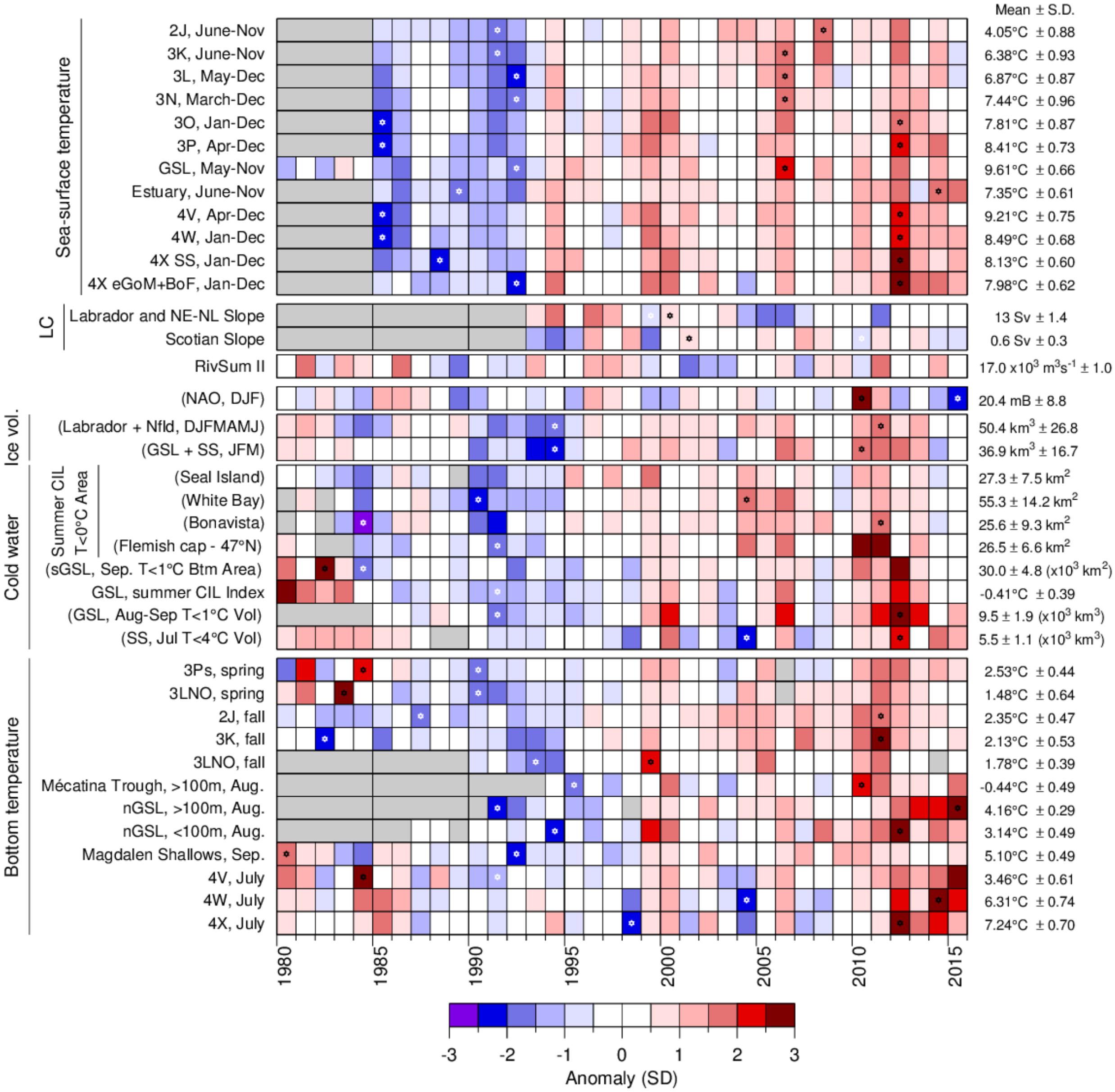

Figure 7. Time series of oceanographic variables, 1980–2015. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1981–2010 when possible; a red cell indicates above-normal conditions, and a blue cell below-normal. Variables whose names appear 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]).

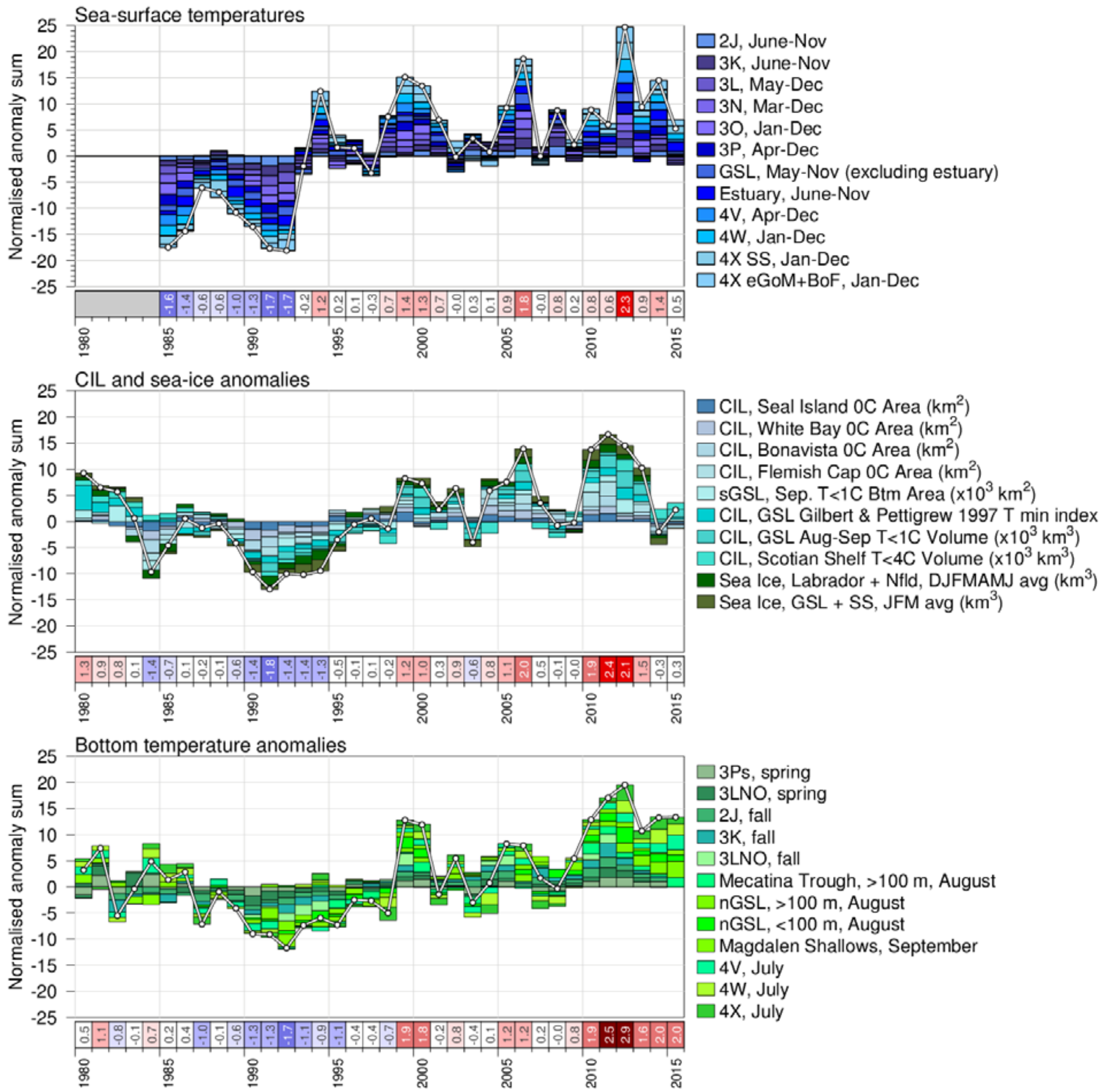

Figure 8. Composite climate indices (white lines and dots) derived by summing various standardized anomalies from different parts of the environment (colored boxes stacked above the abscissa are positive anomalies, and below are negative). Top panel sums sea-surface temperature anomalies, middle panel 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.

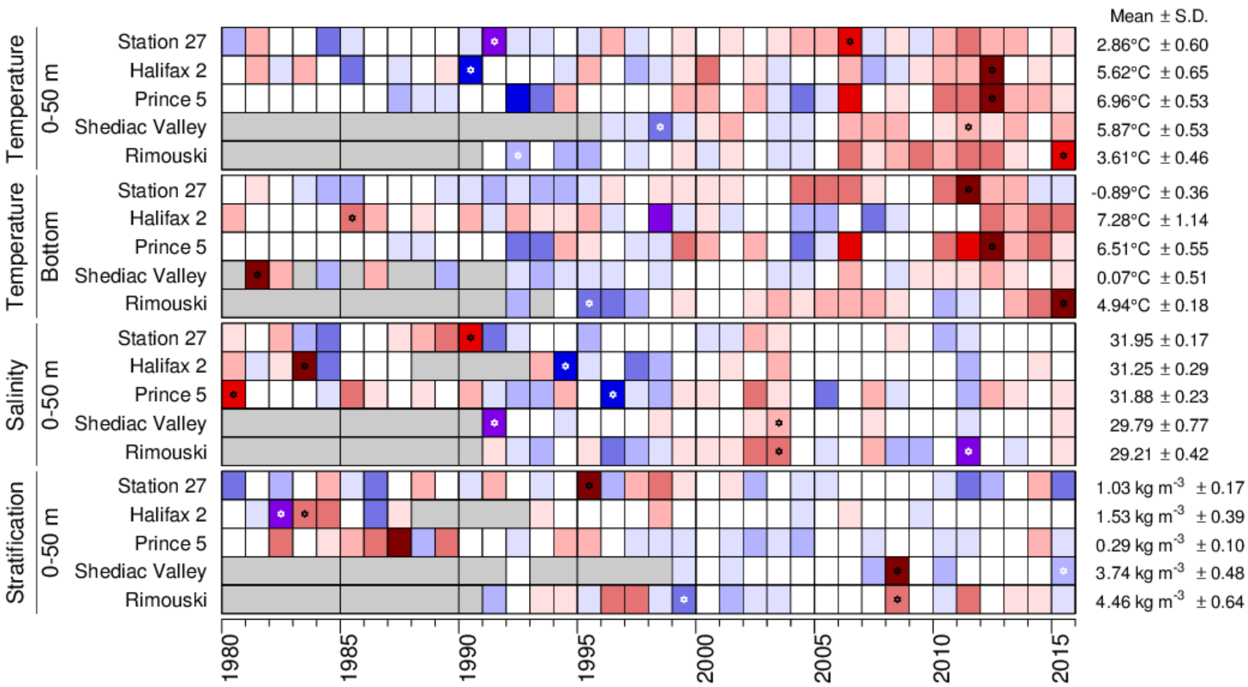

Figure 9. Time series of oceanographic variables at AZMP high-frequency sampling stations, 1980–2015. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1981–2010 when possible; for high-frequency station depth-averaged temperature, a red 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.

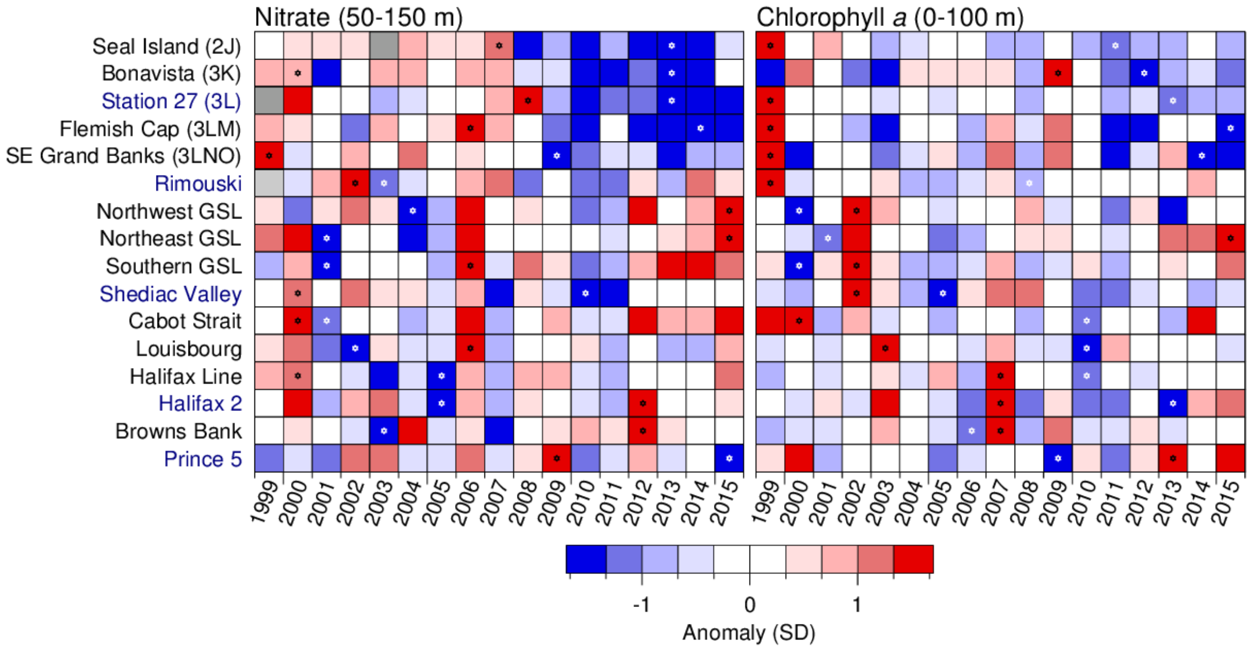

Figure 10. Time series of deep water nitrate inventories (50-150 m) and surface phytoplankton standing stocks (expressed as chlorophyll a 0-100 m mean concentration) at AZMP sections (labelled in red in Figure 2) and high-frequency sampling stations (labelled in blacks in Figure 2), 1999–2015. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1999–2010; 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.

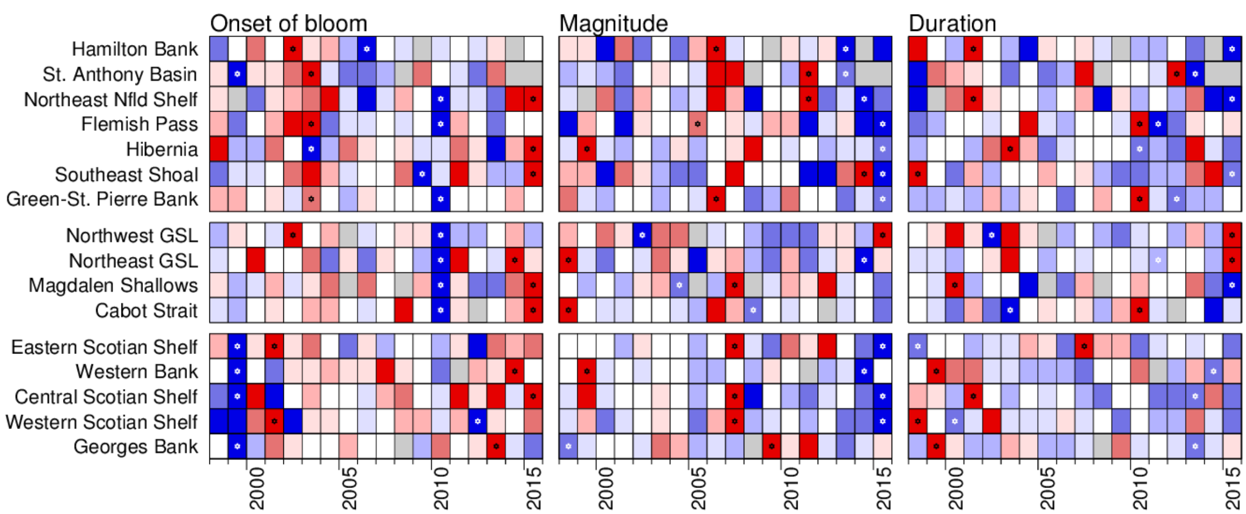

Figure 11. Time series of remotely sensed bloom parameter anomalies in various regions (onset of bloom, magnitude and duration),1998-2015. Data are from SeaWIFS for the period 1998-2008 and from MODIS onwards. Series minimum and maximums are indicated by a star. See Figure 3 for area definitions. Palette as in Figure 10.

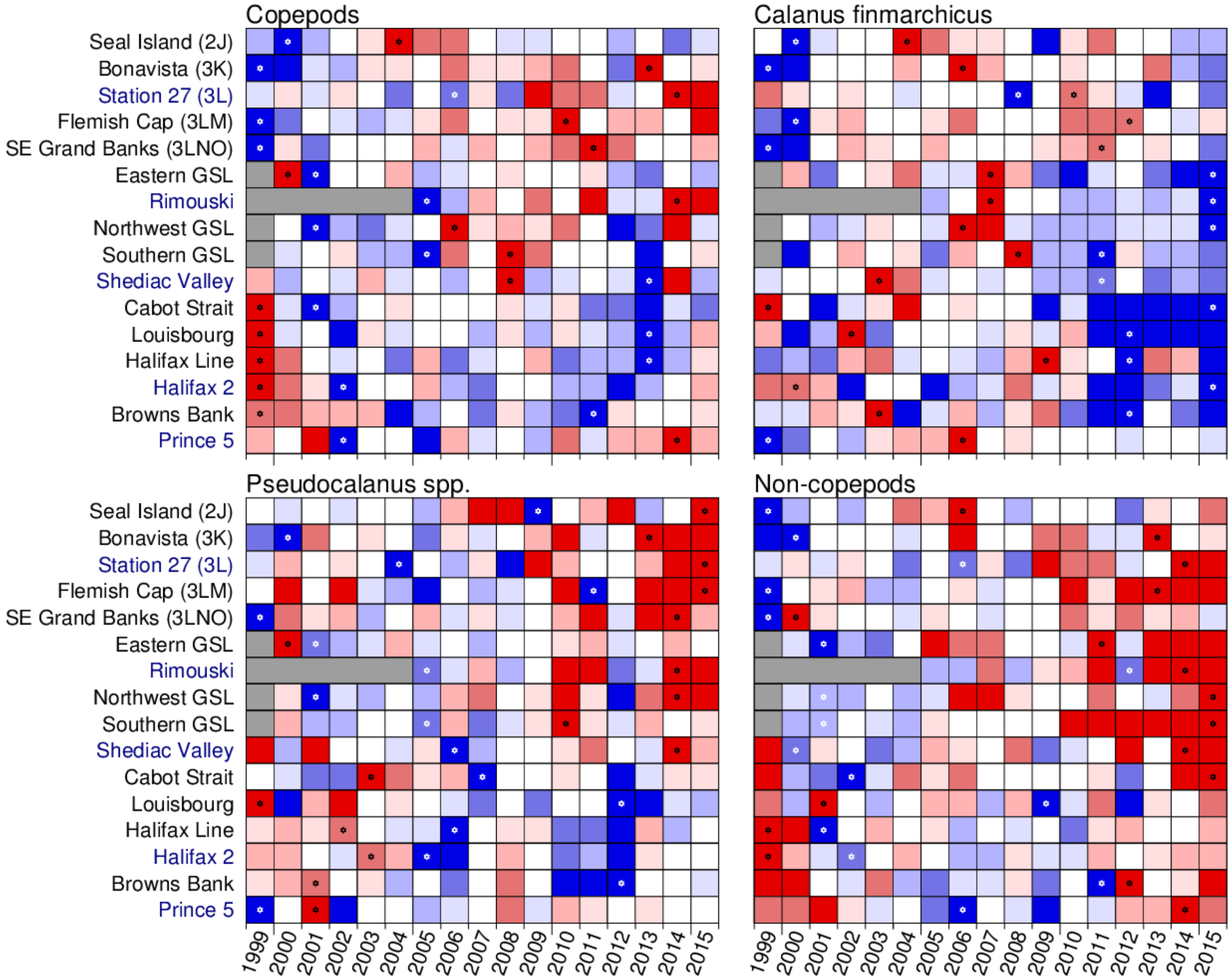

Figure 12. Time series of the standing stocks of total copepods, Calanus finmarchicus, Pseudocalanus spp., and non-copepod zooplankton, 1999–2015. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1999–2010; a red cell indicates above normal 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 10.

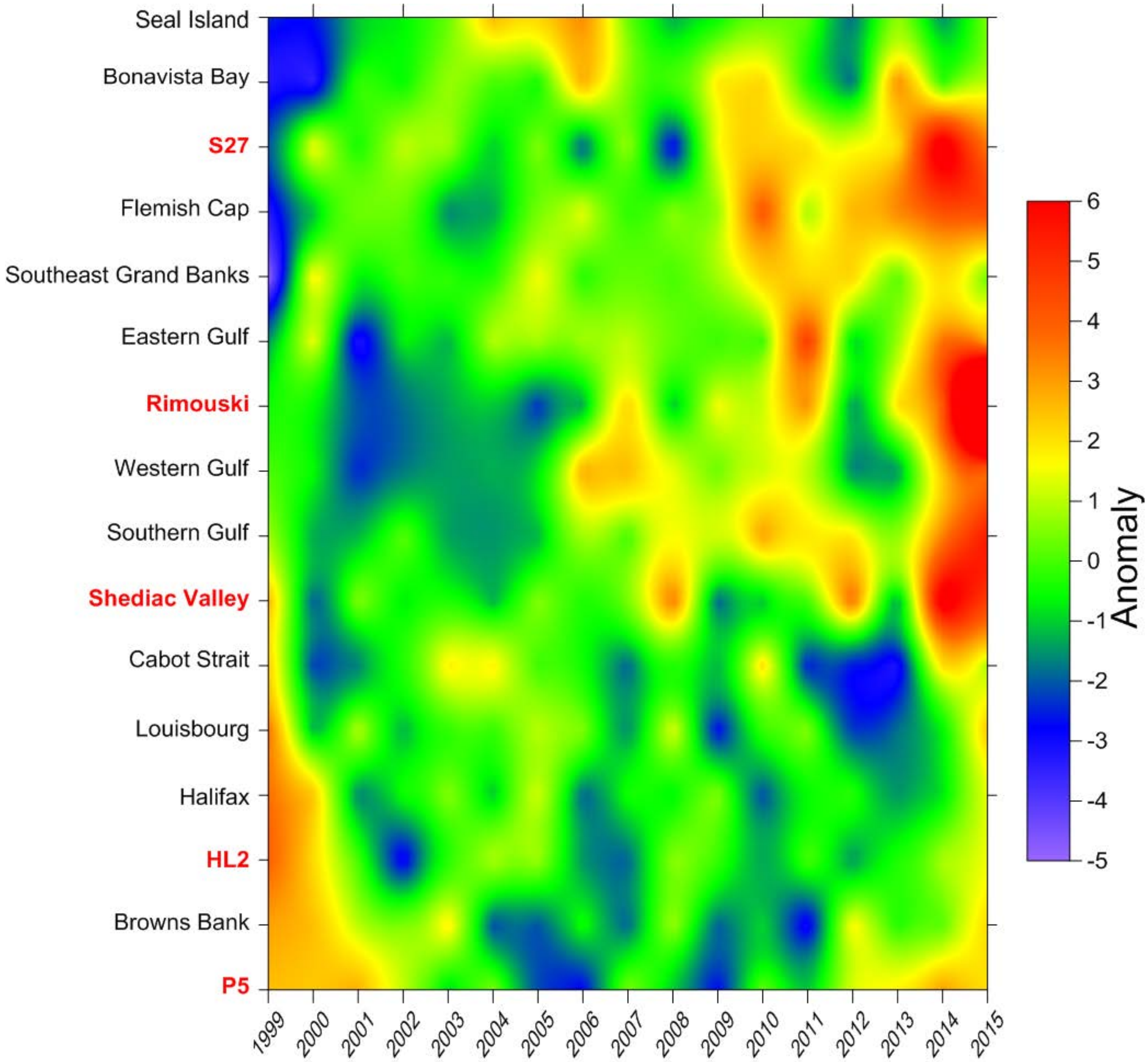

Figure 13. Schematic heat map of the summed copepod and non-copepod abundance anomalies along oceanographic sections and at high frequency sampling stations (highlighted in red on the left); blue indicates below average abundance while red indicate above average abundance.

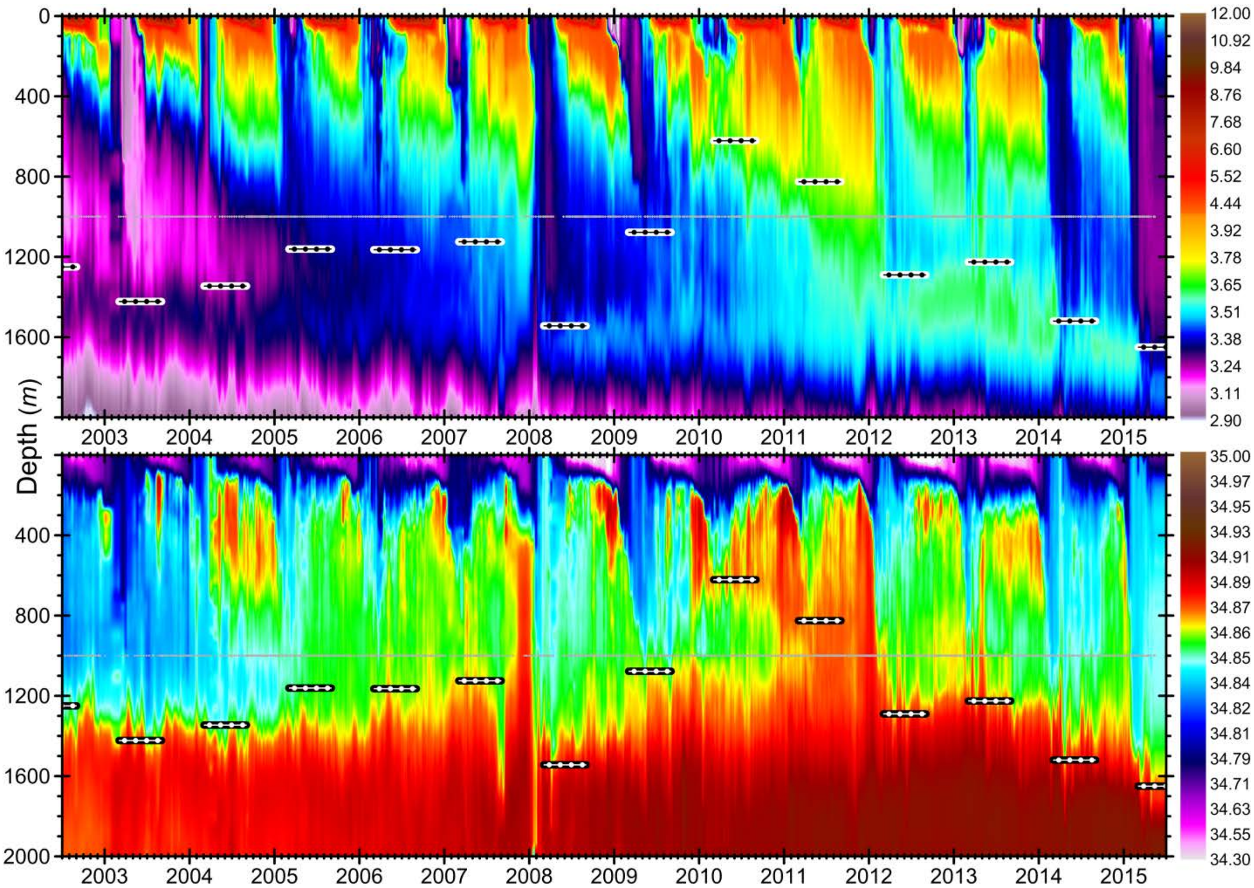

Figure 14. Temperature and salinity in the central Labrador Sea based on the measurements collected by the Argo floats and research vessels during 2002-15. The short horizontal lines indicate typical convection depth in each winter of this period.

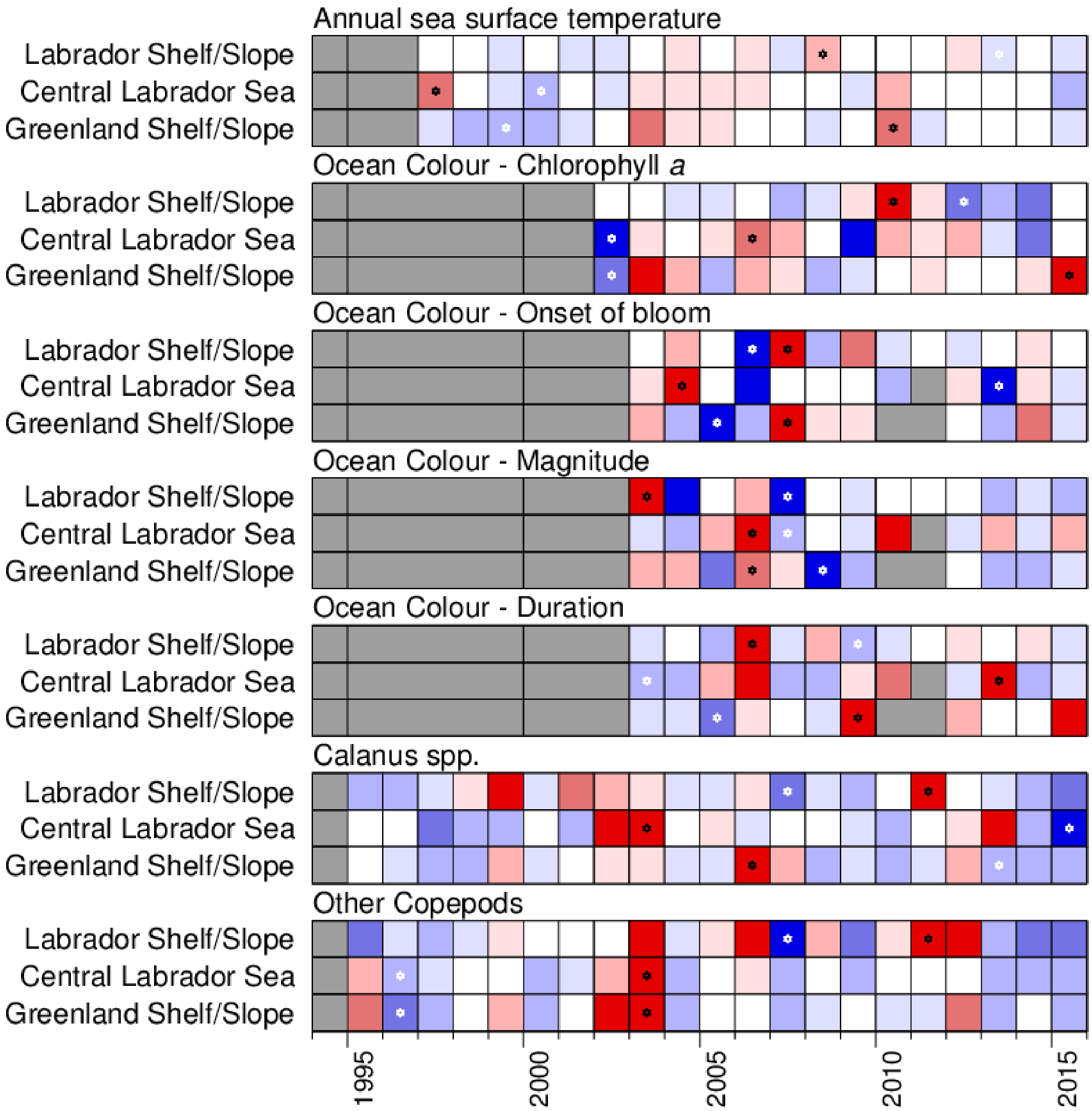

Figure 15. For the Labrador Sea region, normalized annual anomalies of remote sensed SST integrated over large spatial scale. Blooms parameters (onset of bloom, magnitude and duration) are derived entirely from remote sensing. Zooplankton data represent anomalies of abundance estimation collected in May/June along the AR7W line between 1995 and 2015. Palette as in Figure 10.

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