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**Newfoundland and Labrador, Quebec, Gulf, and Maritimes Regions**

**Canadian Science Advisory Secretariat**
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# OCEANOGRAPHIC CONDITIONS IN THE ATLANTIC ZONE IN 2016

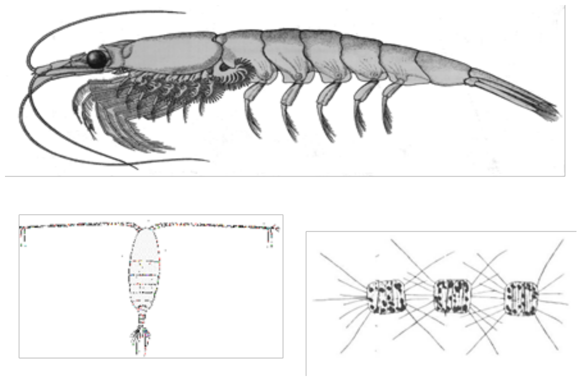

*Figure 1. Key taxa of the pelagic food web: euphausids (top), phytoplankton (bottom right), and copepods (bottom left).*
*Images: Fisheries and Oceans Canada*

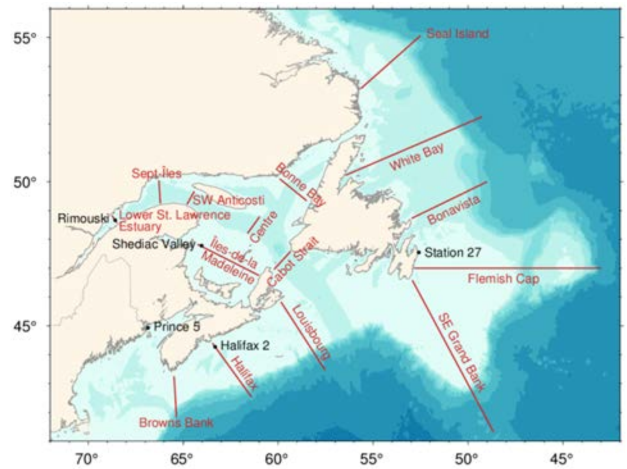


*Figure 2. Atlantic Zone Monitoring Program high-frequency sampling stations (black) and selected section lines (red).*

**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

- Winter sea surface temperatures (SSTs) were above normal from the Scotian Shelf to the Bay of Fundy, including many record levels (since 1985) in March and April. Temperatures were also at record levels in November from the southwest Grand Bank (Division 3O), through St. Pierre Bank (Div. 3P), Cabot Strait (Div. 4V), the Gulf of St. Lawrence and the St. Lawrence Estuary. Sea surface temperatures averaged over ice-free months were near normal on the Labrador and Eastern Newfoundland Shelf and above normal elsewhere in the zone. Temperatures averaged over 0 to 50 m water depth were above normal at all five AZMP high-frequency stations, including a record high at Rimouski station.

- Winter average sea ice extent was near normal on the Newfoundland and Labrador (NL) Shelf but was 4th lowest since records began in 1969 in the Gulf of St. Lawrence. Consistent with this, summer cold intermediate layer (CIL) conditions were mostly near normal on the NL Shelf, or at least not strongly anomalous, but were much warmer than normal in the Gulf of St. Lawrence and the Scotian Shelf.
- Bottom temperatures were normal to above normal across the zone, including very high anomalies on the Scotian Shelf, a 33-year record high in 3Ps and a 100-year record high in the deeper waters of the northern Gulf of St. Lawrence. Rimouski station bottom temperatures were also at a series record high.
- Deep nutrient inventories demonstrated considerable spatial heterogeneity and were near normal throughout much of the Atlantic zone but strong negative anomalies occurred at Station 27, on the eastern Scotian Shelf and in the Bay of Fundy. The return to normal conditions represents a reversal of periods of persistent low inventories on the Newfoundland Shelf (seven years) and high inventories throughout much of the Gulf of St. Lawrence (four years).
- Annual chlorophyll *a* inventories were generally below normal throughout the zone, with the strongest negative anomalies occurring on the Newfoundland Shelf and in the northwest 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 Gulf of St. Lawrence where the bloom on the Magdalen Shallows was well above normal; bloom duration was highly variable, with short blooms on the Newfoundland Shelf, northern Gulf of St. Lawrence and Central Scotian Shelf, and longer than average blooms in the southern Gulf of St. Lawrence and eastern Scotian Shelf.
- 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 2016; the lowest negative anomalies in *C. finmarchicus* occurred on the Scotian Shelf while strong positive anomalies in *Pseudocalanus* sp. and non-copepods occurred in the Gulf of St. Lawrence and the Newfoundland Shelf.
- In the winter of 2016 the Labrador Sea experienced the deepest convection since 1994. That was the fourth year of progressive intensification and deepening of convective mixing and production of Labrador Sea Water since 2012. Both upper, 0-200 m, and deeper, 200-2,000 m, layers have been cooling since 2010. The Labrador Current was intensified in 2016 relative to the previous four years. Although the spring phytoplankton bloom initiation and amplitude were only average, the longer duration and higher magnitude in the Labrador Shelf and Basin brought this year's chlorophyll over the average typically recorded. Interannual to multi-decadal variability of temperature and salinity in the Labrador Sea is dominated by decadal-scale changes making any long-term trends less obvious.

# BACKGROUND

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

1. Increasing Fisheries and Oceans Canada's (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, NL) 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 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 Environment

This is a summary of physical oceanographic conditions during 2016 for eastern Canadian oceanic waters (Figures 2 and 3) as reported annually by the AZMP in three reports (e.g. Colbourne et al. 2016, Galbraith et al. 2016 and Hebert et al. 2016 for conditions of 2015).

Air temperatures were above normal across the zone in winter. In summer, they were below normal to normal on the NL Shelf, normal to above normal in the Gulf of St. Lawrence and above normal on the Scotian Shelf. Record highs were reached in November at many sites across the zone (+2.1°C averaged over 11 stations in the Gulf, +2.6°C at St. John’s, and +2.0°C at Sable Island where it was the highest value recorded since 1897).

Sea surface temperatures were above-normal from the fall of 2015 through to May 2016 from the Scotian Shelf to the Bay of Fundy, including many record levels in March and April (Figures 4 to 6). These records were of +1.7°C (+2.5 to +3.0 SD) in Div. 4W and both subdivisions of Div. 4X in March, and of +1.0°C to +1.7°C (+2.0 to +2.2 SD) in Div. 4V, Div. 4W and both subdivisions of Div. 4X in April. Temperatures were also at record levels in November from the Southwest Grand Banks (Div. 3O; +3.0°C, +2.1 SD), through St. Pierre Bank (Div. 3P; +2.2°C, +2.2 SD), Cabot Strait (Div. 4V; +1.7°C, +2.1 SD), the Gulf of St. Lawrence (+1.7°C, +2.2 SD) and the St. Lawrence Estuary (+1.8°C, +2.3 SD). Averaged over ice-free months, they were near-normal on the Labrador and Eastern Newfoundland Shelf and above-normal elsewhere in the zone (Figure 7), including a record high in the St. Lawrence Estuary (+1.5°C, +2.4 SD).

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, an upwards trend between 2001 and 2011. The annual mean run-off of 2016 was above normal (17,600 $m^3s^{-1}$, +0.6 SD; Figure 7).

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 2016, the winter NAO index remained in a positive phase at 0.5 SD above normal but decreased from the largest value in the 120 year record (+ 2.0 SD) observed in 2015. The index was not consistent with above normal winter air temperature on the NL shelf.

For the past decade, ice volumes on the NL Shelf, the Gulf of St. Lawrence and the Scotian Shelf have generally been lower than normal reaching a record-low value in the Gulf of St. Lawrence in 2010 and on the NL Shelf in 2011. In 2016, seasonally-averaged sea ice volume was near-normal on the NL Shelf (-0.4 SD) but was 4th lowest since records began in 1969 in the Gulf of St. Lawrence, with no sea-ice exported onto the Scotian Shelf.

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 northeastern Newfoundland Shelf and the northern Grand Bank, followed by similarities between the Gulf of Lawrence and the Scotian Shelf. In a manner consistent with winter sea-ice cover, summer CIL conditions were mostly near-normal on the NL Shelf, or at least not strongly anomalous, but were much warmer-than-normal in the Gulf of St. Lawrence and the Scotian Shelf (by 0.8 to 1.9 SD). Thus a north-to-south gradient was observed again in CIL conditions in 2016, for the third consecutive year.

Bottom temperatures were again normal or above-normal across the zone, reaching record highs in the northern Gulf at depths over 100 (+1°C, +3.3 SD; Figure 7). This is associated with 100-year high-temperature records for the Gulf at depths of 250 m and 300 m. The series record high recorded in the northern Gulf 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 or three 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 has made its first appearance in the northwest Gulf since at least the mid-1980s. In other areas of the zone, bottom temperature were third highest since 1980 in Subdiv. 3Ps in spring (+0.9°C, +2.0 SD) and in Div. 4V in July (+1.3°C, +2.2 SD), and second highest in Div. 4W (+1.8°C, +2.4 SD) and 4X (+1.9°C, +2.6 SD) in July.

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 2016 were above normal for all three components. While the bottom temperatures were third highest of the time series overall, they were near normal in Divs. 3LNO of the Newfoundland Shelf.

In 2016, seasonally or annually averaged 0-50 m temperatures at high-frequency sampling stations were above-normal at all five AZMP stations (Figure 9), including a series record high at Rimouski station (+1.5°C, +3.3 SD) and second highest at Prince 5 since the series began in 1926 (+1.7°C, +3.1 SD). Bottom temperatures were normal at Station 27 and above-normal at other stations, including a series record high at Rimouski station (5.54°C, +0.6°C, +3.3 SD) and second highest at Prince 5 (8.16°C, +1.7°C, +3.0 SD). The annual 0–50 m salinity anomalies varied in sign across the zone. The annual 0–50 m stratification index was near-normal at all stations except Prince 5 where it was below normal (-1.5 SD). Stratification on the Scotian Shelf increased 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. 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.

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, only one was colder than normal, 10 were within normal values and 33 were above normal, indicating a continuation of warmer than normal oceanographic conditions in 2016 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 2016, the annual mean transport was above normal over the Labrador and northeastern Newfoundland Slope (+1.3 SD) and below normal (-1.1 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. 2017), Gulf of St. Lawrence (GSL) (Devine et al. 2015) and Scotian Shelf (SS) (Johnson et al. 2017) 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 1999-2016 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) demonstrated considerable spatial heterogeneity and were near normal throughout much of the Atlantic zone. This represents a shift from primarily below normal values on the Newfoundland Shelf from 2008/09 to 2015 (Figure 10). In the Gulf of St. Lawrence, deep nitrate inventories have reverted to near normal after a period of above normal values from 2012 to 2015 (Figure 10). The strongest negative anomalies of deep nitrate (< -1.5 SD) occurred at Station 27, on the eastern Scotian Shelf and 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. Annual chlorophyll *a* inventories were generally below normal throughout the zone, with the strongest negative anomalies occurring in the northwest Gulf of St. Lawrence and on the Newfoundland Shelf, including a record low anomaly on the Flemish Cap section (Figure 10). A positive chlorophyll anomaly was observed only in the southern 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] 1998-2007; Moderate Resolution Imaging Spectroradiometer [MODIS] 2008-2011); Visual Infrared Imaging Radiometer Suite [VIIRS] (2012-present) (Figure 11). 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 Gulf of St. Lawrence where the bloom on the Magdalen Shallows was well above normal; bloom duration was highly variable, with short blooms on the Newfoundland Shelf, northern Gulf of St. Lawrence and Central Scotian Shelf, and longer than average blooms in the southern Gulf of St. Lawrence and eastern Scotian Shelf.

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 2016, zooplankton abundance indices continued to demonstrate relatively large scale coherence (Figure 12). A zooplankton community shift has been observed in recent years, characterized by lower abundance of the large energy-rich copepod *C. finmarchicus*, higher abundances of small and warm water copepods, and higher abundance of non-copepods. This pattern persisted in 2016. Total copepod abundances continued to be higher than normal in many regions, particularly on the NL Shelves and in the Gulf of St. Lawrence, with record high values at Station 27, Rimouski, and in the northwest Gulf of St. Lawrence. Copepod abundances were mainly above average on the Scotian Shelf, similar to 2015, and there was a record high value in the Bay of Fundy, following positive anomalies since 2012. Non-copepod zooplankton, which consist principally of the larval stages of benthic invertebrates, many carnivores that feed on other zooplankton, and small-particle feeding taxa, were above average throughout the zone, with record high values observed in all three regions. The lowest negative anomalies in *C. finmarchicus* occurred on the Scotian Shelf. The strongest positive anomalies in *Pseudocalanus* sp. and non-copepods occurred in the Gulf of St. Lawrence and the Newfoundland Shelf.

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 2016 in the Gulf of St. Lawrence the abundance of summer-fall shelf copepods (*Centropages* spp. and *Paracalanus* sp.) remained well above normal whereas warm-associated deep copepods (*Metridia lucens*) showed record-high positive anomaly, probably reflecting the above normal surface temperature and the very warm conditions observed in the deep water layer in the region. Otherwise, the cold water/arctic copepods *Calanus glacialis* and *Metridia longa* showed abundance respectively below and above normal in the region in 2016. On the Scotian Shelf in 2016, cold water/arctic copepod abundance continued to be lower than normal. The abundances of warm water/summer-fall copepods (*Centropages* spp., *Paracalanus* sp., and *Temora longicornis*), subtropical off-shelf copepods and cosmopolitan (*Oithona atlantica*) were all higher 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 Ocean warming. On the Newfoundland Shelf and Grand Bank in 2016, cold water arctic copepods including *C. glacialis* and *Calanus hyperboreus* were more abundant, likely associated as a result of cooler conditions observed in recent years in the region. Conversely, cold water copepods *Euchaeta norvegica* and *Metridia longa* showed mixed signals across the region. The occurrence of warm water shelf (*Centropages typicus*, *T. longicornis*, and *Paracalanus* sp.) and deep-water copepods (*M. lucens*) were generally less abundant on the Newfoundland Shelf and Grand Bank in 2016.

The patterns of variation of copepods and non-copepod abundance have a moderate positive association. 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 levels 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 2015-16, the mid-high latitude North Atlantic experienced more moderate surface heat loss in the region than in the previous few years when it was rather on the extreme side, culminating in the winter of 2014-15. Despite the weaker heat loss from the ocean to the atmosphere, the water column preconditioning caused by convective mixing in the previous years led nevertheless to the most significant formation, in terms of volume and depth, of Labrador Sea Water (LSW) since 1994. Temperature, salinity and dissolved oxygen profiles show that winter mixed layer and hence convective overturning in the central Labrador Sea reached 2,000 m in 2016 following a maximum of 1,600 m in 2014 and 1,700 m in 2015 (Figure 14). The 2016 vintage of LSW is associated with low temperature (< 3.3°C) and salinity (< 34.85) between 1,000 and 1,700 m. The winter convection in 2016 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 2016 led to increased gas (dissolved oxygen, anthropogenic gases, and carbon dioxide) uptakes in the Labrador Sea that now typically spread below 1,900 m and in some cases 2,000 m.

The progressive cooling of the top 2,000 m, and deep and intense winter mixing during the three consecutive winters of 2013-14, 2014-15 and 2015-16 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 15).

For the most recent class of Labrador Sea Water, there was a further increase in Total Inorganic Carbon (TIC) as a result of the gradual invasion of anthropogenic carbon dioxide into the surface ocean and this was accompanied by a slight decrease in pH on the total scale. The overall increase in TIC since 1994 is best described by a linear regression ($R^2 = 0.93$) with a mean rate of 0.86 $\mu$mol kg$^{-1}$ y$^{-1}$, whereas the decline in pH has also been linear, although more variable than TIC ($R^2 = 0.51$), with a mean rate of -0.002 y$^{-1}$. Concentrations of the dissolved gases dichlorodifluoromethane (CFC-12) and sulphur hexafluoride ($SF_6$) in the recent LSW class (formed and replenished during 2012-2016) had not changed significantly since 2015 despite an increase in the depth of convective mixing during 2016. Presumably the net air/sea flux of $SF_6$ and CFC-12 into the generally undersaturated LSW was offset by the entrainment of deep water having low concentrations of these gases.

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 NAO is continuing to drive the recurrent convection (Figure 15). 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.

These extreme atmospheric and physical ocean processes in the winter and spring of 2015-16 also had profound impacts on the biological properties of the Labrador Sea. Biweekly climatology of chlorophyll *a* constructed from a time series of remotely-sensed ocean colour from 2003 to 2016 indicates that the annual spring bloom of phytoplankton started at an average date but the duration of the bloom was lengthy again this year at a large spatial scale but the intensity of the bloom was not as strong as observed in 2015 (Figure 16). The occurrence of a fall bloom again this year seems to indicate that this feature is becoming more the norm than the exception.

*Calanus finmarchicus* dominates the mesozooplankton throughout the central region of the Labrador Sea, while on the Labrador and Greenland shelves, *C. finmarchicus* show regional year-to-year variations in abundance that are generally related to regional differences in the timing of the life-cycle events and environmental conditions. *Calanus* spp. and other copepods may have benefitted from high phytoplankton availability during the entire growing season. In 2016, the lower than normal abundance estimates of *C. finmarchicus* in May in all parts of the

Labrador Sea may be largely attributable to the sampling date, which this year occurred prior of the spring bloom.

In summary, deep-water convection from the previous years put in place preconditions that favour this year record deep convection. 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 2016 may differ from those observed during the previous deep convection events in 2013-14, 2014-15 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 with sea-surface temperatures that reached record values across the zone in summer 2012. In 2016, they were above-normal in winter on the Scotian Shelf and Bay of Fundy, including many record levels (since 1985) in March and April. Temperatures were also at record levels in November from the southwest Grand Bank (Div. 3O), through St. Pierre Bank (Div. 3P), Cabot Strait (Div. 4V), the Gulf of St. Lawrence and the St. Lawrence Estuary. 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 4$^{th}$ 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, or at least not strongly anomalous, but were much warmer than normal in the Gulf of St. Lawrence and the Scotian Shelf. Thus a north-to-south gradient was observed in CIL conditions. Bottom temperatures were normal to above-normal across the entire zone, including very high anomalies on the Scotian Shelf, a 33-year record high in 3Ps and a 100-year record high in the deeper waters of the northern Gulf of St. Lawrence 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 generally below normal across the entire Atlantic Zone. The abundance of different groups of zooplankton also demonstrated strong spatial structure in the patterns of variation. The abundance of the large copepod *C. finmarchicus* was well below normal throughout the Atlantic Zone while the abundance of the small copepod *Pseudocalanus* spp. was above normal in the NL Shelf, the Gulf of St. Lawrence and the eastern Scotian Shelf. Non-copepod taxa abundance was above normal across the entire Zone, which represents a spatial expansion of above normal conditions relative to 2013.

In the central Labrador Sea, the winter mixed layer and convective overturning reached a maximum depth of 1,900-2,000 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. 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 Nineteenth Annual Meeting of the Atlantic Zone Monitoring Program (AZMP) held March 14-17, 2017. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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# APPENDIX

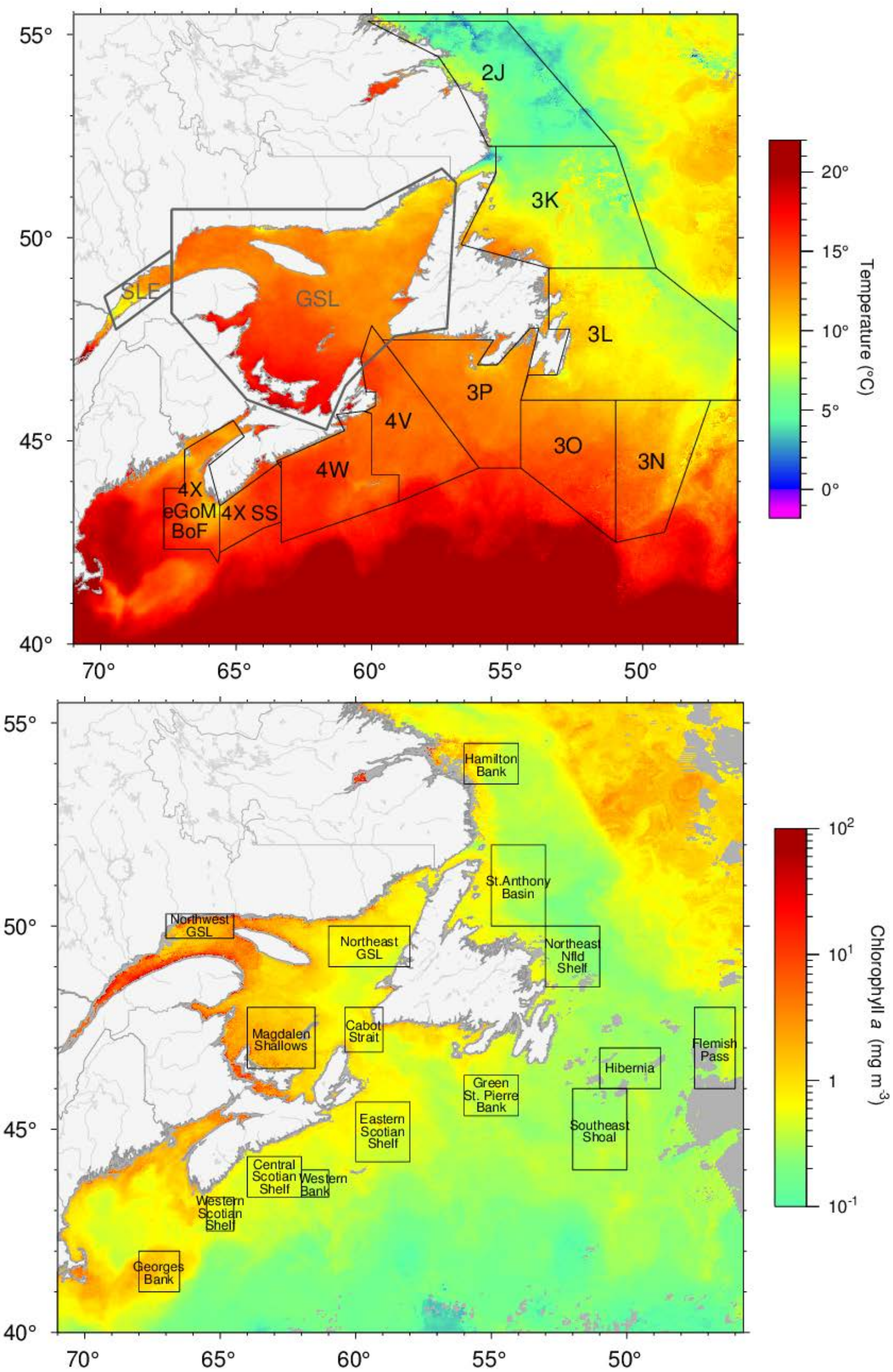


*Figure 3. Areas used for (top) temperature and (bottom) ocean color averages. (Top) North Atlantic Fisheries Organization Divisions are cut off at the shelf break. The acronyms GSL and SLE are Gulf of St. Lawrence and St. Lawrence Estuary respectively. Sea-surface temperatures are shown for July 2016 and ocean colour chlorophyll a concentrations are for the second half of July 2016.*

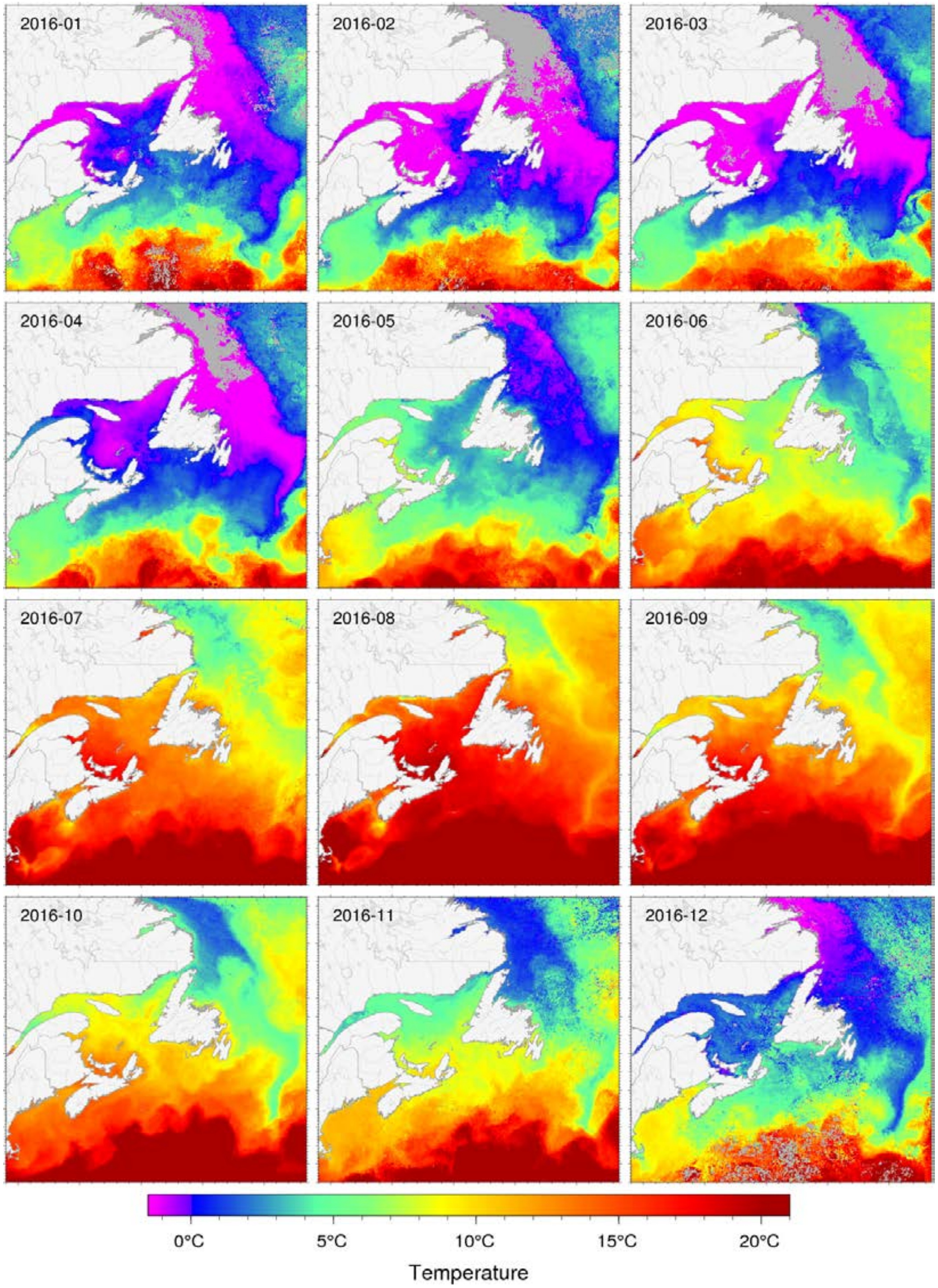


*Figure 4. Sea-surface temperature monthly averages for 2016 in the Atlantic zone.*

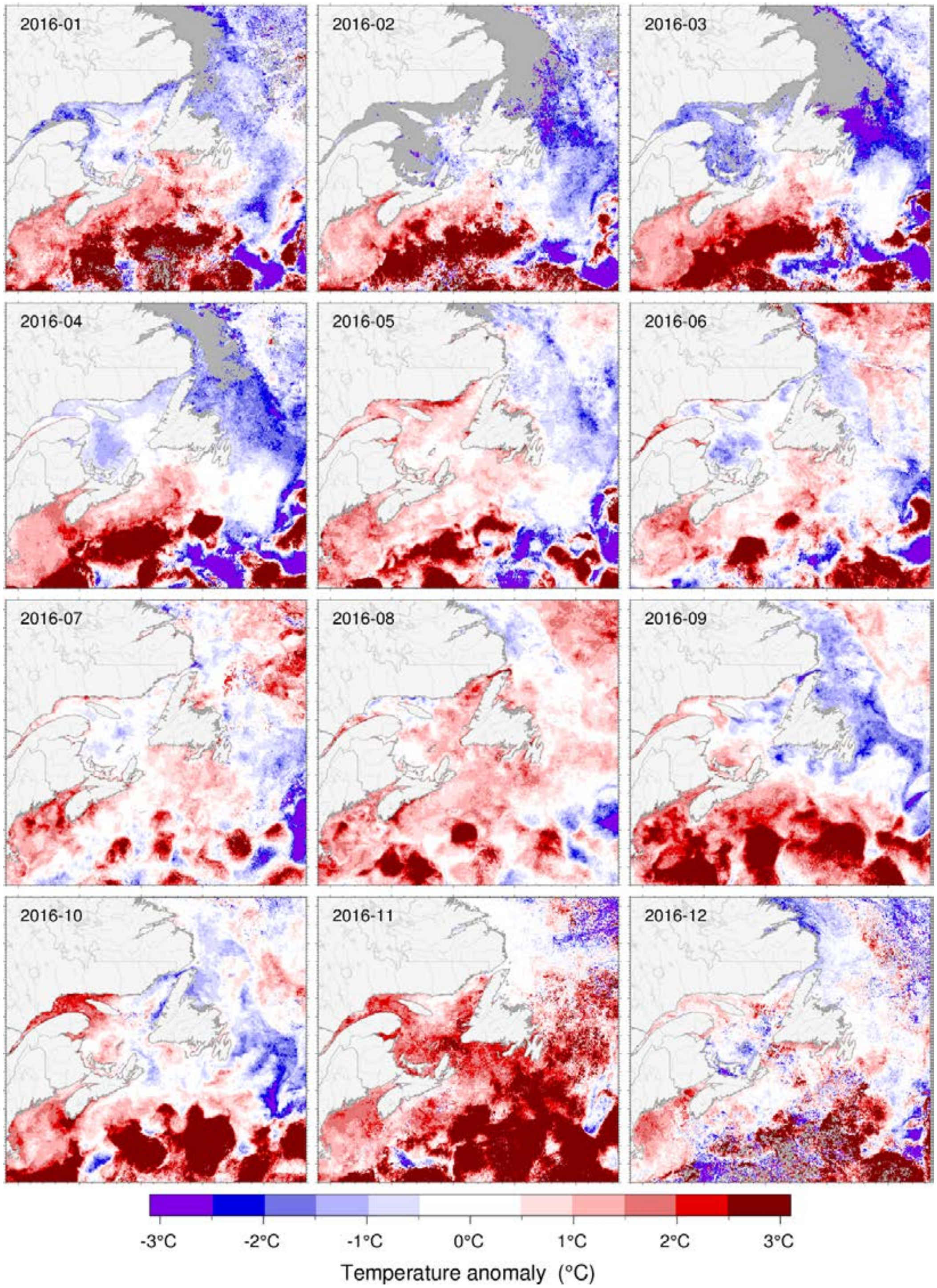


*Figure 5. Sea-surface temperature monthly anomalies for 2016 in the Atlantic zone. Temperature anomalies are based on a 1985-2010 climatology.*

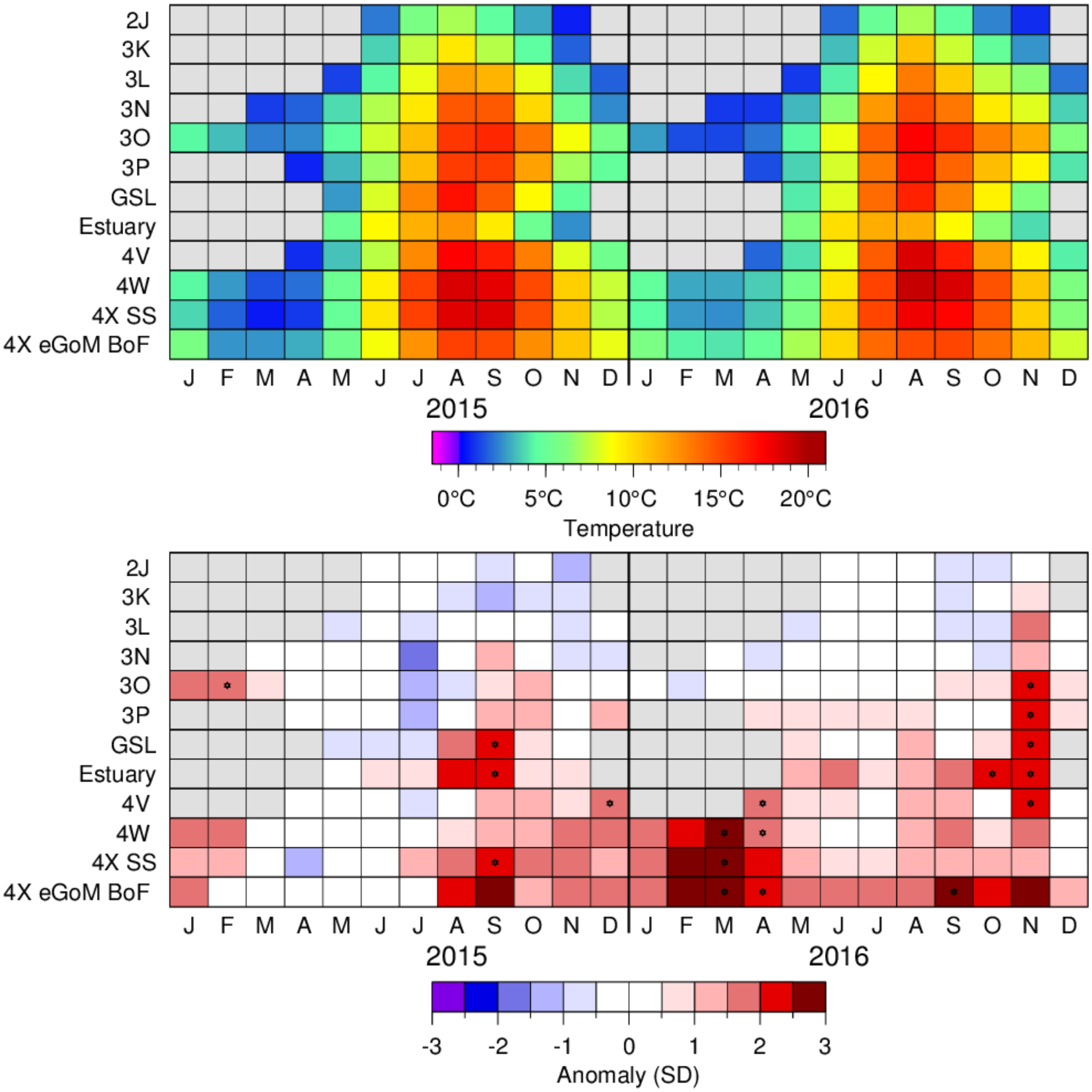


*Figure 6. Monthly sea-surface temperature temperatures (top) and anomalies (bottom) for ice-free months of 2015-16, averaged over the 12 regions shown in Figure 3. Regions and months for which the average temperature was at a record high are indicated by a star.*

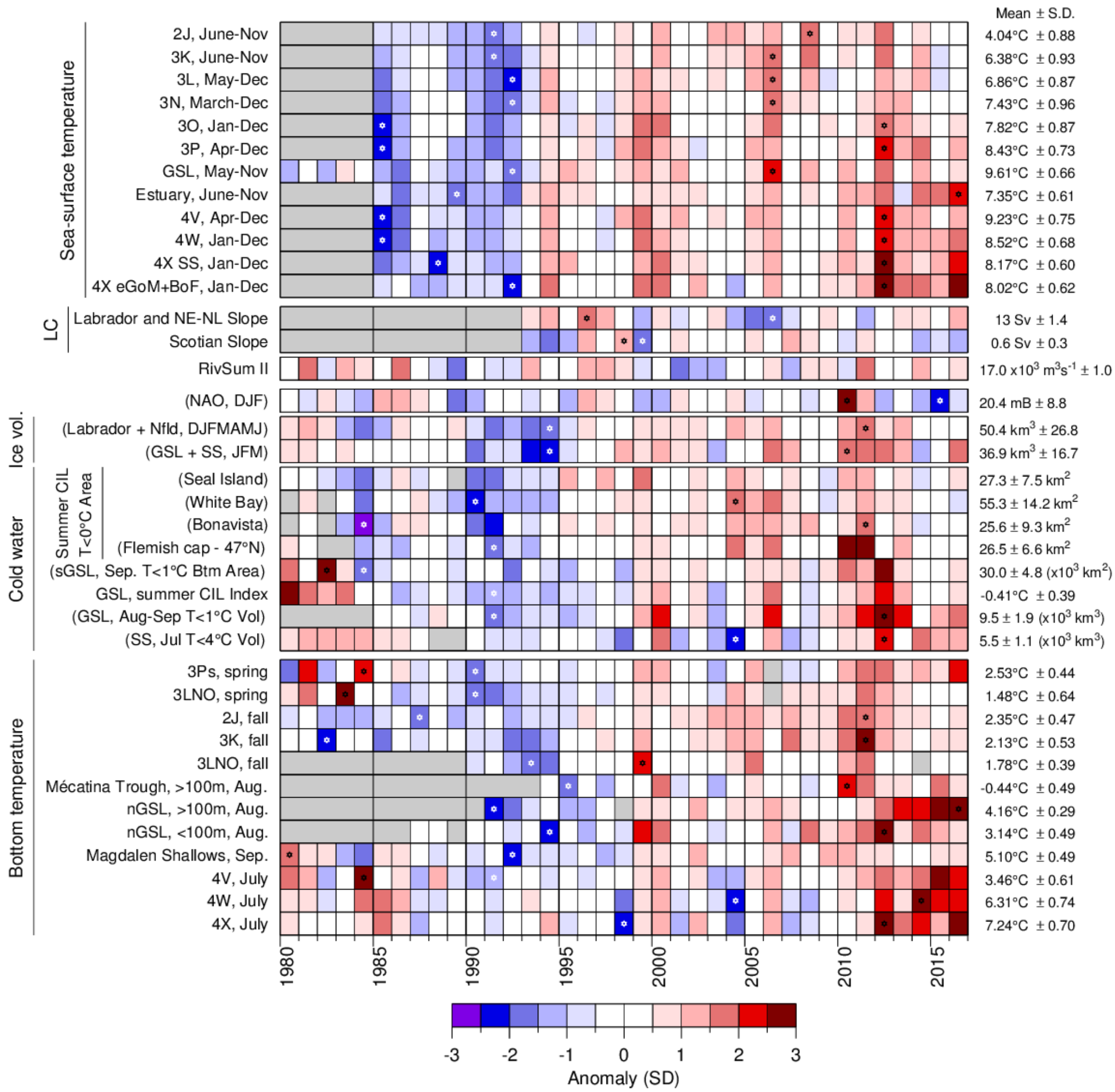


*Figure 7. Time series of oceanographic variables, 1980–2016. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1981–2010 when possible; a red cell indicates above-normal conditions, and a blue cell below-normal. Variables whose names appear 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 minimums 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]).*

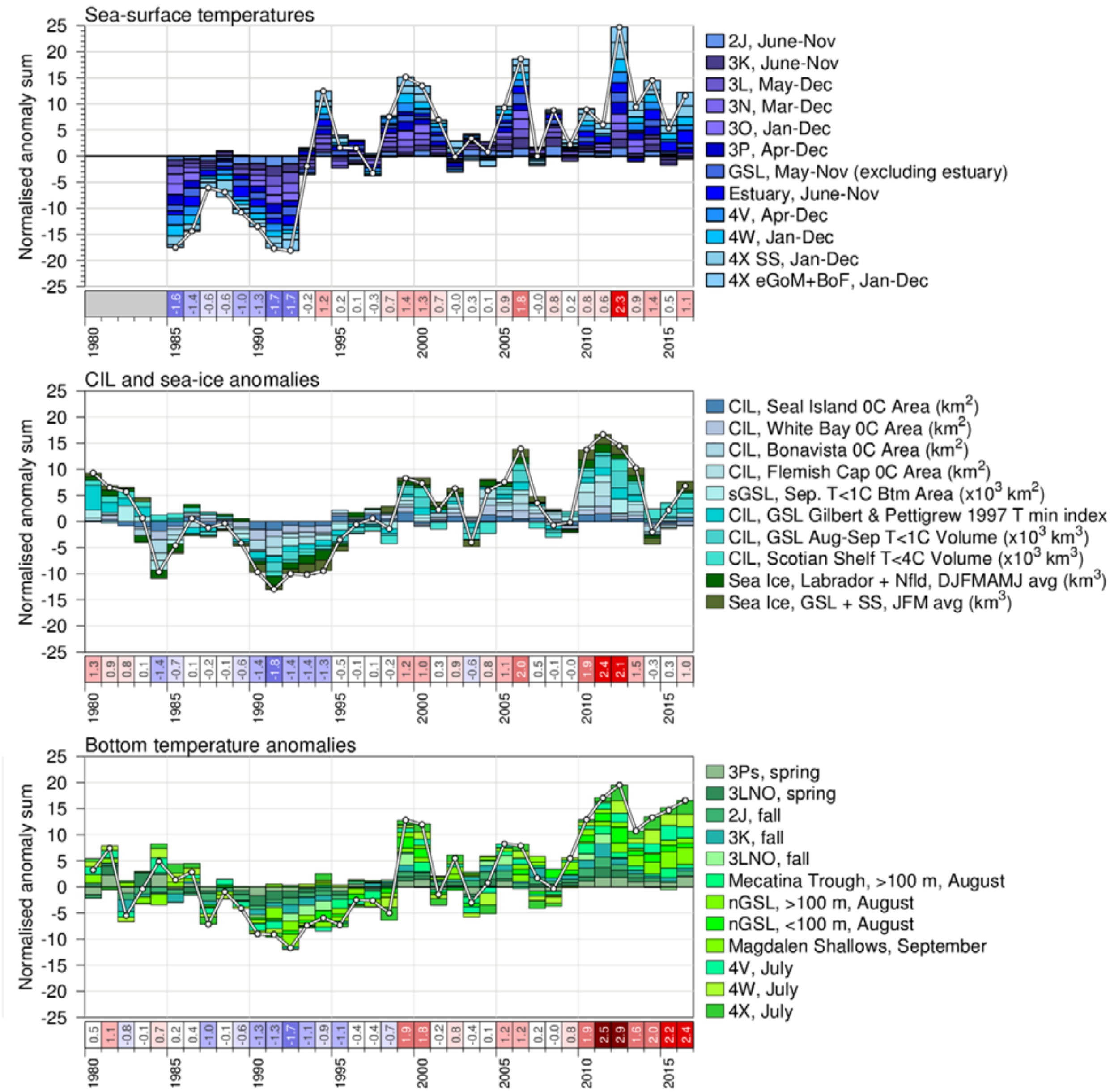


*Figure 8. Composite climate indices (white lines and dots) derived by summing various standardized anomalies from different parts of the environment (colored boxes stacked above the abscissa are positive anomalies, and below are negative). Top panel sums sea-surface temperature anomalies, middle panel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

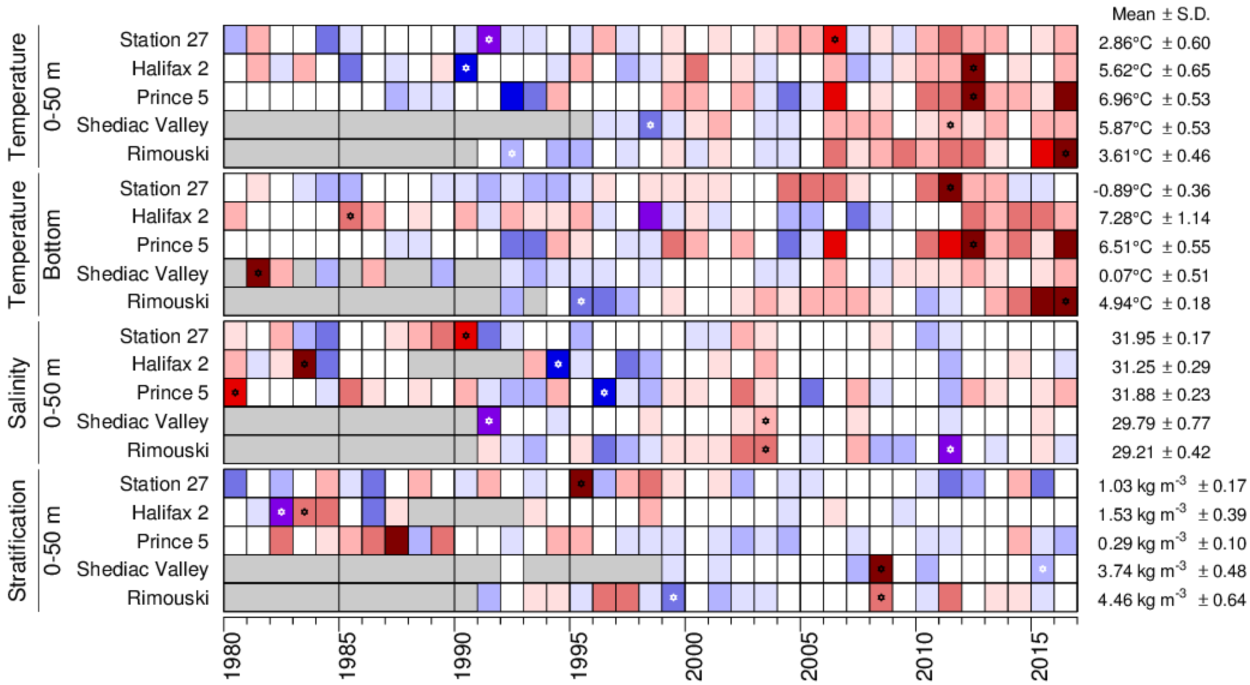


*Figure 9. Time series of oceanographic variables at AZMP high-frequency sampling stations, 1980–2016. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1981–2010 when possible; for high-frequency station depth-averaged temperature, a red 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 minimums 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.*

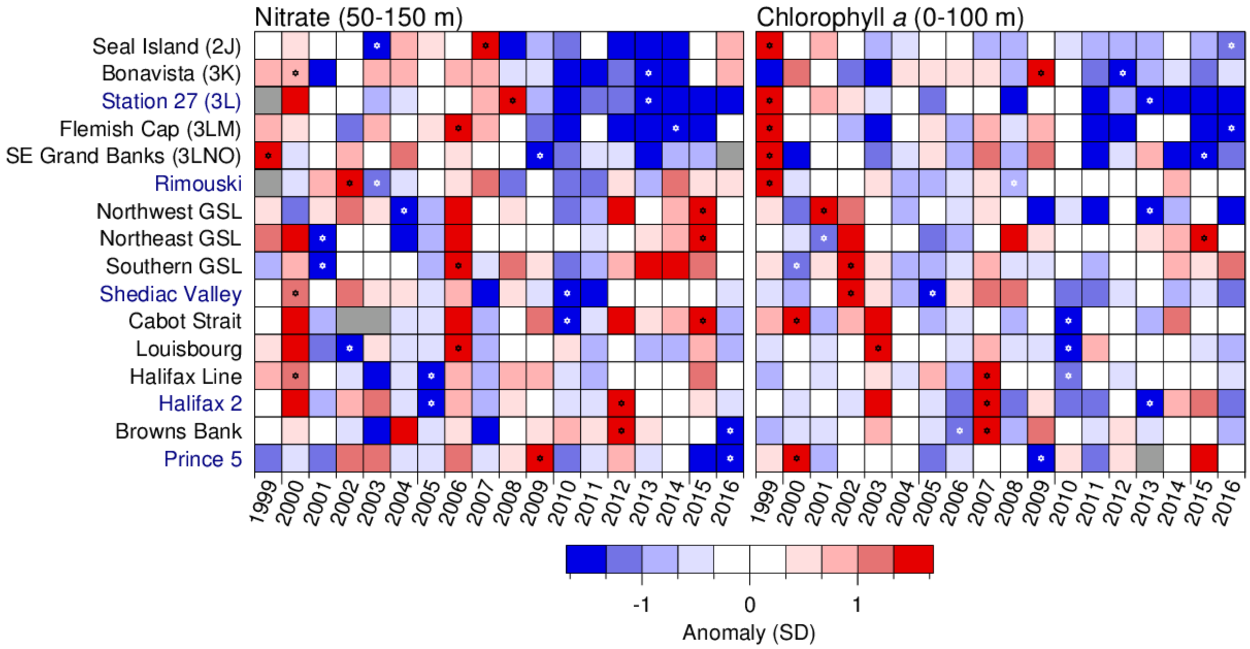


*Figure 10. Time series of deep water nitrate inventories (50-150 m) and surface phytoplankton standing stocks (expressed as chlorophyll a 0-100 m mean concentration) at AZMP sections (labelled in red in Figure 2) and high-frequency sampling stations (labelled in blacks in Figure 2), 1999–2016. A grey 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 minimums and maximums are indicated by a star; note change in palette.*

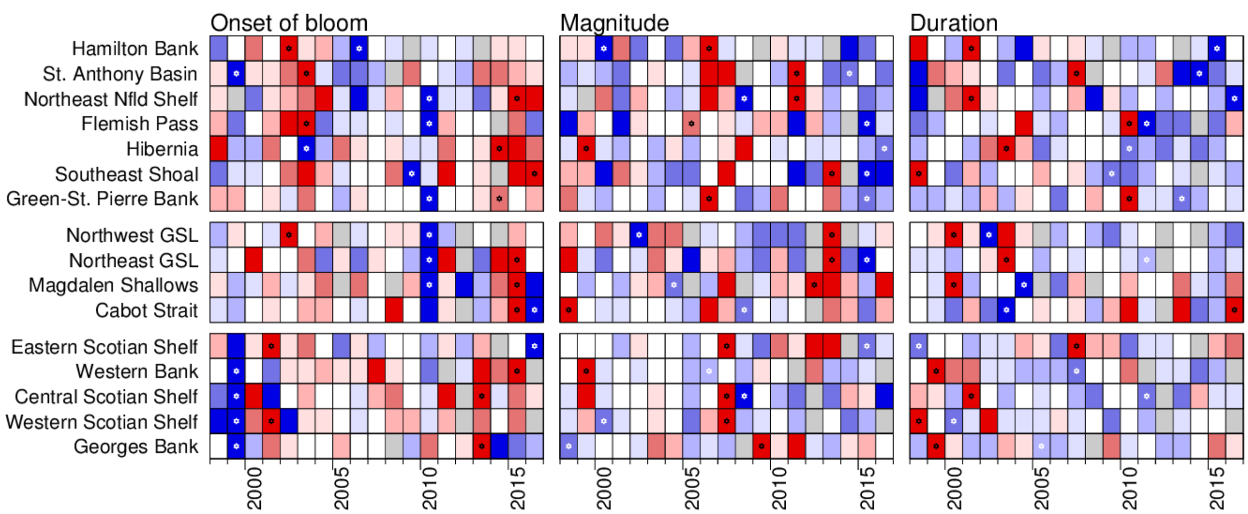


*Figure 11. Time series of remotely sensed bloom parameter anomalies in various regions (onset of bloom, magnitude and duration) 1998-2016. Data are from SeaWIFS for the period 1998-2007, from MODIS for 2008-11, and VIIRS for 2012-16. Series minimums and maximums are indicated by a star. See Figure 3 for area definitions. Palette as in Figure 10.*

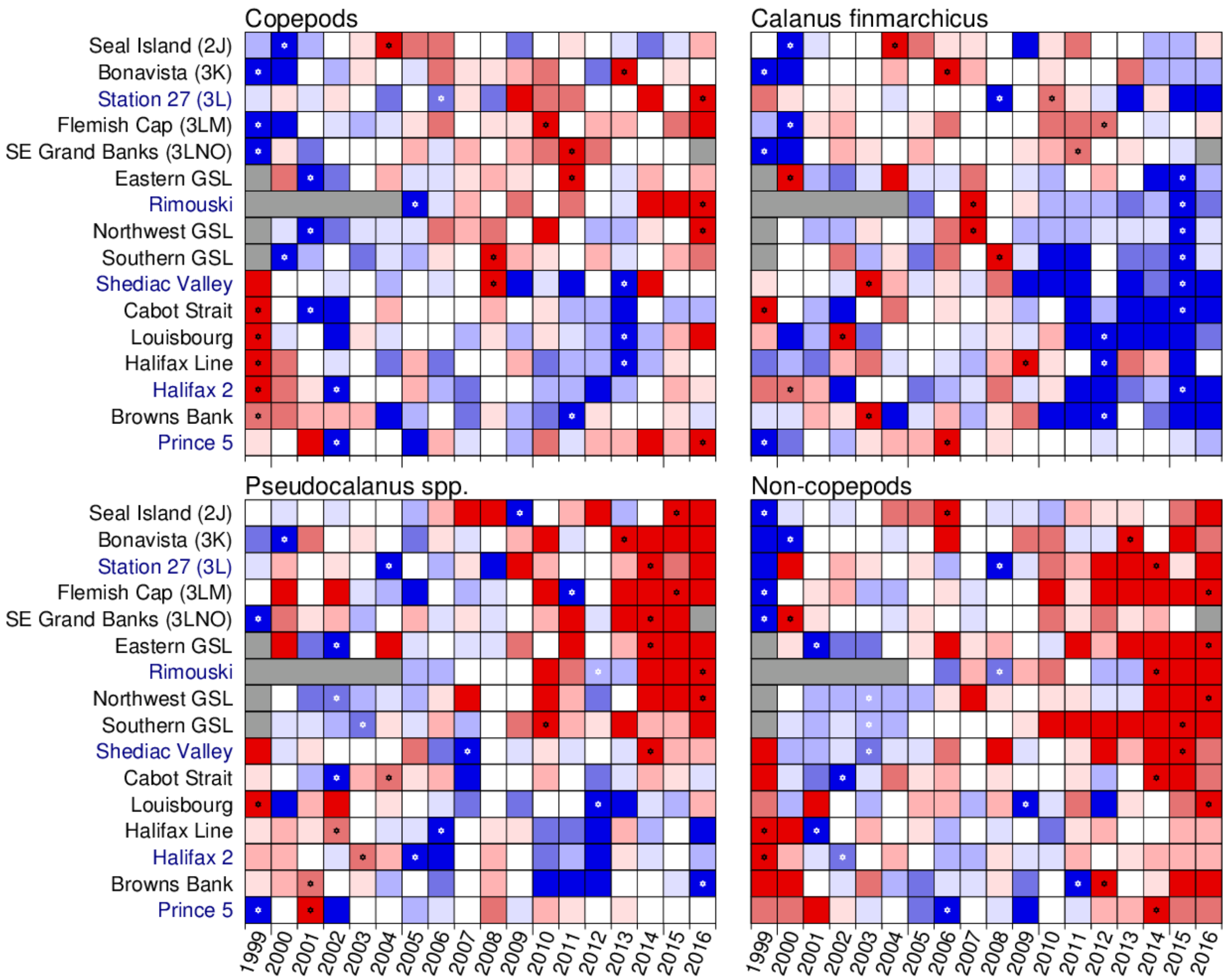


*Figure 12. Time series of the standing stocks of total copepods, C. finmarchicus, Pseudocalanus spp., and non-copepod zooplankton, 1999–2015. A grey cell indicates missing data, a white cell is a value within 0.5 SD of the long-term mean based on data from 1999–2010; a red cell indicates above normal inventories, a blue cell below normal. More intense colours indicate larger anomalies. Series minimums and maximums are indicated by a star. Palette as in Figure 10.*

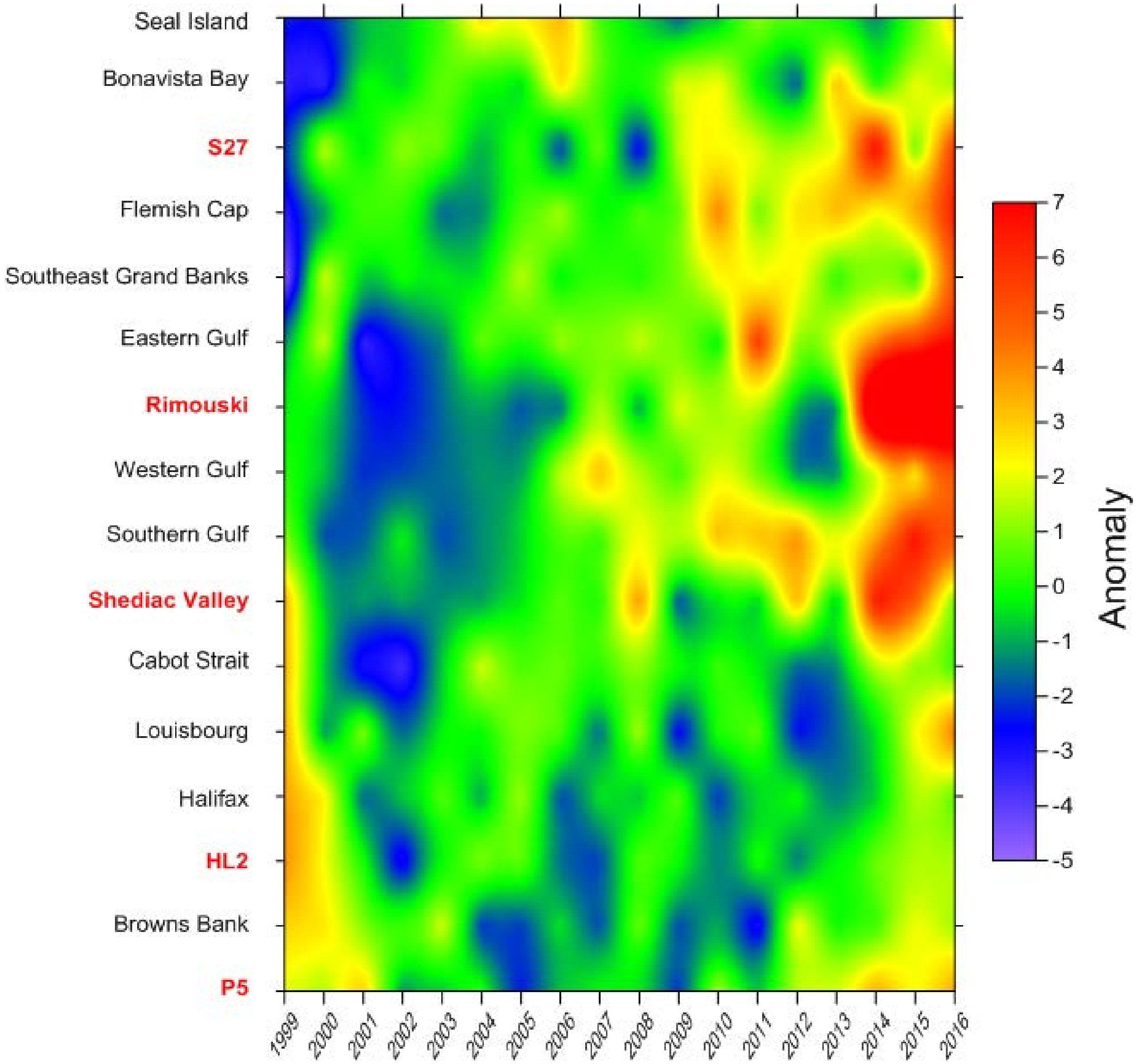


*Figure 13. Schematic heat map of the summed copepod and non-copepod abundance anomalies along oceanographic sections and at high frequency sampling stations (highlighted in red on the left); blue indicates below average abundance while red indicate above average abundance.*

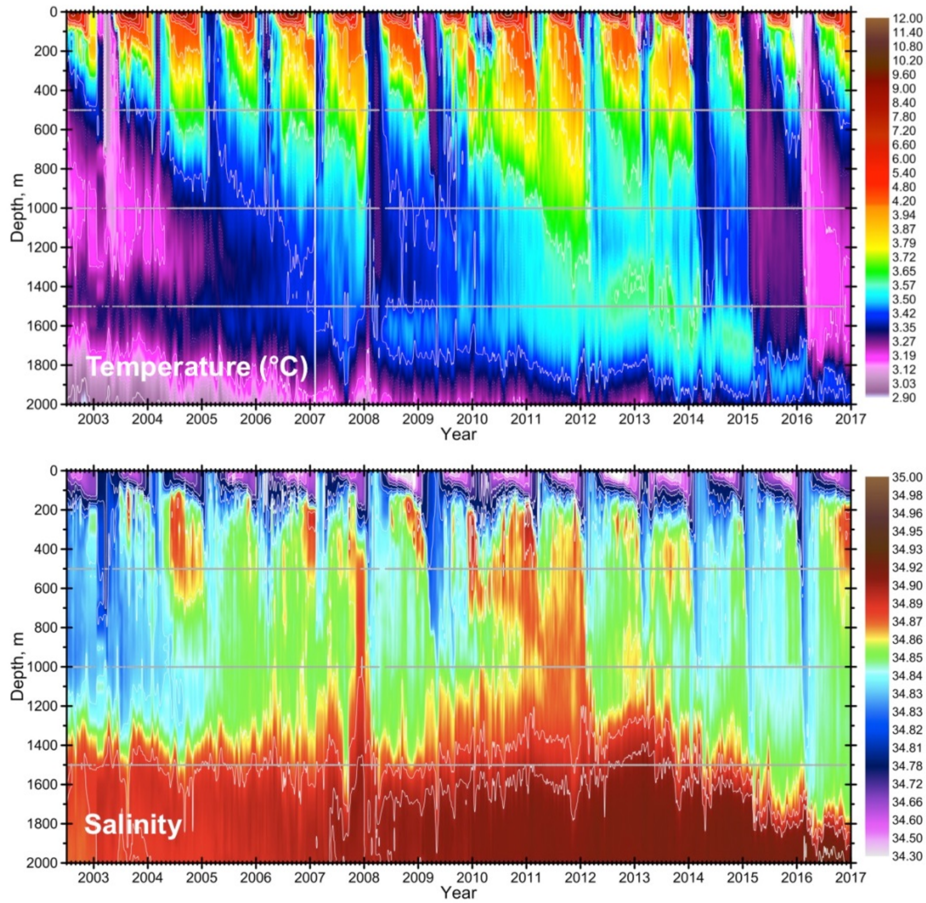


*Figure 14 Temperature and salinity in the central Labrador Sea based on the measurements collected by the Argo floats and research vessels during 2002-16.*

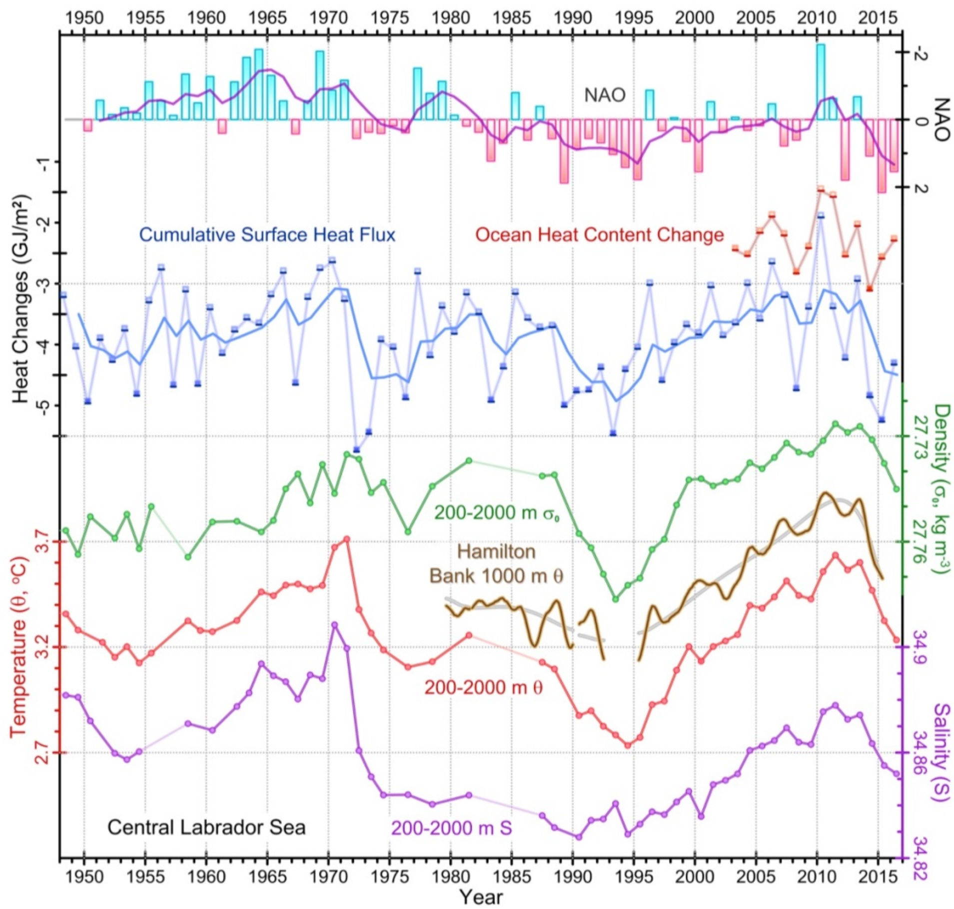


*Figure 15. Key climatic indices for the central Labrador Sea since 1948. The upper bar graph shows the normalized winter NAO index (inverted scale). The next two time series represent heat changes in the central Labrador Sea during each yearly cooling season: first, the change in ocean heat content 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 ($\sigma_0$, referenced to the surface; inverted scale), mean temperature (θ) and salinity (S) averaged over the 200–2,000 m interval in the central Labrador Sea, and temperature from near-bottom current meter at about/approximately 1,000 m depth east of Hamilton Bank.*

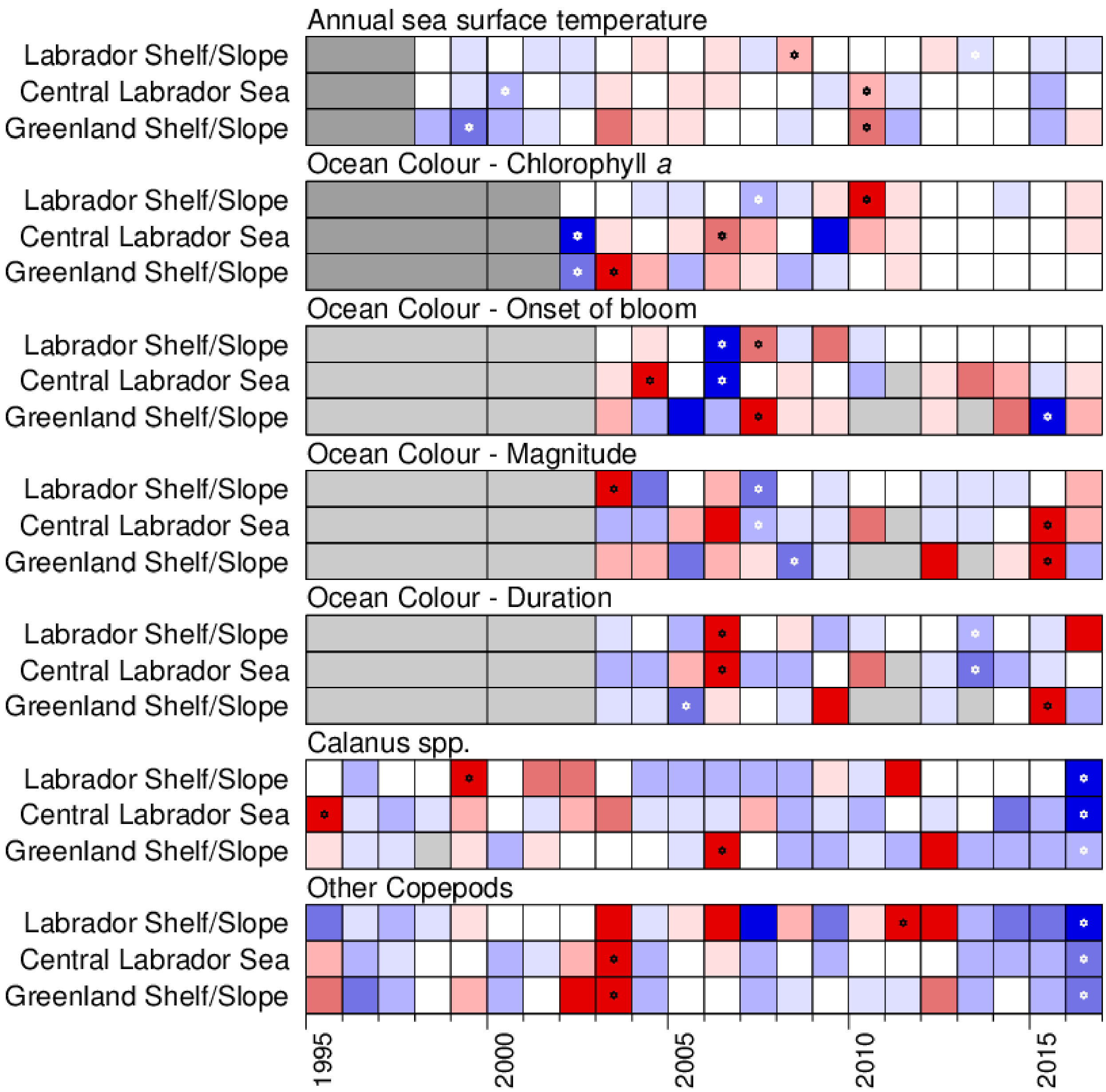


*Figure 14. Normalized annual anomalies of remote sensed SST integrated over the Labrador Sea. Bloom parameters (onset of bloom, magnitude and duration) are derived from remote sensing observations. Zooplankton data represent anomalies of abundance estimation collected in May/June along the AR7W line between 1995 and 2016. Palette as in Figure 10.*

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