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OCEANOGRAPHIC CONDITIONS IN THE ATLANTIC ZONE IN 2014

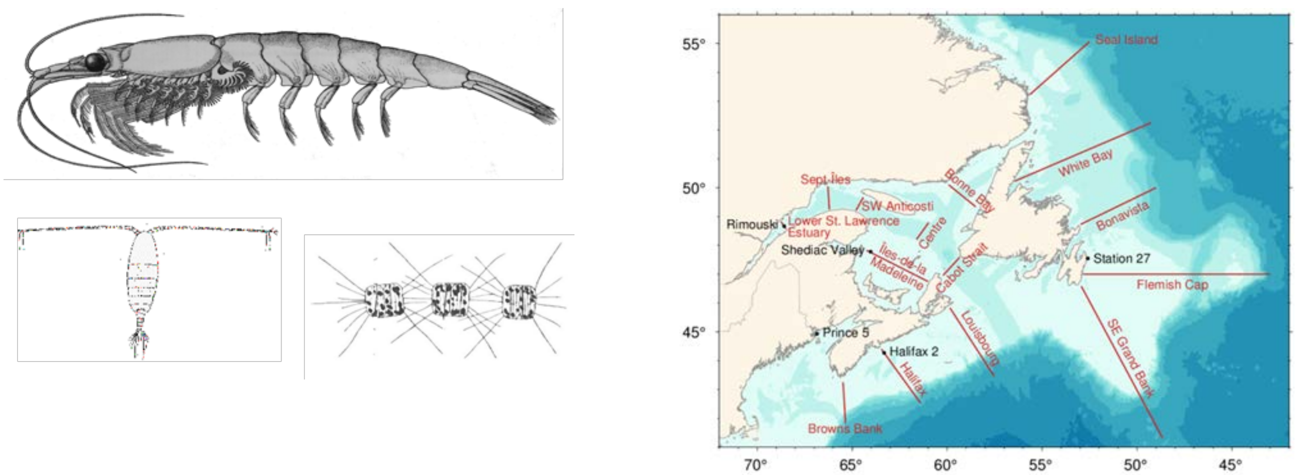

Figure 1. (Left) Key taxa of the pelagic food web: euphausids (top), phytoplankton (bottom right), and copepods (bottom left). Images: Fisheries and Oceans Canada; (Right) Atlantic Zone Monitoring Program high-frequency sampling stations (black) and selected section lines (red).

Context:

The Atlantic Zone Monitoring Program (AZMP) was implemented in 1998 with the aim of increasing 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

- Surface temperatures averaged over all ice-free months were at record highs in the St. Lawrence Estuary and were above normal in all but one region across the zone.
- August surface temperatures were at record highs in 7 of 12 regions in the zone. Surface temperatures in Division 4X-east and Gulf of Maine-Bay of Fundy were at record highs for the months of September through December.
- Sea ice volume returned to near normal conditions on the Newfoundland and Labrador (NL) Shelf, highest since 1994, and to the highest average volume in the Gulf of St. Lawrence since 2003. Sea ice was exported to the Scotian Shelf for the first time since 2009.
- Cold Intermediate Layer (CIL) area or volume showed a gradient from larger than normal on the Newfoundland and Labrador Shelf to near normal in the Gulf of St. Lawrence and smaller than

normal on the Scotian Shelf. The CIL area on the Grand Banks was the largest since 1985 in spring and since 1997 in July. The July CIL on the Scotian Shelf was the second smallest and was related to transport of warm waters from offshore.

- Bottom temperatures were generally normal or above normal across the zone, including record highs in the deeper waters of the northern Gulf of St. Lawrence and in 4W.
- At high-frequency sampling stations, the 0-50 m temperatures and stratification were normal to above-normal, and the salinities were near-normal.
- Bottom temperatures were below normal at Station 27, near-normal at the Shediac Valley station where bottom temperatures are influenced by CIL conditions, and above-normal at Halifax 2, Prince 5 and Rimouski station. Temperatures were at a series record high at Rimouski station.
- Seasonal cycles in air and sea surface temperature showed a year of extremes: temperatures were well below average in winter, while well above average values and record highs occurred in summer.
- The Labrador Current transport index was near normal over the Labrador and northeastern Newfoundland Slope and below normal over the Scotian Slope.
- In the Labrador Sea, extreme heat losses in the winter of 2013-14 led to the most significant volume of newly ventilated Labrador Sea Water since 2007-08. Winter-time mixed-layer depths in 2013-14 exceeded 1700 m.
- Two notable freshening events were observed in 2008-10 and 2011-14 across the Labrador Sea.
- Deep nitrate inventories on the Newfoundland and Labrador Shelf in 2014 averaged 2.5 SD below normal, continuing the decline that started in 2008. In contrast, deep nitrate inventories in the Gulf of St. Lawrence have increased since 2010, now averaging 0.95 SD above normal. Deep nitrate inventories are near normal on most of the Scotian Shelf.
- Chlorophyll *a* inventories were near the long-term average throughout much of the Atlantic Zone.
- Since 2004, there has been a trend toward an earlier onset of the spring phytoplankton bloom coupled with lower spring bloom magnitude in the waters off Newfoundland.
- A delayed onset of the spring bloom throughout most of the Atlantic zone in 2014 may have been a reflection of the cold winter in that year. The magnitude of the spring bloom was also below normal throughout most of the zone.
- In 2014, copepod abundance throughout most of the zone has increased relative to levels observed in 2013 but declined to below normal levels in the Labrador Sea and off northern Newfoundland.
- The abundance of *Calanus finmarchicus* was below to well below normal through much of the Atlantic Zone and the Labrador Sea, with the exception of the Central Scotian Shelf.
- The abundance of *Pseudocalanus* spp. increased throughout the Gulf of St. Lawrence and most of the Newfoundland Shelf while there has been a decline on the Scotian Shelf and Labrador Shelf.
- Non-copepod taxa demonstrated a considerable increase in abundance on the Grand Banks and throughout the Gulf of St. Lawrence and Cabot Strait. This appears to be the continuation of a trend that started in 2004.

BACKGROUND

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

(1) increasing the 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 observational 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. An understanding of the production cycles of plankton is an essential part of an ecosystem approach to stock assessment and fisheries management.

The AZMP derives its information on the state of the marine ecosystem from data collected at a network of sampling locations (high-frequency stations, cross-shelf sections, ecosystem surveys) in each of DFO's administrative regions in Eastern Canada (Quebec, Maritimes, Gulf, Newfoundland and Labrador) sampled at a frequency of weekly to once annually (Figure 1). The sampling design provides for basic information on the natural variability in physical, chemical, and biological properties of the Northwest Atlantic continental shelf. Trawl (groundfish) 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.

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 nutrients, phytoplankton and zooplankton. Similarly, blue represents colder than normal conditions, and 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 2014 for eastern Canadian oceanic waters (Figure 2) as reported annually by the Atlantic Zonal Monitoring Program (AZMP) in three reports (e.g. Colbourne *et al.* 2014, Galbraith *et al.* 2014 and Hebert *et al.* 2014 for conditions of 2013).

Air temperatures were below normal across the zone in winter and spring, transitioned to record highs in the summer, remaining above normal in the fall. Averaged over 13 meteorological stations in the Gulf of St. Lawrence, July had the warmest air temperatures on record, since 1873 (+2.1°C, +2.3 SD). Series record highs were set for that month at Plum Point (since 1972, +3.2°C, +2.4 SD), Baie-Comeau (since 1965, +2.2°C, +3.0 SD), Îles-de-la-Madeleine (since 1934, +2.8°C, +2.0 SD) and Daniel's Harbour (since 1947, +3.6°C, +2.5 SD), while the air temperature reached a high since 1921 at Stephenville (+2.8°C, +2.5 SD). The warm spell persisted into August in the St. Lawrence Estuary and northwest Gulf, with an anomaly of +2.2°C at Sept-Îles (highest since 1955; +2.3 SD) and anomalies of +1.8°C at Mont-Joli and Baie-Comeau. In Newfoundland and Labrador (Cartwright and St. John's), annual mean air temperatures were near normal. Of the stations on the Scotian Shelf, Sable Island had the largest anomaly (+1.2°C, +1.7 SD), Shearwater and Yarmouth were above normal at +0.7°C (+0.9 SD) and +0.6°C (+0.9 SD) respectively, but other stations had near normal anomalies.

Sea-surface temperatures (SST) during ice-free months were at a record-high in the Estuary and were above normal in all but one region across the zone in spite of below normal spring temperatures in many areas (Figures 3 to 5). While the seasonal average anomalies were not as high as the record highs observed for many regions in 2012, August surface temperatures were at record highs in 7 of the 12 areas (Figure 5). Surface temperatures in Division 4X-east Gulf of Maine-Bay of Fundy were record highs for the months of September through December (Figure 5).

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. For example, the average 0–20 m salinity in the Magdalen Shallows (not shown) for the low runoff period of 1999-2007 is approximately 0.5 salinity units more than the average for high runoff years in the 1970s,1980s, and 1990s. This represents approximately an extra 17 km^3 of freshwater in the upper 20 m of the Shallows. The runoff into the St. Lawrence Estuary had been decreasing since the early 1970s but appears to be increasing again since 2001 (Figure 6). The mean runoff was above-normal (+1.1 SD) in 2014, as was the spring freshet (+1.8 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 2014, the winter NAO index was above-normal (+1.3 SD; 5th largest positive value), consistent with the low winter air temperatures the highest volume of sea ice since 1994 on the NL Shelf and the overall increase in CIL area (Figure 6). The last occurrences of such a high value were in 1995 and 2012.

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 2014, sea ice volume returned to near-normal conditions on the NL Shelf (+0.5 SD) and increased to the highest average volume in the Gulf of St. Lawrence since 2003 (Figure 6). Sea-ice was exported to the Scotian Shelf for the first time since 2009.

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 6). For the latest 30 year period, the highest similarities are found between cold water indices from the southern Labrador and northeast Newfoundland Shelf and the northern Grand Bank, followed by similarities between the Gulf of St. Lawrence and the Scotian Shelf. CIL conditions represented colder-than-normal to normal conditions on the NL Shelf in 2014. The Gulf of St. Lawrence CIL returned to near-normal in 2014 after the record (since the early 1980s) warm and thin conditions of 2012. The Scotian Shelf CIL volume (T <4°C) was small, second lowest of the time series after the record low of 2012 and was related to transport of warm waters from offshore. Thus a north-to-south gradient was observed in CIL conditions.

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 4W of the Scotian Shelf (Figure 6). However this represents a decrease on the NL Shelf in Divisions 3LNO and 3K after record highs were recorded in 2011. A series record high was recorded in the northern Gulf in deeper waters (depths greater than 100 m, +2.0 SD) as a warm anomaly first observed in Cabot Strait in 2010 is propagating towards the heads of the channels. Bottom temperatures in Esquiman Channel were at a record high in 2014, with large areas exceeding 6°C. Warm waters have again been observed at 200-300 m in Cabot Strait in 2014, indicating that the average temperature of the deep waters of the Gulf should continue to increase in the next 2 or 3 years.

Figure 7 shows three annual composite index time series constructed as the sum of anomalies from Figure 6, 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 2014 were above-normal for surface and bottom water temperatures, and overall near-normal for CIL conditions. The sea-surface temperatures were second-highest of the time series, while the bottom temperatures were third highest.

In 2014, annually averaged 0-50 m temperatures at high-frequency sampling stations were above-normal (+0.6 and +1.3 SD) at Halifax 2 and Prince 5, and near-normal at other stations (Figure 8). Bottom temperatures were below normal at Station 27, near-normal at the Shediac Valley station where bottom temperatures are influenced by CIL conditions, and above-normal at Halifax 2, Prince 5 and Rimouski station. Temperatures were at a series record high at Rimouski station (5.29°C; +0.26°C; +1.8 SD). The annual 0-50 m salinity anomalies were near-normal across the zone. The annual 0–50 m stratification index was either near-normal or above-normal at all stations. Over a large scale, stratification on the Scotian Shelf weakened in 2014 compared to 2013 due to an increase in surface density as a result of a higher salinity, and was nearly equal to the 1981-2010 mean value. 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 0.31 kg m^{-3} over 50 years. This change in mean stratification is due mainly to a decrease in the surface density (85% of the total density change), composed of half warming and half freshening.

A total of 43 indices listed in Figures 6 and 8 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, 4 were colder than normal, 15 were within normal values and 24 were above normal, indicating a continuation of warmer than normal oceanographic conditions in 2014.

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 6). 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 three years the Labrador Current was close to its normal strength. In 2014 its annual-mean transport was near normal over the Labrador and northeastern Newfoundland Slope and below normal by 0.6 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 representing nitrate inventories, phytoplankton standing stock, features of the spring phytoplankton bloom derived from satellite observations, and zooplankton abundance from the Newfoundland and Labrador Shelf (NL) (Pepin *et al*. 2015), Gulf of St. Lawrence (GSL) (Plourde *et al.* 2014) and Scotian Shelf (SS) (Johnson *et al*. 2014) are summarized as time series (1999-2014) of annual values in matrix form in Figures 9-11.

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 inter-annual 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 1999-2014 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 variability among regions. Deep inventories in the Newfoundland Region continued the decline that started in 2008 and in 2014 averaged 2.5 SD below the 1999-2010 mean (Figure 9). In contrast, deep inventories in the Gulf of St. Lawrence have shown a general increase since 2010, now averaging 0.95 SD above normal, although there is considerable variability at individual sites from year-to-year. Conditions on the Scotian Shelf show considerable site-to-site variability, with the highest and lowest values occurring in the eastern part of the region whereas the central and western shelf areas were near the long term average.

Chlorophyll inventories (0-100 m; Figure 9), 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 were near the long-term average throughout much of the Atlantic Zone in 2014, within approximately ± ⅔ SD units of the 1999-2010 average. Chlorophyll anomalies have been below normal across much of the Newfoundland and Labrador Shelf since 2010 and have demonstrated considerable interannual variability on the Grand Banks in recent years. 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 on the Newfoundland Shelf 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 10). Conditions in 2014 show a general change toward a delayed onset of the spring bloom, a reflection of the cold winter in that year, with the exception of the SE Shoal and areas from the Central Scotian Shelf to Georges Bank. In general, the magnitude of the spring bloom was below to well below average, with the exception of the area over the SE Shoal.

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 2014, zooplankton abundance indices demonstrated relatively large scale coherence (Figure 11). Copepod abundance throughout much of the zone has increased consistently relative to levels observed in 2013, with the exception of the northeast Newfoundland Shelf (NAFO areas 2J3K) where a notable decline has occurred. The abundance of *Calanus finmarchicus*, a key species in most ecosystems of the North Atlantic and an important prey for many species of planktivorous fish, is below to well below normal throughout much of the Atlantic Zone, with the exception of the Central Scotian Shelf (Halifax line). The abundance of *C. finmarchicus* has been below normal for approximately 5 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. Its abundance reached the lowest levels on record in parts of the Gulf of St. Lawrence and on the eastern Scotian Shelf (Cabot Strait and Louisbourg), whereas abundance levels were only slightly below normal across most of the Newfoundland and Labrador Shelf. The abundance of *Pseudocalanus* spp., another important prey for many species of young fish, increased in 2014 throughout much of the Gulf of St. Lawrence and the Newfoundland Shelf while there was a decline on the Scotian Shelf and off Labrador.

Non-copepod zooplankton consists principally of the larval stages of benthic invertebrates and many of the carnivores that feed on other zooplankton. In 2014 this group demonstrated a considerable increase in abundance on the Grand Banks and throughout the Gulf of St. Lawrence and Cabot Strait. A variety of taxonomic groups contributed to the increase in non-copepod abundance. The non-copepods have shown a general trend toward increased abundance in these parts of the Atlantic zone over the last 5 years whereas conditions on the Scotian Shelf have seen relatively little change during the same period.

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 11), 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 12). 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 (AZOMP) 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, losses of heat in winter are a key process in the formation of dense waters, which drive the global ocean overturning circulation. In the winter of 2013-14, the mid-high latitude North Atlantic experienced the most extreme heat loss in the region since 1979; this was primarily forced by strong 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 2007-08. Winter-time mixed-layer depths in 2013-14 exceeded 1700 m outlining a reservoir filled with a newly ventilated, cold and fairly fresh LSW, which is rich in carbon dioxide and other dissolved gases. This new LSW is evident in Figure 13, where it is associated with a layer with low temperature (< 3.4°C) and salinity (< 34.86 ppt) between 1000 and 1500 m. In a similar manner to the last significant renewal of LSW (winter 2007-08), the deep and intense winter mixing of 2013-14 has interrupted the general warming trend that has persisted in the intermediate waters of the Labrador Sea since the mid-1990s. Preliminary analysis of research cruise measurements made north of Flemish Cap in June 2014 indicate that the new LSW is already spreading in the subpolar North Atlantic away from its source following the ocean's western boundary and interior pathways.

Two noticeable surface freshening events were observed in 2008-10 and 2011-14 that spread across the Labrador Sea (Figure 13) with the largest near-surface salinity anomalies observed over the Labrador slope. In the earlier period, freshening of the upper layers on the Greenland side of the Labrador Sea more or less coincided with freshening on the Labrador side, while in the latter period freshening in the western Labrador Sea lagged the Greenland-side by almost a year. Furthermore, a delay of about one year was observed in the spreading of this freshening from either side of the Labrador Sea into the interior. During the convection period this fresh anomaly was mixed into the intermediate depth layers of the Labrador Sea and helped shape the LSW vintage observed in 2013-14.

These extreme atmospheric and physical ocean properties in the winter of 2013-14 also had profound impacts on the biological properties of the Labrador Sea that can be easily tracked until at least mid-summer. A biweekly climatology of chlorophyll *a* constructed from a time series of remotely-sensed ocean colour from 2003 to 2014 indicates that the annual spring bloom of phytoplankton 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 2014 initiation of the spring bloom was 2-3 weeks late, beginning in the first week of May on the Greenland Shelf and late May on the Labrador Shelf. It is also worth noting the observation of a strong bloom on the Labrador Shelf in October with a concentration of chlorophyll over 2 mg m^{-3}. The annual average normalized anomalies for 2014 were below normal across the Labrador Sea region (Figure 14).

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. The intense deep convection in 2014 in the Labrador Sea seems to have delayed the spring season conditions leading to a low abundance of the *C. finmarchicus* (Figure 14). On the Labrador Shelf, *C. finmarchicus* abundances are generally relatively low in spring, as was the case in 2014 with near-normal conditions. There was no significant trend in springtime abundance of *C. finmarchicus* between 1996 and 2014 on the Labrador Shelf, Labrador Basin or the Greenland Shelf. In the Central Labrador Sea, total *C. finmarchicus* abundance is generally relatively low in spring and summer, with a low proportion of young stages. *Calanus finmarchicus* abundances are generally higher in the eastern Labrador Sea than further west in spring, because the spring bloom starts earlier there, which leads to earlier reproduction in *C. finmarchicus*. Population development Index (PDI) represents the proportion of copepodite stages C1 to C3 over the entire population expressed in percent and shows the magnitude of recently produced young stages within the region. In all three regions of the Labrador Sea, the indices in 2014 were among the lowest observed between 1995 and 2014.

In summary, the severe winter heat loss of 2013-14 was remarkable in magnitude and impacts both in the Labrador Sea and across the mid-high latitude North Atlantic. Furthermore, we can measure these impacts on the biological properties of the Labrador Sea, all the way up to the lower trophic level. The biological response in 2014 was similar to that observed during the previous deep convection event in 2008.

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 site.

CONCLUSIONS

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, remaining generally above-normal in 2014 with record August values in 7 of 12 areas across the zone and setting a new May-November record in the St. Lawrence Estuary. Before 2014, sea ice cover had been below normal for four consecutive winters 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. The Scotian Shelf CIL volume (T<4°C) was contrastingly small (corresponding to warm conditions) with the second lowest value of the time series after the record low of 2012, 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 record highs recorded in Division 4W of the Scotian Shelf (again associated with transport of warm salty offshore waters), as well as 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 close to normal throughout much of the zone although areas of the Newfoundland and Labrador Shelf were below average. 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* is normal across or below normal throughout much of the Atlantic Zone while the abundance of the small copepod *Pseudocalanus* spp. and non-copepod taxa are above normal in the Newfoundland Shelf and the Gulf of St. Lawrence.

SOURCES OF INFORMATION

This Science Advisory Report is from the Seventeenth Annual Meeting of the Atlantic Zone Monitoring Program (AZMP), held March 16-19, 2015. 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., Craig, J., Senciall, D., Bailey, W., Stead, P., and Fitzpatrick, C. 2014. Physical oceanographic conditions on the Newfoundland and Labrador Shelf during 2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/094. v + 38 p.

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APPENDIX I - FIGURES

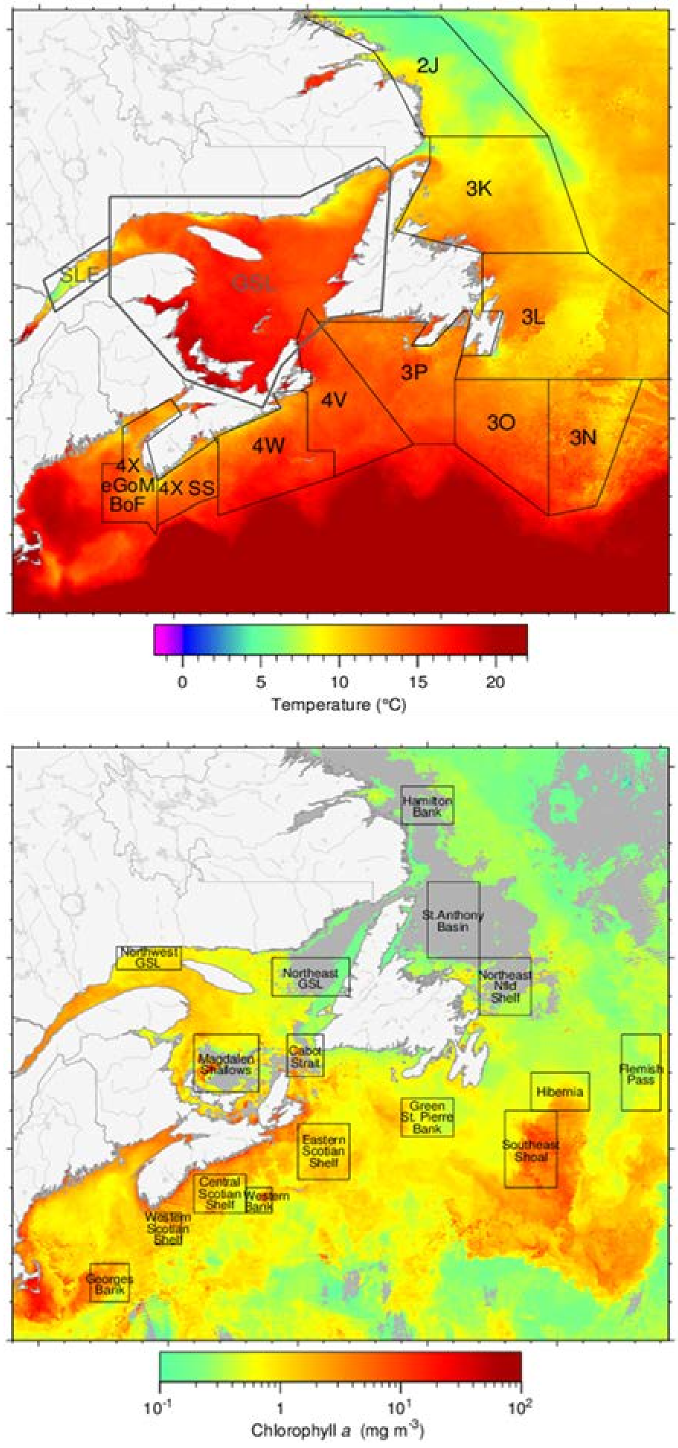

Figure 2. Areas used for (top) temperature and (bottom) ocean color averages. (Top) NAFO Divisions are cut off at the shelf break. The acronyms GSL and SLE stand for Gulf of St. Lawrence and St. Lawrence Estuary respectively. Sea-surface temperatures are shown for July 2014 and ocean colour chlorophyll a *concentrations are for the first half of April 2014, emphasizing that certain areas are still ice covered when the bloom occurs in many parts of the zone.*

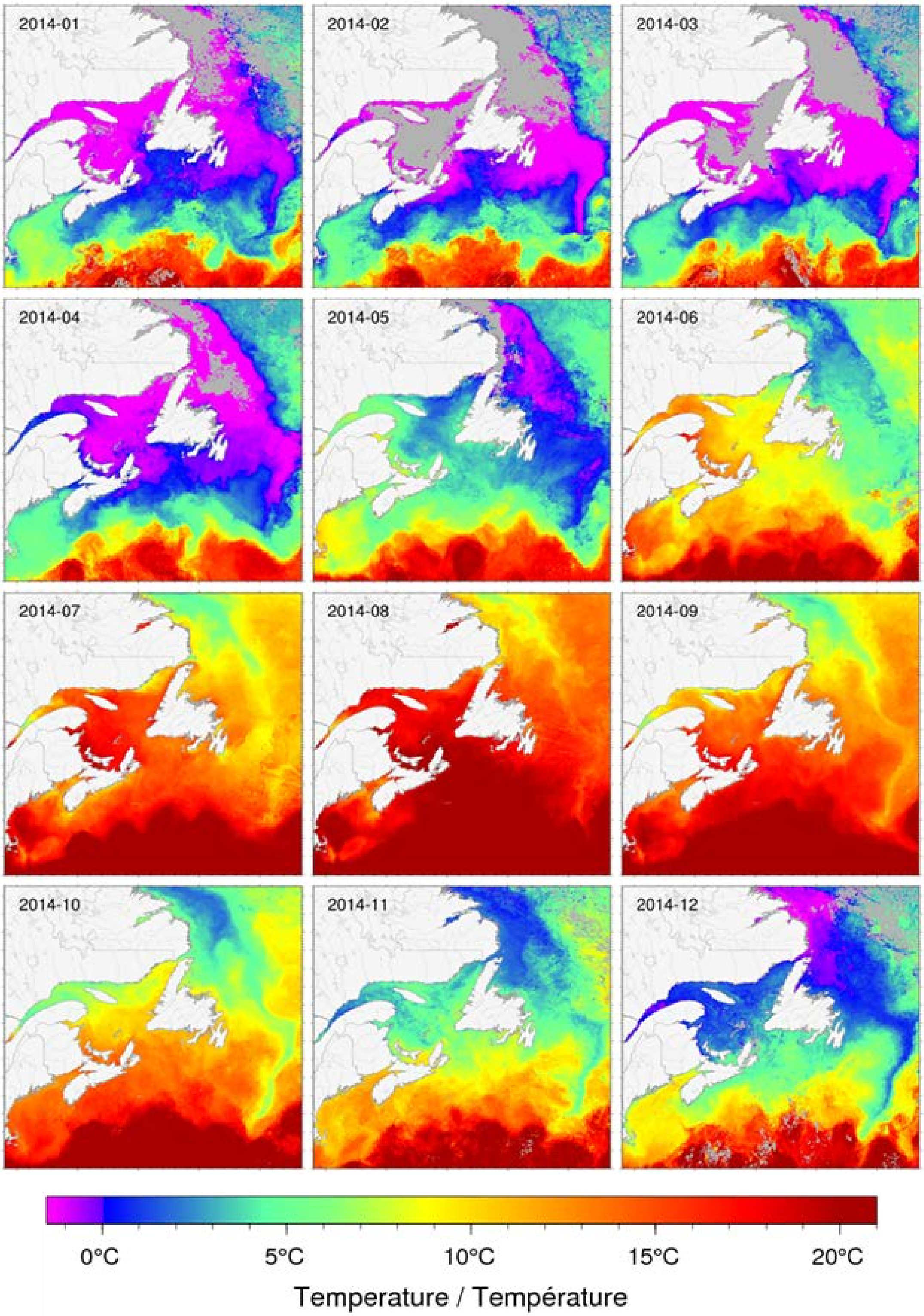

Figure 3. Sea-surface temperature monthly averages for 2014 in the Atlantic zone.

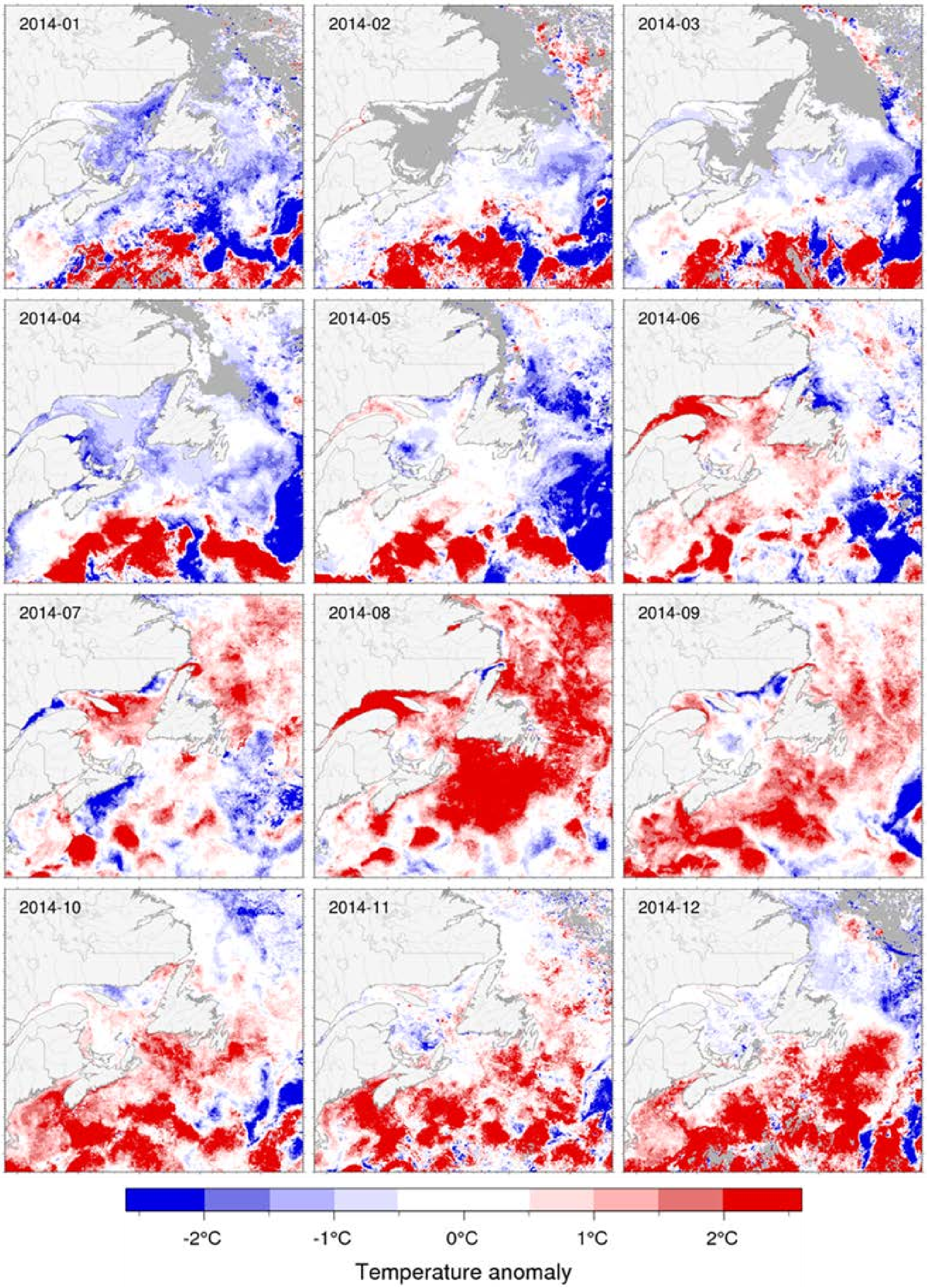

Figure 4. Sea-surface temperature monthly anomalies for 2014 in the Atlantic zone. Temperature anomalies are based on a 1999-2010 climatology.

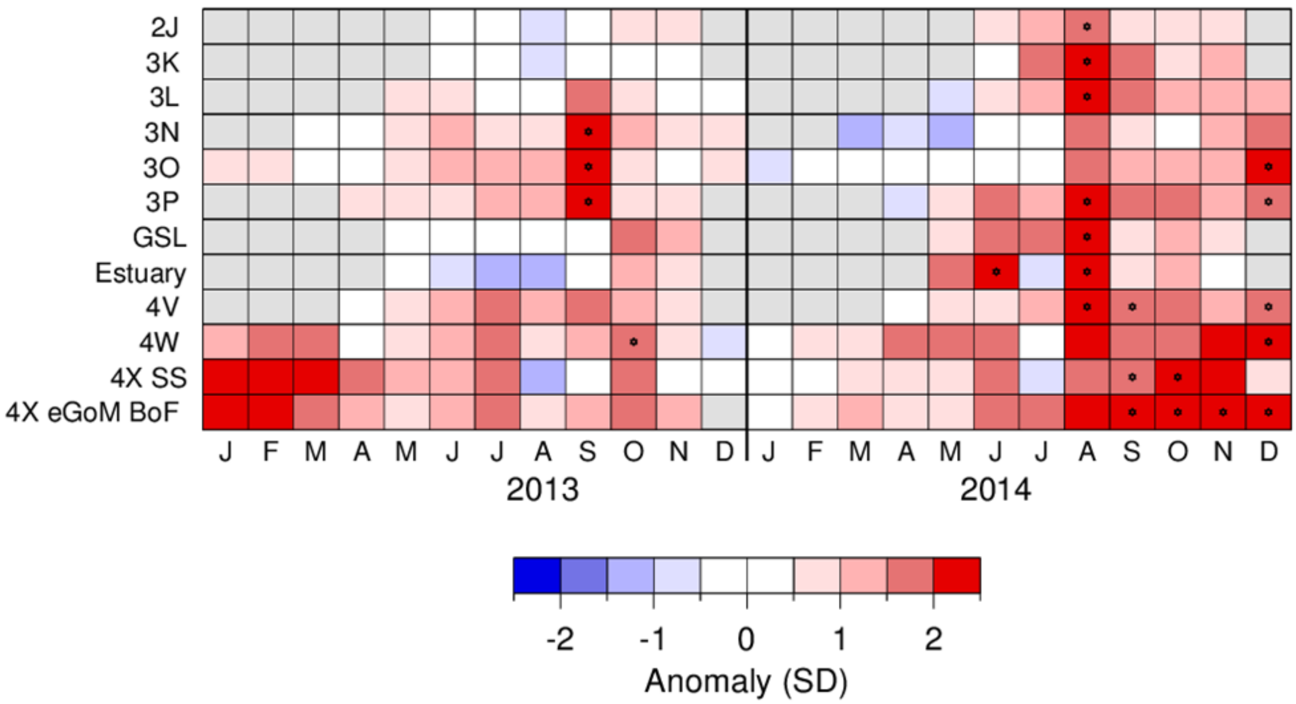

Figure 5. Monthly sea-surface temperature anomalies for ice-free months of 2013-2014, averaged over the 12 regions shown in Figure 2. Regions and months for which the average temperature was at a record high are indicated by a star. Grey cells indicate that data were not available in certain months.

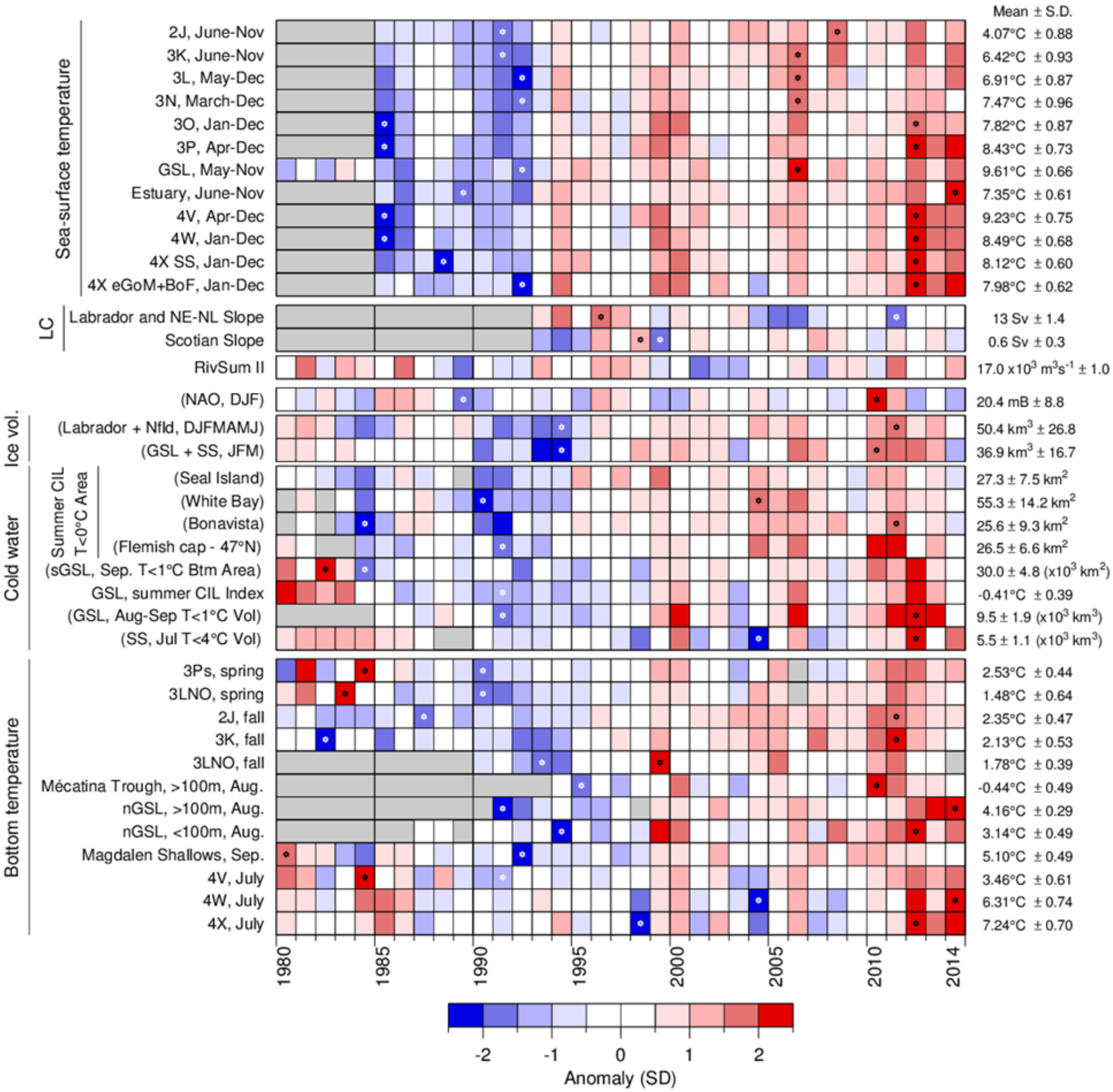

Figure 6. Time series of oceanographic variables,1981–2014. A grey cell indicates missing data, a white cell is a value within 0.5 standard deviation of the long-term mean based on data from 1981–2010 when possible; a red cell indicates above-normal conditions, and a blue cell below-normal. Parameters 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 1980-1984 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]).

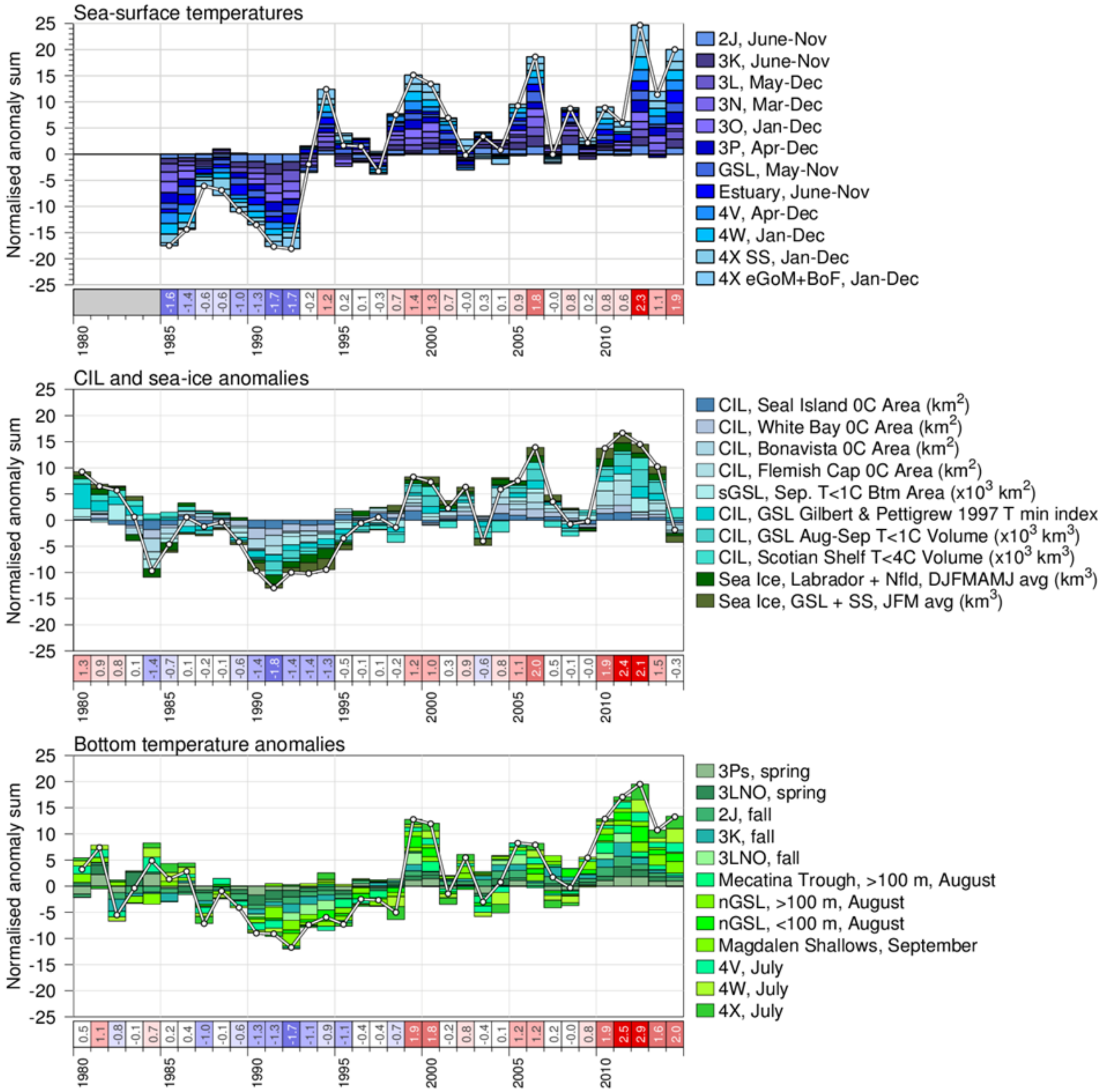

Figure 7. Composite climate indices (white lines and dots) derived by summing various standardized anomalies from different parts of the environment (colored boxes stacked above the abscissa are positive anomalies, and below are negative). Top panel sums sea-surface temperature anomalies, middle panel 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.

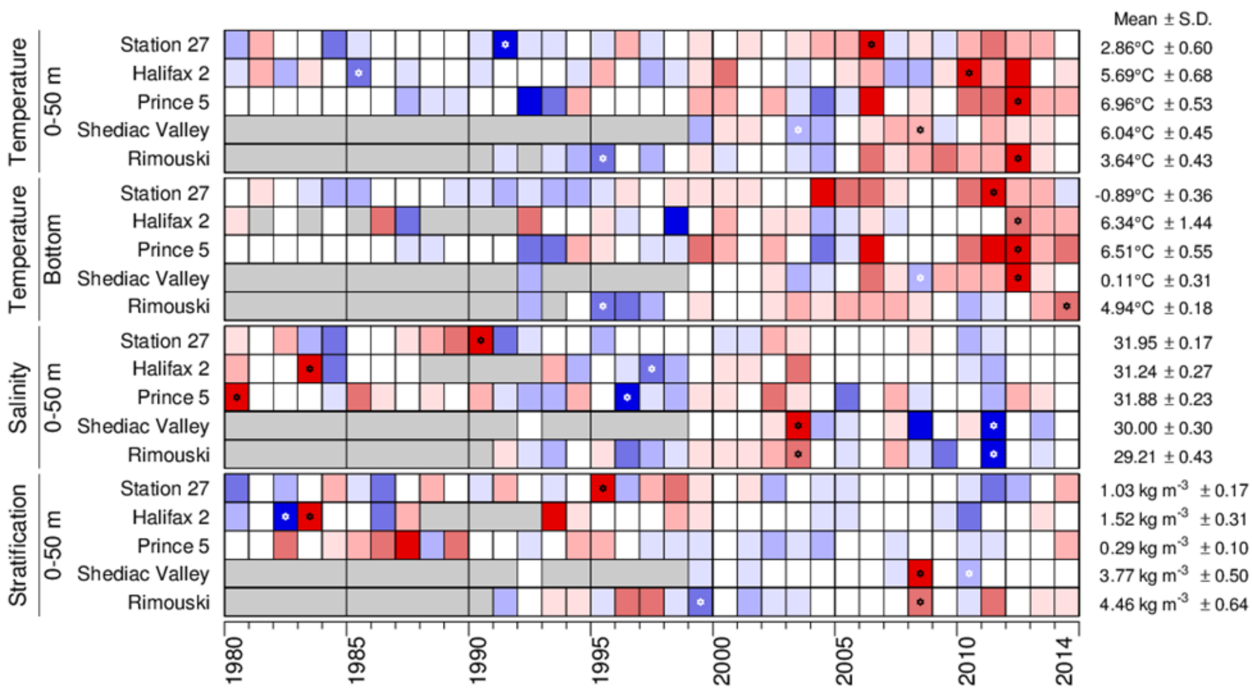

Figure 8. Time series of oceanographic variables at AZMP high-frequency sampling stations, 1981–2014. A grey cell indicates missing data, a white cell is a value within 0.5 standard deviation of the long-term mean based on data from 1981–2010 when possible; for high-frequency station depth-averaged temperature, 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 5 and 6.

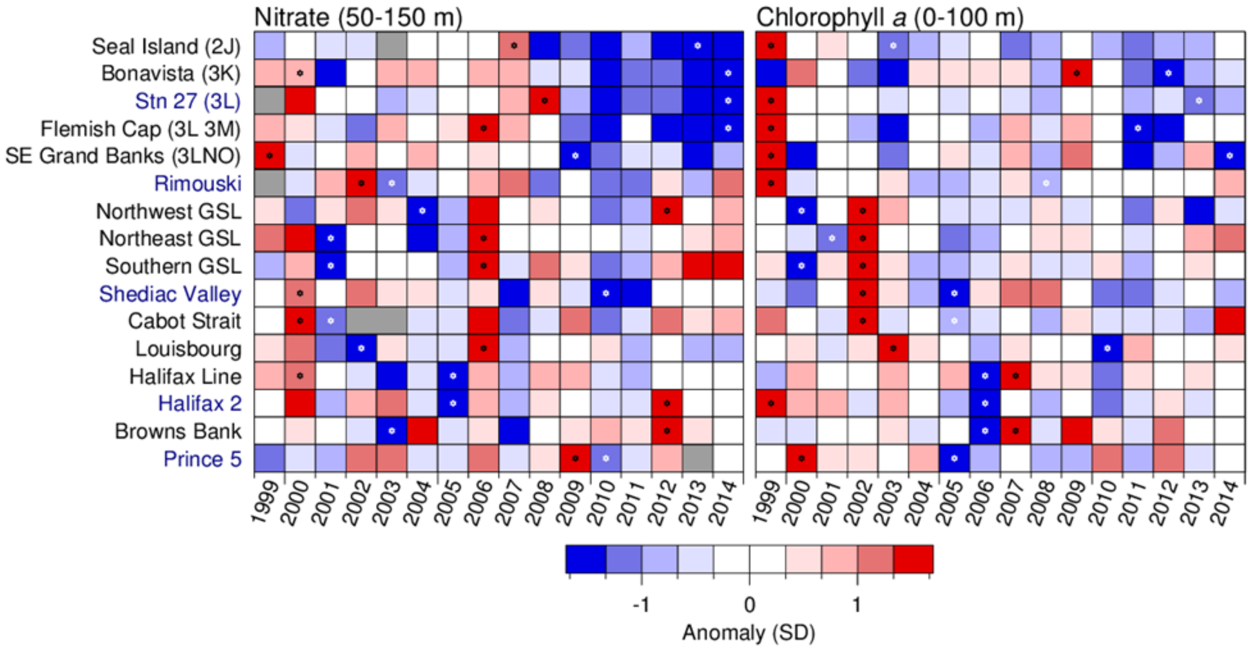

Figure 9. Time series of nitrate inventories for the surface (0-50 m) and phytoplankton standing stocks (expressed as chlorophyll a *0-100 m mean concentration) at AZMP sections (labelled in black) and high-frequency sampling stations (labelled in blue), 1999–2014. A grey cell indicates missing data, a white cell is a value within ± ⅓ standard deviation 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.*

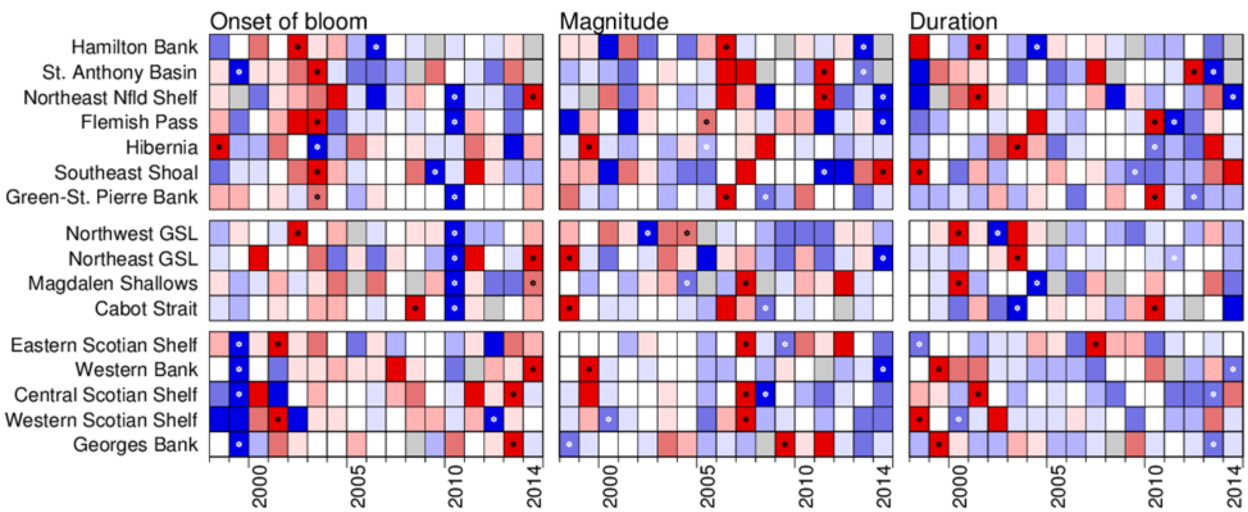

Figure 10. Time series of remotely sensed bloom parameter anomalies in various regions (onset of bloom, magnitude and duration),1998-2014. Data are from SeaWIFS for the period 1998-2008 and from MODIS onwards. Series minimum and maximums are indicated by a star. See Figure 2 for area definitions. Palette as in Figure 9.

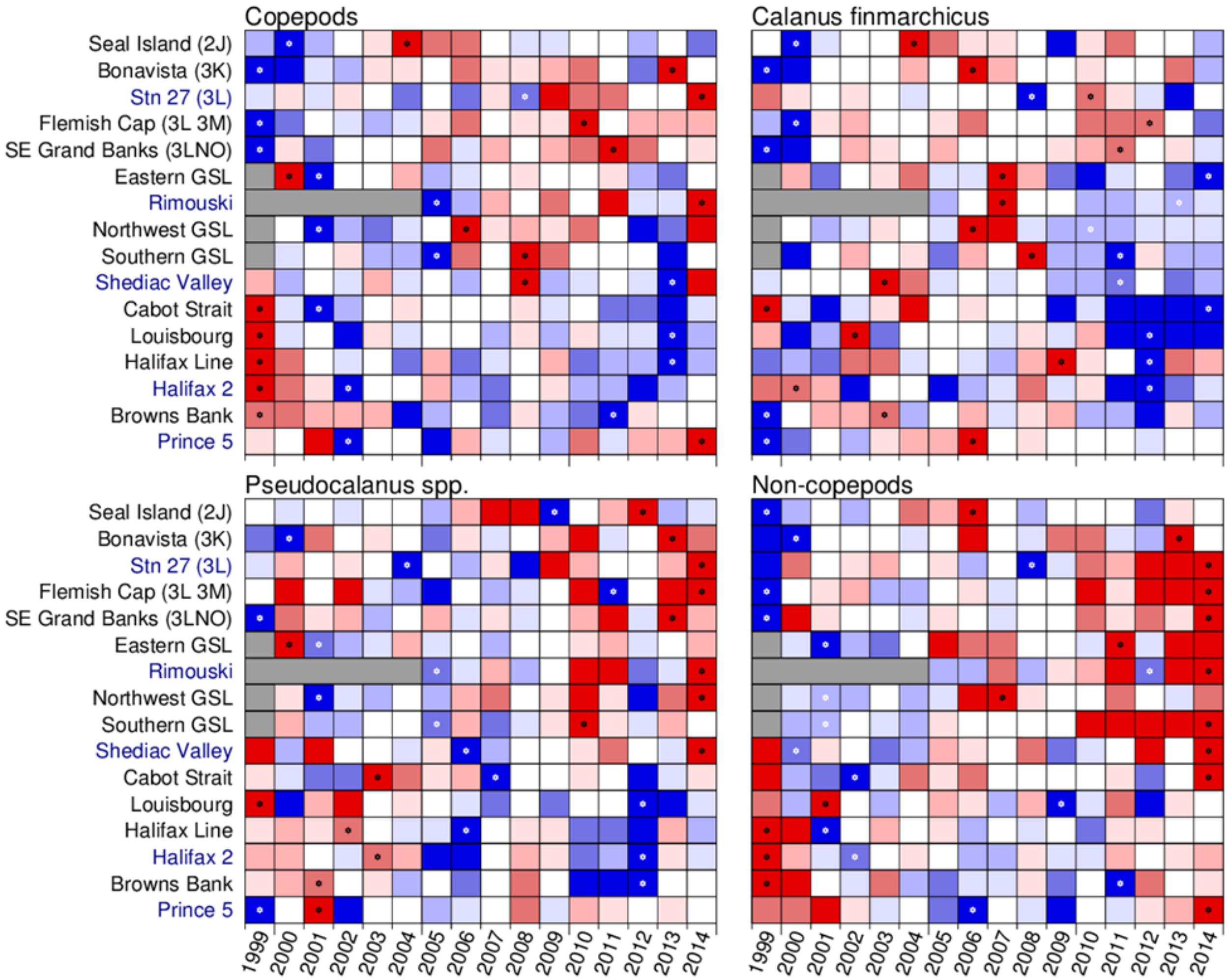

Figure 11. Time series of the standing stocks of total copepods, Calanus finmarchicus, Pseudocalanus spp., and non-copepod zooplankton, 1999–2014. A grey cell indicates missing data, a white cell is a value within ⅓ standard deviation of the long-term mean based on data from 1999–2010; a red cell indicates 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 9.

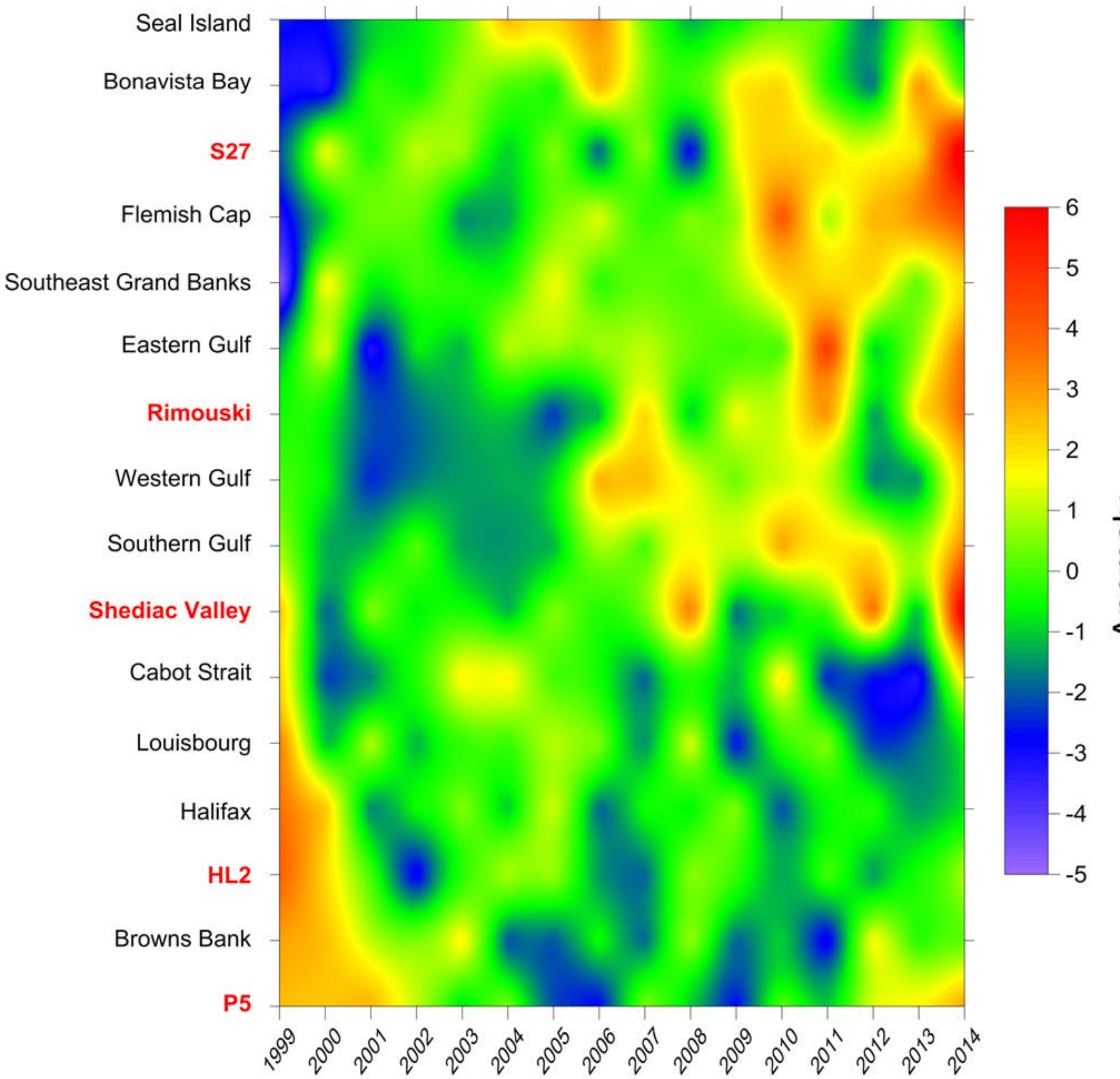

Figure 12. Schematic heat map of the summed copepod and non-copepod abundance anomalies along oceanographic sections and at high frequency sampling stations (highlighted in red on the left); blue indicates below average abundance while red indicate above average abundance.

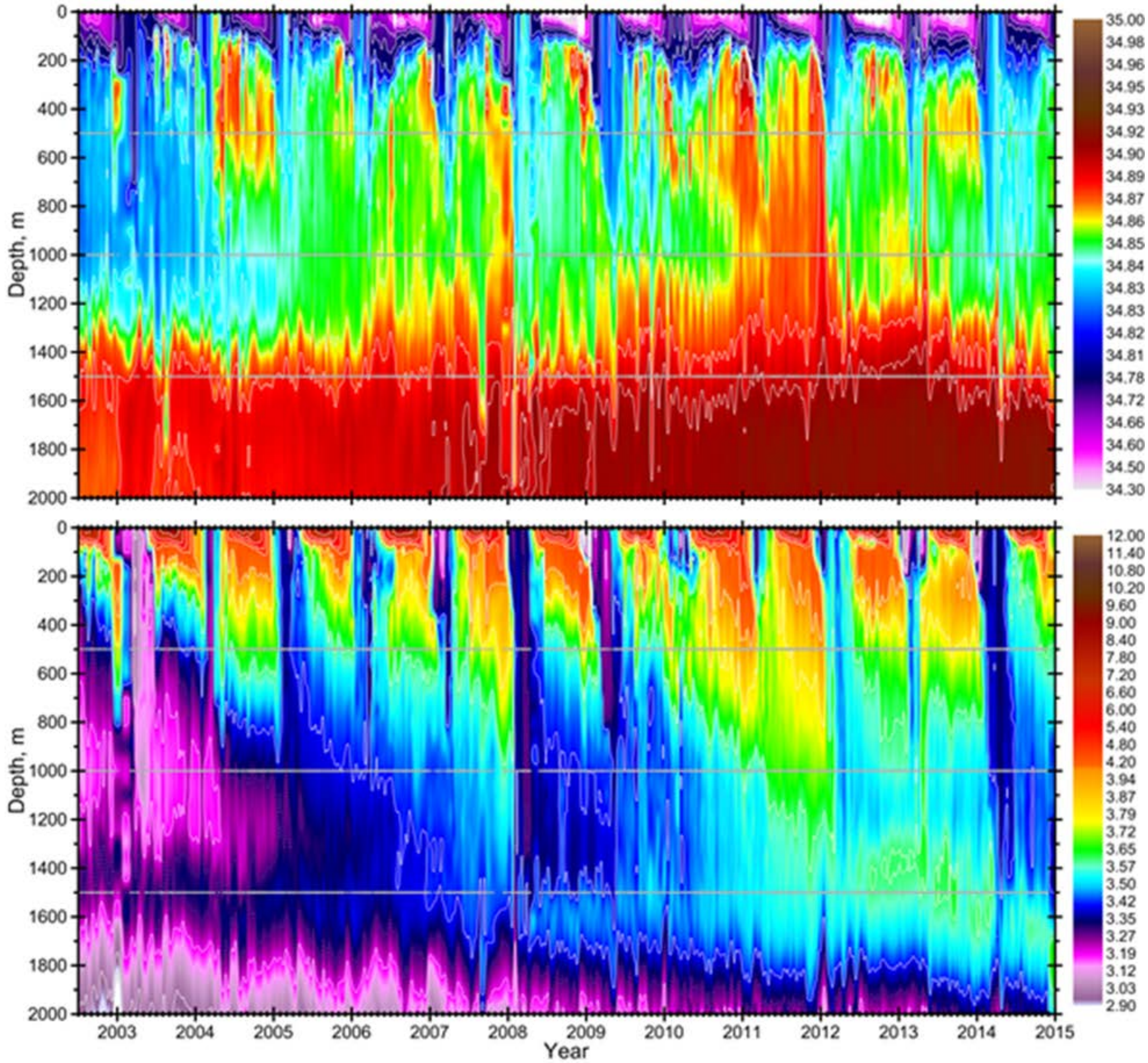

Figure 13. Time evolution of (top) salinity and (bottom) temperature in the western to central Labrador Sea derived from profiling Argo floats for the period 2002-2014.

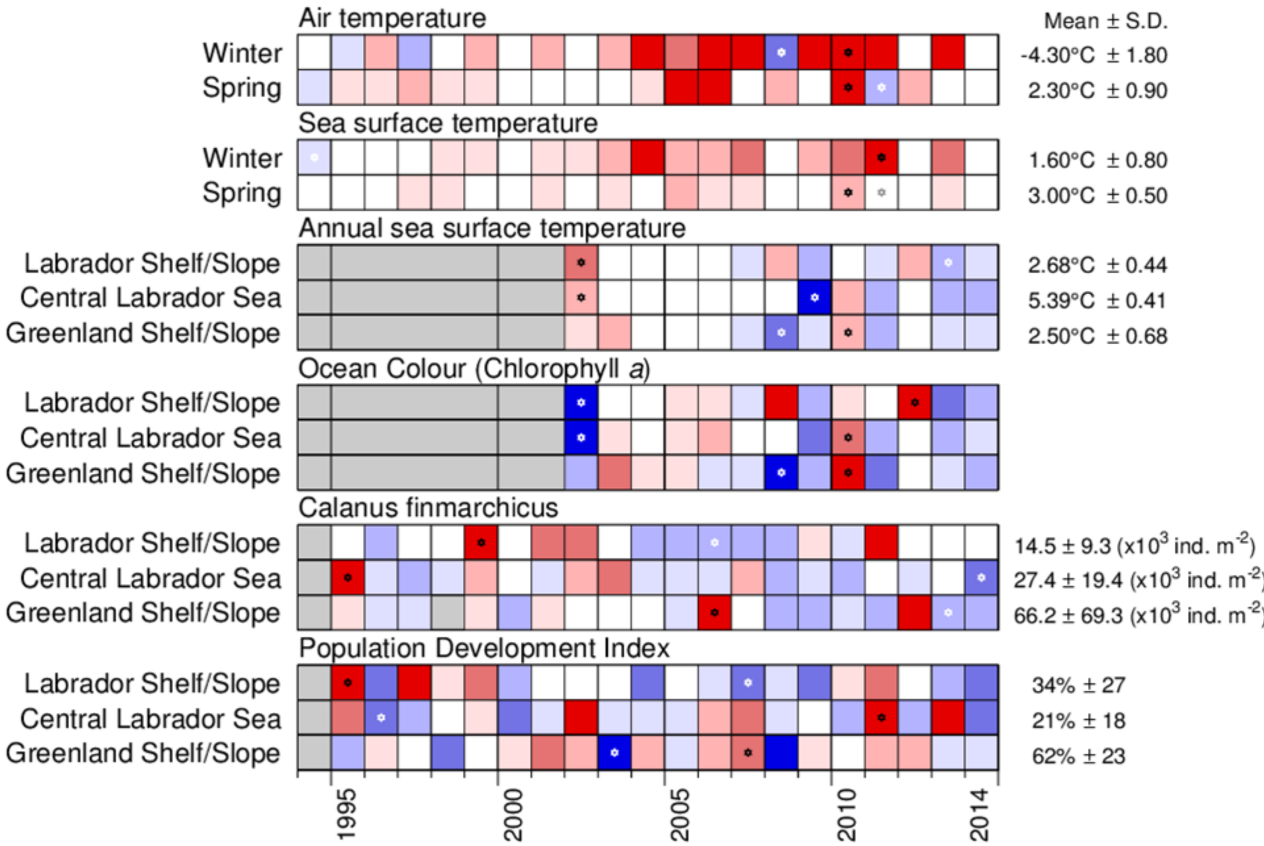

Figure 14. For the Labrador Sea region, normalised annual and/or seasonal anomaly of physical and biological variables integrated over large spatial scales estimated using reanalyzed data sets, remotely sensed data and zooplankton between 1994 and 2014. Temperatures within ±½ SD are defined as near normal (palette such as in Figure 5) while all biological parameters are defined as near normal when within ±⅓ SD (palette such as in Figure 9).

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