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Environmental Conditions in the Labrador Sea during 2013

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Abstract

The North Atlantic Oscillation (NAO) index for the Dec-Jan-Feb (DJF) period of 2012-13 was moderately negative, which is a significant reduction from the analogous period of 2011-12. During the previous two years, the NAO index was close to the level in the early 1990's, a period characterized by the highest values in the last 2 decades. The NCEP reanalysis of surface air temperature also indicated above normal conditions with an anomaly ranging between 3 – 7°C above normal in the Labrador Sea during the winter period; about 0.5°C above normal for the most of Labrador Sea during the spring; approximately 0-0.5°C above normal for the summer period; with an anomaly of -2 – 0.5°C during the fall period. The negative anomalies were mostly in the Baffin Bay/Davis Strait area north of the Labrador Sea, and the central and eastern portion of Labrador Sea region had mostly positive anomalies, though the magnitudes of the anomalies are relatively small. Sea surface temperature (SST) anomalies in the Labrador Sea followed the pattern observed in the air temperature: positive (1 to 6°C) in the winter and positive (about 0.5°C) in the summer. The Labrador Shelf ice concentration was below normal in January and March of 2013 (reference period: 1979-2000), while in February 2013, the ice concentration was higher than normal for the northwestern part of Labrador Shelf. Winter time convection in 2013 reached to 1000 m, which is significantly shallower than the 1400 m seen in the previous year, although still deeper than in the years of reduced convective activity (e.g., 2007 and 2011). The 1000-1500 m layer of the central Labrador Sea has been gradually warming since 2012. Under the warming trend, the winter ice extent has also decreased on the Labrador shelf. Increasing TIC and decreasing pH react as predicted by absorbing the excess anthropogenic atmospheric CO2. When the ice extent on the shelves decreases, phytoplankton blooms occur earlier. In addition, blooms on the shelves, which occur following stratification caused by ice-melt, generally occur earlier than those in the central basin, where stratification is more the result of surface warming. Despite an increase in the magnitude of the spring blooms, when averaged over the year the chlorophyll-*a* biomass has tended to decline. The earlier and more intense production in the spring is certainly beneficial for the *Calanus* spp younger stages but the overall annual average decrease in chlorophyll could also be reflected in a decrease in total annual copepod abundance.

Introduction

Since 1990, the Ocean and Ecosystem Sciences Division at the Bedford Institute of Oceanography has carried out annual occupations of a hydrographic section across the Labrador Sea (Figure 1) The section was designated AR7W (Atlantic Repeat Hydrography Line 7 West) in the World Ocean Circulation Experiment (WOCE). Other than traditional physical seawater characteristics (temperature, salinity, density, currents), these surveys also include chemical (e.g., dissolved oxygen, nutrients, chlorofluorocarbons, sulfur hexafluoride, total inorganic carbon, pH) and biological measurements (e.g., bacteria until 2012, phytoplankton and mesozooplankton). The AR7W line is the major component of the Canadian

Department of Fisheries and Oceans (DFO) Atlantic Zone Off-shelf Monitoring Program (AZOMP) and the main Canadian contribution to the international Global Climate Observing System (GCOS) and to the (international) Climate Variability (CLIVAR) component of the World Climate Research Programme (WCRP). The section spans approximately 880 km from the 130 m contour on the inshore Labrador shelf to the 125 m contour on the West Greenland shelf. Sea ice sometimes limits coverage at the ends of the section. DFO also contributes to the international Argo program by deploying floats in the Labrador Sea and managing and processing the Argo data streams.

Since this transect has been surveyed for more than two decades, the data now exist to make a meaningful examination of multiyear trends. In addition, the near real time temperature and salinity data from ARGO floats (started from 2002) can provide large scale picture of the hydrography in Labrador Sea. The hydrographic conditions demonstrate seasonal, inter-annual, decadal and longer-term variability, and the variations are largely governed by the changing contributions of several factors including heat lost to the atmosphere, heat and salt gained from Atlantic Waters carried northward into the Labrador Sea by the West Greenland Current, freshwater input from ice and melt from the Arctic and Greenland, continental runoff and precipitation. Occasional severe winters lead to greater cooling: and in exceptional cases, the resulting increases in the surface density can lead to convective mixing of the water column to depths exceeding 1500 m and in extreme cases 2000 m. Milder winters lead to lower heat losses, an increased presence of the warm and saline Atlantic Waters, and stronger stratification in the subsurface (>200 m) layers. The atmospheric conditions commonly expressed by the North Atlantic Oscillation (NAO) index play an important role in setting the deep convection events in the Labrador Sea, which can help explain development of significant long-term hydrographic phenomena in the region. Under the global warming scenarios, the increasing freshwater inputs from Greenland glacier melting and the Arctic also contribute to the hydrographic variations at seasonal, inter-annual and longer time scales. Continuation of the AR7W transect surveys and the on-going ARGO project will help understand the variations at various timescales, and may eventually lead to a more thorough understanding of the role of the Labrador Sea in global climate system.

A sequence of severe winters in the early 1990s led to deep convection that peaked in 1993–1994. Milder atmospheric conditions prevailed in the following years and the upper layers gradually regained their vertical stratification in density and other physical and chemical properties. The trends of increasing temperature and decreasing density established in the upper 1000 m of the Labrador Sea with the cessation of extreme convection of the first pentad of the 1990 were interrupted in the winters of 2000, 2002 and 2008 when deep convection was observed to extend to the depths approaching and even exceeding 1500 m in the central Labrador Sea. In 2012, the Labrador Sea experienced a high NAO period, and the convection depth reached 1400 m.

Atmospheric System

North Atlantic Oscillation

The NAO is an important teleconnection pattern influencing atmospheric processes in the Labrador Sea (Barnston and Livezey, 1987). When the North Atlantic Oscillation (NAO) is in its positive phase, low-pressure anomalies over the Icelandic region and throughout the Arctic combined with high-pressure anomalies across the subtropical Atlantic produce stronger-than average westerlies across the mid-latitudes. During a positive NAO, conditions are colder and drier than average over the northwestern Atlantic including the Labrador Sea region. Both NAO phases are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport (Hurrell, 1995), resulting in changes in temperature and precipitation patterns.

The NAO exhibits considerable interseasonal to interdecadal variability, and prolonged periods of both positive and negative phases of the pattern are common, which seem to have more influence on convection in the Labrador Sea than its short-term fluctuations (Yashayaev, 2007). The wintertime NAO also exhibits significant multi-decadal variability (Hurrell, 1995). An upward trend of the NAO index from the 1960s through the 1990s was noted by Visbeck et al (2001), however since the peak in the 1990s there has been a slight downward trend in the index.

In 2010, the NAO index was observed to reach a record low (Figure 2), leading to warmer than normal conditions in this region, which was confirmed by Argo data and AR7W survey. In 2011, the NAO index rebounded from the record low but still remained significantly below the 30-year average (1981-2010). In 2012, however, the NAO index was strongly positive (12 mbar), up to a level comparable to those in early 1990s. Significant change in winter NAO index was seen in 2013 with it being a moderate negative year (-3 mbar).

Surface Air Temperature

The NCEP/NCAR Reanalysis Project is a joint project between the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The goal of this joint effort is to produce new atmospheric analyses using historical data (1948 onwards) and as well to produce analyses of the current atmospheric state (Kalnay et al., 1996).

In 2013, the NCEP reanalysis of surface air temperature indicated above normal conditions with an anomaly ranging between 3 - 7°C in the Labrador Sea during the winter period; about 0.5°C above normal conditions were seen for the most of Labrador Sea during the spring (Figure 3). For the summer period the anomaly was mostly positive with a range of approximately 0-0.5°C; the fall period was characterized by a range of anomaly of -2 – 0.5°C in the region (Figure 3), the negative anomalies were mostly on the Baffin Bay/Davis Strait area north of the Labrador Sea. The central and eastern portion of Labrador Sea region had mostly positive anomalies, though the magnitudes of the anomalies are relatively small.

Sea Surface conditions

Temperature

Labrador Sea sea-surface temperatures (SST) during JFM 2013 were 1 to 6°C above normal (climatology for this data set is 1981-2010) for the winter period (Figure 4). This is consistent with the aforementioned large positive anomaly in surface air temperatures in the Labrador Sea during this winter period. Based on the NCEP reanalysis ocean heat losses are estimated to be 25% smaller than those in 2012, and only larger than those in 2010 over the past seven years. This analysis is based on methods detailed in Yashayaev and Loder (2009). During spring (AMJ) of 2013, the central Baffin Bay sea-surface temperatures were 0 to 1°C below normal, and the Labrador Sea SST was 0 to 2°C above normal (Figure 4). For the summer (JAS), the SST in Labrador Sea was about 0.5°C above normal. The fall (OND) SST in the Labrador Sea showed a combination of below and above normal anomalies, the northwestern part of the region was mostly 0 to 1°C below normal, while the in other areas Labrador Sea SST anomalies were about 0 to 2°C above normal.

Sea Surface Height

The sea surface height anomalies are weekly merged data from AVISO, which are an objectively mapped product of TOPEX/Poseidon/Jason-1, ERS-1, ERS-2, Geosat-Follow-on, and Envisat along-track altimeter data, with a ¼ ^{o} Mercator projection grid. The zonal and meridional spacing for each grid is identical and varies with latitude. Therefore, the spatial resolution increases with latitude. We compare the winter and spring data for 2012 and 2013.

For the winter, strong negative anomalies were observed along the west Greenland Shelf with magnitudes ranging from 0 to -10 cm in 2012; conditions in this region in 2013 were close to normal (Figure 5). In the central Labrador Sea, both 2012 and 2013 showed positive anomalies, with the 2012 anomalies being stronger (Figure 5).

For the spring period, both 2012 and 2013 data showed negative (positive) anomalies along the west Greenland Shelf (central Labrador Sea) with stronger anomalies in 2012.

The changes in the sea surface height anomalies between these two years imply that the geostrophic circulation during these two years, and in these two seasons, changed substantially.

Sea Ice

The U.S. National Snow and Ice Data Center sea ice index shows that the ice extent from January to February in 2013 was close to normal, while the ice extent was below normal in the northern part of Labrador Sea in March (Figure 6). Sea ice concentration anomalies on the Labrador Shelf were more than 20% below normal for January and became 15% above normal in the northwestern part of the Labrador Shelf in February, remaining at about 25% below normal elsewhere. The month of March saw slightly below normal ice concentration for the most of Labrador Shelf, and about 40% below normal in the northern part of Labrador Sea, which was mainly due to less ice cover in this region. Sea ice concentration conditions in Baffin Bay were close to normal from January to March.

AR7W Hydrography

Sea ice generally prevents access to the Labrador Shelf before mid-May; notwithstanding this constraint, the annual AR7W surveys normally take place as early in the spring as practical to provide a consistent view of interannual changes in the face of strong seasonal changes in physical, chemical, and biological properties. In addition to the AR7W Line, a full AZOMP survey also includes sampling of the extended Halifax Line (XHL) to monitor variability on the Scotian Rise and Slope in the deep western boundary flows of the North Atlantic and to obtain additional information on oceanographic and lower-trophic-level variability of the Slope Water affecting the Scotian and adjacent shelves. The survey in 2013 was conducted aboard the *CCGS Hudson* from the 6th to the 28th of May.

Yearly changes in temperature and salinity in the upper layers of the Labrador Sea occur in response to changes in: atmospheric forcing, warm and saline inflows in the West Greenland Current, and freshwater inputs originating from precipitation, runoff and glacier melt. Seasonal cycles in each of these three forcing terms drive a strong seasonal cycle in the properties of the upper layers of the Labrador Sea. During the early 1990s, deep winter convection in the Labrador Sea filled the upper two kilometers (in some years it reached 2400 m and possibly deeper) of its watercolumn with cold and fresh water. Milder winters in recent years have produced more limited amounts of mode waters, which have gradually become warmer, saltier, and less dense than a decade and a half ago. This recent trend changed abruptly during the cold winter of 2008 during which deep convection to 1600 m was observed. The environmental conditions which contributed to the 2008 deep convection have been documented by Yashayaev and Loder (2009).

Significant decadal variability has been observed in the central Labrador Sea. While there has been relatively little variability below 2500 m, there have been significant decade-long events in the upper 2000 m. A period of warming and increase in salinity during the mid-1960s to mid-1970s was followed with an inverse period of cooling and freshening during the 1990s. These changes are believed to be linked to a decade-long shift in NAO between these periods.

The advent of the International Argo Project has provided the oceanographic community with unprecedented, year-round coverage of temperature and salinity in the Labrador Sea. A composite of data from Argo floats in the Labrador Sea is presented in Figure 7. The time series clearly demonstrates the seasonal and interannual variability observed over the last decade in this region. The deep convection event of 2008 is evident in both the temperature and salinity fields. The Argo composite indicates that the winter of 2011 was similar to the preceding winter with very limited convection (approximately 200 m). Deep convection was down to 1400 m in 2012, which is clearly shown by temperature and salinity data from Argo floats. The salinity in the top 200 m in 2012 was the lowest since 2003, particularly in the top 50m. Convection also occurred in the winter of 2013, but it was not as deep as in the previous year, mostly limited to the top 1000 m.

The hydrographic survey of the AR7W line conducted in May of 2013 (Figure 8a) shows that the convective mixing that took place in the previous winter reached 1000 m depth and possibly deeper, which is consistent with the analysis based on Argo profiles (Figure 7). There is also a possibility that the source of convection was limited in area, but that convection was prolonged in duration so that the newly-mixed water spread from its local source out and across the Labrador Sea. The cold and less saline water mass layer below 3000 m is clearly shown in the hydrographic data from this survey. Due to heavy ice conditions on the Labrador Shelf in 2013, the inshore part of the survey took place along a new line east of Belle-Isle Strait (Figure 8b); this part of the survey indicated strong stratification at top 50 m, and this feature of this line suggests the existence of the strong baroclinic current through this line which is consistent with the presence of the inshore Labrador Current.

Wintertime convection in the Labrador Sea is a key process in the Atlantic Meridional Overturning Circulation (AMOC), and the Labrador Sea is one of the few areas in the global ocean where surface water is exchanged with the deep ocean. It also has an important role in biogeochemical cycling in the Labrador Sea, and strong convection enhances the entrainment of gases such as oxygen and carbon dioxide into the deep water from the atmosphere, as well as from surface freshwater.

Total Inorganic Carbon and pH

About one quarter of carbon dioxide (CO_2) released by human activities (anthropogenic CO_2, mainly by fossil fuel combustion) has been taken up by the oceans, altering the basic ocean chemistry, specifically the marine carbonate system. The dissolution of anthropogenic CO_2 has decreased ocean pH by 0.1 units over the past 200 years, corresponding to 30% increase in acidity (Caldeira and Wickett, 2003). If global emissions of CO_2 continue at their present rate, ocean pH is predicted to fall an additional 0.3 units by 2100. The oceans have not experienced such a rapid pH decrease (ocean acidification) or one of this great a magnitude for at least 20 million years (Feely et al., 2004), raising serious concerns about the ability of marine ecosystems to adapt. The major impact of decreasing pH will be felt by organisms that form calcium carbonate ($CaCO_3$) shells and skeletons, because rising acidity increases the solubility of $CaCO_3$. Since $CaCO_3$ shells and skeletons are naturally more soluble at lower temperatures and higher pressures, high latitude and deep water ecosystems will be more vulnerable to the added stress of ocean acidification. Furthermore, rapid environmental changes such as retreating ice extent and enhanced hydrological cycles may amplify these problems.

Arctic outflow and the local uptake of anthropogenic CO_2 in the deep convection region of the Labrador Sea are major controlling mechanisms of the state of ocean acidification in the Northwest Atlantic. The Arctic water flows out on highly productive regions with important commercial fisheries more susceptible to future ocean acidification (Azetsu-Scott *et al*., 2010). The Labrador Sea is the site of a strong "solubility pump"; anthropogenic CO_2 sequestration from the atmosphere to the depths by chemical and physical processes. In the newly ventilated Labrador Sea water (NV-LSW), which ranges between 150-500m deep for stations in the central part of the Labrador Basin, DIC increased by 16 µmol/kg from 1996 to 2013, due to the local uptake of anthropogenic CO_2 (Figure 9). As a result, pH decreased by 0.08 units (in the total pH scale) during the same period (Figure 9). pH has declined at a rate of 0.0031/year, higher than the global average of 0.002/year. Ocean acidification influences the capacity of the ocean uptake of CO_2 from the atmosphere. Continued monitoring of the chemical state and investigation of biological responses to ocean acidification in the Northwest Atlantic are urgently needed.

Ocean colour from remote sensing

Ocean colour, which is an indicator of sea surface chlorophyll a (SSC), is derived from observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua Earth Observing System satellite. Remotely-sensed images of ocean colour for the Labrador Sea are composited on a 2-week basis from the beginning of March to the end of October each year. From November to February, the data are too sparse to be useful. From these composites, ocean colour data are extracted from 511 pixels comprising the AR7W transect. A biweekly climatology of chlorophyll *a* constructed from the time series of ocean colour from 2003 to 2013 (Figure 10) 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). Within the two-dimensional spatial regional boxes defined by Harrison and Li (2008), the concentration of sea surface chlorophyll averaged over the period from March 2013 to October 2013, SSC was 0.55 mg m^{-3} on the Labrador Shelf, 0.59 mg m^{-3} in the central Labrador Basin, and 0.82 mg m^{-3} on the Greenland Shelf. The annual average normalized anomalies for 2013 were respectively -0.14, +0.12, and -0.03, the three regions together being close to normal, with the Labrador shelf just above normal, the central basin slightly below and the Greenland shelf almost even (Figure 11).

Phytoplankton

Upper ocean ($z \leq 100m$) phytoplankton sampled on AR7W in the spring and early summer from 1994 to 2013 shows region-specific characteristics (Figure 12). The Greenland Shelf is a region with high concentrations of chlorophyll *a* and nanophytoplankton, but low concentrations of picophytoplankton. Conversely, the central Labrador Basin is a region with lower concentrations of chlorophyll *a* and nanophytoplankton, but high concentrations of picophytoplankton and bacteria. The Labrador Shelf has the lowest concentrations of chlorophyll *a* and nanophytoplankton, but intermediate concentrations of picophytoplankton. During the most recent sampling period of June 2013, concentrations of chlorophyll *a* in all 3 regions appeared to be within the range of region-specific variability (Figure 12). For program reasons, the time series of picophytoplankton, nanophytoplankton, and bacteria were discontinued in 2013.

Mesozooplankton: Calanus finmarchicus et al.

One species of copepod, *Calanus finmarchicus*, dominates the mesozooplankton biomass throughout the central region of the Labrador Sea, while on the shelves two Arctic *Calanus* species, *C. glacialis* and *C. hyperboreus*, are as important (Head et al. 2003). *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, which are themselves influenced by environmental conditions. On the Labrador Shelf, *C. finmarchicus* abundances are generally relatively low in spring (Figure 13), as was the case in 2013. In spring, populations here generally have few young stages from the new years' generations, but the abundances of these increase in summer when they dominate the populations. One unusual case was in spring 2011, when there were many more young stages than usual, so that it looked more like an early summer population: the reason for this is not clear. There was no significant trend in springtime abundance of *C. finmarchicus* between 1996 and 2013. In the Central Labrador Sea, total *C. finmarchicus* abundance is generally relatively low in spring and summer, with a low proportion of young stages; one exception being the summer of 1995, when young stages were dominant and total abundance was relatively high. There was no trend in springtime total abundance between 1996 and 2013 and the abundance in 2013 was within the range seen in previous springs. *C. finmarchicus* abundances are generally higher in the eastern Labrador Sea than farther west in spring, because the spring bloom starts earlier here, which leads to earlier reproduction in *C. finmarchicus*. Abundances are generally higher here in summer than in spring, but the highest concentration of all occurred in spring 2006.The abundance in 2013 was within the range of values seen in previous springs, and there was no trend in springtime abundance between 1996 and 2013.

Calanus glacialis and *Calanus hyperboreus*, which are both Arctic species, are usually more abundant in the Arctic waters covering the shelves than in the central basin. The abundance of *C. glacialis* in spring 2013 was near average on the Labrador Shelf, slightly above average in the central basin and relatively low on the Greenland shelf. The abundance of *C. hyperboreus* in 2013 was also relatively low on the Greenland Shelf, but relatively high in the other two regions.

Abundances of macrozooplankton as well as the very ubiquitous small copepod *Oithona* spp. were above average on the Labrador Shelf in 2013, but remained relatively unchanged over time in the central basin, and were around average in 2013 on the Greenland Shelf. The macrozooplankton are mostly represented by Euphausids and gastropoda in their larval stages. It is possible that a phase match with earlier algal blooms might have triggered their emergence immediately before our sampling, thus accounting for an increase in measured abundance. Gastropoda, includes a number of of hard shelled "snail like" organisms, which are found at intermediate depths in the water column and are most likely among the first that will be directly impacted by the lowering of the pH. Their abundance appears to be likely on the rise on the Labrador Shelf, where they are certainly more abundant than within the 2 other regions.

Continuous Plankton Recorder (CPR)

The Continuous Plankton Recorder (CPR) is an instrument that is towed by commercial ships that collects plankton at a depth of ~7 m sandwiched between two long continuous ribbons of silk (~260 µm mesh). The position on the silk corresponds to the location of collection of the samples. CPR data are analysed to detect differences in the indices of phytoplankton (colour and relative numerical abundance) and zooplankton relative abundance for different months, years or decades in the northwest Atlantic. The indices indicate relative changes in concentration (Richardson et al. 2006). The sampling methods from the first surveys in the northwest Atlantic (1960 for the continental shelf) to the present are essentially the same so that valid comparisons can be made between years and decades.

The tow routes between Reykjavik and the Gulf of Maine are divided into eight regions: the Western Scotian Shelf (WSS), the Eastern Scotian Shelf (ESS), the South Newfoundland Shelf (SNL), the Newfoundland Shelf (NS) and four regions in the NW Atlantic sub-polar gyre, divided into 5 degree of longitude bins (Fig. 14). In this report a broad-scale comparison is presented for CPR data collected in all regions and all sampling decades. More detailed analyses for the Scotian Shelf and Newfoundland Shelf regions are presented in the AZMP Reports from the Maritimes and Newfoundland Regions. These latter reports concentrate on results from data collected since 1992, since these are comparable to AZMP survey results, which date back to 1999.

Monthly abundances ($\log_{10}(N+1)$ transformed for all but PCI[1] were calculated for 15 CPR taxa by averaging values for all individual samples collected within each region for each month and year sampled. Monthly averages for each region and year were averaged over the decades prior to 2009, (i.e. for the 1960-1969, 1970-1979, 1980-1989, 1990-1999 and 2000-2009 periods) to give decadal annual average abundances. Monthly averages were similarly averaged for 2010 and 2011 to give a bi-annual average abundance, and for 2012 to give an annual average abundance. For the shelf regions and in the 25-30°W region there was insufficient sampling during the 1980s to calculate decadal annual abundances. For the three regions between 30°W and 45°W, linear interpolation was used to fill in for 2 months (January and December) that were never sampled during the 1980s. Linear interpolation was also used to fill in values for the missing months in the 2010-2011 period (1 month in each of the shelf regions) and in 2012, when there were 2 or 3 missing months in all regions except the 25-30°W region where there was sampling in every month and the SNL region, where there was sampling in only 4 months so that no annual abundance could be calculated. Linear interpolation would not have been used had the 3 missing months been consecutive in any of the other regions, but they never were. Decadal (1960s, 1970s, 1980s, 1990s, 2000s), bi-annual (2010-2011) and annual (2012) abundance anomalies were calculated based on the climatological values derived by averaging the annual values for the decades sampled in each region between the 1960s and 2000s. Continuous Plankton Recorder (CPR) data collected from January to December 2012 were made available in January 2014 to add to the DFO data archive.

Phytoplankton

The phytoplankton colour index (PCI).

The climatological annual averages (1960-2009) for the phytoplankton colour index (PCI) are highest in the two Newfoundland Shelf regions (NS, SNL), intermediate in the Scotian Shelf (WSS, ESS) and 25-30°W regions and lowest in the regions between 30 and 45°W (Fig. 15). Decadal average PCI values increased in all regions between the 1970s and 1990s and remained high thereafter in the sub-polar gyre, but decreased in shelf regions in the 2000s and 2010-2011, remaining relatively low in 2012, especially on the ESS.

Diatoms

The climatological annual abundance for diatoms is generally highest in the NS, SNL and 25-30°W regions, but only slightly lower elsewhere. Decadal abundances increased after the 1970s, with highest values in the 1990s (ESS) or

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[1] PCI – Phytoplankton colour index, a semi-quantitative measure of total phytoplankton abundance.

2000s (other regions). Thereafter abundance anomalies remained high (east of 45^{o}W), increased (NS) or decreased (SNL, ESS, WSS) in 2010-2011, and increased on the WSS, but did not change or decreased elsewhere in 2012 (Fig. 15).

Dinoflagellates

The climatological annual abundance for dinoflagellates is highest in the SNL region, intermediate in the other shelf regions and lower farther east. Dinoflagellate abundance increased after the 1970s with highest values in the 1990s (25-30^{o}W, ESS, WSS) or 2000s (other regions). Dinoflagellate abundance remained high or increased in most regions in 2010-2011, except in the 30-35^{o}W and WSS regions where it decreased. Dinoflagellate abundance was generally lower in 2012 than in 2010-2011, except in the WSS, where it was substantially higher (Fig. 15).

Zooplankton

Calanus I-IV

The climatological annual average abundance for *Calanus I-IV* (mostly *Calanus finmarchicus*) is similar in all regions except the NS, where it is higher than elsewhere (Fig. 16). Decadal abundances decreased in most regions between the 1960s and 1990s and increased everywhere in the 2000s. In 2010-2001, *Calanus I-IV* abundance anomalies increased again, except on the Scotian Shelf, where they decreased. This latter decline continued in 2012, although elsewhere levels remained high or decreased only slightly.

Calanus finmarchicus V-VI

The climatological annual average abundance for *C. finmarchicus V-VI* is slightly higher on the NS and farther east than in the SNL region and farther west. Decadal abundance anomalies were higher in the 1960s or 1970s than in the 1990s, except for regions between 30^{o}W and 40^{o}W. The 25-30^{o}W and NS regions have had low abundance anomalies since the 1990s, whereas other regions showed recoveries in the 2000s or 2010-2011. The recovery on the Scotian Shelf in the 2000s was short-lived, however, with all-time low values occurring in 2012.

Calanus glacialis V-VI

The climatological annual average abundance for *C. glacialis* is highest on the NS and slightly higher in the shelf regions to the west, than in the deep waters to the east. Decadal abundance anomalies increased in all regions over the decades with maximum values in the 2000s. In 2010-2011 *C. glacialis* abundance remained high or increased in most regions, while in 2012, its abundance decreased everywhere.

Calanus hyperboreus III-VI

The climatological annual average abundance for *C. hyperboreus* is highest on the NS. Decadal abundance anomalies increased from relatively low values in the 1960s and 1970s to high values in 1990s (NS and farther east) or 2000s (SNL and farther west). Since then abundances have generally been lower, except in 2010-2011 in the 25-30^{o}W region and on the WSS, and between 35^{o}W and 45^{o}W in 2012.

Small copepod taxa (Copepod nauplii, Paracalanus/Pseudocalanus, Oithona spp.)

The three small copepod groups have higher climatological annual average abundances in shelf regions (NS and to the west) than in the sub-polar gyre (Fig. 17). The decadal annual abundance of copepod nauplii increased between the 1960s and 2000s, thereafter increasing further in some regions (25-30^{o}W, 40-45^{o}W, NS, SNL), decreasing in others (30-35^{o}W, 35-40^{o}W, ESS) and fluctuating on the WSS. Decadal (2000s), bi-annual (2010-2011) and annual (2012) abundance anomalies for the *Paracalanus/Pseudocalanus* taxon have been higher since the 1990s than in previous decades in deep ocean regions, while in shelf regions they have been lower. The decadal annual abundance for *Oithona* spp. was highest in the 1990s in the 25-30°W region and all shelf regions, and in the 1960s in the 30-35°W region. Bi-annual (2010-2011) and/or annual (2012) abundance anomalies have been relatively high since the 2000s in the deep ocean and NS regions, and relatively low since the 1990s in the SNL, ESS and WSS regions.

Macrozooplankton

The climatological annual average abundances of euphausiids and hyperiid amphipods are both higher in the deep ocean regions of the sub-polar gyre, intermediate in the NS region, and lowest in the SNL and ESS regions (Fig. 18). The timing of peaks in euphausiid abundance over the decades has varied regionally, but all regions had relatively low abundance anomalies in the 2000s, which persisted into 2010-2011 and 2012. In contrast, abundances of hyperiid amphipods were higher in the 1990s and 2000s than in previous decades although since 2010 there have been low abundances in the NS and ESS regions.

Acid-sensitive taxa

Coccolithphores, phytoplankton that are covered with calcite scales, and foraminifera (forams) whose shell composition includes calcium carbonate, have only been counted in CPR samples since 1992. They are generally more abundant in the sub-polar gyre than on the shelves, although coccolithophores are as abundant on the SNL (Fig. 19). Coccolithophore and foram abundances increased significantly in 2010-2011 compared with previous decades everywhere except on the WSS, where instead there was a large increase in abundance in 2012. Elsewhere in 2012 abundance anomalies remained relatively high. Pteropods of the genus *Limacina* have shells that are composed of aragonite, which is a form of calcium carbonate that is especially sensitive to dissolution. The climatological annual abundance of *Limacina* shows a more-or-less flat distribution across all regions. Over the decades there has been a general upward trend in abundance for *Limacina* in regions east of the Scotian Shelf, while abundances there have fluctuated. In 2012-2011 and 2012 abundances were generally relatively high, except on the ESS in 2012, where the abundance was very low.

Continuous Plankton Recorder (CPR) – Summary & Discussion

In terms of the climatological (1960-2009) annual average abundances, six of the 15 CPR taxa analysed for this report are generally more abundant in shelf regions than the sub-polar gyre: the three phytoplankton taxa and the three “small copepod” taxa. All three phytoplankton taxa were more abundant everywhere in the 1990s and/or 2000s than in previous decades although since 2010 there have been increases or decreases in abundance, varying by region and taxon. Changes in abundance of the small copepod taxa have been mainly positive over the decades in the deep ocean, with abundances generally peaking in the 1990s in shelf regions.

Calanus I-IV, Calanus glacialis and *Calanus hyperboreus* show peaks in climatological annual average abundance on the NS, which is as expected for the latter two, which are Arctic species, since this region is strongly influenced by Arctic water inflow from the north. Both species occur here only between late winter and early summer and both are re-introduced each year from source populations farther north. Most *Calanus I-IV* are probably *C. finmarchicus*, which is considerably more abundant than the two Arctic species on an annual basis and which is a boreal North Atlantic species. This being the case, it is surprising to see a peak in abundance on the NS. This peak is, however, the result of very high decadal annual abundances on the NS in the 1960s and 1970s. During the 1990s and 2000s *Calanus I-IV* was more evenly distributed across all regions (Fig. 20). By contrast, late stage *C. finmarchicus* (*i.e. C. finmarchicus V-VI*) were relatively evenly distributed across regions in the 1970s and 2000s, but were lower in abundance west of the NS in the 1960s and 1990s.

Euphausiids and hyperiids both show high climatological annual average abundances in regions between 25 and 45°W, where waters of both Atlantic and Arctic origin occur. Euphausiids are more associated with Atlantic water and hyperiids with Arctic water, so that the generally decreasing trend in abundance for the former and increasing trend for the latter suggest an increased contribution of Arctic water in recent decades.

The changes in pH that have resulted from increasing carbon dioxide levels in the atmosphere have not yet been great enough to elicit negative effects on any of the three acid-sensitive taxa, which have actually increased in abundance over the last two or more decades in most regions. The increase in coccolithophore abundance may be linked to an increasing degree of stratification (Raitsos et al. 2006), while the increases in foram and *Limacina* abundances in the sub-polar gyre could be due to increases in food (phytoplankton) supply for both taxa, or in the contribution of Arctic water for the latter.

Summary

The Labrador Sea is a key component of the global ocean circulation system and provides one of the few sites where deep convection during the winter serves to exchange surface waters with the deep ocean and, in the process, entrain gases such as carbon dioxide and oxygen. Fisheries and Oceans Canada has carried out long-term environmental monitoring of the Labrador Sea through the Atlantic Zone Off-Shelf Monitoring Program (AZOMP; http://www.bio.gc.ca/science/monitoring-monitorage/azomp-pmzao/azomp-pmzao-eng.php). This program provides high-quality observations of core variables in a timely manner to the Canadian data archives as well as a number of international data centres (e.g., NODC, ICES, CCHDO, CDIAC). Please refer to figures 21 and 22 for a summary of the entire time series anomalies.

Processes in the Labrador Sea have significant variability on decadal and longer time scales and, therefore, long-term data sets are critical for climate studies of this region. It is apparent from the data available that the upper 2000 m of the Labrador Sea has been experiencing significant warming over the last decade following a very cold period of the early to mid-1990s. After the weaker convection in the winters of 2010 and 2011, the 2012 winter deep convection was down to 1400 m under strongly positive NAO of about the same magnitude as those in 1990s. However, the convective mixing in 2013 although moderately strong was limited to the top 1000 m. The 1000-1500 m layer warming since 2002 with the two short-term resets in 2008 and 2012, respectively, has been warming continuously since 2012.

A sustained feature in the Labrador Sea is the increasing trend of total inorganic carbon and the decreasing trend of pH. Notably, however, there was no clear response of the carbonate system to the 2012 deep convection event.

For the year of 2013 as a whole, chlorophyll *a* estimated from 2-week ocean colour composite images was below normal on the Labrador and Greenland Shelves, but normal in the central Labrador Basin. In 2013 *Calanus finmarchicus* abundances were similar to those seen in other years when sampling was in spring. Regional differences were also consistent between 1996 and 2013: abundances were relatively low on the Labrador Shelf and in the central basin and relatively high in the eastern region of the basin. Between 1996 and 2013 total abundances in spring showed no significant trends on the Labrador Shelf, in the central basin, or its eastern region.

Although CPR routes pass south of the Labrador Sea, these observations from ships-of-opportunity seem to corroborate trends observed along the AR7W transect. The spatial and temporal scope of this unique time series also shows the importance of long time series: the CPR multidecadal results show a strong change in mean state of the plankton system during the nineties which was not captured in the AR7W time series.

Acknowledgements

We would like to thank William Li and Blair Greenan for their helpful comments and suggestions. The NCEP Reanalysis data were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA. The sea ice concentration anomaly data are the US National Snow and Ice Data Center. The authors wish to thank the many staff and associates at BIO have contributed to the AZOMP which was carried out by the Ocean and Ecosystem Sciences Division in 2013. These efforts, together with those of the officers and crew of CCGS *Hudson*, are gratefully acknowledged.

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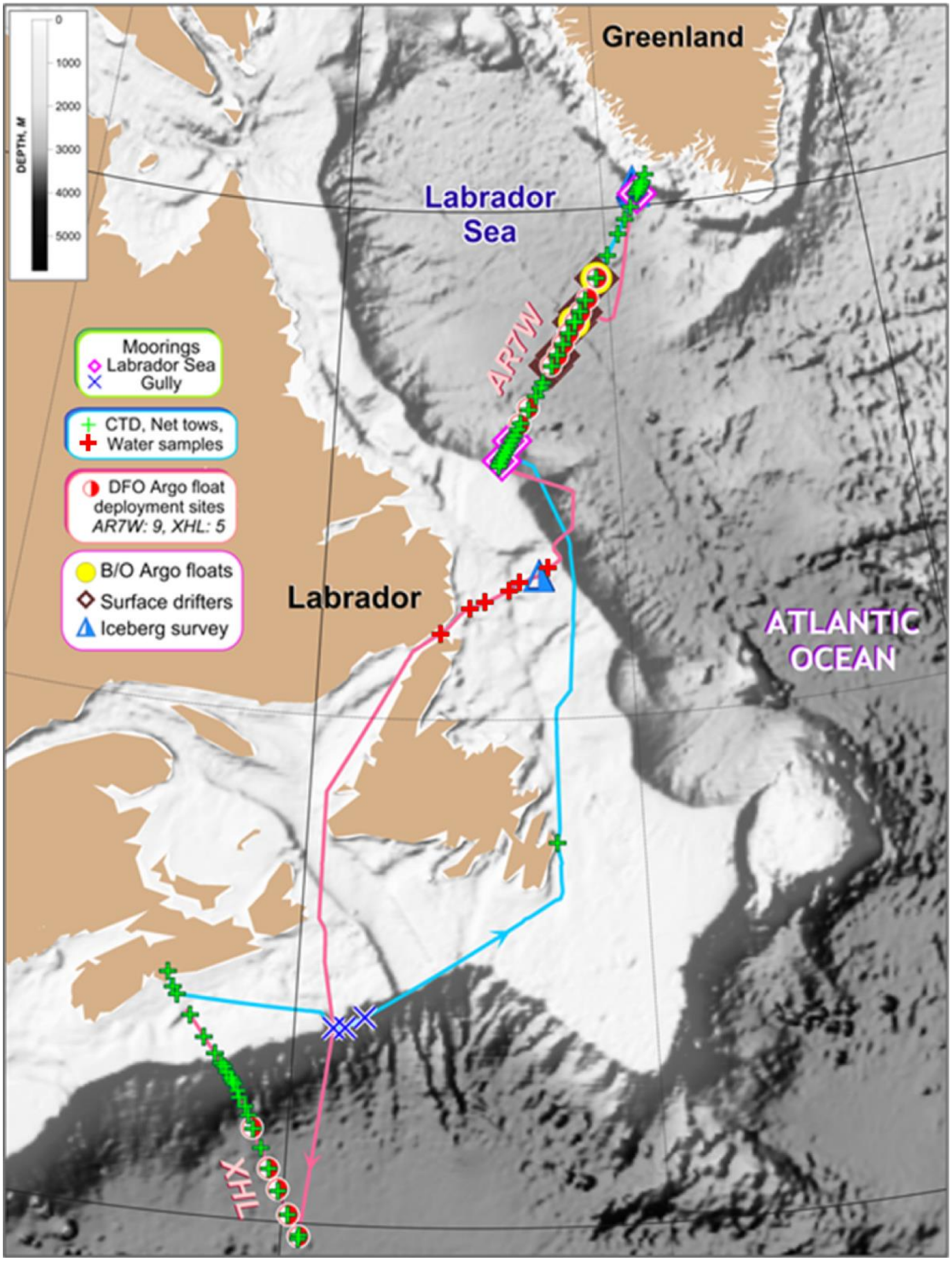


Figure 1: Schematic of the Labrador Sea component of the DFO Atlantic Zone Offshore Monitoring Program (AZOMP). Standard stations along the section are shown as green plus signs and red ones indicate the added shelf stations south of the pack ice. Location of Argo profiler deployments are indicated by the red/white circles. Yellow circles indicate BIO Argos deployments.

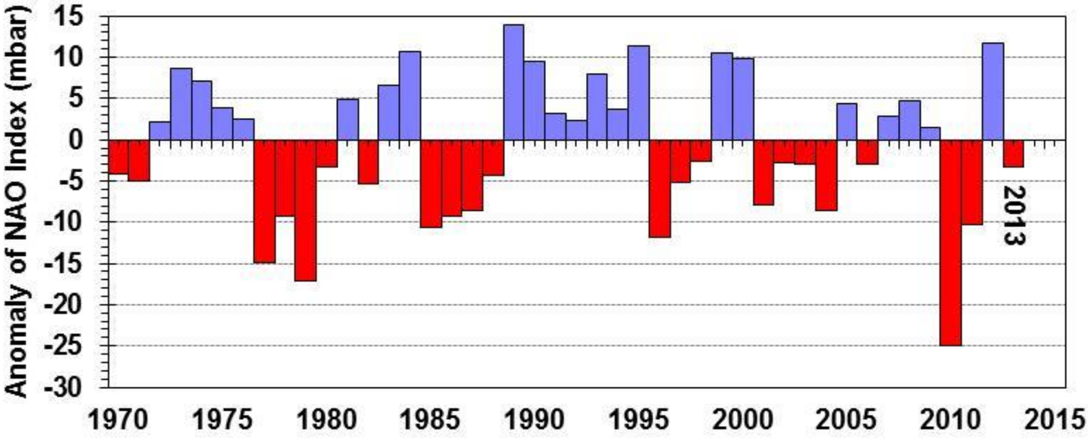


Figure 2: Average Sea Level Pressure for Dec, Jan, Feb in mbar (Winter North Atlantic Oscillation Index)

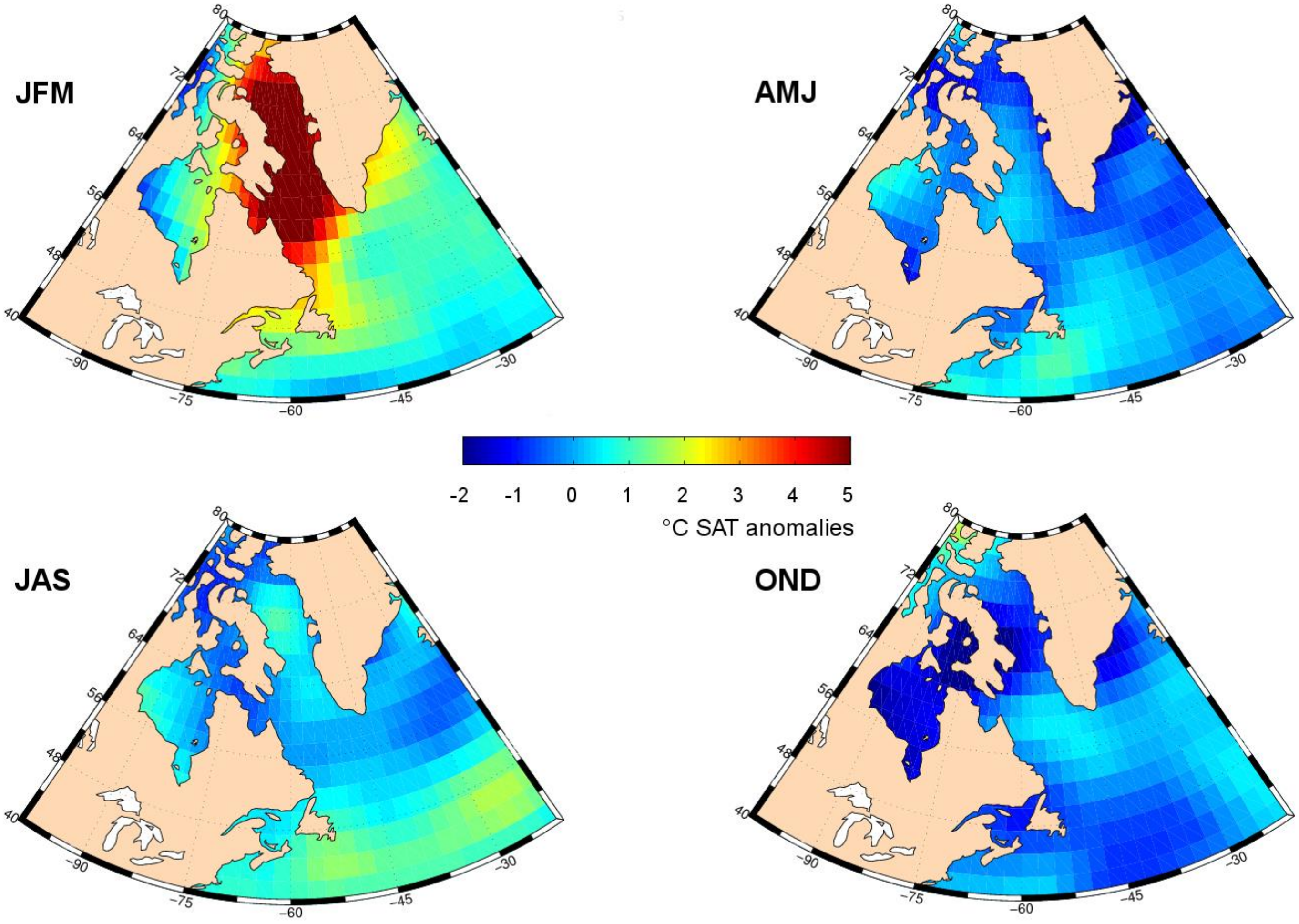


Figure 3: Surface air temperature anomaly for winter, spring, summer and fall periods in 2013 as derived from NCEP/NCAR reanalysis. http://www.esrl.noaa.gov/psd/

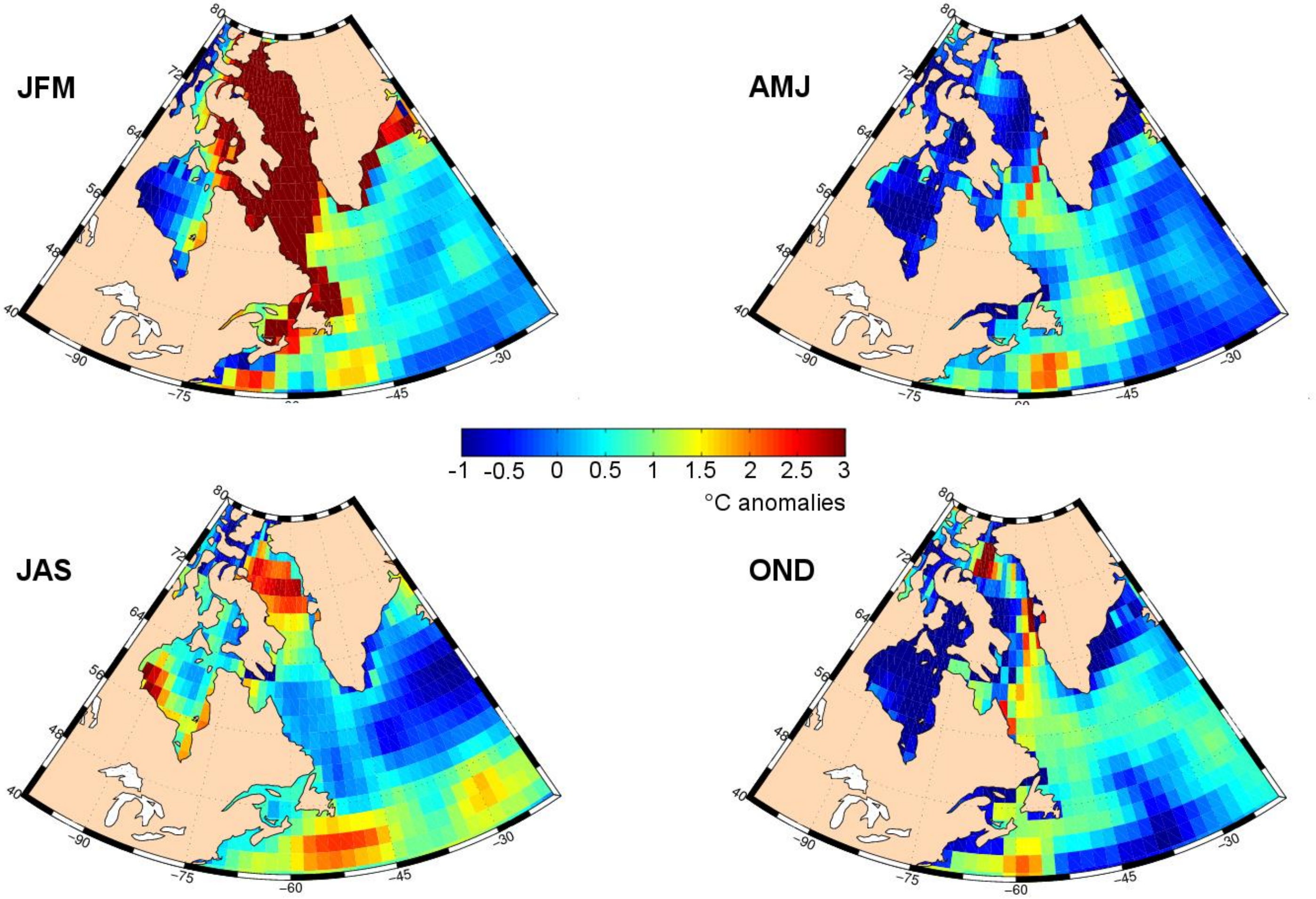


Figure 4: Sea surface temperature anomalies for winter, spring, summer and fall 2013 derived from NCEP/NCAR reanalysis. http://www.esrl.noaa.gov/psd/

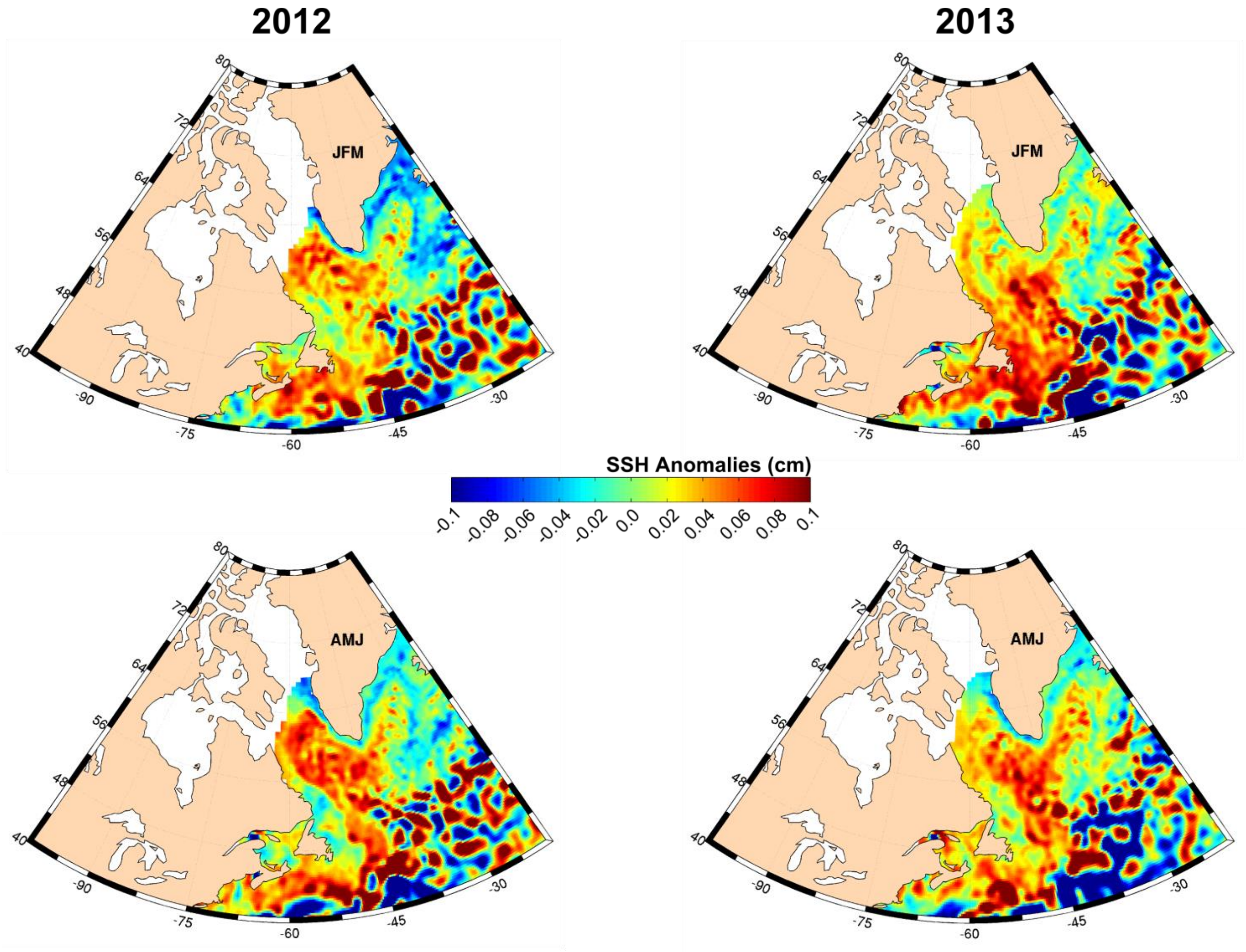


Figure 5: Weekly merged Sea surface height anomalies for winter (January-February-March) and spring (April-May-June) 2012and 2013 from AVISO an objectively mapped product of TOPEX/Poseidon/Jason-1, ERS-1, ERS-2, Geosat-Follow-

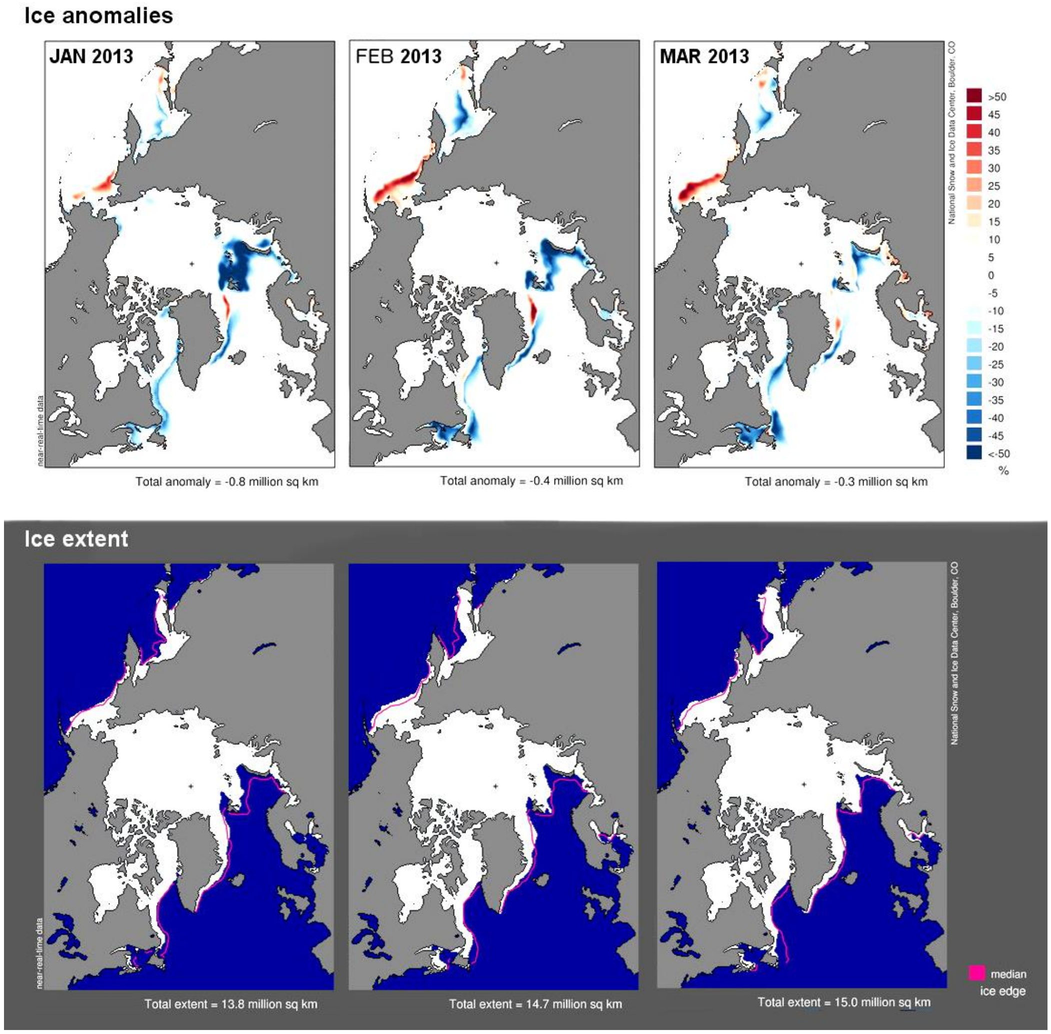


Figure 6. Sea ice concentration anomalies (A) and sea ice extent (B) for Jan-Mar 2013 as derived by the US National Snow and Ice Data Center (reference period 1979-2000) http://nsidc.org/data/seaice_index/archives/index.html

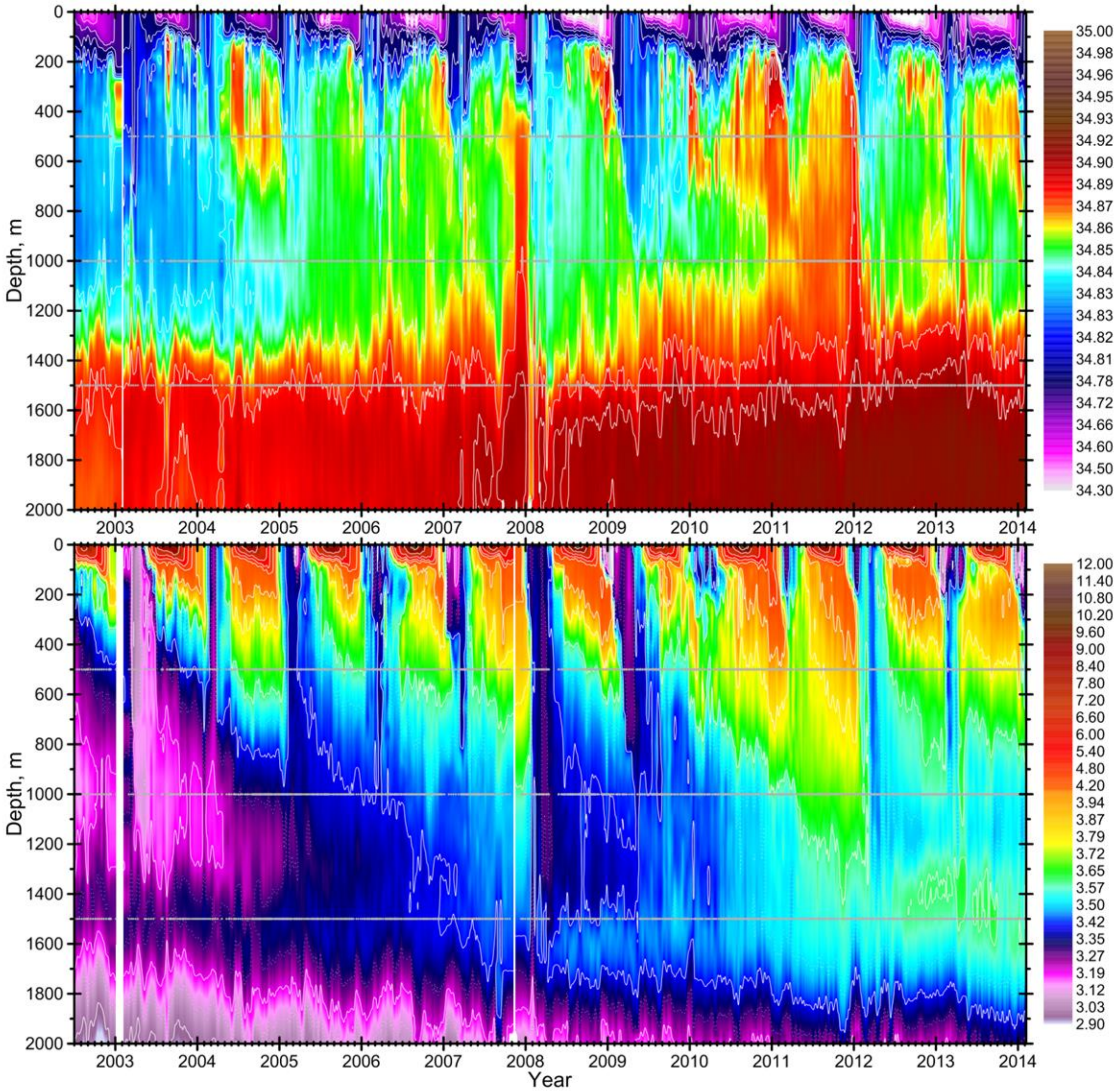


Figure 7: Salinity (top) and potential temperature (bottom) from Argo drifters in the Labrador Sea. The winter 2008 deep convection event is clearly evident to a depth of 1600 m, and 2012 winter deep convection reaches 1400 m. Convection was limited to a depth of about 200 m in the winters of 2010 and 2011.

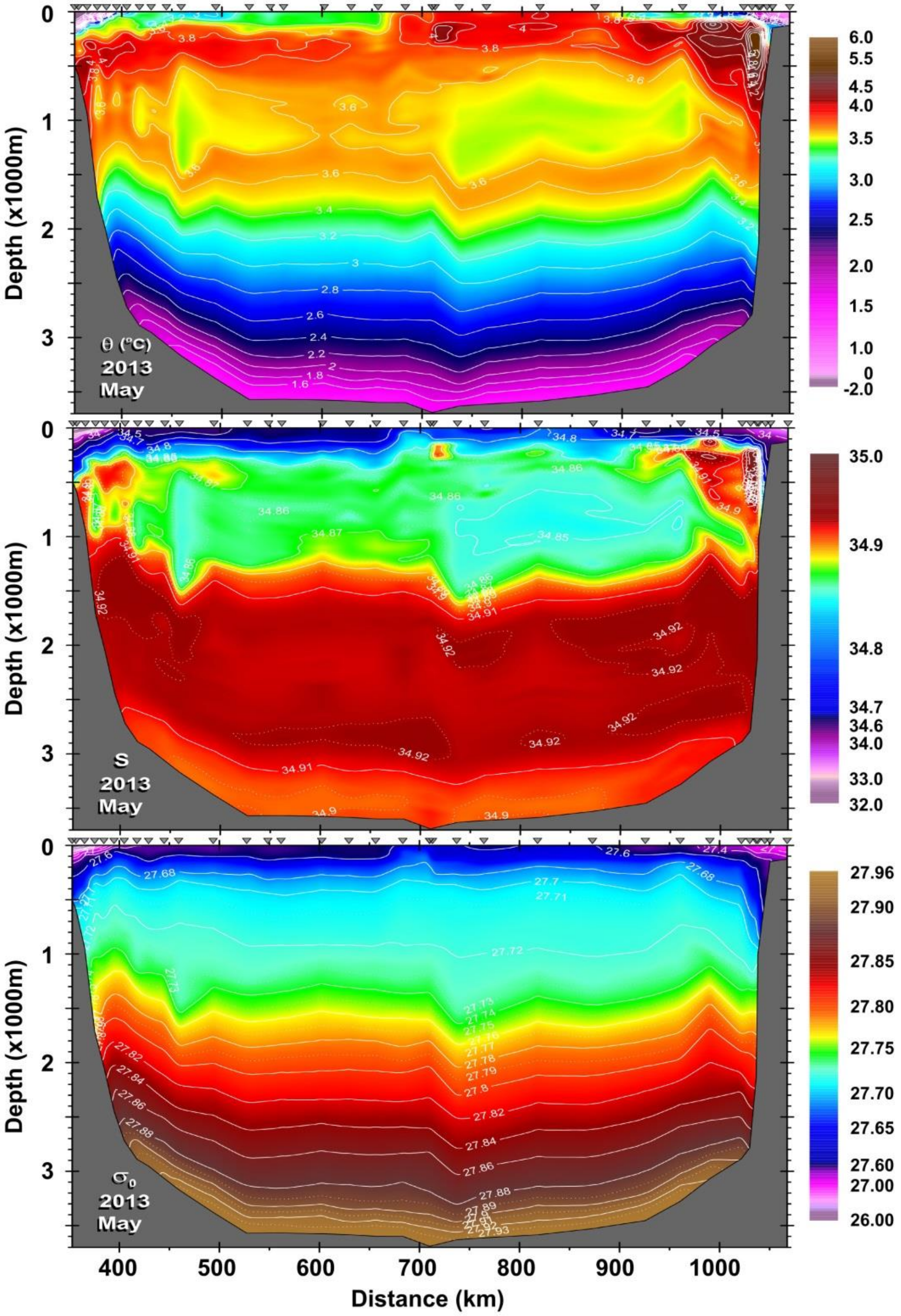


Figure 8: Labrador Sea (AR7W Section) potential temperature (top row), salinity (middle row) and potential density (bottom row).

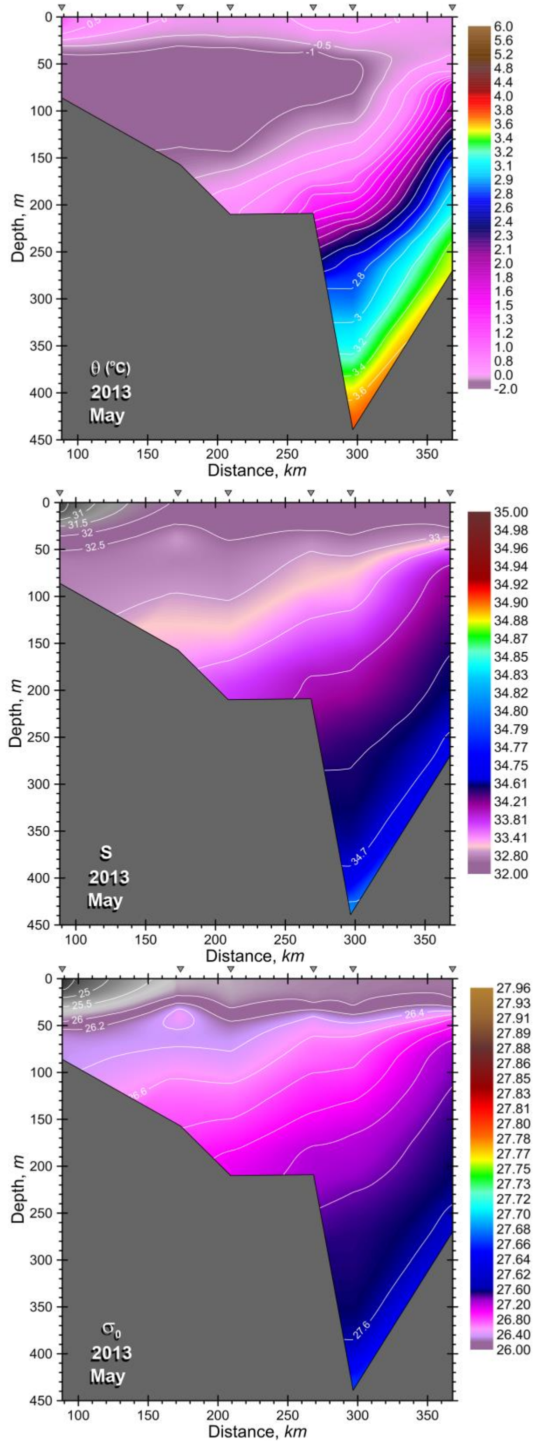


Figure 8a: Belle-Isle Strait new line density (top row), salinity (middle row) and potential temperature (bottom row). This section was added to cover the shelf area of Hamilton Bank that was inaccessible because of heavy ice concentration on the AR7W line.

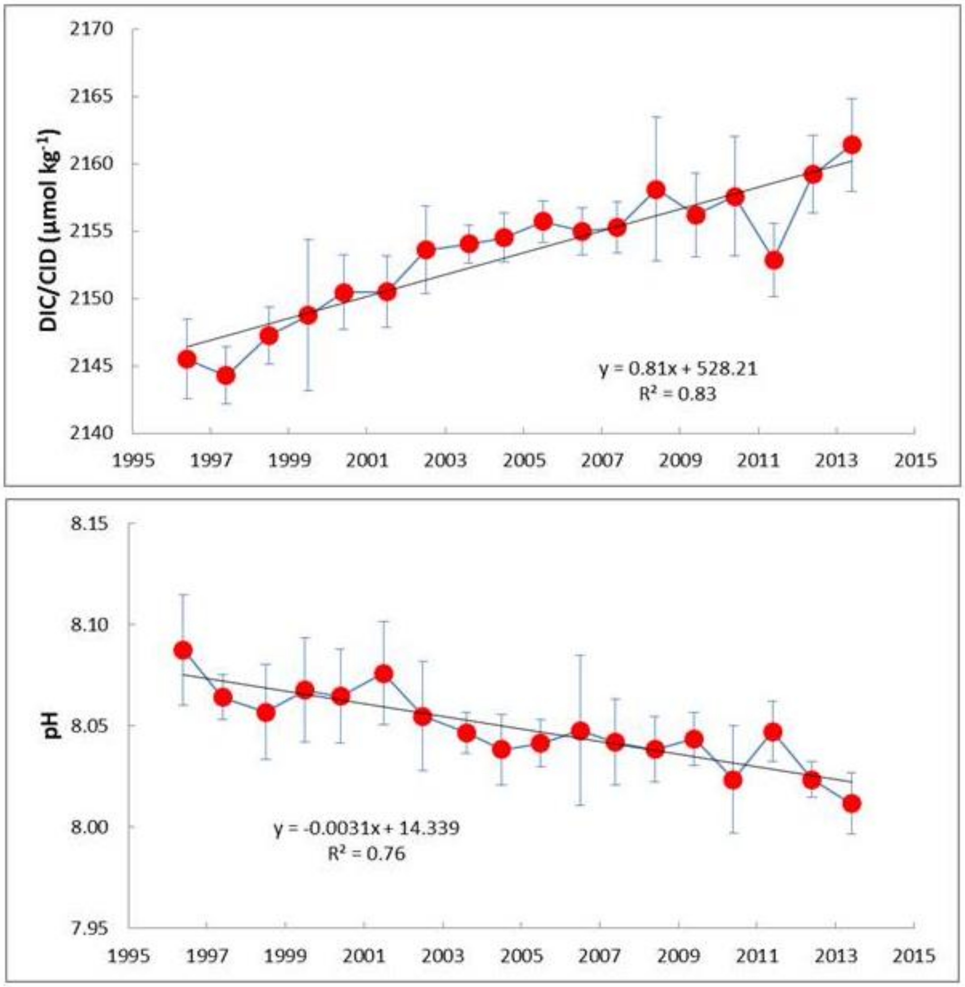


Figure 9: Time series of total inorganic carbon (TIC) and PH, top panel for TIC, bottom panel from PH. TIC and PH in in the 150–500 m depth range and corresponding regression lines for stations in the central part of the Labrador Basin for the period 1996–2013

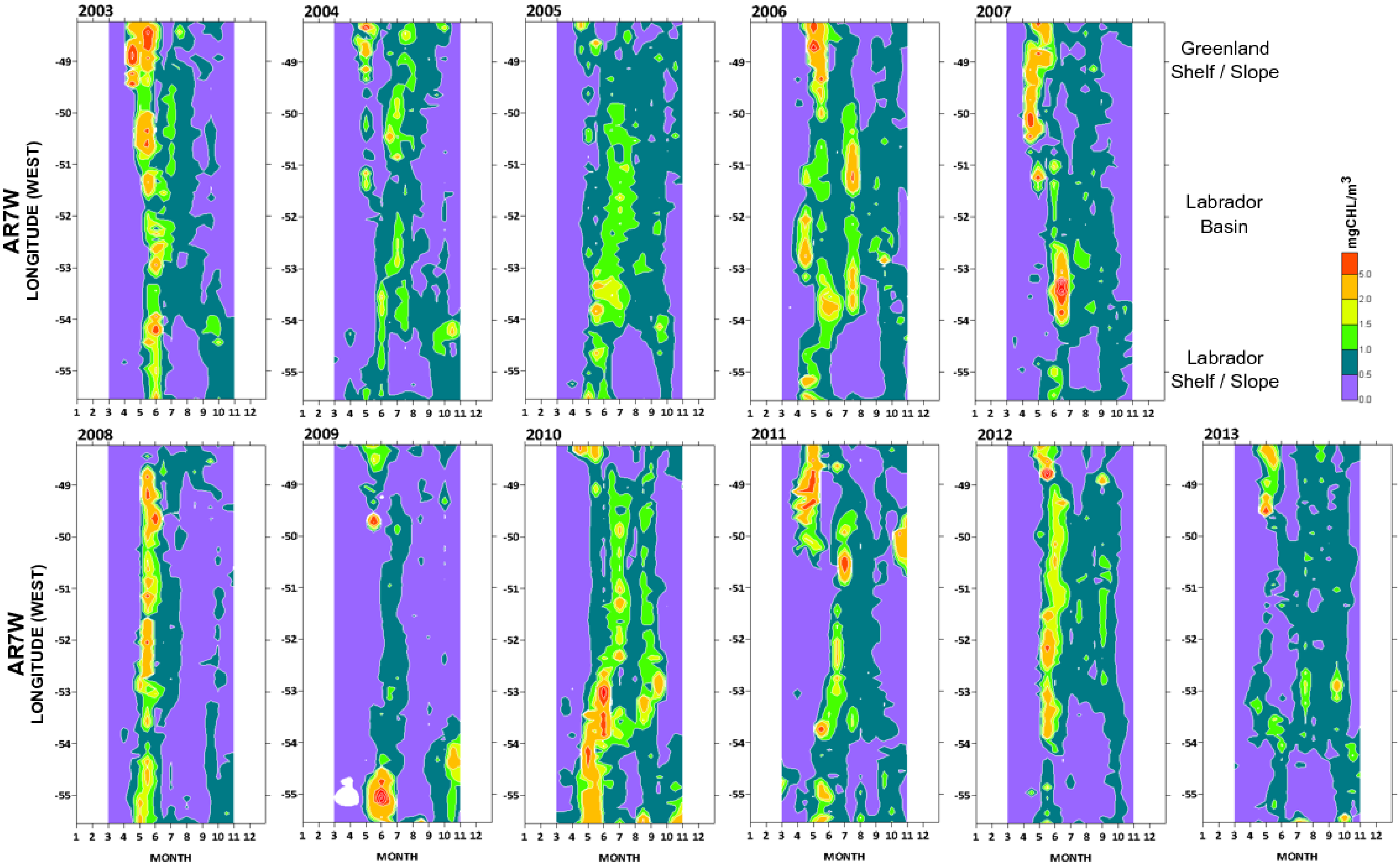


Figure 10: The concentration of sea surface chlorophyll a estimated from remotely-sensed ocean colour at 2-week intervals from March to October spanning a 10-year time series, 2003-2013.

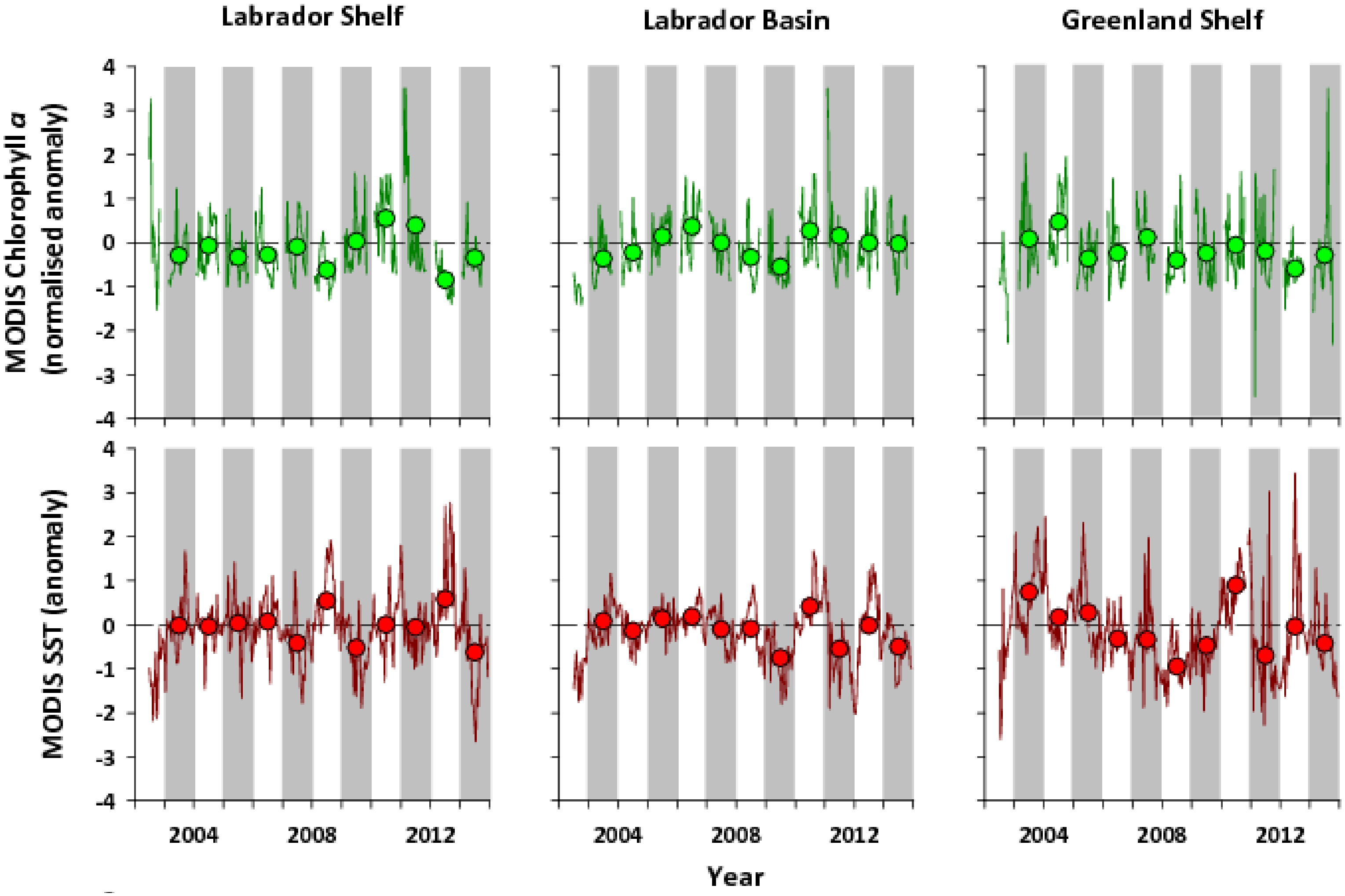


Figure 11: Chlorophyll a normalized anomaly and SST anomaly time series (2003-2013) for Labrador shelf (left column), Labrador Basin (middle column) and Greenland Shelf (right column) estimated from bi-weekly MODIS data. Lines indicate biweekly anomalies, circles indicate annual average anomalies.

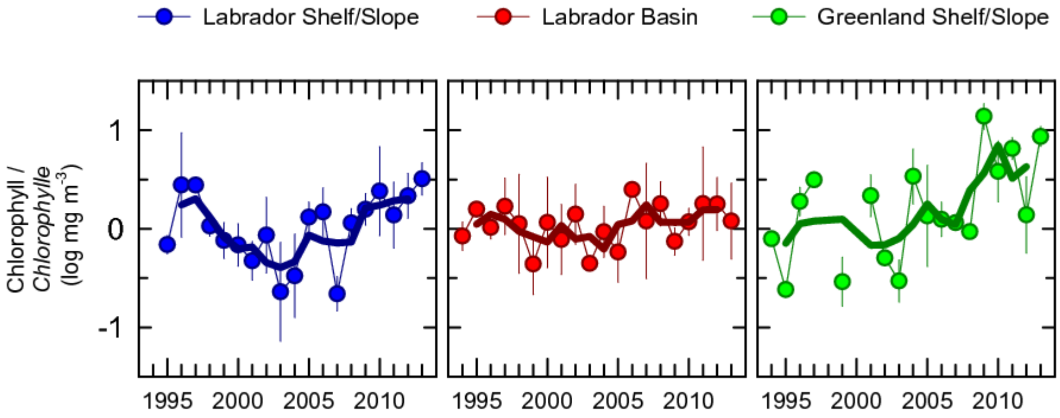


Figure 12: Upper ocean (z<100m) average concentrations of phytoplankton on AR7W sampled in spring or early summer from 1994 to 2013. Circles indicate mean value for stations designated within each region, error bars indicate among-station standard deviation, and heavy line indicates 3-year running average of the time series.

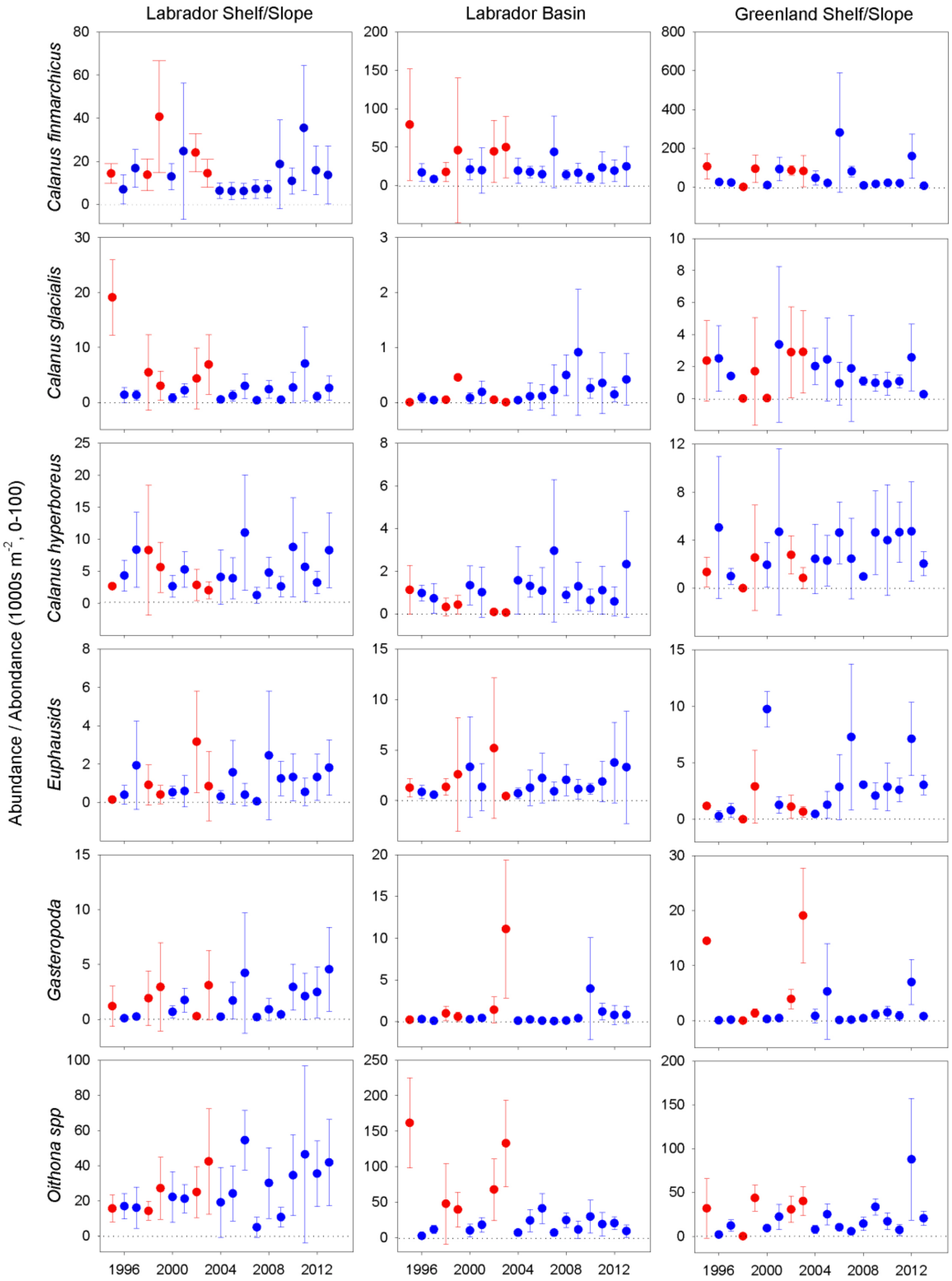


Figure 13: Time series of *Calanus finmarchicus*, *C. glacialis*, *C. hyperboreus*, Euphausids, Gastropoda and *Oithona* spp. from Spring – Summer 1995 - 2013. Blue symbols show results for years when sampling was in spring; red symbols show results for years when sampling was in summer.

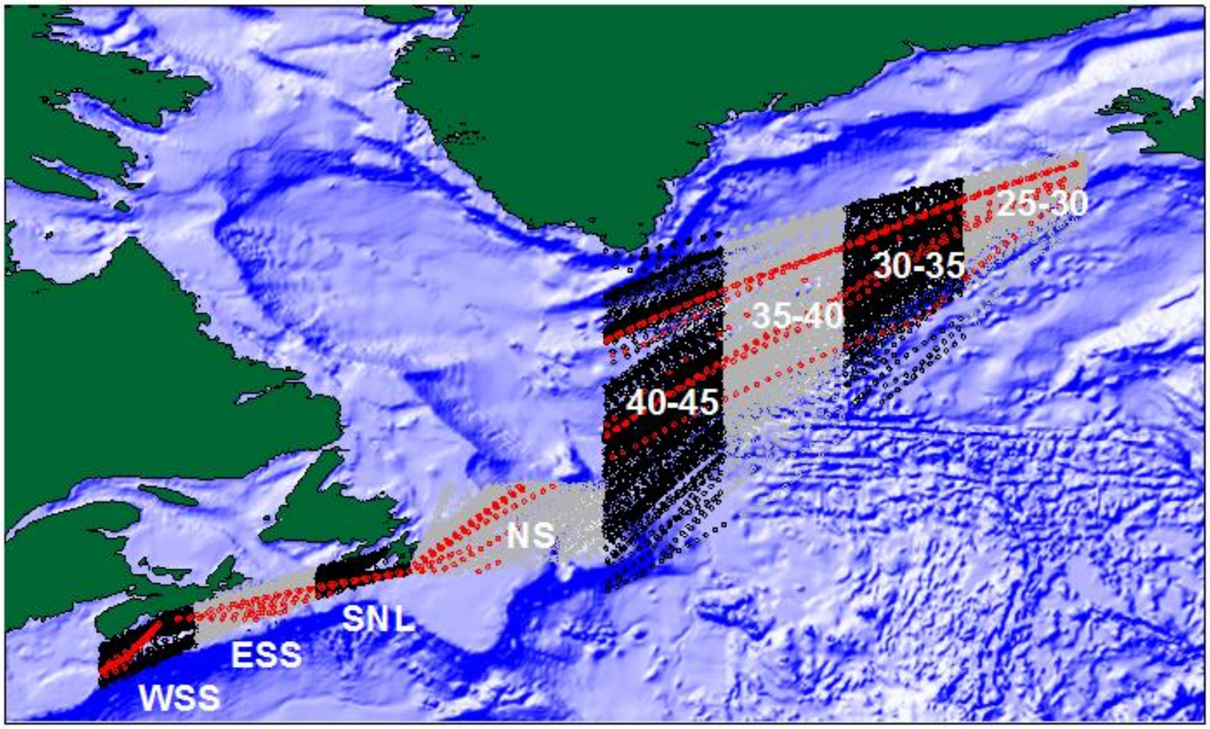
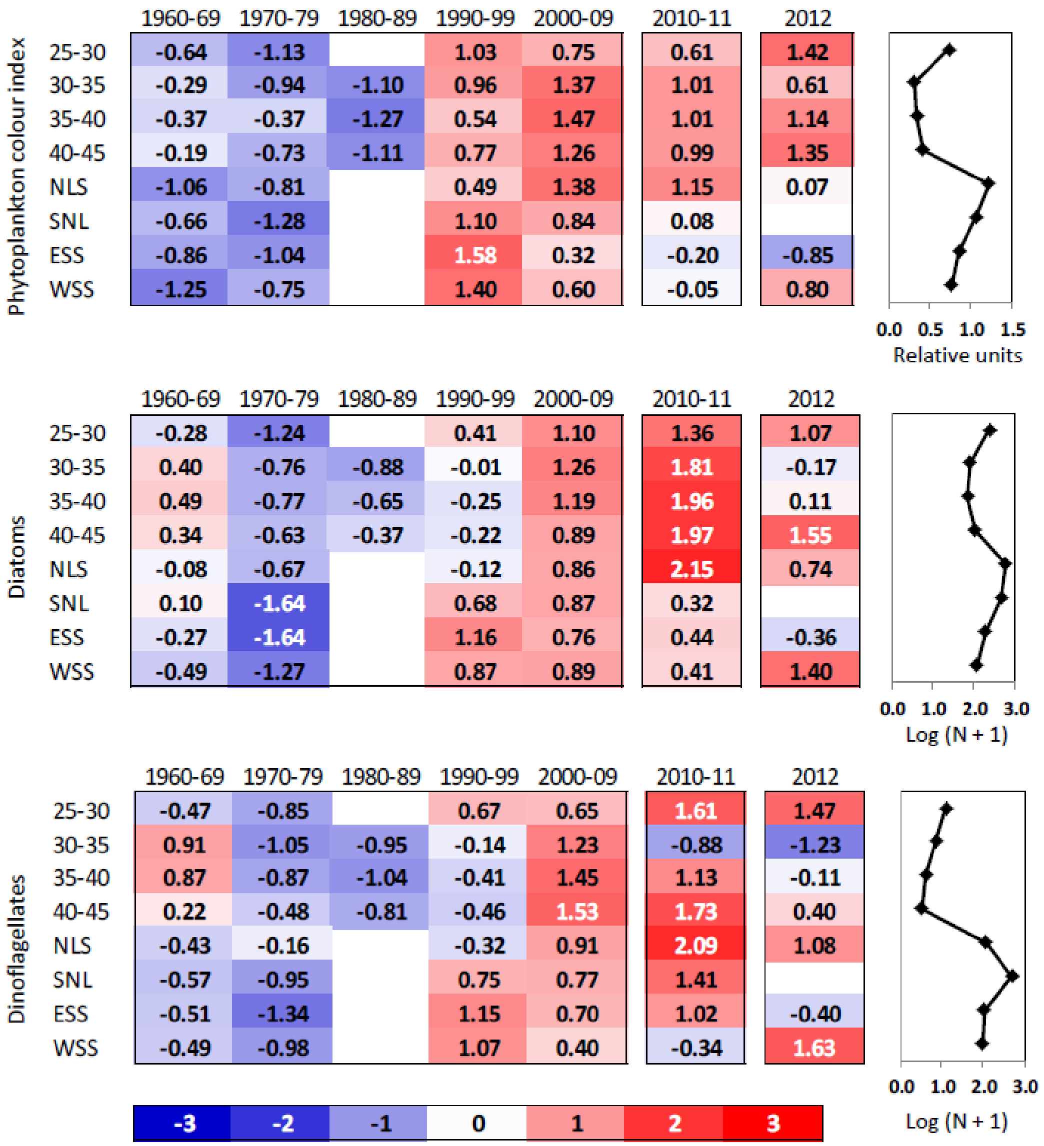


Figure 14. Continuous Plankton recorder (CPR) lines and stations 1957 to 2012. Stations sampled in 2012 are shown in red. Data are analysed by region. Regions are: Western Scotian Shelf (WSS), Eastern Scotian Shelf (ESS), South Newfoundland Shelf (SNL), Newfoundland Shelf (NS), and between longitudes 40-45°W, 35-40°W, 30-35°W, 25-30°W.



Phytoplankton colour index

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	-0.64	-1.13		1.03	0.75	0.61	1.42
30-35	-0.29	-0.94	-1.10	0.96	1.37	1.01	0.61
35-40	-0.37	-0.37	-1.27	0.54	1.47	1.01	1.14
40-45	-0.19	-0.73	-1.11	0.77	1.26	0.99	1.35
NLS	-1.06	-0.81		0.49	1.38	1.15	0.07
SNL	-0.66	-1.28		1.10	0.84	0.08	
ESS	-0.86	-1.04		1.58	0.32	-0.20	-0.85
WSS	-1.25	-0.75		1.40	0.60	-0.05	0.80

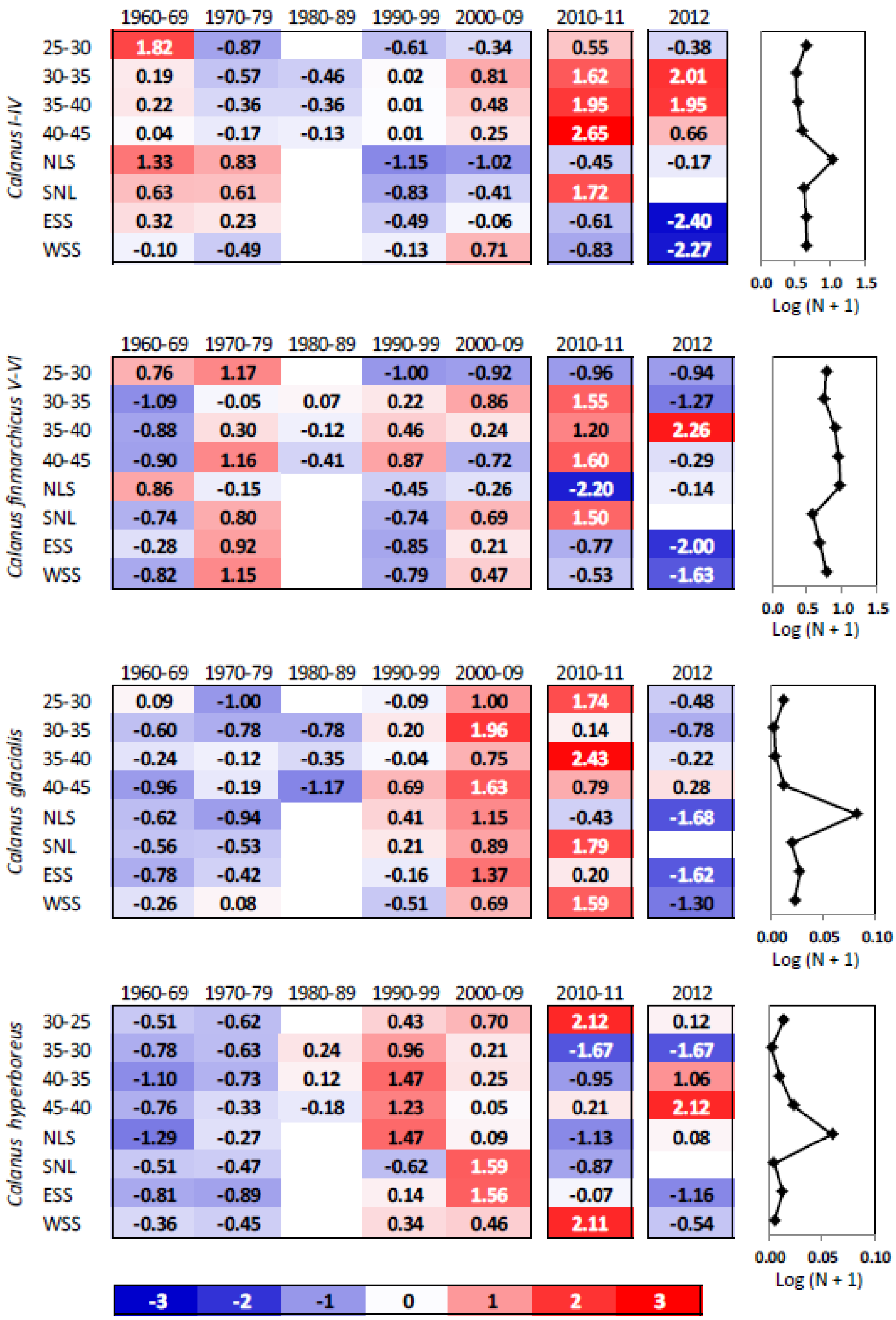
Diatoms

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	-0.28	-1.24		0.41	1.10	1.36	1.07
30-35	0.40	-0.76	-0.88	-0.01	1.26	1.81	-0.17
35-40	0.49	-0.77	-0.65	-0.25	1.19	1.96	0.11
40-45	0.34	-0.63	-0.37	-0.22	0.89	1.97	1.55
NLS	-0.08	-0.67		-0.12	0.86	2.15	0.74
SNL	0.10	-1.64		0.68	0.87	0.32	
ESS	-0.27	-1.64		1.16	0.76	0.44	-0.36
WSS	-0.49	-1.27		0.87	0.89	0.41	1.40

Dinoflagellates

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	-0.47	-0.85		0.67	0.65	1.61	1.47
30-35	0.91	-1.05	-0.95	-0.14	1.23	-0.88	-1.23
35-40	0.87	-0.87	-1.04	-0.41	1.45	1.13	-0.11
40-45	0.22	-0.48	-0.81	-0.46	1.53	1.73	0.40
NLS	-0.43	-0.16		-0.32	0.91	2.09	1.08
SNL	-0.57	-0.95		0.75	0.77	1.41	
ESS	-0.51	-1.34		1.15	0.70	1.02	-0.40
WSS	-0.49	-0.98		1.07	0.40	-0.34	1.63

Figure 15. CPR time series for the annual averages for three indices of phytoplankton concentration, calculated from monthly averages over decadal (1960-2009), bi-annual (2010-2011) or annual (2012) periods for eight regions in the NW Atlantic. Blank cells correspond to years or decades where sampling was too sparse to give annual values. Red (blue) cells indicate higher (lower) than normal values. The climatological averages were calculated from the decadal annual averages between 1960 and 2009, and are shown in the panels on the right. The numbers in the cells are the standardised anomalies. The regions are: Western Scotian Shelf (WSS), Eastern Scotian Shelf (ESS), South Newfoundland Shelf (SNL), Newfoundland Shelf (NS), and between longitudes 40-45°W, 35-40°W, 30-35°W, 25-30°W.



Calanus I-IV

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	1.82	-0.87		-0.61	-0.34	0.55	-0.38
30-35	0.19	-0.57	-0.46	0.02	0.81	1.62	2.01
35-40	0.22	-0.36	-0.36	0.01	0.48	1.95	1.95
40-45	0.04	-0.17	-0.13	0.01	0.25	2.65	0.66
NLS	1.33	0.83		-1.15	-1.02	-0.45	-0.17
SNL	0.63	0.61		-0.83	-0.41	1.72	
ESS	0.32	0.23		-0.49	-0.06	-0.61	-2.40
WSS	-0.10	-0.49		-0.13	0.71	-0.83	-2.27

Calanus finmarchicus V-VI

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	0.76	1.17		-1.00	-0.92	-0.96	-0.94
30-35	-1.09	-0.05	0.07	0.22	0.86	1.55	-1.27
35-40	-0.88	0.30	-0.12	0.46	0.24	1.20	2.26
40-45	-0.90	1.16	-0.41	0.87	-0.72	1.60	-0.29
NLS	0.86	-0.15		-0.45	-0.26	-2.20	-0.14
SNL	-0.74	0.80		-0.74	0.69	1.50	
ESS	-0.28	0.92		-0.85	0.21	-0.77	-2.00
WSS	-0.82	1.15		-0.79	0.47	-0.53	-1.63

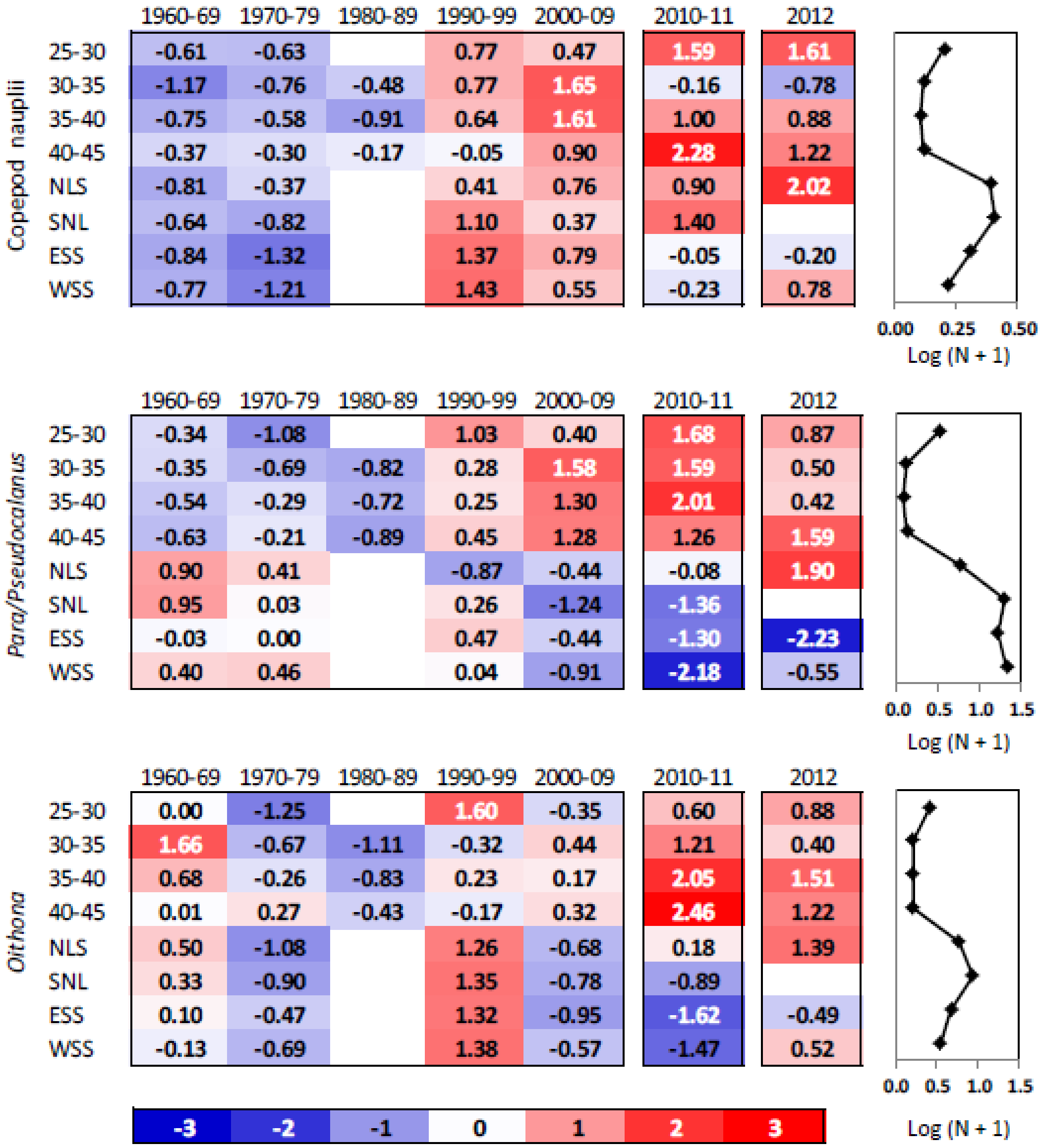
Calanus glacialis

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	0.09	-1.00		-0.09	1.00	1.74	-0.48
30-35	-0.60	-0.78	-0.78	0.20	1.96	0.14	-0.78
35-40	-0.24	-0.12	-0.35	-0.04	0.75	2.43	-0.22
40-45	-0.96	-0.19	-1.17	0.69	1.63	0.79	0.28
NLS	-0.62	-0.94		0.41	1.15	-0.43	-1.68
SNL	-0.56	-0.53		0.21	0.89	1.79	
ESS	-0.78	-0.42		-0.16	1.37	0.20	-1.62
WSS	-0.26	0.08		-0.51	0.69	1.59	-1.30

Calanus hyperboreus

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
30-25	-0.51	-0.62		0.43	0.70	2.12	0.12
35-30	-0.78	-0.63	0.24	0.96	0.21	-1.67	-1.67
40-35	-1.10	-0.73	0.12	1.47	0.25	-0.95	1.06
45-40	-0.76	-0.33	-0.18	1.23	0.05	0.21	2.12
NLS	-1.29	-0.27		1.47	0.09	-1.13	0.08
SNL	-0.51	-0.47		-0.62	1.59	-0.87	
ESS	-0.81	-0.89		0.14	1.56	-0.07	-1.16
WSS	-0.36	-0.45		0.34	0.46	2.11	-0.54

Figure 16 CPR time series for the annual average abundances for four Calanus taxa, calculated from monthly averages over decadal (1960-2009), bi-annual (2010-2011) or annual (2012) periods for eight regions in the NW Atlantic. Blank cells correspond to years or decades where sampling was too sparse to give annual values. Red (blue) cells indicate higher (lower) than normal values. The climatological averages were calculated from the decadal annual averages between 1960 and 2009, and are shown in the panels on the right. The numbers in the cells are the standardised anomalies. The regions are: Western Scotian Shelf (WSS), Eastern Scotian Shelf (ESS), South Newfoundland Shelf (SNL), Newfoundland Shelf (NS), and between longitudes 40-45°W, 35-40°W, 30-35°W, 25-30°W.



Copepod nauplii

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	-0.61	-0.63		0.77	0.47	1.59	1.61
30-35	-1.17	-0.76	-0.48	0.77	1.65	-0.16	-0.78
35-40	-0.75	-0.58	-0.91	0.64	1.61	1.00	0.88
40-45	-0.37	-0.30	-0.17	-0.05	0.90	2.28	1.22
NLS	-0.81	-0.37		0.41	0.76	0.90	2.02
SNL	-0.64	-0.82		1.10	0.37	1.40	
ESS	-0.84	-1.32		1.37	0.79	-0.05	-0.20
WSS	-0.77	-1.21		1.43	0.55	-0.23	0.78

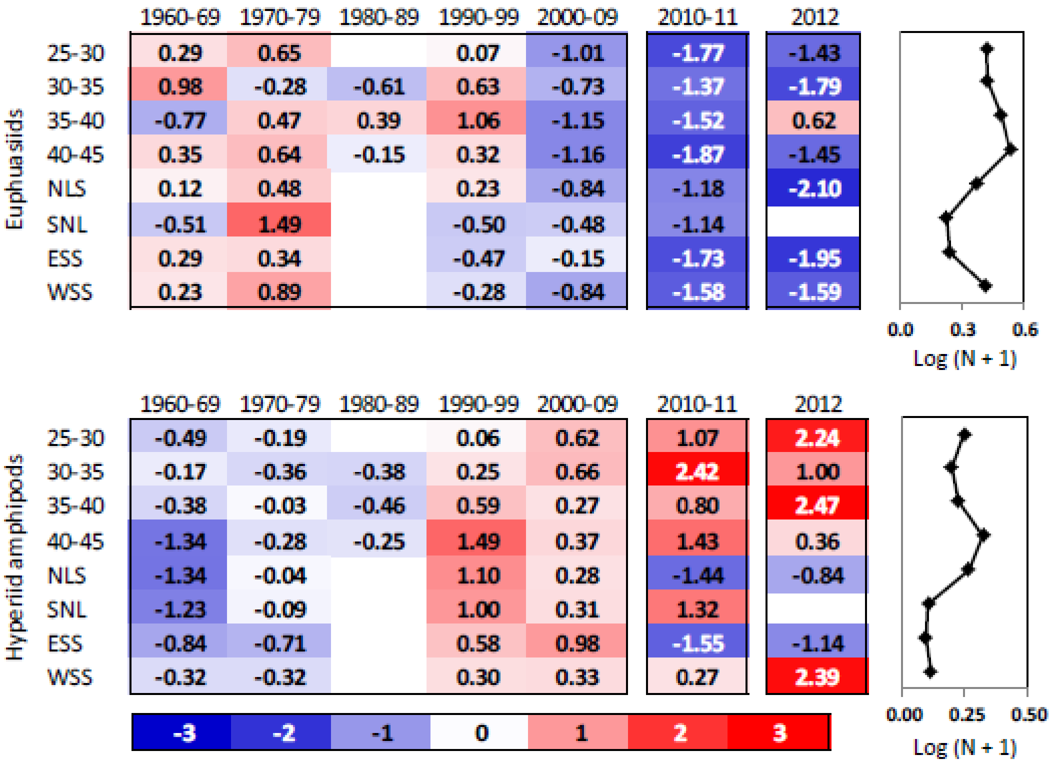
Para/Pseudocalanus

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	-0.34	-1.08		1.03	0.40	1.68	0.87
30-35	-0.35	-0.69	-0.82	0.28	1.58	1.59	0.50
35-40	-0.54	-0.29	-0.72	0.25	1.30	2.01	0.42
40-45	-0.63	-0.21	-0.89	0.45	1.28	1.26	1.59
NLS	0.90	0.41		-0.87	-0.44	-0.08	1.90
SNL	0.95	0.03		0.26	-1.24	-1.36	
ESS	-0.03	0.00		0.47	-0.44	-1.30	-2.23
WSS	0.40	0.46		0.04	-0.91	-2.18	-0.55

Oithona

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	0.00	-1.25		1.60	-0.35	0.60	0.88
30-35	1.66	-0.67	-1.11	-0.32	0.44	1.21	0.40
35-40	0.68	-0.26	-0.83	0.23	0.17	2.05	1.51
40-45	0.01	0.27	-0.43	-0.17	0.32	2.46	1.22
NLS	0.50	-1.08		1.26	-0.68	0.18	1.39
SNL	0.33	-0.90		1.35	-0.78	-0.89	
ESS	0.10	-0.47		1.32	-0.95	-1.62	-0.49
WSS	-0.13	-0.69		1.38	-0.57	-1.47	0.52

Figure 17. CPR time series for the annual average abundances for three small copepod taxa, calculated from monthly averages over decadal (1960-2009), bi-annual (2010-2011) or annual (2012) periods for eight regions in the NW Atlantic. Blank cells correspond to years or decades where sampling was too sparse to give annual values. Red (blue) cells indicate higher (lower) than normal values. The climatological averages were calculated from the decadal annual averages between 1960 and 2009, and are shown in the panels on the right. The numbers in the cells are the standardised anomalies. The regions are: Western Scotian Shelf (WSS), Eastern Scotian Shelf (ESS), South Newfoundland Shelf (SNL), Newfoundland Shelf (NS), and between longitudes 40-45°W, 35-40°W, 30-35°W, 25-30°W.



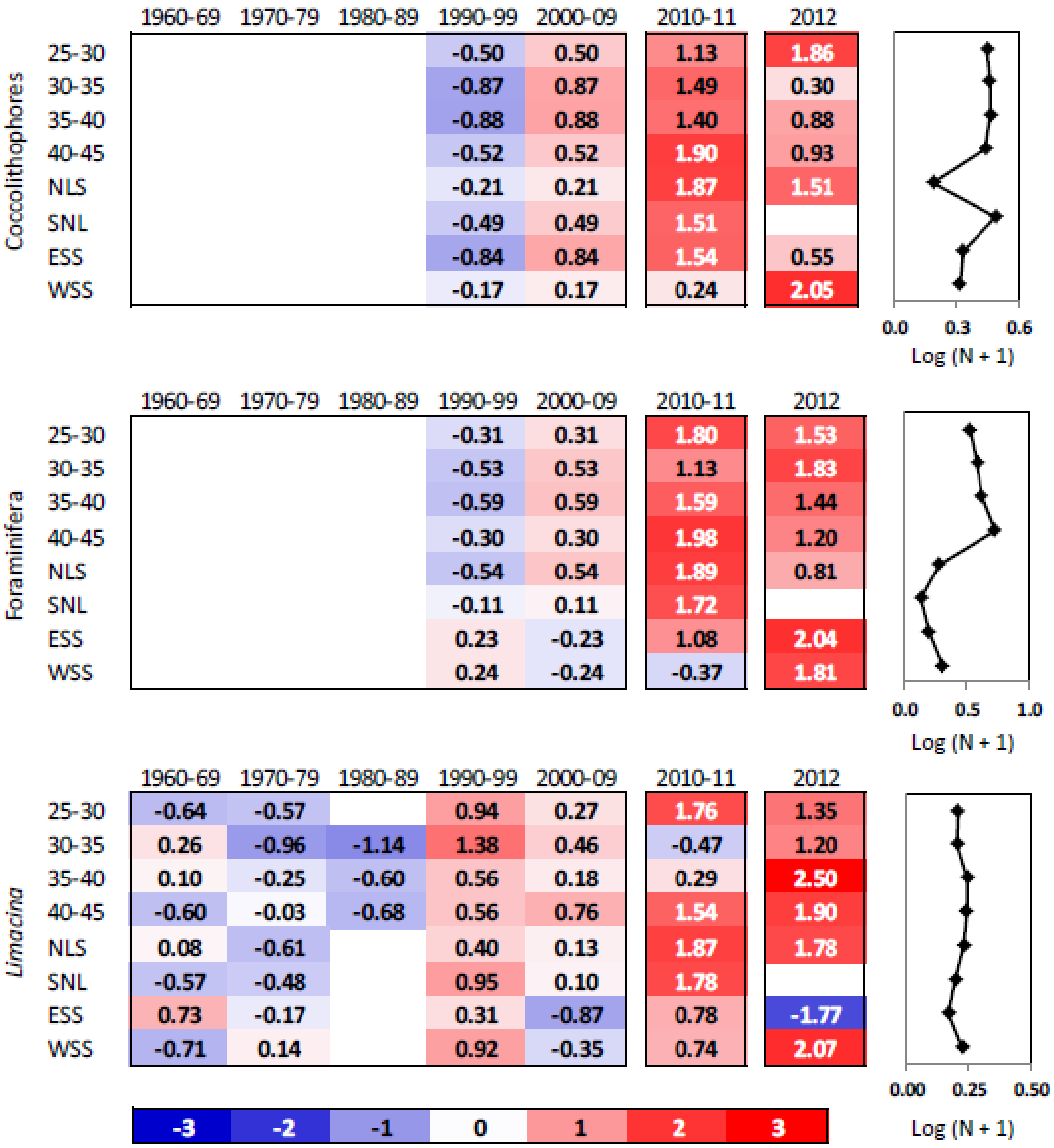
Euphausiids

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	0.29	0.65		0.07	-1.01	-1.77	-1.43
30-35	0.98	-0.28	-0.61	0.63	-0.73	-1.37	-1.79
35-40	-0.77	0.47	0.39	1.06	-1.15	-1.52	0.62
40-45	0.35	0.64	-0.15	0.32	-1.16	-1.87	-1.45
NLS	0.12	0.48		0.23	-0.84	-1.18	-2.10
SNL	-0.51	1.49		-0.50	-0.48	-1.14	
ESS	0.29	0.34		-0.47	-0.15	-1.73	-1.95
WSS	0.23	0.89		-0.28	-0.84	-1.58	-1.59

Hyperid amphipods

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	-0.49	-0.19		0.06	0.62	1.07	2.24
30-35	-0.17	-0.36	-0.38	0.25	0.66	2.42	1.00
35-40	-0.38	-0.03	-0.46	0.59	0.27	0.80	2.47
40-45	-1.34	-0.28	-0.25	1.49	0.37	1.43	0.36
NLS	-1.34	-0.04		1.10	0.28	-1.44	-0.84
SNL	-1.23	-0.09		1.00	0.31	1.32	
ESS	-0.84	-0.71		0.58	0.98	-1.55	-1.14
WSS	-0.32	-0.32		0.30	0.33	0.27	2.39

Figure 18. CPR time series for the annual average abundances for two macrozooplankton taxa, calculated from monthly averages over decadal (1960-2009), bi-annual (2010-2011) or annual (2012) periods for eight regions in the NW Atlantic. Blank cells correspond to years or decades where sampling was too sparse to give annual values. Red (blue) cells indicate higher (lower) than normal values. The climatological averages were calculated from the decadal annual averages between 1960 and 2009, and are shown in the panels on the right. The numbers in the cells are the standardised anomalies. The regions are: Western Scotian Shelf (WSS), Eastern Scotian Shelf (ESS), South Newfoundland Shelf (SNL), Newfoundland Shelf (NS), and between longitudes 40-45°W, 35-40°W, 30-35°W, 25-30°W.



Coccolithophores

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30				-0.50	0.50	1.13	1.86
30-35				-0.87	0.87	1.49	0.30
35-40				-0.88	0.88	1.40	0.88
40-45				-0.52	0.52	1.90	0.93
NLS				-0.21	0.21	1.87	1.51
SNL				-0.49	0.49	1.51	
ESS				-0.84	0.84	1.54	0.55
WSS				-0.17	0.17	0.24	2.05

Foraminifera

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30				-0.31	0.31	1.80	1.53
30-35				-0.53	0.53	1.13	1.83
35-40				-0.59	0.59	1.59	1.44
40-45				-0.30	0.30	1.98	1.20
NLS				-0.54	0.54	1.89	0.81
SNL				-0.11	0.11	1.72	
ESS				0.23	-0.23	1.08	2.04
WSS				0.24	-0.24	-0.37	1.81

Limacina

	1960-69	1970-79	1980-89	1990-99	2000-09	2010-11	2012
25-30	-0.64	-0.57		0.94	0.27	1.76	1.35
30-35	0.26	-0.96	-1.14	1.38	0.46	-0.47	1.20
35-40	0.10	-0.25	-0.60	0.56	0.18	0.29	2.50
40-45	-0.60	-0.03	-0.68	0.56	0.76	1.54	1.90
NLS	0.08	-0.61		0.40	0.13	1.87	1.78
SNL	-0.57	-0.48		0.95	0.10	1.78	
ESS	0.73	-0.17		0.31	-0.87	0.78	-1.77
WSS	-0.71	0.14		0.92	-0.35	0.74	2.07

Figure 19. CPR time series for the annual average abundances for three acid-sensitive taxa, calculated from monthly averages over decadal (1960-2009), bi-annual (2010-2011) or annual (2012) periods for eight regions in the NW Atlantic. Blank cells correspond to years or decades where sampling was too sparse to give annual values. Red (blue) cells indicate higher (lower) than normal values. The climatological averages were calculated from the decadal annual averages between 1990 and 2009 for the coccolithophores and foraminifera, and between 1960 and 2009 for Limacina, and are shown in the panels on the right. The numbers in the cells are the standardised anomalies. The regions are: Western Scotian Shelf (WSS), Eastern Scotian Shelf (ESS), South Newfoundland Shelf (SNL), Newfoundland Shelf (NS), and between longitudes 40-45°W, 35-40°W, 30-35°W, 25-30°W.

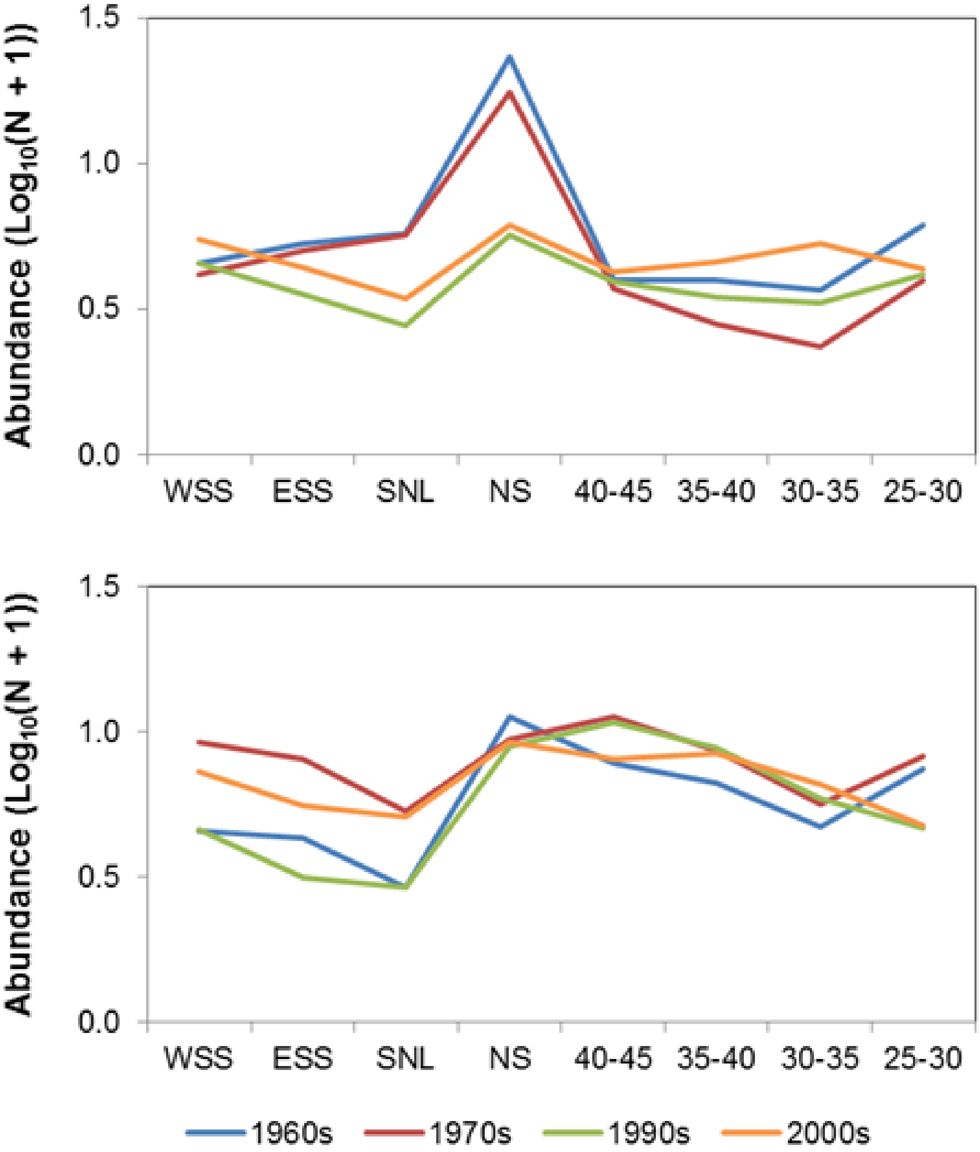
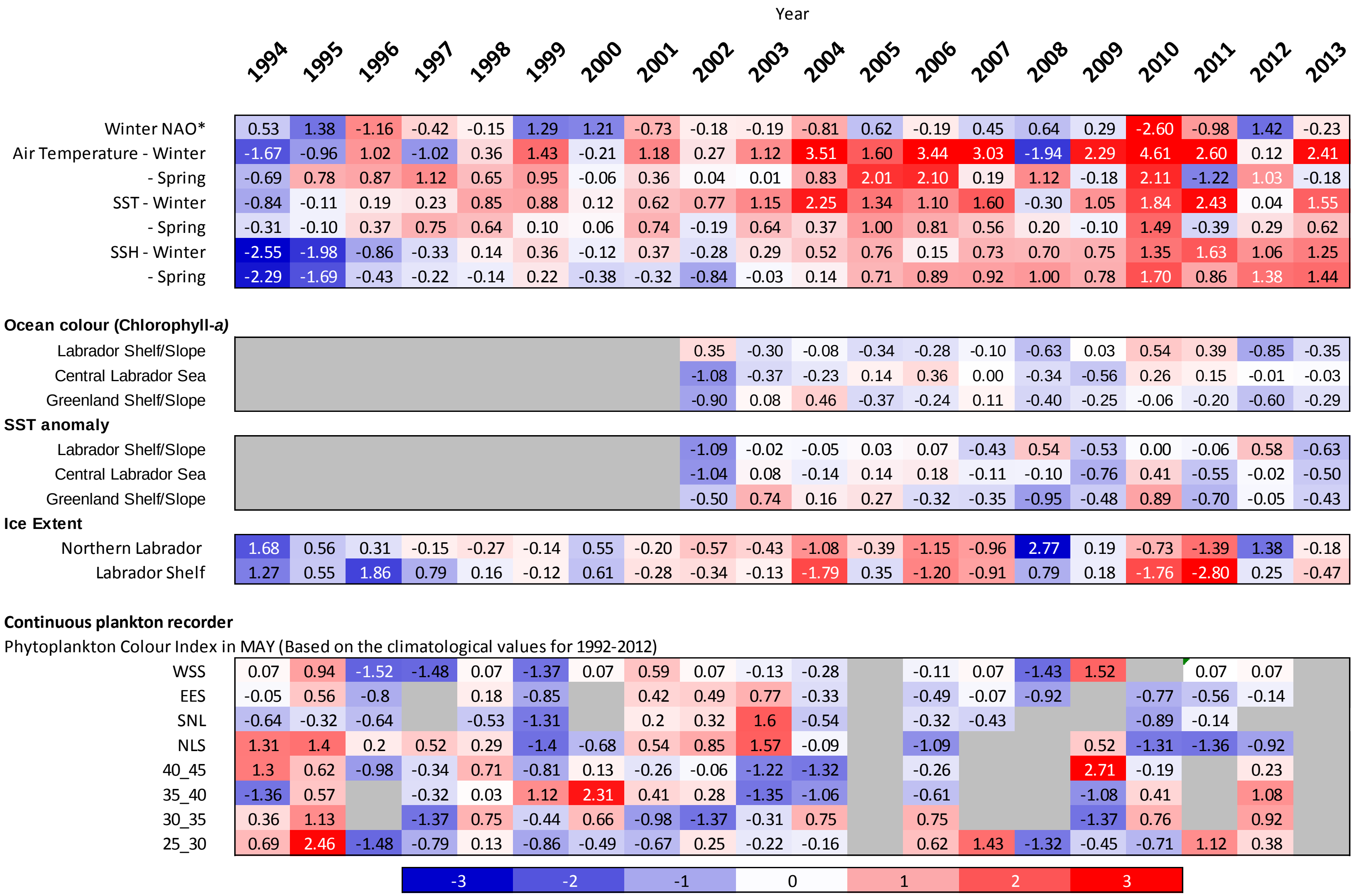


Fig. 20. Decadal annual average abundances for Calanus I-IV (upper panel) and Calanus finmarchicus V-VI (lower panel) during the 1960s, 1970s, 1980s and 2000s for eight regions in the Northwest Atlantic. The regions are: Western Scotian Shelf (WSS), Eastern Scotian Shelf (ESS), South Newfoundland Shelf (SNL), Newfoundland Shelf (NS), and between longitudes 40-45°W, 35-40°W, 30-35°W, 25-30°W.



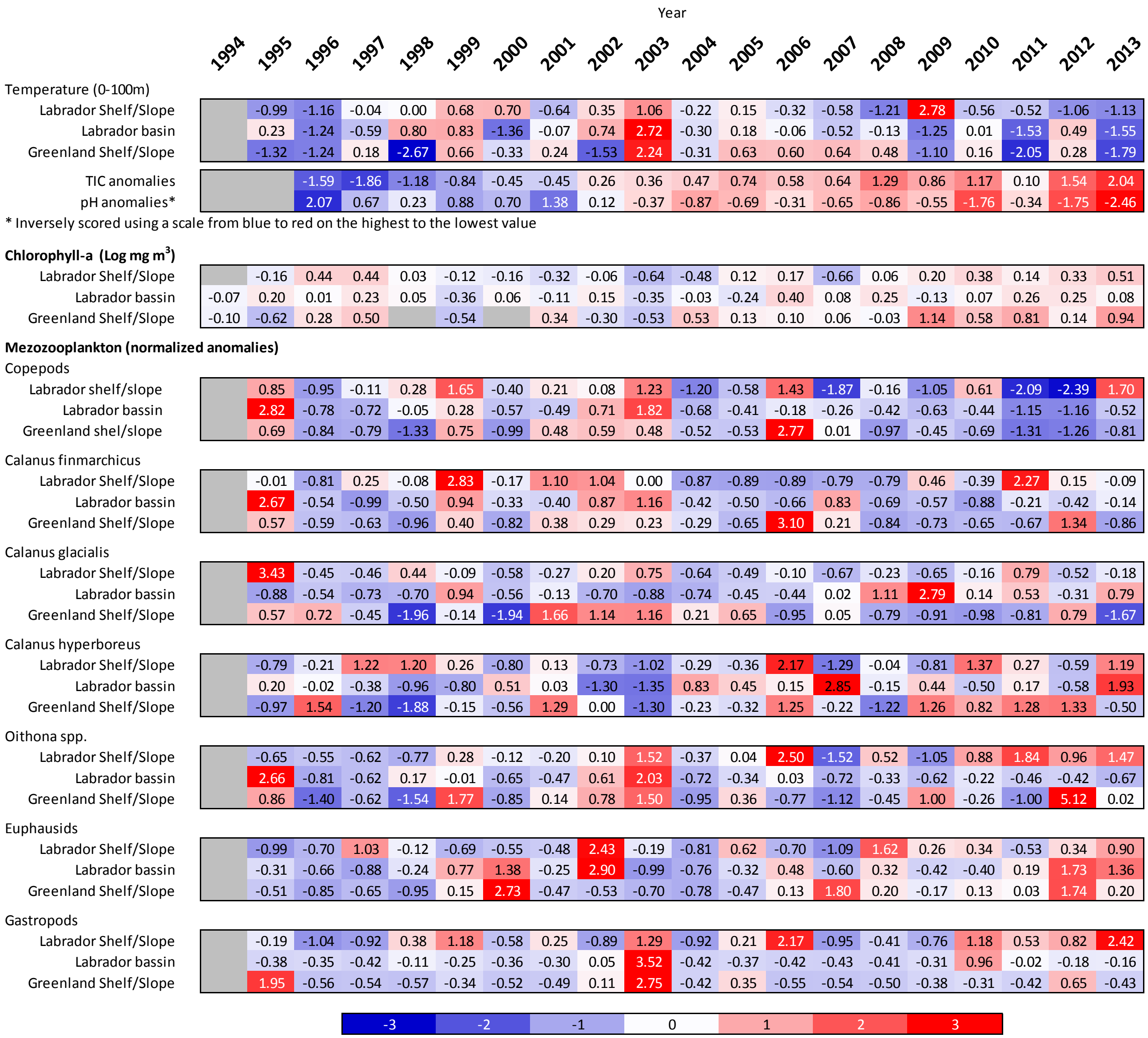
Year

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Winter NAO*	0.53	1.38	-1.16	-0.42	-0.15	1.29	1.21	-0.73	-0.18	-0.19	-0.81	0.62	-0.19	0.45	0.64	0.29	-2.60	-0.98	1.42	-0.23
Air Temperature - Winter	-1.67	-0.96	1.02	-1.02	0.36	1.43	-0.21	1.18	0.27	1.12	3.51	1.60	3.44	3.03	-1.94	2.29	4.61	2.60	0.12	2.41
- Spring	-0.69	0.78	0.87	1.12	0.65	0.95	-0.06	0.36	0.04	0.01	0.83	2.01	2.10	0.19	1.12	-0.18	2.11	-1.22	1.03	-0.18
SST - Winter	-0.84	-0.11	0.19	0.23	0.85	0.88	0.12	0.62	0.77	1.15	2.25	1.34	1.10	1.60	-0.30	1.05	1.84	2.43	0.04	1.55
- Spring	-0.31	-0.10	0.37	0.75	0.64	0.10	0.06	0.74	-0.19	0.64	0.37	1.00	0.81	0.56	0.20	-0.10	1.49	-0.39	0.29	0.62
SSH - Winter	-2.55	-1.98	-0.86	-0.33	0.14	0.36	-0.12	0.37	-0.28	0.29	0.52	0.76	0.15	0.73	0.70	0.75	1.35	1.63	1.06	1.25
- Spring	-2.29	-1.69	-0.43	-0.22	-0.14	0.22	-0.38	-0.32	-0.84	-0.03	0.14	0.71	0.89	0.92	1.00	0.78	1.70	0.86	1.38	1.44
Ocean colour (Chlorophyll-*a*)																				
Labrador Shelf/Slope									0.35	-0.30	-0.08	-0.34	-0.28	-0.10	-0.63	0.03	0.54	0.39	-0.85	-0.35
Central Labrador Sea									-1.08	-0.37	-0.23	0.14	0.36	0.00	-0.34	-0.56	0.26	0.15	-0.01	-0.03
Greenland Shelf/Slope									-0.90	0.08	0.46	-0.37	-0.24	0.11	-0.40	-0.25	-0.06	-0.20	-0.60	-0.29
SST anomaly																				
Labrador Shelf/Slope									-1.09	-0.02	-0.05	0.03	0.07	-0.43	0.54	-0.53	0.00	-0.06	0.58	-0.63
Central Labrador Sea									-1.04	0.08	-0.14	0.14	0.18	-0.11	-0.10	-0.76	0.41	-0.55	-0.02	-0.50
Greenland Shelf/Slope									-0.50	0.74	0.16	0.27	-0.32	-0.35	-0.95	-0.48	0.89	-0.70	-0.05	-0.43
Ice Extent																				
Northern Labrador	1.68	0.56	0.31	-0.15	-0.27	-0.14	0.55	-0.20	-0.57	-0.43	-1.08	-0.39	-1.15	-0.96	2.77	0.19	-0.73	-1.39	1.38	-0.18
Labrador Shelf	1.27	0.55	1.86	0.79	0.16	-0.12	0.61	-0.28	-0.34	-0.13	-1.79	0.35	-1.20	-0.91	0.79	0.18	-1.76	-2.80	0.25	-0.47
Continuous plankton recorder																				
Phytoplankton Colour Index in MAY (Based on the climatological values for 1992-2012)																				
WSS	0.07	0.94	-1.52	-1.48	0.07	-1.37	0.07	0.59	0.07	-0.13	-0.28		-0.11	0.07	-1.43	1.52		0.07	0.07	
EES	-0.05	0.56	-0.8		0.18	-0.85		0.42	0.49	0.77	-0.33		-0.49	-0.07	-0.92		-0.77	-0.56	-0.14	
SNL	-0.64	-0.32	-0.64		-0.53	-1.31		0.2	0.32	1.6	-0.54		-0.32	-0.43			-0.89	-0.14		
NLS	1.31	1.4	0.2	0.52	0.29	-1.4	-0.68	0.54	0.85	1.57	-0.09		-1.09			0.52	-1.31	-1.36	-0.92	
40_45	1.3	0.62	-0.98	-0.34	0.71	-0.81	0.13	-0.26	-0.06	-1.22	-1.32		-0.26			2.71	-0.19		0.23	
35_40	-1.36	0.57		-0.32	0.03	1.12	2.31	0.41	0.28	-1.35	-1.06		-0.61			-1.08	0.41		1.08	
30_35	0.36	1.13		-1.37	0.75	-0.44	0.66	-0.98	-1.37	-0.31	0.75		0.75			-1.37	0.76		0.92	
25_30	0.69	2.46	-1.48	-0.79	0.13	-0.86	-0.49	-0.67	0.25	-0.22	-0.16		0.62	1.43	-1.32	-0.45	-0.71	1.12	0.38	

-3	-2	-1	0	1	2	3

* Inversely scored using a scale from blue to red on the highest to the lowest value

Figure 21. Normalised annual and/or seasonal anomaly of physical and biological variables integrated over large spatial scales estimated using NCEP , remote sensed data or Continuous plankton recorder (CPR) between 1994 and 2013.



Year

	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Temperature (0-100m)																				
Labrador Shelf/Slope		-0.99	-1.16	-0.04	0.00	0.68	0.70	-0.64	0.35	1.06	-0.22	0.15	-0.32	-0.58	-1.21	2.78	-0.56	-0.52	-1.06	-1.13
Labrador basin		0.23	-1.24	-0.59	0.80	0.83	-1.36	-0.07	0.74	2.72	-0.30	0.18	-0.06	-0.52	-0.13	-1.25	0.01	-1.53	0.49	-1.55
Greenland Shelf/Slope		-1.32	-1.24	0.18	-2.67	0.66	-0.33	0.24	-1.53	2.24	-0.31	0.63	0.60	0.64	0.48	-1.10	0.16	-2.05	0.28	-1.79
TIC anomalies			-1.59	-1.86	-1.18	-0.84	-0.45	-0.45	0.26	0.36	0.47	0.74	0.58	0.64	1.29	0.86	1.17	0.10	1.54	2.04
pH anomalies*			2.07	0.67	0.23	0.88	0.70	1.38	0.12	-0.37	-0.87	-0.69	-0.31	-0.65	-0.86	-0.55	-1.76	-0.34	-1.75	-2.46
* Inversely scored using a scale from blue to red on the highest to the lowest value																				
Chlorophyll-a (Log mg m^3)																				
Labrador Shelf/Slope		-0.16	0.44	0.44	0.03	-0.12	-0.16	-0.32	-0.06	-0.64	-0.48	0.12	0.17	-0.66	0.06	0.20	0.38	0.14	0.33	0.51
Labrador bassin	-0.07	0.20	0.01	0.23	0.05	-0.36	0.06	-0.11	0.15	-0.35	-0.03	-0.24	0.40	0.08	0.25	-0.13	0.07	0.26	0.25	0.08
Greenland Shelf/Slope	-0.10	-0.62	0.28	0.50		-0.54		0.34	-0.30	-0.53	0.53	0.13	0.10	0.06	-0.03	1.14	0.58	0.81	0.14	0.94
Mezozooplankton (normalized anomalies)																				
Copepods																				
Labrador shelf/slope		0.85	-0.95	-0.11	0.28	1.65	-0.40	0.21	0.08	1.23	-1.20	-0.58	1.43	-1.87	-0.16	-1.05	0.61	-2.09	-2.39	1.70
Labrador bassin		2.82	-0.78	-0.72	-0.05	0.28	-0.57	-0.49	0.71	1.82	-0.68	-0.41	-0.18	-0.26	-0.42	-0.63	-0.44	-1.15	-1.16	-0.52
Greenland shel/slope		0.69	-0.84	-0.79	-1.33	0.75	-0.99	0.48	0.59	0.48	-0.52	-0.53	2.77	0.01	-0.97	-0.45	-0.69	-1.31	-1.26	-0.81
Calanus finmarchicus																				
Labrador Shelf/Slope		-0.01	-0.81	0.25	-0.08	2.83	-0.17	1.10	1.04	0.00	-0.87	-0.89	-0.89	-0.79	-0.79	0.46	-0.39	2.27	0.15	-0.09
Labrador bassin		2.67	-0.54	-0.99	-0.50	0.94	-0.33	-0.40	0.87	1.16	-0.42	-0.50	-0.66	0.83	-0.69	-0.57	-0.88	-0.21	-0.42	-0.14
Greenland Shelf/Slope		0.57	-0.59	-0.63	-0.96	0.40	-0.82	0.38	0.29	0.23	-0.29	-0.65	3.10	0.21	-0.84	-0.73	-0.65	-0.67	1.34	-0.86
Calanus glacialis																				
Labrador Shelf/Slope		3.43	-0.45	-0.46	0.44	-0.09	-0.58	-0.27	0.20	0.75	-0.64	-0.49	-0.10	-0.67	-0.23	-0.65	-0.16	0.79	-0.52	-0.18
Labrador bassin		-0.88	-0.54	-0.73	-0.70	0.94	-0.56	-0.13	-0.70	-0.88	-0.74	-0.45	-0.44	0.02	1.11	2.79	0.14	0.53	-0.31	0.79
Greenland Shelf/Slope		0.57	0.72	-0.45	-1.96	-0.14	-1.94	1.66	1.14	1.16	0.21	0.65	-0.95	0.05	-0.79	-0.91	-0.98	-0.81	0.79	-1.67
Calanus hyperboreus																				
Labrador Shelf/Slope		-0.79	-0.21	1.22	1.20	0.26	-0.80	0.13	-0.73	-1.02	-0.29	-0.36	2.17	-1.29	-0.04	-0.81	1.37	0.27	-0.59	1.19
Labrador bassin		0.20	-0.02	-0.38	-0.96	-0.80	0.51	0.03	-1.30	-1.35	0.83	0.45	0.15	2.85	-0.15	0.44	-0.50	0.17	-0.58	1.93
Greenland Shelf/Slope		-0.97	1.54	-1.20	-1.88	-0.15	-0.56	1.29	0.00	-1.30	-0.23	-0.32	1.25	-0.22	-1.22	1.26	0.82	1.28	1.33	-0.50
Oithona spp.																				
Labrador Shelf/Slope		-0.65	-0.55	-0.62	-0.77	0.28	-0.12	-0.20	0.10	1.52	-0.37	0.04	2.50	-1.52	0.52	-1.05	0.88	1.84	0.96	1.47
Labrador bassin		2.66	-0.81	-0.62	0.17	-0.01	-0.65	-0.47	0.61	2.03	-0.72	-0.34	0.03	-0.72	-0.33	-0.62	-0.22	-0.46	-0.42	-0.67
Greenland Shelf/Slope		0.86	-1.40	-0.62	-1.54	1.77	-0.85	0.14	0.78	1.50	-0.95	0.36	-0.77	-1.12	-0.45	1.00	-0.26	-1.00	5.12	0.02
Euphausids																				
Labrador Shelf/Slope		-0.99	-0.70	1.03	-0.12	-0.69	-0.55	-0.48	2.43	-0.19	-0.81	0.62	-0.70	-1.09	1.62	0.26	0.34	-0.53	0.34	0.90
Labrador bassin		-0.31	-0.66	-0.88	-0.24	0.77	1.38	-0.25	2.90	-0.99	-0.76	-0.32	0.48	-0.60	0.32	-0.42	-0.40	0.19	1.73	1.36
Greenland Shelf/Slope		-0.51	-0.85	-0.65	-0.95	0.15	2.73	-0.47	-0.53	-0.70	-0.78	-0.47	0.13	1.80	0.20	-0.17	0.13	0.03	1.74	0.20
Gastropods																				
Labrador Shelf/Slope		-0.19	-1.04	-0.92	0.38	1.18	-0.58	0.25	-0.89	1.29	-0.92	0.21	2.17	-0.95	-0.41	-0.76	1.18	0.53	0.82	2.42
Labrador bassin		-0.38	-0.35	-0.42	-0.11	-0.25	-0.36	-0.30	0.05	3.52	-0.42	-0.37	-0.42	-0.43	-0.41	-0.31	0.96	-0.02	-0.18	-0.16
Greenland Shelf/Slope		1.95	-0.56	-0.54	-0.57	-0.34	-0.52	-0.49	0.11	2.75	-0.42	0.35	-0.55	-0.54	-0.50	-0.38	-0.31	-0.42	0.65	-0.43

-3	-2	-1	0	1	2	3

Figure 22. Normalised anomaly of physical, chemical and biological in-situ measurements on the AR7W line between 1994 and 2013.