NOT TO BE CITED WITHOUT PRIOR
REFERENCE TO THE SECRETARIAT

Northwest Atlantic Fisheries Organization

Serial No. N6170 **NAFO SCR Doc. 13/019**

SCIENTIFIC COUNCIL MEETING – JUNE 2013

Environmental Conditions in the Labrador Sea during 2012

I. Yashayaev, E.J.H. Head, Z. Wang,
W.K.W. Li, K. Azetsu-Scott, B.J.W. Greenan,
J. Anning and S. Punshon

Department of Fisheries and Oceans, Maritimes Region
Ocean and Ecosystem Sciences Division, Bedford Institute of Oceanography
P.O. Box 1006, Dartmouth, N.S. B2Y 4A2

Abstract

Following three years of negative state of North Atlantic Oscillation (NAO) with the 2009-10 value being a record low in the entire time series, the NAO index for the Dec-Jan-Feb (DJF) period of 2011-12 was strongly positive, close to the level in early 1990s, a period which experienced the highest NAO index values in the last 2 decades. The NCEP reanalysis of surface air temperature also indicated below normal conditions with an anomaly of 0 to -2°C in the Labrador Sea during the winter period; for the summer period the anomaly was positive with a range of approximately 1-3°C; the fall period was characterized by a strong positive anomaly of 4-6°C in the Baffin Bay/Davis Strait area north of the Labrador Sea. Sea surface temperature (SST) anomalies in the Labrador Sea followed the pattern observed in the air temperature being negative (0 to -1°C) in the winter and positive (1 to 3°C) in the summer. The Labrador Shelf ice anomaly was below normal in Jan-Feb 2012 (reference period: 1979-2000). In the March 2012, sea ice conditions on the northern Labrador Sea/Davis Strait area were well above normal. Winter time convection in 2012 reached to 1400 m, which is significantly deeper than the 800 m seen in 2011, though still less than the 1600 m of 2008. The 1000-1500m layer has been warming since 2002 with resets in 2008 and 2012 only. The increasing trend of the total inorganic carbon and decreasing trend of pH continue. For the year of 2012 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. The abundance of *Calanus finmarchicus* was near (above) normal on Labrador (Greenland) Shelf.

Introduction

Labrador Sea hydrographic conditions demonstrate seasonal, inter-annual, decadal and longer-term variability, and the variations are largely governed by the changeable 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: 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 Arctic also contribute to the hydrographic variations at seasonal, inter-annual and longer time scales.

Since 1990, Ocean 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). These surveys include chemical and biological measurements. The AR7W line is the major component of the Canadian Department of Fisheries and Oceans (DFO) Atlantic Zone Off-shelf Monitoring Program (AZOMP) and contributes to the international Global Climate Observing System (GCOS). Related physical oceanography research programs are linked 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.

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.

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 combine with high-pressure anomalies across the subtropical Atlantic to 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, PiO, 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, hence strong deep convection would be expected.

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).

The NCEP reanalysis for 2011 indicated that, while the air temperature in the Labrador Sea region was above normal for the winter period. For the remaining seasons of 2011, the air temperature was close to normal (i.e. within a few degrees). The warmer than normal air temperatures continued a trend observed from the eight years (2000–2007) preceding the 2008 deep convection event. NCEP reanalysis of winter 2012 (defined as January–

February–March, JFM) indicated surface air temperatures were 0 to -2°C below normal in the Labrador Sea and Baffin Bay (Figure 3). The reference period for this analysis was 1981 to 2010. The 2012 winter air temperatures were much colder than those observed in 2011 and were close to the winter of 2008, which was the coldest since 1993 and the 8th coldest in the 61-year NCEP reanalysis (1948–2008) for this region. The Spring (AMJ) and Summer (JAS) temperatures were 1 to 2.5°C above normal for this region. The Fall (OND) period of 2012 showed very high positive anomalies of 4 to 6°C in the Baffin Bay/Davis Strait area north of Labrador Sea.

Sea-Surface Temperature

Labrador Sea sea-surface temperatures (SST) during JFM 2012 (Figure 4) was 0 to -1°C below normal (climatology for this data set is 1981-2010) for the winter period. This is consistent with the aforementioned large negative anomaly in surface air temperatures in the Labrador Sea during this winter period. This negative SST anomaly should result in reduced heat flux from the ocean to the atmosphere and this is consistent with heat content estimates from Argo floats which indicate a strong decrease during the winter of 2012 (Figure 5). Based on the NCEP reanalysis ocean heat losses are estimated to be only smaller than those in 2008, and larger than those for other years from 2002 to 2012. This analysis is based on methods detailed in Yashayaev and Loder (2009). During spring (AMJ) of 2012, the northwestern Labrador Sea and western Baffin Bay sea-surface temperatures were 0 to -1°C below normal, the eastern Labrador Sea SST was 0 to 1°C above normal. For the summer (JAS) and fall (OND), the SST in Labrador Sea was 1 to 3°C above normal.

Sea Ice

The U.S. National Snow and Ice Data Center sea ice index does not show significantly below-normal winter conditions for sea ice extent in 2012 in the north and western Labrador Sea as it did in 2010 (Figure 6). Sea ice concentration anomalies on the Labrador Shelf were more than 20% below normal for January and became slightly closer to normal in February and March. Sea ice concentration anomalies on the northern Labrador Sea/Davis Strait area were, however, 30% above normal, consistent with the below-normal winter surface air temperatures in the Labrador Sea region. Notice: the sea ice concentration was slightly above normal for the Labrador coastal regions in February and March. There are several other factors that can also contribute to changes in the sea ice concentration besides air temperature, such as changes in the wind (direction and strength), salinity, etc.

AR7W Hydrography

The annual AR7W surveys normally take place as early in the spring of the year as practical to provide a consistent view of interannual changes in the face of strong seasonal changes in physical, chemical, and biological properties. Sea ice generally prevents access to the Labrador Shelf before mid-May. The survey typically takes place on the CCGS Hudson. Due to scheduling of its refit in 2012, the annual AZOMP survey of the AR7W Line in the Labrador Sea took place on CCGS Martha L. Black during the period of 2-17 Jun 2012, about a month later than a typical AR7W survey of previous years. 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. However, an occupation of XHL did not take place in 2012 due to the limited time available on the CCGS Martha Black.

The temperature and salinity of the upper layers of the Labrador Sea change from year to year in response to changes in atmospheric forcing, changes in the warm and saline inflows in the West Greenland Current, and changes in fresh water inputs of both liquid and ice from the Arctic and Greenland. 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 kilometres of its water column 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. Specifically, there was a period of warming and increased salinity during the mid-1960s to mid-1970s contrasting with a 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 (http://www.argo.net/) 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, which clearly demonstrates the seasonal and interannual variability observed in this region over the last decade. 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.

The hydrographic survey of the AR7W line conducted in June of 2012 (Figure 8) confirmed the statement based on the analysis of Argo profiles (Figure 7) that in the previous winter (ending in March of 2012) the Labrador Sea convected to 1400 m across the entire basin. There is also a possibility that the source of convection was limited, but convection was prolonged in duration and the water has just spread across the Labrador Sea. Unlike the situation with 2008 convection, the strong winter cooling triggering deeper than average convection in 2012 coincided with the high NAO index (2011/2012) discussed in the previous section.

The 2012 occupation of AR7W showed that the water column was well mixed during the winter from the surface to 1400 m, which is clearly evident in the temperature, salinity and density fields (Figure 8). This 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. Deep convection also has an important role in the biogeochemical cycle of 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.

Mean Argo Currents

The Argo program provides important year-round monitoring of the Labrador Sea temperature and salinity in the upper 2000 m. This information is complementary to that supplied by the annual shipboard surveys, and it can also be used to examine seasonal variations in temperature and salinity. In addition to the CTD data, an analysis of the drift rates of the floats at the parking depth of 1000 m provides estimates of currents at that depth, which can be used to demonstrate large scale movements of water masses, such as occur via both the Deep Western Boundary Current (DWBC) and inner circulation gyres of the Labrador Sea. In addition, Argo data can also serve as a dataset for validating numerical model results. The results indicate that the flow in the boundary currents was much stronger during 2008-2013 (Figure 10) than in 2000-2007 (Figure 9).

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. 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 21 million years, 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 in lower temperature and higher pressure, 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 outflow makes 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 (NV-LSW), which ranges150-500m deep for stations in the central part of the Labrador Basin, a time series study from 1996 to 2012 shows that DIC has increased by 14 µmol/kg over the past 16 years due to the local uptake of anthropogenic CO_2. As a result, pH has decreased by 0.05 units (in the total pH scale) during the same period (Figure 11). The decreasing rate of pH is 0.0029/year and 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

Ocean colour, which is an indicator of sea surface chlorophyll *a* (SSC), is derived 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* (not shown) constructed from the time series of ocean colour from 2003 to 2012 (Figure 12) 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). Averaged over the period from March 2012 to October 2012, computed concentration of SSC was 0.50 mg m^{-3} on the Labrador Shelf (AR7W stations L3-01 to L3-10), 0.82 mg m^{-3} in the central Labrador Basin (AR7W stations L3-11 to L3-23), and 0.73 mg m^{-3} on the west Greenland Shelf (AR7W stations L3-24 to L3-28). Respectively, these average concentrations are -0.87, +0.31, and -0.41 standard deviates away from the climatological norm. These standardized annual anomalies computed for the one-dimensional AR7W transect are closely similar to those computed for the two-dimensional spatial regional boxes defined by Harrison and Li (2008). In these regional boxes, the annual average anomalies for 2012 were as follows. On the Labrador Shelf, SST was above normal, SSC was below normal. In the central Labrador Basin, both SST and SSC were normal. On the West Greenland Shelf, SST was normal, SSC was below normal (Figure 13).

Phytoplankton and Bacteria

Upper ocean ($z \leq 100$m) microbial plankton sampled on AR7W in the spring and early summer from 1994 to 2012 show region-specific characteristics (Figure 18). The Greenland Shelf tends towards high concentrations of chlorophyll *a* and nanophytoplankton, but low concentrations of picophytoplankton. Conversely, the central Labrador Basin tends towards lower concentrations of chlorophyll *a* and nanophytoplankton, but high concentrations of picophytoplankton and bacteria. The Labrador Shelf tends towards the lowest concentration of chlorophyll a and nanophytoplankton, but intermediate concentrations of picophytoplankton.. During the most recent sampling period of June 2012, concentrations of phytoplankton and bacteria in all 3 regions appeared to be within the range of region-specific variability (Figure 14).

Mesozooplankton: the copepod *Calanus finmarchicus*

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. *C. finmarchicus* abundances show regional variations that are generally consistent from year-to-year and are related to 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 15), as was the case in 2012. In spring, populations here generally have few young stages from the new years' generations, and these, and total abundances, increase in summer. 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. Total abundance in spring showed an upward but insignificant trend on the Labrador Shelf between 1996 and 2012. 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 2012 and the abundance in 2012 was within the range seen in previous springs. *C. finmarchicus* abundances are generally higher in the eastern Labrador Sea (the area most influenced by the Irminger Current) than farther west in spring, because the spring bloom starts earlier here, which leads to earlier reproduction in *C. finmarchicus*. Although abundances are generally higher here in summer than in spring, the highest concentration of all occurred in spring 2006. The abundance in 2012 was within the range of values seen in previous springs and there was no trend in springtime abundance between 1996 and 2012.

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). 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).

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 lack of deep 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. The 1000-1500 m layer has been warming since 2002 with resets only in 2008 and 2012.

The mapping of circulation at 1000 m using Argo floats provides a new approach to view the deep currents, and enriches the usages of Argo.

The increasing trend of total inorganic carbon and decreasing trend of pH continue, not immediate clear response from the 2012 deep convection event was observed.

For the year of 2012 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 2012 *Calanus finmarchicus* abundances were similar to those seen in other years when sampling was in spring. Regional differences were also consistent between 1996 and 2012: 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 2012 total abundances in spring showed an upward but insignificant trend on the Labrador Shelf and no trends in the central basin, or its eastern region.

Acknowledgements

The NCEP Reanalysis data were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/. The sea ice concentration anomaly data are the US National Snow and Ice Data Center from their website http://nsidc.org/data/seaice_index/archives/index.html. 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 2012. These efforts, together with those of the officers and crew of CCGS Martha Black, are gratefully acknowledged.

References

Azetsu-Scott, K., A. Clarke, K. Falkner, J. Hamilton, E. P. Jones, C. Lee, B. Petrie, S. Prinsenberg, M. Starr and P. Yeats, (2010) Calcium Carbonate Saturation States in the waters of the Canadian Arctic Archipelago and the Labrador Sea, 115, C11021, doi:10.1029/2009JC005917 *Journal of Geophysical Research.*

Barnston, A. G., and R. E. Livezey, 1987: Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Wea. Rev*., **115**, 1083-1126.

Climate Prediction Center. 2010. NOAA/National Weather Service, National Centers for Environmental Prediction. Camp Springs, MA. http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml#publication

Fetterer, F., K. Knowles, W. Meier, and M. Savoie. 2002, updated 2011. Sea ice index. Boulder, CO: National Snow and Ice Data Center. Digital media.

Harrison, W.G. and W.K.W. Li. 2008. Phytoplankton growth and regulation in the Labrador Sea: light and nutrient limitation. J. Northwest. Atl. Fish. 39:71-82.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. Science, **269**, 676-679.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-Year Reanalysis Project., Bull. Amer. Meteor. Soc., 77, No. 3, 437-470.

Visbeck, M.H., J.W. Hurrell, L. Polvani and H.M. Cullen. 2001: The North Atlantic Oscillation: Past, Present and Future. Proc. Nat. Acad. Sci., **98**, 12876-12877 doi: 10.1073/pnas.231391598

Yashayaev, I. 2007: Hydrographic changes in the Labrador Sea, 1960-2005, Progress in Oceanography, 73, 242-276.

Yashayaev, I., and J.W.Loder. 2009: Enhanced production of Labrador Sea Water in 2008. Geophys. Res. Lett., 36: L01606, doi:10.1029/2008GL036162.

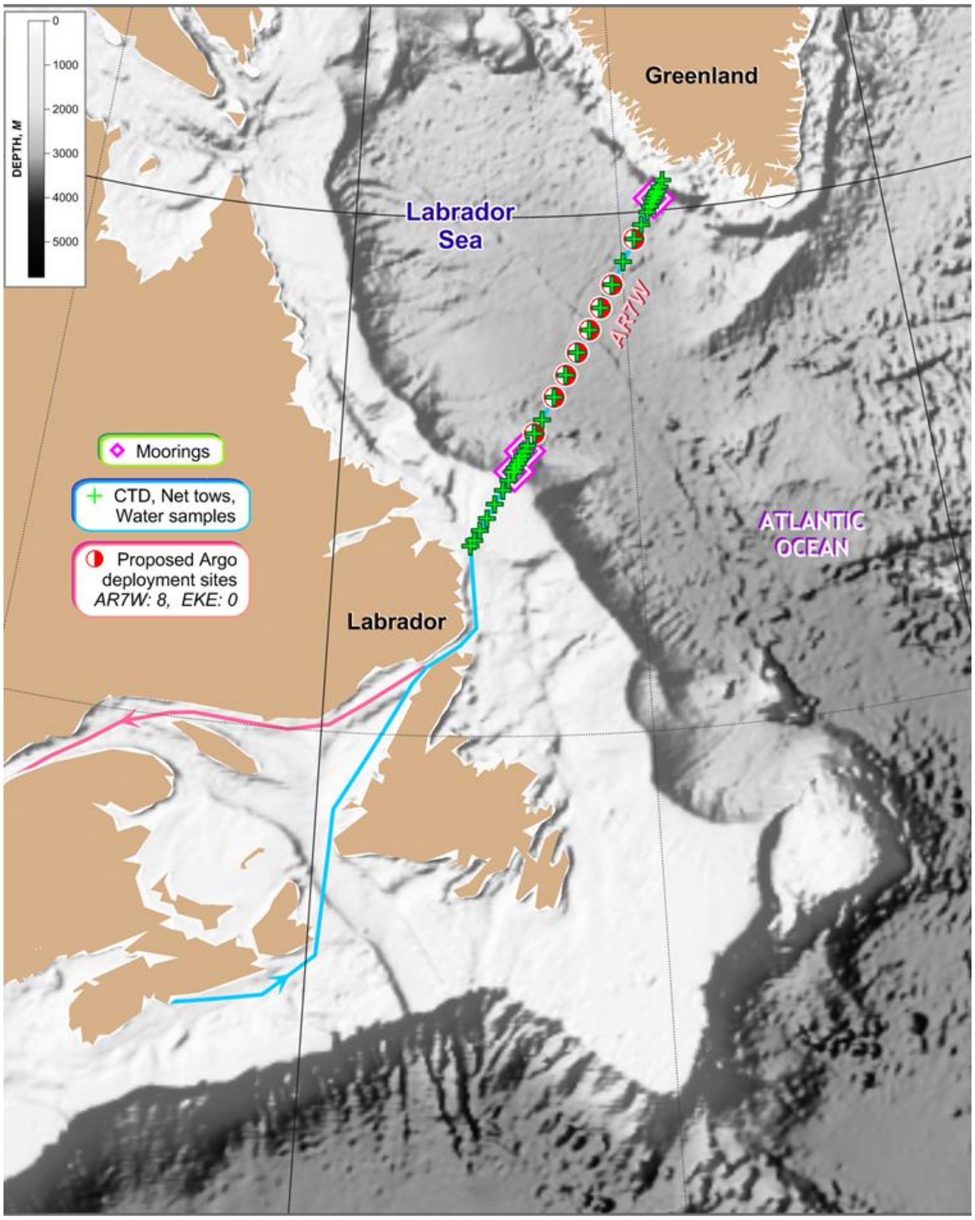

Figure 1: Schematic of the Labrador Sea component of the DFO Atlantic Zone Offshore Monitoring Program (AZOMP). Standard stations along the section are shown as green plus signs. Location of Argo profiler deployments indicated by the red/white circles.

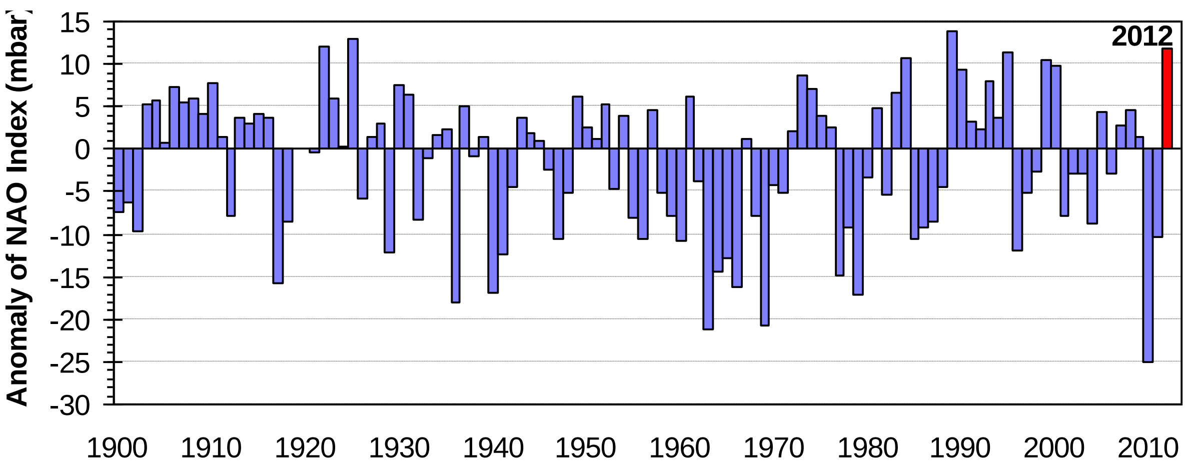

Figure 2: Average Sea Level Pressure for Dec, Jan, Feb in mbar (Winter North Atlantic Oscillation Index)

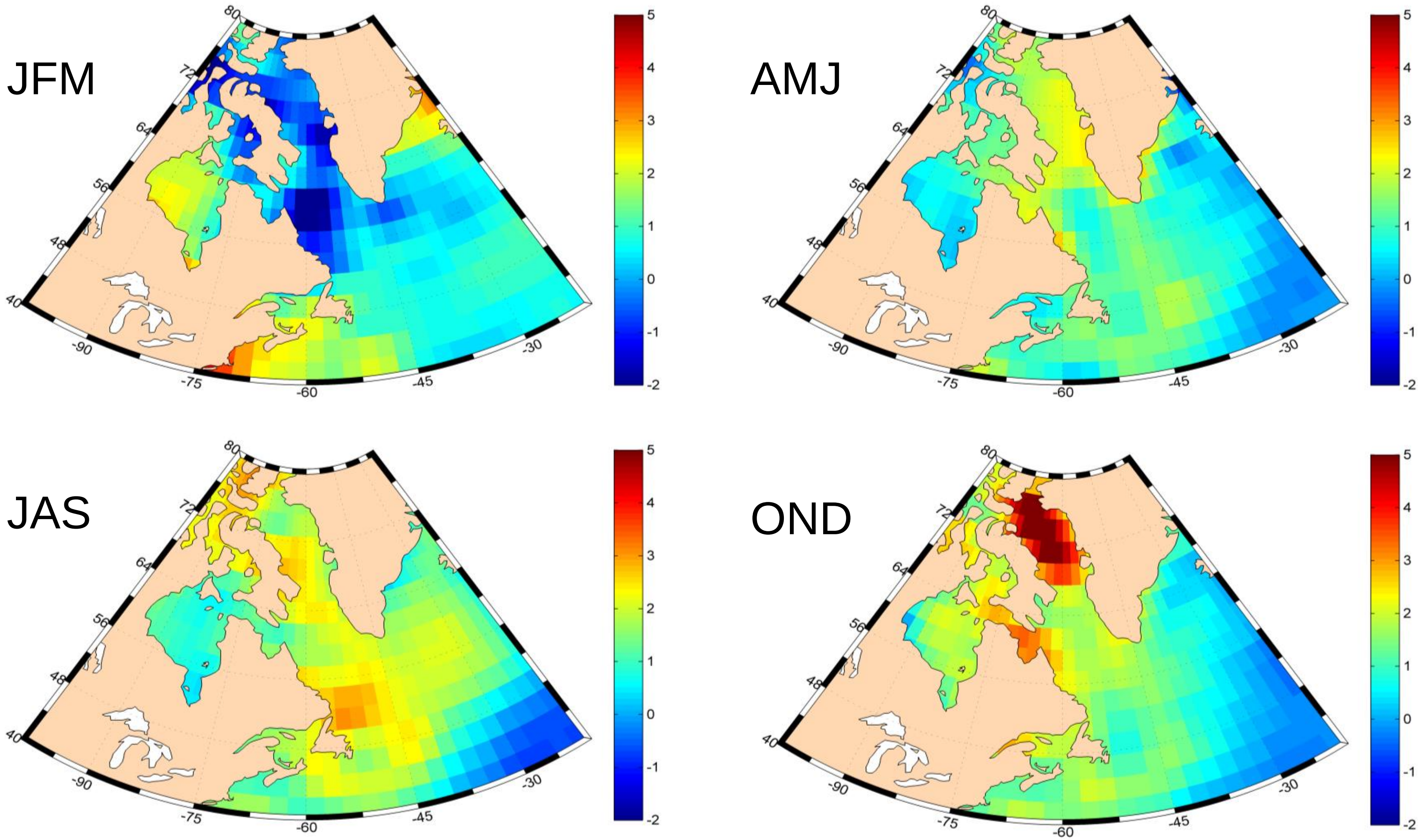

Figure 3: Surface air temperature anomaly for winter, spring, summer and fall periods in 2012 as derived from NCEP/NCAR reanalysis. http://www.esrl.noaa.gov/psd/

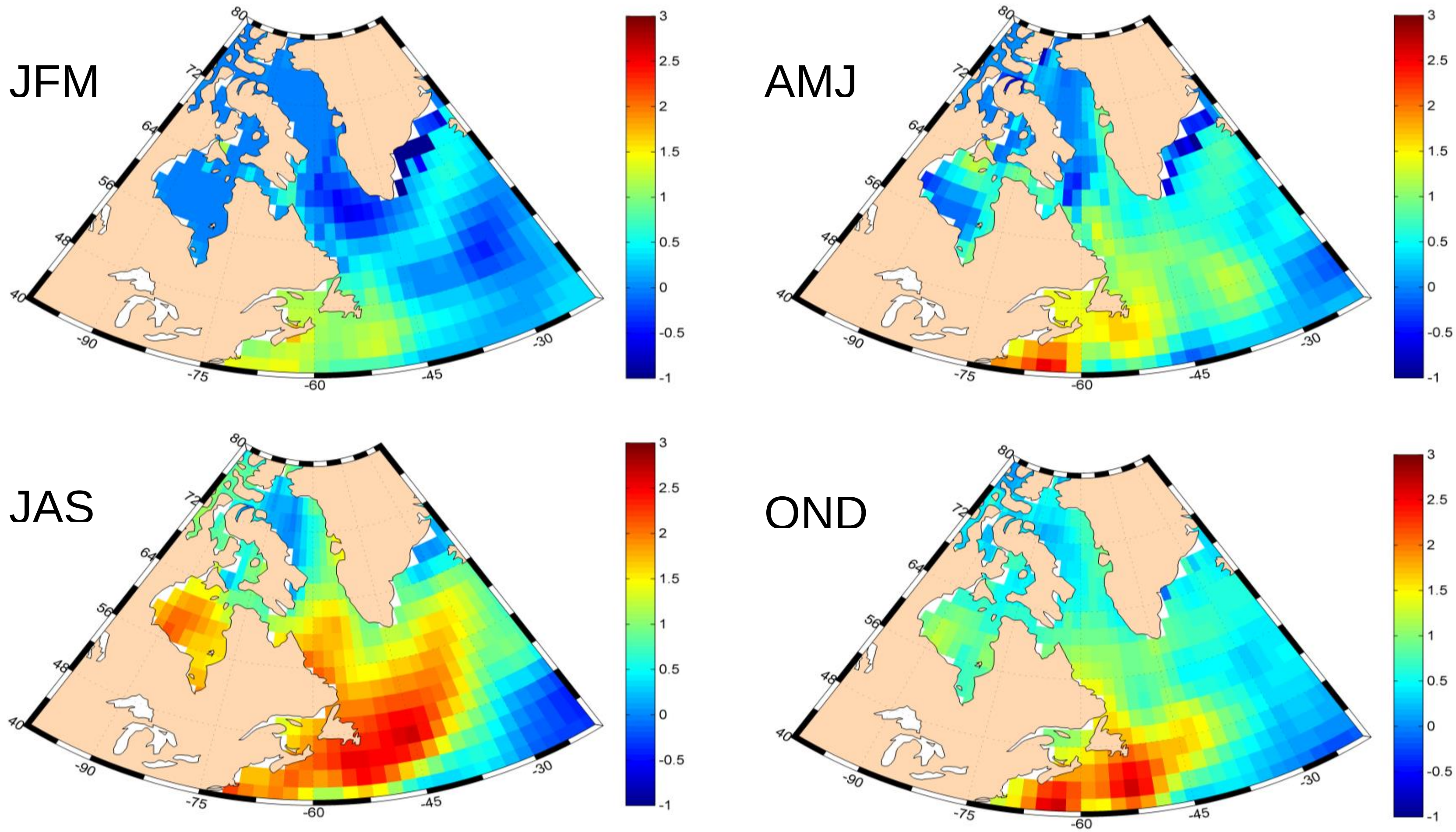

Figure 4: Sea surface temperature anomalies for winter, spring, summer and fall 2012 derived from NCEP/NCAR reanalysis. http://www.esrl.noaa.gov/psd/

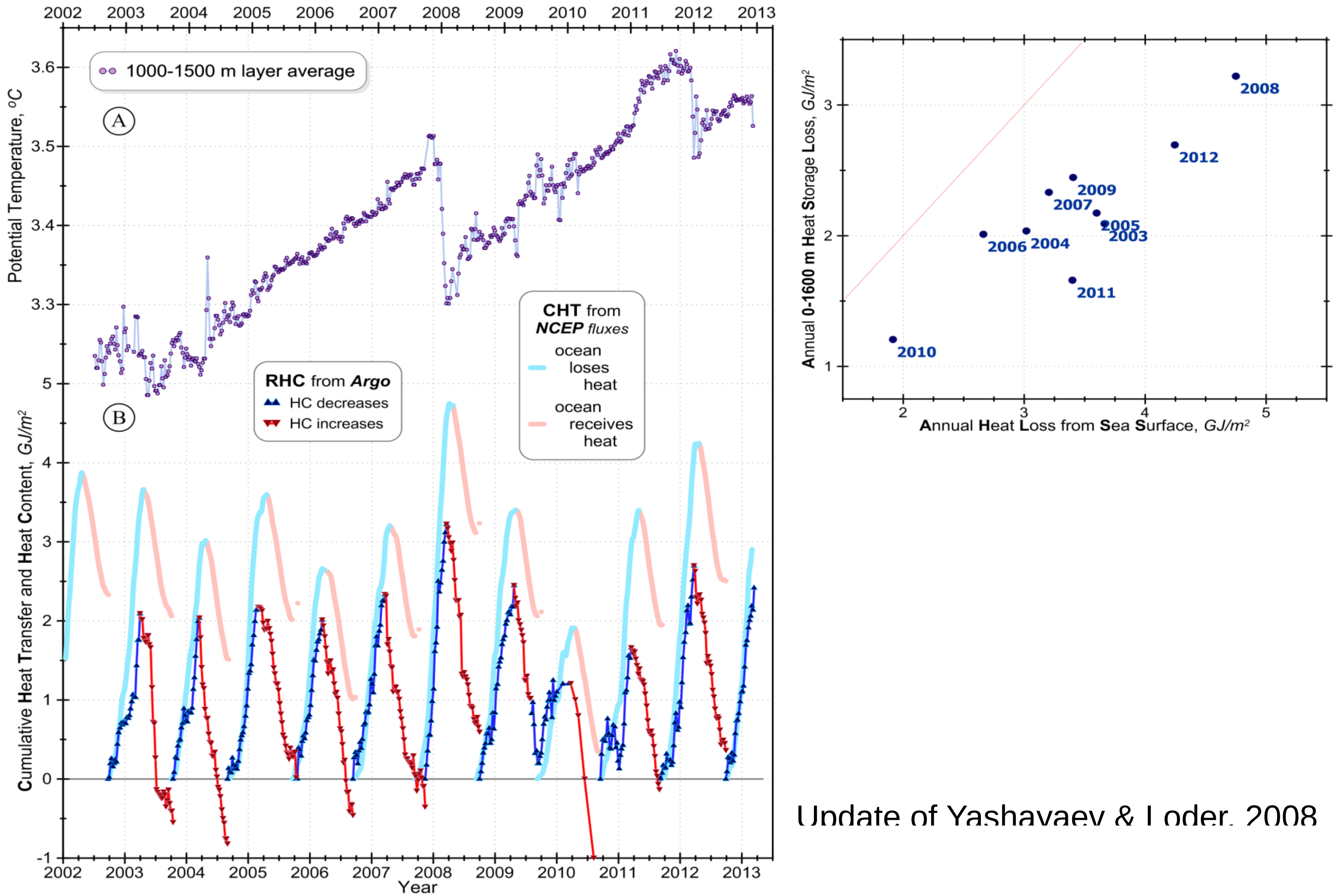

Figure 5: A) Potential temperature in the 1000-1500 m layer of the Labrador Sea derived from Argo floats and B) cumulative heat transfer using NCEP reanalysis and heat content from Argo floats.

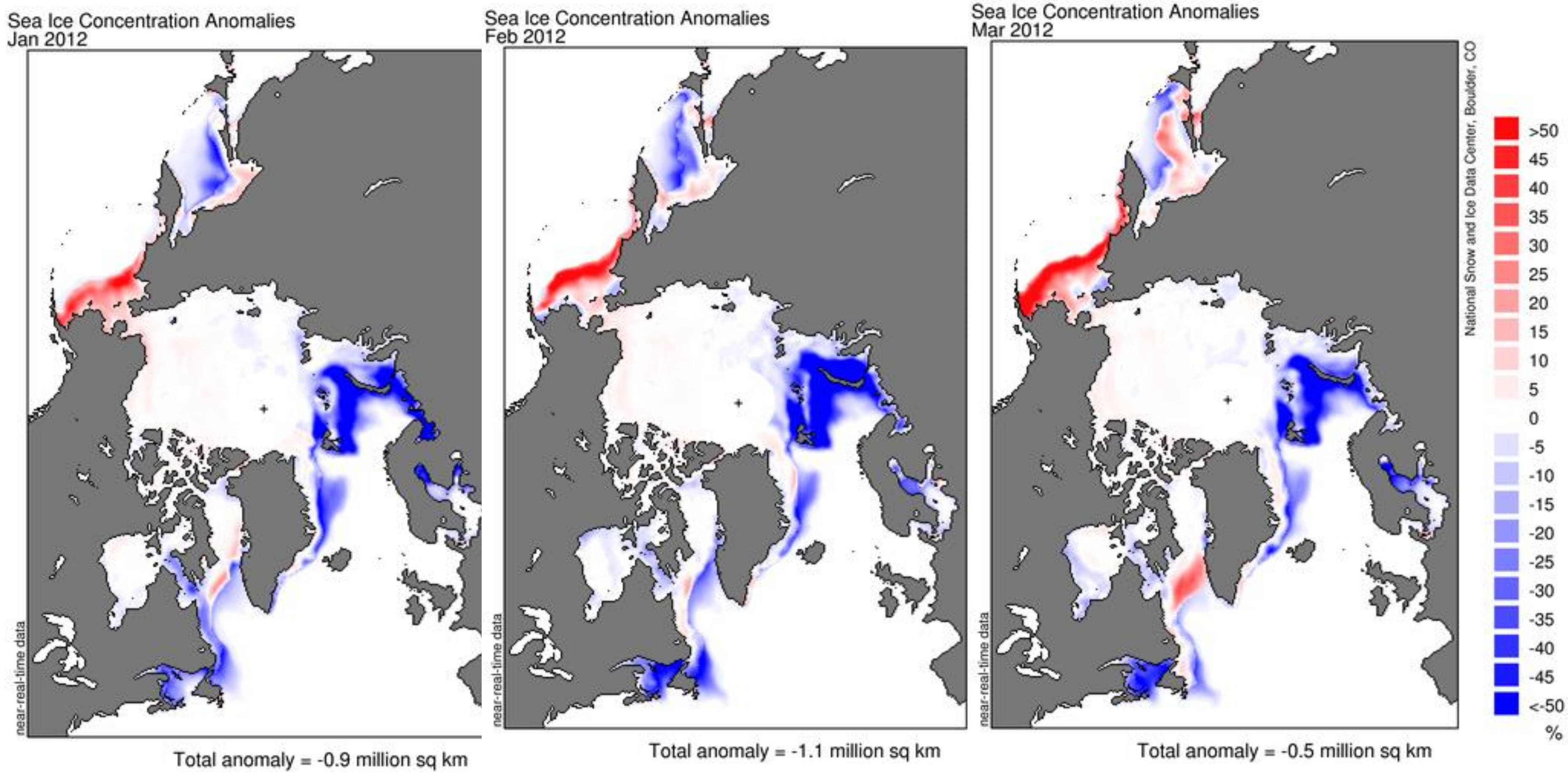

Figure 6: Sea ice concentration anomalies for Jan-Mar 2012 as derived by the US National Snow and Ice Data Center (reference period 1979-2000) http://nsidc.org/data/seaice_index/archives/index.html

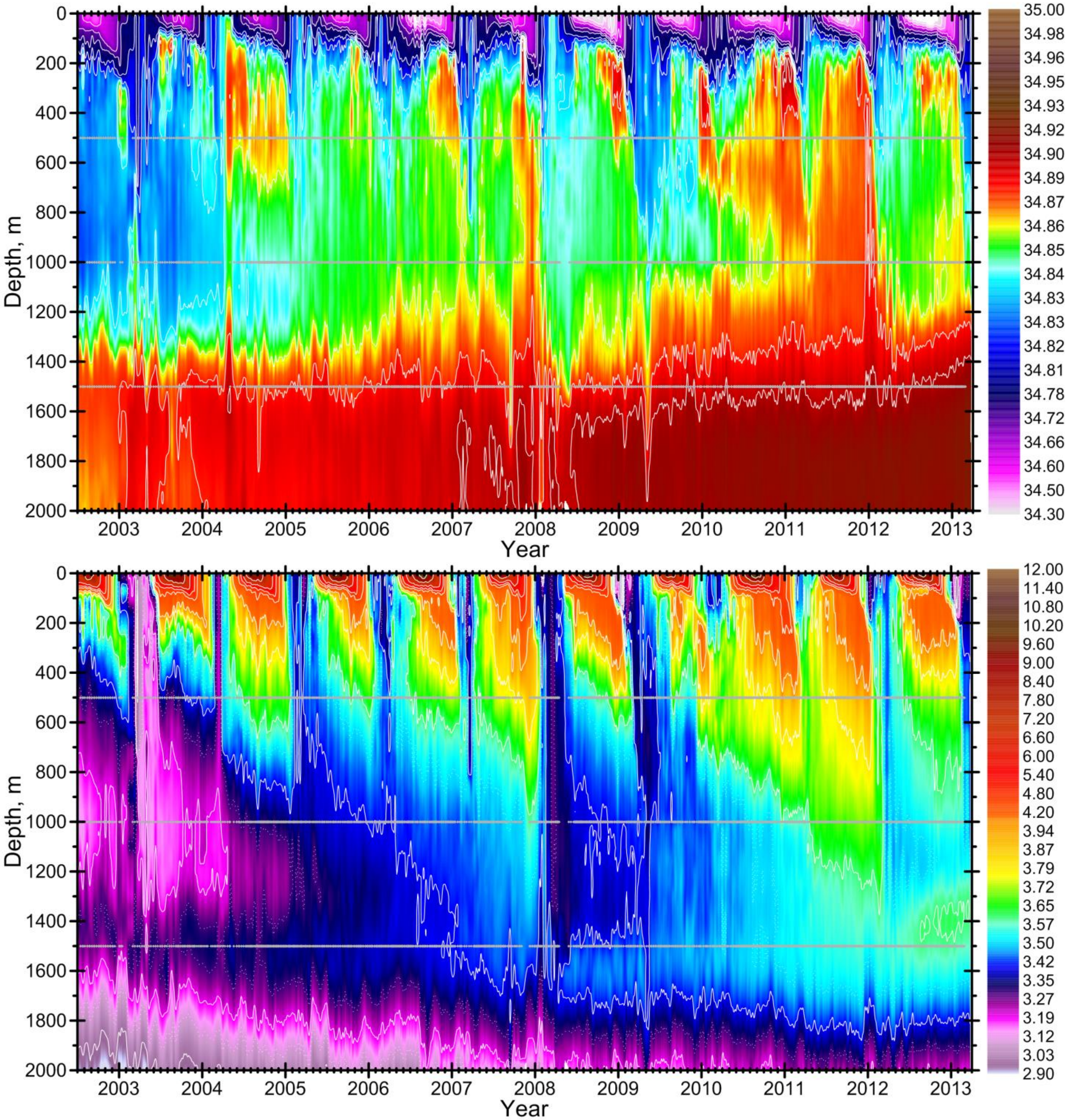

Figure 7: Salinity (top) and potential temperature (bottom) from Argo drifters in the Labrador Sea. The winter 2008 deep convection event is clearly evident to a depth of 1600 m, and 2012 winter deep convection reaches 1400 m. Convection was limited to a depth of about 200 m in the winters of 2010 and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

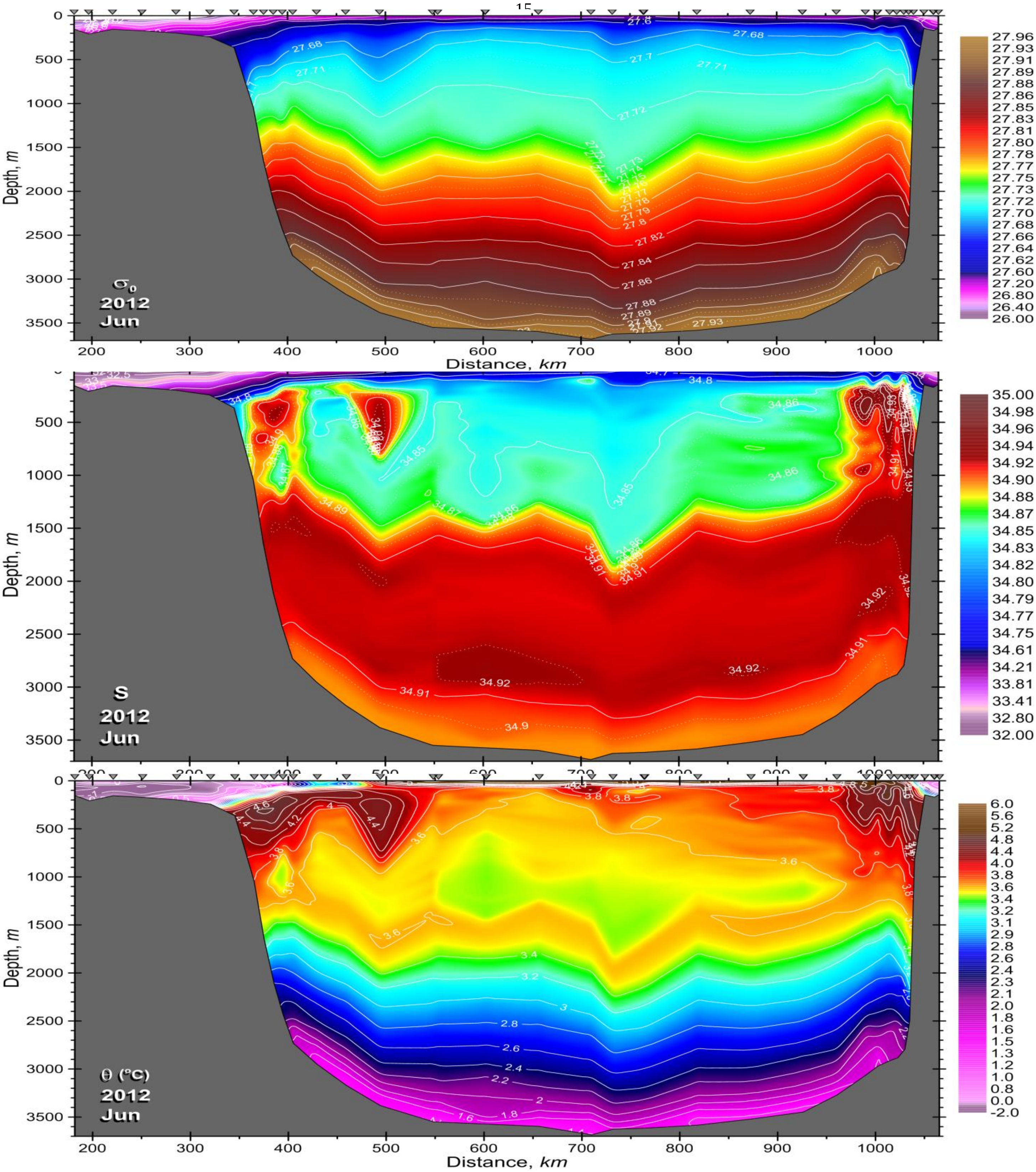

Figure 8: Labrador Sea (AR7W Section) density (top row), salinity (middle row) and potential temperature(bottom row).

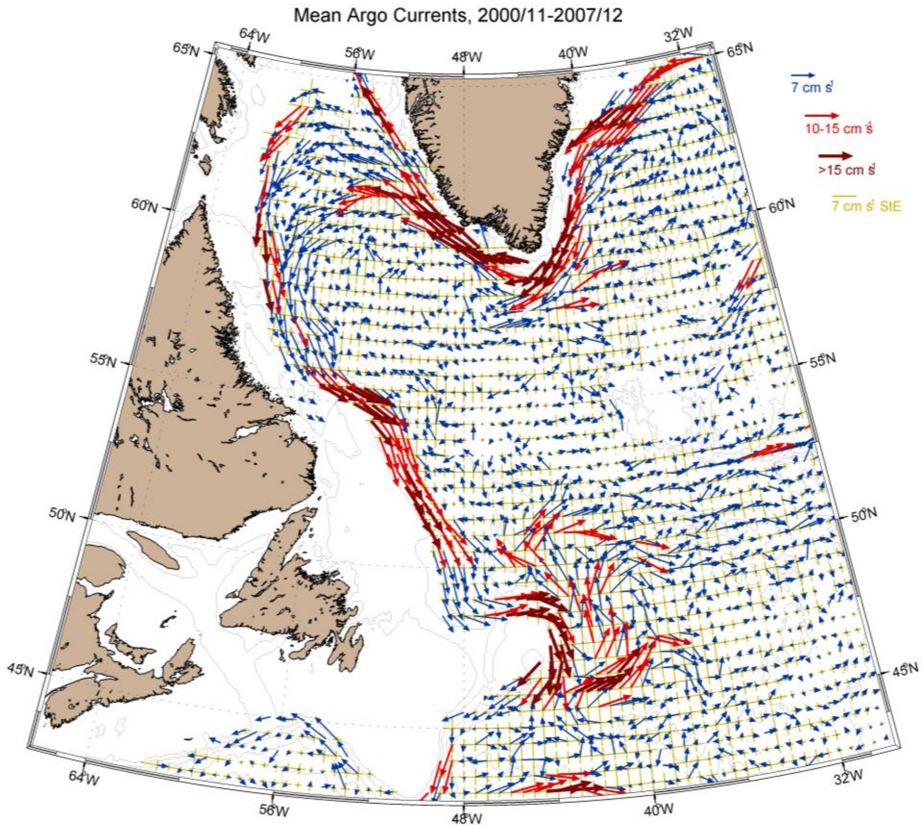

Figure 9: Mean Argo currents at 1000m from 2000/11 to 2007/12

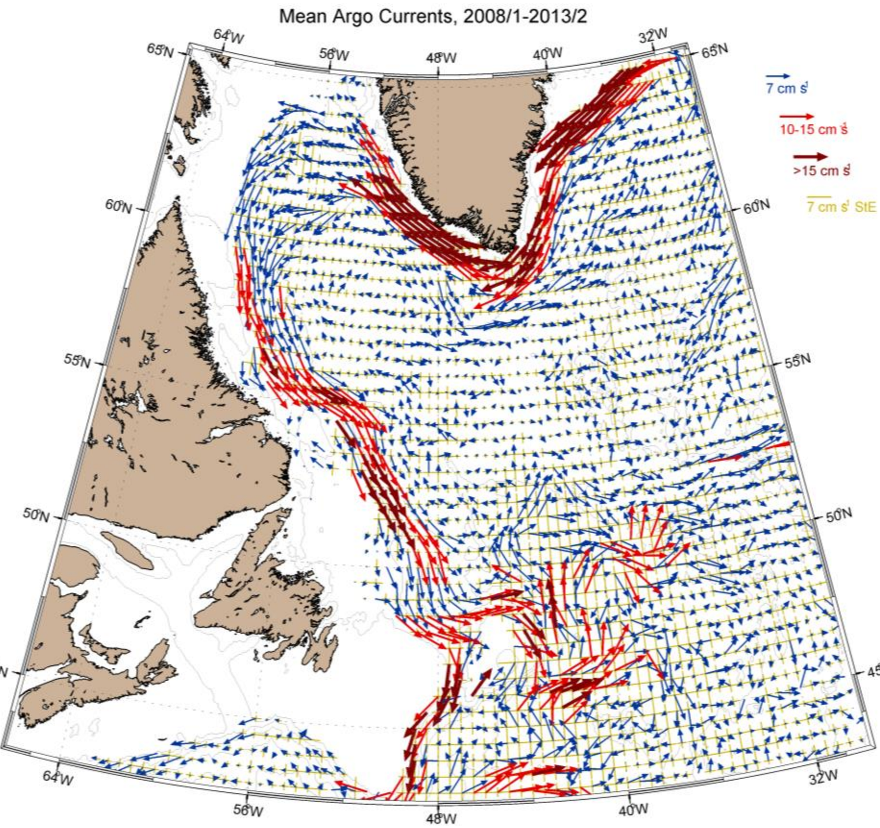

Figure 10: Mean Argo currents at 1000m from 2008/1 to 2013/2

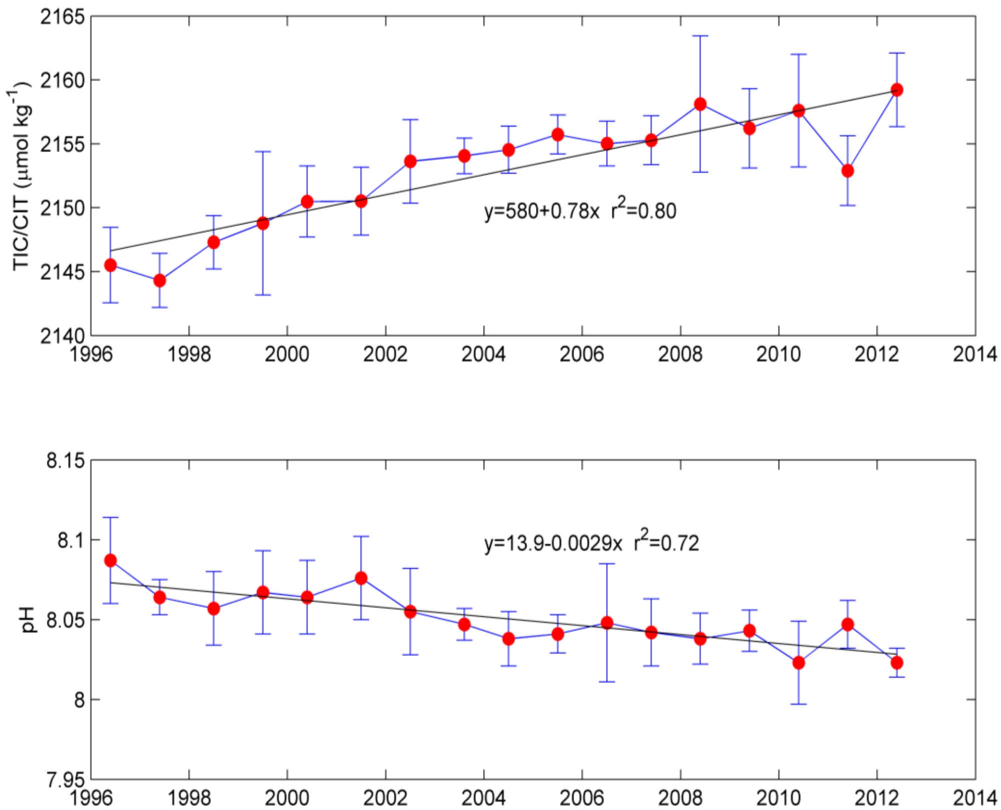

Figure 11: Time series of total inorganic carbon(TIC) and PH, top panel for TIC, bottom panel from PH. TIC and PH in in the 150–500 m depth range and corresponding regression lines for stations in the central part of the Labrador Basin for the period 1996–2012. pH in 2012 is a direct measurement because alkalinity measurements were not available due to an instrument failure.

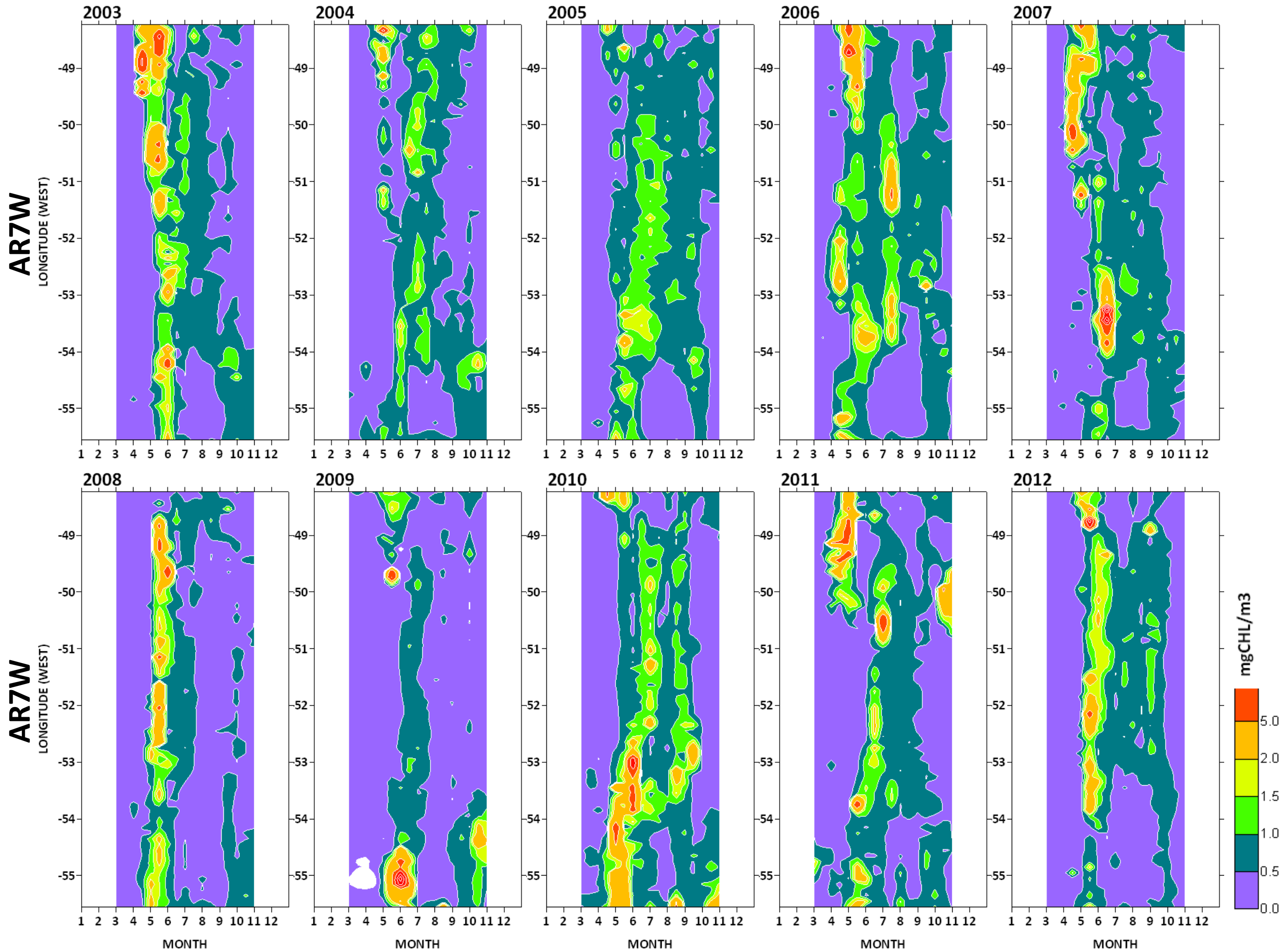

Figure 12: The concentration of sea surface chlorophyll *a* estimated from remotely-sensed ocean colour at 2-week intervals from March to October spanning a 10-year time series, 2003-2012.

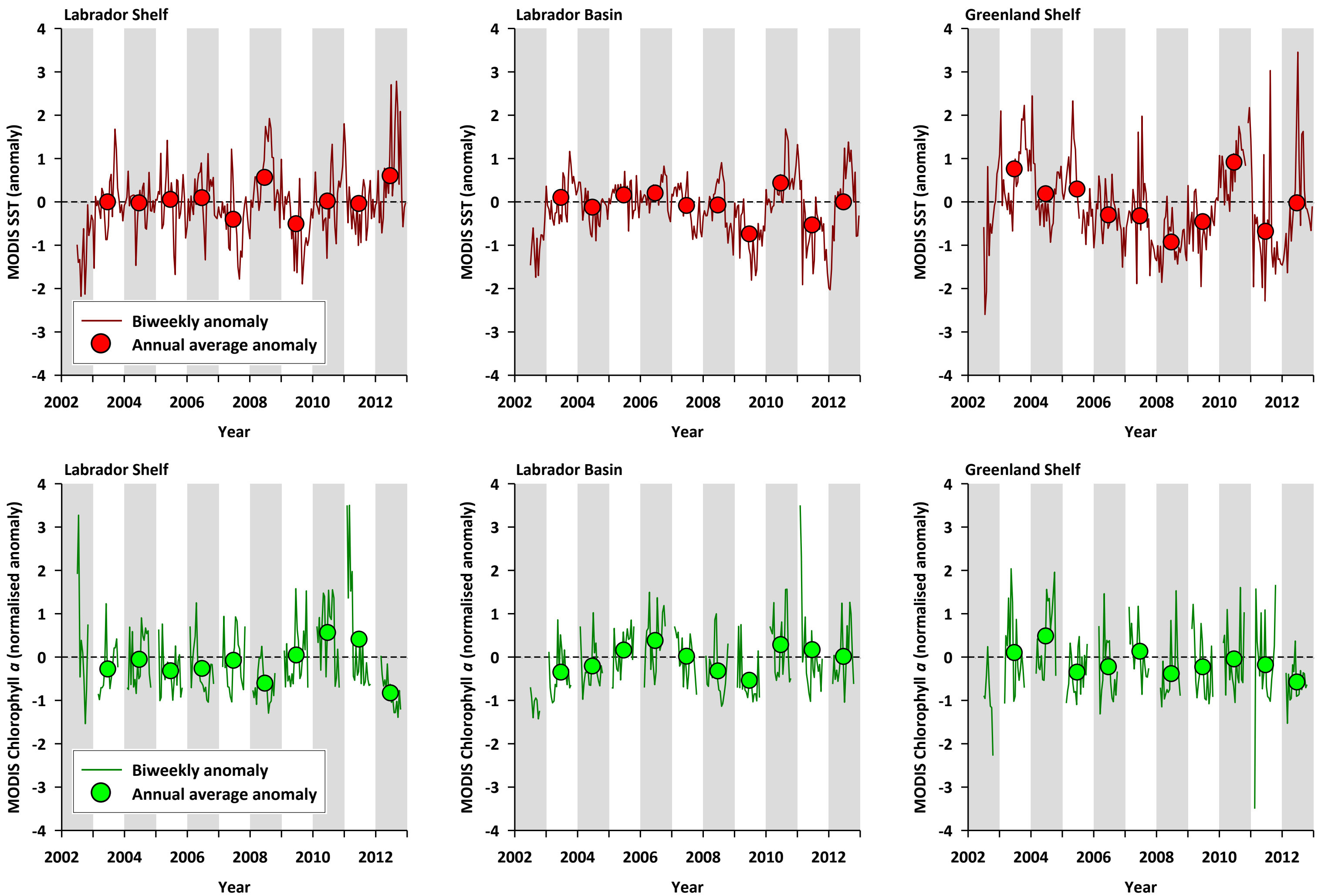

Figure 13: Chlorophyll *a* normalized anomaly time series (2003-2012) for Labrador shelf(left column), Labrador Basin(middle column) and Greenland Shelf(right column). Lines indicate biweekly anomalies, circles indicate annual average anomalies.

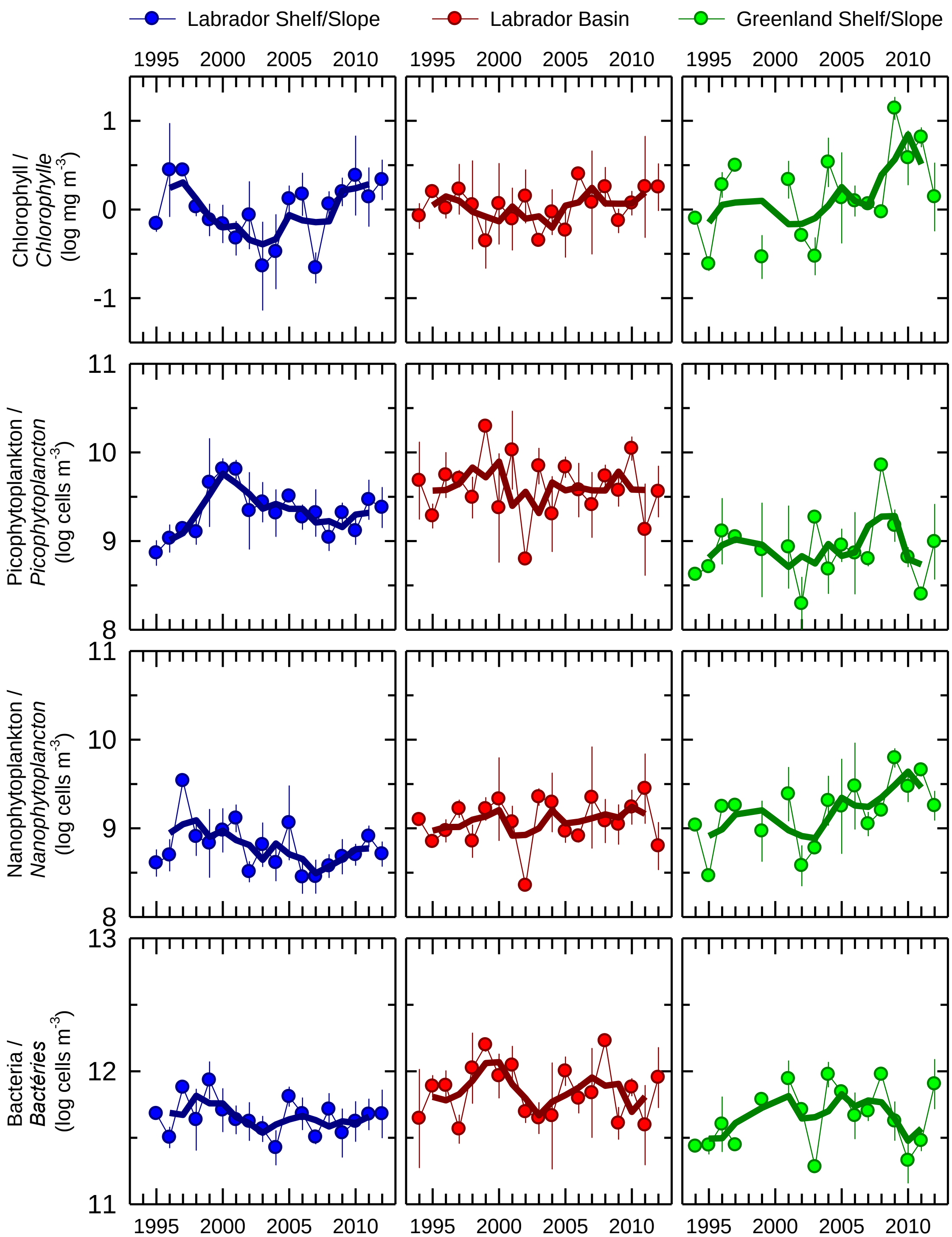

Figure 14: Upper ocean (z≤100m) average concentrations of phytoplankton and bacteria on AR7W sampled in spring or early summer from 1994 to 2012. Circles indicate mean value for stations designated within each region, error bars indicate among-station standard deviation, heavy line indicates 3-year running average of the time series.

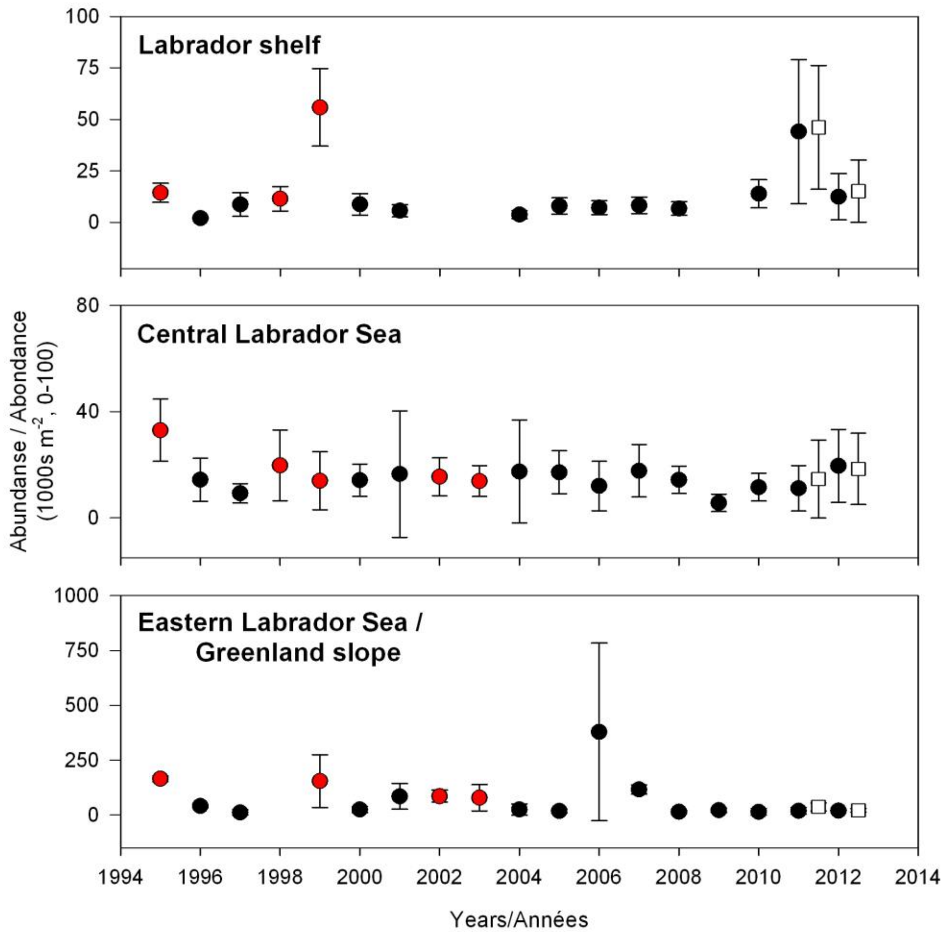

Figure 15: Time series of *Calanus finmarchicus* (Spring – Summer 1994 - 2012). Dark blue symbols show results for years when sampling was in spring; red symbols show results for years when sampling was in summer. Filled symbols show results calculated assuming the volume of water filtered by the net was given by the product of the tow depth and the net mouth-area; open symbols (for 2011 and 2012 only) show results calculated using the volume of water filtered by the net as measured by a flow meter.