NOT TO BE CITED WITHOUT PRIOR
REFERENCE TO THE SECRETARIAT

Northwest Atlantic Fisheries Organization

Serial No. N6042 **NAFO SCR Doc. 12/18**

SCIENTIFIC COUNCIL MEETING – JUNE 2012

Environmental Conditions in the Labrador Sea during 2011

I. Yashayaev and B.J.W. Greenan

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 the trend of the last three years, the Labrador Sea experienced warm winter surface air temperatures in 2011; temperatures ranged from approximately 6°C above normal in the northern region near Davis Strait to about 2°C above normal in the southeastern Labrador Sea. Sea surface temperature anomaly was more than 5°C in the Labrador Sea during the winter of 2011 but close to normal throughout the remainder of the year. In 2011, wintertime convection was mostly limited to the upper 200 m of the water column, which is very similar to that observed in 2010. Sea ice anomalies were substantially negative (below 50% of normal) in January 2011 and remained well below the normal long-term means for the rest of the winter. While the upper layer (10-150m) demonstrates a strong trend of increasing temperature since the mid-1990s, the trend in salinity is much weaker. In the layer impacted by convection (20-2000m), there is a strong increasing trend in both temperature and salinity since the mid-1990s. A strong contrast is observed between the 1994 and 2011 surveys of temperature, salinity, density and dissolved oxygen.

Introduction

Labrador Sea hydrographic conditions depend largely on 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, fresh water input as 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 and an increased presence of the warm and saline Atlantic Waters.

Since 1990, Ocean Sciences Division at the Bedford Institute of Oceanography has carried out annual occupations of a hydrographic section across the Labrador Sea (**Error! Reference source not found.**). The section was designated AR7W (Atlantic Repeat Hydrography Line 7 West) in the World Ocean Circulation Experiment (WOCE). These surveys now 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.

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. A new regime of shallow wintertime overturning seemed to establish itself beginning in the early 2000s. This has led to the formation of warm, saline, and low-density mode waters in the upper 1000 m of the water column. This trend was interrupted in the winters of 2000 and 2008 when deep convection was observed to extend to the depths exceeding 1500 m in the central Labrador Sea. However, the previous trends in temperature and salinity continued in the following years with significantly milder winters.

North Atlantic Oscillation

The North Atlantic Oscillation (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), which results in changes in temperature and precipitation patterns.

The NAO exhibits considerable interseasonal and interannual variability, and prolonged periods of both positive and negative phases of the pattern are common. 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 (**Error! Reference source not found.**) indicating that conditions in this region should be warmer than normal, which is in agreement with the change recently observed in a variety of the oceanographic/hydrographic variables presented below; however, we should note that the NAO is not always correlated with local conditions. In 2011, the NAO index rebounded from the record low but still remained significantly below the 30-year average (1981-2010). Hence, a continued warming trend would be expected in the Labrador Sea.

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).

NCEP reanalysis of winter 2010 (defined as January–February–March, JFM) indicated surface air temperatures were up to 10°C above normal in southern Davis Strait and the northern Labrador Sea. The reference period for this analysis was 1968 to 1996. JFM 2010 surface air temperatures over the central and southern Labrador Sea were approximately 5°C above normal. The 2010 winter air temperatures are even warmer than those observed in 2009 and are in strong contrast to the Winter 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 also above normal for this region, but only by several degrees. The Fall (OND) period of 2010 showed very high positive anomalies in the Labrador Sea which might contribute to a reduction in winter convection in 2011. The NCEP reanalysis for 2011 indicates that, while the air temperature in the Labrador Sea region was above normal for the winter period, it was cooler than experienced in 2010 (**Error! Reference source not found.**). For the remaining seasons of 2011, the air temperature was close to normal (i.e. within a few degrees). This return of air temperatures in 2011 to closer to normal conditions is consistent with the NAO index presented in **Error! Reference**

source not found.. The warmer than normal air temperatures continues a trend observed from the eight years (2000–2007) preceding the 2008 deep convection event.

Sea-Surface Temperature

Labrador Sea sea-surface temperatures (SST) during JFM 2011 (**Error! Reference source not found.**) indicate that a more positive anomaly existed compared to the previous winter. SST was 2-6°C above normal (climatology for this data set is 1971-2000) for the winter period. This is consistent with the aforementioned large positive anomaly in surface air temperatures in the central and southern Labrador Sea during this winter period as well as that observed during the preceding fall. This positive 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 at relative small decrease during the winter of 2011 (**Error! Reference source not found.**). However, based on the NCEP reanalysis ocean heat losses are estimated to be significantly larger than those for 2010. This analysis is based on methods detailed in Yashayaev and Loder (2009).

The annual mean anomalies for 2011, which include the underlying seasonal variability, were similar in pattern and magnitude to those observed during the winter. The peak SST anomalies for 2011 occurred in the Labrador Sea during the winter period when they reached values greater that 6°C. These results continue the trend of similar observations for 2009 & 2010 during which the winter SST was above normal in the central Labrador Sea.

Sea Ice

The U.S. National Snow and Ice Data Center sea ice index (Fetterer et al., 2011) shows significantly below-normal winter conditions for sea ice extent in 2011 in the north and western Labrador Sea (**Error! Reference source not found.**). Sea ice concentration anomalies on the Labrador Shelf we more than 50% below normal for January and became slightly closer to normal in February and March. This is consistent with the above-normal winter surface air temperatures in the Labrador Sea region. Similar results were also observed in the preceding winters of 2009 and 2010 during which above-normal air temperature conditions were observed. A reduction in sea ice concentration increases the possibility of enhanced surface heat fluxes in these shelf areas and could lead to increased shelf-slope exchanges.

AR7W Hydrography

Depending on shiptime availability, the annual AR7W surveys 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 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 both liquid and ice from 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 also 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 using a combination of ship and Argo float data for the period of 1937-2011 (**Error! Reference source not found.**).

While there is relatively little variability below 2500 m, there are significant decade-long events observed in the upper 2000 m; for example there is a period of warming and increased salinity during the mid-1960s to mid-1970s contrasting a period of cooling and freshening during the 1990s. During the last decade the temperature has been trending upward in the upper half of the ocean. The advent of the International Argo Project (http://www.argo.net/) has provided the oceanography 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 , 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 (mainly not exceeding 200 m).

The AZOMP survey in May 2011 confirms the results observed by the Argo floats (Figure 1) and implies that winter convection was limited to a few hundred meters across the Labrador Sea. A comparison of AZOMP surveys from 1994 and 2011 shows significant changes in the physical environment over the last two decades. In 1994, the water column was well mixed during the winter from the surface to 2000 m and this clearly evident in the temperature, salinity and density fields. This is a key process in the Atlantic Meridional Overturning Circulation (AMOC) and is one of the few areas in the global ocean where surface water sinks to greater depths (e.g. >2000 m in 1900-1994, 1600 m in 2008) and spreads into the intermediate and deep layers of the surrounding basins and far (well) beyond. Deep convection also has an important role in the gas exchange and utilization, and in the biogeochemical cycle of the Labrador Sea as is observed in the high dissolved oxygen concentrations in the deep ocean in May 1994 (Figure 10**: Sea (AR7W Section) density (top row), dissolved oxygen (middle row) and oxygen saturation (bottom row) for 1994 (left column) and 2011 (right column).**). There is stark contrast between 2011 and 1994 with much lower oxygen concentrations below 1000 m. The reduced oxygen concentrations are consistent with the changes in the temperature and salinity fields. The 2011 AZOMP survey provides results very similar to those observed for 2010 during which very weak convection was observed. Weak convection limits entrainment to the deep water of gases such as oxygen and carbon dioxide from the atmosphere as well as surface freshwater.

Annual means of temperature and salinity anomalies (**Error! Reference source not found.**) for the upper layer (10 – 150 m) of the Labrador Sea are derived using a combination of ship and Argo (starting in 2003) measurements over the last six decades. Both the temperature and salinity anomalies had been decreasing since 2003, but the temperature started to rise sharply in 2009 and 2010. Surface salinity in the Labrador Sea is controlled by lateral flux of freshwater from the Labrador and Greenland shelves, by vertical mixing with underlying more saline waters, and, to some degree, by precipitation and is consistent with observations from 2010. The longer-term trend in temperature shows a warming of this region since the mid-1990s with the anomaly being the highest on record.

Results of combined ship and Argo data for the 20-2000 m (**Error! Reference source not found.**) indicate that both the temperature and salinity have been increasing since the mid-1990s. While temperature is now the highest in the record, salinity is about 0.01 less than that observed in the late 1960s. The impact of the deep convection event of 2008 is evident in the temperature time series, but this is quickly overridden by the three subsequent years with warm winters.

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 deliver (transfer) surface waters to 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 centers (e.g. CCHDO, CDIAC).

Processes in the Labrador Sea have significant variability on seasonal, interannual, decadal and longer time scales and, therefore, long-term data sets in combination (in conjunction) with unprecedentedly high temporal resolution of Argo data stream are critical for climate and process 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 1990s. The lack of deep convection in the winter of 2010 and 2011 is an important feature to note in the recent observations of the Labrador Sea. Not only does this impact the physical environment, it also has significant impact on biogeochemical processes that must be monitored.

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 authors wish to thank the many staff and associates at BIO have contributed to the AZOMP which was carried out by the Ocean Sciences Division and Ecosystem Research Division in 2011. These efforts, together with those of the officers and crew of CCGS Hudson, are gratefully acknowledged.

References

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.

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

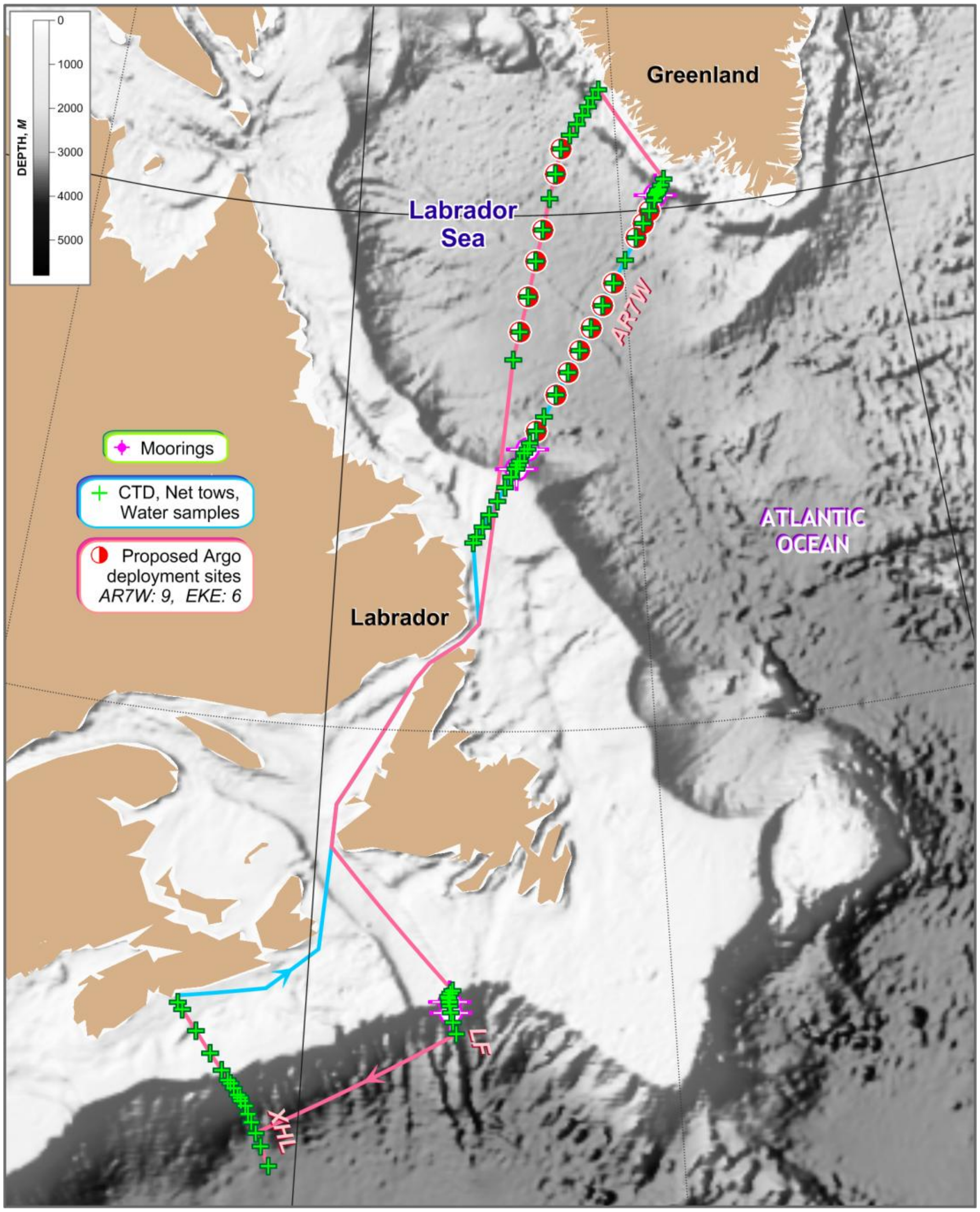

Figure 1: Schematic of the Labrador Sea component of the DFO Atlantic Zone Offshore Monitoring Program (AZOMP). Standard stations along the section are shown as green plus signs. Location of Argo profiler deployments indicated by the red/white circles.

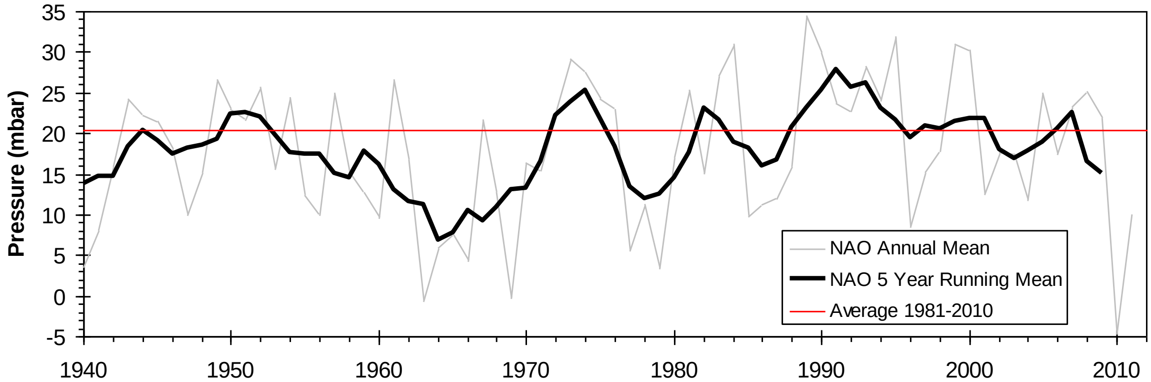

Figure 2: North Atlantic Oscillation index annual mean (grey line) and 5-year running mean (black line).

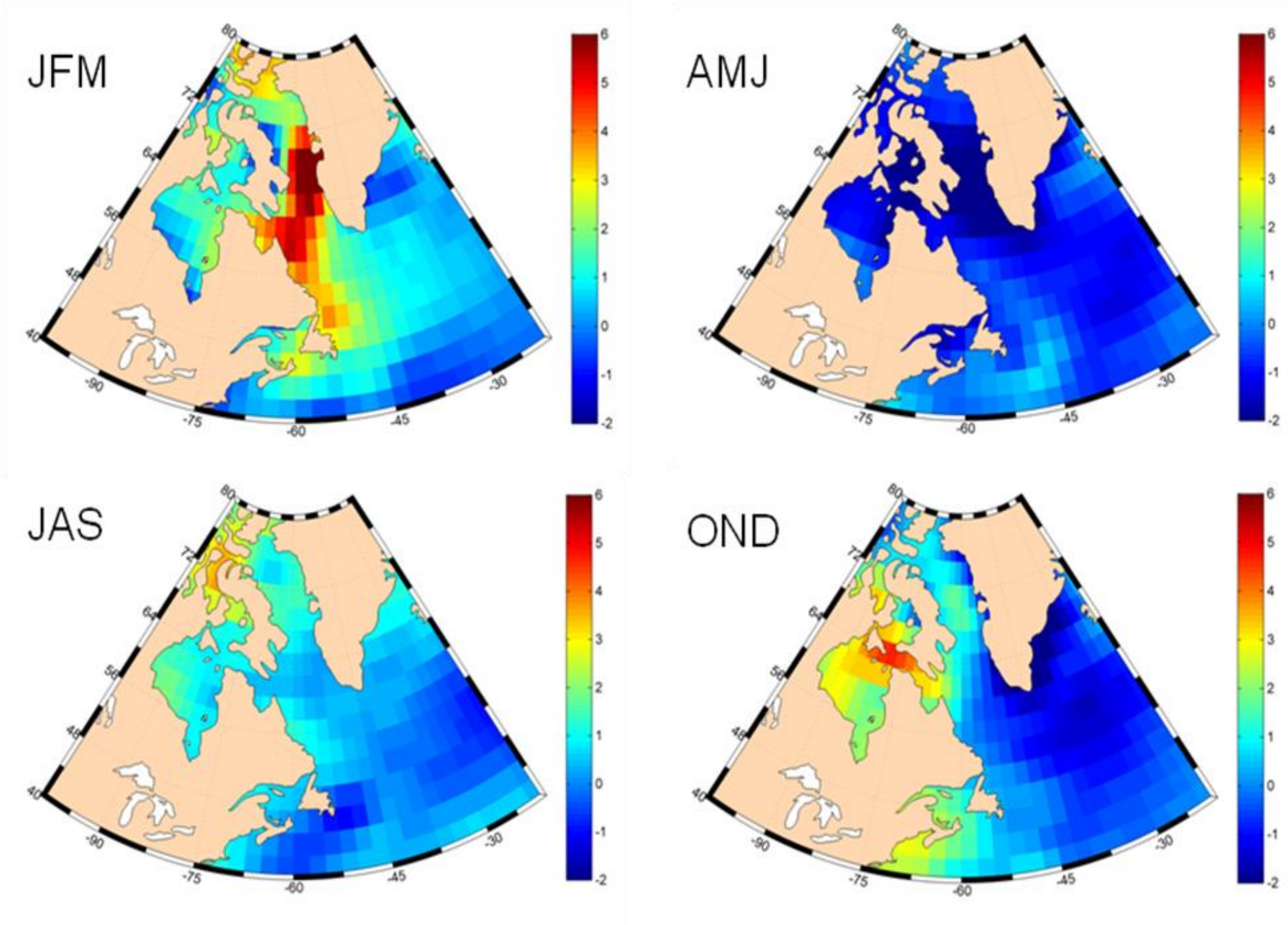

Figure 3: Surface air temperature anomaly for winter, spring, summer and fall periods in 2011 as derived from NCEP/NCAR reanalysis. http://www.esrl.noaa.gov/psd/

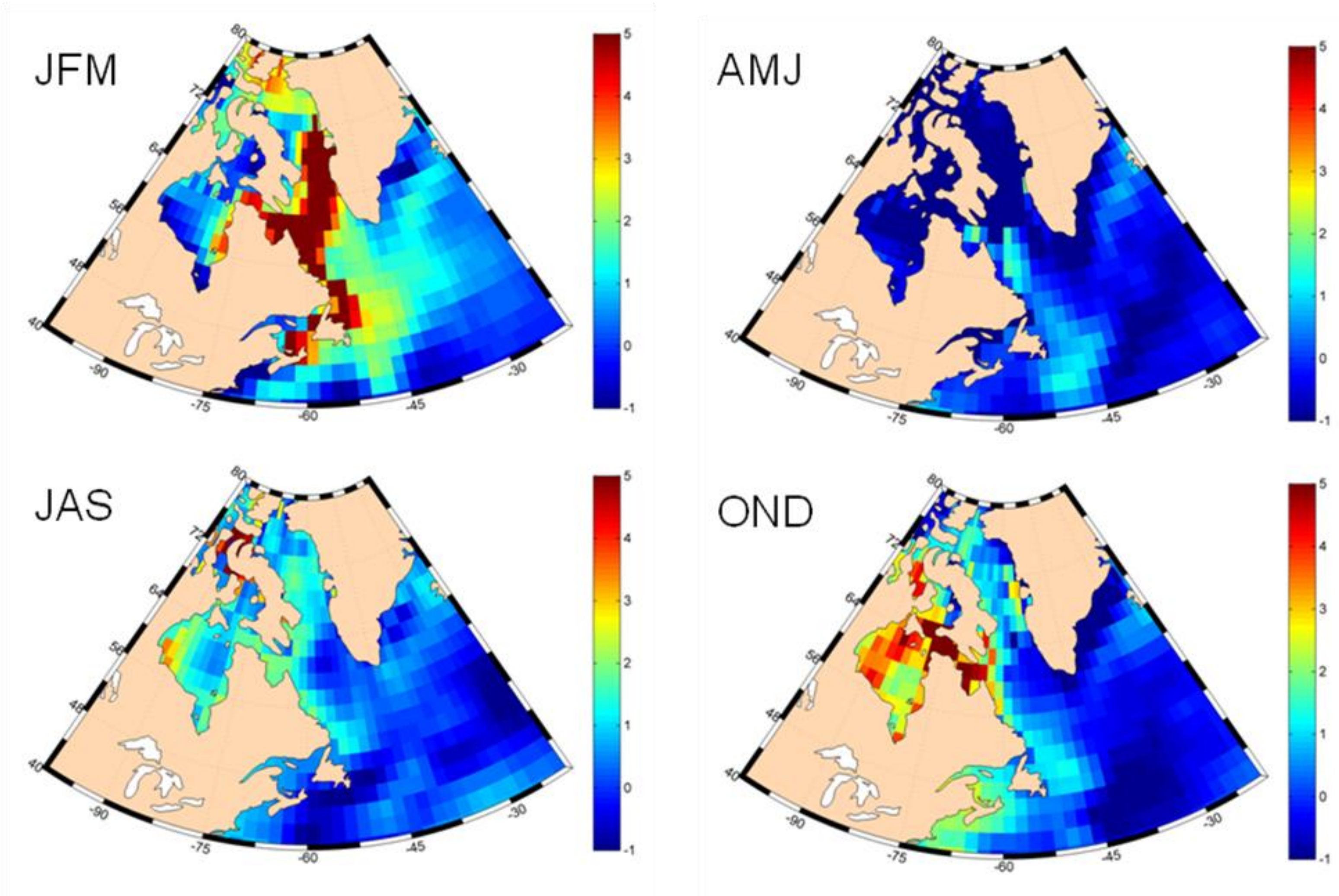

Figure 4: Sea surface temperature anomalies for winter, spring, summer and fall 2011 derived from NCEP/NCAR reanalysis. http://www.esrl.noaa.gov/psd/

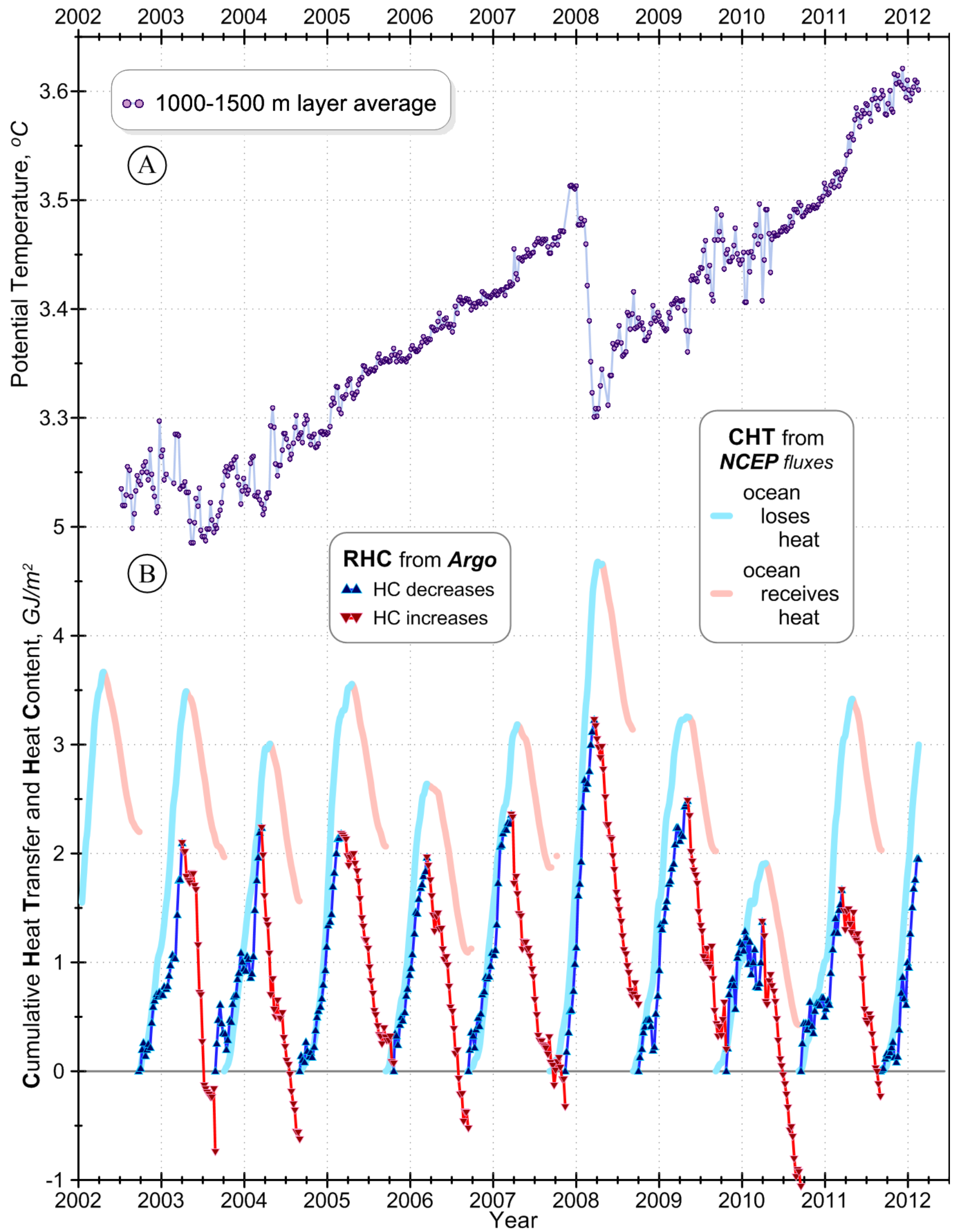

Figure 5: A) Potential temperature in the 1000-1500 m layer of the Labrador Sea derived from Argo floats and B) cumulative heat transfer using NCEP reanalysis and heat content from Argo floats.

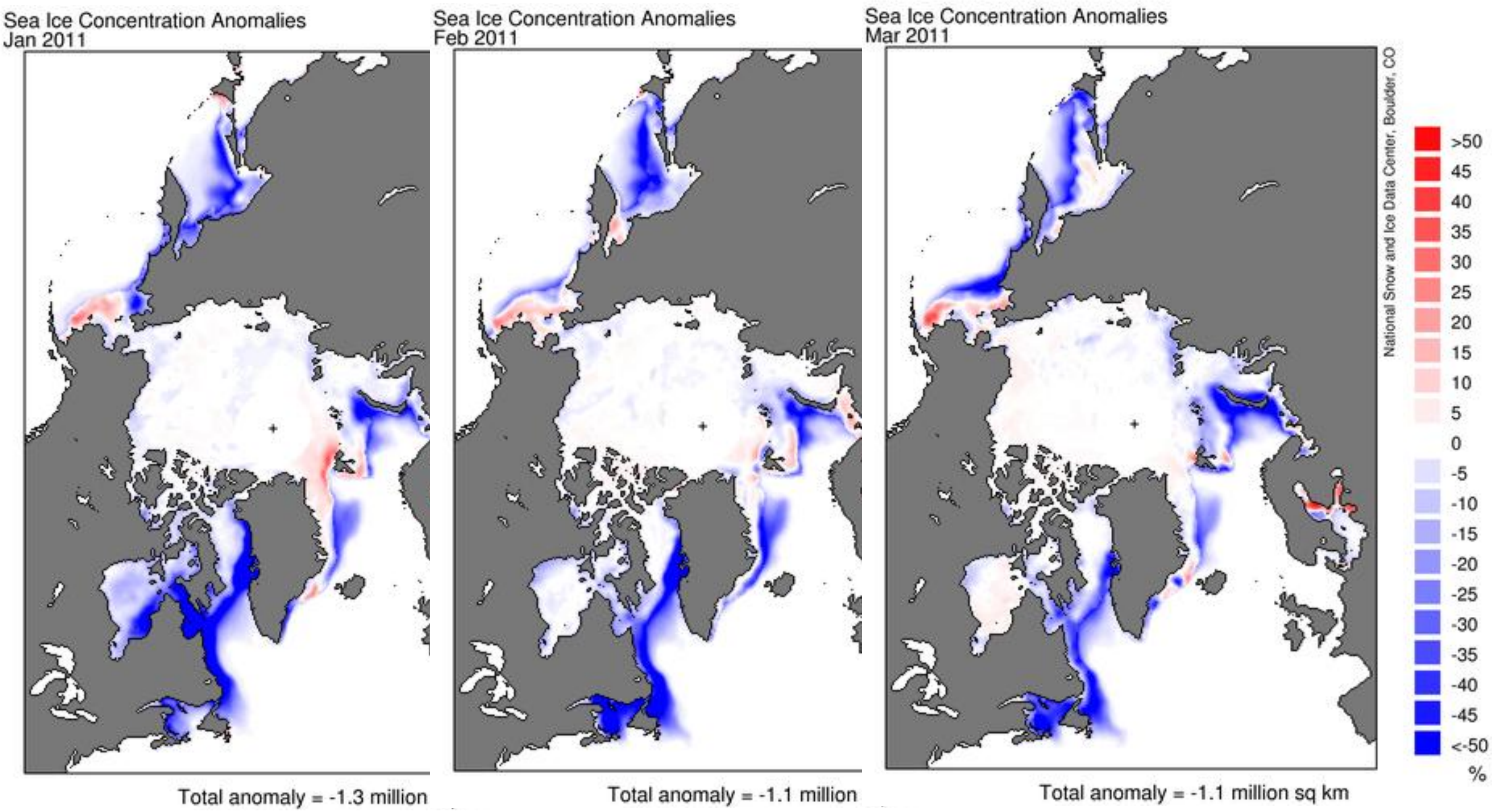

Figure 6: Sea ice concentration anomalies for Jan-Mar 2011 as derived by the US National Snow and Ice Data Center (reference period 1979-2000) http://nsidc.org/data/seaice_index/archives/index.html

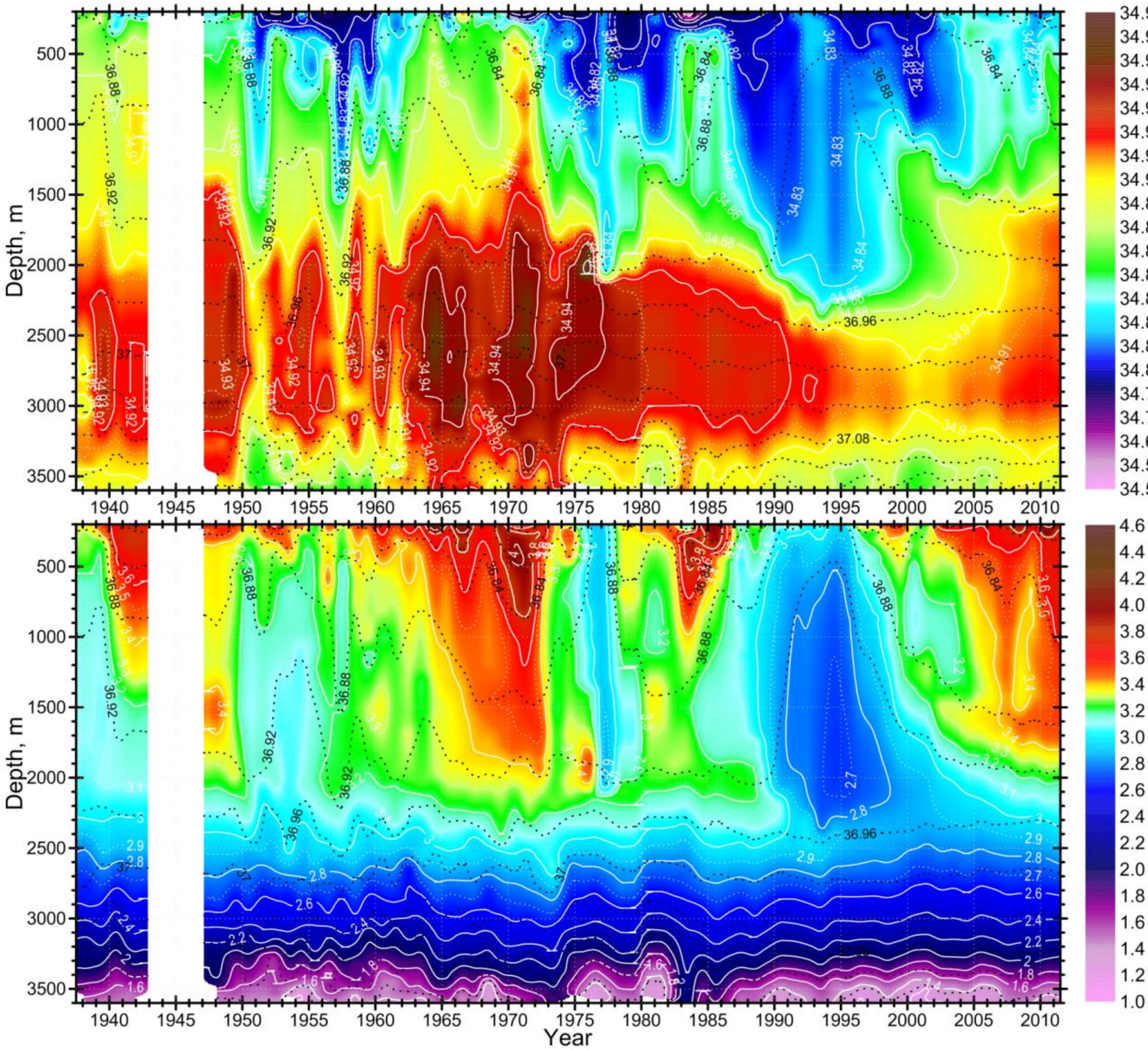

Figure 7: Labrador Sea salinity (top) and potential temperature (bottom) for the period 1937-2011 based on a combination of ship and Argo float data.

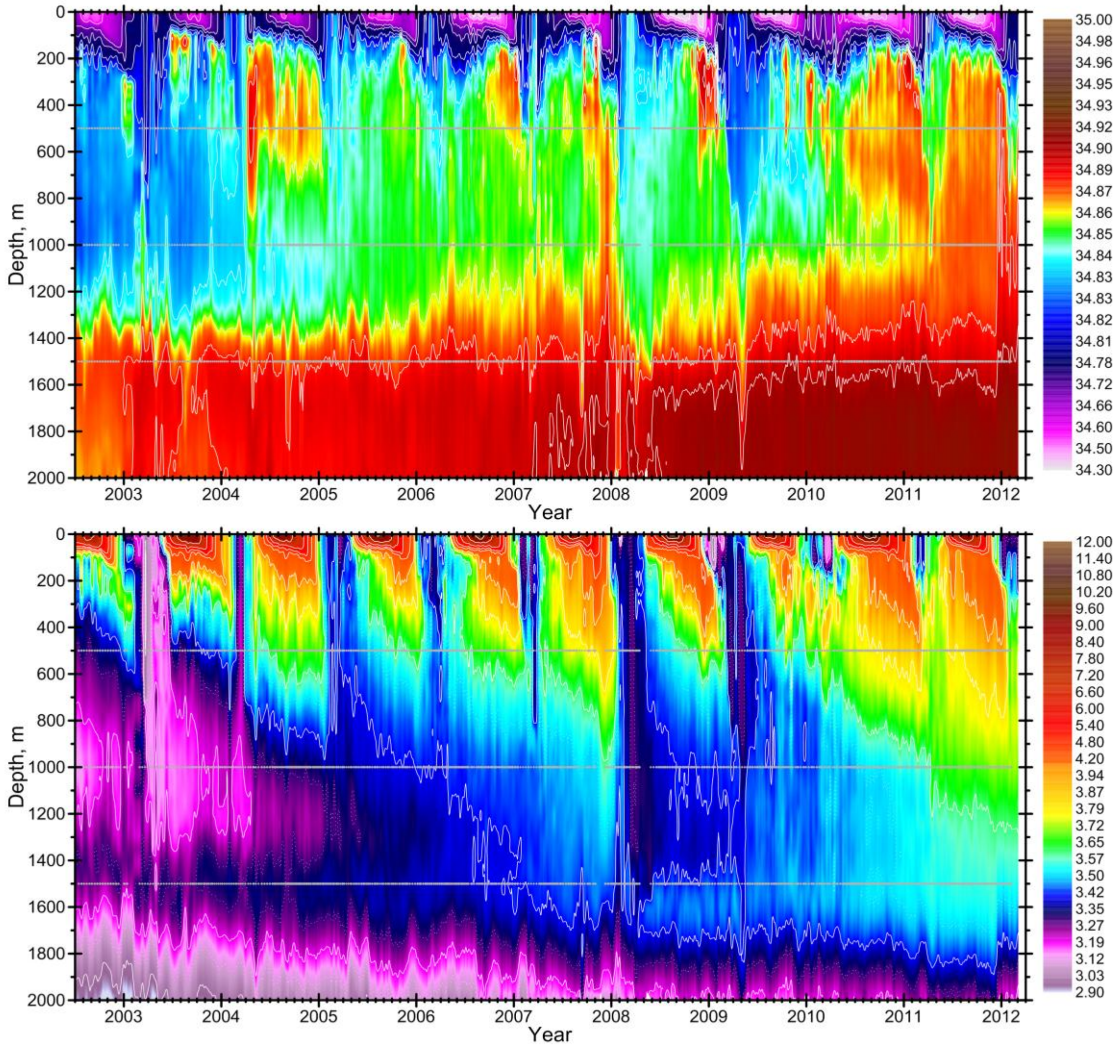

Figure 8: Salinity (top) and potential temperature (bottom) from Argo drifters in the Labrador Sea. The winter 2008 deep convection event is clearly evident to a depth of 1600 m. Convection was limited to a depth of about 200 m in the winters of 2010 and 2011.

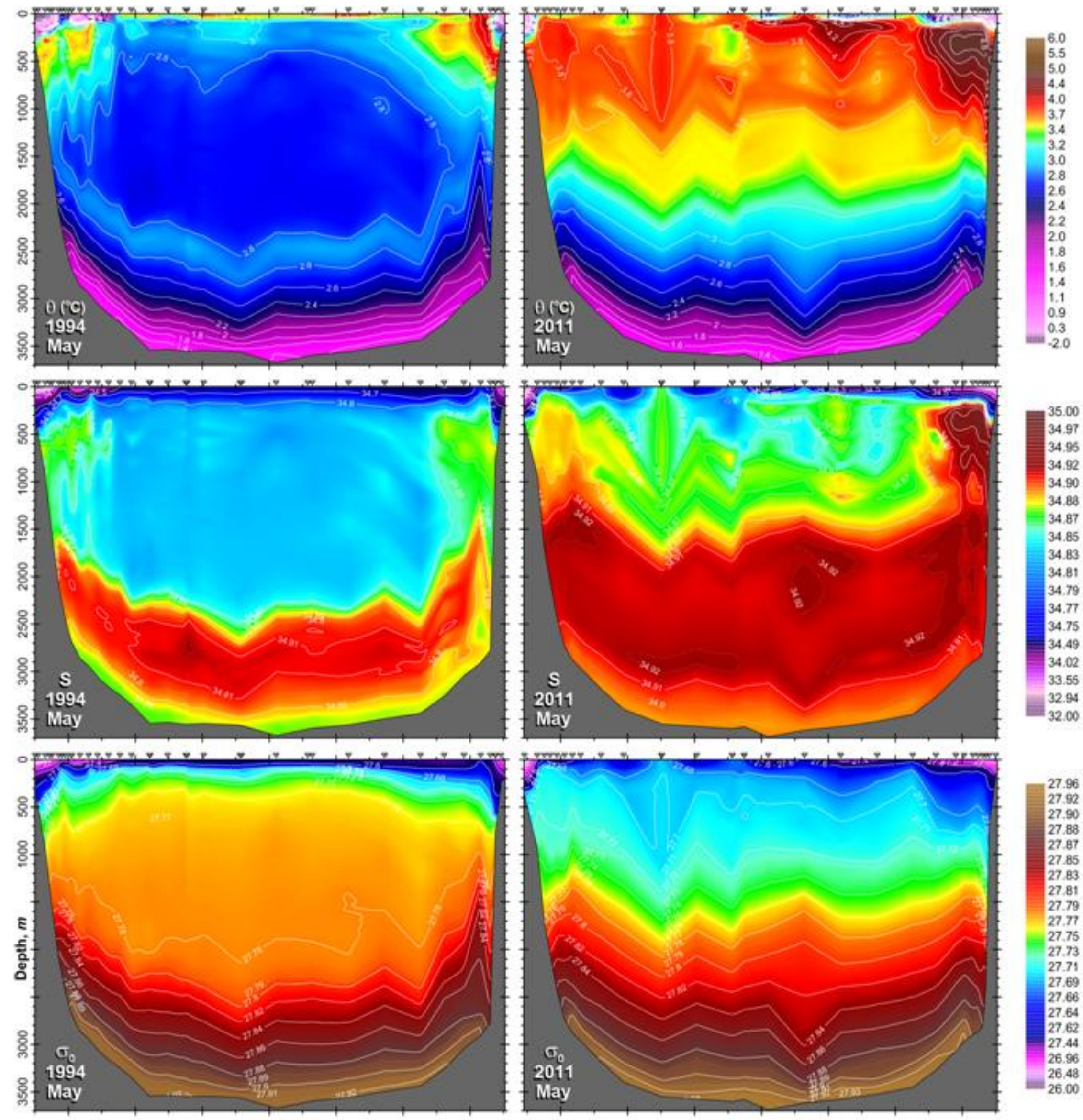

Figure 1: Labrador Sea (AR7W Section) potential temperature (top row), salinity (middle row) and density (bottom row) for 1994 (left column) and 2011 (right column).

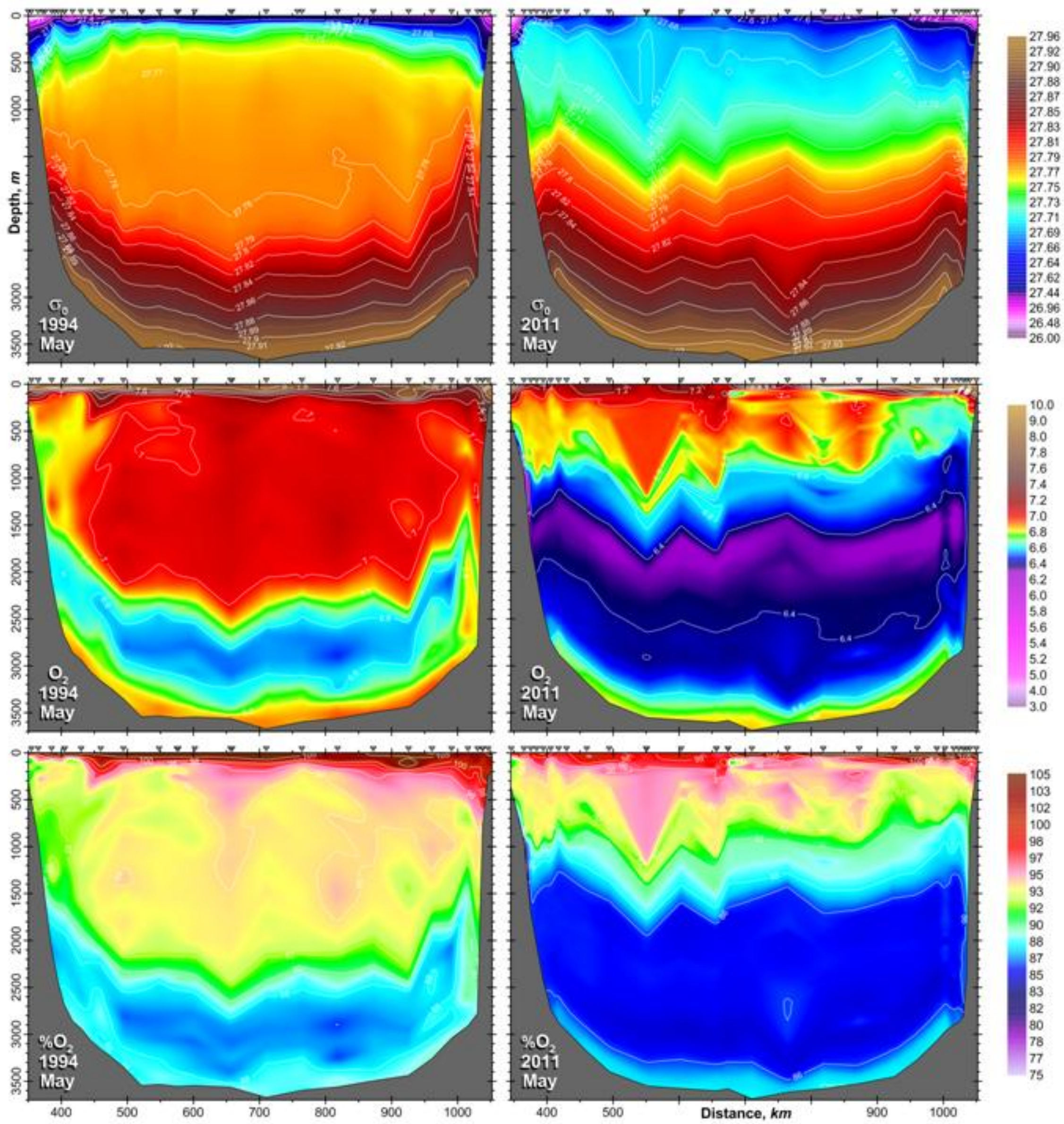

Figure 10: Sea (AR7W Section) density (top row), dissolved oxygen (middle row) and oxygen saturation (bottom row) for 1994 (left column) and 2011 (right column).

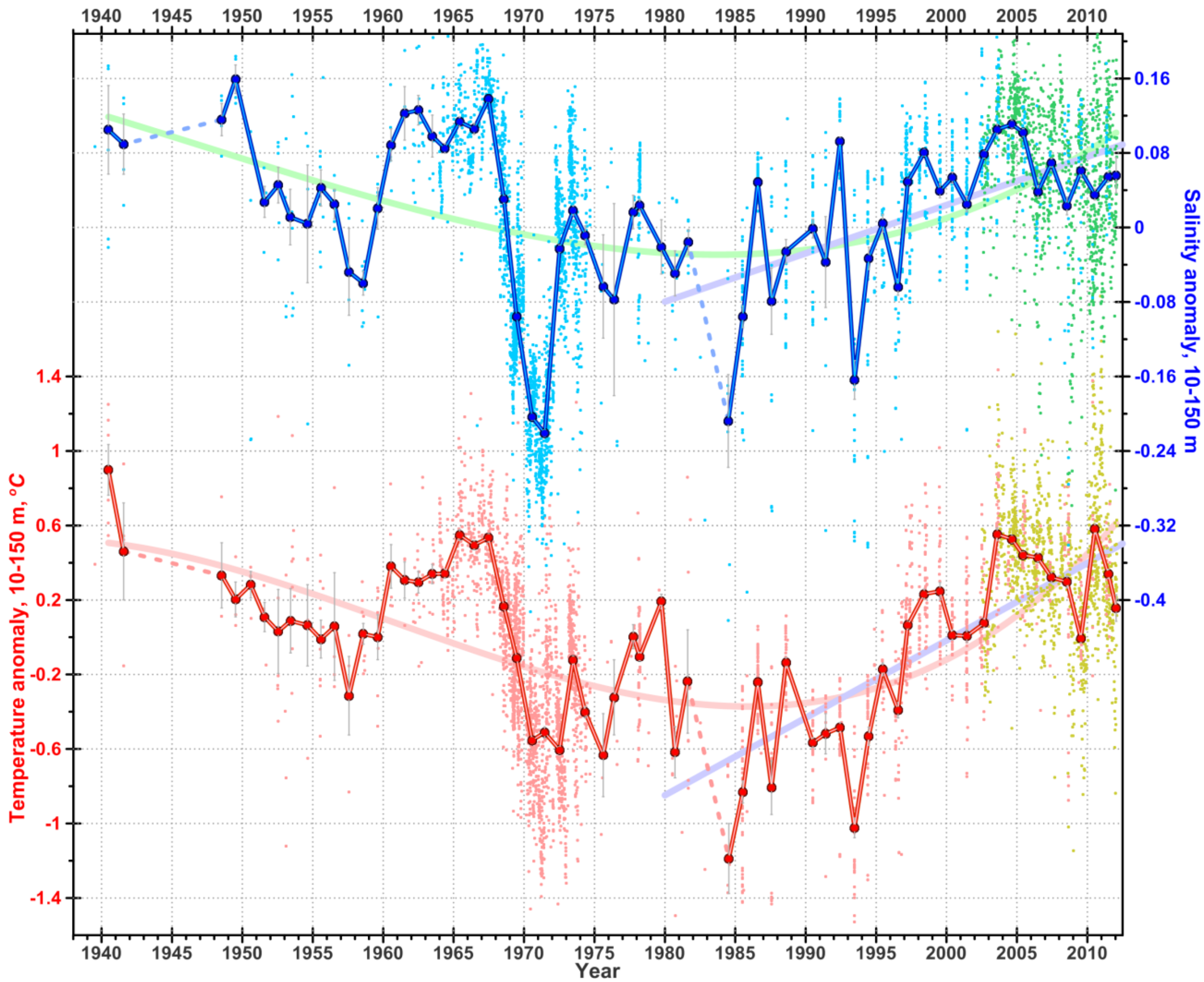

Figure 11: Temperature and salinity anomalies (10-150 m) for the Labrador Sea based on a combination of ship and Argo float data.

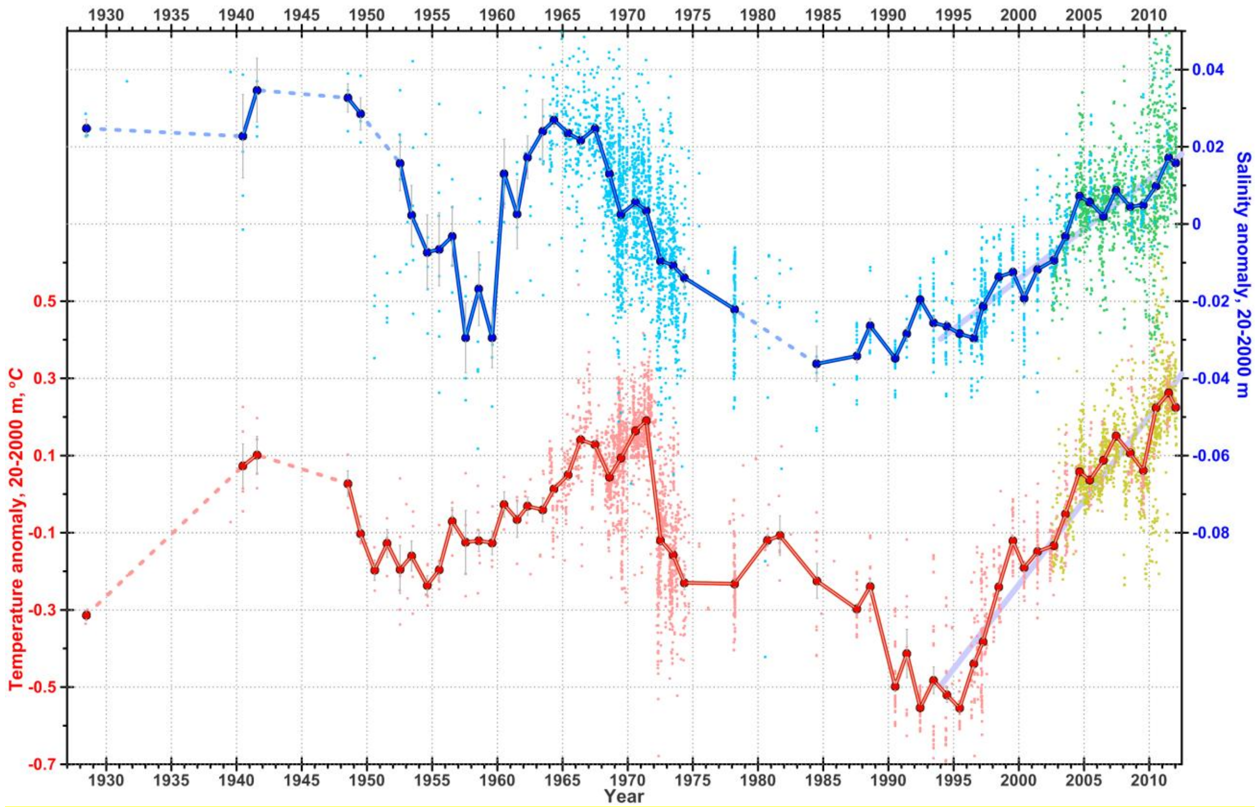

Figure 12: Temperature and salinity anomalies (20-2000 m) for the Labrador Sea based on a combination of ship and Argo float data.