Issue No. 4 November 2005

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Editorial

Science Features

ASOF Related Meetings

News from ASOF

by Bob Dickson, ASOF Chairman

ASOF is now 5 years old. It had its origins in three discussion meetings held in Cambridge, Tromso and LDEO in the year 2000, and we seem to have come quite far and quite fast since. Just how far can be gauged by taking a look back at sort of the questions we were anticipating having to address in these early discussions, many of which had to do with whether and how a particular key measurement might be attempted, and though such issues still remain ----making sustained measurements of ocean fluxes under the ice on the Greenland and Labrador shelves, for example---- these issues of how seem much less dominant than they once were. With the three outstanding observational gaps west of Greenland now filled by modern arrays, (Smith Sound, Davis Strait and Hudson Strait now complementing the pioneering arrays of Simon Prinsenberg and Humfrey Melling across Lancaster Sound and its tributary passages), and with the continued elaboration of the EC-VEINS arrays across the boundaries of the Nordic Seas, we would probably take the view that most of the key ocean fluxes important to 'the role of the Northern Seas in Climate' are now being measured. The issue now would probably centre on the question of whether our lengthening series are yet long enough to distinguish the signal of persistent change from the noise, and if so, whether we understand how the various elements of the ocean-atmosphere-cryosphere system of northern seas have conspired to bring about such changes.

The ASOF themes themselves are the same as ever: how do the poleward fluxes of heat, salt and mass from subarctic seas drive change in the Arctic Ocean and particularly in its perennial sea-ice; and how are the signals of Arctic change brought south through subarctic seas to drive change in the Atlantic Meridional

Overturning Circulation (AMOC). With Ruth Curry's article (P…) this 4th issue of the ASOF Newsletter completes the reporting of the 'freshwater day' that was held, with the support of ESF-COST, as part of the 4th ASOF ISSG meeting in Vigo, October 2004. With ASOF specifying the questions and a group of scientists at the cutting edge of the subject attending to answer them, this session (see Newsletter 3) was extremely successful in driving our thinking forward. And through analyses such as Ruth's, we have begun to appreciate the immense scale of the recent changes in freshwater flux through subarctic seas. Her HYDROBASE analysis, reveals that a total of 19,000 km^3 of freshwater has been added to the watercolumn of the Nordic Seas and Labrador Sea since the mid-1960s, including a 10,000 km^3 contribution from the Great Salinity Anomaly alone.

The bulk of this Newsletter describes a selection of important new results from the special session OS10 on "Detection and Understanding of the Heat and Freshwater Budget Changes and Transports in the Northern Oceans" that was convened by Igor Yashayaev (BIO) and Michael Karcher (A-W-I) of the ASOF SSG at the EGU General Assembly in Vienna in April 2005, with the able support of Peter Koltermann. From the 33 papers and posters provided, we report six with an emphasis on the Labrador Sea. As the basin which receives, recirculates and transforms ocean climate signals from the whole ASOF domain before passing them on to the Deep Western Boundary Current, and as the production site of both classical and new Labrador Sea Water (LSW), observing, modelling and predicting the monumental changes observed here over the past half Century have constituted a major part of the ASOF effort, and can be assumed to hold the key to understanding change in the MOC.

Later in the year, at the 5th ISSG Meeting in Villefranche, 16-18 November, the ASOF special interest in Arctic-to-North Atlantic freshwater fluxes was re-stated and the related scientific tasks re-defined in an internal White Paper 'On the dynamics of freshwater storage and release in the Arctic and subarctic and its interaction with the meridional overturning circulation---insights from numerical modelling' compiled by Michael Karcher, Sirpa Hakkinen and Johann Jungclaus and the ASOF Numerical Experimentation Group (WG7). This paper continues the essential iteration between modelling and observations in ASOF--- with models tested against their ability to reproduce well-defined ocean climate signals as they pass through the ASOF domain and with the observing effort reshaped in consequence ---, which has been a key to the rapid development of ASOF as a Programme since 2000.

ASOF as a study, however, is presently in a state of transition. The three ASOF-EC projects (North, West and MOEN) are all currently coming to an end; and as the World heads for the IPY in April 2007-April 2009, all of the multi-national constituents of ASOF, and the funding agencies that support them, are currently considering the nature and extent of their future involvement. Understandably then the Villefranche ISSG Meeting devoted an important amount of its time to debating whether and how the spirit of ASOF might be maintained. In a discussion session led by Jens Meincke, the question of 'whether' was soon resolved. The SSG was unanimous in seeing the need to continue to develop and steer a flexible and responsive ASOF subset within the massive and pan-arctic observing effort that is likely to be deployed for the IPY. What that pan-arctic future observing effort will look like is also becoming clearer. A plan for a pan-Arctic integrated Arctic Ocean Observing System (iAOOS) ------one of over 1250 Expressions of Interest (EoI) received by the IPY Project Office ----has been endorsed by both the Arctic Ocean Sciences Board (AOSB) and the Climate and Cryosphere (CliC) program of WCRP, and was accorded lead status for 'Ocean-circulation: Arctic' by the ICSU Joint Cttee for the IPY in August 2005. All of the ocean flux arrays involved in ASOF will be necessary components of iAOOS, either because they inform what might be called 'the input function' for Arctic change ('Can we predict the flux of heat and salt to the Arctic Ocean?') or because they capture the 'outputs and impacts' of Arctic change ('What switchgear controls the f'w flux to the Atlantic MOC? And why/how does that vary?'). Thus the future need for the ASOF gateway moorings through the IPY seems assured and as one (#14) of 135 endorsed 'Coordination Proposals' for the IPY, affiliation with iAOOS will now be a requirement for IPY-project submissions to many national funding agencies.

The business of piecing together the iAOOS effort is already underway across three continents. As this is written, the initial meeting of the newly-funded Integrated Project DAMOCLES (*Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies) begins in Paris, with much of the former ASOF-EC effort included. Announcements of Opportunity for the IPY by both US-NSF and Canada are imminent. A Specific Support Action ('SEARCH for DAMOCLES') has been submitted for joint US-EC funding whose entire aim is international integration:--how might the new DAMOCLES effort be meshed with a subset of US-SEARCH to provide an optimal pan-Arctic observing effort for the IPY? National IPY plans are being compiled; consolidated bids for the UK-NERC effort in the IPY were decided in late-November; the Norwegian IPY effort is expected to be defined in January. Thus although it remains true that the actual extent and capability of iAOOS will be determined only when the national funding rounds are completed, in practice this is expected to be resolved very quickly and quite soon.

Following-up our 'Freshwater Day' last year, the final one and a half days of the Villefranche ISSG meeting was devoted to a 'Tracer Session' in which invited experts described the use of the broadest possible spectrum of ocean tracers to describe the ocean circulation and its variations all the way from the circum-Arctic rivers to the deep west Atlantic. From the viewpoint of modernity and completeness, this session must surely have been one of the best ocean-tracer meetings in the World this year, and it will form the basis for a 5th ASOF Newsletter, due early in 2006.

How much Freshwater was added to the Northern North Atlantic in Recent Decades?

by **R. Curry**
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The salinities of watermasses originating in the high latitude North Atlantic have been cascading downward since the early 1970s (Dickson et al., 2002). But missing from the evolving picture thus far has been an explicit quantification of how much additional fresh water (FW) it took to cause the observed salinity changes, how fast it entered the sub-Arctic ocean circulation, and where that FW was stored. These issues are relevant to understanding the impact enhanced FW fluxes may have on the Atlantic meridional overturning circulation (MOC) and its northward heat transport -especially in a warming 21st century when those fluxes are expected to increase (Wu et al. 2005; IPCC, 2001).

To explore these questions, Curry and Mauritzen (2005, hereafter CM2005) reconstructed a history of volumetric changes in ocean temperature, salinity, and density in the Nordic Seas and Subpolar Basins and estimated the magnitude of FW storage and net volume flux anomalies required to account for the observed dilution over the last fifty years. They then examined the degree to which density responded to this freshening, and used this perspective to infer how much additional FW might be required to equalize the density contrast that contributes to the exchange of mass and heat between the Nordic Seas and Subpolar North Atlantic.

Because salinity is approximately conserved in the ocean, salinity anomaly fields can be used to quantify the volume of extra FW that had to be added or removed to account for salinity changes accumulated through the entire water column. Mapping this quantity, layer-by-layer, timeframe by timeframe, throughout the domain describes the evolution of FW storage in space and time. Integrating it over a geographic area provides a time history of the volumetric FW storage anomaly in cubic kilometers (km^3), and differencing this storage anomaly in consecutive timeframes implies a rate of change -the net FW flux anomaly- in Sverdrups (Sv).

Timeseries of FW storage anomaly and net flux anomaly for the Nordic Seas and Subpolar Basins were considered separately and as a whole (Fig. 1, page 11). From the earliest part of the record through the 1960s, salinities increased in the upper 2000 meters of all the Subpolar Basins. Its volumetric expression was a net loss in subpolar FW storage of ~5000 km^3 between 1955 and 1965. By contrast, the net change in the Nordic Seas was comparatively small at that time. Between 1965 and 1990, however, both the Nordic Seas and Subpolar Basins became increasingly freshened. Net FW storage increased by ~19,000 km^3, of which ~4000 km^3 spread into the Nordic Seas and ~15,000 km^3 accumulated in the Subpolar Basins. A recovery from the early 1990's peak of FW storage in the Subpolar Basins occurred in the mid-1990s, but the volumetric analysis falters there for the last timeframe (1998-2002) due to inadequate data coverage. For the Nordic Seas, an approximate balance between import and export of fresh and saline waters resulted in little net volumetric change in the late 1990s.

The most striking event of the timeseries occurred in the early 1970s, a consequence of the Great Salinity Anomaly (GSA, Dickson et al., 1988). It contributed approximately 10,000 km^3 of extra FW to the sub-Arctic seas in the late 1960s and early 1970s, implying a net flux anomaly of ~0.07 Sv during a 5-year period. The GSA was previously thought to be equivalent to ~2300 km^3 of excess FW, and has been attributed to several years of anomalously large sea ice export from the Arctic. The Arctic FW budget includes inflows from the Pacific (~1600 km^3 yr^{-1}) and rivers (~3500 km^3 yr^{-1}) that are mainly balanced by annual exports of FW and sea ice through Fram Strait and the Canadian Archipelago of ~5000 km^3 yr^{-1} (Aagard and Carmack, 1989). Thus, volumetric changes in FW storage suggest that exports associated with the GSA ran ~40% above normal on average during that 5-year timeframe.

Only a fraction of the GSA's FW remained in the Nordic Seas. Fluxes from the boundary into the interior Nordic basins were minimal, and the majority was directly transported south of Denmark Strait via the East Greenland Current. Freshening of the Subpolar and Nordic Seas continued from the GSA period into

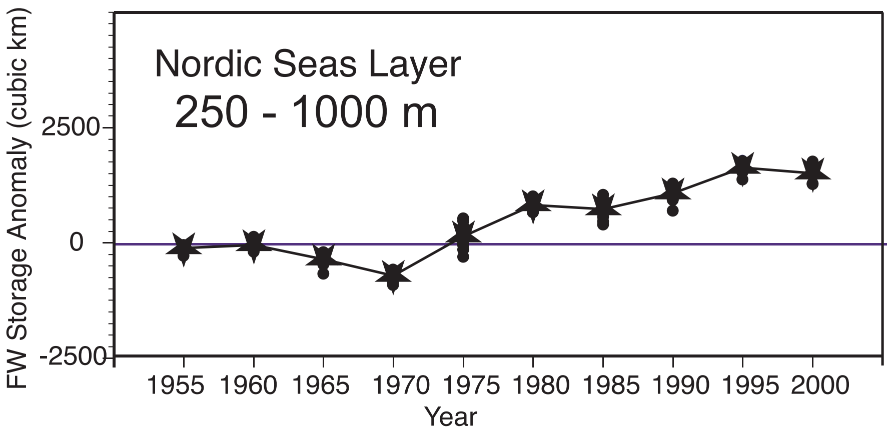

Figure 2. Timeseries of FW storage (cubic km) in Nordic Seas layer 250-1000 m.

the early 1990s as pulses of excess FW and ice appear to have been emitted from the Arctic in the 1980s and 1990s. Since the late 1990s, warm, saline influences have been building in the eastern Subpolar Basins, as they did in the late-1950s to early-1960s, and there are also indications of higher salinities in the Atlantic inflow to the eastern Nordic Seas. But the most conspicuous feature there is the steady accumulation of FW in the upper 1000 meters -a layer that is critical to the MOC because it feeds the Nordic Seas overflows.

Of the total 19,000 km^3 extra FW that diluted the northern Atlantic since the 1960s, only 4000 km^3 remained in the Nordic Seas. Of this latter volume, approximately 2500 km^3 accumulated in the layer 200 – 1000 m between 1970 and 1995. This observed rate of net accumulation (~100 $km^3\ yr^{-1}$) integrates various dynamical processes controlling the mixing of FW into this layer and provides a basis for estimating future dilution. At the observed rate, CM2005 inferred that it could take about a century to accumulate enough FW (e.g. 9000 km^3) to significantly affect the ocean exchanges across the Greenland-Scotland Ridge, and nearly two centuries of continuous dilution to stop them. In this context, abrupt changes in ocean circulation do not appear imminent. Rates of FW input to the high latitude oceans are expected to increase in this century -a consequence of melting glaciers and enhanced precipitation as the planet warms. The ability to confidently predict the magnitude of these changes, however, is still quite limited at this time.

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References

Aagard, K. and E. Carmack, 1989. The role of sea-ice and other freshwater in the Arctic Circulation. J. Geophys Res 94:14485-14498.

Curry, R. and C. Mauritzen, 2005. Dilution of the Northern North Atlantic in Recent Decades. Science, 308: 1772-1774.

Dickson, R.R., J. Meinke, S.-A. Malmberg, and A.J. Lee, 1988. The 'Great Salinity Anomaly' in the northern North Atlantic 1968-1982. Prog. Oceanogr., 20: 103-151.

Dickson, R.R., I. Yashayaev, J. Meincke, W. Turrell, S. Dye and J. Holfort, 2002. Rapid Freshening of the Deep North Atlantic over the past Four Decades. Nature, 416: 832-837.

IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J. T., Y.Ding, D.J. Griggs, M. Noguer, P. van der Linden, X. Dai and K. Maskell (eds.)] Cambridge Univ. Press, U.K. pp 944.

Wu, P., R. Wood, and P. Stott, 2005. Human influence on increasing Arctic river discharges. Geophys. Res. Ltrs., 32, L02703.

Heat and Freshwater Budget and Transports in the Northern Oceans

Summary of OS10 Session[1] held at European Geosciences Union General Assembly 2005 (Vienna, Austria, 24 – 29 April)

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Recent studies have shown that the climate system of the North has been undergoing prominent changes including:

• widespread and sustained freshening in the Arctic and subpolar North Atlantic between the 1970s and 1990s;
• reversal in the freshening trend and the recent temperature and salinity increase in the Labrador and Irminger Seas;
• changes in water mass formation rates and mixing, particularly the impacts of winter convection in the Labrador Sea and other basins on production of intermediate and deep water, resulting in changes in hydrography and circulation on the larger scales;
• reduction of the area covered by Arctic ice;
• warming of the Atlantic layer of the Arctic Ocean;
• transient freshening and cooling events with different magnitude and space-time scales.

[1] *OS10 - Detection and Understanding of the Heat and Freshwater Budget Changes and Transports in the Northern Oceans, convened by Igor Yashayaev (Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada) and Michael Karcher (Alfred-Wegener-Institut, Bremerhaven, Germany).*

These and other documented changes represent either causes or consequences of the shifts in the planetary dynamics, distribution and redistribution of heat and freshwater. Motivated by the growing comprehension of consistency between these changes and expecting to reveal strong linkages between the elements of the climate system, we organized a theme session devoted to observational monitoring and modeling of the oceanic heat and fresh water budgets and transports. The session was hosted by the European Geosciences Union General Assembly 2005 (Vienna, Austria, 24–29 April) and was primarily aimed to provide a better understanding of the temporal and spatial changes, local and remote interactions in the Arctic and Subarctic Oceans from observational and modeling points of view. 33 poster and oral presentations spanned a range of topics from local process studies to global syntheses. In terms of analyzed timescales these presentations ranged from seasonal variations to decadal changes. The data sources used in the studies included recent and historic hydrographic measurements, meteorological data, model simulations, remote sensing and modern and developing technologies.

The session was organized proceeding from large scale syntheses of observed and modeled variability to regional and local studies. Where possible, the OS10 conveners drew links between presentations and promoted discussions on the nature of the changes and possible mechanisms involved. Below we will highlight some of the OS10 contributions. Four articles prepared by OS10 participants based on their presentations are also included in this Newsletter.

The ocean and global scale inventories of the heat and fresh water content presented at the session indicate significant variations in the ocean budgets on decadal and longer time scales. Using both public and unreleased Soviet/Russian hydrographic data, Alekseev et al. (Warming and cooling Events in the Arctic Ocean and Nordic Seas during XXth Century) describe two outstanding warm episodes in the 1930s and 1990s. The two episodes had different manifestations in the Arctic Ocean and in the Nordic Seas, but they both followed periods of cooling. The most recent mooring data from the central Arctic were presented by Ivanov et al. (A new pulse of warm North Atlantic water observed in the Arctic Ocean) who document an intense warming (by 0.8ºC) in the core of the intermediate Atlantic Water of the Arctic Ocean at the Laptev Sea slope in 2004. A comparison with model results (NAOSIM) and upstream observations allows backtracing of the event to Fram Strait (1999) and Svinoy (1997/8) as discussed by Beszczynska et al. (Warm Anomalies and heat flux variability in Fram Strait in 1997-2004: A comparison between observations and model results) (Figure 1, page 11). The anomaly is followed by yet another warm inflow pulse passing Fram Strait in 2004. The model used in both investigations provides good reproduction of the timing and intensity of these events. Their intensity is comparable with another anomaly first seen in the Eurasian Basin in the early 1990s, which later spread over much of the central Arctic Ocean, followed by a cooler phase. Fieg et al. (Modeling heatflux and freshwater transport through Fram Strait) started to use a higher resolution version of NAOSIM to better capture the details of Fram Strait circulation and provide assistance in mooring array design and interpretation.

Consolidation of historic reconstructions, recent data and ongoing monitoring in the Arctic Ocean will, in particular, help to identify the contribution of the Arctic change to the freshening of the deep North Atlantic between the 1960s and 1990s (Dickson et al., 2002). This and other multi-decadal changes in temperature and salinity of the North Atlantic waters have resulted in changes in sea water density and possibly large-scale dynamics. Lozier (On the Density Compensation of the North Atlantic Waters over the Past Fifty Years) discusses the extent of compensation of the temperature and salinity contributions to the density changes in both the subpolar and subtropical gyres of the North Atlantic and compares these contributions with the residual decrease in density. The cooling and freshening of the subpolar gyre are largely density-compensated, as are the warming and salinification of the subtropical gyre (Figure 2, page 11). However, the residual density decrease over the past fifty years is attributed to the freshening in the subpolar basin and warming in the subtropical basin. The degree to which the observed temperature and salinity changes are density compensated sheds light on whether there are any dynamical consequences of these changes.

The radical changes during the second half of the XXth century were not restricted to the Arctic and North Atlantic regions; Gouretski (Temperature and salinity changes in the Global Ocean since 1920's) reports significant secular differences between historical global scale values and the measurements collected during the World Ocean Circulation Experiment (1990-1997).

Several modeling studies presented at the session attempted to reproduce and understand the signature and causes of the observed changes in the Arctic and Subarctic regions. The processes resolved by these models range from regional to inter-ocean. Three studies deal with the freshwater variability and exchanges between the Arctic and Subarctic using large scale coupled ice-ocean or ice-ocean-atmosphere models. Haak and Jungclaus (Arctic Ocean fresh water budget variability) found that the freshwater transports through the Canadian Arctic Archipelago (CAA) and Fram Strait are anti-correlated. For the Arctic Ocean they show no trend in the freshwater content in the 1860-1999 period, but a large increase in the CAA freshwater exports for the next 100 years in a simulation with atmospheric CO_2 2 time higher then the present level.

Koeberle and Gerdes (Mechanisms determinining Arctic fresh water export variability) pointed out that in model investigations both Arctic fresh water reservoirs (liquid as well as solid) show a pronounced decline since the 1960s. The source for this freshwater decline is an increase in the freshwater export that exceeds the increased rate of ice melt in the Arctic. Their analysis of an IPCC scenario run of HadCM3 exhibits an increase in fresh water content (mostly due to precipitation and runoff increases) and a decrease in ice volume.

The relative importance of freshwater exports to the subarctic seas via the CAA and Fram Strait was reported in several presentations. Maslowski al. (The Arctic Ocean Freshwater content and fluxes into the North Atlantic: 1979-2003 model results) found a dominant export path via the CAA. However the key problem of Arctic–Subarctic exchanges remains open and further efforts in modeling and observing the freshwater export pathways (the CAA and Fram Strait) are required to determine their dynamics and the factors governing their relative importance.

Some of the noted changes in hydrographic structure and transports on the large scales may arise from regional changes in the freshwater budgets and circulation in the high latitudinal seas. Harms and Karcher (Modeling Kara Sea freshwater dispersion and export) point to the fact that the supply of ice and runoff from the shelves to the central Arctic Basin may be discontinuous on an interanual scale. They found that a blocking situation of atmospheric pressure distribution led to a reversal of ice and ocean circulation in the late 1990s and a temporal storage of liquid and solid freshwater on the shelf.

What causes the changes in the freshwater distribution and ultimately export from the Arctic and Subarctic regions? What can be expected from possible changes in the other components of the climate system contributing to the oceanic budgets of heat and freshwater? Wu et al. (Human influence on increasing Arctic river discharges) found that the Arctic river flow increase simulated in HadCM3 is consistent with monitored runoff. A substantial part of the trend (8.7 km^3/yr since the 1960s) is due to increasing precipitation over the high latitudes. The authors interpret this as an early stage of the intensifying global hydrological cycle primarily caused by anthropogenic factors, as they do not see the trend in the same model forced with natural factors alone.

The changes in the exports from the Arctic influence the large scale ocean dynamics. Olsen and Schmith (A model study of the exchanges across the Greenland-Scotland ridges using an ensemble approach) reported a general slowdown of the Atlantic meridional overturning circulation from an ensemble of NCEP/NCAR reanalysis (1948-2001) driven model experiments. The overflows across the Greenland-Scotland ridges showed no trend in these runs, but a freshening of surface and deep Nordic Seas and Labrador Sea was found.

Still controversial are the relative contributions of the local atmospheric forcing and variability in the overflows to the change in the deep North Atlantic. One of many approaches to this problem was presented in a study by Lu et al. (Modelling hydrographic changes in the Labrador Sea over the past five decades) in which the influence of variable Arctic inflows on the North Atlantic conditions was deliberately suppressed. Their numerical hindcast experiments showed that the changes in the upper 2000 m of the Labrador Sea are well correlated with changes in atmospheric conditions. However the modeled freshwater variations in the deep layers are much smaller than inferred from the observations. This implies that accounting for the Arctic outflows is a necessary step in the development of North Atlantic models.

The main conclusion reached by our session was that further progress in understanding the processes and variability in the Northern Oceans depends on our ability to go beyond territorial restrictions and comprehend all complexity of Arctic – Subarctic linkages and feedbacks. Such an approach is promoted by the ASOF study. Thanks to ASOF observational efforts it has been possible to map for the first time the freshwater fluxes through the ASOF research domain. Additionally, negotiations are underway to collaborate with ESF-COST on the oceanic components of the northern higher latitude freshwater cycle. A joint activity is promoted on the ocean variability and coupling to terrestrial and atmospheric components. We believe this EGU session has contributed to the scope of ASOF and we hope to gather the interest of the community and convene a similar session for one of international assemblies in 2006-2007.

Acknowledgments

The OS10 conveners express their gratitude to Peter Koltermann for his encouragement and help with hosting of the session. Our appreciation also extends to Bob Dickson and Jens Meincke for their support of this event and to Dan Wright for valuable editorial comments.

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Some Thoughts on Freshwater Fluxes within the Greenland and Icelands Seas

by **S. Jonsson**
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The main inflow of freshwater to the Nordic Seas occurs through Fram Strait. This has been estimated by several authors, e.g. Aagaard and Carmack (1989) that calculated the total freshwater flux, using 34.93 as a reference salinity, to be 125.000 m^3/s = 125 mSv. The solid part of this was found to be 88 mSv while the rest was flow in liquid form.

It was estimated by Jónsson and Briem (2003) using geostrophy referenced to current meter measurements, that 5.5 mSv of this freshwater is diverted into the Iceland Sea with the East Icelandic Current (EIC). A part of the freshwater is also diverted into the Greenland Sea with the Jan Mayen Current (JMC). This can be estimated using data from Stone (1996) combined with a one year long direct current meter measurements from 1987-1988 with 3 moorings north of the Jan Mayen Fracture Zone covering the whole width of the JMC reported by Aagaard et al. (1991). Stone (1996) calculated the geostrophic current relative to 1000 db and the freshwater transport associated with it. She estimated that about 11 mSv of freshwater was transported with the JMC. However she also noted that 5 mSv of this returned back to the East Greenland Current (EGC) with the JMC meander. Aagaard et al. (1991) found that the JMC was barotropic and using their values at the shallowest instruments (60-80 m depth) for referencing the geostrophic velocities and then estimating the freshwater transport of the JMC, excluding the part recirculated back to the EGC, gives 11 mSv. Therefore a relatively small amount (<15%) of the freshwater exported from the Arctic Ocean through Fram Strait is diverted into the Greenland and Iceland Seas. Along the route from Fram Strait to Denmark Strait freshwater is added from the Greenland ice sheet but this is also small since IPCC (2001) estimates the runoff from the whole Greenland ice sheet to be about 17 mSv.

This leads to the conclusion that most of the freshwater entering the Nordic Seas through Fram Strait continues uninterrupted with the EGC to Denmark Strait and exits through it into the North Atlantic and that the freshwater flux through Denmark Strait should be of the same order of magnitude as that through the Fram Strait. Whether this is true or not can be estimated with data collected during the GSP and WOCE projects from 1987-1997. During this period CTD data were obtained from the Kogur section from Iceland to Greenland about 200 km north of the sill in September each year (Figure 1). The only exception was 1993 when there was so much ice in the area that it hindered measurements. During parts of the period current meter moorings were deployed both over the Greenland and Iceland slopes and also in the center of the channel (Figure 1). Usually there was a current meter at about 80 m depth within the polar water layer. The measurements were not continuous but the annual average velocity at all the positions was close to 10 cm/s towards the sill. At IS6 a 3 year average was 9.5 cm/s, at IS9 and IS7 a 2 year average gave 12.4 cm/s at both positions. There is therefore a consistent flow of relatively fresh polar water towards the sill along the whole width of the strait except for the Icelandic shelf. The freshwater thickness above 150 m depth relative to a salinity of 34.93 has been calculated for all the CTD stations and the average at each station for all the years is shown in Figure 2. Combining the freshwater thickness data and the velocity data gives a freshwater transport of 210 mSv. This is actually considerably larger than the freshwater transport through Fram Strait estimated by Aagaard and Carmack (1989) so either freshwater is added along the way in greater quantities than previously

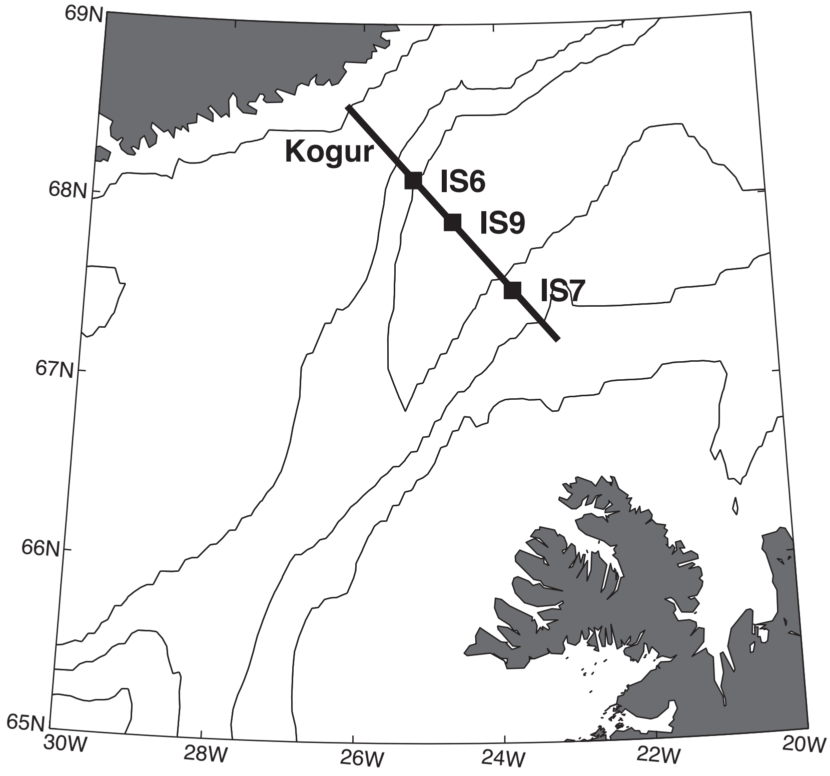

Figure 1. Map showing the Kogur section and the current meter moorings used. The depth contours are 200, 500, 1000 and 2000 m.

thought or it might also be that the freshwater flux through Fram Strait has been underestimated.

The results obtained here are consistent with the fact that only a small amount of the freshwater flux through the Fram Strait is diverted into the Greenland and Iceland Seas and most of the freshwater continues uninterrupted with the EGC and exits the Nordic Seas through the Denmark Strait. We still only know the order of magnitude of the freshwater fluxes in the Nordic Seas and improvements are needed to better quantify this important flow.

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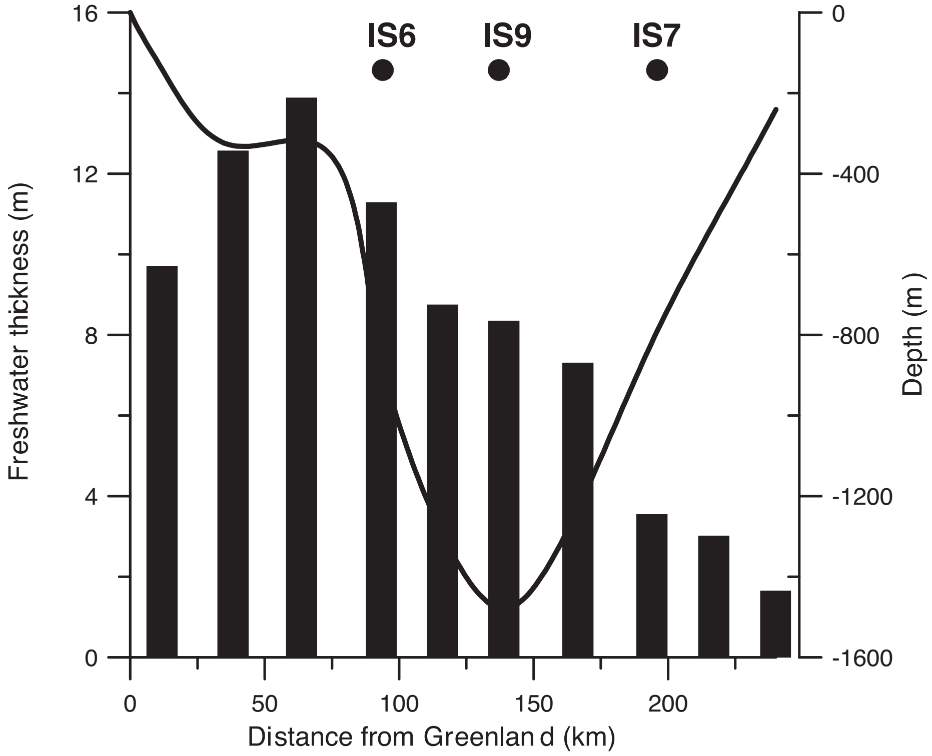

Figure 2. The bars show the freshwater thickness at stations on the Kogur section. On the x-axis is shown the distance from the coast of Greenland. The solid line shows a smoothed topography along the Kogur section (depth on the right axis). The dots show the positions of the current meters in the polar water.

References

Aagaard, K., and Carmack, E. C., 1989: The role of sea ice and other fresh water in the Arctic circulation. Journal of Geophysical Research, 94, 14485-14498.

Aagaard, K., Fahrbach, E., Meincke, J. and Swift, J. H., 1991: Saline outflow from the Arctic Ocean: Its contribution to the deep waters of the Greenland, Norwegian, and Iceland Seas. Journal of Geophysical Research, 96, 20433-20441.

IPCC, 2001: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. J.T. Houghton,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (eds.). Cambridge University Press, 881pp.

Jónsson, S. and Briem, J. 2003: The transport of water and fresh water with the East Icelandic Current. ICES CM 2003/T:05, 12 pp.

Stone, M. D., 1996: The Jan Mayen Current from 1989 and 1990 summer data. Master's thesis, Naval Postgraduate School, Monterey, California, 125pp.

Changes in Labrador Sea Precipitation minus Evaporation and Freshwater Content

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A number of recent studies (Dickson et al., 2002, Curry et al, 2004, Curry and Mauritzen, 2005) have suggested that the high latitudes of the North Atlantic Ocean have been freshening over the last several decades and this signal is being transferred into the deep oceans (Dickson et al., 2002). Sources for the enhanced supply of freshwater to the northern North Atlantic over recent decades include changes in atmospheric excess precipitation (Josey and Marsh, 2005), river runoff (Peterson et al, 2002), melt from the Greenland ice cap (Steffen et al, 2004) and the export of sea-ice from the Arctic Ocean (Dickson et al, 2000). As well as the long term freshening, observations have been made of 2 (or 3) strong low salinity anomalies (termed Great Salinity Anomalies – GSAs) propagating around the sub-polar gyre (Dickson et al, 1988, Belkin et al, 1998).

	1000 m Interior Region			3000 m Interior Region		
Period	P-E	E	P	P-E	E	P
1960-74	0.22	0.65	0.87	0.10	0.73	0.83
1975-2000	0.31	0.65	0.97	0.28	0.73	1.01
1975-2000 minus 1960-74	0.09	0.00	0.10	0.18	0.00	0.18

Table 1. Long term mean P-E, P and E over both our Labrador Sea interior regions. All units are given in m yr^{1}.

Josey and Marsh (2005) examined the variability in the air-sea flux of freshwater in the eastern half of the sub-polar gyre and showed a major increase in P-E within the region during the 1970s. Walsh and Portis (1999) also used reanalysis data to examine variations of precipitation and evaporation over the North Atlantic Ocean during the last 4 decades. They found an inverse relationship between precipitation and the NAO for an extended Labrador Sea region and some evidence for reduced precipitation in the middle 1960s to early 1970s. However, the variation in P and E for the Labrador Sea alone was not quantified. Here we examine interdecadal changes in the freshwater flux to the Labrador

Sea using both NCEP/NCAR and ERA40 reanalyses with the focus being on the interior of the basin. We use two definitions of the interior of the basin, both shown in figure 1. One includes all of the basin beyond the continental shelves and upper slopes, defined where the water depth is greater than 1000 m. The area of this region is 10^6 km^2. We also focus on a smaller region, defined where the water is deeper than 3000 m, and with an area of 4 x 10^5 km^2. We focus on the interior of the basin, not including the boundary currents, as there are unanswered questions related to how much freshwater is exchanged from the boundary currents to the interior. We should note that the results presented here are a subset of a more detailed work on this subject (Myers et al, 2005).

We use output from the two major atmospheric model reanalyses (NCEP/NCAR and ECMWF) as well as oceanic salinity data in this study. We have analysed NCEP/NCAR output (which we use for our primary analysis) for the period 1949-2002 but focus on the interval from 1958 onwards as the earlier fields are less reliable due to reductions in the amount and type of data available for assimilation. The ERA40 reanalysis covers the interval Sep 1957 - Aug 2002 and was used to support the NCEP/NCAR results although we do not present the details of this comparison here.

The salinity data that we have employed were extracted from the extensive hydrographic database maintained by the Bedford Institute of Oceanography (BIO). To allow us to examine the time variability in salinity and freshwater within the Labrador Sea, the data were mapped into overlapping 3-year running mean triads, covering the period 1949-1999. Each triad was defined to include all the data collected in a given year, as well as all available data in the preceding and following year. The data were objectively mapped onto a 1/3 by 1/3 degree grid over the entire Labrador. Vertical binning and averaging was carried out using isopycnal coordinates. To concentrate on changes within the interior of the Labrador Sea, the triad data were then averaged over the region within the 3000 m isobath (Fig. 1) to give an average central

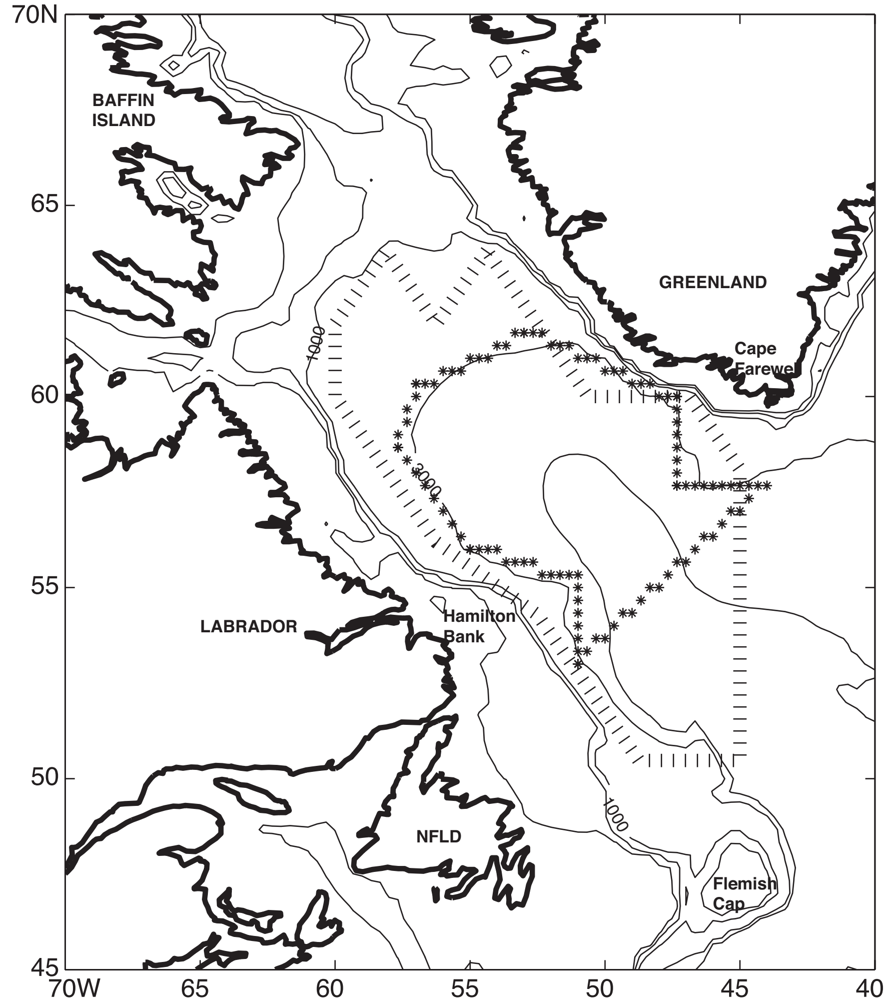


Figure 1. Map of the Labrador Sea study region. The dashed region is our study region within the 1000 m contour, while the starred region is our study region within the 3000 m contour.

Labrador Sea salinity for the central year of each triad, at each level. Details of the data processing (including quality control), as well as further analysis of the resulting fields can be found in Cetin (2005).

The P-E field has excess precipitation through most of the sub-polar gyre, with maxima along the Greenland and Labrador Sea coasts, and a transition to net evaporation south of 45N. The component fields show that E tends to decrease towards the coastal margins, possibly reflecting the effects of ice cover, whereas P remains relatively constant. These fields are broadly consistent with other observationally derived products as well as with the ERA40 reanalysis (Josey and Marsh, 2005). We have calculated the mean P-E for a Labrador Sea interior by averaging over each grid cell in the atmospheric analyses that falls within this domain. The full period annual mean value is an excess precipitation of 27 cm yr^{-1} for the 1000 m region and 20 cm yr^{-1} for the 3000 m region, both of which are smaller than previous estimates (e.g. 40 cm yr^{-1} – Walsh and Portis, 1999) that included the more highly precipitative boundary current regime. It should be pointed out that, at least in other regions of the globe, NCEP is known to suffer from a strong dry bias (Li and Chen, 2005). In addition, Josey and Marsh (2005) also found a dry bias with respect to rain gauge measurements in the eastern subpolar gyre. However, they also found very good agreement between the temporal variability in NCEP/NCAR and the rain gauges, and it is this variability that we are interested in here.

Time series of annual P-E anomalies for our interior Labrador Sea regions are shown in Fig. 2. We note although the specifics do vary between the regions, the general behaviors are very similar. Anomalies have been formed by subtracting the full period annual mean from the individual annual means. The P-E time series are dominated by interannual variability but the 5-year running means show a clear shift from negative to positive anomalies in the mid-1970s. The time series thus have two main phases, relatively low net precipitation from the 1950s through to the 1970s and relatively high net precipitation post the mid-1970s. Whether this shift is part of a long term trend to an environment with an increased atmosphere to ocean freshwater flux or just two phases in a long period oscillation cannot be determined from the given time series length. We note that the mid-1970s shift in Labrador Sea P-E shows similar timing to that described by Josey and Marsh (2005) for the eastern part of the North Atlantic sub-polar gyre. The change in excess precipitation over the Labrador Sea is driven primarily by changes in the precipitation component rather than evaporation (not shown). There is no clear long term trend in E but the P time series exhibits a marked shift towards increased precipitation during the mid-1970s. Note that Josey and Marsh (2005) have already noted that changes in P were the dominant cause of the interdecadal variability in the eastern subpolar gyre. Our analysis suggests that parallel changes in P over the Labrador Sea are the dominant factor influencing

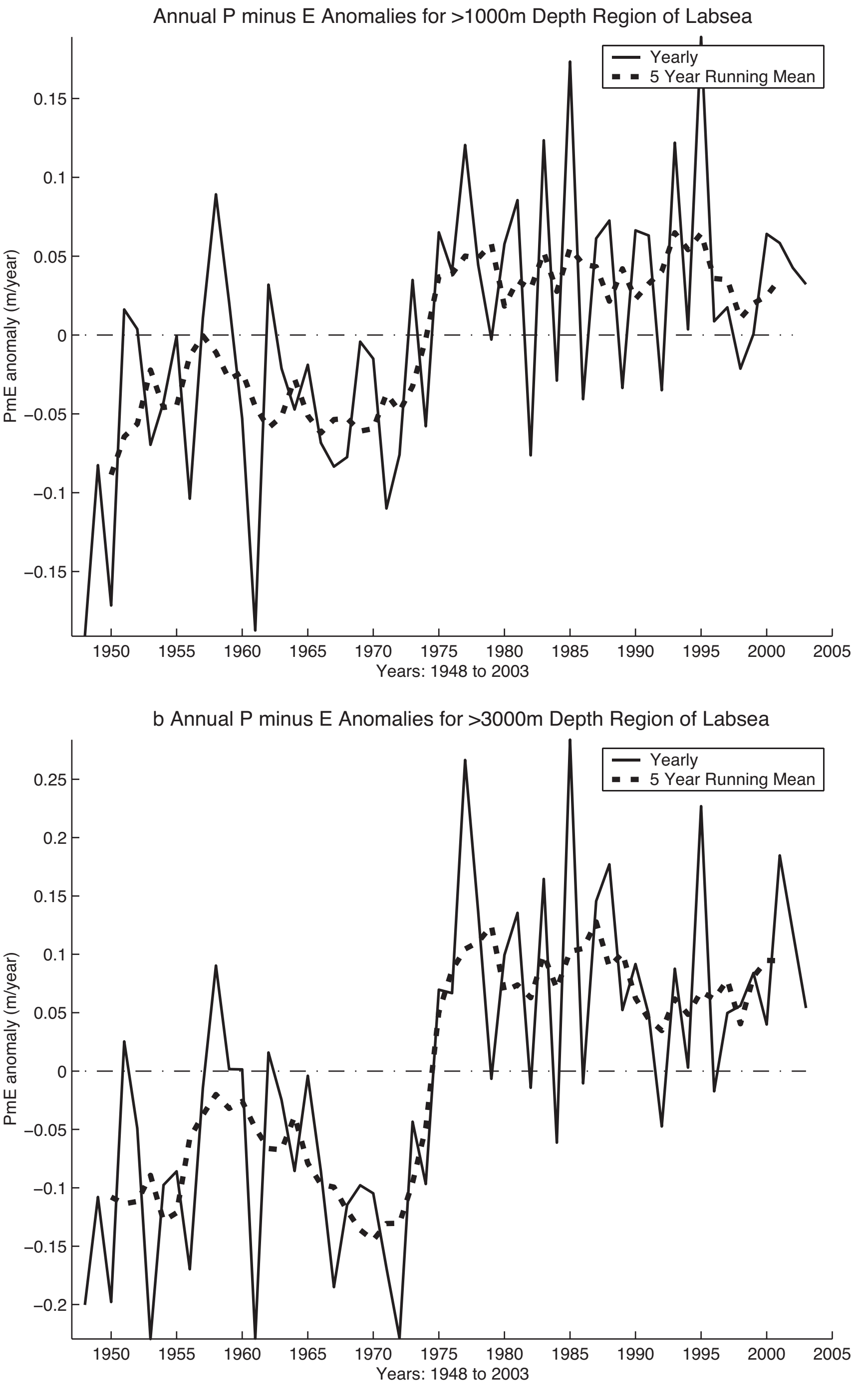
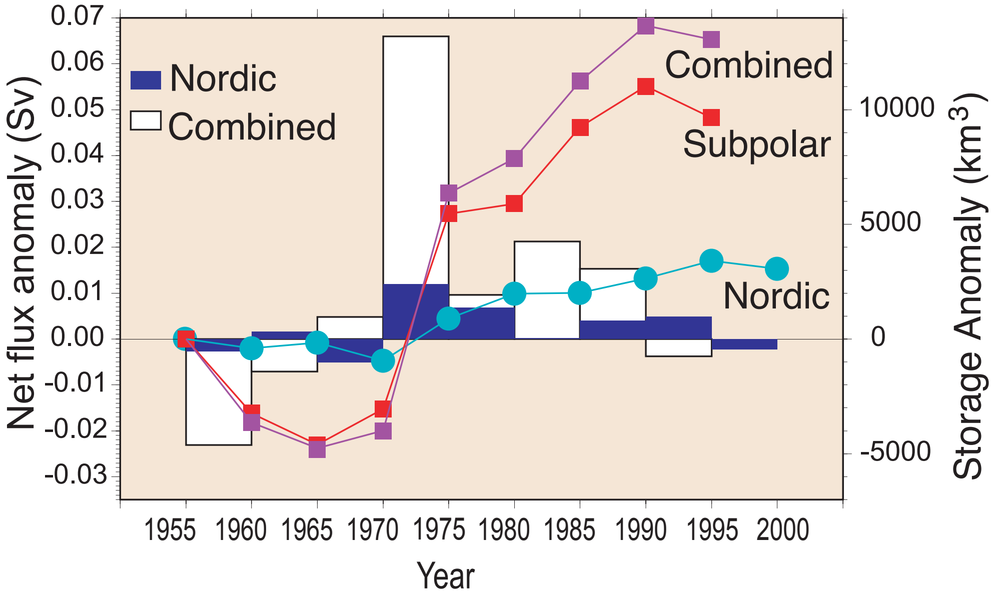
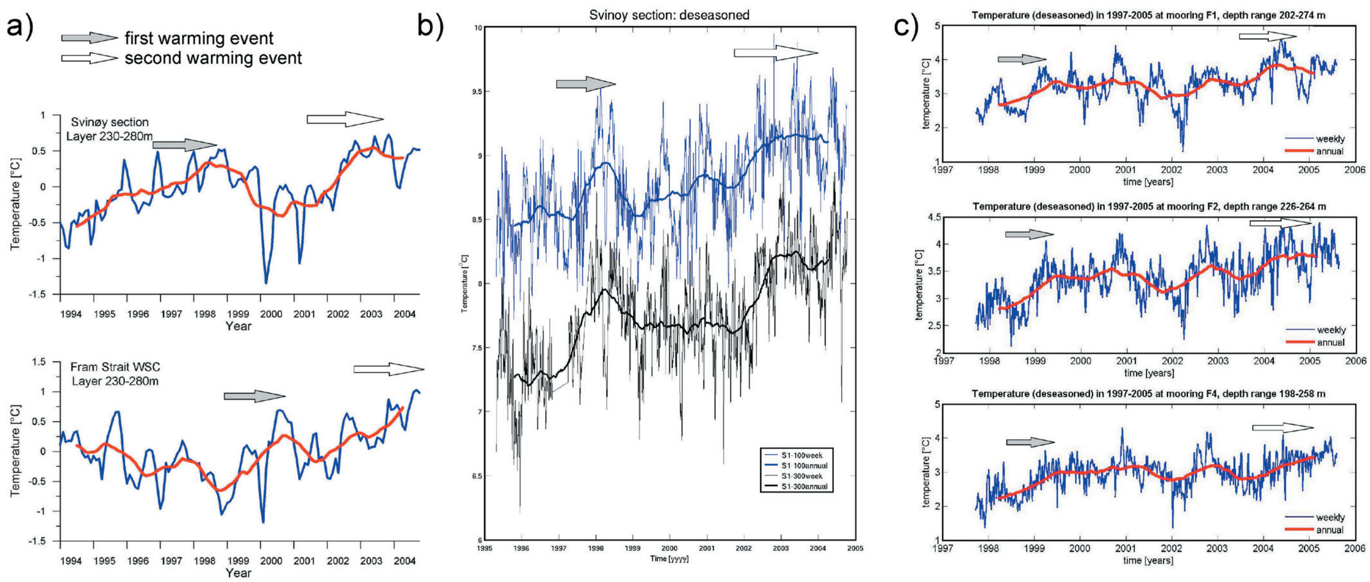


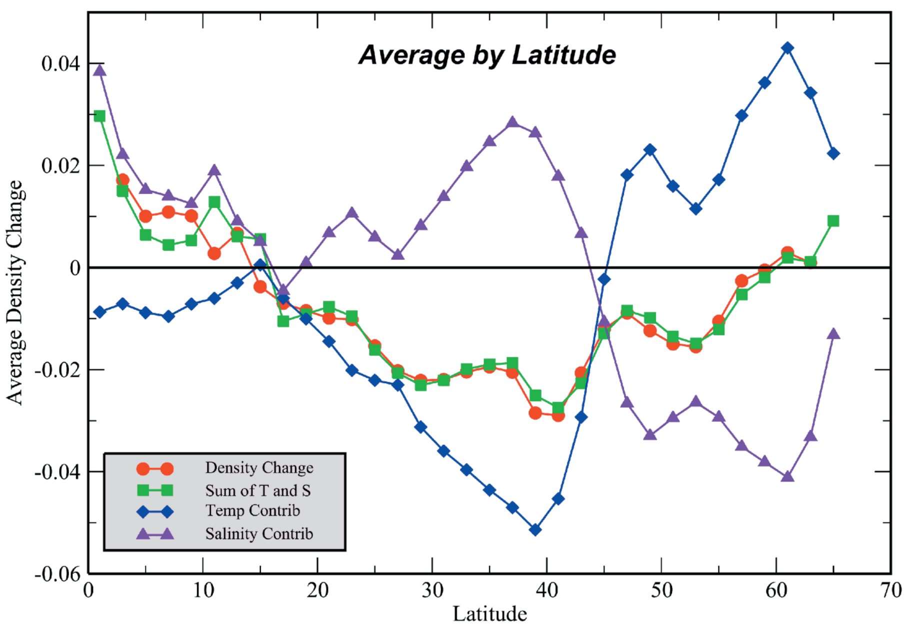
Figure 2. Timeseries of annual anomalies and 5-year running means of P-E from NCEP/NCAR for the 1000 m depth interior region (top) and the 3000 m interior region (bottom).

right: Figure 1 (from R. Curry article at page 3). Timeseries of FW storage anomaly in km3 (symbols, scale on right axis) for Nordic Seas (cyan circles), Subpolar Basins down to 50oN (red squares), and both regions combined (purple squares). The difference in storage anomaly between successive 5-year timeframes, the net FW flux anomaly in Sverdrups (Sv), is shown as bars with scale on left axis. The Nordic Seas component of the net flux anomaly is blue. The Subpolar Basins component is white and has been added to the Nordic Seas to give the total FW flux anomaly.





top: Figure 1 (from I. Yashayaev et al. article at page 4). Timeseries of temperature of northward flowing Atlantic Water at Svinoy and in Fram Strait: a) model results at both locations (from Karcher et al.), b) observations at Svinoy (from Skogseth), c) observations in Fram Strait (from Beszczynska et al.). Arrows depict the two warming events from recent years.



left: Figure 2 (from I. Yashayaev et al. article at page 4). Density change at 1000 m in the North Atlantic basin over the past fifty years - the temperature (blue) and salinity (purple) contributions to the density change, their sum (green), and unpartitioned density change (red). Values are averaged longitudinally. Presented by Susan Lozier at EGU Assembly 2005 (On the Density Compensation of the North Atlantic Waters over the Past Fifty Years).

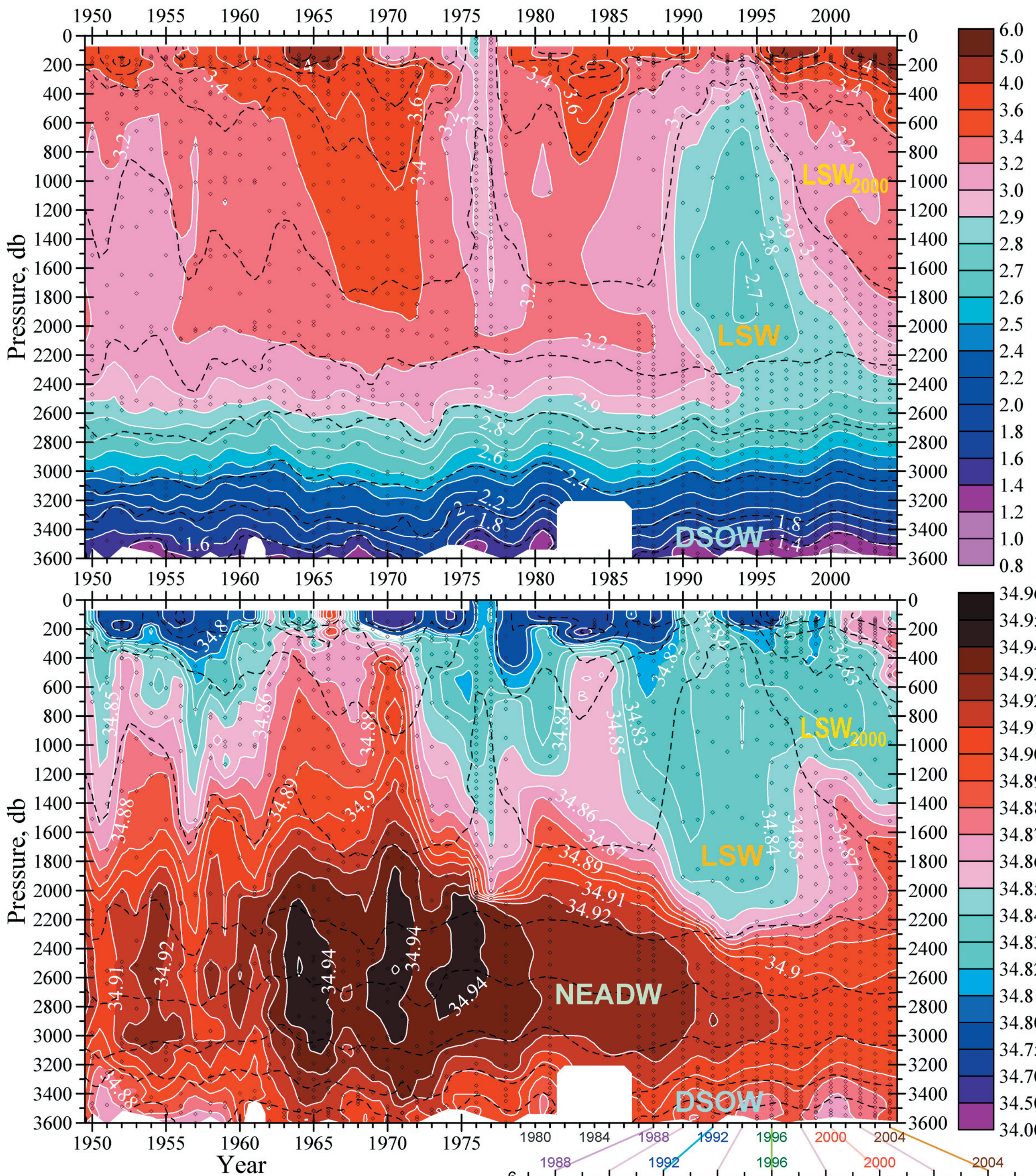
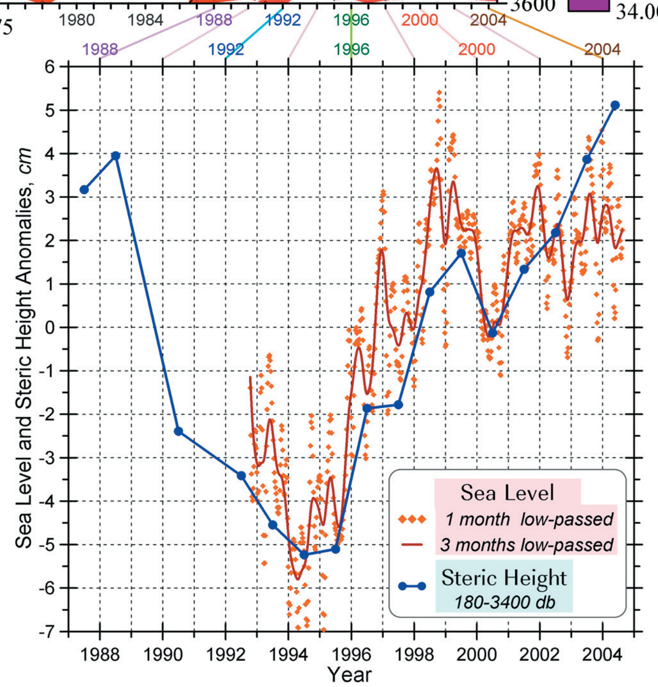


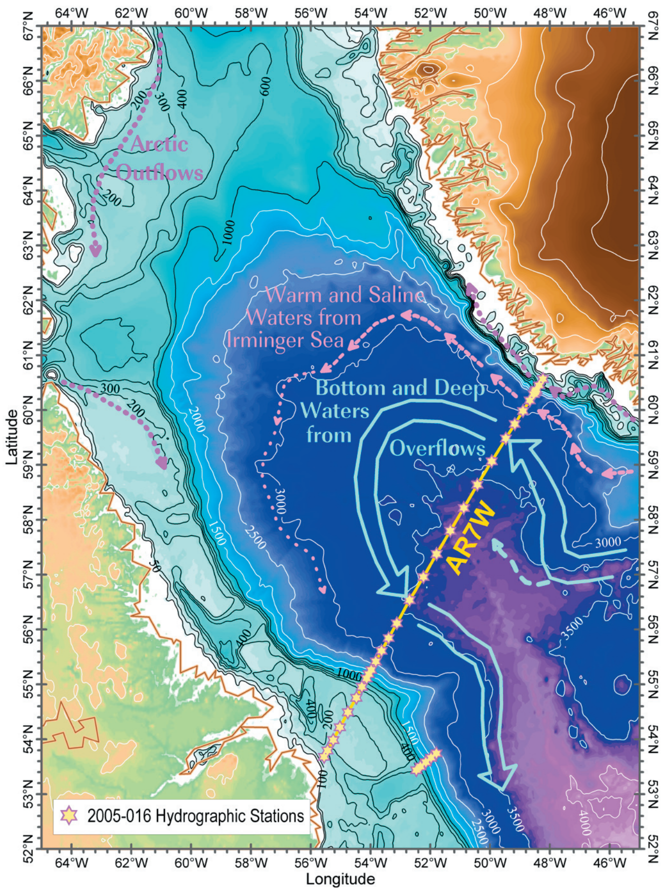
Figure 2 (from I. Yashayaev and A. Clarke article at page 17). . Temperature (upper, 1949-2004), salinity (centre, 1949-2004) and steric height (lower, blue line, 1987-2004) in the central Labrador Sea. Sea level anomalies relative to the record mean are also shown in the lower plot (red dots for 1 month low-passed and brown line for 3 month low-passed, 1992-2004).

The central Labrador Sea was confined by the 3250 m isobath.

Density contours (dashed lines in the upper and central images) indicate that the LSW produced between 1990 and 1994 was the densest in the record.

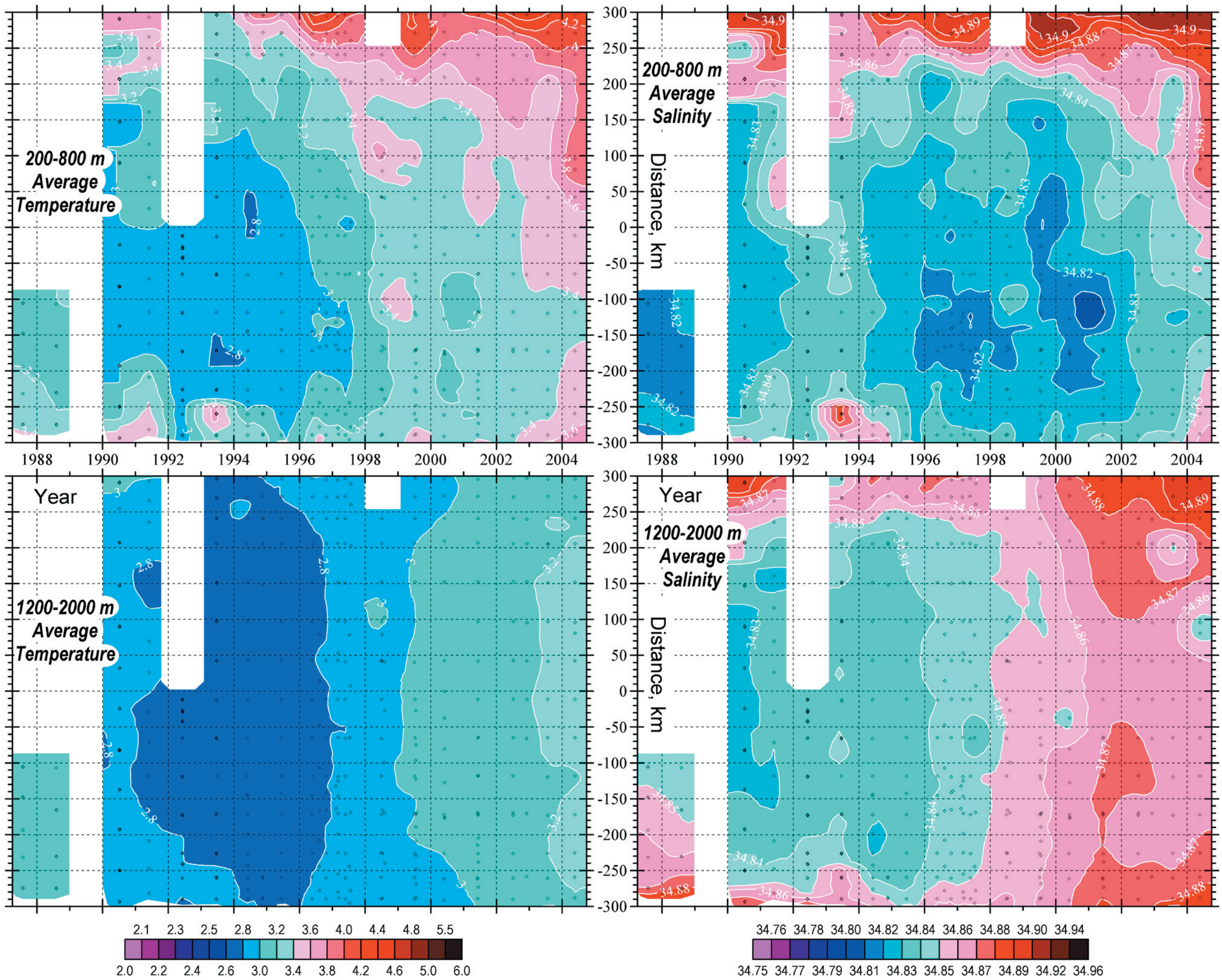
The steric height was derived from the AR7W hydrography. The sea level anomalies were derived from satellite altimeter data available from the Topex/Poseidon and Jason missions.

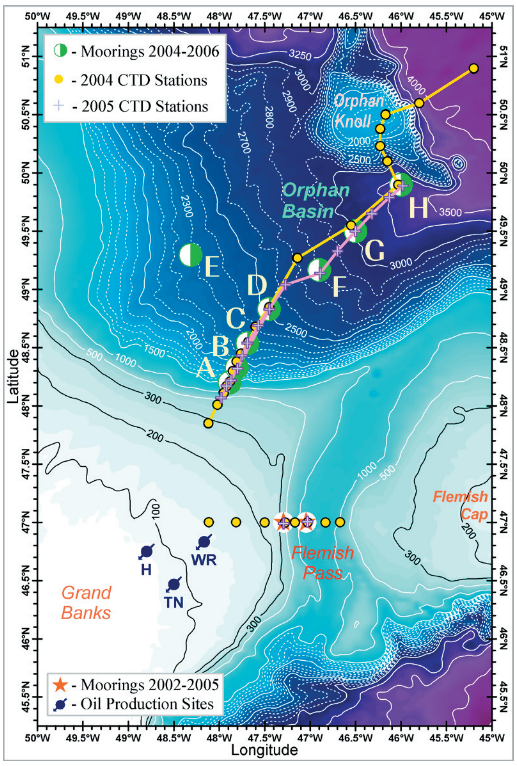




left: Figure 1 (from I. Yashayaev and A. Clarke article at page 17). Location of CTD stations occupied by BIO in the Labrador Sea in the spring of 2005 (May 29 - June 4). AR7W is a standard section line.

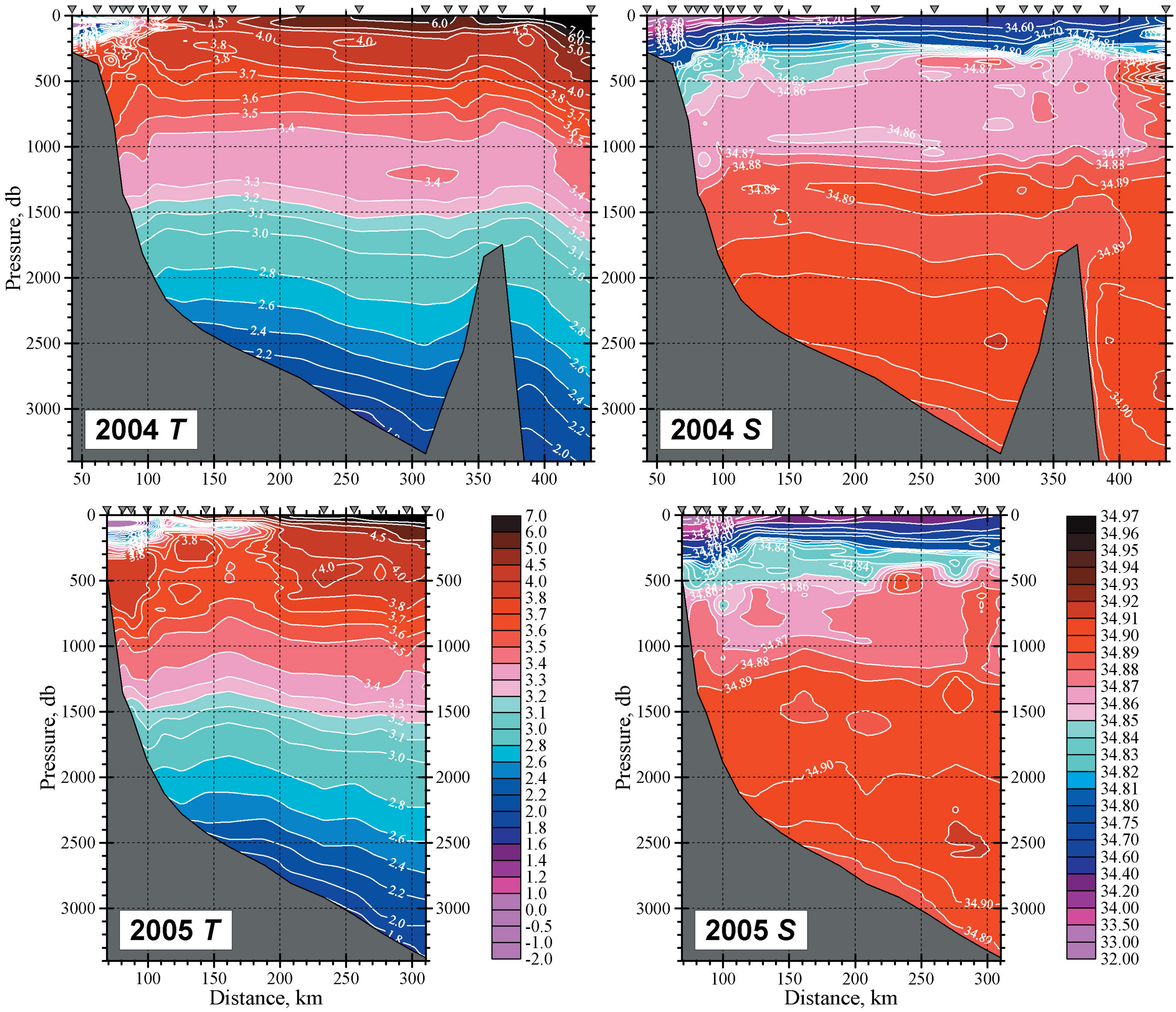
bottom: Figure 3 (from I. Yashayaev and A. Clarke article at page 17). Temperature (left) and salinity (right) averaged over 200-800 m (upper) and 1200-2000 m (lower) layers along the Labrador Sea section AR7W (Figure 1). The vertical axis is the distance to the central point of the section line, the values increase toward the Greenland coast (positive direction) and decrease toward the Labrador coast (negative direction). OWS Bravo is near ~ -100 km.





right: Figure 1 (from J. Loder and I. Yashayaev article at page 19). Locations of current meter moorings and CTD stations deployed and occupied in the Flemish Pass and Orphan Basin regions in 2004 and 2005. Oil production sites on the northeast Grand Bank are indicated by solid dark-blue circles.

bottom: Figure 2 (from J. Loder and I. Yashayaev article at page 19). Potential temperature (T) and salinity (S) on the Orphan Basin hydrographic sections occupied in 2004 (May-June) and 2005 (May).



Layer	1950-75 Anomaly	1976-99 Anomaly	Difference	Freshwater Increase (km^3)
0-100 m	0.089	-0.100	-0.189	217
0-500 m	0.031	-0.035	-0.066	391
0-1000 m	0.023	-0.026	-0.049	563
0-1500 m	0.020	-0.022	-0.042	724
0-2000 m	0.018	-0.020	-0.038	874

Table 2. Salinity Anomalies (compared to 1950-1999 mean) for various layers, in the interior of the Labrador Sea, for 2 time periods, as well as the increase in freshwater between the two periods (with respect to a reference salinity of 34.8).

the atmospheric freshwater flux to this basin.

The changes in E, P and P-E over the Labrador Sea interior are summarized in Table 1. For the larger Labrador Sea region, over the period 1960-1974, for which the NCEP data is considered to be more reliable, we find that the net precipitation has increased by 9 cm yr^{-1}, and in this case, is entirely driven by the changes in precipitation. In we focus on our smaller Labrador Sea region, then the changes are even larger. We find an increase in net precipitation of 18 cm yr^{-1}. We also note that the results are insensitive to the choice of the specific year in the 1970s that is used as the separator between the two periods. We recalculated the averages using every year from 1972 to 1978 as the bounding year and found no qualitative differences in the results. Considering all months (not shown), spring and summer changes are the dominant factor in the increased annual P-E after the mid-1970s. We note that in contrast for the eastern subpolar gyre, Josey and Marsh (2005) found significant contributions to the increase occurred in all months of the year and that changes in net precipitation were largest in winter. The changes that we have found for the Labrador Sea thus show a different seasonal dependence to the eastern gyre which suggests that they may be linked to a different mode of atmospheric variability.

We now try to link the changes in the air-sea freshwater flux to the observed freshening in the Labrador Sea over the last several decades. As shown in Table 1, the atmospheric flux of freshwater to the surface of the interior of the Labrador Sea has increased by 9/18 cm yr^{-1} to 31/28 cm yr^{-1} for the 1975-2000 period as compared to 22/10 cm yr^{-1} for the 1960-1974 period. Given the areas of our two Labrador Sea regions, the increase in P-E would have led to the provision over the 25 year period 1975-2000 of an extra 2.25 x 10^{12} m^3 of freshwater to the interior region deeper than 1000 m, and an extra 1.8 x 10^{12} m^3 for the 3000 m region.

Curry and Mauritzen (2005) reported that the freshwater content of the sub-polar gyre had increased by ~15,000 km^3 between 1965 and 1995, with a significant contribution from the advective Great Salinity Anomaly. We suggest that part of the 5,000 km^3 increase reported occurring after 1975 is related not to advective processes but instead to increases in the atmospheric P-E signal. In a pure budget sense, 2250 km^3 of additional freshwater was provided to the western sub-polar gyre (Labrador Sea) during the post 1975 period by the atmosphere. This last number is large in magnitude and indicates that the atmospheric freshwater flux may have played a significant role in the freshening. Further, we note that the Labrador Sea is only a part of the sub-polar gyre region of Curry and Mauritzen (2005) and that the analysis of Josey and Marsh (2005) reveals an additional gain of 4000 km^3 from the atmosphere within the eastern part of the sub-polar gyre. However, one has to remember than the increase in freshwater from the atmosphere will only contribute to the observed change in freshwater content if it is stored within the sub-polar gyre and so the overall effect of the P-E increase remains to be fully determined.

What is the fate of the freshwater found at the surface of the Labrador Sea? Could it contribute to the observed freshening changes in the sub-polar gyre? In a dataset of surface drifters examined by Cuny et al (2002), all drifters released in the Labrador Sea remained in the sub-polar gyre. Surface water is also taken up in the LSW formed in winter. Three pathways for LSW have been documented, into the Irminger Sea, into the eastern basin under the NAC and south along in the deep western boundary current. Only this last pathway involves the export of freshwater from the sub-polar gyre. Although we want to be careful in not overstating its importance, since there are many factors that provide freshwater to the sub-polar North Atlantic, we think that it is reasonable to suggest that the enhancement of excess precipitation over the Labrador Sea (and the sub-polar gyre as a whole) has played a role in the increase in freshwater content seen in the sub-polar North Atlantic over the last 25 years.

What about the impact of the changes in the atmospheric provision of freshwater to the Labrador Sea itself? We have used the mapped 3-year triads of salinity discussed in Section 2 to examine this question. We look at the changes in salinity through various layers in the Labrador Sea, between 1950-1975 and 1975-1999 – see Table 2. The freshening is largest at the surface, up to 0.19 psu, but remains significant through the water column, 0.04 - 0.07 psu at greater depths. Thus, the long term freshening in the Labrador Sea, noted by others previously, is clearly seen with this data and the magnitude of the changes is consistent with previous studies. We have also computed the associated change in freshwater between the two periods, with respect to a reference salinity of 34.8. The results are given in table 2, with an increase of 724 km^3 for the top 1500 m.

Houghton and Visbeck (2002) found the magnitude of the freshwater anomaly (over the top 300 m) associated with the first GSA to be ~700 km^3. which is close to the total change in freshwater in the Labrador Sea that we find between the two periods. However, although the first GSA may explain some of the rapid drop in salinity in the 1970s, consideration of flushing timescales indicates that it cannot explain all of the freshening between the two periods. The reason for this is that the interior of the Labrador Sea is a small region where advection is important. For example, the flushing timescale for Labrador Sea Water is approximately 4 years (Lazier et al, 2002). Thus, although some of the freshwater from the first GSA may have been stored in the Labrador Sea, most of it has probably been flushed out into other parts of the sub-polar gyre (for which the flushing timescale is much longer). In contrast to the short term nature of the first GSA, and subsequent advective events, the increase in P-E in the 1970s has been maintained to the present day thus enabling the atmosphere to make an ongoing contribution to the freshening within the Labrador Sea.

In the most simple sense, to consider the freshening of the Labrador Sea over the last 25 years, we can just think in terms of the difference between the inflow and export of freshwater. If the inflow exceeds the outflow, then the freshwater content increases, as that of the Labrador Sea has. Although this could in theory come about from a decrease in the freshwater export as easily as an increase in the import, detailed knowledge on temporal changes in the freshwater export is not available, while we know that there have been increases in the freshwater import to the Labrador Sea. Other than the changes directly provided by the atmosphere, all the other sources of additional freshwater (Arctic discharge (both liquid and solid), Greenland ice cap melt, precipitation changes elsewhere in the Atlantic) enter the Labrador Sea through it boundary currents and then are transferred to the interior through eddy and mixing processes. Variability in these processes must have occurred but we are not sure how to quantify this either at this point in time. But what we can say is that the atmospheric input of extra freshwater over the 1975-2000 period totaled 1800 km^3. As it was provided fairly regularly over the 25 year period, the changes in the atmospheric forcing have not led to any of the rapid changes observed in Labrador Sea salinity but probably played a role in the long term freshening. Further investigation is needed in trying to quantify the role of the different freshwater sources in the observed freshening of the Labrador Sea.

Acknowledgments

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References

Belkin, I. M., S. Levitus, J. Antonov, and S.-A. Malmberg (1998), Great Salinity Anomalies in the North Atlantic, Progress in Oceanography, 41, 1-68

Cetin, N. (2005), A diagnostic study of the Labrador Sea circulation based on climatological data analysis with an insight into the freshwater variability, Ph.D. thesis, University of Alberta.

Cuny, J., P. B. Rhines, P. P. Niiler, and S. Bacon (2002), Labrador Sea boundary currents and the fate of Irminger Sea Water, Journal of Physical Oceanography, 32, 627-647.

Curry, R., and C. Mauritzen (2005), Dilution of the northern North Atlantic Ocean in recent decades, Science, 308, 1772-1774.

Curry, R., B. Dickson, and I. Yashayaev (2003), A change in the freshwater balance of the Atlantic Ocean over the past four decades, Nature, 426, 826-829.

Dickson, R. R., J. Meincke, S.-A. Malmberg, and A. J. Lee (1988), 'The Great Salinity Anomaly' in the northern North Atlantic 1968-1982, Progress in Oceanography, 20, 103-151.

Dickson, R. R., T. J. Osborn, J. W. Hurrell, J. Meincke, J. Blindheim, B. Adlandsvik, T. Vinje, G. Alekseev, and W. Maslowski (2000), The Arctic Ocean response to the North Atlantic Oscillation, Journal of Climate, 13, 2671-2696.

Dickson, R. R., T. J. Osborn, J. W. Hurrell, J. Meincke, W. Turrell, S. Dye, and J. Holfort (2002), Rapid freshening of the deep North Atlantic Ocean over the past four decades, Nature, 416, 832-837.

Houghton, R. W., and M. H. Visbeck (2002), Quasi-decadal salinity fluctuations in the Labrador Sea, Journal of Physical Oceanography, 32, 687-701.

Josey, S. A. and R. Marsh (2005): Surface Freshwater Flux Variability and Recent Freshening of the North Atlantic in the Eastern Subpolar Gyre, Journal of Geophysical Research, 110, C05008, doi:10.1029/2004JC002521.

Lazier, J., R. Hendry, A. Clarke, I. Yashayaev, and P. Rhines (2002), Convection and restratification in the Labrador Sea, 1990-2000, Deep Sea Research, 49, 1819-1835.

Li, H., and B. Chen (2005), The evolution of precipitable water associated with the Asian and Australian monsoons as revealed from MODIS/SSMI, ECMWF and NCEP reanalysis data sets, Geophysical Research Letters, 32, doi:10.1029/2005GL022570.

Myers, P.G., S. Josey, B. Wheler and N. Cetin (2005), Interdecadal Variability in Labrador Sea Precipitation Minus Evaporation and Salinity, Progress in Oceanography, submitted

Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vorosmarty, R. B. Lammers, A. I. Shiklomanov, I. A. Shiknomanov, and S. Rahmstorf (2002), Increasing river discharge to the Arctic Ocean, Science, 298, 2171-2173.

Steffen, K., S. V. Nghiem, R. Huff, and G. Neumann (2004), The melt anomaly of 2002 on the Greenland Ice Sheet from active and passive microwave satellite observations, Geophysical Research Letters, 31, L20402, doi10.1029/2004GL020444.

Walsh, J. E., and D. H. Portis (1999), Variations of precipitation and evaporation over the North Atlantic Ocean, 1958-1997, Journal of Geophysical Research, 104, 16,613-16,631.

Recent Warming of the Labrador Sea

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Over the past 16 years (1990-2005), the Ocean Sciences Division of the Bedford Institute of Oceanography (BIO) has conducted annual occupations of a hydrographic section across the Labrador Sea (Figure 1, page 13). These observations, when combined with the U. S. Coast Guard's Ocean Weather Ship (OWS) Bravo time series (1950-1974) and other archived data, document prominent interannual and decadal changes at all depths (Figure 2, page 12).

The largest changes in the stratification and sea water properties, observed between 500 and 2000 m, are associated with production, evolution and dissipation of Labrador Sea Water (LSW), an important intermediate water mass of the North Atlantic. In the Labrador Sea, the core of this water mass was identified by a temperature-salinity or density class occupying the largest volume (Yashayaev et al., 2004). The LSW and the entire central Labrador Sea became warmer and saltier over the 1960s into the early 1970s before transforming to what were then anomalously cold and fresh conditions during the severe winters of 1974 and 1976. This cooling and freshening was short-lived: between 1980 and 1985, the LSW was warmer and saltier than in the mid-1970s, but not as saline as it was between 1963 and 1971.

A series of strong winter convections from 1987/88 to 1993/94 produced a large homogeneous volume of exceptionally cold, fresh and dense LSW reaching ~2300 m. This LSW was colder, fresher, denser and deeper than at any previous deep measurements in the Labrador Sea. From 1960 to 1994, the LSW became 0.08 fresher, 0.9ºC colder, 0.08 kg/m^3 denser; its thickness more than doubled. Extending this analysis to the entire sub-polar gyre of the North Atlantic, we estimated that the average production rate of LSW was about 2 Sv (1Sv=10^{6}m^3/sec) over 25 years between 1960 and 1995 (Yashayaev et al., 2004).

The warm and salty conditions in the 1960s and the early 1970s and the fresh and cold conditions from the late 1980s to the late 1990s represent the two extreme states of LSW over the entire period of reliable observations (since the 1930s).

Since 1994, there has been a substantial decrease in the net annual heat loss from the Labrador Sea to the atmosphere resulting in less intense convective mixing mostly limited to the shallower depths of the LSW. This has meant that the LSW layer formed in 1994 has continued to get warmer, saltier and thinner (Lazier et al., 2002; Yashayaev et al., 2003). The combination of lower heat loss to the atmosphere and continued mixing of heat and salt into the LSW layers (brought by warm and salty boundary flows and LSW recirculation) has caused the upper 1500 metres of the Labrador Sea to become warmer and saltier.

The most recent significant winter convection event occurred in 2000, reached 1600 m and was extensive enough to produce a distinct LSW class still seen in the Labrador and Irminger Seas. The density of this 2000 LSW class was in the lighter range of LSW densities. Its lower density arises because it is warmer and fresher than the LSW formed in 1994. Since 2000, winter convection has failed to alter the density and thus this layer of LSW has also become warmer, saltier and thinner.

These changes of the water mass properties and stratification caused significant variations in the steric height and sea level in the central Labrador Sea (lower plot in Figure 2, page 12, the steric height and sea level anomalies were calculated for the same region). The intense cooling of the early 1990s resulted in a 9 cm drop of steric height in the central Labrador Sea and the subsequent restratification over the past decade raised the steric height to its earlier levels. Since 1992, sea level data have been available from the Topex/Poseidon and Jason satellite missions. The sea level anomalies (SLA) shown in Figure 2 (page 12) were computed from SLA values, which were extracted from the maps of globally gridded SLA (1/3°x1/3°), computed with respect to a seven-year mean. These maps (stored in NetCDF format, one file every 3.5/7 days, from 1992 to 2004, merged missions) were downloaded from: http://www.jason.oceanobs.com/html/donnees/produits/msla_uk.html. Temporal variations of the steric height and sea level agree well and reflect most of the major changes seen in the Labrador Sea hydrography. In 2004, the sea level in the central Labrador Sea was about 7-8 cm higher than in 1994.

The annual occupation of AR7W since 1990, allows us to examine how the various intermediate and deep water masses evolve across the Labrador Basin. In Figure 3 (page 13), the changes in the LSW are examined by averaging the data at each station into an upper layer (200-800 m) and a lower layer (1200-2000 m). Through the early 1990s, both layers have similar temperatures and salinities because the entire depth range is filled with the developing 1994 class of LSW. After 1994, the upper layer shows continued freshening (except near the Greenland coast) as winter convection renews the upper LSW layers while the lower layer documents the decay of the 1994 class of LSW through advection and mixing. The deep LSW (lower panels) has been steadily becoming warmer and saltier since 1994, whereas the warming of the upper layer was interrupted by the cooling of 1999/2000. In 2000, the 200-800 m layer was the freshest in 15 years. These two layers feature two major LSW events since 1990.

The May 2004 survey showed that the upper 1500 metres of the Labrador Sea were the warmest since the beginning of annual occupations of AR7W in 1990 which were conducted under the aegis of the World Ocean Circulation Experiment (WOCE). The most rapid warming of this layer occurred between 2003 and 2004. This warming was not simply a consequence of the warming in the surface and LSW layers. In 2004, a large volume of warm and salty water appeared over the continental slopes on the Greenland and Labrador ends of the section. This water is thought to have come from the Irminger Sea, carried north and west by the Irminger Sea branch of the North Atlantic Current. The upper layer (Figure 3, page 13, upper) shows a rapid increase in temperature and salinity over the whole eastern part of the Labrador Sea between 2003 and 2004. This warm and salty water from the Irminger Sea, seen along the eastern and (in some years) western rims of the Labrador Sea, spread out to the centre of the Labrador Basin in 2004, filling the whole eastern part of the basin between 100 m and 800 m. As a result, temperature and salinity at 700 m in the eastern part of the Labrador Sea increased in a year by 0.6°C and 0.05.

Although the volume of these Irminger Sea waters did not further increase in our most recent occupation (May–June, 2005), the warming trend in the upper 2000 metres over most of the AR7W line did persist. The Labrador Sea is approaching the conditions last seen in the late 1960s. If these trends continue, the Labrador Sea temperatures could soon become the warmest ever recorded.

This 16 year series of annual occupations, first undertaken as a contribution to WOCE and continued as part of the Climate Variability and Prediction (CLIVAR) and the Global Ocean Observing System (GOOS) projects, is a key observation of the interannual variability of the North Atlantic near the high latitude source regions for the North Atlantic merdional overturning circulation. The monitoring of the Labrador Sea is also a key task in the Arctic-Subarctic Ocean Flux (ASOF) action plan aiming "to measure and model the variability of fluxes between the Arctic Ocean and the Atlantic Ocean with the view to implementing a longer-term system of critical measurements needed to understand the high-latitude ocean's steering role in decadal climate variability". Finally, the value of such observations to the understanding of ocean climate lies in the long term sustained nature of the sampling since the variability is significant over years, decades and even longer.

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References

Lazier J, Hendry R, Clarke A, Yashayaev I. and Rhines P, 2002, Convection and Restratification in the Labrador Sea, 1990-2000, Deep-Sea Research I, 49, no.10, P.1819-1835.

Yashayaev, I., Lazier, J.R.N. and Clarke, R.A., 2003, Temperature and Salinity in the Central Labrador Sea, ICES Marine Symposia Series, 219, P.32-39.

I. Yashayaev, M. Bersch, H. van Aken, and A. Clarke, 2004, A New Study of the Production, Spreading and Fate of the Labrador Sea Water in the Subpolar North Atlantic, Arctic/Subarctic Ocean Fluxes Newsletter, Issue No. 2, P.20-23.

Moored Current Measurements and Hydrographic Programs in Flemish Pass and Orphan Basin

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In May of 2005 the CCGS Hudson successfully recovered two moorings from Flemish Pass and five moorings from Orphan Basin on the Eastern Newfoundland Slope, and deployed six moorings in Orphan Basin. The vessel also occupied a CTD section across Orphan Basin and several CTD stations in Flemish Pass, partially repeating sampling conducted in June of 2004. This work was carried out as part of the Canadian Program on Energy Research and Development, and DFO climate and environmental variability programs at the Bedford Institute of Oceanography (BIO), with support from the oil and gas industry. Flemish Pass and Orphan Basin are deep-water areas of oil and gas exploration that lie in the path of subpolar outflows from the Labrador Sea region (Figure 1, page 14).

The Flemish Pass program has involved two current-meter moorings deployed since July 2002 in the upper-slope Labrador Current on the Flemish Cap (47N) line of the DFO Atlantic Zone Monitoring Program (AZMP). With the recovery of its final moorings in May 2005, the program has provided nearly 3 years of continuous observations in the core of the shelf-edge Labrador Current, and the first year-round time series from water depths greater than 500 m in the Pass where previous moorings have been lost due to foreign trawlers or icebergs. The initial estimate of the mean Labrador Current transport from the moorings is about $7^{x}10^{6}$ m^3/s. This is comparable to circulation model diagnosis with the observed upstream barotropic inflow specified. The observations provide the first observational estimate of the Labrador Current's seasonal cycle at this latitude from current meter data. This seasonal cycle has a range of about 3 x 10^6 m^3/s peaking in winter and includes both baroclinic and barotropic components. Analyses of the moored measurements for variability in currents and sea water properties are being carried out in conjunction with analyses of hydrographic and Acoustic Doppler Current Profiler sections from the AZMP, and surface current estimates from altimetry, by colleagues at the Northwest Atlantic Fisheries Centre

The five current-meter moorings (sites A-E, Figure 1, page 14) recovered in Orphan Basin had been deployed in June 2004 in water depths of 1500 to 2500 m across the slope off the northern Grand Bank. They provide the first moored measurements through the water column in this large continental-margin basin where portions of subpolar outflows such as the Labrador Current, the Deep Western Boundary Current (DWBC) and Labrador Sea Water approach the topographic promontory of Flemish Cap. The six new moorings (B-D, F-H) deployed across Orphan Basin provide extended spatial and temporal coverage from the 1900 m to 3300 m isobaths, with recovery planned for the spring of 2006.

Hydrographic sections across Orphan Basin occupied in June of 2004 and in May of 2005 are presented in Figure 2 (page 14). These sections have confirmed the presence of the above-noted outflows, and also revealed significant basin-wide changes in the upper, intermediate, deep and bottom waters. Even though the section was occupied earlier in 2005 than in 2004 (so that colder sea surface conditions were expected), the upper and intermediate waters in 2005 were notably warmer (by more than 1°C), especially in the eastern part of Orphan Basin. While the intermediate waters (Labrador Sea Water) were saltier in 2005 than in 2004, the upper 300 m layer was notably fresher (by 0.3). Between 2004 and 2005 the bottom waters of Orphan Basin became fresher (~0.015) and colder (~0.2°C), especially between 2500 and 3000 m. This bottom water represents the densest limb of the DWBC which enters the North Atlantic across the sills of the Denmark Strait. The first indication of this freshening was observed entering the eastern Labrador Sea in May 2004 so that it has moved around the Labrador Sea to Orphan Basin in less than a year, giving an average current speed (for the DWBC) of ~10cm/s. It is expected that the penetration of this signal through the western North Atlantic will be observed by a coordinated international set of mooring and survey programs extending from the Nordic Seas to the Bahamas as part of the ASOF, Atlantic CLIVAR (Climate Variability) and related programs. This should provide new insights into variability in the North Atlantic's thermohaline overturning circulation and lead to a better understanding of the global ocean's response and contributions to climate change. The Bedford Institute is contributing to this international effort through its annual occupation of the AR7W hydrographic line across the Labrador Sea, the Flemish Pass and Orphan Basin programs, the Davis Strait program (in cooperation with University of Washington), moorings on the Scotian Slope and Rise off Halifax, collaborative analyses and interpretations of North Atlantic variability, and its collaborative North Atlantic circulation modelling program with the Dalhousie Center for Marine Environmental Prediction.

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Spectra of Isotopic Records: Marine Sediments vs Ice Core

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On time scale of 1-100 ka the inflow of the fresh water into the world oceans is closely linked to the process of growth and decay of ice sheets. At the Last Glacial Maximum sea level lowered by 80-165 m and the major input to this decrease can be explained by the accumulation of water in the Northern Hemisphere ice sheets (Clark and Mix, 2000). To first approximation, the global ocean volume variations (or, equivalently, glacio-eustatic component of global sea level) can be correlated with the change of isotopic content of foraminifera in deep-sea sediment cores (Shackelton, 1987).

Driving forces of quasi-periodic intermittence of glacial and inter-glacial conditions during the Pleistocene period are poorly known. They are generally believed to be the consequence of forcing by harmonic variations of solar insolation induced by variations of the orbital parameters of the Earth - eccentricity, obliquity and precession. Though discussion about roots and mechanisms of the millennial climatic variations is beyond the scope of the current research, it should be mentioned that alongside the unconditional acceptance of the astronomic forcing as the only possible driving mechanism of glacial-interglacial changes, certain researchers suggest alternative views on climate change mechanisms (e.g. Wunsch, 2000, 2004; Dobrovolski, 2000; Ashkenazy et al., 2005).

Together with marine sediments, ice cores serve as a good proxy for the climatic variations of the past. The physical mechanisms which separate oxygen and hydrogen isotopes in the precipitation over ice sheets are different compared to those for oceanic proxies, and depend mainly on variations of the air temperature on the upper boundary of the inversion layer. Since both types of isotopic records (marine and ice) ultimately depend on the common factor – variations of climatic conditions – a comparison of spectral properties of these records and estimation of cross-spectral parameters are of great interest. At present day, the longest ice core record is one obtained at Dome Concordia (Dome C) station in East Antarctica (EPICA community members, 2004). The ice core δD record, below referred to as DC, is thus compared with four $\delta^{18}O$ records from marine sediments. All records are briefly described at Table 1.

As a method of analysis the Maxim Entropy Method (MEM) of scalar and vector series was used. Basic computational algorithms are described by Privalsky and Jensen (1995).

Preliminary, DC and S704 we re-sampled at even time intervals. All records were averaged in a "hopping" manner over 4-ka periods to dump high-frequency variability and to reduce the optimum order of the relevant autoregressive (AR) models. Statistically meaningful linear trends were extracted.

Spectra of records and their 90% confidence limits are shown in Figure 1. Since energy of oscillations decreases exponentially it is more convenient to consider spectral densities in logarithmic coordinates. The spectral resolution (number of spectral peaks) depends mostly on the AR model provided the true spectral density has these peaks. S704 does not exhibit any statistically meaningful peak at all. The other four spectra have meaningful peaks at the period 100 ka (89 ka in case of B94), which could be associated with variations in eccentricity. Additionally, B94 and SPECMAP have significant peaks at 23.5 ka associated with the precession variations. Peaks at 40-42 ka (obliquity) are not statistically significant. Apparently, 90% confidence levels are to some extent arbitrary values. Sometimes, the absence of a peak in a spectral curve means "absence at the certain level of confidence". In the case of S704 the absence of peaks is explained by

Name of the record	Reference	Type of data	Time span, ka BP	Linear trend over the whole record	Optimum ARM order	First-order AR coefficient
B94	Bassinot et al., 1994	Planktic $\delta^{18}O$	890 - 6	-	20	0.859
SPECMAP	Imbrie et al., 1984	Planktic $\delta^{18}O$	782 - 0	0.448	16	0.877
S704	Hodell et al., 2000	Planktic $\delta^{18}O$	663 - 0	0.264	4	0.823
K2002	Karner et al., 2002	Benthic $\delta^{18}O$	861 - 5	0.177	11	0.919
DC	EPICA community members, 2004	Ice core δD	739 - 0	-	13	0.827

Table 1. Description of the analysed records.

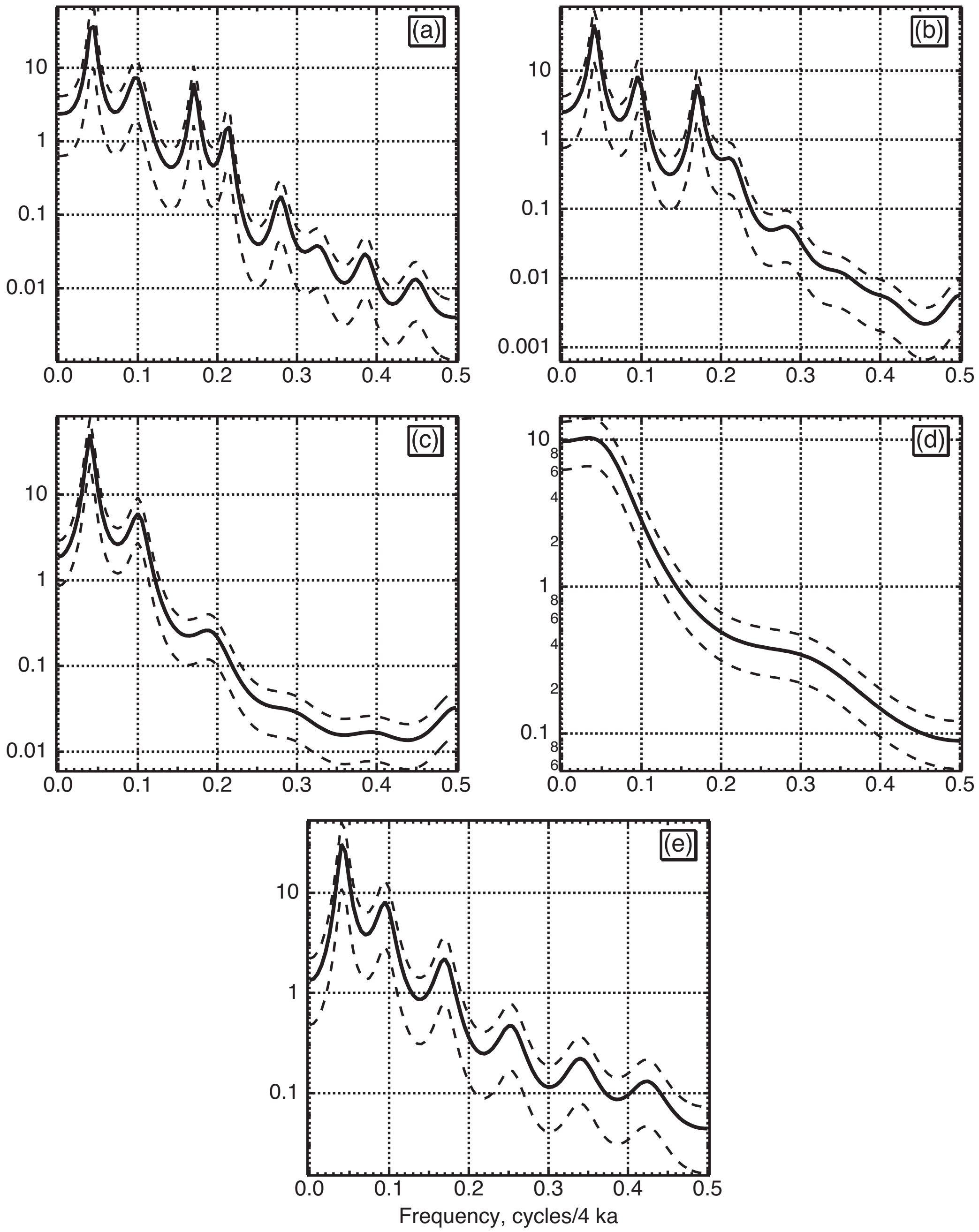

Figure 1. Spectral densities (solid lines) of marine sediment records B94 (a), SPECMAP (b), K2002 (c), S704 (d), and of the ice-core record DC (e). 90% confidence limits are shown by dashed lines. Vertical axis is scaled logarithmically.

the structure of the series.

It is clearly seen that the precession input in B94 and SPECMAP is higher than in DC. Compared to these three series K2002 seems not sensitive to precession variability. Spectral densities characterise records "in average". In other words the evolutionary patterns, which probably exist in the records, are not defined. The basic complication in the interpretation spectra of the proxy data is the construction of a chronological scale for an isotopic record. Explicitly or implicitly, the Milankovitch cyclicity is used as the a priori assumption, though to a different extent in the tuning of particular records. That is why the evaluation the role of Milankovitch forcing on climate dynamic is very difficult (Ashkenazy et al. 2005).

Cross-spectral characteristics were described in terms of coherences, gain factors and phase factors and corresponding time lags of linear models, where DC was used as an input and B94, SPECMAP and K2002 as outputs. Coherences (see Figure 2) are rather high (0.75-0.91) at an eccentricity period. In the obliquity band (40 ka) coherence is still considerable. For the rest frequency intervals oceanic series behave in different ways. K2002 and S704 are not at all linearly correlated with DC, B94 and SPECMAP are still correlated at the precession band (23.5 ka) but at a somewhat lower limit. The lower confidence limit of coherence at high frequencies (below 12.5 ka for B94, and lower for other

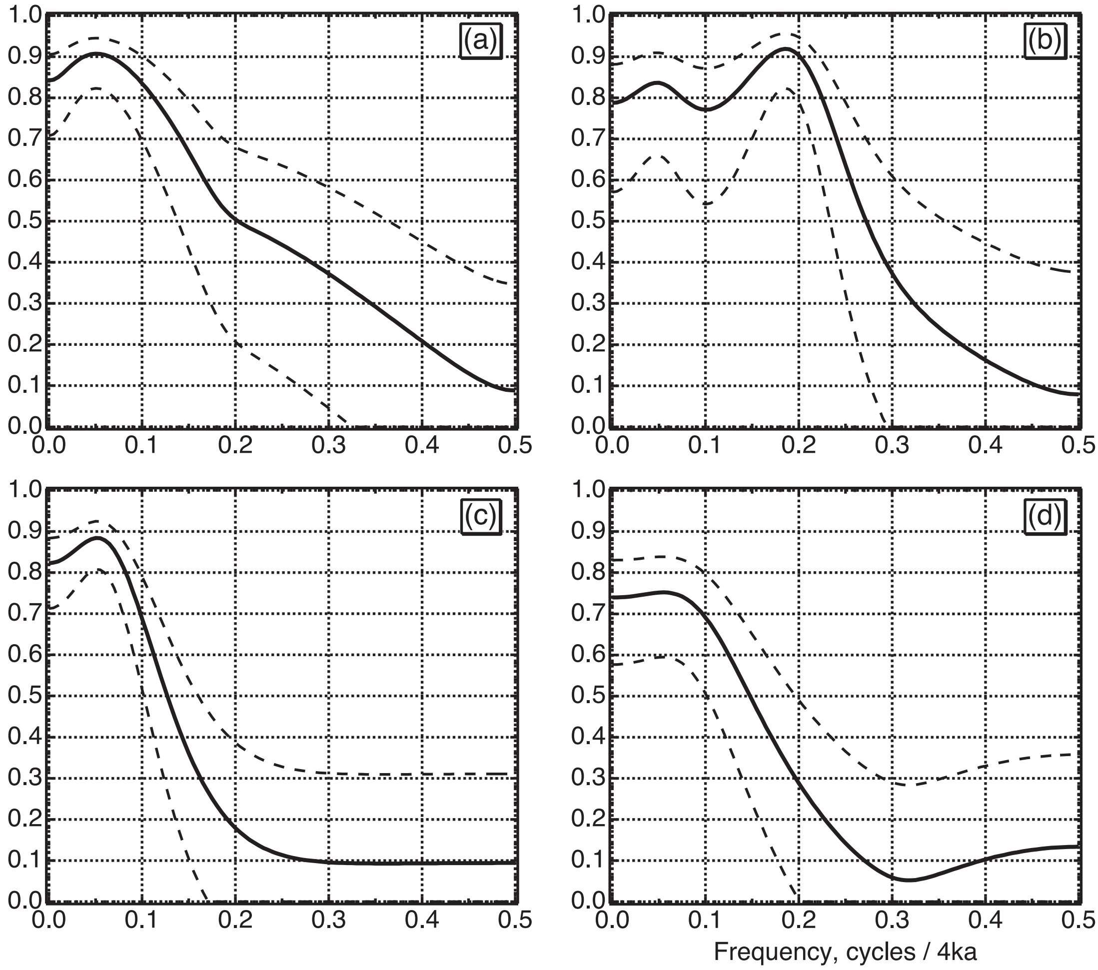

Figure 2. Coherencies (solid lines) and their 90% confidence limits (dashed lines). Inputs: B94 (a), SPECMAP (b), K2002 (c), S704 (d); DC as output.

series) is zero. It may mean that higher coherence at low frequencies is due to the tuning procedure, though in all five cases it was done in different ways.

Marine records composed from isotopes of benthic (K2002) and planktic (B94 and SPECMAP) origin differ in respect of their phasing with the ice-core isotope record (DC). Similarly (from the point of view of the spectral structure) B94 and SPECMAP lag from changes in DC, but this lag reduces with growth of frequency. The lag of K2002 is much smaller at lower frequencies and remains almost constant in the whole frequency band. Additional cross-spectral analysis of B94 vs K2002 shows that the first lags from the second in respect to the change of isotopic composition.

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References

Ashkenazy, Y., Baker, D.R., Gildor, H., 2005: Simple stochastic models for glacial dynamics. Journal of Geophysical. Research, 110, C02005, doi:10.1029/2004JC002548.

Bassinot, F.C., Labeyerie, L.D., Vincent, E., Quidelleur, X., Shakelton, N.J., Lancelot, Y., 1994: The astronomical theory of climate and the age of the Bruhnes-Matuyama magnetic reversal. Earth and Planetary Science Letters, 126, 91-108.

Clark, P.U., Mix, A.C., 2000: Ice sheets by volume. Nature, 406, 689-690.

Dobrovolski, S.G., 2000: Stochastic Climate Theory. Models and Applications, Spinger-Verlag: Berlin, 282 p.

EPICA community members, 2004: Eight glacial cycles from an Antarctic ice core. Nature, 429, 623-628.

Hodell, D.A., Charles, C.D., Ninnemann, U.S., 2000: Comparison of interglacial stagesin the South Atlantic sector of the southern ocean for the past 450 kyr: implifications for Marine Isotope Stage (MIS) 11. Global and Planetary Change, 24, 7-26.

Imbrie, J.Z., Hays, J.D., Martinson, D.G., MacIntyre, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L., Shackelton, N.J., 1984: The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}O$ record. In: Berger, A., Imbrie, J.Z., Hays, J.D., Kukla, G., Saltzman, B. (Eds.), Milankovitch and Climate (pp 269-305), Dordrecht: D. Reidel.

Karner, D.B., Levine, J., Mederios, B.P., Muller, A., 2002: Constructing a stacked benthic δ^{18}O record, Paleoceanography, 17, doi: 10.1029/2001PA000667.

Privalsky, V.E., Jensen, D.T., 1995: Assessment of the influence of ENSO on annual global air temperatures. Dynamics of Atmospheres and Oceans, 22, 161-178.

Shackelton, N.J., 1987: Oxygen Isotopes, Ice Volume and Sea Level. Quaternary Science Reviews, 6, 183-190.

Wunsch, C., 2003: The spectral description of climate change including the 100 ky energy. Climate Dynamics, 20, 353-363.

Wunsch, C., 2004: Quantiative estimate of the Milankovitch-forced contribution to observed Quaternary climate change. Quaternary Science Reviews, 23, 1001-1012.

Calendar

2006

28 June -1 July	ASOF Open Science Conference	Torshavn FAROE IS.
9 - 11 May	13th International Symposium on Polar Sciences	Seoul KOREA
2 - 7 April	EGU General Assembly 2006	Vienna, AUSTRIA
16 -18 March	36th Annual Arctic Workshop	Boulder, USA
27 February- 1 March	Workshop on Arctic Navigation and Communications for High-Latitude Ocean Research	Seattle USA

2007

29 - 31 August	Polar Dynamics: Monitoring, Understanding and Prediction	Bergen NORWAY

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