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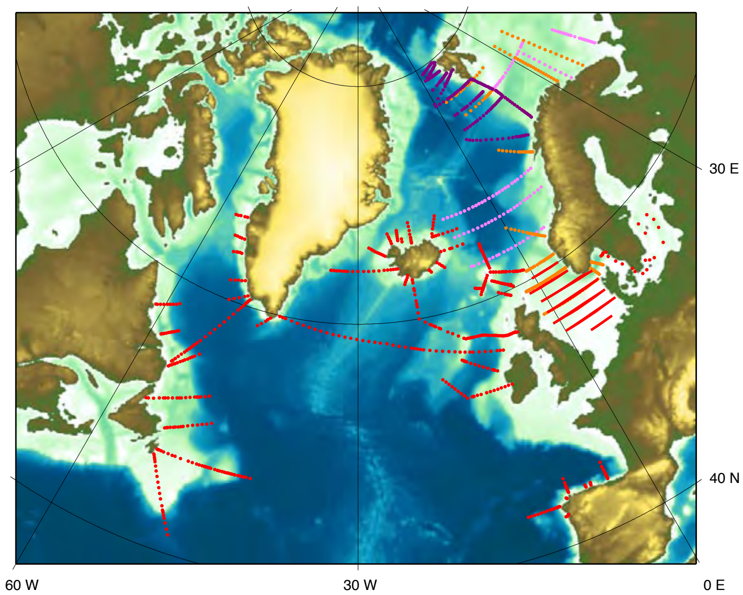
The Oceanography of the North Atlantic and adjacent Seas



I.C.E.S.

The International Council for the Exploration of the Sea

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ICES CIEM

CLIVAR is an international research programme dealing with climate variability and predictability on time-scales from months to centuries.

WCRP
World Climate Research Programme

CLIVAR is a component of the World Climate Research Programme (WCRP). WCRP is sponsored by the World Meteorological Organization, the International Council for Science and the Intergovernmental Oceanographic Commission of UNESCO.

Editorial

I am grateful to Penny Holliday and Sheldon Bacon for acting as guest editors for this edition of Exchanges which, as you will see, is joint with ICES. Penny and Sheldon provide some background to ICES in a short article on page 2 as an introduction to the articles which follow. In addition to the ICES articles, we also include accounts of the recent meetings of CLIVAR's Southern Ocean Region and Global Synthesis and Observation Panels and of the joint CLIVAR/CCl/JCOMM Expert Team on Climate Change Detection and Indices. The start of 2007 has seen some important changes for CLIVAR. Tony Busalacchi has now stepped down as co-chair after 4 years in that position and some 10 years as a member of the CLIVAR SSG overall. We are indeed most grateful to Tony for all the guidance he has provided for CLIVAR over the years. I am pleased to note that he now joins the Joint Scientific Committee for WCRP, so we will continue to have the benefit of his inputs to CLIVAR, if in a different guise. Thanks again, Tony. Welcome now to Jim Hurrell who has now joined Tim Palmer as SSG co-chair. Jim, whose work will be well known to many, is the Director of the Climate and Global Dynamics Division at NCAR, USA, and a Senior Scientist within the Climate Analysis Section. His research interests include climate variability and anthropogenic climate change and he has contributed to the Intergovernmental Panel on Climate Change (IPCC) assessments. I'm sure that all of us associated with CLIVAR look forward to working with Jim over the coming years. Finally I would also like to welcome a new staff member to the ICPO, Anna Pirani, whose background is in ocean modeling. Anna, who started with us in the New Year, will provide support to CLIVAR's modeling working groups and to the CLIVAR/PAGES intersection. We are indeed very pleased to have her on board as a member of the ICPO staff.

Howard Cattle

A word from the guest editors

N. Penny Holliday and Sheldon Bacon
Corresponding authors: nph@noc.soton.ac.uk, shb@noc.soton.ac.uk

The International Council for the Exploration of the Sea (ICES) was established in 1902 to "promote and encourage research ... for the study of the sea, particularly the living resources thereof", with a focus on the North Atlantic and adjacent seas. It is a regional, intergovernmental organisation, and it provides advice to governments and other bodies on such matters as fisheries and pollution.

The physics of ocean circulation and the long-term variability in ocean climate has always been important to ICES, and this issue of Exchanges focuses on the work by members of the ICES Working Group on Oceanic Hydrography (WGOH). The Group meets once a year to discuss the most recent observations of the deep ocean and adjacent deep and shallow basins: the North Atlantic and Nordic (Greenland, Iceland and Norwegian) Seas, and the Labrador, Barents, Baltic and North Seas. Typically data are presented that are only months or even weeks old, making this an excellent forum for understanding the present physical state of the ocean. Each new data set is presented in the context of long term observations – some records go back as far as 100 years. With data spread across the region, the WGOH is also in a good position to understand the basin-scale processes that link individual time series.

The members of the WGOH are research and fisheries scientists dedicated to making high quality measurements and using them to understand how the ocean works; given the area in which we work, we have particularly close links with the North Atlantic Fisheries Organisation (NAFO), with which we share data. The articles in this Newsletter provide a selection of the current research being undertaken by members. They cover a wide range of topics from surface processes to deep overflows, across the North Atlantic from the western deep ocean basins to the wide eastern shelf seas. The focus is on interannual to decadal variability and the mechanisms that determine properties and transports.

Each year the WGOH produces a summary of their results in the ICES Report on Ocean Climate (IROC, formerly known as the ICES Annual Ocean Climate Status Summary). The IROC is presently published as an ICES Cooperative Research Report and fulfils the ICES remit of the group, that is to provide information about physical conditions in the North Atlantic that can be used in fisheries management advice. But more than that, the report is packed full of information of interest to climate scientists and oceanographers.

Some useful websites:
For further information about the WGOH, including links to the IROC2005 (Hughes and Holliday, 2006) are at http://www.noc.soton.ac.uk/ooc/ICES_WGOH/index.php

The ICES general website: http://www.ices.dk/

For information about NAFO: http://www.nafo.int/

Isopycnal analysis of near-surface waters in the Norwegian-Barents Sea Region

Tom Rossby[1], Vladimir Ozhigin[2], Victor Ivshin[2], and Sheldon Bacon[3].
[1]Graduate School of Oceanography, URI, USA,
[2]Knipovich Polar Research Institute of Fisheries and Oceanography (PINRO), Murmansk, Russia,
[3]National Oceanography Centre, Southampton, UK.
Corresponding author: trossby@gso.uri.edu

Introduction

No ocean region has been studied for as long or as thoroughly as the Nordic Seas. Already in 1887, Mohn published a chart of the circulation of the Norwegian Sea clearly indicating the inflow of warm North Atlantic waters on the eastern side and flow south of Arctic waters in the west. This was followed by the groundbreaking Helland-Hansen and Nansen (1909) study of the hydrography of these northern waters. Using water mass analysis (reversing thermometers and accurate salinity titrations) and the dynamic method, their circulation patterns have stood the test of time impressively well. Even today their figure of salinity in the southern Norwegian Sea and across the Iceland-Faroe Ridge stands out as an extraordinarily prescient synthesis of circulation in the region. A striking aspect of Helland-Hansen and Nansen (1909) was their emphasis on the horizontal structure of the density field. They could do this thanks to the systematic hydrographic surveys throughout the Nordic Seas. For an up-to-date overview, see Blindheim and Østerhus (2005).

Many hydrographic surveys have been conducted throughout the region. Some focused on the hydrographic properties and how these vary spatially and temporally, but perhaps the majority of the surveys have taken place as part of fish stock assessment studies in particular areas such as around the Iceland-Faroe Ridge, the Lofoten region and throughout the Barents Sea. While these surveys concentrate on the upper ocean with limited coverage of deeper waters, they constitute an enormous resource for examining the mean fields of the upper ocean and how they vary with time.

In this note we report on our work to use isopycnal analysis to more clearly separate out dynamical variations from changes in T/S-properties along isopycnal surfaces. We routinely use T/S analysis to characterize water masses in various basins, but with a large enough database, one can look at the characteristics of isopycnal surfaces directly, their depths and physical properties. This way one retains the full spatial context in which any change is taking place. For example, a change in depth of an isopycnal implies a change in the density and hence pressure field, a change of dynamical consequence, whereas a change in temperature/salinity make-up (or "spiciness") on an isopycnal implies a change in water characteristics. The latter does not impact the pressure field although it contains much information regarding the prior history of the waters. We have been using this large database to explore how the Nordic Seas vary over time. This involves first constructing the mean structure of the upper ocean on and along isopycnal surfaces which then serve as the framework for a closer analysis of dynamical variations on the one hand and property changes on the other. In this brief report we focus on the mean properties of the specific volume anomaly (δ) surface = 2.1x10^{-7} m^{3}kg^{-1}.

The approach taken here is to first construct the mean hydrographic state of the upper ocean. The resulting climatologies of these upper ocean density surfaces provide a wealth of information about the basic state of the Nordic

Seas. For example, as one proceeds north, surface waters lose heat such that the lighter isopycnals disappear and underlying isopycnals shoal and eventually outcrop. We can see more clearly where and how this shoaling takes place. Next, these mean fields can be subdivided to look at seasonal variations. Finally, one can use the climatologies to examine how the Nordic Seas vary spatially from year-to-year, but now considering separately changes due to depth variability and changes in spiciness.

Data preparation

The data used here combine data (1946-2004) in the ICES archives and Russian data at PINRO in Murmansk, Russia. The database comprises some 268,000 stations throughout the Nordic Seas from the Iceland-Faroe Ridge in the southwest to the Barents Sea in the northeast. These stations are used to calculate depth, temperature and salinity of various specific volume anomaly surfaces, in this case the $\delta = 2.1 \times 10^{-7}$ m^{3}kg^{-1} surface. Given pairs of temperature and salinity (T and S), delta values were calculated for each measurement depth for each hydrographic station. Density inversions were checked for each hydrographic station. Stations with a density decrease (inversion) of more than 0.005 kg/m^3/m were eliminated (deleted). Further quality checks are planned.

For each month for the 1946-2004 period, Z, T and S values for the corresponding isopycnals were interpolated into grid nodes. Grid spacing was 30' along parallels (30°W to 30°E) and 15' along meridians (50°N to 80°N). The surface mapping system SURFER 8.01 (Golden Software, Inc) was used with the Triangulation with Linear Interpolation method applied for gridding Z, T and S. This method is an exact interpolator (honors data points exactly when the point coincides with the grid node, meaning a coincident point carries a weight of 1.0). It creates a good representation of moderate-sized data sets (250-1000 observations) and does not extrapolate values beyond the range of data. The result of this stage is a set of more than 6 000 contour maps (12 months, 59 years, 3 parameters, 3 isopycnals). These surfaces can be manipulated in various ways, such as to obtain the annual cycle, the summer month means, the overall mean, interannual variations, etc. Here we focus on the mean summer field.

Summer (July – September) mean state

Figure 1 (page 15) comprises four panels: depth, temperature, salinity and Montgomery potential for the $\delta = 2.1 \times 10^{-7}$ m^{3}kg^{-1} surface (corresponding to σt = 27.9) which is the shallowest surface that exists all year in both the Norwegian and Greenland Seas (see Figure 2 for the location of principle basins and topographic features mentionined in the text). (Depending upon the particular conditions in winter this surface may on occasion outcrop in the Greenland Sea, i.e. for a small subset stations $\delta = 2.1 \times 10^{-7}$ does not exist in winter.) The depth of the isopycnal shows clearly the baroclinic inflow from the Iceland-Faroe Front north of the Faroe Islands, turning rather sharply to the north and away from the Norwegian coast towards the western Lofoten Basin where the isopleths turn almost east and northeast and then curving north towards the Fram Strait. This would be the pathway of North Atlantic waters that have entered the Nordic Seas between Iceland and the Faroes. This pattern accords well with the sketch of the North Atlantic inflows in Orvik (2004).

The great depth of this surface in the Lofoten Basin, about 600m, compared to anywhere else in the Nordic Seas is very curious. What forces this deepening, and why is it so localized? Why does it extend north as a narrow trough along the Barents Sea escarpment? That these features stand out so clearly even in a half-century long climatology is noteworthy. (They show

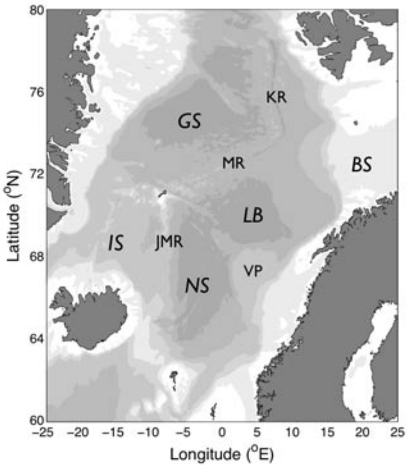

Figure 2. Bathymetry of the Nordic Seas. The italic letters refer to the principal basins: Norwegian Sea, Iceland Sea, Lofoten Basin, Greenland Sea and Barents Sea. The smaller letters refer to the major topographic features: Vøring Plateau, Jan Mayen Ridge, Mohn Ridge and Knipovich Ridge. Depth contours at land, 200, 500, 1000, 2000, 3000 m.

up clearly in the other three seasons too.) This deepening can't be wind-driven, as the windstress curl is positive, and in any event the scale of the feature is far smaller than that of the wind system. The deepest spot is clearly centered in the Lofoten Basin. In another article in this issue of CLIVAR Exchanges (Mork et al. page 4) the deep circulation in the Lofoten Basin is shown from the tracks of several Argo floats at 1500 m depth to be strikingly cyclonic. This is really quite remarkable: a cyclonic wind system, a deep cyclonic circulation, yet a well-defined anticyclonically-structured density field. The tilt of this surface is most sharply defined in the north by the Mohn Ridge, so one possibility might be that the deepening results from a vertically-sheared or baroclinic flow along the topography there. The Mongomery potential (lower right panel) represents the baroclinic streamfunction on this density surface relative to 1000 dbars. It provides a measure of the strength of the circulation and velocity field on this surface. The ~0.08 dyn. m. difference across the flow along the ridge, divided by a width of 100 km say, implies geostrophic speeds of about 0.08 ms^{-1}, a number comparable to the Argo drifter velocities at 1500 m depth, but in the opposite direction. This suggests near cancellation between the two such that the surface flows along the ridge might change sign in response to year-to-year variations in strength and distribution of the winds.

The panels of temperature (top right) and salinity (lower left) show clearly the warm salty waters of the North Atlantic on the eastern side and the cold fresh waters from the Arctic in the Greenland and Iceland Seas. We further see a very sharp gradient in "spiciness" along the Jan Mayen, Mohn and Knipovich Ridges (the topography is not shown). This is a very fundamental result: these ridges, although much deeper, serve as dynamical barriers to mixing between these two major water masses from the North Atlantic and Arctic, respectively. Without this 'topographic impedance', the fresh waters from the Arctic could reduce the salinity of the North Atlantic waters to the point that they might not sink in wintertime and produce the dense waters that spill back out into the Atlantic and beyond.

It is interesting to note that the high gradients of spiciness do not coincide with gradients in depth ("baroclinicity"). The latter indicates a velocity shear, whereas the former indicates a transition from one water mass type to another. A property gradient may imply a lack of mixing or exchange of waters. The fact that the two do not generally coincide anywhere other than over the Mohn Ridge suggests that different physical mechanisms are controlling the density (flow) and spiciness (mixing) fields. This 'misalignment' becomes even more striking on shallower surfaces where the baroclinicity moves closer to Norway over the Vøring Plateau yet the property gradient remains firmly locked to the ridges.

An interesting feature to emerge from these analyses is the field of warm salty water in the Lofoten Basin west of northern Norway. As near as we can tell these spicy waters have not been advected into the region, but appear to result from the loss of heat and 'densification' of the salty surface waters. As these waters sink to a deeper isopycnal, they are saltier than the pre-existing waters on the deeper surfaces, and thus appear as warm salty water. The actual mechanism by which this vertical flux might take place needs much more study, but one possibility appears to be through saltfingering (Pereskokov, 1999). In the light of this, we checked over 100 CTD profiles for the characteristic step-structure often associated with saltfingering, but without luck. The magnitude of the anomaly is not large, perhaps 1°C and 0.1 PSU respectively. This may help explain why these spicy waters have not received much attention.

Summary

The isopycnal analyses shown here seek to distinguish between dynamical change as measured by changes in depth *of* and property change due to T/S variations *on* an isopycnal. In conventional x-y-depth displays it can be difficult to distinguish between the two due to the basic stratification of the water column. This is, of course, well known, but the large volume of stations in the Nordic Seas allows one to explore the spatial structure of the density field in considerable detail, both spatially and temporally. In this note we have focused on one density surface for the summer season for which the data coverage is best. (The mean fields for the other three seasons are very similar.) A central result is that the mean fields of depth and property have distinct and different patterns. We find that the mid-ocean ridges serve as a dynamical (in the sense that the ridges are much deeper but are felt throughout the entire water column) barrier to interbasin exchange. We also found that dynamical fronts need not and often do not coincide with property fronts. This 'mis-alignment' may not be so obvious when we examine fields as a function of depth because what looks like a large property change across a front, may actually result from water of the same property appearing at different depths.

Once the basic state has been determined, it can serve very effectively as a basis for exploring anomalies and their behavior in the Nordic Seas. This is where the large database will be very useful. We have already noticed striking interannual variations in depth of the isopycnals in the Nordic Seas, almost certainly due to varying winds. We envisage that these analyses will be useful for studies of ocean response due to changing windstress curl patterns (Jonsson, 1991) and ocean-atmosphere heat exchanges. But it also seems likely that these fields, or reanalyses to borrow a phrase from meteorology, may prove useful for testing and verifying numerical models and simulations of the Nordic Seas circulation.

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A Lagrangian study of pathways from surface and subsurface drifters in the northern North Atlantic

Kjell Arne Mork[1], Mark Prater[2], Tom Rossby[2], Hedinn Valdimarsson[3]
[1] Institute of Marine Research and Bjerknes Centre for Climate Research, Norway
[2] University of Rhode Island, USA
[3] Marine Research Institute, Reykjavik, Iceland
Corresponding author: kjell.arne.mork@imr.no

Introduction

The Nordic Seas are a region that has been well covered and continuously monitored with hydrographic observations. However there have been relatively few direct current measurements in the open ocean, and the view of the large-scale ocean circulation in the Nordic Seas has therefore traditionally been based on hydrography. The large-scale ocean circulation within the Nordic Seas has been known for a century to be influenced by the ocean basins. Helland-Hansen and Nansen (1909) observed that even the surface flow in the Nordic Seas follows topographic features. However, the large number of surface drifters released during the last 10-15 years have increased our knowledge of the surface circulation in the Nordic Seas (Orvik and Niiler, 2002). Recently, several projects have been initiated that have used surface and subsurface drifters in the Nordic Seas. In this note we will show some examples of new results from these projects. The focus will be on trajectories from a selection of drifters used in three different projects. Trajectories give us essential information on how fluid parcels move. Whereas hydrography gives us information of the hydrographic condition it is difficult to identify the mechanisms or dynamics responsible for the observed distributions because of the uncertainty between advection and diffusion. Floats give us the ability to distinguish between these over a very wide range of space and time scales. They also permit a detailed examination of the role of topography in constraining flow. The trajectories that are presented in this note originate from the use of three different types of drifters: surface drifters, subsurface RAFOS floats (drift at 200 m depth) and subsurface Argo floats (parking depth at 1500 m).

Surface Drifters

As part of the World Ocean Circulation Experiment Surface Velocity Programme the Marine Research Institute in Iceland deployed, in co-operation with Scripps Institution of Oceanography, 120 drifters in the years 1995 to 1998. These drifters were deployed repeatedly at the same locations during these years, filled in a gap in drifter observations in the global coverage at that time (Valdimarsson and Malmberg, 1999) and gave valuable information on the surface currents of the North Atlantic (Fratantoni, 2001; Orvik and Niiler, 2002; Jakobsen et al., 2003; Reverdin et al., 2003). As the data have mostly been studied in a statistical way it can be interesting to look at repeated deployments and the variability of the surface drift. In late August and early September 1995 there were 5 drifters deployed south of Iceland. The drift and deployment locations are shown in Figure 1. The five buoys drifted to the west and crossed the Reykjanes Ridge, a pattern not typical for all deployments during the three years. Two crossed over to Greenland in the Denmark Strait and three drifters made it into the waters north of Iceland. One stranded while the other two took on a long journey and came to the Iceland-Faroe Ridge from the north and continued through the Norwegian Sea north to Svalbard (Malmberg and Valdimarsson, 1999). Five drifters deployed in August 1996 revealed a rather different and "more common" drift (Figure 2) than was observed the year before. The three easternmost drifters went on to the Iceland-Faroe Ridge and continued over to the Norwegian Sea and one even to the Barents Sea. The westernmost drifter travelled north along the shelf break west of Iceland while the other drifter drifted close to shore after being brought eastward in the start of its drift. These two deployments were strikingly dissimilar and the reason is not clear. A contributing factor could have been the change in the air pressure field between 1995 and 1996 (reflected in a large decrease in the North Atlantic Oscillation index between these years). The mean air pressure for the last six months of 1995 compared to the same for 1996 (NCEP/NCAR reanalysis, www.cdc.noaa.gov) reveals that the Iceland Low was positioned much farther to the west and south in this period in 1995 than in 1996. This could have contributed to the westward surface flow in 1995.

Subsurface RAFOS floats

In recent years the flow in North Atlantic has quite extensively been studied with RAFOS floats by American, German and French scientists (Bower et al., 2002). In the Nordic Seas French scientists have conducted subsurface float studies in the Greenland Sea (Gascard et al., 2002) and also in the Lofoten Basin the last 3 years (Gascard, pers. com.). Within a project at the University of Rhode Island 60 isobaric RAFOS floats were deployed in 2004 at nominal depths of 200 m in Atlantic water, 30 east of Iceland and 30 more west of the Faroe Islands. In a collaborative work, using the same sound sources, 30 RAFOS floats were also deployed in Arctic water at 800 m depth just north of the Iceland-Faroe Ridge (Søiland, pers. com.). Here we focus on the trajectories of two RAFOS floats that were deployed at 200 m depth in November 2004, see Figure 3 (over page). The dotted segments indicate difficulties with the acoustic tracking environment especially over the ridge between Iceland and the Faroes. One float passed north of the Faroes, the other probably passed just south of the Faroes, very likely in shallow waters as it couldn't be tracked. Although the starting and ending positions of the two floats are almost identical, the pathways through the Norwegian Sea are dramatically different, and show two predominant circulation patterns: a near shore path that crosses the Vøring Plateau and continues northward along the Norwegian shelf, and a path that follows the ridge system and continues northward along Mohn Ridge.

Subsurface Argo floats

The goal of the international Argo programme (www.argo.ucsd.edu) is to have 3000 operative autonomous floats that collect temperature, salinity and current in the World Ocean. An Argo float drifts with the deep currents at a chosen parking depth and every ten days it takes a CTD-profile when it ascends to the surface. At the surface, data and positions are sent to land before the floats descend back to the parking depth. Within the Argo programme the Institute of Marine Research has deployed eleven Argo floats in the Norwegian Sea. The first floats were deployed in 2002 while the two last floats were deployed in March/April 2006. The latter two floats, which also include oxygen (Aanderaa optode), fluorescence and turbidity sensors, have a parking depth at 1200 m depth while the others have a parking depth at 1500 m depth. A depth at 1200 m or 1500 m is in the Norwegian Sea Deep Water, below the Arctic Intermediate Water, with potential temperature less than –0.5 ^{o}C and salinity near 34.91. In addition, the University of Hamburg has the last two years deployed 20 Argo floats that drift at 1000 m depth in the Nordic Seas. At present there are now 26 active Argo floats in the Nordic Seas drifting at 1000-1500 m depth. Trajectories of two Argo floats that drift at 1500 m depth in the Norwegian Sea are shown in Figure 4 (over page). Both floats were deployed in the Norwegian Basin but the northeastern float drifted directly into the Lofoten Basin. Both floats show strong influence by the topography even at small scales. The float that stayed in the Norwegian Basin drifted the first four months southward before it was trapped by a narrow (only 20-30 km wide) channel, with bottom depths greater than 3500 m, which it followed to the northeast . After it passed near the deployment location of the other Argo float it drifted cyclonically around the Basin and ended in the southern Norwegian Sea. This float drifted for about 3.5 years. Calculating the speed of the drift between two neighbouring positions gives an averaged speed of 3.1 cm/s for this float when using all positions. The Argo float that drifted into the Lofoten Basin shows clearly the cyclonic circulation in the Lofoten Basin. It circulated cyclonically two and half times around the Lofoten Basin before it ended at the Mohns Ridge. This float drifted for nearly 3 years and took about one year to make one cycle around the Basin. The averaged speed for this float was 6.7 cm/s.

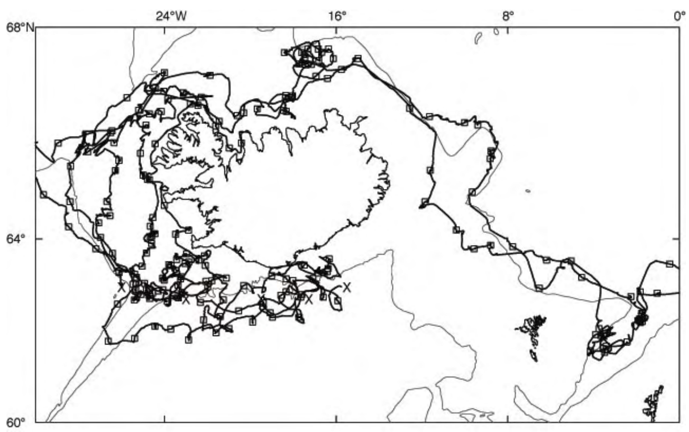

Figure 1. Drifter tracks from August 1995 deployments. Marks on track for every 30 days. Depth contour shown for 1000 m

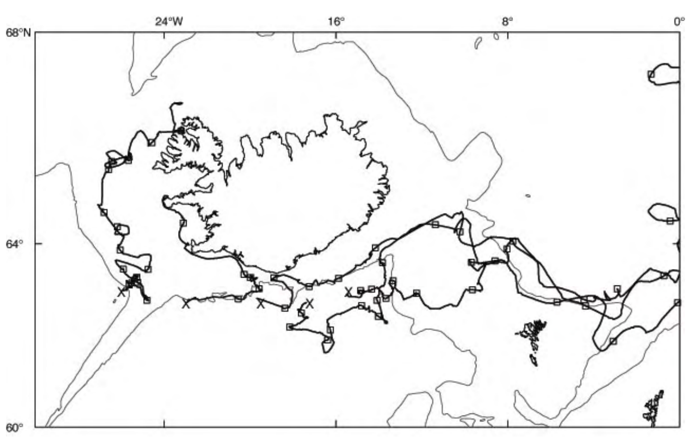

Figure 2. Drifter tracks from August 1996 deployments. Marks on track for every 30 days. Depth contour shown for 1000 m.

Summary

This analysis shows results from three different types of drifters: the surface drifters, the subsurface RAFOS floats, and the subsurface Argo floats. Each type of drifter reveals several different pathways. The pathways can be remarkably different even when they start from (or are at) the same location. This can be observed for all the different types of drifters. That the flow in the Nordic Seas is strongly influenced by the topography can be seen in all figures. The RAFOS floats reveal the two branches of the Norwegian Atlantic Current that has been observed from surface drifters (Orvik and Niiler, 2002). In the deep ocean the large-scale circulation is cyclonic for both the Norwegian and Lofoten Basins. However, near the Mohn Ridge, between the Greenland Sea and the Lofoten Basin, the direction in deeper layers is opposite to the subsurface RAFOS float at 200 m depth (compare Figs. 3 and 4) and also to what Orvik and Niiler (2002) found. This study shows only results from a few drifters and much more work can be done when including all the drifters for the different types.

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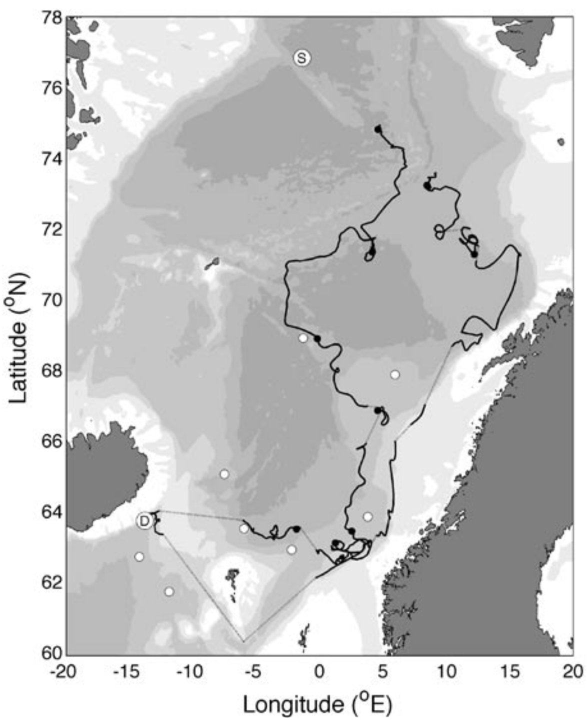

Figure 3. Trajectories of two isobaric RAFOS floats at nominal depths of 200 m. Both floats were deployed by Dr. Hedinn Valdimarsson east of Iceland in November 2004 (marked by the "D"), and surfaced 25 km apart 17 months later between Spitsbergen and Greenland (marked by the "S"). Bathymetry shades change at 3000, 2000, 1000, 500, and 200 m. The open white circles denote positions of the sound sources. Large dots along the trajectories are at 60-day intervals. The dotted segments indicate difficulties with the acoustic tracking environment.

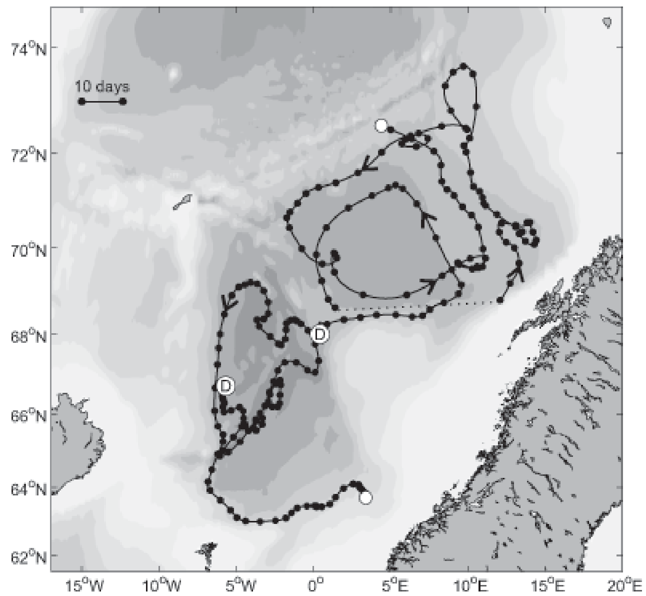

Figure 4. Trajectories of two Argo floats that drifted at 1500 m depth. The most southern float was deployed in June 2002 and last registered position was in November 2005. The most northern float was deployed in August 2003 and last registered position was in June 2006. Location of deployment is marked by "D". A white dot indicates last position. Bathymetry shades change at every 500 m. Dots along trajectories indicate surfacing of the float. The interval between each surface position is 10 days. Dashed line is missing positions. The 10 days scale in the upper-left corner corresponds to a mean speed of 10 cm/s at that latitude (i.e. 73°N).

Variations of the Atlantic inflow and related heat flux through Fram Strait in the last decade

A. Beszczynska-Möller, U. Schauer, E. Fahrbach
Alfred-Wegener-Institute, Bremerhaven, Germany
Corresponding author: abeszczynska@awi-bremerhaven.de

During the last decade the extraordinary warm Atlantic Water (AW) inflow into norther high lititudes has been reported to progress from the eastern North Atlantic into the Nordic Seas and further towards the Arctic Ocean (Hughes and Holliday, 2006; Holliday et al., this issue). Preceded by the warming in early 1990s, this constitutes a prolonged period of increased heat input to the Arctic Ocean. The earlier warm anomaly was mostly generated inside the Nordic Seas in response to higher air temperatures and reduced heat loss (Furevik, 2001), and to a lesser extent was enhanced by the stronger AW inflow (Karcher et al., 2003). In contrast, the warming over the last decade had its origins in the increased northward advection of subtropical waters related to westward shift of the Subarctic Front and a contraction of the subpolar gyre (Hátún et al., 2005; Bersch et al., in preparation). As a consequence, the anomalously warm and saline waters have been transported by the intensified North Atlantic Current into the Nordic Seas since 1995.

After passing over the Greenland-Scotland Ridge, most of the AW inflow continues as the Norwegian Atlantic Current (NwAC). Orvik and Niiler (2002) showed that NwAC maintains the two-branch structure throughout the Nordic Seas towards Fram Strait with a wide wedge of AW between the main cores. Both branches follow topography, the eastern NwAC branch constitutes a coherent barotropic current along the continental slope west of Norway while the western branch of NwAC flows as a baroclinic, topographically steered jet along the underwater ridges (Orvik, 2004). North of Norway the eastern NwAC branch separates into the stream of AW entering the Barents Sea, and the West Spitsbergen Current (WSC) carrying the warm and saline AW further northward. Hydrographic observations by Walczowski et al. (2005) suggest that due to the form of the sea bed, the northern extension of the western NwAC branch flowing along the Knipovich Ridge converges again with the WSC (namely the northward extension of the eastern NwAC branch) in Fram Strait. But only a part of this joint AW flow continues into the Arctic Ocean, while a significant amount recirculates directly in Fram Strait and returns southward to the Nordic Seas (Schauer et al., 2004).

As the only deep passage, Fram Strait is also the sole conduit conveying warm anomalies from the Northern Atlantic to the Arctic Ocean. Due to subduction and insulation of the AW layer from the surface, its mean temperature, which is in the range of 3-5°C on the way between Norway and Spitsbergen, drops to 2°C in the AW leaving Fram Strait to the Arctic Ocean (Furevik et al., 2002). At the same time the AW water passing through the shallow Barents Sea completely loses its signature due to atmospheric cooling and enters the Arctic Ocean with temperature close to 0°C. In Fram Strait the mean AW volume flux of 1.7 Sv (Beszczynska-Möller et al., in prep) is comparable with the mean AW inflow to the Barents Sea (1.5 Sv ; Ingvaldsen et al., 2004) for AW temperature defined as in the upstream area (T>3°C). If modification of the AW temperature during its passage through Fram Strait is taken into account, the volume flux of AW warmer than 1°C in the WSC increases to 4.4 Sv. Thus the AW inflow through Fram Strait is a main supply of heat to the Arctic Ocean and its variations will modify the temperature of the intermediate layers of the Eurasian Basin.

Since 1997 oceanic fluxes through Fram Strait have been monitored by the array of moorings deployed between 6°30'W and 8°40'E at the latitude 78°50'N. Due to the complex bottom topography the AW flow in the WSC splits into three branches (see Figure 1 over page). The core of the WSC flowing over the upper shelf slope constitutes the AW branch entering the Arctic Ocean north of Svalbard, the offshore WSC branch continues northward along the Yermak Plateau slope and the remaining part of AW recirculates immediately in Fram Strait as the third branch. For the first 3 years of measurements Schauer et al. (2004) reported a strong increase in net heat transport from 16 to 41 TW through Fram Strait due in equal parts to a higher temperature and a stronger flow of AW in the WSC.

Nearly decadal time series of the winter-centered annual means of net volume and heat transports presented in Figure 2 (over page) reveal that the first period of increased heat flux was followed by a decrease in 2000-2003 and the second, even stronger rise occurred between 2003 and 2005 when net heat flux was close to 50 TW, and despite a slight drop in 2006, still remains high. In the WSC (including both the core and offshore branches) the strongest increase of net heat flux reaching maximum of 63 TW was found in the first 3 years when it was accompanied by significantly stronger volume flux. Relatively high values of 50-55 TW, representing a second increase in heat flux after 2003 were observed, despite the decreased volume flux in the WSC in the second half of the observation period. It indicates that independently of the AW transport, the temperature rise was sufficient to create higher heat flux.

Figure 3 (page 15) presents spatial versus temporal changes of the mean temperature (a) and vertically integrated fluxes (b, c) calculated for water warmer than the temperature to which the heat transport was referenced, -0.1°C. Being warmer than the mean temperature of the Arctic outflow, this water indicates the heat supply into the Arctic Ocean. Its small net volume transport, 0.2 Sv to the north (as compared with 2.2 Sv to the south in the colder deep layers) goes together with the net heat flux of 32 TW, while deep colder waters add only 6 TW (mean values for 1997-2006; Beszczynska-Möller et al. in prep). The mean temperature in Figure 3a shows that against the background of the strong seasonal signal, significant warming is observed during periods of increased heat flux. Not only do warm anomalies appear in the WSC core, but most of all, an intensive warming propagates to the west, comprising the WSC offshore branch and recirculation area. AW warmer than 3°C (picture not shown) which earlier seasonally disappeared from Fram Strait during winter months, has been permanently observed since 2003 in the whole WSC and with its thickness more than doubled. Since 2004 such anomalously warm water could also be found during most of the year in the recirculation area.

The vertically integrated volume flux of water with T>-0.1°C (Figure 3b) reveals that the most intense variability is observed in the offshore branch of the WSC and recirculating AW. On an interannual time scale a nearly constant volume flux of 2 Sv in the WSC core is modified by variations of the volume flux in the offshore WSC branch ranging from 4 to 6 Sv. In the recirculation area the net volume transport varies between northward and southward within a range of 2 Sv but is uncorrelated with the volume flux in the offshore WSC branch. The vertically integrated heat flux in Figure 3c presents a similar spatial pattern to the volume flux. An almost uniform

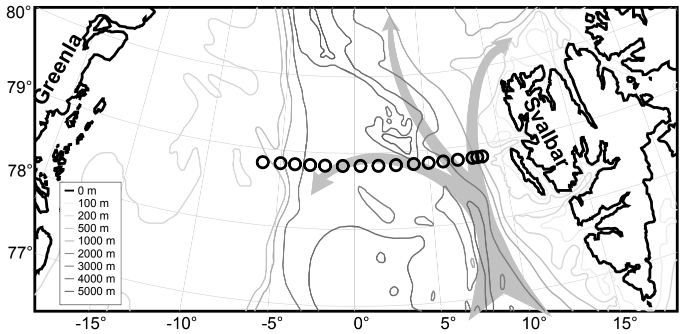

Figure 1 Location of moorings in Fram Strait in 1997-2006. Schematic of the three AW branches

heat flux in the WSC core was maintained during the first half of the observation period by the stronger volume flux, and during the second half by increased temperature in a presence of the weaker flow. The mean heat flux in the WSC core was the same as in the offshore WSC branch (27 TW in each branch) but the variability of the latter was significantly higher (given by standard deviations 7 and 14 TW respectively). During warming periods the recirculating branch contributed to the increased heat transport through Fram Strait by reduced southward or even weak northward heat flux.

Variations of volume and heat fluxes in the WSC core and offshore branch seem to be consistent with different upstream origin of the AW in both branches. The strongly barotropic WSC core shows similar behaviour as the eastern branch of the NwAC where an increase of the AW temperature was found to be balanced by a weaker flow and produced no increase in the heat flux (Orvik and Skagseth, 2005). Due to the coherent structure of the shelf edge current, warm anomalies seem also to propagate faster between the eastern NwAC branch and the WSC core in Fram Strait than signals carried by the slower baroclinic western NwAC branch, where AW is additionally modified during a longer detour before joining the WSC offshore branch. It could explain a time delay in the occurrence of anomalous warming and the higher variability of heat flux in the offshore branch. The redistribution of AW among three branches of the WSC in Fram Strait is of a vital consequence for

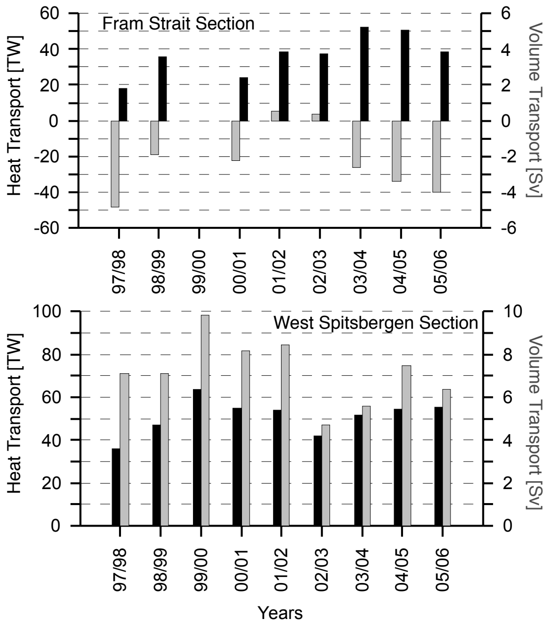

Fig. 2. Winter-centered annual means of net volume transport (pale grey) and heat transport (dark grey) through the entire Fram Strait section (upper panel) and in the West Spitsbergen Current (lower panel).

the heat flux into the Arctic Ocean. Only the AW carried in the WSC core enters the Arctic boundary current and travels further around the Eurasian Basin. The AW flowing in the WSC offshore branch will release a considerable amount of heat to ice and atmosphere in the region north of Fram Strait or recirculate in a short loop, joining the earlier recirculated branch of the WSC. The latest communication by Walczowski et al. (2006) based on hydrography observed in summers 2000-2005 suggests that the warm anomaly and increased heat flux will continue for the few next years with the strongest signature coming to Fram Strait from the western branch of the NwAC. This can significantly influence the oceanic and ice conditions north of Fram Strait, while expected warming in the interior of the Arctic Ocean depends rather on the temperature increase in the WSC core that has been observed in the last decade.

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Climate variability in the Barents Sea

Harald Loeng[1], Ken Drinkwater[1], Randi Ingvaldsen[1], Vidar Lien[1], Vladimir Ozhigin[2] and Øystein Skagseth[1]
[1]Institute of Marine Research (IMR) and Bjerknes Centre for Climate Research Bergen, Norway
[2]Knipovich Polar Research Institute of Marine Fisheries and Oceanography (PINRO), Murmansk, Russia
Corresponding author: harald.loeng@imr.no

Almost a century ago, Helland-Hansen and Nansen (1909) pointed out that variations in the physical conditions had great influence on the biological conditions of various marine fish species, and that ocean temperature variations "are the primary cause of the great and hitherto unaccountable fluctuations in the fisheries". They made the first in-depth analysis of the physical oceanography of the Barents and Nordic Seas, suggesting that variation in the marine climate of the region is probably of advective origin. However, it has been shown over the ensuing decades that most of the physical variability of the Barents Sea is at least in part due to other causes. The inflow of Atlantic Water (AW), for example, is to a large extent determined by local atmospheric conditions, which themselves are linked to large-scale atmospheric features such as the North Atlantic Oscillation (NAO). Consequently, the marine climate in the Barents Sea is a result both of upstream and local conditions.

In a pan-Arctic framework, the Barents Sea is one of the important pathways for transport of AW to the Arctic Ocean. It is important for the ventilation of the Arctic Ocean by transforming AW, and observations demonstrate that it produces intermediate water that can reach a depth of ~1200 m in the Arctic Ocean (Rudels et al., 1994). The relation between the physical and biological conditions in the Barents and the Norwegian Seas is still one of the main driving forces for research and monitoring in the area. This article summarizes some of the main features of the oceanographic conditions in the Barents Sea.

Observations

The monitoring of the Barents Sea climate began in 1900, with gaps from 1906-1921 and during World War II. Those gaps have been filled using interpolation and different statistical methods (Bochkov, 1982). From early 1950s, both PINRO and IMR established several other monitoring sections in the Barents Sea (Figure 1 page 16). The key IMR section is the section between Norway and Bear Island, where also current measurements have been carried out since 1997 in order to monitor the Atlantic inflow to the Barents Sea.

Bottom topography

The Barents Sea is one of the shallow shelf seas that collectively form the Arctic Continental Shelf. The western boundary is defined by the shelf break between Norway and Svalbard and the eastern by Novaya Zemlya (Figure 1). The coast of Norway and Russia form the southern boundary, and the continental shelf break towards the deep Arctic Ocean forms the northern boundary.

The Barents Sea covers 1.4 million km^2 and has an average depth of 230 m. The maximum depth is ~500 m, which occurs in the western part of the Bear Island Trench. The eastern Barents Sea is characterised by two relatively deep areas, the Southeast and the Northeast Basins, both of which connect to the Arctic Ocean through a strait between Novaya Zemlya and Franz Josef Land.

General circulation and water masses

Because it is relatively shallow, the currents in the Barents Sea are characterised by a marked influence of the bottom topography. There are 3 main watermasses; Coastal, Atlantic and Arctic Waters that each are associated with their own current system. The Norwegian Coastal Current flows northeastwards into the Barents Sea (Figure 1) and the Coastal Water has low salinity (<34.7) and a wide temperature range. Unlike the other water masses, Coastal Water is vertically stratified all year round, especially near the Norwegian coast.

The Norwegian Atlantic Current carries Atlantic Water northwards into the Barents Sea. AW is defined by salinities >35.0 and its temperature varies seasonally and interannually from 3.5-7.5°C in the inflow area between Norway and Bear Island. As a rule, temperature and salinity decrease in north and eastward directions within the Barents Sea. AW is normally predominant in the southwestern Barents Sea.

Cold Arctic Water arrives mainly from the Arctic Ocean, invading the Barents Sea between Nordaustlandet and Franz Josef Land and between Franz Josef Land and Novaya Zemlya, to cover the northern part of the Barents Sea. Arctic Water is characterised by low salinity (34.4-34.7) and a core temperature of <–1.5°C. The Arctic Water is separated from the Atlantic Water by the Polar Front (Figure 1).

In addition to the three main water masses, there are local water masses produced as cooling and freezing transforms the AW into denser water. In the western Barents Sea this water has to leave the area towards the west, and in the deepest part of the Bear Island Trench there is usually a well-defined westward-flowing current. From the eastern Barents Sea, most leaves north of Novaya Zemlya and enters the Arctic Ocean.

Most currents in the Barents Sea can be regarded as barotropic, particularly where the AW enters. In areas where the local topography determines the current flow and direction, the directional stability is pronounced, while in other areas it is low.

The velocity field of the Atlantic flow into the Barents Sea exhibits substantial and complex variation on time scales ranging from a few days to months as well as seasonally. The key factor is the wind field, creating converging and diverging Ekman transports that generate sea level elevation gradients, with resultant geostrophic currents. The Ekman drift is non-uniform due to a shear in the wind field and the effect is magnified by the topographic constraints given by the Norwegian coast to the south and the open areas to the north. Due to a close coupling between regional atmospheric pressure and the ocean currents, the volume transport across the Barents Sea varies with the season. Prevailing southwesterly winds during winter accelerates the inflow, whereas the weaker and more fluctuating northeasterly wind common during summer

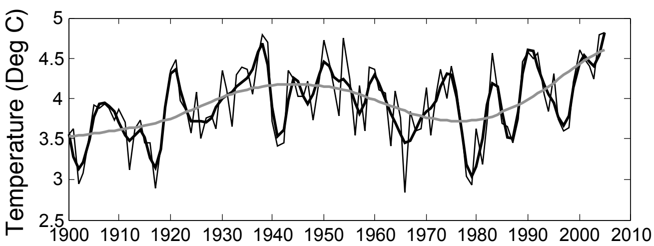

Figure 2. Mean temperature in the Kola section 0-200 m depth including 2005. The thin black line is the annual mean, and the thick black and grey lines are 5 and 30-year low-pass filtered data respectively.

slows it. In years during which the marine climate changes from a cold to a warm state, the seasonal cycle can be inverted. Moreover, due to an annual event of northerly winds, there is usually a pronounced spring minimum in inflow to the extent that, in extreme years, it can cause an outward flow for a whole month.

Models indicate that water entering from the Norwegian Sea spends 2-4 years in the Barents Sea, ultimately flowing into the Arctic Ocean. The net exit flow is of the same magnitude as the flow into the Barents Sea, on average ~2 Sv.

Variability

The results from the temperature observations in the Kola section are shown in Figure 2. The time series is considered to reflect temperature variability in the southern Barents Sea and serves as an indicator of marine climate variability (Bochkov, 1982; Ingvaldsen et al., 2003). The climate varies on time scales from a few years to several decades. Since the beginning of the 1980 there has been a steady warming, and the period 2001-2005 is the warmest five-year period ever observed (Figure 3). At the end of 2005 and beginning of 2006, the highest temperature anomalies ever were observed, close to 1.5°C at the western entrance of the Barents Sea. Observations up to September 2006 show the year to be the warmest on record.

The volume transport between Norway and Bear Island has a strong variability on time scales ranging from months to season and years (Figure 4). The strongest fluctuations occur in late winter and early spring, with both maximum and minimum in this period. The overall mean of AW flux is 1.8 Sv (range 0.8 - 2.9 Sv) on an annual time scale. The lowest values of the volume transports occurred in the winter of 2000-2001 and in 2004. From mid 2004 to the end of the time series in early summer 2006, there has been a strong increase in volume flux. The volume flux and the temperatures are not varying in phase. This is because the volume flux varies in direct response to the wind field (Ingvaldsen et al., 2004), while the temperature has a strong advective signal from the Norwegian Sea (Furevik, 2001).

Forcing Mechanisms

The large-scale atmospheric pressure patterns, as reflected in the North Atlantic Oscillation index (NAO), influence the circulation patterns and hydrographic conditions in the Norwegian and Barents seas especially at decadal time scales. For example, the Norwegian Atlantic Current is stronger and closer to the Norwegian coast during the positive phase of the NAO and weaker and further offshore during its negative phase (Blindheim et al., 2000). The difference between its broadest recorded extent (1968) and its narrowest (1993) exceeds 300 km. For the Barents Sea there is an increase in the amount, temperature and width of the Atlantic water inflow during high NAO years (Dickson et al., 2000; Ingvaldsen, 2005).

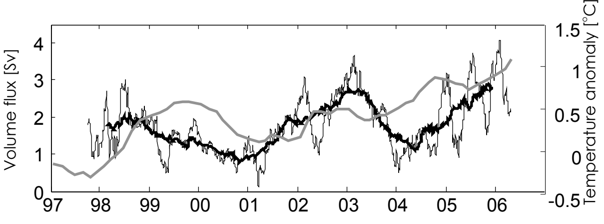

Figure 4. The black lines show Atlantic Water volume flux across the section Norway-Bear Island. Time series are 3 and 12-month running means. The grey line shows the 12-month running means of the temperature anomalies on the section Fugløya – Bear Island section.

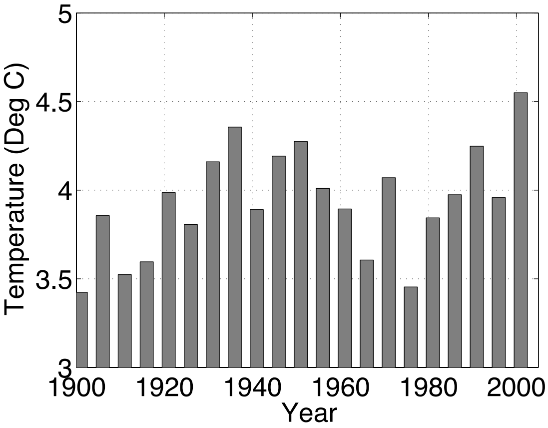

Figure 3. Five year average temperatures in the Kola-section.

However, the NAO index, being a simple two-point pressure difference, is not able to capture all the important details in the Barents Sea (Stenseth et al., 2003). There is temporal variability in the ability of NAO to account for the variability in the physical conditions, as well as the biological. Part of this is related to the spatial variability in the atmospheric pressure patterns, in particular east-west shifts in the position of the Icelandic Low. Local winds also contribute with a close connection between winds at the western entrance of the Barents Sea and both the transports of Atlantic and Arctic waters at the entrance and the hydrographic properties in the Barents Sea (Ådlandsvik and Loeng, 1991; Ingvaldsen et al., 2004). A warm Barents Sea is associated with a stable low-pressure situation over the region, while low temperature is linked to a high-pressure system (Ådlandsvik and Loeng, 1991). The year-to-year variability in sea temperatures in the southern region is strongly influenced by the changes in the properties and volume of the Atlantic inflow (Ingvaldsen et al., 2003), as well as by regional heat exchange with the atmosphere (Ådlandsvik and Loeng, 1991).

There is also significant variability at lower frequencies, for example 60-80 year periods, dubbed the Atlantic Multidecadal Oscillation (AMO) by Sutton and Hodson (2005). Following a cold period in the late 19th century and early 20th, temperatures throughout the northern North Atlantic, including the Norwegian and Barents Seas, increased during the 1920s and remained warm through the 1960s (Drinkwater, 2006). This is clearly shown in the temperatures of the Kola Section (Figure 2).

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North Sea variability: Changing influence of Atlantic Water and ecological consequences

Holger Klein[1], Sarah L Hughes[2], Einar Svendsen[3]
[1]Federal Maritime and Hydrographic Agency, Hamburg, Germany; [2]Fisheries Research Services, Marine Laboratory, Aberdeen, Scotland; [3]Institute of Marine Research, Bergen, Norway;
Corresponding author: holger.klein@bsh.de

Introduction

The variability of temperature, salinity, and currents in the North Sea has significant influence on its ecosystem and fish stocks. Inflow of Atlantic Water (AW) to the North Sea brings with it salt, heat, nutrients and plankton and is estimated to contribute more than 90 % of the nutrient input into the North Sea (Reid et al., 2003). Increasing sea water temperatures in the North Sea over the last decade have been linked to an increase in the presence of warm-water/sub-tropical planktonic species and a decrease in sub-arctic species. These changes are thought to be detrimental to the North Sea ecosystem as although the diversity of plankton species has increased the overall biomass has decreased (Edwards, et al. 2006). There are numerous other examples in the literature of new species occurring in the North Sea in recent years. Periods of strong inflow have also been associated with a strong North Atlantic Oscillation (NAO) index, with the NAO Index accounting for approximately 50% of the modelled variability of winter volume flux into the North Sea. Here we examine the recent trends in North Sea temperature and salinity and show that since 2000, despite the NAO index being weak and variable, temperature and salinity in the North Sea have remained higher than normal and there are indications of a significant influence of Atlantic Water.

Circulation

The exchange between the North Sea and the Atlantic is dominated by the northward outflow of the Norwegian Coastal Current (NCC) and the inflow of AW at the western edge of the Norwegian Trench. The inflows are highly variable, with day-to-day variability being greater than their mean values (Otto et al., 1990). Some AW also enters the North Sea east of the Shetlands with a great year to year variability (Svendsen et al., 1991). Known as Fair Isle Current (FIC) mixed Scottish coastal water and AW enter through the Orkney-Shetland Channel also with a great seasonal and daily variability. Between 58.5° and 59°N a combination of topographic steering and Ekman transport forces a great part of the AW inflow into a cyclonic turn so that it flows back northward with the NCC (Turrell, 1992). Monthly mean modelled fluxes of water into the North Sea derived from the NORWECOM model also show a high degree of variability (IMR Norway, 2005) and show that strong pulses of inflowing water cannot necessarily be identified from mean inflow conditions.

The intensity of the general cyclonic North Sea circulation is influenced by the North Atlantic Oscillation (NAO) as represented by the winter (DJFM) NAO index: High values of the NAO index (>2) are associated with a strong zonal wind component causing an intensification of the North Sea circulation which also affects the shallower southern part of the North Sea (BSH, 2003). The NAO has a typical quasi-cyclic periodicity of about 7.7 years and has also been strongly correlated with the pattern of rainfall and freshwater runoff.

Temperature

North Sea temperature is influenced by the advection of warm AW, local solar heating, and heat exchange with the atmosphere. In the southern North Sea atmospheric forcing is the dominant influence on temperature as shown by the strong correlation between the NAO Index and temperatures at Helgoland Roads (Fig. 1 left, over page). In the northern North Sea the link is less direct. However, analysis of two long (>100 years) timeseries of sea surface temperature (SST) in the North Sea between 1878-1980 (Becker et al.1997) found that the NAO periodicity can be found in both time series (Helgoland Roads - HR and Scottish East Coast - SEC). But there are also signals with a period of between 11 and 13 years (HR and SEC) and 17 years (HR). This interdecadal variability is most likely linked to changes in the large-scale oceanic circulation of the North Atlantic.

In the northern North Sea conditions are more closely associated with those of oceanic waters. The temporal development of near-surface temperature anomalies in the FIC, in the core of the high saline Faroe-Shetland Channel (FSC) and in the Rockall Trough are shown in Fig. 1, along with data from the southern North Sea. For comparison the anomalies have all been normalised by their standard deviation. All three of these timeseries exhibit quasi-cyclic variations of 6 to 9 years which correspond to the periodicity of the NAO. However since 2000, the atmospheric conditions across the north Atlantic have not resulted in sea level pressure anomalies with a typical north-south dipole and as a consequence the NAO Index has been weak and variable and not necessarily representative of the true atmospheric conditions across the North Atlantic.

Weekly and monthly maps of area averaged Sea Surface Temperature (SST) for the whole North Sea have been produced by the Bundesamt für Seeschifffahrt und Hydrographie (BSH, Germany) since 1968. The 1972 to 2004 monthly SST anomalies revealed a bistable SST regime, with a warm period starting before 1972 followed by a cold period from December 1976 until

August 1987. The system switched back rapidly to the warm status in September 1987 (BSH, 2005). The mean temperatures of the phases differ by 0.6°C and 0.9°C respectively. These sudden changes between warm and cold phases can also be observed in the HR SST for at least 130 years (Fig. 2, page 16). The last warm period peaked in 2002 which was the warmest year since the beginning of the area averaged SST records in 1968. Since June 2001, the SST anomalies have been consistently higher than normal with the exception of June and August 2005, and of March, April, and June 2006. The highest anomaly was observed in October 2006 (2.4°C).

The total heat and salt content of the North Sea (bounded by 60°N) have been calculated for each summer period since 1999 (Table 1). The salt content for 1999 and 2001 has not been included as the data quality is uncertain. Whilst the SST in the North Sea showed a peak in 2002, the total heat content peaked one year later in 2003 and decreased during the following years.

Salinity

In contrast to the 2003 peak in heat content, the total summer salt content of the North Sea (Table 1) increased from 2002 until 2005, an indication that during this period there may have been a strong inflow of Atlantic water. The temperature and salinity of surface waters flowing along the UK continental shelf have been rising over the past decade and in some areas the salinity has been the highest observed for more than 50 years (Hughes and Holliday, 2006).

Analysis of salinity data at HR has shown that the salinity in the German Bight is influenced by river run-off from continental rivers as well as advected salinity signals from the English Channel and the northern entrances. However, the sea surface salinity data at HR point to a rather constant ratio between the advection of North Atlantic water and river run-off and precipitation (Becker et al., 1997). Figure 1 (right) shows the salinity at HR compared to other stations in the North Sea.

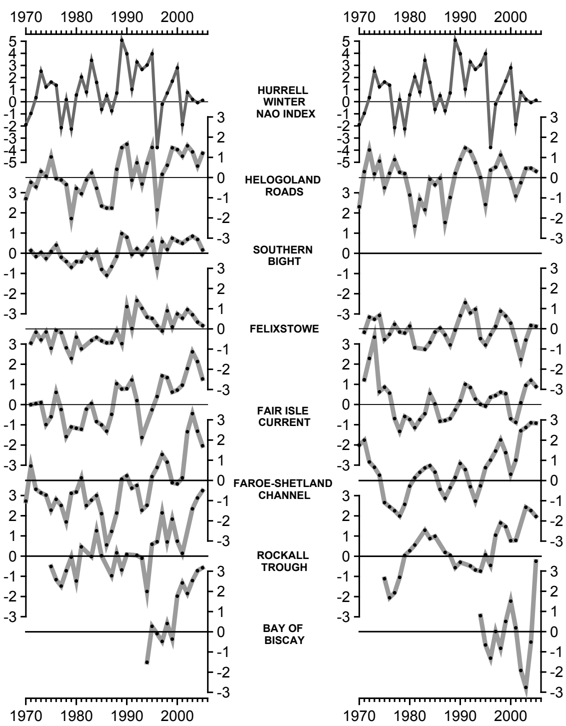

Figure 1: Near-surface normalised temperature (left) and salinity (right) anomalies with respect to the 30-year mean value (1971-2000) at stations in the North Sea the North Atlantic. The upper graph in each panel shows the Hurrell Winter (DJFM) NAO index. The timeseries are those described in (Hughes and Holliday, 2006) No salinity data are collected from the Felixstowe timeseries station.

Consequences of changing physical conditions

Rising temperatures in the North Sea have already influenced a major re-structuring of the indigenous planktonic ecosystem and allowed the successful colonisation of the area by new plankton species. For example, North Sea calanoid assemblages have shifted northward by around 10° latitude while organisms favouring more boreal conditions have declined (Johns et al., 2005). It is thought that many of these species enter the North Sea after being advected in the Shelf Edge Current. The North Sea and English Channels are also busy shipping areas, and non-native species can be brought into the area through ballast waters. In warmer conditions there is the potential for more of these non-native species to remain in the North Sea.

Using model results covering the period 1976-2000 Iversen et al. (2002) revealed a strong correlation between winter inflow of AW and the Norwegian fleet's catch of horse mackerel in the following autumn (r^2=0.70). Figure 3 shows the modelled winter inflow (JFM) into the North Sea trough the Orkney-Utsira section (2° 30'W to 5° 15'E along 59° 17'N) from 1955 and extended until 2006 and the variation of the winter (DJFM) NAO index which explains around 50% of the transport variability. Of particular interest are the simulated huge inflows in the beginning of the 1990's which nearly doubled (from the norm) values in 1990 and 1993.

Holliday and Reid (2001) suggested that sudden changes in the ecosystem can be triggered by pulses of oceanic water entering the North Sea rather than by prolonged periods of increased transports. Periods of strong Atlantic water inflow were inferred from biological data and appeared to occur at the same time as unusually high transports of warm saline upper water through the Rockall Trough. The two periods identified (1989/1990 and 1998/1999) are also coincident with the above mentioned changes of the bi-stable SST regimes in the North Sea. The Scottish Shelf Edge Current is a possible connection between the Rockall Trough and the North Sea, but as yet there is no direct evidence of a direct link and it is possible that both are responding to a common forcing.

Summary

Historical records of North Sea temperature and salinity show that in the 20th century the physical conditions were directly related to changes in atmospheric forcing captured by the NAO index. There are no direct measurement of Atlantic Water inflow but a model has captured changing conditions and inflow well, and has shown a good correlation with the NAO index. However since 2002, and despite the weak and variable NAO Index, the increasing heat and salt content of the North Sea indicates that there has been an significant influence of water from the North Atlantic. Model results do not show a marked increase in inflow, so we believe that the increases are caused by the increased temperatures and salinities in the inflowing Atlantic water (Fig. 1) in combination with very mild winters. Biological evidence points to sustained if not increasing influence of warmer waters in the North Sea during this period.

Acknowledgements

The Helgoland Roads Data are kindly provided by Biologische Anstalt Helgoland/Alfred-Wegener-Institut für Polar- und Meeresforschung.

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Date of Cruise	cruise	total heat content [J]	total salt content [t]
09.07.1999	G335	1.359x10^{21}	-
16.08.2000	G353	1.497x10^{21}	1.140x10^{12}
27.07.2001	G370	1.346x10^{21}	-
25.07.2002	G385	1.517x10^{21}	1.135x10^{12}
04.08.2003	G405	1.625x10^{21}	1.138x10^{12}
12.08.2004	G425	1.594x10^{21}	1.148x10^{12}
23.08.2005	G446	1.550x10^{21}	1.153x10^{12}
1900-1996 mean (Janssen et al, 1999)		1.400x10^{21}	1.192x10^{12}

Table 1:Total heat and salt content of the North Sea. Data from R/V GAUSS summer cruises

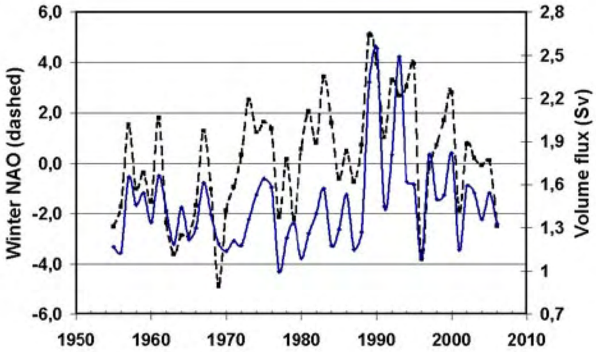

Figure 3: Winter (DJFM) NAO index 1955-2006 and modelled winter (JFM) inflow into the North Sea through the Orkney-Utsira section (r^2=0.46).

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Baltic variability and exchanges

Karin Borenäs[1] and Jan Piechura[2]
[1] Swedish Meteorological and Hydrological Institute, Västra Frölunda, Sweden and Göteborg University, Göteborg, Sweden,
[2]Institute of Oceanology, Polish Academy of Science, Sopot, Poland
Corresponding author: karin.borenas@smhi.se

1. Introduction.

The Baltic Sea is a semi-enclosed sea characterized by a large freshwater excess, mainly due to the runoff from several rivers emanating into the area (Figure 1, over page). Brackish water is transported out of the Baltic in the surface layer while there is an inflow of more saline water in the deeper layer. As a result a two layer structure of water is observed with the strong salinity/density gradients between them. The surface salinity increases from 3 in the Bothnian Bay to over 30 in the Skagerrak; while in the near bottom waters salinity varies from about 4 to 35. The saline water enters the Baltic Sea through the Danish Straits where mixing with the ambient waters takes place. Inside the Baltic Sea the dense water fills up the deeper parts of the Arcona Basin (maximum depth 45 m) from which it subsequently overflows into the Bornholm Basin. After passing the Stolpe Channel it finally reaches the Baltic proper. Along its way the more saline water is mixed with the local water, hence increasing the volume of the inflow. At the same time vertical mixing between layers is restrained by the pycnocline, especially in the more quiescent basins. In the Baltic proper the inflowing water is embedded at its density level, usually close to the halocline. Occasionally large inflow occurs and reaches the deepest parts of the Baltic proper thereby renewing the bottom water. Between these events there are periods of stagnation which have large impact on the oxygen situation.

2. Vertical salinity distribution.

The characteristic circulation with outflowing brackish water and inflowing saline water produces a more or less pronounced halocline. This feature is demonstrated in Figures 2a and 2b (over page) showing the salinity profiles from one station in the Bornholm Basin and one on the downstream side of the Stolpe Channel. The figures are based on water-bottle/CTD data from 1957-1999, in all 550 profiles from BY5 (the Bornholm Basin station) and 400 from BCSIII-10 (Borenäs et al. 2006). The mean value, as well as the standard deviation, is shown for standard depths. The first thing to notice is that the upper layer salinity is very stable. In the Bornholm Basin the salinity is almost constant down to 50 meters; it then increases with depth to twice the surface value. In the deeper parts the variability is larger as a consequence of inflows varying in frequency and size. The corresponding profile for BCSIII-10 reveals that a lot of mixing has taken place when passing through the Stolpe Channel (which has a sill depth of 63 meters.)

3. Exchange variability.

Water exchange through Danish Straits is a process crucial to

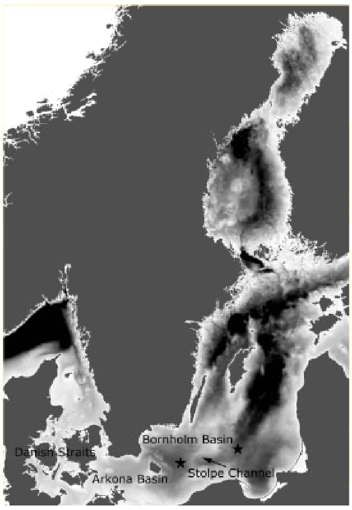

Fig. 1. The Baltic Sea basin. Map by courtesy of SMHI, Sweden. The stars indicate the position of station BY5 (to the left) and BCSIII-10 (to the right).

the Baltic Sea's hydrography, environment and ecosystem. A special role is ascribed to rapid inflows bringing hundreds of cubic kilometers of well oxygenated, saline waters into the Baltic Sea within a few days. The temperature of these waters depends on the time of year when the inflow occurs, but usually it is a few degrees higher than that of deep waters in the southern Baltic (Piechura 1993). The occurrence of inflows depends mainly on the atmospheric circulation and requires an appropriate sequence of wind forcing and sea level changes. Though these are irregular phenomena, over 90% of such events take place during late autumn and winter, until the 1980s on average every 4-5 years (Matthäus &: Franck 1992). Since that time, however, large inflows have taken place much less frequently (1983, 1993, 2003), about once every 10 years. The consequences are less oxygen supply in the deep layer on one hand, but lower vertical density gradient and better mixing possibilities on the other.

The latest inflow and its consequences within the Baltic Sea led to the first comprehensive investigation of the phenomenon, 15 cruises of research vessels from Sweden, Germany, Poland, Russia and Finland taking place from December 2002 until August 2003.

The inflow that started in the middle of January 2003 brought about 200 km^3 of salty and cold waters. This placed it into the medium sized category of inflows according to the classification by Matthäus and Franck (1992).

The low temperature of these inflow waters (close to 1°C) was a very exceptional feature: previously observed inflows carried waters distinctly warmer than the local Baltic Sea waters. This coincided with another exceptional feature: the very high temperature of the deep waters within the Baltic (11-12°C), caused by another, warm, inflow which had taken place in August 2002 (Feistel et al. 2004). This created a large difference in temperature between the inflowing and ambient waters (Figure 3 page 17) that provided a unique opportunity to follow the movement of the inflowing water within the Baltic and to learn more about the mixing processes. Piechura et al (2004) show a further exceptional feature of this particular inflow; that the water moved very rapidly with an average speed of 30 cm/s, and maximum velocity reaching 45 cm/s. On its journey along the chain of deep basins and channels inflow waters are pushing upward and to the east local "old" water. Intensive mixing and heat exchange in particular takes place at the same time. This movement is accompanied by numerous mesoscale eddies of different size: from tens to hundreds of kilometers. Changes of temperature-salinity characteristics in the Bornholm Deep caused by the inflow are shown in Figure 4.

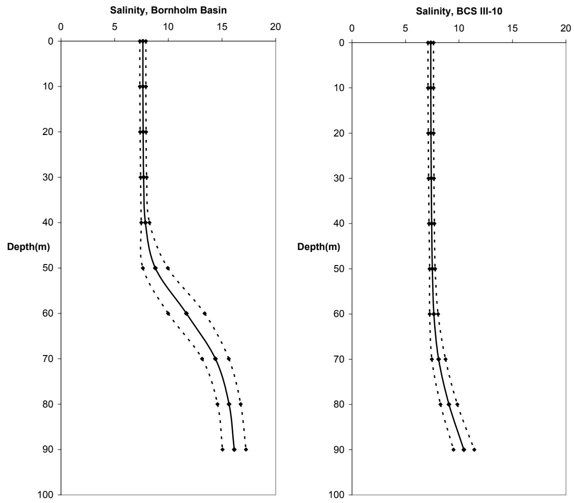

Fig. 2. Mean and standard deviations of observed salinity profiles 1957-1999. a) BY5 in the Bornholm Basin b) BCSIII-10 downstream of Stolpe Channel

In recent years another type of inflow was observed more frequently then before; the so co-called barocline inflows, taking place in summer time and bringing warm waters into the Baltic Sea (Feistel et al. 2004). This type of inflow was observed in 2002, 2003 and 2004 (Figure 5 page 17). These warmer and less dense waters usually moved in the intermediate layer of the Baltic Sea, and did not renew bottom water.

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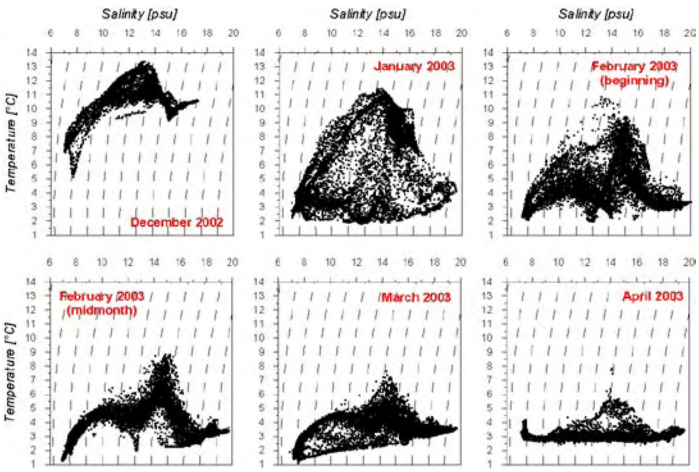

Fig. 4. Transformation of water masses during the successive stages of inflow in 2003 in Bornholm Basin

From Rossby et al, page 2: Isopycnal Analysis of Near-surface Waters in the Norwegian-Barents Sea Region

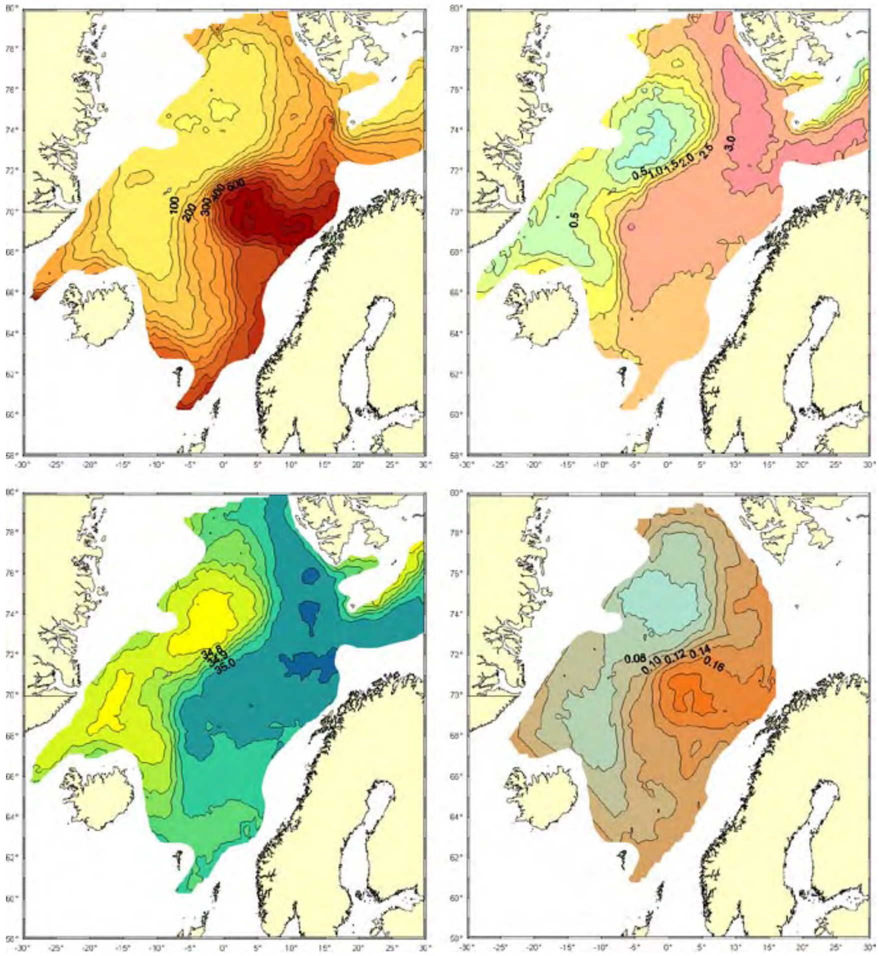

Figure 1: The four panels (left to right, top to bottom) show depth, temperature, salinity and Montgomery potential for the $\delta = 2.1x10^{-7}$ m^3kg^{-1} surface. The contour intervals are 50m, 0.5°C, 0.05PSU and 0.02 dyn. meters, respectively. The Montgomery potential exists only for depths >1000 m.

From Beszczynska-Möller et al, page 7: Variations of the Atlantic inflow and related heat flux through Fram Strait in the last decade

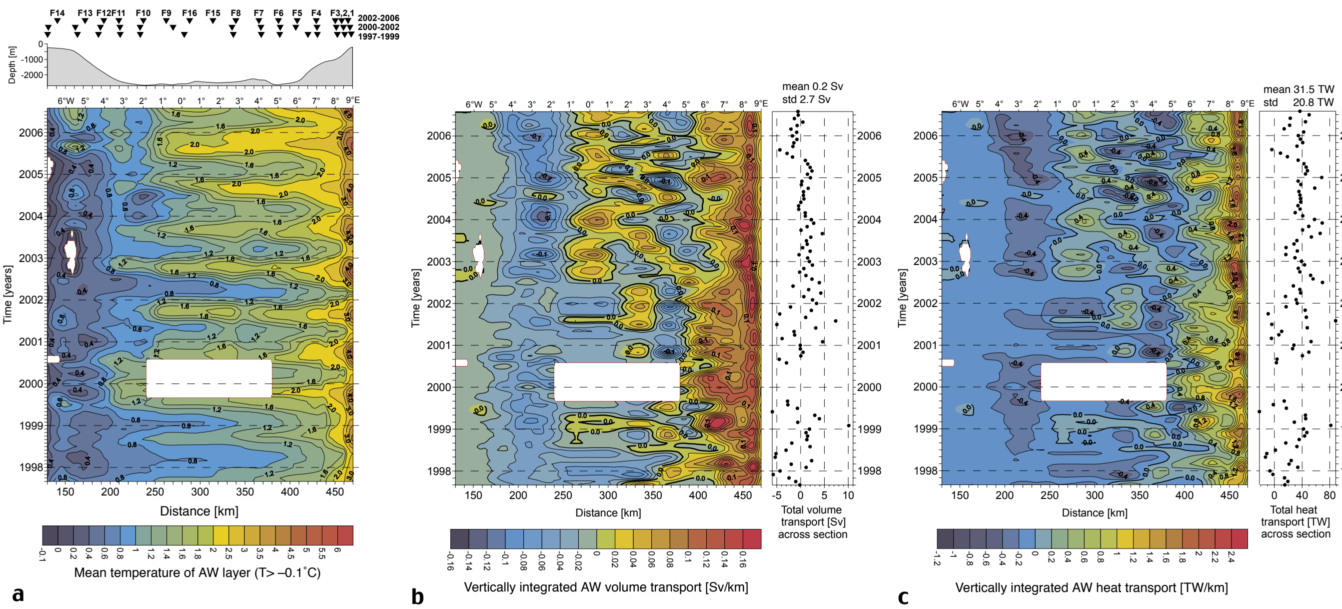

Figure. 3 Hovmoeller diagrams of (a) mean temperature, (b) the vertically integrated volume and (c) heat fluxes for water with temperature higher than -0.1°C. Positions of moorings in different years and the bottom contour are shown above each plot. For (b) and (c) total fluxes integrated over entire section are shown on the right panels.

From Loeng et al, page 9: Climate variability in the Barents Sea

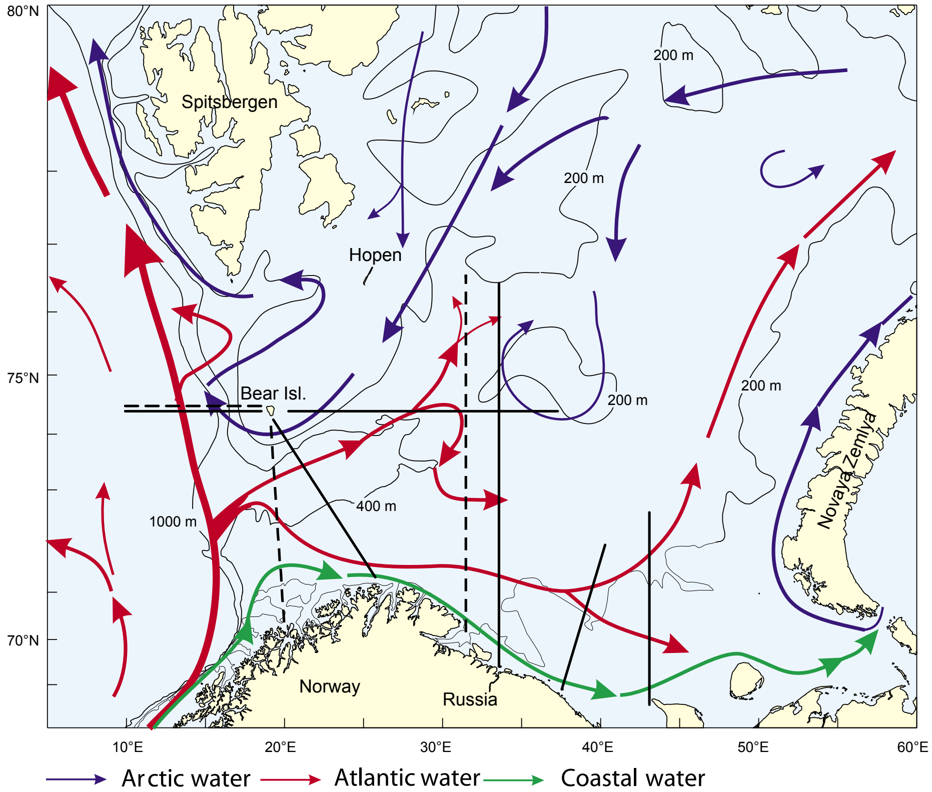

Figure 1: Main currents in the Barents Sea and the hydrographic sections observed by IMR (dashed lines) and PINRO (solid lines). Kola section is at 33.3°E and the Fugløya – Bear Island section is at 20°E.

From Klein et al, page 11: North Sea Variability: Changing influence of Atlantic Water and Ecological Consequences

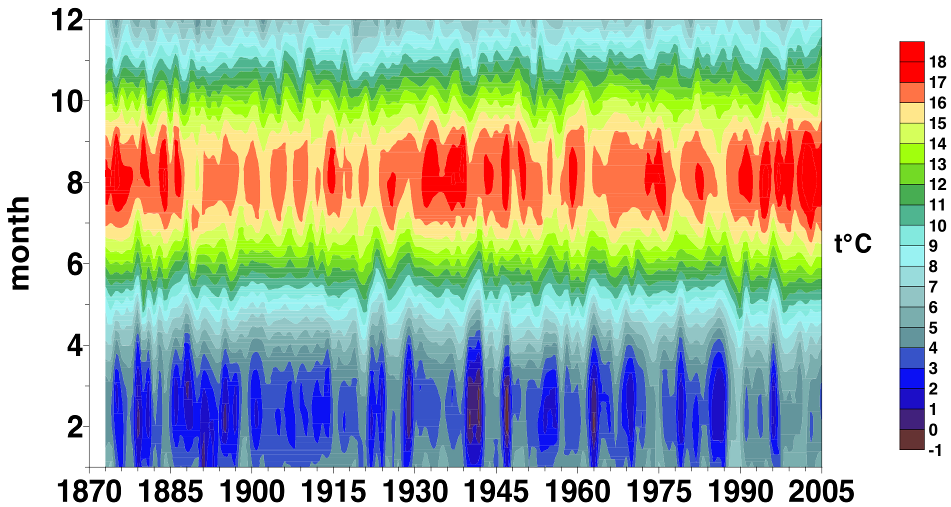

Figure 2: Helgoland Roads (HR) temperature time series.

From Borenäs and Piechura, page 13: Baltic variability and exchanges

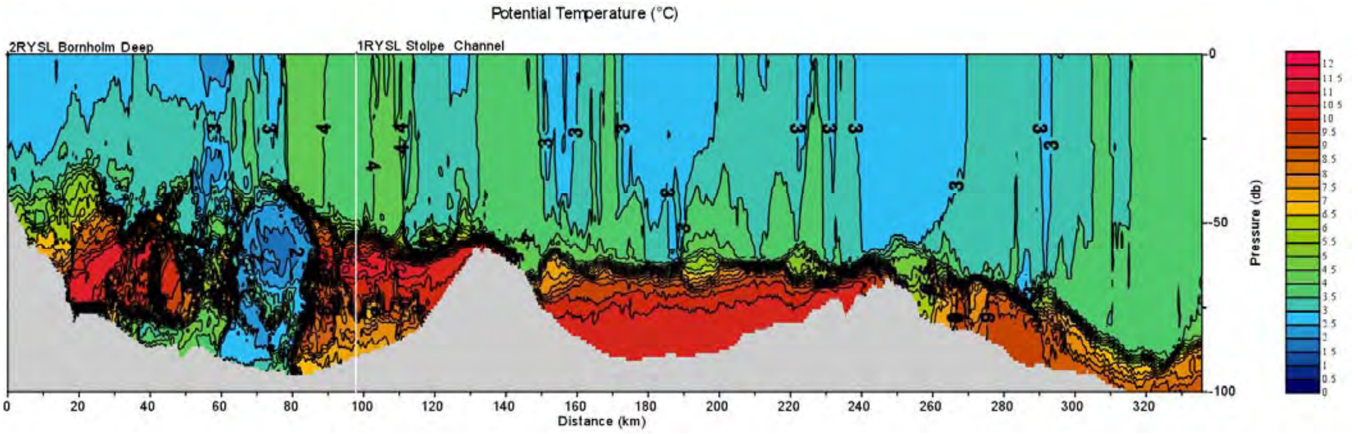

Fig. 3. Temperature along the Gdańsk Deep-Bornholm Deep transect. 25-26 January 2003

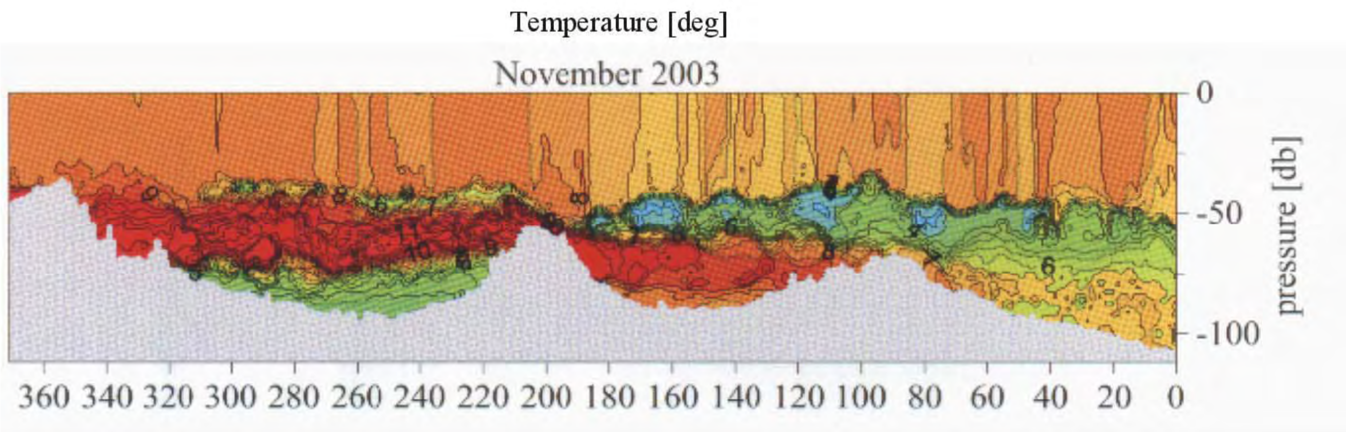

Fig. 5. Temperature at Bornholm Deep-Słupsk (Stolpe) Channel-Gdańsk Deep transects measured by r/v "Ocenaia" in November 2003

From Holliday et al, page 19: The end of a trend? The progression of unusually warm and saline water from the eastern North Atlantic into the Arctic Ocean

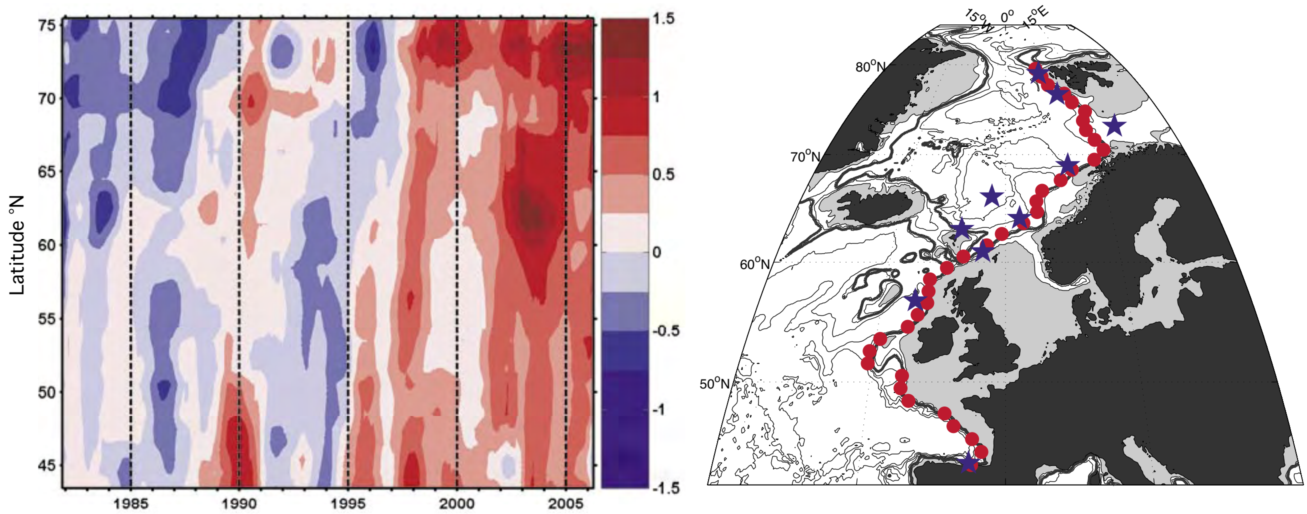

Figure 2. Smoothed monthly sea surface temperature anomalies (°C) along the eastern margin of the North Atlantic (left panel). Data were obtained from the NOAA Optimum Interpolation SSTv2 data set provided by the NOAA-CIRES Climate Diagnostic Centre, USA. The map (right panel) gives locations of the time series of SST data (red dots) and approximate locations of the hydrographic sections shown in Figure 1 (blue stars).

From Valdimarsson and Jónsson, page 23: Time series and hydrographic variability in Icelandic waters

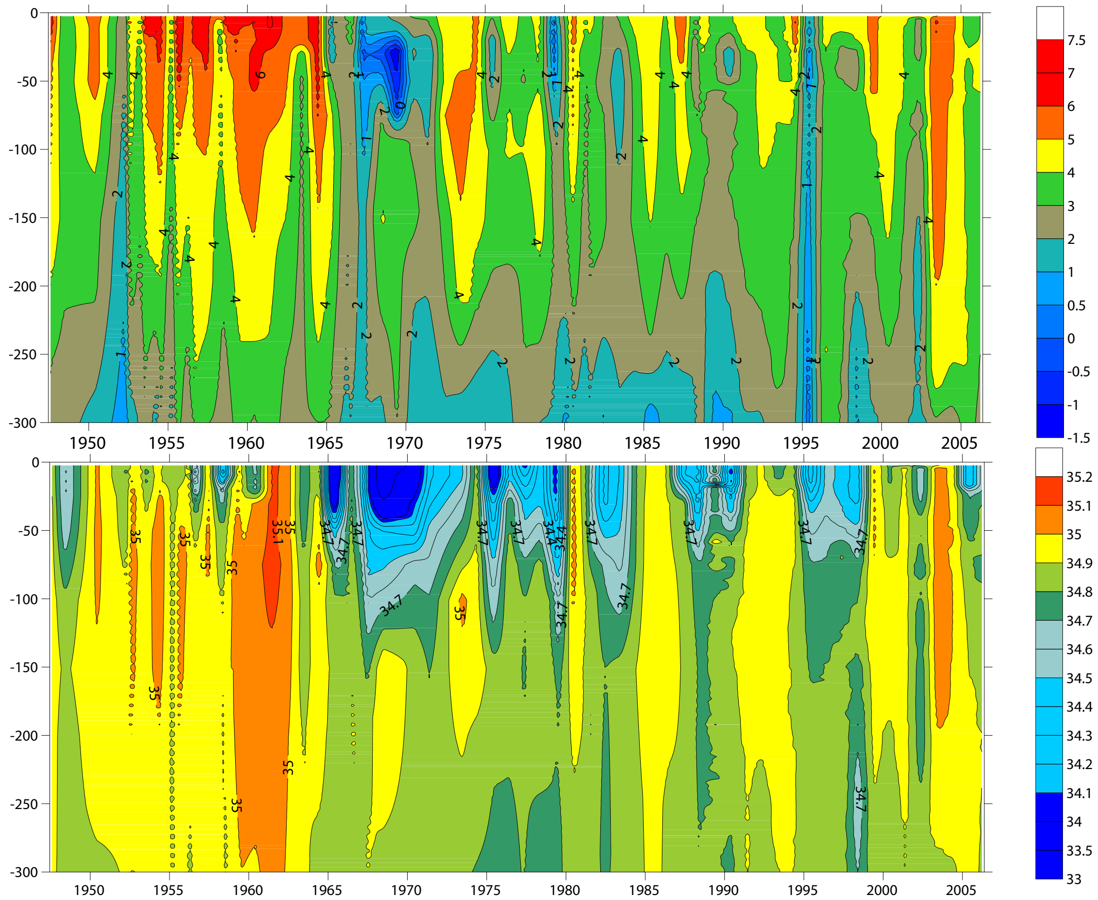

Figure 2. Temperature and salinity in spring at station 3 on the Siglunes section north of Iceland. Upper part shows temperature and lower part salinity for the upper 300 db of the water column.

From Hendry et al, page 25: Monitoring the ventilation of the Irminger and Labrador Seas

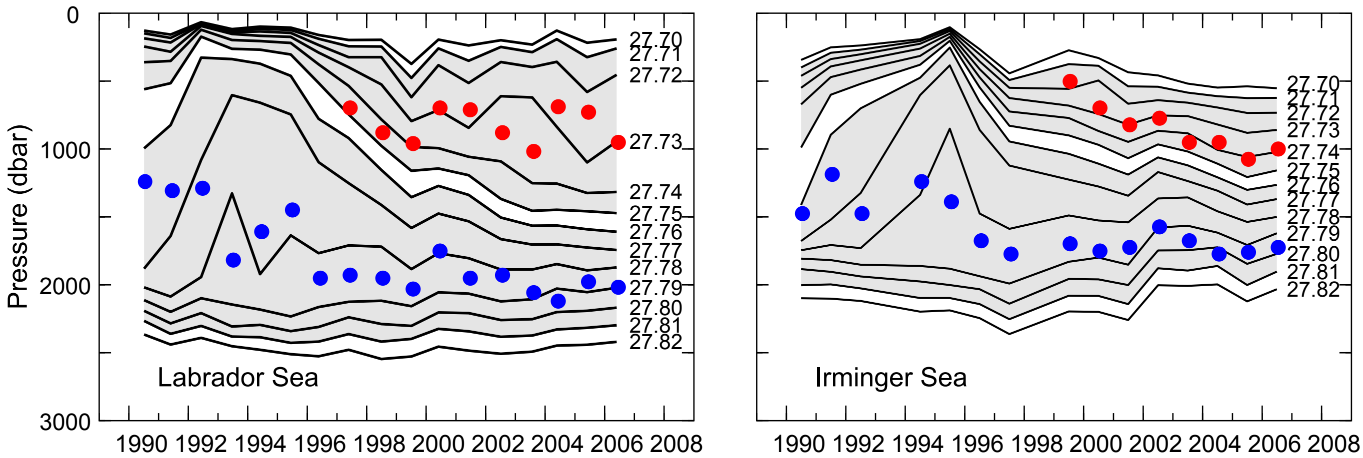

Figure 3. Time series of pressure on selected potential density surfaces averaged over stations in the west-central Labrador Sea (left panel) for spring and early summer AR7W surveys and the central Irminger Sea (right panel) for summer AR7E sections from 1990 to 2006. Filled symbols mark pressures at relative minima in potential vorticity in the two shaded potential density anomaly layers 27.76–27.81 kg/m^3 (lower) and 27.71–27.75 kg/m^3 (upper).

The end of a trend? The progression of unusually warm and saline water from the eastern North Atlantic into the Arctic Ocean.

N.P. Holliday[1], S. L. Hughes[2], A. Lavín[3], K. A. Mork[4], G. Nolan[5], W. Walczowski[6], A. Beszczynska–Möller[7].
[1]National Oceanography Centre, Southampton, UK. [2]Marine Laboratory, FRS, Aberdeen, Scotland. [3]Instituto Español de Oceanografia, Santander, Spain. [4]Institute of Marine Research and Bjerknes Centre for Climate Research, Norway
[5]Marine Institute, Galway, Ireland [6]Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland
[7]Alfred–Wegener–Institute, Bremerhaven, Germany
Corresponding author: nph@noc.soton.ac.uk

In the context of recent reports describing long-term freshening of the subarctic North Atlantic (Curry and Mauritzen, 2005, Peterson et al, 2006), it is surprising to observe that the upper ocean (500-1000 m) of the eastern North Atlantic and Nordic Seas in 2004-2006 are dominated by the most saline water observed for over 50 years (Hughes and Holliday, 2006). Here we show that changes in the subpolar gyre in the mid-1990s led to an increase of warm saline subtropical water being entrained into subarctic circulation (Hátún et al, 2005); a different regime that has continued to the present day (2006). The progression of the subtropical-influenced water has been traced along the pathway of Atlantic inflow into the Nordic Seas, and finally in 2004 was observed to enter the Arctic Ocean (Walczowski and Piechura, 2006). Based on observational evidence, we predict that this unusually warm and saline water will continue to flow into the Arctic Ocean and Greenland Sea for at least the next 6 years (Holliday et al, in prep).

The Atlantic Inflow (AI) into the Nordic Seas contains mixed and modified North Atlantic Current water that has flowed from the subtropics through the Iceland Basin and the Rockall Trough, entraining fresh subpolar surface and intermediate water, receiving freshwater from the atmosphere, and losing heat to the atmosphere. Branches of the AI flow over the Greenland-Scotland Ridge in three main locations: in the Irminger Current west of Iceland, over the Iceland-Faroes Ridge and through the Faroe-Shetland Channel, and they converge in the southern Norwegian Sea. The AI travels northwards through the Norwegian Sea in two branches; some spills eastwards into the Barents Sea, most becomes the West Spitzbergen Current which flows through the Fram Strait into the Arctic and recirculates into the Greenland Sea. Throughout its pathway the AI maintains a clear signal of relatively high salinity and temperature, despite local modification.

In the mid-1990s a significant increase in the heat content of the interior of the subpolar gyre led to a weakened circulation and a westward movement of the subarctic front in the Iceland Basin (Bersch, 2002, Hakkinen and Rhines, 2004). The consequence was that more warm saline subtropical water from the Bay of Biscay region was drawn northwards into the eastern Iceland Basin and Rockall Trough. The upstream waters of the AI began to increase in salinity and temperature while net precipitation and surface heat flux remained relatively unchanged (Holliday, 2003, Hátún et al 2005). At that time the Bay of Biscay upper ocean showed no discernible increase in salinity, indicating more than a simple propagation of a Biscay region salinity anomaly. By 1998, the values of upper ocean salinities (0-800 m) in the Rockall Trough and Iceland Basin had exceeded any measurement made since 1975.

Over the following years, sustained ocean observations at locations along the pathway of the AI began to show similar increases in temperature and salinity. The time series of anomalies are given in Figure 1, and the locations of the sections are shown in Figure 2 (page 17). Each section shows a high level of noise which is due to local mixing and mesoscale variability, so a straightforward tracing of interannual patterns from section to section is not feasible. However, the increase in salinity from the mid-1990s onwards has been continuing for 10 years and has become visible as a multi-year trend along the AI pathway. In the longest time series at OWS Mike in the southern Norwegian Sea, it can be seen that the recently reported multi-decadal freshening trend come to an end in the mid to late 1990s. Indeed, the 2005 salinity values exceeded the previous highest level which occurred in 1961, making the 2005 salinities them the highest observed since 1949.

Figure 2 shows the temporal progression of sea surface temperature (SST) anomalies along the eastern margin of the region (locations of data points given by red dots). It can be seen that south of 57°N the temperature anomalies show no indication of propagation and are somewhat disconnected features. This suggests they are the result of local processes. However, from the Rockall Trough northwards, ie from the start of the Atlantic inflow path influenced by the subarctic front, the temperature anomaly features move coherently northwards with time. Sea surface temperature is highly variable due to ready interaction with the atmosphere, but the large scale anomaly features derived from upper-ocean mean salinity and temperature are also visible in the high temporal resolution SST. This implies that the main anomalies are driven by advection rather than local air-sea heat flux.

The time series in Fram Strait is not as long as the one from OWS Mike, but in 2005 the salinity far exceeded the previous high in 1984. From this, and from a more detailed analysis of local conditions by Walczowski and Piechura (2006), we conclude the high salinity AI formed by 1998 in the eastern subpolar gyre reached the Fram Strait in 2004 and has continued into 2006. With uncertainties due to sampling frequency, we estimate a net transit time of 6±2 years from 57°N (Rockall Trough and Iceland Basin) to 78°N (Fram Strait). By tracing the time evolution of the sea surface temperature anomalies along the AI pathway (Figure 2) we can gain an additional estimated transit time of 4±1 years from 57°N (Rockall Trough) to 75°N (West Spitsbergen Current).

Finally we can use our knowledge of the circulation and the upstream time series to make a prediction of the Atlantic Inflow into the Arctic Sea through the Fram Strait. The observations in the Rockall Trough display a multi-year trend to higher salinities (and higher temperatures) from 1996 to 2005, despite some higher frequency noise. This is also the case downstream through the Faroe-Shetland Channel and into the Norwegian Sea, the latter showing an increase from around 2000. So with some confidence we can predict a continuation of the unusually warm and saline inflow through the Fram Strait into the Arctic Ocean for at least a further 5±1 years from 2006 (Holliday et al, in prep).

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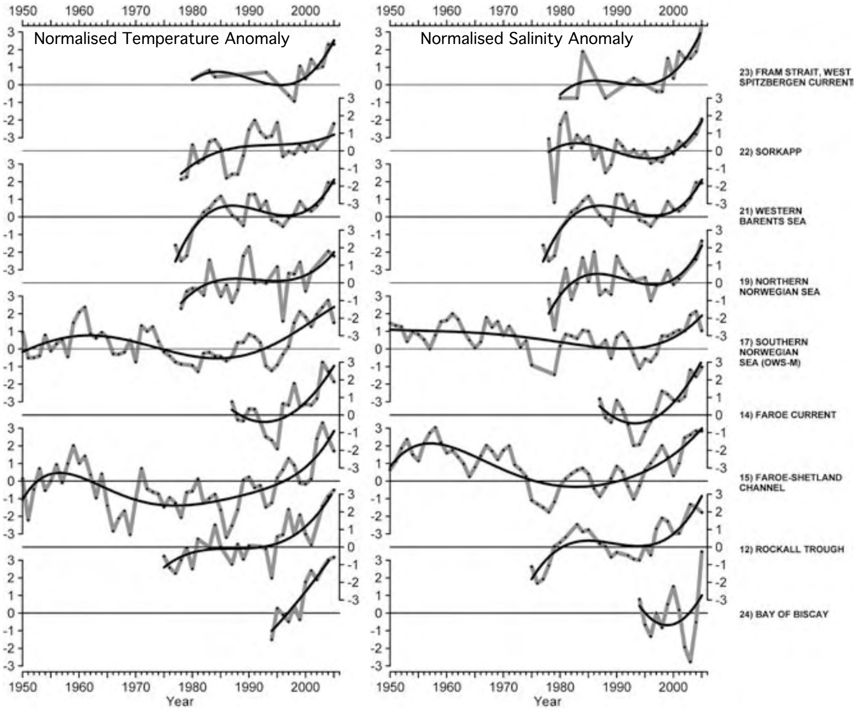

Figure 1. Time series of upper ocean temperature anomalies (left panel) and salinity anomalies (right panel) from sustained ocean observations along the pathways of Atlantic Inflow from the intergyre Biscay region (bottom) to the Fram Strait (top). Locations of sections are shown in Figure 2. Data are presented as normalised anomalies from the long-term mean (1971-2000).

The overflow of dense water across the Greenland–Scotland Ridge

S. Dye[1], B. Hansen[2], S. Østerhus[3], D. Quadfasel[4], B. Rudels[5]
[1]Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, UK, [2]Faroese Fisheries Laboratory, Tórshavn, Faroe Islands, [3]Bjerknes Centre, Bergen, Norway, [4]University of Hamburg, Hamburg, Germany, [5]Finnish Institute of Marine Research, Helsinki, Finland
Corresponding author: stephen.dye@cefas.co.uk

1. Introduction

The overflow of cold, dense water from the Nordic Seas to the Atlantic Ocean across the Greenland-Scotland Ridge is an important component of the global thermohaline circulation. According to estimates (Saunders, 2001), about half of the overflow passes through the Denmark Strait (Fig. 1). The other half passes east of Iceland in three different areas.

The total overflow is estimated to transport about 6 Sv across the Ridge, but intensive mixing immediately downstream of the Ridge induces strong entrainment of ambient Atlantic waters into the overflow plumes. This reduces the density of the overflow water but enhances the volume flux by a factor of about two, according to estimates. Based on this, the overflows are the main contributor to North Atlantic Deep Water (Fig. 2). The entrainment process has not been well studied and will not be discussed further in this short note, which will also ignore the two weak overflows across the Iceland-Faroe and the Wyville-Thomson ridges (dashed arrows in Figure 1). Here, the focus is on the two main overflows, which are discussed separately, below.

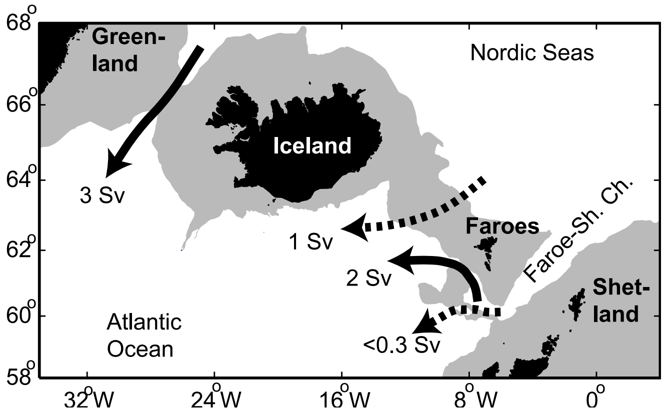

Figure 1. The four overflow branches that cross the ridge. Shaded areas are shallower than 750 m.

2. Denmark Strait overflow

The first current-meter measurements of the Denmark Strait overflow were made during the late 1960s and helped form the modern view of the water transformations of the Arctic Mediterranean (Worthington, 1969, 1970). Here we present some of the measurements and questions that are being raised in response to current meter moorings and hydrographic sections of VEINS (Variability of Exchanges in the Northern Seas) and ASOF (Arctic – Subarctic Ocean Fluxes) north and south of the Denmark Strait.

- Overflow Transport: An array of current meters has been deployed annually by the University of Hamburg (UHH), the Finnish Institute of Marine Research (FIMR) and the UK's Centre for Environment, Fisheries and Aquaculture Science (Cefas) since the mid-1990s about 500 km south of the Denmark Strait sill on the Greenland continental slope. This repeats the locations of moorings in the late 1980s (Dickson & Brown, 1994) which found a total 'overflow' flux of about 10 Sv (including all water denser than 0=27.8 kg σ_θ m^{-3}). The new measurements confirm those from the 1980s (the portion attributed to the Denmark Strait, σ_θ 0>27.85 kg m^{-3}, amounts to 3-4 Sv) and cannot identify any trend over the 2 decades. However, the time-series can now identify significant interannual variability of around 25%.
- Is the source of DSOW in the Iceland Sea or the East Greenland Current (EGC)? This debate remains open; Rudels et al. (2002, 2005) found evidence for the EGC as the main pathway for source water and proposed that the Atlantic waters as well as the different intermediate waters present in the EGC contributed the bulk of the overflow (Fig. 3). On the other hand, Jónsson and Valdimarsson (2004) found evidence supporting the Iceland Sea as the source when they observed a barotropic jet on the Iceland continental slope, following the 600 m isobath toward Denmark Strait.
- Overflow plume. Six standard hydrographic sections across the East Greenland slope have been performed annually since 1997, led by UHH, spread from close to the sill in the north to Cape Farewell (the most southern is part of WOCE Section A1E). These hydrographic sections have demonstrated that the upper part of the Denmark Strait overflow plume consists of low salinity water from north of the sill. This low salinity cap can be detected down to 3000 m and as far south as Cape Farewell. The question this leaves to be resolved is: does the persistence of the 'cap' mean that direct entrainment of ambient water into the plume is small?
- Overflow freshening. Since 1998 the current-meter array has been augmented by the addition of high precision moored CTDs, giving high frequency measurements of the temperature and salinity. The multi-decadal overflow freshening trend of about 0.01 per decade identified in sporadic cruise measurements (Dickson et al., 2002) is given new context by the moored salinity measurements which show freshening 'events' of up to 0.08 occurring over a few months at the bottom of the overflow plume (Fig. 4). Is this evidence of the change in the source region for overflow? Additional instruments will soon give further information on the temporal variation in the vertical properties of the plume.

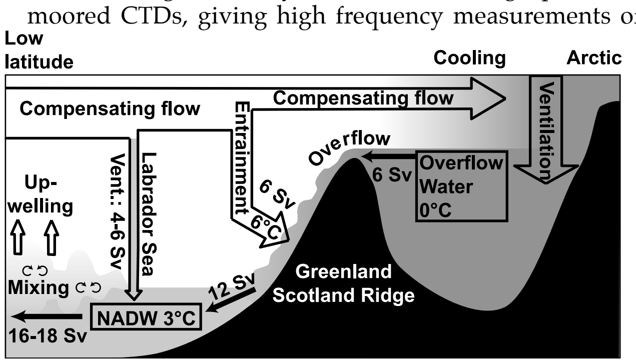

Figure 2. After passing the ridge, the overflows mix intensively and entrain ambient waters, which increase the temperature and volume flux. Both overflow and entrained water require a compensating flow, which carries heat and salt northwards.

These measurements are now providing time-series that demonstrate change in this important component of the ocean circulation. The evidence they provide through the International Polar Year will help understand the impacts of change in the Arctic as they pass into the North Atlantic across the Greenland- Scotland Ridge.

3. Faroe Bank Channel overflow

The Faroe Bank Channel (FBC) is more than 200 m deeper than any other passage across the Greenland-Scotland Ridge and through it passes the coldest and densest overflow from the Nordic Seas into the Atlantic. Since 1988, the Faroese Fisheries Laboratory has occupied a CTD standard section at least four times a year. Since 1995, an ADCP has been moored at the sill continuously, except for short annual servicing periods. In addition, several other short-term experiments have been made (Fig. 5).

A detailed description of the results 1995-2005 has been submitted to Progress in Oceanography (Hansen et al., subm.). Here, only a few highlights are noted:

- The FBC-overflow is very stable. During the 10-year period, the daily averaged bottom temperature at the sill never exceeded 0.1ºC and the daily averaged along-channel velocity in the current core never fell below 50 cm s^{-1}.
- Variations in hydrography and current in the overflow layer are coherent across the channel, no doubt because the channel width at the depth of the overflow only is about one baroclinic Rossby radius.

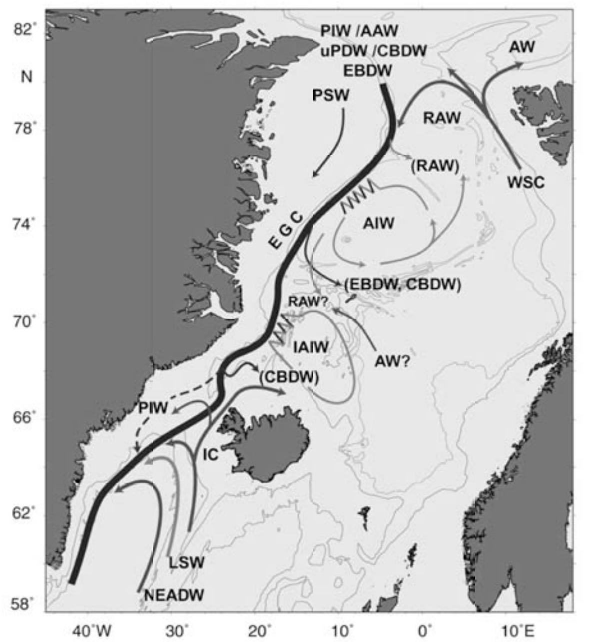

Figure 3. The East Greenland Current (EGC) provides the mechanism to pass water of the Nordic Seas and Arctic (such as Recirculating Atlantic Water, RAW; Polar Intermediate Water, PIW; Arctic Intermediate Water, AIW) into the overflow. From Rudels et al., 2002.

- This makes the channel easy to monitor, because the volume flux can be determined from one ADCP with a high accuracy (10%).
- For the whole 1995-2005 period, the average kinematic overflow flux, defined purely from the velocity field, was 2.1±0.2 Sv.
- The volume flux of water denser than 27.8 kg m^{-3} for this period was estimated as 1.9±0.3 Sv with average temperature 0.25 ˚C and density 28.01 kg m^{-3}.
- The kinematic volume flux exhibits a clear seasonal variation with maximum flow in summer and an amplitude around 10% of the average flux. The bottom temperature also varies seasonally with minimum in summer, probably because a stronger flow sucks up water from larger depths upstream.
- In spite of annual variations, the volume flux of the FBC overflow shows no persistent trend in the 1995-2005 period (Fig. 6) and neither does the temperature. The salinity did, however, increase, especially for the warmer part of the overflow water, implying a slight (0.01 kg m^{-3}) average density increase.
- The suggested link between between FBC overflow and isopycnal depth at Ocean Weather Ship M (Hansen et al., 2001) is not supported by the full data set (Fig. 6), making their conclusion of a weakening FBC overflow since 1950 doubtful.

When including the entrained water, FBC-overflow contributes about 25% of the NADW production (Fig. 2), i.e. a similar amount as Labrador Sea convection (but denser). Probably, it is also the most stable component of the North Atlantic THC (Wilkenskjeld and Quadfasel, 2005). Any sign of a persistent change in FBC-overflow would therefore be a clear warning of THC change. As demonstrated, the FBC overflow can be monitored accurately and cheaply. This clearly should be done.

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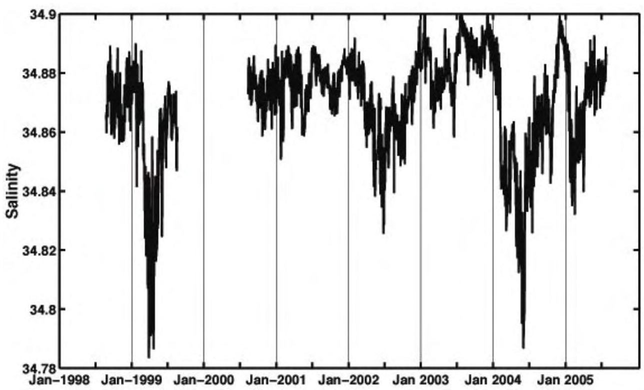

Figure 4. Salinity from a CTD moored 20 m above the bottom in the core of the overflow at about 2000m on the East Greenland Continental Slope. The event in 2004 was observed across the width of the overflow plume from the 1250 m to 2350 m contour.

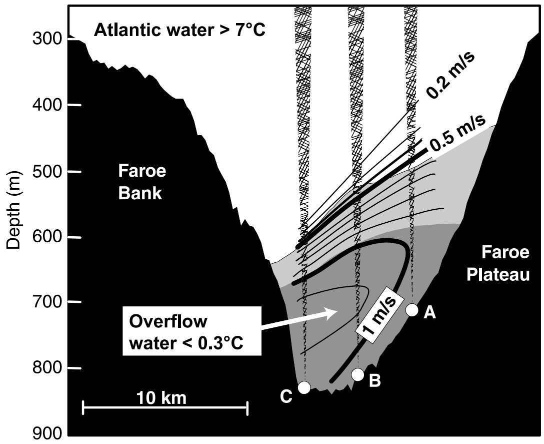

Figure 5. A cross-section over the sill of the FBC. Background shading indicates typical temperature distribution. Isolines indicate average along-channel velocity. White circles with cross-hatched cones indicate moored ADCPs with sound beams. The central ADCP (B) has been in operation since Nov 1995, the others for shorter periods.

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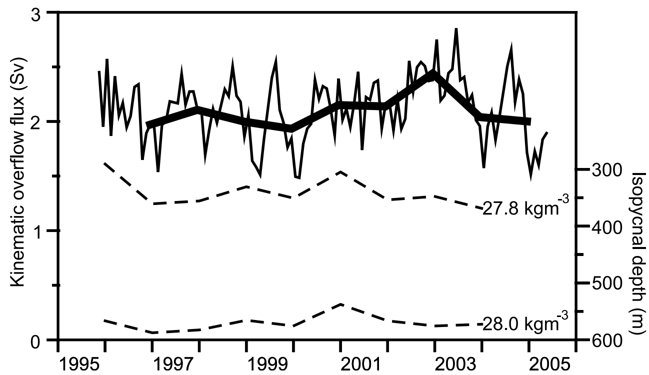

Figure 6. Monthly (thin line) and annually (thick line) averaged kinematic FBC overflow flux and depth of two isopycnals at Ocean

Time series and hydrographic variability in Icelandic waters

Héðinn Valdimarsson[1] and Steingrímur Jónsson[2]
[1]Marine Research Institute, Reykjavic, Iceland
[2]University of Akureyri and Marine Research Institute, Akureyri, Iceland
Corresponding author: hv@havro.is

Introduction

The submarine ridges that stretch from Greenland over to Scotland have profound effects on the ocean currents and climate around Iceland. The waters north and east of the country are exposed to influences coming all the way from the Arctic Ocean via the East-Greenland Current flowing south along the Greenland coast and with the East Icelandic Current, which is a branch breaking from the East Greenland Current that flows across the Iceland Sea into the Norwegian Sea. The waters south and west of the country are influenced by the North Atlantic Drift and the Sub Polar Gyre through the Irminger Current sweeping north along the western shelf and coast. As the country is lying so close to the polar front its climate and waters vary both on short and long timescales.

Regularly repeated observations in spring in Icelandic waters began around 1950, with annual surveys in connection with herring surveys north of Iceland. Seasonally repeated observations started after 1970 on stations around the country (Figure 1). These data have grown into valuable time series on climatic variability in the area and reveal interannual and decadal variability in temperature and salinity. Here we summarise the main features of the climate variability around Iceland.

North of Iceland

Station 3 (Si 3) on the Siglunes section north of Iceland has often been used as an indicator of conditions in the shelf area. It is located in the core of the warm and saline inflow of Atlantic Water of the North Icelandic Irminger Current. Correlation is generally high between the five stations south of 67°N (Malmberg and Desert, 1999). In general the variability has been related to variable inflow of Atlantic water (Jónsson and Valdimarsson, 2005), atmospheric forcing and sea-ice conditions (Malmberg and Kristmannsson, 1992, Malmberg et al 1996, Malmberg and Jónsson, 1997). Figure 2 (page 18) shows spring temperature and salinity for station Si3. Data before 1990 are from interpolated water bottle values and after that CTD data are used. The period from 1947 to 1965 was characterized by warm and saline waters. Sea surface temperature measurements suggest that warming started in the decade after 1910 (Hanna et al, 2006). The years from 1965 to 1971 have been called the "sea-ice years" when polar water and sea-ice were persistent in North Icelandic waters. These years were followed by more variable conditions in spring until 1996 whereafter Atlantic water has again been more common north of Iceland and reaching more often farther to the east on the shelf.

Variability in the East Icelandic Current is shown in Figure 3 as means for temperature and salinity on stations 2 to 4 on the section Langanes NE, in the depth interval 0 to 50 m. The section Langanes NE lies from the coast northeast to the Iceland Sea and crosses the East Icelandic Current. Prior to 1965, conditions in the Iceland Sea were warmer and more saline. During the sea-ice years the current changed from being arctic to being frequently of polar character. Since 1970, temperature and salinity have been variable without a clear trend. The cold conditions during the ice years have been associated with the Great Salinity Anomaly and with contributing to the collapse of the Norwegian spring spawning herring stock (Malmberg and Blindheim, 1994, Malmberg et al 1996, Vilhjálmsson 1997).

South and West of Iceland

South and west of Iceland there have been regular observations since 1970. These time series show climate variability, although not as dramatic as the changes in the northern area. Figure 4 shows mean temperature and salinity at station Fx 9, located off the shelf break west of Iceland, as a mean for the depth interval 0 to 200 m. This is where the core of the Irminger Current is located bringing the warmer and saline water northwards along and on the western shelf. Low salinity in the seventies has been related to "the Great Salinity Anomaly" south of Iceland (Malmberg and Kristmannsson, 1992). The fresh water in the early nineties was in the period of strong convection and cooling in the Labrador Sea. While the the warmer and more saline period after that at Fx 9 can be related to larger scale variations in the Irminger Sea and the Sub Polar Gyre (Bersch 2002, Mortensen and Valdimarsson 1999, Reverdin et al 2002, Hátún et al. 2005). Similar change in salinity and temperature

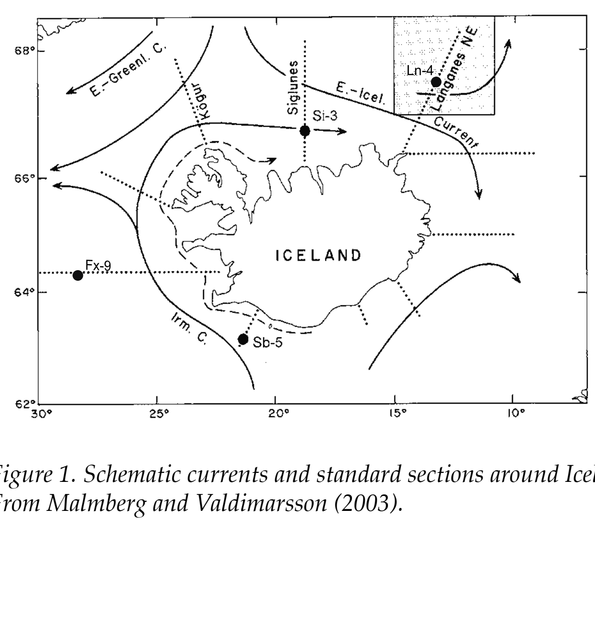

Figure 1. Schematic currents and standard sections around Iceland. From Malmberg and Valdimarsson (2003).

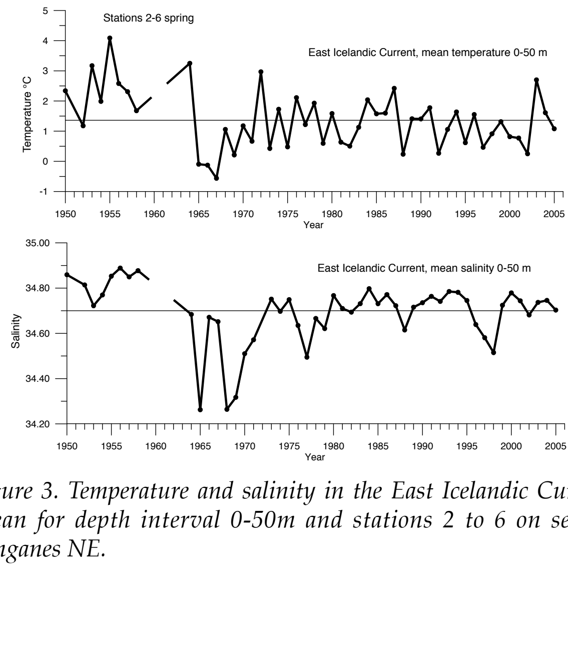

Figure 3. Temperature and salinity in the East Icelandic Current. Mean for depth interval 0-50m and stations 2 to 6 on section Langanes NE.

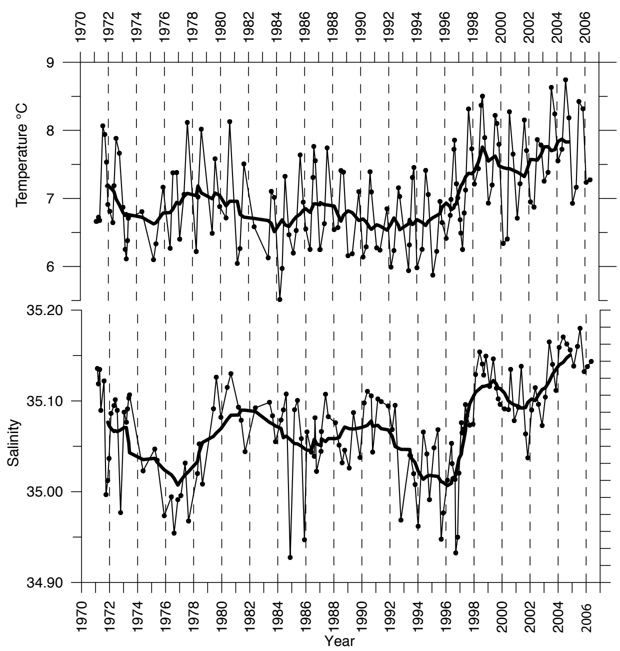

Figure 4. Mean temperature and salinity for 0 to 200 m, at station 9 at Faxafloi section (Reykjanes 8 prior to 1984). Thick line is running mean for 13 observations or approximately 3 years.

has also been observed southeast of Iceland on the Stokksnes section at station 5 (Figure 5). This station is in the warmest and most saline water around Iceland and has been showing increasing salinity and temperatures the last decade similar to that which has been observed in other regions around the sub polar gyre (Hátún et al, 2005). The time series in the waters south and west of Iceland have shown record high temperatures and salinities the most recent years, but longer time-series of sea surface temperature on the northern shelf show that similar conditions may have been the case prior to the mid 1960s and before 1880 (Hanna et al., 2006).

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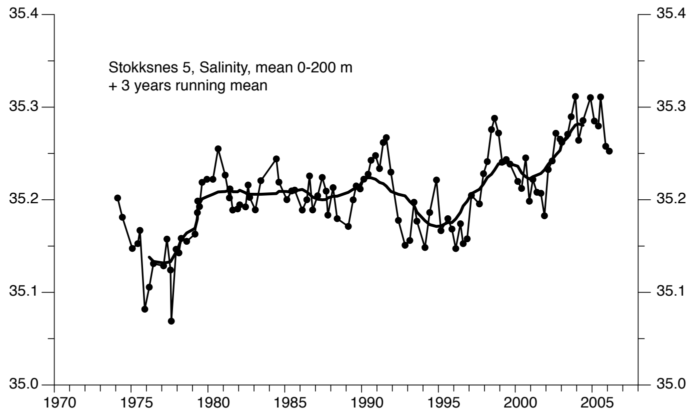

Figure 5. Salinity at Stokksnes 5 station southeast of Iceland. Mean for 0-200m depth.

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Bob Dickson

Congratulations to Bob Dickson on his award of Commander of the British Empire (CBE) by Her Majesty the Queen. Well done indeed Bob, well deserved.

Monitoring the ventilation of the Irminger and Labrador Seas

R.M. Hendry[1], H. van Aken[2], and I. Yashayaev[1]
[1]Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, Canada
[2]Royal Netherlands Institute for Sea Research, Den Burg (Texel), The Netherlands
Corresponding author: hendryr@mar.dfo-mpo.gc.ca

Introduction

The Irminger and Labrador Seas in the subpolar North Atlantic are a special part of the "cold water sphere" that makes up the bulk of the world ocean. These areas provide a direct link between the atmosphere and the deep ocean. Winter cooling and wind-mixing create deep surface mixed layers in the sub-polar oceans where vertical stratification is weak, compared to conditions in the subtropics. In episodic severe winters, buoyancy losses give rise to increases in surface density large enough to cause convective overturning that penetrates to depths as great as 2 km. Milder winters lead to lower heat losses, shallower mixed layers, and a decrease in convective activity.

Deep convection in the Labrador and Irminger Seas provides an important pathway for atmospheric gases such as oxygen, carbon dioxide, and chlorofluorocarbons (CFCs) to pass from the surface mixed layer to intermediate depths. Sub-surface flows then distribute the dissolved gases to other regions.

On an annual average, the surface waters in these areas lose heat to the overlying atmosphere and give up a corresponding amount of buoyancy. They gain fresh water (and buoyancy) from the regional excess of precipitation over evaporation, from river run-off, and from ice melt waters of Arctic origin. They gain heat and salt from warm and saline Atlantic Waters carried northward into the Irminger and Labrador Seas. Hydrographic conditions depend on a balance between air-sea heat and fresh water exchanges and advective sources. There is an energetic interannual variability in air-sea heat and momentum fluxes. Associated changes in ocean circulation modulate the inflows of fresh water from northern sources and warm and saline waters from more southerly latitudes. The result is a complex system with strong interannual variability.

Historical background

Recent studies have emphasized the role of the Labrador Sea in the ventilation of the sub-polar North Atlantic. Lazier (1980) observed winter mixed layers of Labrador Sea Water (LSW) as shallow as 200 m and as deep as 1500 m in 1963-1974 data from Ocean Weather Station (OWS) Bravo (Figure 1). Clarke and Gascard (1983) observed convection to 1600 m depths in the same area in early 1976. They pointed out that the 1976 vintage of LSW had temperature and salinity properties quite different from mode waters formed in earlier years.

Convection creates water masses with low or vanishing vertical stratification and correspondingly low values of potential vorticity. The mode water properties set during the formation processes evolve only slowly after the newly-formed water masses are removed from contact with the overlying atmosphere by seasonal restratification. Talley and McCartney (1982) used potential vorticity as a tracer to study the distribution of sub-polar mode waters in the northern North Atlantic. They concluded that LSW formed in the Labrador Sea was exported along several paths, including one leading north-eastward into the Irminger Sea.

Bacon et al. (2003) and Pickart et al. (2003a, 2003b) argue that mode water formation with properties similar to LSW also occurs in the Irminger Sea. Pickard et al. (2003b) review earlier studies suggesting significant formation of sub-polar mode waters occurred in the Irminger Sea; they remark that an historical bias may have been introduced because OWS Alpha (Figure 1) was in an unfavourable location for deep convection. Pickart et al. (2003a) also recognized the importance of LSW exports to the Irminger Sea.

The AR7 Section

The AR7 section (Figure 1) subdivided into western (AR7W) and eastern (AR7E) segments was one of the repeat sections occupied during the World Ocean Circulation Experiment (WOCE). The rationale for repeating this section (Needler and Koltermann et al., 1988) included the charge to "Estimate amounts and characteristics of various mode waters transformed during each successive cooling cycle." In 1990, Canada began a series of annual early summer occupations of the AR7W Labrador Sea section as a contribution to WOCE. At the same time, investigators from Germany and the Netherlands began repeated occupations of the AR7E section.

Following the end of the WOCE field program in 1997, national research and monitoring efforts by Canada (DFO, BIO), Germany (IfM Hamburg), and the Netherlands (NIOZ, Texel) have maintained regular occupations of AR7W and AR7E. The resulting high quality hydrographic measurements contribute to the CLIVAR goal of describing and understanding ocean processes responsible for climate variability and predictability. Annual updates of conditions in the Labrador and Irminger Seas based on the surveys are reported in the annual ICES Report on Ocean Climate.

Recent results

The sub-polar North Atlantic has experienced major atmospheric and oceanic changes in the 17-year period of repeated AR7 surveys. As one example, Figure 2 shows January-February-March (JFM) sea-air heat flux anomalies from the west-central Labrador Sea and the west-central Irminger Sea from NCEP Reanalysis data. Maximum heat losses occur in winter months, and the interannual variability is dominated by changes in heat loss during these months. The variance in the Irminger Sea is about half that observed in the Labrador Sea, but the forcing is qualitatively similar in the two areas. Both areas show a period of increased wintertime heat flux associated with the severe winters of the early 1990s and a subsequent trend toward milder winters and lower heat losses. The NCEP Reanalysis

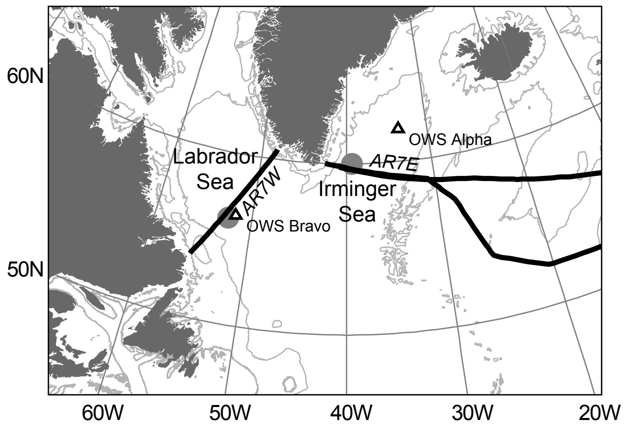

Figure 1. Chart showing the AR7 sections. Marked positions are: OWS Alpha and Bravo (triangles) and NCEP Reanalysis grid points (filled circles).

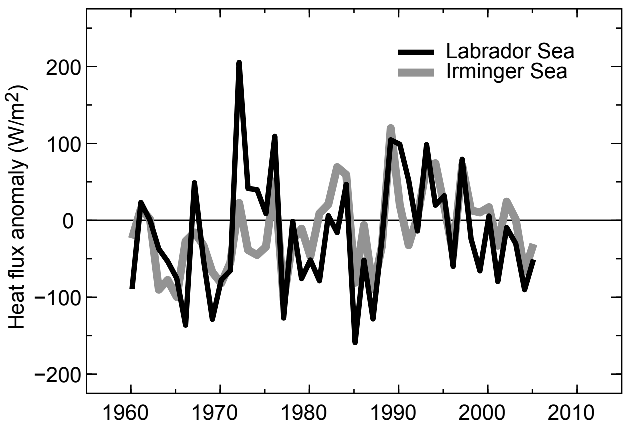

Figure 2. Time series of JFM NCEP Reanalysis sea-air heat flux anomalies relative to 1971-2000 from 1960 to 2005 for the west-central Labrador Sea (black line) and the west-central Irminger Sea (grey line).

values provide at least a qualitative overview but probably overestimate the true fluxes (Renfrew et al., 2002).

The upper layers of the Labrador Sea re-stratify rapidly (Lazier, 1980) but annual surveys can monitor the interannual evolution of sub-surface signatures of winter convection. Lazier et al. (2002) discuss the development of deep convection in the Labrador Sea in the early 1990s and the restratification phase that followed based on AR7W surveys from 1990-2000

Figure 3 (page 18) shows time series of the pressure on selected potential density anomaly surfaces from average profiles in the west-central Labrador Sea (spring and early summer surveys) and the central Irminger Sea (late-summer surveys) as an overview of inter-annual variability of the ventilation of the Labrador and Irminger Seas based on AR7 surveys since 1990. Pressures within two potential density anomaly intervals shaded in Figure 3 where vertical minima in potential vorticity were encountered are marked with colour-coded filled circles.

Lower layer 27.76 - 27.81 kg/m^3

The wide separation during the early 1990s of the potential density anomaly surfaces bounding the deeper shaded layer in the left panel of Figure 3 reflects the deep convection in the Labrador Sea discussed by Lazier et al. (2002). The maximum separation was observed in 1993. Figure 3 shows increasingly thick homogeneous layers in the same density range in the Irminger Sea in the early 1990s, reaching a maximum in 1995. Note that no Irminger Sea observations are available for 1993. The deep layers thinned rapidly after reaching maximum thickness.

Figure 4 shows time series of minimum potential vorticity for each of the two layers in Figure 3. Low values of potential vorticity correspond to widely separated isopycnals.

The deep convection in the Labrador Sea in the early 1990s is reflected in the low values of lower-layer minimum potential vorticity during 1991-1994 (blue symbols in Figure 3). The core of this early 1990s LSW had potential temperature near 2.7 ˚C, salinity near 34.83, and potential density anomaly near 27.78 kg/m^3. The volume of water in this potential density range decreased rapidly from 1995 to 1999, and decreased more slowly in subsequent years. The minimum potential vorticity in this layer has steadily increased since 1994. Figure 4 shows minima in potential vorticity in the lower layer in the Irminger Sea in the summers of 1994 and 1995 that were essentially identical to the extreme minima in the Labrador Sea. From 1996 onwards the minimum potential vorticity in the deeper Irminger Sea layer increased in step with the corresponding Labrador Sea values. The Irminger Sea values appear to have levelled off since about 2004.

Upper layer 27.71 - 27.75 kg/m^3

The upper shaded layers in Figure 3 with potential density anomalies in the 27.71 - 27.75 kg/m^3 range show an increase in thickness beginning in the late 1990s in both the Labrador and Irminger Seas. A low-stratification upper layer marked by a relative minimum in potential vorticity first appeared in the Labrador Sea in 1997 and was well-established by 2000. For the most-recent four-year period the shallower Labrador Sea layer is characterized by potential temperatures near 3.3 ˚C, salinities near 34.84, and potential density anomalies near 27.73 kg/m^3. Figure 3 shows a similar but less prominent increase in thickness of the upper Irminger Sea layer since 1999. The associated values of minimum potential vorticity in Figure 4 are higher than the corresponding Labrador Sea values. In recent years the shallow Irminger Sea layer is characterized by potential density anomalies near 27.74 kg/m^3, slightly higher than the corresponding Labrador Sea values. The fact that the AR7W surveys took place in late spring or early summer and most of the AR7E section took place in late summer/early autumn may contribute to the observed differences between the two regions. In any case, the complex but regionally-coherent upper-layer signal suggests renewed mode water formation involving less-dense and shallower winter mixed layers.

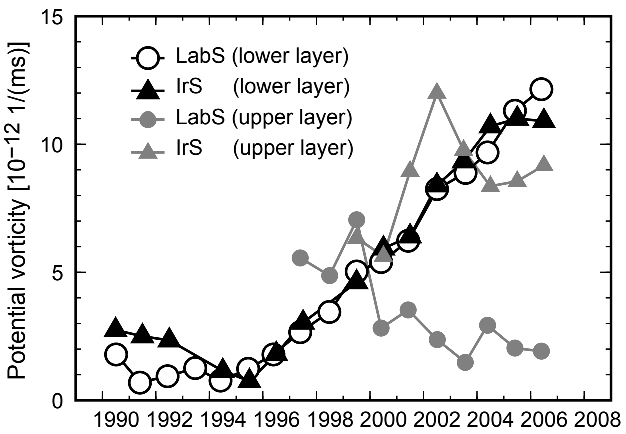

Figure 4. Minimum potential vorticity for the two potential density layers 27.76–27.81 kg/m^3 (lower layer) and 27.71–27.75 kg/m^3 (upper layer) in the west-central Labrador Sea (LabS) and the central Irminger Sea (IrS).

Tracers

Many of the AR7 surveys include related chemical measurements. Examples from occupations of AR7E are presented in Figure 5. The left panel of Figure 5 shows dissolved oxygen profiles from the centre of the Irminger Sea from 1991, 1994, 1997, 2000, and 2005. Maxima in dissolved oxygen concentrations near 1200 dbar in the 1994 profile reflect the ventilation of these layers by the deep overturning that occurred in the early 1990s. Oxygen concentration in the upper 1200 dbar decreased significantly by the time of the 1997 survey. In 2000, a shallow oxygen maximum had developed near 650 dbar, corresponding to the shallow convection regime discussed above. The 2005 oxygen profile shows a weaker subsurface maximum near 760 dbar.

The right panel of Figure 5 shows profiles of total dissolved inorganic carbon (total CO_2) measured in the Irminger Sea in 1991 and 2005. Between these two surveys total CO_2 increased significantly by more than 10 μmol/kg at the intermediate levels (~400 to 1800 dbar) where the mode waters are found. The details of these changes are related partly to changes in the convective formation of the mode waters. The secular trend is related to the anthropogenic increase in atmospheric CO_2.

Summary and Outlook

The hydrographic properties of the Labrador and Irminger Seas share the strong inter-annual variability of the larger-scale North Atlantic climate system. AR7 surveys since the early 1990s saw a period of intense deep convection and abundant mode water formation, followed by a period of re-stratification and a present-day trend to warmer and more saline conditions. A shallower convective regime appears to have established itself in recent years.

The historical record suggests that natural variability on decadal time scales will continue to force intermittent deep convection such as observed in the mid-1970s and the early 1990s. The controlling balances are complex and potentially sensitive to shifts in climatic conditions such as could be caused by global warming. Continuing the AR7 surveys is one way of monitoring climate variability in this important region.

Acknowledgements

The work of colleagues nationally and internationally have contributed to the AR7 repeat hydrography effort. The German Institut für Meereskunde der Universität Hamburg (IfM Hamburg) and Bundesamt für Seeschifffahrt und Hydrographie (BSH) made essential contributions to this work. Preliminary CO_2 data were made available by H. Zemmelink and S. van Heuven. NCEP Reanalysis data were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA (http://www.cdc.noaa.gov/). H. v.A acknowledges the support of the Netherlands Organisation for Scientific Research (NWO) and the BSIK national infrastructure programme.

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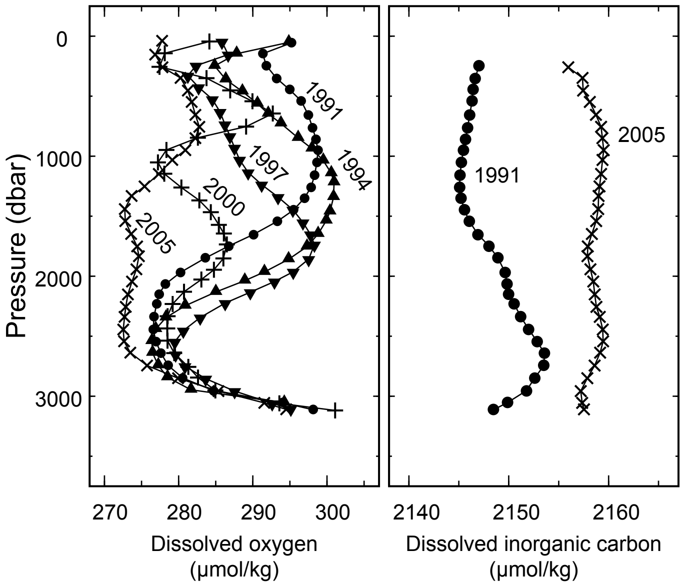

Figure 5. Profiles of dissolved oxygen and total dissolved inorganic carbon (total CO_2) in the centre of the Irminger Sea, measured during different surveys of the AR7E section. Several deep stations from each survey were combined, and some smoothing and interpolation was applied to produce these profiles.

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The CLIVAR/CliC/SCAR Southern Ocean region panel

Sparrow, M.D., K. Speer, I. Renfrew on behalf of the panel and meeting attendees
Corresponding author: m.sparrow@noc.soton.ac.uk

The 4th meeting of the Southern Ocean region panel was held from 14-17 November 2006 in the beautiful Palacio San Martín in Buenos Aires, Argentina.

The first half of the third day was given over to a "Science Morning" consisting of a series of talks and discussions led by local scientists. The subjects of the talks ranged from the influence of the Southern Ocean on climate variability of South America to glacio-climatic investigations in southern Patagonia and Antarctic Peninsula. This provided a good opportunity for the panel and invited experts to interact with local scientists and students and for everyone to see some of the excellent work being done by scientists in Argentina.

Since the last meeting there have been several changes in membership to reflect a more climate rather than ocean focus to the panel (see http://www.clivar.org/organization/southern/members.php). Thus the panel aimed to build on its past activities and strengths, such as involvement with the International Polar Year (IPY) through e.g. the Climate of Antarctica and the Southern Ocean (CASO) project, but also had a strong emphasis on cross-cutting climate questions such as climate indices, IPCC model runs a focus on the whole (ocean-atmosphere-cryosphere) observing system (particularly post-IPY). We summarize some of the main themes tackled during the meeting below.

IPY and the Southern Ocean Observing System

The International Polar Year provides an unprecedented opportunity to improve our observational capacity within and our knowledge of Antarctica and the surrounding oceans (as well as the equivalent northern high latitude system). The panel's involvement in IPY has been mainly through the CASO umbrella project (the lead project in the Ocean Circulation cluster in the south). See: http://www.clivar.org/organization/southern/CASO/index.htm. CASO aims to:

- Obtain the first circumpolar snapshot of the Southern Ocean, including physical, ecological and biogeochemical properties
- Measure the circumpolar extent and thickness of Antarctic sea ice through an annual cycle for the first time
- Observe the sub-ice ocean circulation, water mass properties and biological distributions

Although it should be possible to achieve many aspects of the original aims, it will not be possible to do as much as was originally envisaged. For example, there will be a lack of zonal lines/moorings in the subtropical Indian and Pacific and, crucially, many sections may not be done on ice breakers. Expanding under-ice Argo was also seen to be a priority: at the moment there is good coverage in the Weddell Sea but little elsewhere. The use of animal-borne CTDs (e.g. the SEaOS project: http://biology.st-andrews.ac.uk/seaos/) is one promising method of helping to fill this gap. The meeting attendees also noted that there seemed to be no integrated modeling structure within IPY and drafting recommendations for this was seen as a key action item.

The panel felt that a priority was a plan for a post-IPY sustained observing system. This would link strongly with the Southern Ocean Observing System (SOOS) being coordinated by the SCAR/SCOR Oceanography Expert Group. The current state of the observing system is summarised on the panel's website at: http://www.clivar.org/organization/southern/CLIVAR_CliC_Obs.html. Whereas IPY will give the first true snapshot of the Southern Ocean any future sustained observing system is needed to give a measure of the variability in the system. The optimal requirements of any such system are being discussed by the panel, but some initial ideas include:

- Repeat at least six of the shorter sections every 2-5 years
- Moorings/stations on select sections, mainly for properties
- Argo plus sea-ice zone observations
- Meteorological buoys/stations

As well as the sustained observing system, a discussion was held on possible future process studies in the region. Such process studies are required to parameterise certain processes in models. Several suggestions were made, for example process studies to look at the grounding line and shelf slope exchange.

On a related matter, an IPY-era synthesis was also proposed. Groups involved in synthesis noted that they plan to extend the current syntheses through IPY, so the output will be available.

Attendees of the 4th CLIVAR/CliC/SCAR Southern Ocean region panel meeting in the Palacio San Martin in Buenos Aires

What is also suggested is that seed funds for analyses be made available, perhaps along the lines of what was done for the IPCC 4th assessment model runs, in order to fully exploit the new information from polar regions.

Indices in the Southern Ocean Region

The use of indices to describe the state of the climate system by examining the connections between the ocean, cryosphere and atmosphere is well known (e.g. ENSO, SAM etc.). Groups such as the Ocean Observations Panel for Climate (OOPC) and the CCI/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETTCDI) are interested in such indices, especially those that could be used to help give an idea of model skill. One goal of this meeting was to suggest and develop ideas for new indices in the Southern Ocean region, e.g. a scalar index of the state of a feature of the climate system that is known to vary over daily to decadal timescales. A summary of the proposed indices will be made available on the panel's webpage (http://www.clivar.org/organization/southern/southern.php).

Ice Shelves and Climate Change

The Panel recognised that one of the largest uncertainties regarding sea level changes in the future come from possible ice shelf movement. Progress could be made in reducing uncertainties of sea-level rise with a concerted effort to monitor the grounding line, representing the boundary between the ice sheet and the ocean. Measuring and modelling the characteristics of convection in ice-shelf cavities, calving, and the intersection of ice streams with the ocean are necessary parts of this effort. As a step in this direction the panel recommended establishing a remotely-sensed "grounding line index" based, for example, on Rignot et al (1998). Eventually an operational system for monitoring the circumpolar location of the grounding line could be put into place and maintained. Another step is to create ocean and ice-sheet models capable of exchanging mass with one another, i.e., possessing a migrating grounding line capability.

IPCC Models in the Southern Ocean Region

The Southern Ocean is one of the regions where the scatter between the results of the different IPCC models is the largest, both for the last 30 years, for which we have relatively good observation data to compare models with, and for future projections. The panel therefore devoted much of an afternoon to discussing how the IPCC models fare in the Southern Ocean region. The text below outlines some of the main points. A full summary will appear in the meeting report.

The climate simulation of the southern extratropics has improved since the Third Assessment Report. In addition, most coupled models no longer employ flux adjustments. However, large biases in many aspects of the Southern Ocean system in individual models still persist. In particular, the westerly wind stress maximum and the location of the Antarctic Circumpolar Current (ACC) are usually placed too far north in most models.

In general, models with sufficient resolution show considerable skill in reproducing extratropical storm tracks. However, simulated storm tracks are often too zonally oriented and many models show deficiencies in the distribution, intensity and number of cyclones.

Both observations and simulations show a trend in the Southern Annular Mode (SAM) towards its positive phase. The associated poleward shift of the storm tracks is accompanied by a similar shift in the midlatitude jets and surface zonal wind stress which in turn is important for driving upwelling in the Southern Ocean and the ACC flow through the Drake Passage.

Despite the large scatter between the various models, the multimodel average sea ice extent is in good agreement with the observations, meaning that there is apparently no systematic bias in the models. On the other hand, the models generally tend to overestimate the variability of the ice extent compared to observations.

Over the 20th century, the multimodel average simulates a stronger warming around the peninsula compared to other regions, which is in qualitative agreement with observations.

The simulated strength of the ACC varies a lot between the different models, ranging from less than 50Sv to more than 200 Sv. Various factors could explain those large inter-model differences. In particular, the strength of the westerly wind over Drake Passage and the salinity gradient across the ACC seem to play a dominant role.

The large variability in the Southern Ocean region on interannual to interdecadal time scales poses problems in the assessment of the quality of model simulations and in the finding of robust signals. Longer times series of surface temperature and sea ice extent, for instance, would be particularly helpful in this context, enabling better estimates of the observed interdecadal variability and trends over the 20th century and allowing us to better check model preformance.

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Report of the second session of the CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices

A. Caltabiano, F. Zweirs and A. Klein–Tank, on behalf of the panel and meeting attendees.
Corresponding author: caetano@noc.soton.ac.uk

The Expert Team on Climate Change Detection and Indices (ETCCDI) is a joint panel co-sponsored by the World Meteorological Organisation (WMO) Commission for Climatology (CCl), CLIVAR, and more recently, by the Joint Commission for Oceanography and Marine Meteorology (JCOMM). It has recently had its membership reviewed in order to accommodate members from each of the sponsors. The new members are Francis Zwiers (Environment Canada, co-chair), Albert Klein-Tank (KNMI, The Netherlands, co-chair), Phil Jones (UEA, UK), David Karoly (University of Oklahoma, USA), Gabriele Hegerl (Duke University, USA), Blair Trewin (BoM, Australia), Xuebin Zhang (Environment Canada), Brad Garanganga (DMC, Zimbabwe), Chris Folland (MetOffice, UK), Elizabeth Kent (NOCS, UK), Val Swail (Environment Canada) and Scott Woodruff (NOAA, USA)

The panel met for its second session in the picturesque Canadian town of Niagara-on-the-Lake, on 14-16 November 2006. In addition to panelists, other invited experts who also attended the meeting and greatly contributed to the discussions that took place were Matthew Palmer (Met Office, UK), Tom Peterson (NCDC/NOAA, USA), Xiaolan Wang (Environment Canada) and Lucy Vincent (Environment Canada). Panel co-chair and host, Francis Zwiers opened the meeting welcoming all the participants and made a review of the work developed by the previous Expert Team which was co-sponsored by CCl and CLIVAR only. It was very successful in contributing to the WCRP cross-cutting topic on Anthropogenic Climate Change, through the sponsorship and organisation of regional workshops held in Jamaica, Marocco, South Africa, Brazil, Turkey, Guatemala and India. Participants helped in analysing changes in extremes, and produced a number of published peer-reviewed papers on climate change. Further to these papers, the data assembled during these workshops were helpful in filling gaps in the global datasets, and have been used in a global extremes indices paper, which was done in time to contribute to IPCC AR4. In a number of studies, the global indices data have also been compared to GCM simulations. Moreover, the workshops had an important component as a capacity building mechanism. One of the main outcomes of the ET in preparation for the workshops was the development of a user-friendly software package with user guide written in English and Spanish.

Representatives of the three sponsors of the ETCCDI gave presentations highlighting their perspective on the ET and contributions for a successful development of a work plan for the next three years. Tom Peterson and Omar Baddour gave a presentation on CCl background and WMO programmes with a focus on climate. This included an overview of the structural organisation and planned activities. Nico Caltabiano presented an overview of CLIVAR structure and the "CLIVAR Road Map", as planned during the 14th Session of the CLIVAR Scientific Steering Group (SSG) in Buenos Aires, April 2006. The presentation focused on the aspects of the Road Map that are relevant to the ET, with contributions to the understanding of Anthropogenic Climate Change (ACC), and to ocean observations and the CLIVAR legacy. Val Swail and Scott Woodruff presented the structural organisation of JCOMM, and the contribution that can be made toward ocean indices based on surface and sub-surface variables.

The ET played an important role in the IPCC Fourth Assessment by developing and further understanding indices of climate change, by producing indices with greater geographical coverage than previously available and engaging in their analysis. With JCOMM as a new co-sponsor, the ET had extensive discussion to explore the best approaches to developing ocean and surface marine indices that would be complementary to the terrestrial indices that it has focussed on previously. Chris Folland presented a review of worldwide indices and how they might be best presented to the community. The considerations he identified included: (1) Indices should be primarily based on observed data. However this may include reanalyses where it is judged the science allows this; (2) Wherever possible, indices should have estimates of uncertainty attached to them; (3) Indices, with uncertainties, should be based on more than one recognised data set where possible; and, (4) given an emphasis on Climate Change Detection or even the time scales of seasonal to decadal prediction, selected model predictions of such indices could be usefully displayed side by side with the observed counterparts. Elisabeth Kent led a discussion on surface marine datasets and indices. She indicated that while the inhomogeneity of marine meteorological data is a recognized problem, in situ data products are well advanced in the development of uncertainty estimates. There are still several questions to be addressed as how one can extend the range of marine meteorological indices and to what extent they can be calculated similarly to indices over land. It was agreed that the ET JCOMM representatives would consult extensively with other JCOMM experts and develop a plan to address these issues. Other contributions to the discussion relating to marine and oceanic indices were made by Matthew Palmer, who presented Hadley Centre's subsurface ocean analyses, and Nico Caltabiano, who discussed OOPC's State of the Ocean Climate report, a compilation of ocean climate indices which have been calculated using observational analyses.

Several institutional and organisational partners to the development of the ET plans have been identified. The Asia-Pacific Network (APN) for Global Change Research and the European Climate Assessment & Dataset Project (ECA&D) are two of them. APN has given strong emphasis in capacity building initiatives in the region, and plans to further develop these activities in collaboration with the ET. ECA&D has participants from 42 countries throughout Europe and the Mediterranean. The ECA&D website presents indices for monitoring and analysing changes in climate extremes, as well as the daily datasets needed to calculate these indices. The ET will certainly benefit from the expertise developed by the project in its plans to further use daily data to calculate indices. The final part of the meeting was used for discussion on the further development of the R-based indices software (Xuebin Zhang), which was used in the workshops organised previously, and new methods, algorithms and software to be used for Climate Data Homogenization (Xiaolan Wang). These discussions were very welcome in the production of the ET workplan. The workplan contains new ideas for future workshops, which will update the earlier results and serve as inspiration for continued data rescue and digitization. The ET discussed the possibility to follow some of the thematic APN workshops, which have dealt with metadata and data management. It has already received requests to have workshops that focus on data homogeneity. Final decisions on themes and venues have yet to be decided based on funding opportunities. The workplan and a full meeting report will be available soon. The panel would also like to thank Environment Canada, CCl, WCRP and USCLIVAR for the support provided for the realisation of this meeting.

Report of the second session of the Global Synthesis and Observations Panel

A. Caltabiano, D. Roemmich and D Stammer, on behalf of the panel and meeting attendees.
Corresponding author: caetano@noc.soton.ac.uk

With sunny days and the beautiful views of La Jolla beaches, the Global Synthesis and Observations Panel (GSOP) had its second session at the Scripps Institution of Oceanography on 8-9 December 2006. The meeting had a very good attendance, with panel members, several invited participants, as well as representatives from funding agencies. Panel co-chair Dean Roemmich opened the meeting and charged the panel to focus the discussions on how to demonstrate the value of the existing observing system to society. With levels of funding not rising and with an evolving observing system, it is key to identify which pieces of the observing system will continue to be developed. GSOP is not the only group concerned with the present status of the observing system, but it has a strong voice for needs of climate research since it works towards achieving CLIVAR goals. The meeting was structured in four parts: (1) reports of recent meetings relevant to GSOP, (2) science talks related to global CLIVAR science questions, (3) a review of CLIVAR datasets and data centres, and (4) reports on the status of the observing system on the ocean basins.

Detlef Stammer, GSOP co-chair, presented the outcomes of the 14th session of the CLIVAR Scientific Steering Group, held in Buenos Aires, April 2006, and also the structure of the CLIVAR Road Map, Specifically for GSOP, it seems that one of the key aspects would be helping with the availability of long-term, good quality climate datasets. However, this is a certainly a big task, which might require extra funding to be successful. Therefore, it should be focused first of all on identifying the major gaps in the available datasets for CLIVAR synthesis needs. Detlef Stammer also reported on the second meeting of the WCRP Observation and Assimilation Panel (WOAP). Previously to that meeting, a matrix on data management with information on data policy, metadata, web sites was prepared by T. Koike, with input from GSOP on CLIVAR's data management. This has highlighted the issue on general data management within WCRP. All existing efforts were developed independently, however there is a perception that it needs to be homogenized to ensure synergies. A WCRP task group on data management is being set up by WOAP, with one representative from each of WCRP projects. It will review the status and management of observational data and model output archives, including web sites within WCRP and make recommendations for WCRP-wide overarching structure, site contents and data policy. GSOP, as the panel responsible for such issues within CLIVAR, will nominate CLIVAR's representative to this task force. Another issue discussed at that meeting was on the reprocessing of global datasets to produce high quality reference datasets. As part of the Global Synthesis Evaluation Framework activity led by GSOP (in association with GODAE), CLIVAR is focussed around the concept and goal of "ocean reanalysis" products that synthesize all available ocean satellite and in situ observations by merging them with ocean models using assimilation techniques. Ocean reference datasets and their error fields are required as input for the synthesis efforts, but also to help evaluate the skill, usefulness and limitations of various synthesis and modeling approaches.

Albert Fischer, Ocean Observations Panel for Climate (OOPC)'s Technical Officer, reported on the OOPC's Eleventh Session, held in Tokyo in May 2006. OOPC is planning several international workshops in some areas where there is scope for expert meetings. One of the identified areas is a workshop on ocean sensors, with focus on emerging technologies for autonomous biogeochemical and ecosystems monitoring. Also, a review of the strategy for XBT observations (frequently-repeated and high-density sections) might be necessary in light of Argo. The outcomes of the WCRP/COPES Sea Level Workshop, held in Paris, June 2006, was shown by Stan Wilson, co-chair of the workshop's steering committee. He showed that results presented at the workshop indicate that since 1992, sea level is raising at a rate of 3 mm/yr based on tide gauges and satellite altimeters, compared to a rate of 2 mm/yr over the previous century and based on tide gauges alone. There are still some uncertainties and the workshop participants have made strong recommendations for the completion of a sustained, systematic observing system, for sea level studies.

Masao Fukasawa, co-chair of the organising committee for the International Repeat Hydrography Workshop, held in Japan, November 2005, presented the recommendations made by the participants. One of the objectives of the workshop was to review the post-WOCE global ship-based hydrography activities. The workshop participants felt that the Repeat Hydrography Program network needs to be sustainable. Therefore, they identified the need to establish a International Repeat Hydrography and Carbon (IRHC) Advisory Group, which would be co-sponsored by the International Ocean Carbon Coordination Project (IOCCP), CLIVAR-GSOP, and SOLAS/IMBER Joint Carbon Coordination Group. Names have been identified to take part in this advisory group and the participants of the GSOP meeting endorsed the creation of this group. Detlef Stammer also reported on the CLIVAR/GODAE Meeting on Ocean Synthesis Evaluation, held at ECMWF, UK, in August 2006. This workshop has been unique regarding the amount of collaborative effort among the ocean synthesis groups in providing outputs for the evaluation project, the main goal of which was to evaluate the quality and skill of available global synthesis products and determine their usefulness for CLIVAR. The results presented will serve as a basis for future recommendations made by CLIVAR with regard to future synthesis resource planning.

Chris Sabine presented the first of the science talks held during the GSOP meeting, on the basic approaches of inventories, fluxes and processes used in carbon research, and showed some of the latest results on decadal variability of the ocean carbon cycle based on the results of the WOCE/JGOFS and CLIVAR/ CO_2 Repeat Hydrography Lines. Josh Willis talked next on the "Global Ocean Heat Content", showing the historical estimates and the recent variability of ocean heat content, and the implications for sea level. Josh stressed out the need for sustained observations using in situ instrumentation (eg, Argo), altimetric and graviometric satellite missions. Mike McPhaden gave a presentation on the "Shallow overturning circulation in the Pacific Ocean", where he used observational datasets to evaluate 20th century climate simulations of the tropical Pacific. The eddy permitting MIROCH model seems to be the only one among those included in the study that reasonably reproduces the observed trends in transport convergence, tropical Pacific SST, and SST gradient along the equator over the last half century.

Trends in the southern mid-latitude ocean circulation and water mass formation in the Southern Ocean were discussed in the next two talks by Wenju Cai and Bernadette Sloyan, respectively. Wenju Cai showed that ozone depletion is able to account for most of the change in surface wind in the southern mid-latitudes. Forcing the ocean with the observed wind change produced strong changes in the ocean circulation. The change features a southward shift and intensification of the gyre circulation of the entire mid-latitude Southern Ocean, intensifying by 20% the Eastern Australian Current flow through the Tasman Sea, advecting more warm water south. Bernadette Sloyan presented the results of a study where observations in the formation regions of SAMW and Antarctic Intermediate Water (AAIW) have been compared with climate models. Climate models, with few exceptions, provide a reasonable simulation of SAMW and AAIW in the Southern Ocean. However, in the formation regions, models generally better simulate those water masses in the eastern Pacific Ocean than in the eastern Indian Ocean.

Representatives of all CLIVAR Basin Panels reported the status of the observing system in the regions to GSOP. For the Atlantic, details of the Tropical Atlantic Circulation Experiment (TACE) network were presented. Several moorings will be deployed in extension to the PIRATA array, and several cruises are planned during the core period of the study (2006-2011). The implementation of the Indian Ocean Observing System is well underway. Several moorings have already been deployed in the eastern basin, with strong participation of countries in the region during the deployments. In the Pacific Ocean, two new process studies have been endorsed by the Pacific Panel. VOCALS, which will study the air-sea-land interaction in the southeastern Pacific, has been funded and the field campaigns are planned to start in 2007. The Southwest PacIfic Ocean Circulation and Climate Experiment (SPICE) is still in the planning stages but plans to address many open scientific questions in the southwestern Pacific, with a strong observational component as part of its implementation plan. The status of the observing system in high latitudes, as well plans for the International Polar Year (IPY), were also presented to GSOP. The CLIVAR/CliC/SCAR Southern Ocean Panel has taken the lead in developing plans for IPY in the Southern Ocean, and several activities planned have originated at panel discussions. In the Arctic Ocean, there are a large number of experiments and field campaigns planned to happen during IPY, in a multinational effort to improve the observations in the region.

To finalise the meeting, the participants had an extensive discussion on two issues: data management and plans for an international conference on Ocean Observations. Regarding data management, it is recognised that there are several partners to CLIVAR in providing data to scientists. GSOP, as the responsible panel for overseeing data management activities for CLIVAR, will seek to work closely with these projects, identifying the existing gaps on the data streams and making sure that data collected flows to international data centres. The discussion around the international conference centred in identifying the focus for such event. It was recognised that it is time to demonstrate to society the real value of ocean observations, and include monitoring for ocean biogeochemistry, ecosystem and fisheries. It should also focus on challenges and opportunities, reaffirming commitments to current plans, with a view to seeking increasing funding for sustained observations now funded by research.

The panel would like to thank the support provided by WCRP and US CLIVAR for the realisation of this meeting.

Web Tip: Glossary Explains NAO, PDO, SAM, and other Persistent Patterns

A new glossary from UCAR Communications provides context for recent headline-grabbing weather, from record-setting blizzards on the High Plains to persistent warmth in the Northeast to the lack of snow in northern Europe.

Much of this action is related to persistent patterns that shape weather and climate across large parts of the globe. These include El Nino, the North Atlantic Oscillation, and a pair of polar cycles called the Northern and Southern Annular modes. Also part of the mix are rising global temperatures due to human-produced greenhouse gases.

What are these complex patterns, and how do they influence weather and climate? How is climate change affecting patterns such as El Nino and the NAO? Find quick answers online,: http://www.ucar.edu/news/backgrounders/patterns.shtml

For more information, contact Zhenya Gallon at zhenya@ucar.edu, or see the Web page

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If undelivered please return to:
International CLIVAR Project Office
National Oceanography Centre Southampton
University of Southampton Waterfront Campus
Southampton, SO14 3ZH, United Kingdom