Version 1.1

ASOF

Arctic/Subarctic Ocean Fluxes

The Arctic-Subarctic Ocean Flux Study: rationale, scope and methods

The Earth is warming. According to the current report of the IPCC, "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" (IPCC, 2001, Summary for Policymakers, p10). Whether this conclusion is right or not, we certainly find that when we plot surface temperature anomalies as a function of time and latitude, the warmth of recent decades has an almost global span (Figure 1).

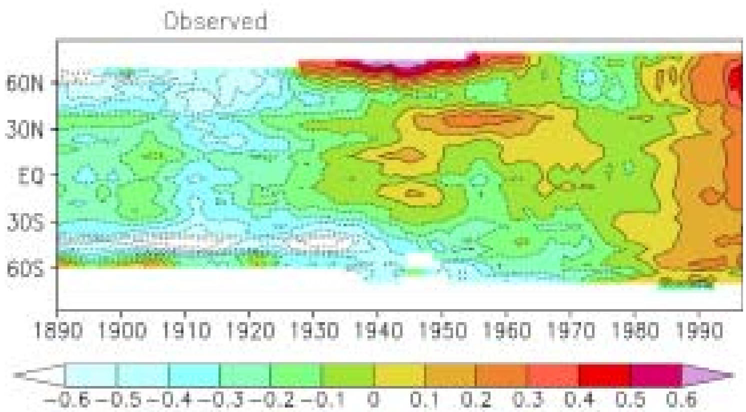

Figure 1. Zonally-averaged anomalies of global surface temperature during the past Century, plotted by time and latitude, and showing an almost global span of warming in recent decades. From Delworth and Knutson (2000).

If Man's activities really are forcing this change, then there are clues as to how the ocean ---- and in particular the Atlantic --- should respond [IPCC, 2001; see also Banks and Wood, 2002]. Most, but by no means all, projections of greenhouse gas induced climate change anticipate a weakened meridional overturning circulation (MOC) in the North Atlantic as a result of increased freshening and warming in subpolar seas (Figure 2).

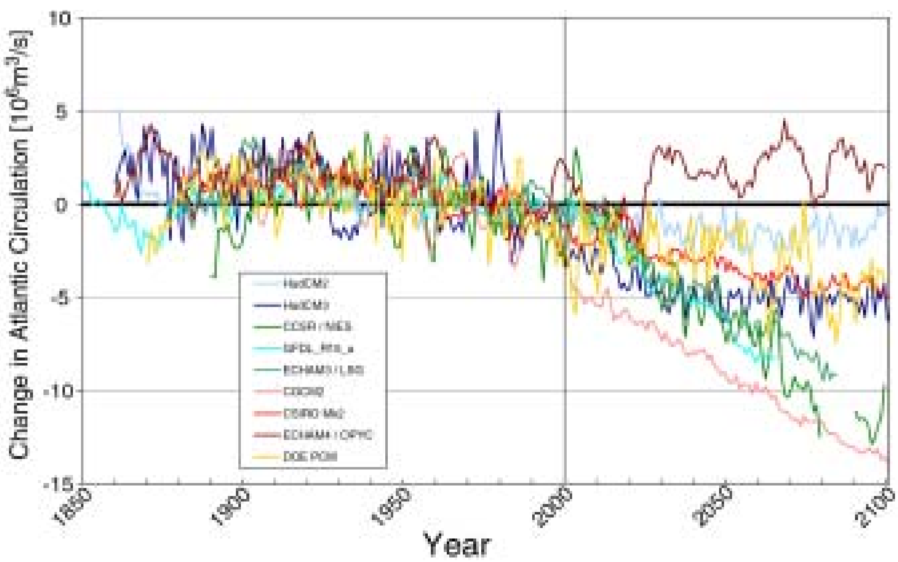

Figure 2. Anomaly of the maximum meridional overturning streamfunction in the Atlantic for a series of coupled model simulations. From IPCC 2001. All assume the same scenario of increasing CO_2, though with different responses to heat and freshwater fluxes, and most indicate a reduction in the overturning rate.

Regional models have highlighted specific '*vulnerabilities*' of the MOC to changes in the Arctic freshwater budget. Figure 3 uses the VEINS community model to show the response of the MOC to an anomaly in the export of ice through Fram Strait; the greatest (simulated) weakening is shown after a time-lag of 5-years.

Wadley and Bigg (2002) ask a very similar question about the freshwater flux through the Canadian Arctic Archipelago (CAA); they show that the rate of the overturning cell in their ocean GCM is much reduced when the CAA is 'open' as opposed to when it is 'closed' (Figure 4). So in both these experiments, an increased freshwater flux from the Arctic towards lower latitudes can slow down the MOC.

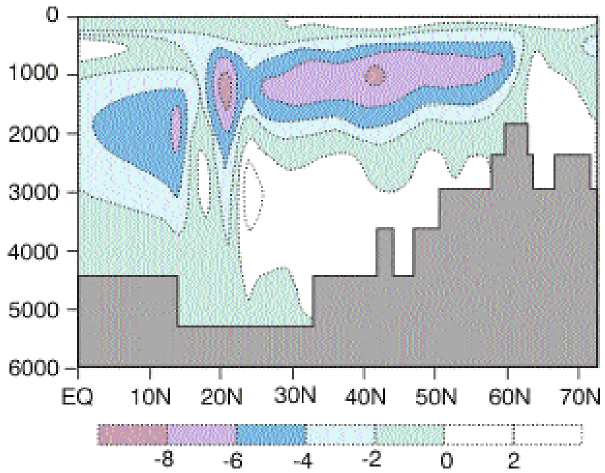

Figure 3. The 5-year lagged response of the MOC to an anomaly in the export of ice through Fram Strait equivalent to one standard deviation above the mean; from Gerdes, 2000).

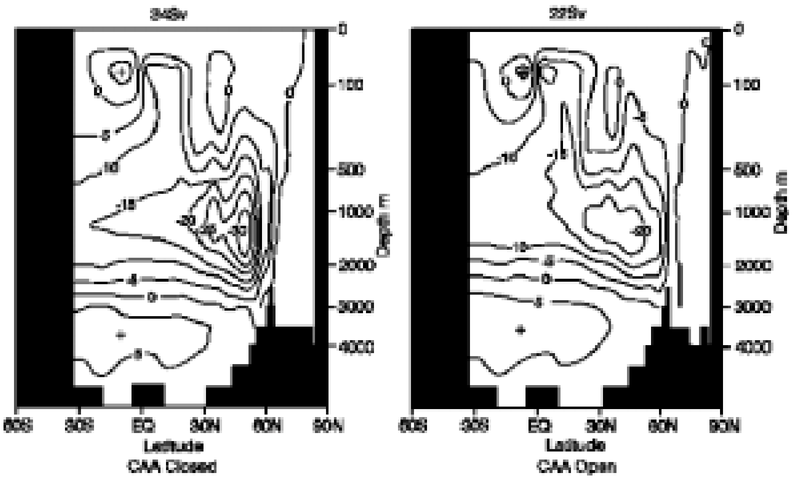

Figure 4. Atlantic Overturning Streamfunction with the Canadian Arctic Archipelago closed (left) and open (right); from a simulation by Wadley and Bigg, 2002

And if the MOC really does slow down ----- from any cause ----- then we can be reasonably certain that there will be a greater-than-regional effect on climate. This is the clear result of sensitivity studies using the Hadley Centre HADCM-3 model (Figure 5). Here, parallel to a 1600-year run driven only by solar input, and without any reference to greenhouse gas forcing, the meridional overturning circulation has simply been switched off by spreading freshwater across the northern North Atlantic. Within decades of this perturbation, a robust cooling sets in over most of the Northern Hemisphere. Countered by a weak warming in the southern hemisphere, the net result is a global cooling by 0.9°C.

While these models are among the most advanced tools available to answer these issues, questions remain as to whether they yet deal adequately with the complexities of the ocean's thermohaline circulation (Figure 6) and its many sources of variability. These controls on the MOC are believed to include: the poleward flux of warm and salty Atlantic surface water; the freshwater & ice flux out of the Arctic; the speed and density of the deep overflows crossing the Greenland-Scotland Ridge; open-ocean convection; mixing near the ocean margins, including the sea surface; ice-ocean and atmosphere-ocean interactions; freshwater input from the atmosphere and rivers.

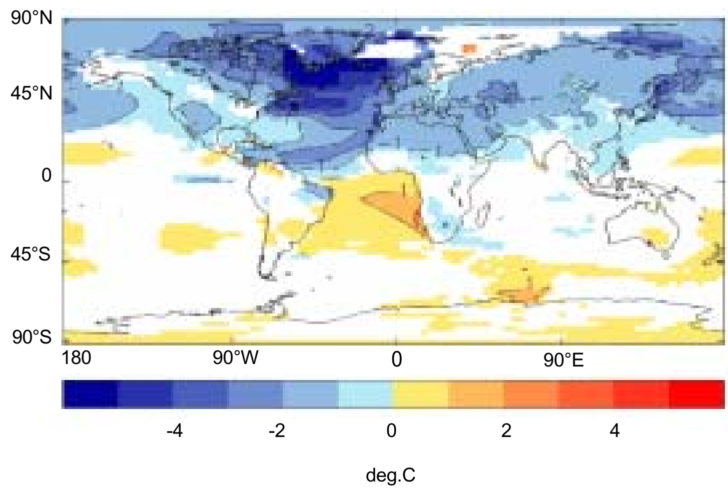

Figure 5. The change in global mean temperature following the suppression of the MOC in HadCM3; from Vellinga and Wood, 2002.

Figure 6. Schematic of the northern loop of the thermohaline circulation in the Northern North Atlantic, as depicted by McCartney, Curry and Bezdek, 1996. Warm, salty subtropical waters pass north into Worthington's "Arctic Mediterranean", give up their heat and return as cold dense overflows crossing the Greenland-Scotland Ridge through the Denmark Strait and Faroe-Shetland Channel. Two freshwater flows pass south under the ice of the east Greenland Shelf and through the Canadian Arctic Archipelago.

These processes and transports are poorly observed and understood. We have no measurements of the freshwater flux between the Arctic Ocean and Atlantic by either of its two main pathways; we have new (EC-VEINS) measurements of the heat and salt flux to the Arctic Ocean but not yet of its variability on any scale; we have a growing knowledge of the long-term variability of the hydrography of the dense overflows which "drive" the MOC but only embryonic ideas as to their causes, etc; and our present observations of the MOC (in the North Atlantic or anywhere else) are insufficient to detect whether it is changing. Understandably then, we would take the view that these key mechanisms and processes are too crudely represented in the present generation of global climate models.

It is ***the aim of ASOF*** to supply these missing observations. More specifically: ***to measure and model the variability of fluxes between the Arctic Ocean and the Atlantic Ocean with a view to implementing a longer-term system of critical measurements needed to understand the high-latitude ocean's steering role in decadal climate variability.***

Full details as to where, what, when and why can be found in the ASOF Science Plan or Implementation Plan at http://asof.npolar.no/ but may be summarised briefly as follows:

❒ **Which sea-areas will ASOF cover?** The ASOF domain is illustrated in Figure 7 in terms of the 6 main tasks around which this program is structured; the purpose of each will be evident from the caption. Plainly, ASOF does not intend to cover the whole or even a large part of the thermohaline circulation of the North Atlantic. Instead, the focus is on understanding the broad range of upstream influences that may impose change on the Deep Western Boundary Current (DWBC). Since these may originate in the Canadian Arctic or Nordic Seas or both, ASOF must certainly attempt to cover all of the main ocean fluxes that connect the Arctic Ocean to North Atlantic through these waters. But as Figure 7 suggests, the observations of ASOF would extend south only as far as the point at which these northern influences have come together in the DWBC.

❒ **For how long?** Since the long, slow shifts of global change are unlikely to be identifiable on any shorter time-scale, it would seem vital to aim for decadal "stamina" in designing and funding the ASOF observing program. And since we cannot yet identify which may be the dominant upstream influences on the DWBC, the emphasis must be on simultaneous rather than sequential observations until one or another of these can be discounted.

❒ **Can all of the key fluxes be measured?** Though we could not have made such a statement even 5 years ago, we now believe that techniques have very recently advanced to the point where all of the observations we need to measure in ASOF can be measured or are in prospect. Some of the most important advances and some practical applications are illustrated in Figure 8 below.

❒ **Why now?** The fact that we *can* now make these measurements is not the only reason for doing so, though it's certainly one reason. Others are (a) the modelling and paleo-evidence that anthropogenic effects on the stability of the thermohaline circulation may be rapid in their onset (eg Stocker and Schmittner, 1997; Stocker, Knutti and Plattner, 2001), (b) the fact that we are beginning to know what the "fingerprint" of anthropogenic climate change should look like in the ocean (Banks and Wood, 2002), and (c) the recent

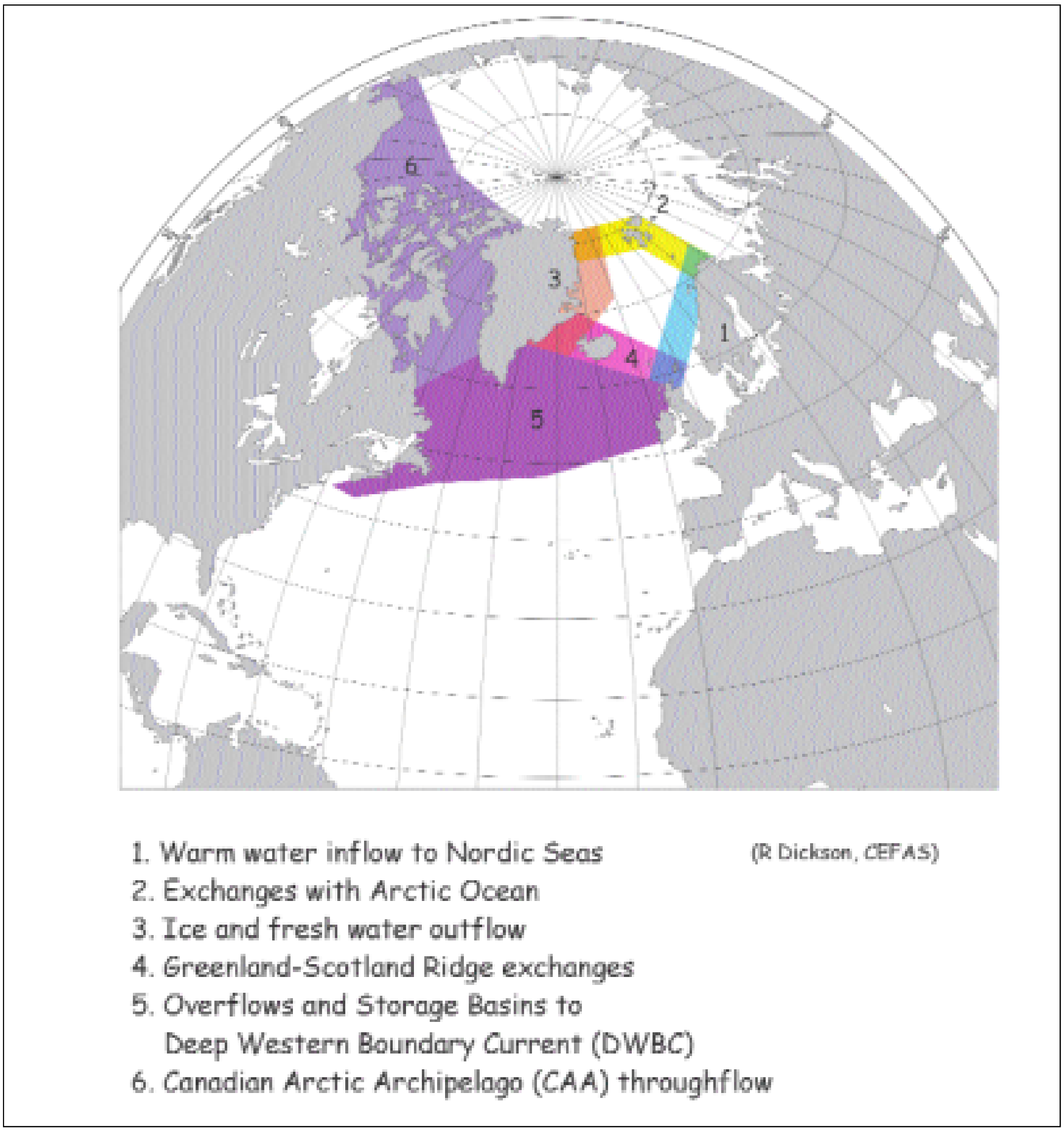

Figure 7. The ASOF domain

observational evidence that large scale decadal changes are already passing through the Atlantic thermohaline system (Hansen et al, 2001; Dickson et al 2002; Figure 9). However, since such an extended and extensive observational effort would be beyond the resources of any single institute or nation, the most persuasive reason to implement ASOF now is probably the fact that so many agencies are currently contributing to the study of the ocean's role in rapid climate change ---- including *inter alia* the RAPID Thematic Programme of UK NERC, the NOClim Project and Polar Climate Research Initiative of the Norwegian Research Council, aspects of the Framework 5 Programme of the EC, and program solicitations (e.g. NSF-02-071) of the NSF Office of Polar Programs and the interagency SEARCH program.

❐ **How will ASOF be managed?** As ASOF moved from Science Plan towards Implementation, it made sense to structure the International Science Steering Group into ASOF-West and ASOF-East groupings to reflect the (North American or EC) sources of their funding. That administrative structure continues. However once ASOF activity had been resolved into its 6 component regional tasks (Figure 7), there was also point in forming local Task-based Workshops in which problems of implementation might be locally resolved. This final organisational step has yet to be taken through the selection of Chairmen and Teams for each regional task by the ISSG, but once these are agreed it is likely that the ISSG itself would continue to cover the largest overarching scale of ASOF project management by correspondence. In this way, the management and coordination system for ASOF would be matched to the overall needs of the program, as well as to the more detailed needs of its regional tasks.

❐ **How will the data be managed?** ASOF intends to conform to the data management model for CLIVAR, first to ensure that ASOF can access the multidisciplinary data sets that will be generated by CLIVAR, second, to ensure that the data sets generated by the individual regional tasks of ASOF will be of maximum use to the wider community, and be directed smoothly into the CLIVAR data stream following any period of confidentiality that might apply. It is also likely that the individual tasks of ASOF might act as, or form part of, the "Regional Application Centres" by which the CLIVAR data will be assembled and checked.

Further details may be found on the ASOF website http://asof.npolar.no/ or obtained from the following corresponding authors:

ASOF Chair
Bob Dickson EQ CEFAS; Centre for Environment, Fisheries and Aquaculture Science (CEFAS), The Laboratory, Pakefield Road, Lowestoft, Suffolk NR33 OHT England. tel: (44) 1502-524282, fax: (44) 1502 513865, e-mail: r.r.dickson@cefas.co.uk

Deputy Chair ASOF-East
Prof. Dr. J. Meincke; Institut fur Meereskunde, Universitat Hamburg, Troplowitzstr. 7, D-22529 Hamburg, Germany phone: +49 (0) 40 - 42838-5985, fax: +49 (0) 40 - 5605724, e-mail: meincke@ifm.uni-hamburg.de

Deputy Chair ASOF-West
Peter B. Rhines Prof. of Oceanography and Atmospheric Sciences, Box 357940, University of Washington Seattle, Washington, 98195. tel: 206-543-0593, (212 ORB-1..office) fax: 206-685-3548 (209 OTB..GFD lab). Web sites: www.ocean. washington.edu/ research/gfd/gfd.html, and www.ocean.washington.edu (=> Faculty => Rhines). e-mail: rhines@ocean.washington.edu

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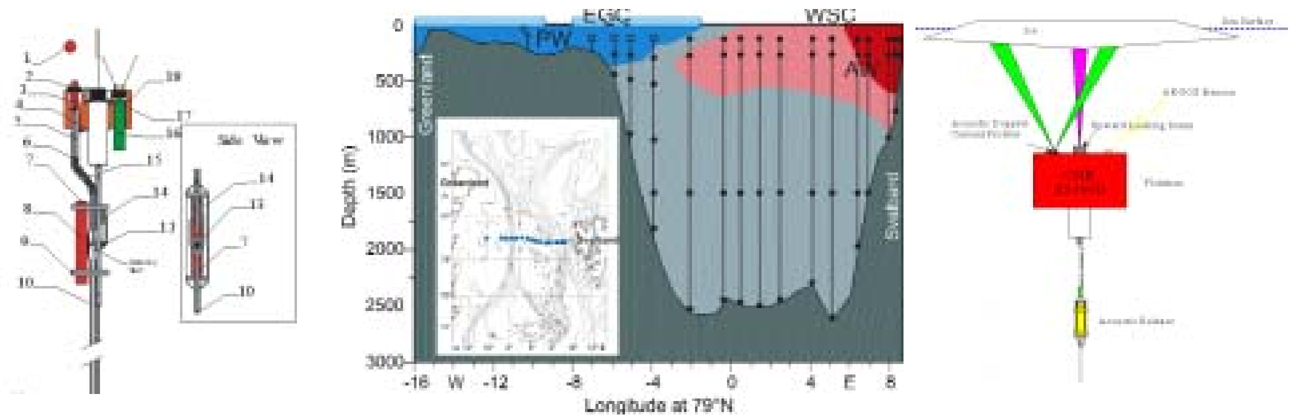
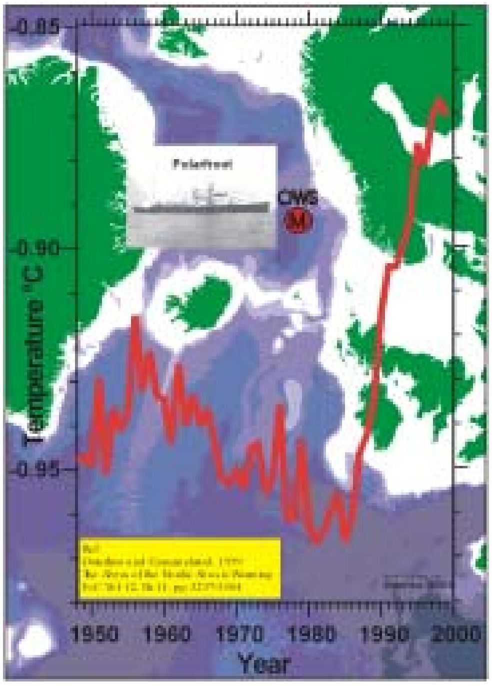
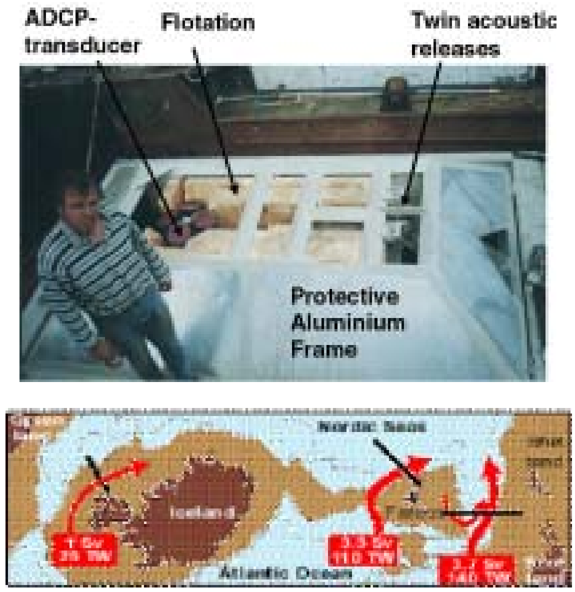
Figure 8. New systems and methods in place or in prospect for ASOF



a) As an addition to ULS & ADCP moorings measuring ice flux through western Fram Strait (right), a new inverted CTP profiler (left) located further west (PW) will begin the task of measuring the freshwater component. [Source Svein Østerhus, UiB.; ASOF-EC(N)]. A picket-fence array of current-meters (dots) occupies the remainder of the section (Source: Eberhard Fahrbach, A-W-I Bremerhaven).

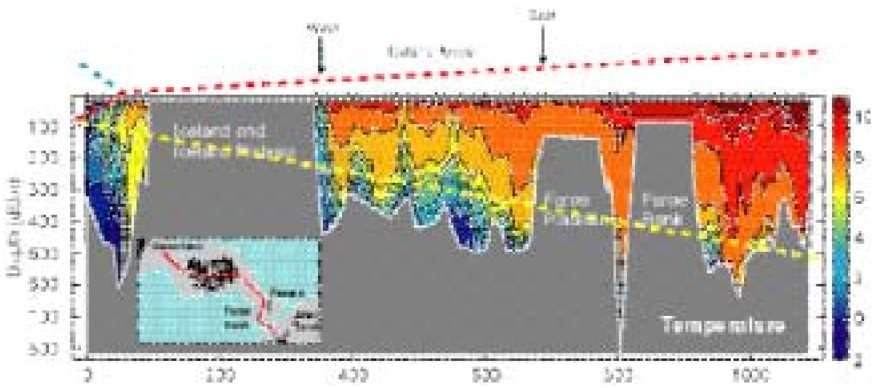


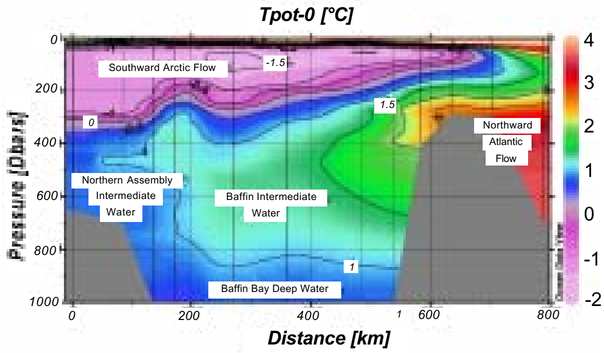
b) A new research role for OWS Mike:- since the Weathership straddles the path of the unconstrained (and as yet unmeasured) offshore branch of the Atlantic Current where it passes through the Norwegian Sea, this long-established station seems ideally placed to begin the study of its rate, variability and dynamics.



d) ADCPs in trawl-proof frames, developed during Nordic WOCE, permitted the first measurements of ocean fluxes through the heavily-fished waters of the Iceland-Scotland Ridge (Hansen and Østerhus, 2000). The ASOF-EC (E) or "MOEN" program of EC-FP5 will protract these key measurements into time-series.

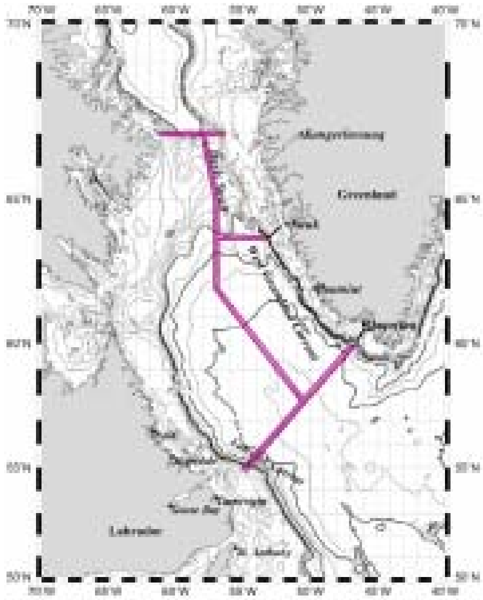
c) A novel task in the ASOF-EC project of EC-Framework 5 will be this attempt to monitor the net balance of all exchanges across the Greenland-Scotland Ridge using satellite altimetry and hydrography (source, Detlef Quadfasel, U. Copenhagen). The sea surface slope and its changes (red dashed line) would be obtained from altimetry; a current SeaGlider proposal by Eriksen and Rhines would help establish the interface slope between warm and cold watermasses (yellow dashed line).

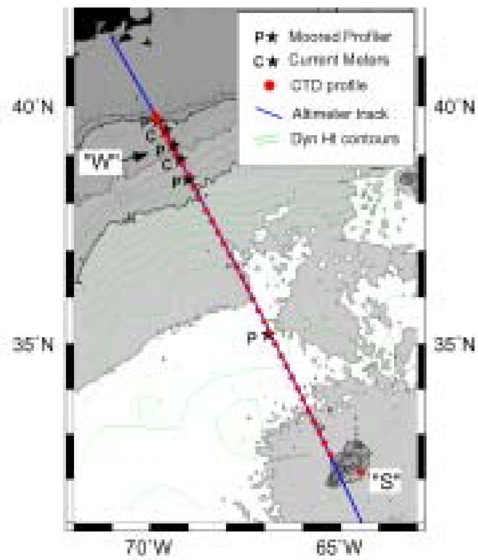




e) The small (≈ 8 km) deformation scales of northern seas means that measurements and moorings have to be closely spaced to resolve them. The development by UK-POL and DML-SAMS of an inexpensive HOMER bottom-moored profiler, based on fishing-reel technology, is therefore a considerable advance for the study of hydrography to the sea-surface or ice-base in northern seas. The hydro-section, (right: source Eddy Carmack, IOS, Canada, Koji Shimada, JAMSTEC, Japan and Students on Ice, Canada) shows one possible application in ASOF---monitoring the wedge of Pacific-origin water in the west side of Baffin Bay.

f) The development of the Watson Compass at BIO, Dartmouth N.S. (not shown; source Simon Prinsenberg) provides a new and necessary means of measuring flow-direction close to the North Magnetic Pole.

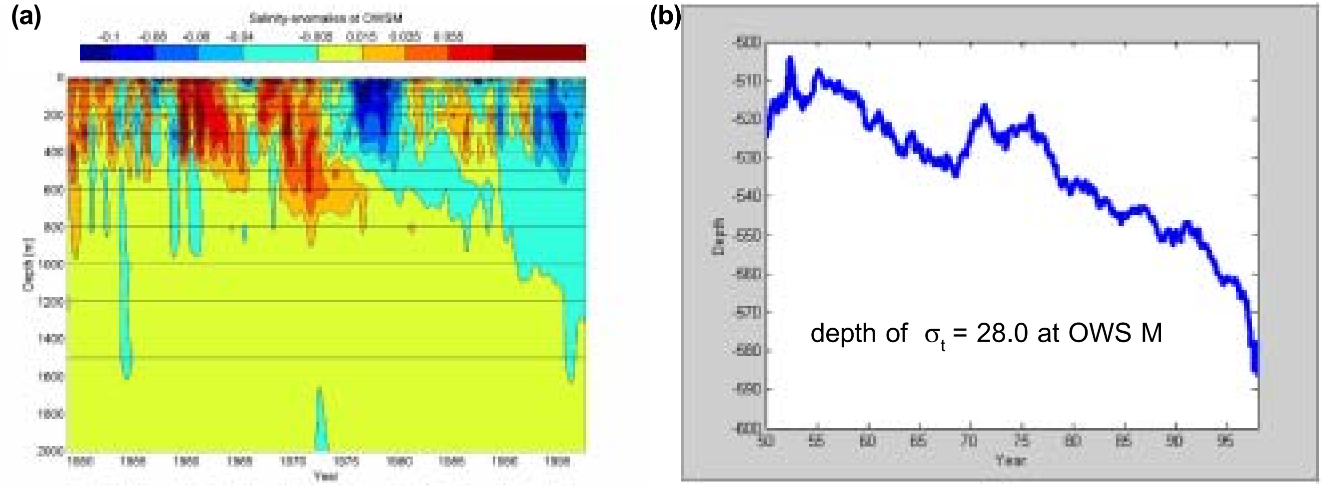


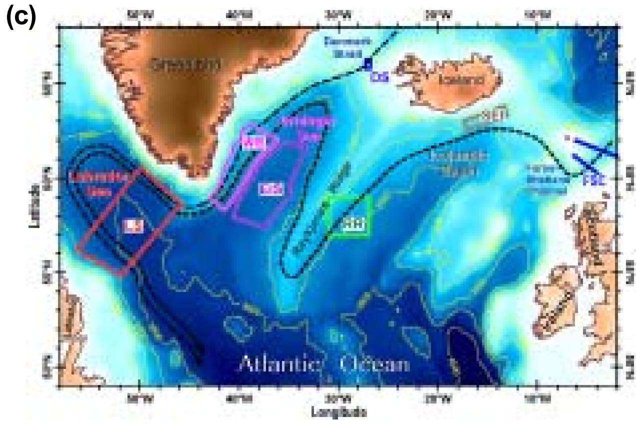


g) Gliders provide a wholly-new ability to enter and repeatedly study the hydrography of inaccessible waters. The sea area shown is more important than most to ASOF — the transition between Baffin Bay and the great storage basin of the Labrador Sea which forms the receiving volume for much of the CAA throughflow. Four Eriksen SeaGliders with Iridium satellite communications (shown here) would repeatedly occupy these sections in a current ASOF-W proposal by Eriksen & Rhines (Source Peter Rhines, UW).

h) As with other new tracers, the rapid arrival of ^{129}I in the abyssal Labrador Sea (not shown; source J.N. Smith, BIO, Canada) may provide a new means of distinguishing recirculation from throughflow in this important basin.

i) Proposed observing array along an altimeter track between Woods Hole and Bermuda, well-placed to observe changes passing south through the southern boundary of the ASOF domain in the Deep Western Boundary Current after the influences of northern seas have been imposed. (Source John Toole, WHOI). Other equipment including moored water samplers may be attracted to this line in consequence during ASOF.





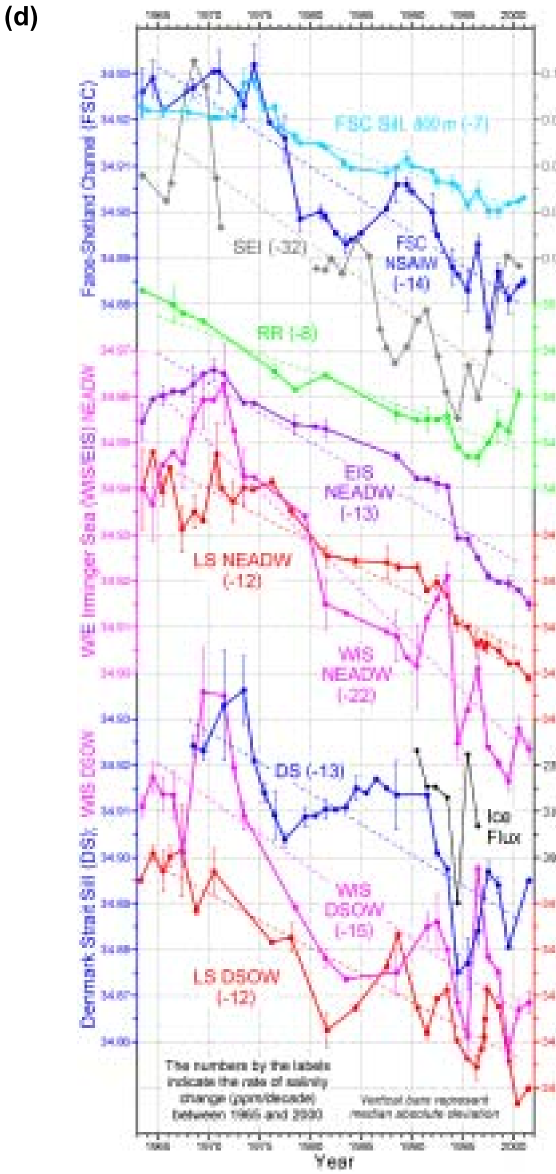


Figure 9. Our longest observational series are beginning to show evidence of large-scale changes of considerable amplitude and subtlety passing through the thermohaline system of the northern North Atlantic. Panel a) typifies the recent long-term freshening of the upper waters of the Nordic Seas, as recorded here at OWS Mike in the Norwegian Sea (source Svein Østerhus, UiB). Partly in response, and partly as a result of an altered deep exchange between the Greenland Sea and the Norwegian Sea (Østerhus and Gammelsrod, 1999), the density surface which forms the interface between Intermediate and Deep watermasses there has been slowly descending over half a Century (Panel b, source Svein Østerhus, UiB). Since this isopycnal determines the pressure head that drives the cold dense overflow through Faroe-Shetland Channel, Hansen, Turrell and Østerhus (2001) interpret this as evidence of a 20% slowdown in the eastern overflow since 1950.

The remaining panels (c,d) provide evidence that following the change in the upper Nordic Seas, the entire system of overflow and entrainment that ventilates the deep Atlantic has steadily changed in character over the past four decades, resulting in a sustained and widespread freshening of the deep and abyssal ocean (Dickson, Yashayaev, Meincke, Turrell, Dye and Holfort, 2002).

Though both of these changes are of the type expected by climate models under certain g.h.g. forcing scenarios, we do not yet know their cause. Regardless of cause, as record perturbations of the Atlantic thermohaline system, their study in ASOF can be expected to be illuminating.