<u>Section C:</u> What measurements should supplement the moored array?

25. The Utility of Tracers in the ASOF Program

Peter Schlosser and Bill Smethie,
Lamont-Doherty Earth Observatory of Columbia University, NY.

There are several oceanographic tracers that can provide unique information about the flux of Atlantic and Arctic Ocean waters through the Nordic Seas and measurement of these tracers would be very beneficial to the ASOF program. These tracers can be divided into four classes: stable isotopes, anthropogenic transient tracers, substances released from the Sellafield and La Hague nuclear fuel reprocessing plants, and SF_6 that was injected into the Greenland Sea.

<u>Stable isotopes</u>

River waters entering the Arctic Ocean have a very distinct $d^{18}O$ signal of about 18 o/oo (Ekwurzel, 1998) compared to nearly zero for seawater and sea ice melt. The oxygen isotope ratio thus provides a means to determine the river water/sea ice melt water composition of the fresh water component (Bauch et al., 1995). The ability to identify sources of fresh water is further enhanced by using tritium (see below) which in also quite enriched in river water, and barium which is much more concentrated in North American rivers than in Siberian rivers (Guay and Falkner, 1997). Measurement of these tracers at monitoring sites along the east coast of Greenland and in the passages of the Canadian Archipelago will provide information on variability of the fresh water sources that feed the fresh water outflow from the Arctic Ocean.

<u>Anthropogenic transient tracers</u>

The anthropogenic tracers that are of use are tritium and its daughter product, ^3He, and the CFCs, CFC-11, CFC-12, and CFC-113. Although tritium entered the Northern Hemisphere as a strong spike in the early 1960s as the result of atmospheric nuclear weapons testing, the tritium that has not been lost by radioactive decay is now refluxing through the hydrological cycle. Meteoric water that enters the Arctic Ocean and Nordic Seas by river runoff, precipitation and water vapor exchange, is enriched in tritium. This provides a tracer of river water as discussed above. It also provides a means to estimate the time subsurface water masses have been isolated from the surface since ^3He formed by tritium decay accumulates in a water mass at a known rate once the water has been isolated from exchange with the atmosphere. CFCs enter the surface ocean from the atmosphere and provide similar information since their concentration in the atmosphere increased continually during the past 4 decades until the mid-1990s. Combining CFC, tritium and ^3He data and using the well known atmospheric time histories also allows the amount of mixing that has occurred since a water parcel left the surface to be estimated (Smethie et al., 2000). Measurement of tritium, ^3He and CFCs on the Fram Strait section, the 75_N section and the Denmark Strait sections will provide information on variability of the source waters that feed Denmark Strait Overflow Water because there is a strong contrast between water exiting the Arctic Ocean that is composed of Atlantic water that has circulated through the Arctic on a decade or longer time scale and local Nordic Sea water masses that form by air-sea-ice interaction during winter. The Arctic Ocean water has a relative high tritium/^{3}He age and low CFC concentration compared to the local Nordic Sea water masses and Atlantic water that recirculates back into the Nordic Seas near Fram Strait. Evolution of these tracer signals between Fram Strait and the Denmark Strait sections will provide information on how the Nordic Sea outflow is affected by mixing within the Nordic Sea.

Another important aspect of measuring these transient tracers in DSOW is that this will provide the boundary condition needed to interpret the tracer distributions in North Atlantic Deep Water downstream of the formation region. The inventories of CFCs (Smethie and Fine, 2000) and tritium + ^{3}He in NADW directly reflects its formation rate, but the concentration of these tracers in the source water as a function of time must be known to calculate the formation rate.

<u>Nuclear fuel reprocessing tracers</u>

Radionuclides that are emitted from the nuclear fuel reprocessing plants at La Hague and Sellafield become incorporated in the Norwegian Current and are thus transported into the Nordic Seas and the Arctic Ocean. These substances can provide much information about the flow of Atlantic water into and through the Nordic Seas and Arctic Ocean and back into the North Atlantic. During the past decade, the ^{129}I concentration in the effluent has increased by more than a factor of 5 and in the mid-1990s, ^{129}I from this increased input was observed in Atlantic water in the Eurasian and Makarov basins (Smith et al., 1999). During the same time, ^{137}Cs decreased by more than a factor of 2 resulting in the ^{129}I/^{137}Cs ratio increasing by more than a factor of 10 (Smith et al., 1999). This rapidly changing ratio can be used to estimate the transit time of Atlantic water from its entry into the Nordic Seas to its exit points from the Arctic Ocean and Nordic Seas. This requires long term measurements of these radionuclides at the inflow points of the Norwegian Current to the Nordic Seas and along the Fram Strait, 75_N, and Denmark Strait sections. This same sampling strategy can also be applied to other radionuclides that may be released in the future and provide a unique temporal signature.

<u>SF_6 in the Greenland Gyre</u>

In 1996 the pycnocline in the interior of the Greenland gyre was spiked with SF_6 at a depth of about 300 m. Most of the SF_6 has remained confined to the Greenland gyre, although some has started to mix out laterally and flow toward the Arctic Ocean and Denmark Strait (Messias et al., 1999). The SF_6 will continue to mix laterally and vertically and at some point will mix into the density horizon that forms DSOW. Long term measurements at the 75_N and Denmark Strait sections will provide information on the exchange of water between the Greenland gyre and the Nordic Seas and the incorporation of this water into the overflow waters. Additional measurements along the Fram Strait section will provide information on exchange of this water with the Arctic Ocean.

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26. Synoptic Survey of the Nordic Seas

Bill Smethie and Peter Schlosser,
Lamont-Doherty Earth Observatory of Columbia University, NY.

The objective of our proposed work is to understand the interactions between water masses that form in the Nordic Seas and water masses that enter the Nordic Seas from the Arctic Ocean, which result in the formation of dense waters that flow over the Greenland-Iceland-Scotland Ridge to initiate the northern branch of the deep thermohaline circulation. To achieve this understanding will require knowledge of fluxes of various water masses into and out of the Nordic Seas (which will be addressed by the ASOF program), water mass formation processes, circulation patterns within the Nordic Seas, and mixing within the Nordic Seas between the various Arctic Ocean and Nordic Sea water masses.

We propose to address this objective with a synoptic hydrographic/tracer/LADCP survey of the East Greenland shelf/slope region from Fram Strait to Denmark Strait and the Nordic Seas. A possible cruise track is shown in Figure 1. It begins with a south-to-north section across the Iceland Sea from Iceland to Jan Mayen. From there, it continues across the Greenland and Boreas basins of the Greenland Sea to the Mid-Ocean Ridge (Mohn Rise), i.e., across all the eastward spreading paths of the Arctic Ocean outflows. It includes carefully-located, closely spaced stations across the Jan Mayen Fracture Zone, a known eastward spreading region for Arctic Ocean outflows (e.g., cf. Swift and Koltermann, 1988). The expedition continues with three northern sections from the EGC extending east to the initial south-north section. Where feasible these will include stations well up on the East Greenland shelf. All sections across the East Greenland slope will include closely-spaced stations (nominally at the [200-300, where feasible], 400, 700, 1100, 1500, 1900, 2300, and 2600 meter isobaths). A section across the Iceland Sea will extend eastward over the Jan Mayen Ridge across the northern Lofoten Basin of the Norwegian Sea in order to observe the southward spreading of Arctic Ocean outflows entering the Norwegian Sea through the Jan Mayen Fracture Zone. Two shelf-to-shelf sections from Greenland to Iceland north of Denmark Strait complete the expedition. We plan sampling, analyses, and data processing for CTDO, salinity, oxygen, nutrients, oxygen isotopes, CFCs, and tritium/^{3}He within all applicable WOCE Hydrographic Program standards.

The data will be used to prepare a complete set of sections for salinity, oxygen, nutrient, CFC, tritium, ^{3}He, d^{18}O and LADCP velocity, quantify the measured water properties by water mass and domain, and determine the flow across the tracks. Important aspects this work include exchanges between the EGC and Nordic Sea waters, the gradients approaching and crossing each ridge, shelf/slope/basin gradients across the EGC, and links between the vertical density structure of the various domains. Patterns of tracer distributions in conjunction with patterns in the distributions of other properties and current speeds measured along the sections will be used to infer basin wide circulation patterns. Close attention will be paid to temporal variability through comparison of the data set with previous surveys, including time series in the Greenland and Norwegian Seas and the long-term observations obtained via the VEINS program.

The formation of DSOW will be investigated by examining the CFC, tritium, and ^{3}He concentrations in the density horizon of DSOW. This will be done for each section normal to the East Greenland coast. For example, if the Fram Strait branch of Atlantic water has resided in the Arctic Ocean for a number of years, we expect to observe a relatively low CFC and tritium concentration in this horizon at Fram Strait. The ^{3}He concentrations and the tritium/^{3}He age, on the other hand, should have relatively high values. Progressing southward to Denmark Strait, the CFC and tritium concentrations should increase if waters that were recently renewed by convection in the Nordic Seas are mixed into this density horizon. The ^{3}He concentrations and the tritium/^{3}He ages of the waters south of Fram Strait should decrease due to loss of ^{3}He to the atmosphere during convection. Using CFCs in conjunction with temperature, salinity, oxygen, tritium and ^{3}He it will be possible to determine how waters from the Arctic Ocean and Nordic Seas are transformed into DSOW and to determine the relative proportions of Nordic and Arctic waters in newly formed DSOW. The southern portion of the long north/south line will be examined carefully for evidence of transport of dense Arctic Ocean waters, including the Barents Sea branch waters, eastward out of the Iceland Sea, which could feed Iceland-Scotland Overflow Water (ISOW). The cruise track presented in Figure 1 does not provide the coverage needed to fully understand the formation of ISOW, but this could be accomplished if the more lines were run in the southern Norwegian Sea.

The deep exchange between the Arctic Ocean and the Nordic Seas will also be investigated using CFCs and tritium/^{3}He. In 1984 the outflow of Eurasian Basin Deep Water through Fram Strait created a minimum in CFC concentration at about 2000 m on the west side of Fram Strait (Smethie et al., 1988) because Eurasian Basin Deep Water is less dense (at pressure) than Greenland Sea Deep Water (e.g. cf. Aagaard et al., 1985). Also, a CFC minimum was found on the east side due to northward flow of old Norwegian Sea Deep Water through Fram Strait. Similar features were observed for tritium and the tritium/^{3}He age (Schlosser et al., 1995). This pattern may no longer exist, however, because Greenland Sea Deep Water has not been renewed by convection since these observations (Bˆnisch et al., 1997). CFC concentrations have remained the same in Greenland Sea Deep Water but have increased in Eurasian Basin Deep Water. The distributions of CFCs, tritium, and ^{3}He in conjunction with temperature and salinity will provide information on the deep circulation patterns in the deep Nordic Seas.

The flux of fresh water out of the Arctic Ocean into the Nordic Seas plays an important role in the formation of dense water that enters the thermohaline circulation. A portion of this water mixes into the Nordic Seas, affecting the density of the overflow waters, and a portion flows through the Nordic Seas into the Irminger and Labrador seas where it influences open ocean deep convection that forms Labrador Sea Water. There are three components of this fresh water flux, sea ice, sea ice melt and river water. River water entering the Arctic Ocean has a distinct $d^{18}O$ signal, -18 o/oo on the average (Ekwurzel, 1998), and will be used to determine the fraction of the fresh water that is derived from rivers.

There has not been a synoptic hydrographic/tracer survey of the Nordic Seas since the Hudson cruise in 1982 and this survey did not include the Iceland Sea and Denmark Strait. Since then, the NAO index has reached is highest recorded level, deep convection in the Greenland Sea has essentially shut down, and there has been a shift towards greater penetration of Atlantic Water into the Arctic Ocean. It is important to determine the hydrographic and water mass structure of the Nordic Seas at this time, at the beginning of the ASOF program, to understand the water mass transformations that are associated with the flux of Arctic and Atlantic waters through the Nordic Seas. Also, water mass transformations in the Nordic Seas affect the density and other properties of dense waters that flow over the Greenland-Iceland-Scotland Ridge into the North Atlantic Ocean, Nordic waters that flow into the Arctic Ocean, and could possibly affect the volume transport of these flows. A synoptic survey at the beginning of ASOF and possibly at other times during the program, is needed to fully understand temporal variability in the thermohaline circulation that is initiated from the Nordic Seas.

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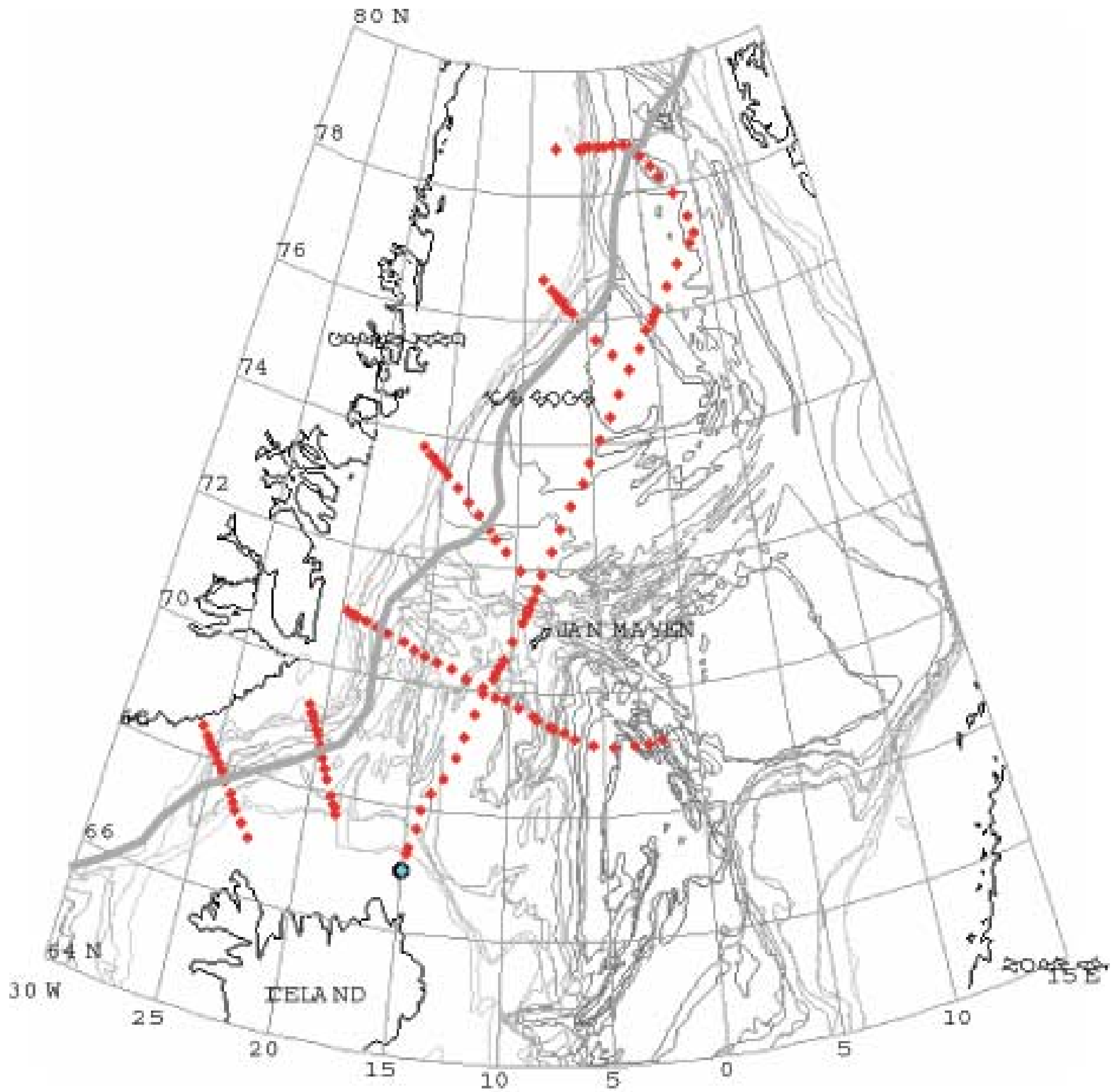


Figure [A]. Proposed station plan, with hypothetical representative mid-summer ice edge.

27. Tracers of key processes; how do we capture their time-dependence?

by

Andrew Watson, School of Environmental Sciences, University of East Anglia, Norwich

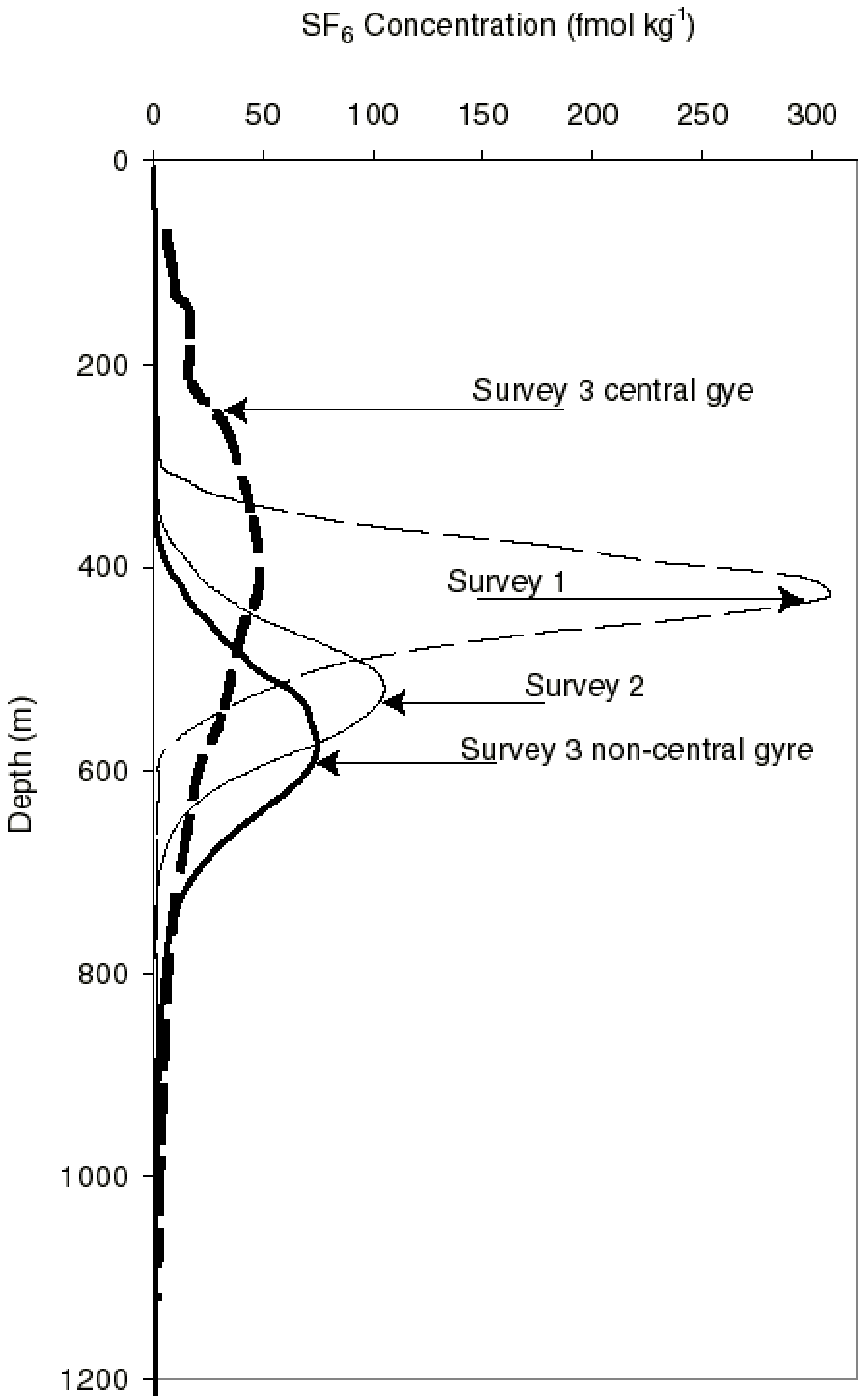
Current ocean general circulation models are very successful in describing many aspects of the wind-driven circulation. However, success in predicting decadal and centennial aspects of climate change will not depend only on understanding the major wind-driven currents. We also need to fully understand the much more subtle water-mass transformation processes which drive the themohaline circulation. For this task, the models are much less well suited, though our success in depicting the wind-driven circulation tends to hide the fact that the models are poor in this regard. Water mass transformation depends on a number of processes some of which are not even properly conceptually understood, let alone adequately represented in models. These include isopycnal and diapycnal mixing processes, interactions with boundaries and and topography, convection and entrainment processes.

These processes are more difficult to observe than are, for instance, surface currents, because they occur sporadically, in special places and/or times. Traditional oceanographic techniques such as oceanographic sections and current meter moorings do not provide the best insight into water mass transformation processes. We need new techniques to better study them, which might include:

1) New instrumentation to provide time series of hydrographic properties (active floats, yo-yo CTDs, etc).
2) Time series observations of tracers such as CFCs, 3He, SF_6 and radio-tracers that can provide information on of the effects of these processes.
3) Specifically designed experiments and observational programmes to provide insight into the mechanisms involved.

All of these techniques are close to operational. In particular, time series of tracers could be obtained using moored programmable whole-water samplers. Such samplers exist, though it may take a little work to make them suitable for use with the more esoteric tracers.

The Greenland Sea tracer release experiment, which is has been running since 1996, is an example of a process experiment aimed at illuminating convection, vertical and horizontal mixing processes in the subarctic. The accompanying figure shows the vertical evolution of the tracer field in the first 9 months after release. During this year, interesting new observations on the effects of convection on water mass transformation and on the rates of vertical turbulent mixing in the Greenland Sea were made possible by the tracer release. The "far-field" observation of the evolution of the tracer patch will provide estimates of water mass mixing and transformation for several years to come in the region. It would be very useful to have remote mooring-based samplers in operation to capture the latter phases of this evolution, for example as the tracer begins to appear in the Denmark Strait overflow.



Figure

Greenland Sea Tracer experiment; mean profiles of tracer against depth 3 months, 6 months and 8 months after release (survey 1, 2 and 3). For the last survey, the profiles in the centre of the Greenland Sea gyre, which underwent deep convection, have been plotted separately have been plotted separately from those surrounding it. The positions of horizontal arrows show the mean depth at which the potential density corresponding to the tracer release, $\square_{0.5}$ = 30.426(8), was found on each survey. The data can be use to derive rates of water mass transformation due to convection and due to turbulent mixing (Watson, A. J. et al, Nature, 401, 902-904).

28. ARCTIC SEA ICE THICKNESS CHANGES

Peter Wadhams
Scott Polar Research Institute
University of Cambridge, Cambridge CB2 1ER, UK.

Our knowledge of the regional and temporal variability of ice thickness in the Arctic comes almost entirely from upward sonar profiling by submarines. Therefore our level of knowledge depends on whether submarines have been able to operate in the area concerned. Until now, data have been obtained mainly from British submarines operating in the Greenland Sea and Eurasian Basin since 1971, and from US submarines operating in the Canada and Eurasian Basins since 1958. Very large new datasets have been obtained from the US SCICEX civilian submarine programme (Rothrock et al., 1999) during 1993-1999. In order to assess whether significant changes are occurring in a region of the Arctic it is necessary to obtain area-averaged observations of mean ice thickness over the same region using the same equipment at different seasons or in different years. Ideally the region should be as large as possible, to allow us to assess whether changes are basin-wide or simply regional. Also the measurements should be repeated annually in order to distinguish between a fluctuation and a trend. Because of the unsystematic nature of Arctic submarine deployments this goal has not yet been achieved, but a number of comparisons have been carried out which strongly suggest that a significant thinning has been occurring.

In the most recent study by Rothrock et al. (1999) sonar data obtained from the US civilian SCICEX submarine programme in September-October of 1993, 1996 and 1997 were compared with data obtained during six summer cruises during the period 1958-1976. Twenty-nine crossing places were identified, where a submarine track from the recent period crossed one from the early period, and the corresponding tracks (of average length 160 km) were compared in thickness. In each case the mean thicknesses obtained were adjusted to a standard date of September 15 using an ice-ocean model to account for seasonal variability. The 29 matched datasets were divided into 6 geographical regions (fig. 1). The decline in mean ice draft was significant for every region and increased across the Arctic from the Canada Basin towards Europe - it was 0.9 m in the Chukchi Cap and Beaufort Sea, 1.3. m in the Canada Basin, 1.4 m near the North Pole, 1.7 m in the Nansen Basin and 1.8 m in the Eastern Arctic. Overall, the mean change in draft was from 3.1 m in the early period to 1.8 m in the recent period, a decline of 42%.

Rothrock et al. commented that the decline in mean draft could arise thermodynamically from any of the following flux increases:-

1. A 4 W m^{-2} increase in ocean heat flux
2. A 13 W m^{-2} increase in poleward atmospheric heat transport, or
3. A 23 W m^{-2} increase in downwelling shortwave radiation during summer.

Clearly a change in ice dynamics can also produce a change in mean ice draft, although it is not known what change in wind forcing would be needed to account for the magnitude and distribution of the observed draft decrease.

This is the most extensive comparison so far, but it should be noted that all datasets involved are from summer, mostly late summer, so that the reported decline refers to only one season of the year, and that most track comparisons occur over the North Pole region and Canada Basin, with few in the Eurasian Arctic and none south of 84° in the Eurasian Basin.

Complementary to the Rothrock et al. study are comparisons from the Eurasian Basin and Greenland Sea made using data from British submarine cruises (one British cruise was also used in the Rothrock study). Wadhams (1990) compared datasets from a triangular region extending from Fram Strait and the north of Greenland to the North Pole, recorded in October 1976 and May 1987 during cruises in which he participated. Mean drafts were computed over 50 km sections, and each value was positioned at the centroid of the section concerned; the results were contoured to give the maps shown in figure 2. There was a decrease of 15% in mean draft averaged over the whole area (300,000 km^2), from 5.34 m in 1976 to 4.55 m in 1987. Profiles along individual matching track lines showed that the decrease was concentrated in the region south of 88°N and between 30° and 50°W. By comparison of the entire shape of the probability density functions of ice draft, Wadhams concluded that the main contribution to the loss of volume appeared to be the replacement of multi-year and ridged ice by young and first-year ice. For instance, taking ice of 2-5 m thickness as an indicator of undeformed multi-year ice fraction, this declined from 47.6% in 1976 to 39.1% in 1987, a relative decline of 18%. This is in agreement with recent results of Johannessen et al. (1999), who found that multi-year ice fraction in the Arctic (estimated from passive microwave data) suffered a 14% decrease during the period 1978-1998. They also found that the multi-year ice variability correlated well with mean ice thickness variability from the eastern Arctic as estimated from surface oscillation measurements made from Russian drifting stations (note that the oscillation technique, an inference based on the peak period of swell propagating through the ice, has not been validated against direct measurements).

Wadhams did not correct for seasonal variability between the 1976 measurements, made in October, and those of 1987, made in April-May. If this is done in the manner used by Rothrock et al (1999), the decrease in mean ice draft (standardised to September 15) becomes much greater at 42%, since April-May is the time of greatest ice thickness. This is in excellent agreement with Rothrock et al.'s results for the entire overall dataset that they analysed, yet occurring within a period of only 11 years. This indicates either that thinning occurs faster in the Eurasian Basin than elsewhere in the Arctic (which is suggested by the geographical trend of the Rothrock et al. data) or that it is invalid to compare datasets from different times of year simply by standardising to "summer" through use of a model.

The latter problem is largely overcome in an analysis of the most recent British dataset, obtained in September 1996 by Wadhams aboard HMS "Trafalgar". A paper in press (Wadhams and Davis, 2000) includes a comparison of these data with results from October 1976. The two submarines followed similar courses between 81°N and 90°N on about the 0° meridian, and it was found that about 2100 km of track from each submarine, when divided into 100 km sections, were close enough in correspondence to count as "crossing tracks" in the sense used by Rothrock et al. The overall decline in mean ice thickness between 1976 and 1996 was 43%, in remarkably close agreement with Rothrock et al. The mean drafts in 1° bins of latitude were as follows:-

Latitude range	Mean draft m in 1996	Mean draft m in 1976	1996 as % of 1976
81-82	1.57	5.84	26.9
82-83	2.15	5.87	36.6
83-84	2.88	4.90	58.7
84-85	3.09	4.64	66.6
85-86	3.54	4.57	77.4
86-87	3.64	4.64	78.5
87-88	2.36	4.60	51.2
88-89	3.24	4.41	73.4
89-90	2.19	3.94	55.5
OVERALL	2.74	4.82	56.8

It can be seen that there was a significant decrease of mean draft at every latitude, but that the decline is largest just north of Fram Strait and near the Pole itself. A characteristic of the ice cover observed from below was the large amount of completely open water present at all latitudes. A seasonality correction to the 1976 data for the slight difference in mean draft between October and September brings the ratio to 59.0% for September, a decline of 41%. Thus the British and the US data are in remarkably good agreement in describing a very significant thickness decrease in Arctic Ocean sea ice.

A cautionary note must be sounded in that these significant thickness decreases from spatially averaged data conceal large random variabilities at given locations. Time series of ice draft at fixed locations have been obtained from moored upward sonar systems, of which the most comprehensive set spans Fram Strait. Vinje et al. (1998), in an analysis of data from 1991-1998, show that interseasonal and interannual varibility in thickness far exceed any trend, although of course the length of the dataset is only 7 years.

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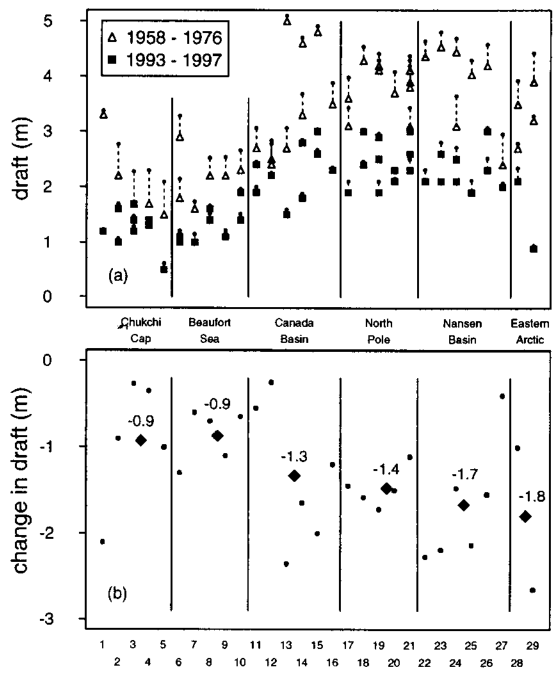

Figure 1 (a) Mean ice drafts at crossings of early cruises with cruises in the 1990's. Early data (1958-1976) are shown by open triangles and those from the 1990's by solid squares, both seasonally adjusted to September 15. The small dots show the original data before the seasonal adjustment. The crossings are grouped into six regions separated by the solid lines and named appropriately. (b) Changes in mean ice draft at cruise crossings (dots) from the early data to the 1990's. The change in the mean ice draft for all crossings in each region is shown by a large diamond.

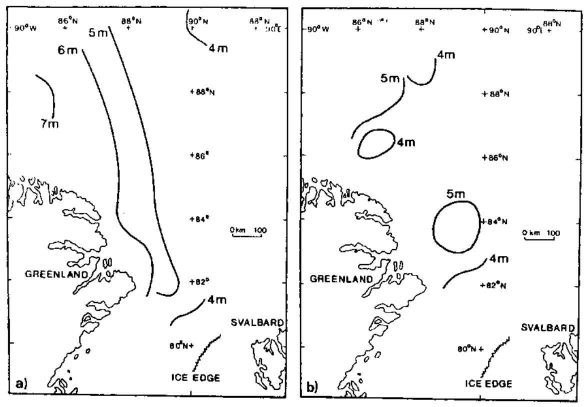

Figure 2 Contour maps of the mean ice drafts from Eurasian Basin, October 1976 and May 1987 (after Wadhams, 1990)

29. The role of oxygen isotopes in monitoring freshwater fluxes through Fram Strait

Michael P. Meredith, Karen Heywood and Paul Dennis
School of Environmental Sciences, University of East Anglia, Norwich, U.K.

Work at UEA has had a strong focus on measuring the ratio of stable isotopes of oxygen ($\delta^{18}O$) in the East Greenland Current (EGC) at Fram Strait, 79°N (Figure 1 shows the location of stations at which $\delta^{18}O$ was measured in 1997). The EGC is observed to be extremely fresh (Figure 2), due to the large runoff flux from the Arctic rivers. As is well documented, there is also a strong and variable sea ice flux through the western Fram Strait, which will also have a strong impact on the salinity field. A full assessment of the freshwater flux requires the consideration of both these factors. $\delta^{18}O$ has the potential to separate the effects of river runoff and sea ice melt, since high-latitude meteoric water is extremely depleted in the heavier $H_2{}^{18}O$ molecule, whilst sea ice melt has an isotopic composition similar to the waters from which it formed. For example, the EGC waters are observed to be amongst the lightest isotopically in the world ocean (Figure 3), indicating the strong presence of the river runoff (if the waters were fresh due solely to sea ice melt, they would be much isotopically heavier).

For a more quantitative assessment, we solve a 3-endmember balance (e.g. Ostlund and Hut, 1984) using the salinity and $\delta^{18}O$ measurements to determine the fractions of sea ice melt and river runoff at each sampling location (Figures 4, 5 respectively; note that negative values in Figure 4 are indicative of a net sea ice formation from these waters). Fractions of river runoff peak around 16% in the EGC; waters at this station have a column inventory of nearly 19m. The extreme sea ice melt is around –6% at the same station, which as an inventory around –10m of sea ice melt. Accounting for the difference in density between the solid and liquid phases of water gives a total net thickness of around 11m for the sea ice formed from the waters of this station.

To convert these spatial distributions of freshwater fractions to volume fluxes requires knowledge of the velocity field at the time of measurement. For the 1997 data, these are being produced by E.Fahrbach (AWI) and co-workers. Previous works (e.g. Bauch et al., 1995) had no contemporaneous velocity measurements, hence for a comparison we are restricted to consideration of relative fluxes. The 1991 $\delta^{18}O$ section used by Bauch et al. gave fluxes for river runoff and sea ice which were identical within given errors. The 1997 section shown here gives a river runoff flux nearly three times the magnitude of the sea ice flux. It is thus clear that there is significant interannual variability in the relative fluxes. The potential for freshwater flux in the EGC to affect convective activity in the Greenland and Labrador Seas has been postulated, thus we are keen to continue monitoring of $\delta^{18}O$ at Fram Strait since this gives us the potential to observe the relative roles of the separate freshwater components. A 1998 section (from FS *Polarstern*) is currently being finalised, and some samples are available from the 1999 RRS *James Clark Ross* transect. However, long-term monitoring is clear required, and we are keen to exploit techniques which will enable this at lower expenditure levels. For the velocity measurements, the BPR/IES arrays proposed by POL and CEFAS have great potential to supplement (and perhaps replace) the current meter arrays used previously. For the $\delta^{18}O$ measurements, we are keen to deploy an Aquamonitor on the Greenland shelf at Fram Strait, since this will allow seasonal components in the isotope composition to be determined, and will provide access to a region of freshwater flow usually inaccessible due to ice. For the main body of the EGC, the conventional sampling and measurement of $\delta^{18}O$ needs to be maintained.

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Figure Captions

Figure 1. Location of stations in Fram Strait occupied by RV *Lance* in 1997. The 500 and 2500m isobaths are plotted.

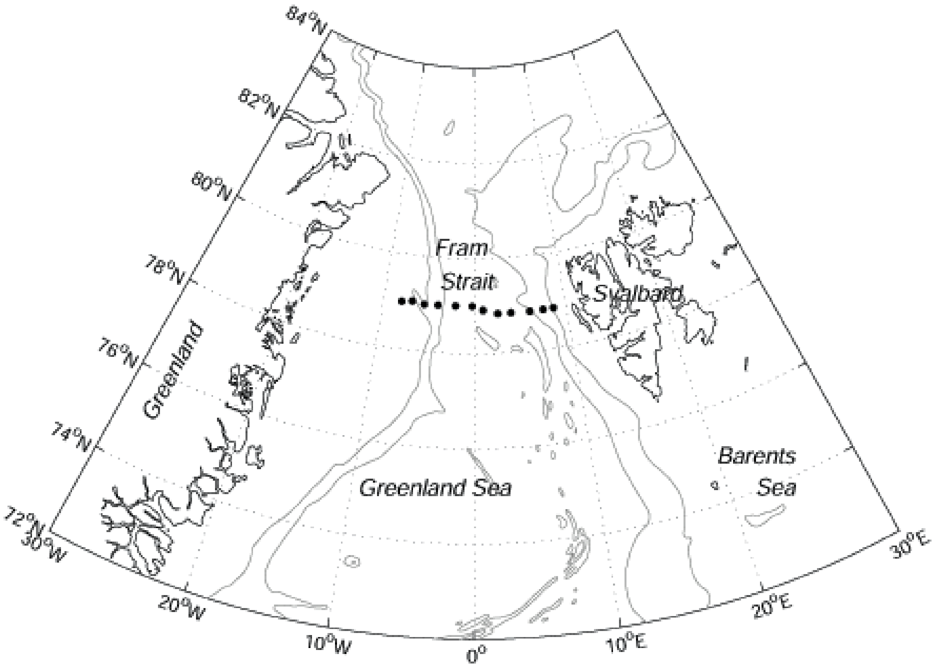
Figure 2. Salinity section across the upper 300 dbar of Fram Strait, 1997. Dots mark locations of discrete bottle sampling.

Figure 3. As for Figure 2, but for $\delta^{18}O$.

Figure 4. Section of sea ice melt percentages across upper 300 dbar of Fram Strait, 1997. Column inventories (calculated as the integral of the percentages with depth) are marked above the top horizontal axis. Negative values imply a net sea ice formation from the waters sampled.

Figure 5. As for Figure 4, but for river runoff percentages.

FIg 1



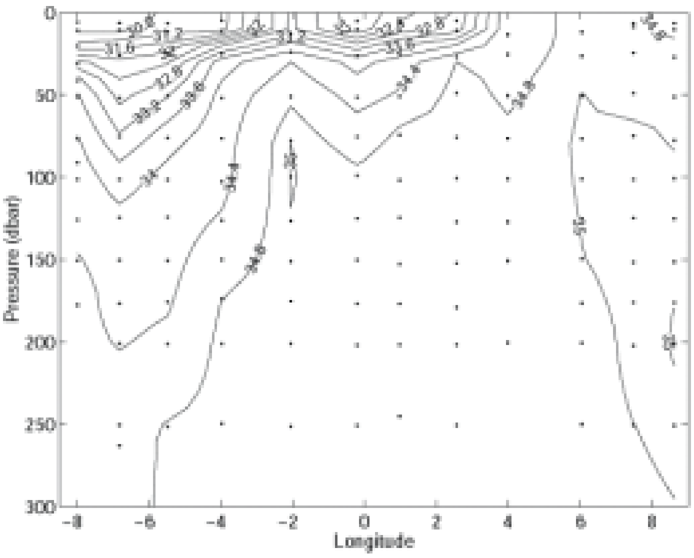


Fig 2

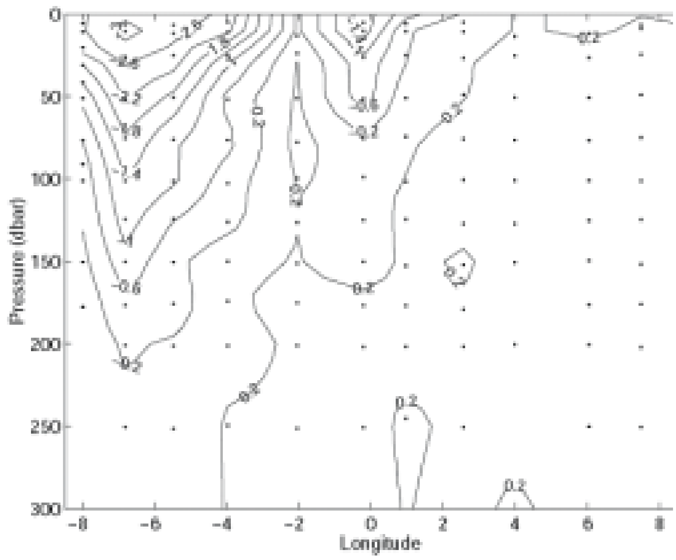


Fig 3

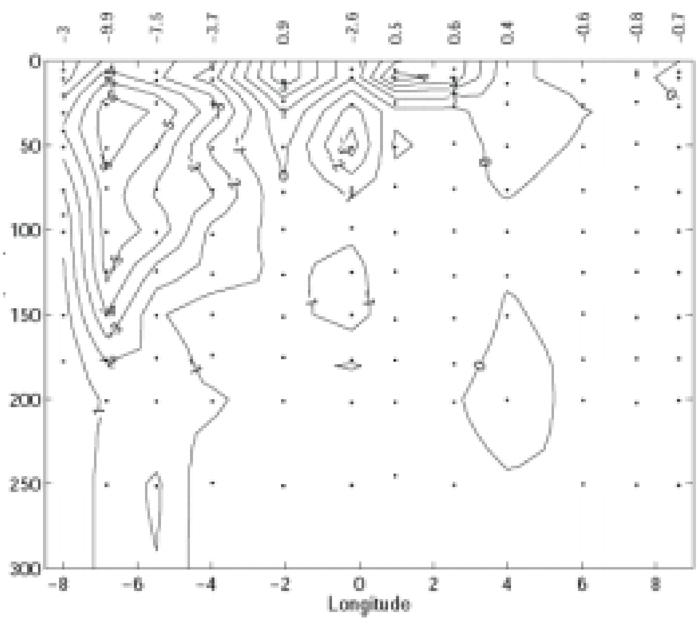


Fig 4

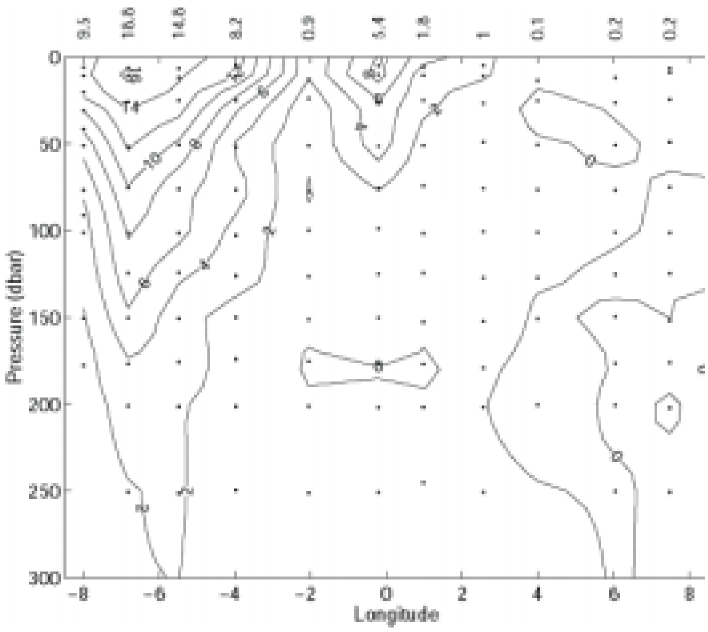


Fig 5

30. Pacific Water in the Arctic and Atlantic Oceans
by
E. P. Jones BIO Dartmouth N.S. Canada (With help from L. G. Anderson, J. H. Swift, J. Olafsson, K. Falkner, and F. McLaughlin)

There is more evaporation than precipitation in the Atlantic Ocean. Much of the evaporated water falls as rain into the Pacific Ocean or is carried there by rivers flowing into it. A significant pathway for the return of fresh water to the North Atlantic Ocean is via the Arctic Ocean. We have been able to trace this pathway of Pacific Ocean water through the Arctic Ocean into the North Atlantic Ocean. Identifying where source waters originate and tracing their circulation is essential so that ocean currents can be appropriately represented in models that describe ocean circulation and it's interactions with the atmosphere. Such models are vital to describe climate and predicting climate change.

The Arctic Ocean lies between the North Pacific and the North Atlantic Oceans. Pacific water flows into the Arctic Ocean north of Alaska from the Bering Sea through the shallow 50 m deep Bering Strait. Atlantic water flows along the northern coast of Norway, entering the Arctic Ocean through the much deeper Fram Strait. Pacific and Atlantic origin waters partially mix within the Arctic Ocean, but with the Pacific water being less dense (less saline) than that entering from the North Atlantic Ocean, it tends to remain more confined in specific regions of the near-surface layers as it flows in the Arctic Ocean. In addition to the two source waters having different salinities, they have constituents that do not affect their densities but that do distinguish one source water from the other. In particular they have different relationships between their dissolved nitrate and phosphate concentrations.

Two processes affect nutrient concentrations in the oceans. As on land, photosynthesis reduces carbon, nitrate, and phosphate concentrations and increases oxygen concentrations. Decay reverses this process, increasing carbon (carbon dioxide), nitrate, and phosphate concentrations, and decreasing oxygen concentrations. But since photosynthesis utilizes these components in fixed ratios, the relationships between nitrate and phosphate are maintained in a water mass that has not mixed with another one. A second process is denitrification, which lowers nitrate concentrations relative to phosphate. Pacific water has an excess of phosphate of about 1 µM relative to nitrate (Figure 1), that results from denitrification in processes in the northern Pacific Ocean. During bacterial decomposition of organic matter there is a need for an electron acceptor that under normal oceanic conditions is oxygen. In low oxygen environments found in sediments or in the oxygen minimum at a few hundred meters depth in the Pacific Ocean, other electron acceptors are important. The first to be used after oxygen is nitrate, resulting in denitrification.

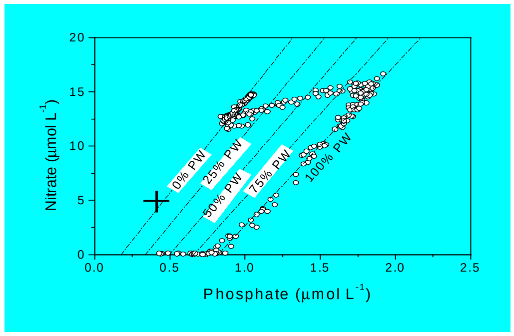
By observing the nitrate and phosphate concentrations, we have been able to delineate boundaries and mixing regions between the source waters in the near surface waters of the Arctic Ocean. What we find is that the boundary between the Pacific and Atlantic water is not entirely within the Arctic Ocean itself, but part of it extends well to the south. Except for contributions from rivers, much of the water flowing through the Canadian Archipelago is of Pacific origin. Within the Canadian Archipelago, Atlantic water can be clearly seen only in deeper water flowing between Ellesmere Island and Greenland.

An unexpected finding was that all of the seawater (i.e., excluding contributions from rivers) in Hudson Bay comes from the Pacific Ocean. While much of the water in Baffin Bay comes from the Atlantic Ocean, mostly from the south, Pacific water flowing through of the Canadian Archipelago forms part of the water flowing south along the east coast of Baffin Island, meeting up with that coming out of Hudson Bay through Hudson Strait. Pacific water continues flowing south and can be identified all along the coast of Labrador, perhaps as far south as the Grand Banks and Flemish Cap, where it is becoming well mixed with Atlantic water and indistinguishable from it. Pacific water also flows out of the Arctic Ocean through Fram Strait and along the east coast of Greenland. As it travels south, it mixes with Atlantic water, but is still identifiable in Denmark Strait between Greenland and Iceland. Near the south of Greenland, available data show no signs of Pacific water.

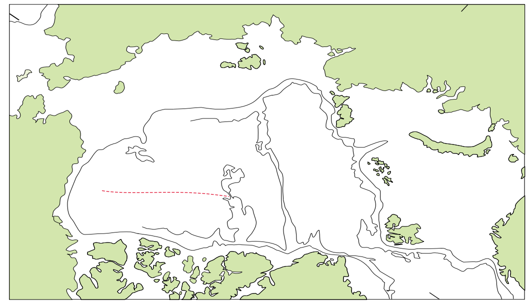
The figures show the N-P relationships in the Arctic Ocean and the Pacific water fraction in Baffin Bay at Davis Strait and in Denmark Strait.

There are only limited time series tracing Pacific water in the Arctic or Atlantic Oceans using N-P relationships. These will be discussed.

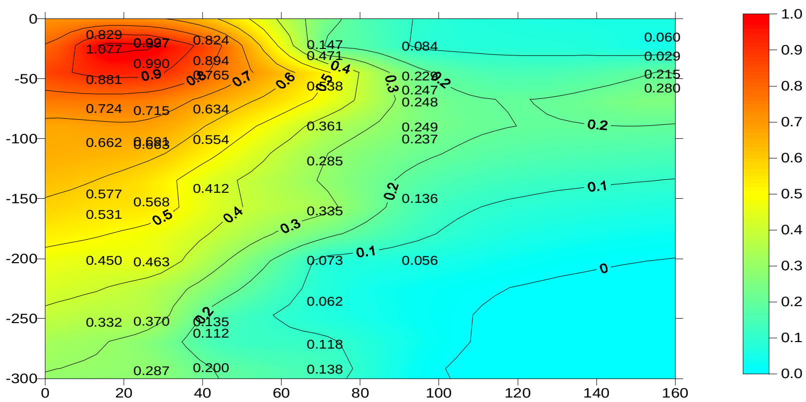
N-P Relationships



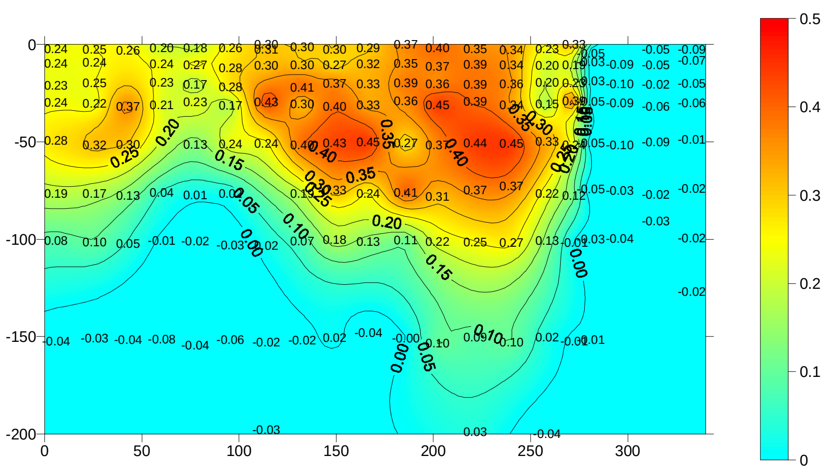
Pacific Water Circulation (Top 30 m)



JOIS 1 Davis Strait



Denmark Strait 91 Pacific Fraction



31. The Meridional Overturning Cell and Deep convection

by

Jean-Claude GASCARD,
LODYC Paris. (gascard@lodyc.jussieu.fr)

Studying and defining the Meridional Overturning Cell (MOC) both from models and observations is quite a complicated task and in particular regarding the MOC component associated with the North Atlantic Subpolar Gyre mainly because of the complexity of the Gyre itself, its interaction with bottom topography, its sensitivity to a highly variable atmospheric forcing etc... Defining the Gyre is not an easy task either since its domain of influence extends far beyond its proper boundaries. For instance, the North East Atlantic Central waters are currently called < subpolar mode waters > (Mc Cartney) although they are located well south of the North Atlantic current. Also the warm and salty waters of Atlantic origin are completing a vast cyclonic loop around the Nansen Basin in the Arctic Ocean before re-exiting through Fram Strait via the East Greenland Current. The North Atlantic subpolar gyre is in fact composed of several seas, the so called Nordic Seas : Norwegian, Greenland, Iceland, Barents seas and also Irminger and Labrador Seas south of the Greenland-Scotland ridge.

Evidently, the MOC cannot be reduced to the Greenland-Scotland overflows but how can we define it ? Is the southward transport of dense and cold waters overflowing the Greenland-Scotland ridge and driving the deep western boundary current downstream, the best index characterizing an increase or a decrease (slowing down) of the MOC ? Or alternatively does it consist in evaluating the strength of the northward advection of warm and salty waters and their intrusions in the Nordic Seas and Arctic ocean ? or both ? So what about the mid-depth deep convection in the Labrador Sea in this context ? Deep convection is certainly a central issue for understanding and characterizing the MOC related to the North Atlantic subpolar circulation since it is a strong link between the warm and cold routes typical of the North Atlantic Subpolar Gyre. This issue can be adressed in many different ways and I would like to pinpoint 3 of them in order to illustrate its importance and relevance for observing and monitoring the MOC, all 3 dealing with deep convection:

1/ Deep convection and Overflows

There exist distinct and somehow divergent ways in relating (or not) deep convection occurring in the Nordic Seas with overflows passing east and west of Iceland across the Greenland-Scotland ridge. On that particular matter, Mauritzen presented new insights quite different indeed from more classical views such as Hansen and Osterhus and also Strass et al., enlightening the role of the East Greenland Current in mixing and conveying water masses formed in the Greenland Sea and Fram Strait towards the DSOW. Tracers are quite helpful for documenting this particular aspect and ESOP2 was, by and large, dedicated to this problem (Watson et al.). An anthropogenic transient tracer, Iodine 129, is currently used in a large domain covering all the Nordic Seas and the Arctic Ocean (Edmonds et al, Smith and Ellis). Multivariate analysis combining T-S properties and transient tracer concentrations is quite an appropriate and powerful approach for optimising our knowledge about origins of water masses formed in the Nordic seas and/or Arctic Ocean and overflowing at sill depths across the Greenland-Scotland ridge into the North Atlantic Ocean to feed on the Deep Western Boundary current with North Atlantic Deep Water.

2/ Deep convection and North Atlantic Oscillation

How can deep convection activity (equivalent to the greatest depth reached by convection any particular winter) best be observed in different areas prone to deep mixing and is this related to NAO? Deep chimneys have recently been identified in the Labrador Sea (Lilly) as well as in the Greenland Sea (Gascard). These chimneys look like long-lived sub-mesoscale coherent anticyclonic vortices penetrating down about 1km through a deep pycnocline. Being quite robust, they serve as a nucleus for preconditioning to deeper and deeper convection in subsequent years. These < Labbies > and < Greenlies > are interesting and fascinating objects since they can serve as precious indicators about the actual state of deep convection. Over the past 20 to 30 years it looks like Labbies have been particularly active in the Labrador Sea (Gascard and Clarke, Lilly et al) and have certainly contributed to a large extent for the spreading of newly formed Labrador Sea deep waters in the North Atlantic (Pickart et al). Interestingly enough < Greenlies > have recently been observed reaching deeper and deeper depths in the Greenland Sea but less so in the Labrador Sea where deep convection is apparently weakening. Is this related to NAO and/or AO ?

3/ Deep convection and Brine formation

It has often been stated that 2 main modes are able to drive deep convection : the thermal mode and the haline mode. The first mode relates to a densification mainly by cooling at (almost) constant salinity and the second mode to a densification by freezing at (almost) constant temperature. The haline mode is undoubtedly responsible for brines resulting from sea ice formation. The thermal mode is certainly the main active mode for triggering deep convection in the Labrador Sea (like in the Mediterranean Sea) although in both cases evaporation has also to be involved as a secondary < haline > type effect. In the actual Greenland Sea (like the Weddell Sea most likely), both modes are active but it seems like the haline mode mainly driven by surface freezing processes, plays the same role as evaporation in deep convective areas not subjected to sea ice formation. In deep ocean, thermal convection is the main driver and the main source of salt comes from the side through advection rather than being convected down below from above. In shallow waters and shelves areas, haline convection is the main source of salt resulting from sea ice formed at surface. It is quite interesting to note that recently paleoceanographers have proposed a < switch mode > scenario between thermal and haline modes in order to explain how the Ocean reacts to glacial interglacial forcing (Dokken and Jansen 1999).

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32. Optimising the Lessons of the Past

Professor Nick McCave
Department of Earth Sciences, University of Cambridge
Downing Street, Cambridge CB2 3EQ

a) What can we do?: Palaeoproxies

What we have to do is examine the sediment record of past ocean behaviour. The dynamical behaviour of the oceans, their flow patterns and speeds, distribution of water masses, temperature (T) and salinity (S) fields, and changes in properties such as pH and CO2 content are acquired in large part through interaction with the atmosphere. The ocean thus contains a record of climate, and the sediments it deposits preserve aspects of these changes. We cannot measure climate directly in sediments, so we rely on measurements of parameters that are proxy for others, eg Mg/Ca ratio and alkenone unsaturation ratio Uk37 which are proxy for temperature; oxygen isotope composition of foraminifera which contains effects of T, S and ice volume [and which at a given time contains a record of density (σ) through combined T and S]; Cd concentration in foraminifera, a proxy for the nutrient phosphorus; Ba/Al ratio as a proxy for productivity; and mean grain size of the "sortable silt" (10-63 μm) size fraction as a proxy for flow speed.

There are many more proxies, often with less secure interpretation, including δ15N, δ13C, Ca, Si and B isotopes, and various trace element ratios. At present we have reached the state where increasingly robust tracers for temperature, salinity, nutrients and flow speed, plus more debatable tracers of water mass origin, are available. This provides a good basis for reconstructing the dynamical behaviour of past oceans and examining responses to severe climatic changes encountered in recent geological history, especially the past 20,000 years since the maximum of the last ice age.

The ideal sedimentary system would be one that laid down annual layers of sediment that remained undisturbed, yielding an annually resolvable record comparable with that from ice cores. This does not normally occur in the open ocean because organisms burrow through the sediment and mix the record. The next best record is rapidly and steadily deposited such that 1 cm of sediment represents 20 years or less (deposition rates of >50 cm/ka). This is more than 10 times the average N Atlantic deposition rate. The difficulty is to find special places that are not otherwise anomalous, and which are well positioned to record important aspects of ocean climate history.

b) Where we can do it?: sediment drifts.

The deep circulation is responsible for constructing large sediment bodies with greater-than-average sedimentation rates. The past variability of key flows and water mass distributions can be approached via cores from drifts (Keigwin & Jones 1989, Bianchi & McCave 1999). The outflows from the Nordic Seas have deposited two principal drifts, Gardar Drift south of Iceland under

Iceland-Scotland Overflow water (ISOW), and the Eirik Drift south of Greenland under the combined Denmark Strait (DSOW) and ISOW overflows. Eirik Drift appears to be the best target for monitoring the outflow related to deep water production in the Nordic Seas. The problem is that there is a strong element of luck in getting a core with super-high sedimentation rates and this requires a significant time spent surveying and coring. Of 18 cores on Gardar Drift, McCave (1994) came up with one containing 4.5 m of Holocene: so with application the goal is achievable. Rather than just one core it is important to get cores from several depths to sample different water masses, or levels within one current.

A further possibility is that the inflow of warm water from the N. Atlantic current to the Norwegian Sea may have left a record of its activity on the Lofoten Drift, and this would be a very useful counterpart to an "outflow monitor" on Eirik Drift (Prof Eystein Jansen, personal communication). At present it is not clear whether the inflow is actually responsible for the construction of this drift and thus whether important dynamical information can be obtained from it.

c) How may this be accomplished and at what cost?

Three phases are envisaged: a) analysis of existing seismic data, b) a long cruise – probably 5 weeks including passage time – to survey and get cores from Eirik drift, and possibly a shorter 2.5 week cruise to Lofoten drift, and c) laboratory analysis of cores.

a). A significant amount of ***seismic data*** exist from Eirik drift, some of it commercial plus Canadian and US academic sources. (Possibly also German and French). This must be tracked down, copied and analysed. 18 months of a PDRA. Cost £100k.

b). Rough ***cruise costs*** are £500k for Eirik and £200k for Lofoten Drifts coring.

c). ***Analysis of cores*** will require a further 2.5 years of PDRA, 2 Research students for 3 years and a lab technician for 3 years. With travel, consumables, minor equipment, analytical costs (O&C isotopes, trace elements, sediments, C-14 ages) this would be about £450k.

Thus the total cost of the work programme is around **£1.25M.**