<u>Section B:</u> Is this the observing array we need to keep pace with these changes?

10.Measuring the poleward heat flux west of Norway

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Method.

Five years of monitoring of flow past the Svinøy section (Orvik, Skagseth and Mork, revised) have given estimates of the mean and seasonally varying volume and heat transport, and have documented the distinct two-branch structure of the flow of Atlantic Water (Figure 1). The eastern branch emerges as a topographically trapped, near barotropic, 30-50 km wide current over bottom depths of 200-800 m. The western branch is also 30-50 km wide but appears as an unstable 400 m deep jet in the Arctic Front centered over the 2000 m isobath. The area between the two branches contains Atlantic Water eddies but no significant mean transport. Previous studies from surface drifters (Poulain et al., 1996), indicate that this structure may be persistent over large parts of the Norwegian Sea. A frontal branch and associated mesoscale variability has previously been found both upstream (Read and Pollard, 1992) and downstream along the northward pathway of Atlantic Water (van Aken et al, 1995).

For the eastern topographically-trapped branch, it appears that a continuation of the conventional current meter array at the Svinøy section offers a reliable monitoring scheme. The 5 years of results obtained so far indicate a close association between the transport of the inshore branch and the NAO Index (Figure 3), though understandably this is less evident during NAO-negative years (eg 1996) when the winter storm track etc shifts southwards. For the western branch, surveys with vessel mounted acoustic doppler current profiler and towed profiling CTD give insights into the structure and variability, but can hardly be performed as part of a regular monitoring scheme. If the western branch is limited by an outcropping isopycnal above quiescent deep water, its geostrophic transport can be estimated from a single density profile. However this is a rather crude method. Moorings with inverted echo sounders and current meters in combination with satellite altimetry are proposed to improve the description, but this remains to be tested. Thus we foresee a certain period with some redundancy and supporting process studies in order to identify a long term monitoring scheme also for the western branch.

Costs.

The projected cost of running the Svinoy hydrographic section and moorings is as follows:

Durable equipment(IN kNOK):

Instrument	Numbers	cost	Total
Recording C/Ms	16	70	1120
Buoyancy floats	5	20	100
IES	4	100	400
Argos transmitters	5	30	150
Acoustic releases	5	80	400

Total = 2170 kNOK

Assuming that the average lifetime of these instruments is three years, the average annual capital cost of deploying this array is therefore **724 kNOK**.

Expendables (in kNOK):

Instrument	Numbers	cost	Total
Mooring cost	5	25	125
Argos positioning cost	1	15	15

Total =**140 kNOK** per year

Ship cost (in kNOK):

14 cruise days is estimated at Total = **100 kNOK** per year

Thus the total per year cost of operating the Svinoy mooring line and hydrography is estimated to be **964 kNOK**. [NB. This estimate is exclusive of direct ship cost, which for Haakon Mosby is 30 kNOK/day; ∴to obtain the complete cost, a further 420 kNOK/yr should be added].

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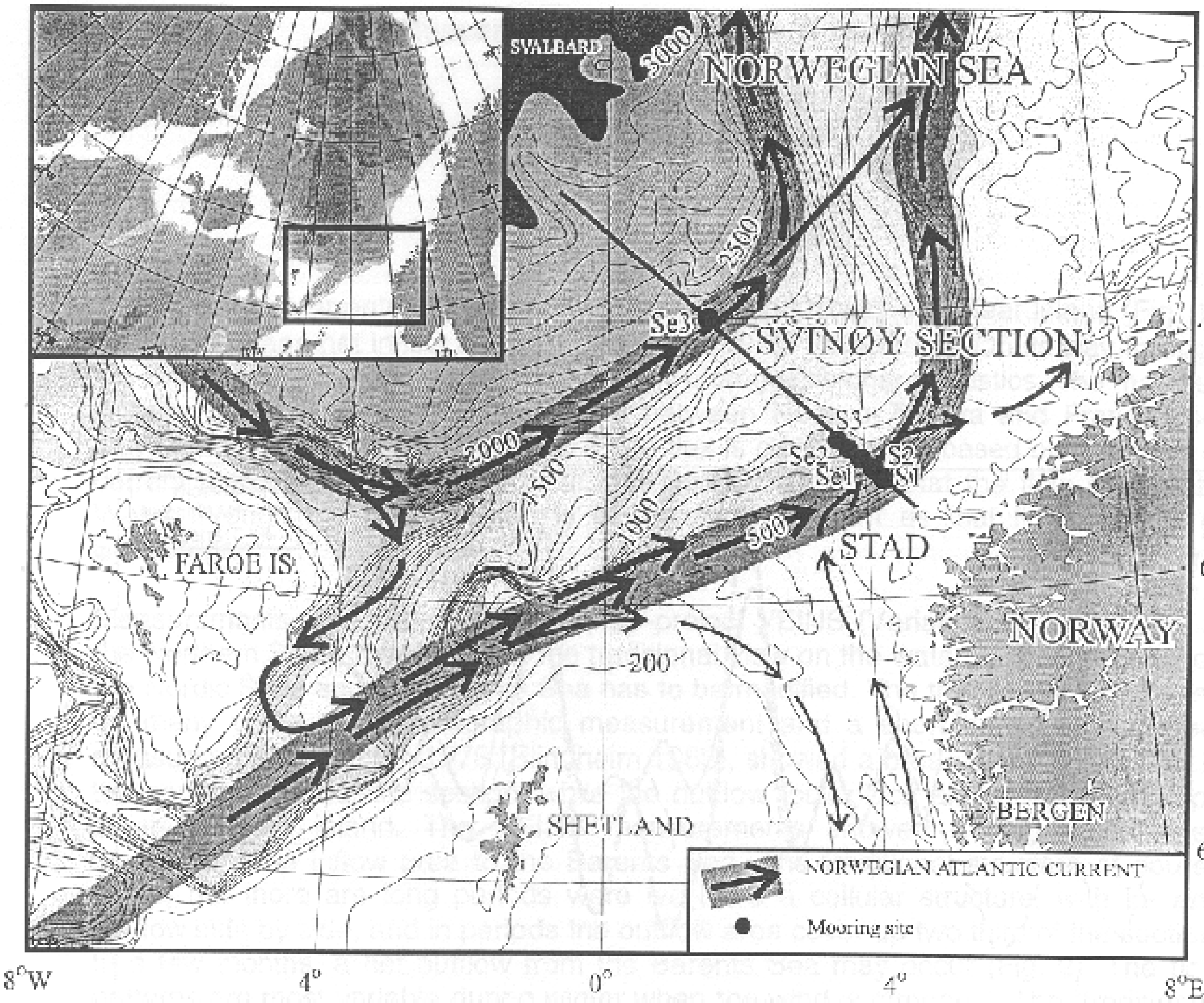

Figure 1. location of the Svinoy Section and moored current meter array in relation to the two branches of the Atlantic Current off SW Norway.

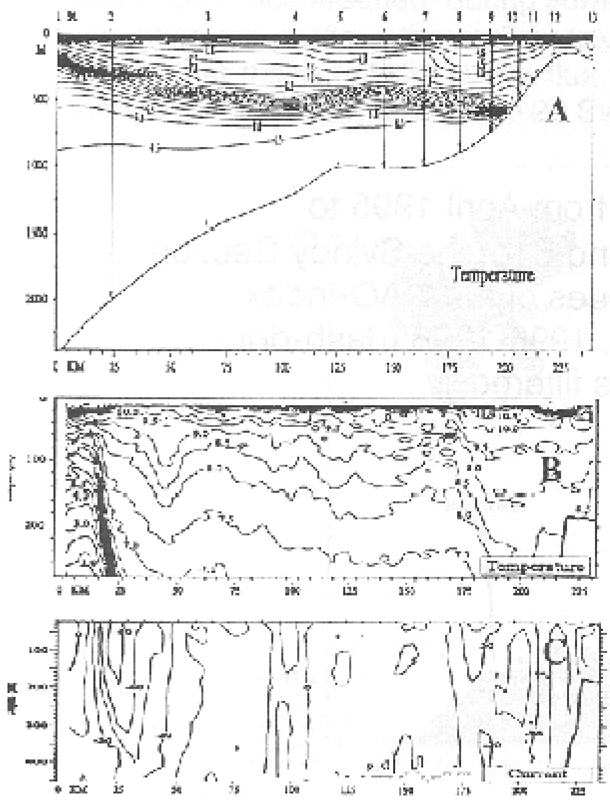

Figure 2. a) CTD, b) SeaSoar-CTD (temperature) and c) ADCP sections along the Svinoy Section, August 1997. Mooring lines and c/m instrument depths are indicated.

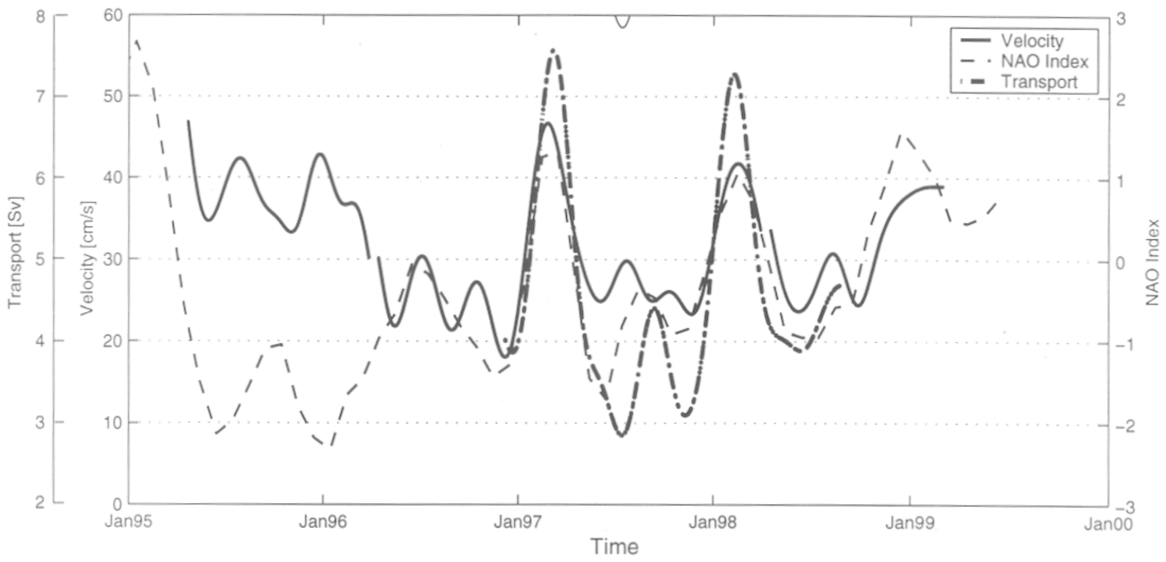

Figure 3. Time series of current speeds from April 1995 to February 1999 at 100 m depth on mooring S1 of the Svinoy Section (solid line) versus contemporaneous values of the NAO-index (dashed line) and the Atlantic water flux, 1996-1998 (dash-dot line). All series are three month low pass filtered.

11. Measuring the Barents Sea Throughflow

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The Atlantic water enters the Barents Sea between Norway and Bear Island (Fig. 1), and the average net inflow is about 2 million m^3s^{-1} (2 Sv(erdrup)). On its way through the Barents Sea the Atlantic water gradually changes its characteristics. The modified Atlantic Water leaves the Barents Sea between Novaya Zemlya and Franz Josef Land and flows into the Arctic Ocean. The flux is close to 2 Sv based on one year of current measurements (Loeng *et al.* 1997), which means that the flow of Atlantic Water through the Barents Sea is of the same amount as that flowing west of Spitsbergen.

Measurements carried out during the EC-project VEINS (Variability of Exchanges in the Northern Seas) revealed that the traditional view on the water exchange between the Nordic Seas and the Barents Sea has to be modified. The traditional view, based on many years with hydrographic measurement and a short period with current measurement in autumn 1978 (Blindheim 1989), showed a broad and stable inflow in the southern part of the section, while the outflow took place along the steep slope south of Bear Island. The VEINS measurements showed a very complicated structure in the inflow area to the Barents Sea. The traditional structure of course occur, but there are long periods were we have a cellular structure, with in- and outflow side by side, and in periods the outflow area cover up two third of the section. In a few months, a net outflow from the Barents Sea may occur (Fig. 2). The flow patterns are most variable during winter when the wind is strongest. The “traditional” flow occurs most frequent during summer time when the wind is weak. In the periods with strongest outflow, the outflow take place in the whole area north of 72°N. Fig. 2 shows that the variability in the flux is more than 10 Sv, and if we calculate daily means, the variability is close to 20 Sv.

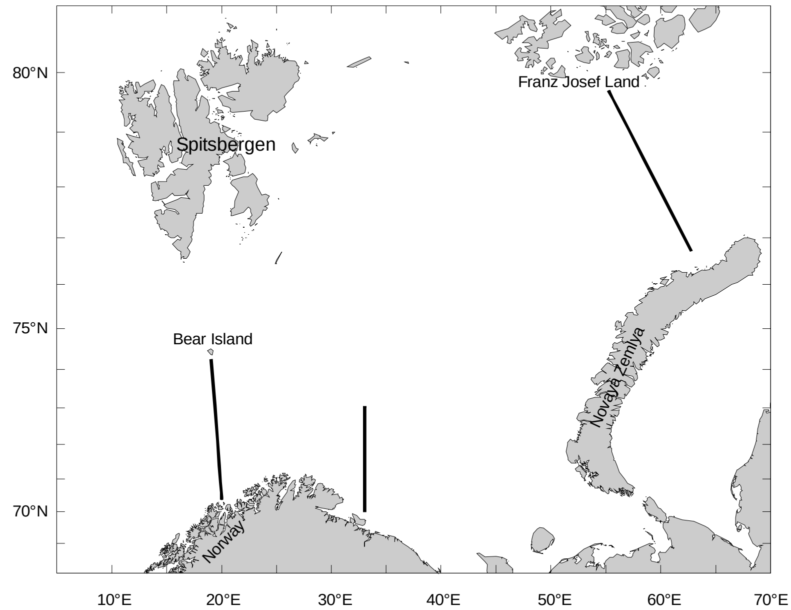

Fig. 1. The position of the two sections between Norway and Bear Island and between Novaya Zemlya and Franz Josef Land is indicated together with the position of the Russian Kola-section (along 33° 30'E).

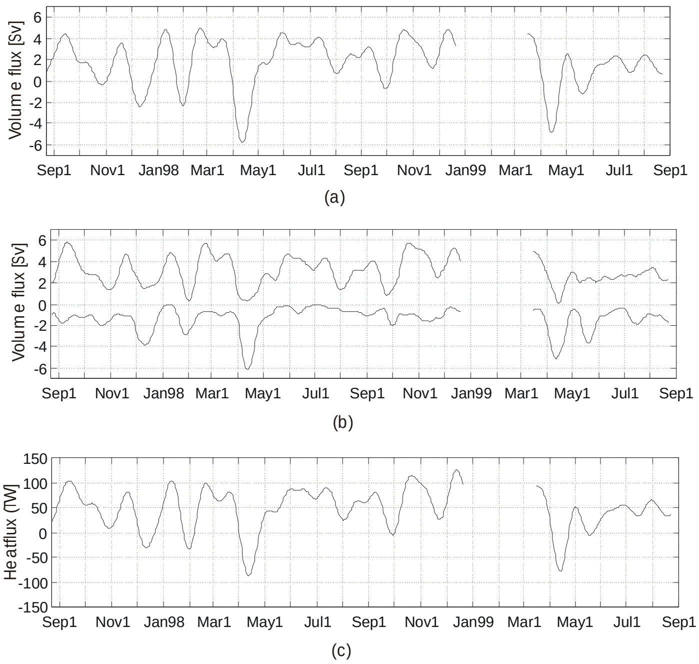

Figure 2. Total volume flux (a), volume flux separated inn inflow (positive) and outflow (negative) (b), and total heat flux across the section (c). All data have been lowpass filtered over 30 days.(Ingvaldsen et al.1999)

One year of measurement (September 1991-September 1992) between Novaya Zemlya and Franz Josef Land revealed a strong permanent outflow close to the bottom in the southern part of the section. In the middle part of the section, the current was unstable. The results from these measurements showed a clear seasonality that has not been observed in the Fugløya Bear Island section. A set of moorings (2-4) in the southern part of the section will be sufficient in order to measure the variability in the flow to the Arctic Ocean.

In order to measure the Barents Sea throughflow, there are two ways of doing it. One alternative is to measure the inflow between Norway and Bear Island and at the same time measure the outflow between Novaya Zemlya and Franz Josef Land. However, the section Novaya Zemlya-Franz Josef Land is not easy accessible due to Russian military restriction. The best (and probably the only) solution seems to involve Russian research institutes like PINRO. If they get the necessary equipment, they will deploy and recover the instruments in the area. They also have historical hydrographic observations from that area which then will be made available. PINRO also maintain the Kola section (Fig.1), the longest time series from variability in Atlantic inflow. The variability in the Kola temperature has been compared with flux calculations in the Norway-Bear Island section from numerical models, and they show an amazing agreement. The temperature variability in the Kola-section is also closely related to variations in NAO for the period after 1950. Therefore, an observation program including regular hydrographic observations from all three section supplied with currents measurements as indicated, will be very important for studying changes in the thermohaline circulation in the Northeast Atlantic. Most probably, changes in the thermohaline circulation will be most easily detected in these marginal areas.

The second alternative for measuring the Barents Sea throughflow is to cover both the in and outflow through the Norway-Bear Island section. During VEINS mainly the inflow of Atlantic water was measured. The results documented large variability in this flow, both on short and long term. VEINS also revealed a rather barotropic flow, and it is possible to reduce the number of mooring and the number of current meters per mooring. The outflow of Arctic water south of Bear Island, however, was not successfully measured during VEINS because the moorings twice where taken by fishing vessels. It is therefore necessarry to use trawl proof bottom mounted ADCPs of the same type that have been used with great success in the under the WOCE experiment and later under VEINS. Together with the result from the Svinøy-section and the Fram Strait component (also discussed in this Strawman) together with modelling activities, the result from this measurements will contribute see how signals (or special characteristics) propagate with the Atlantic Current along the Norwegian coast and to the Arctic Ocean. This will give us a much better understanding of the thermohaline circulation, which is so important for the European climate.

Alternative two is the most realistic one. The Institute of Marine Research will continue to measure with Aanderaa current meter from fixed mooring. The position of the moorings and number of instruments per mooring are based on experience from the VEINS project. However, new equipment is needed in order to measure out flowing current in the fishing area, and it is natural to choose same type of equipment that have been used successfully in the Faroe-Shetland Channel during the VEINS project. The measuring sites are shown in Fig.3. It is not suggested to measure between Bear Island and Spitsbergen. This because we mainly have a recirculation of Atlantic water in that area.

The Institute of Marine Research have sufficient of Aanderaa current meters, but needs two ADCPs to deploy along the shelf break south of Bear Island were there is a rather high fishing activity. A budget is shown below.

Costs

2 broadband ADCP	NOK 1.350.000	Euro 168.750
2 Trawl proof frames	NOK 150.000	Euro 18.750
2 Acoustic releases	NOK 140.000	Euro 17.500
2 Argos transmitters	NOK 80.000	Euro 10.000
2 floats	NOK 50.000	Euro 6.250
Total investments	NOK 1.770.000	Euro 221.250
Running costs per year*	NOK 100.000	Euro 12.500

* includes costs for all moorings (Aanderaa + ADCP)

The **objectives** of the measurements will be:

- Determine transport time series, spatial structure and temporal variability on seasonal and interannual variability.
- Establish quantitative relations between the variations of fluxes in different sections and propagation of water characteristics
- Assess the importance of processes responsible for the transport variability, like boundary currents, eddies and meanders, bottom topography, winter cooling and meteorological parameters.

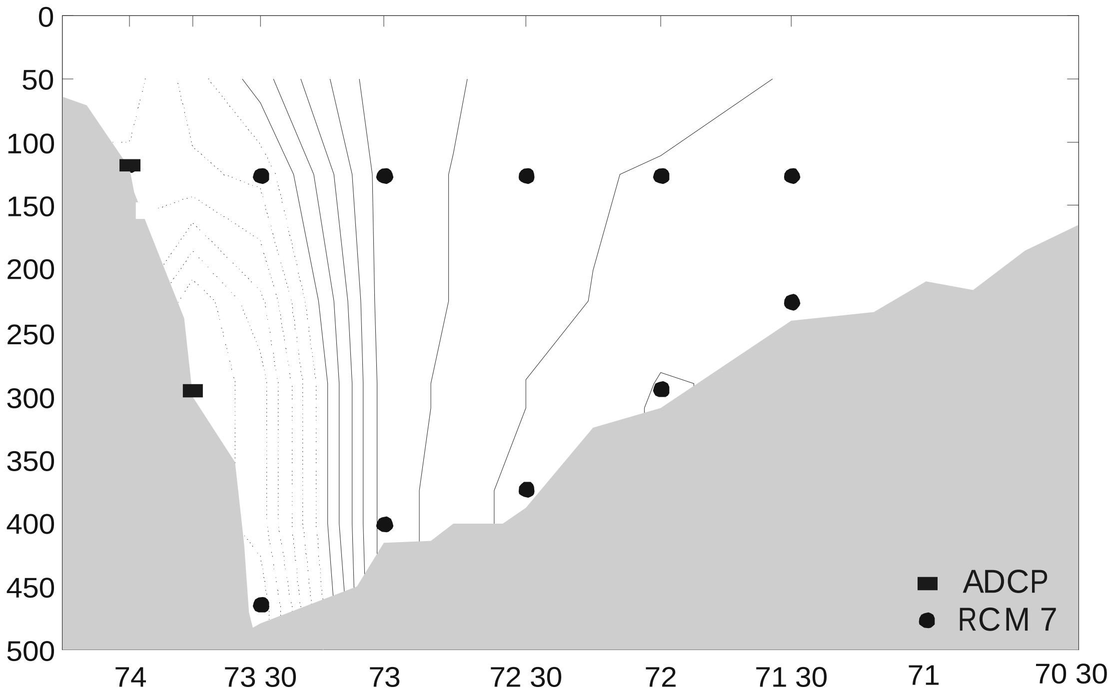

Figure 3. Suggested measuring programme in the Norway (right) – Bear Island (left) section. The continuous lines indicate the area where the Atlantic inflow takes place, while dotted line indicate outflowing currents.

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12. Direct measurements of heat and mass transports through Fram Strait

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To determine the heat and salt/freshwater transports through Fram Strait and their variability, reliable estimates of the volume transport are required. A set of moored instruments with eddy-resolving horizontal spacing is not affordable at present. With the aim of assessing the accuracy of the transport estimates which can be obtained by direct measurement, 14 current meter moorings were deployed in Fram Strait from September 1997 to August 2000 and replaced in September 1998 and 1999 (Fig. 1). The measurements were carried out in cooperation with the Norsk Polar Institutt, the University of Hamburg and partners of the EC MAST III VEINS Programme (Variability of Exchanges in Northern Seas). Their continuation was planned under OPEC (Ocean Processes and European Climate), but that proposal was not accepted for funding. The moored instruments cover the water column from 10 m above the seabed to approximately 60 m below the surface. Three moorings in the East Greenland Current were equipped with upward looking Doppler Current Meters reaching to the sea surface. In the horizontal the measurements extend from 6°51'W ---- the East Greenland shelf break --- to 8°40'E-- - the west coast of Spitsbergen -- along 78°50'N in the eastern part and along 79°N in the western part of the transect. The flow field through the Strait was compiled by interpolation based on the records of 41 current meters for the first year and 45 for the second.

The velocity field averaged over two years from September 1997 to September 1999 reflects the well-known current system in Fram Strait (Fig. 2). The northward flowing West Spitsbergen Current reaches a maximum speed of 24 cm/s in the core over the upper continental slope. The core of the southward flowing East Greenland Current reaches 9 cm/s. The time variability of the area occupied by each of the two current systems on the vertical transect causes their transports to be nonlinear quantities. Averaging over a time series of monthly mean transports (Fig. 3) results in 10.8 Sv to the north and 11.2 Sv to the south (Fig. 4). The observed variability suggests that short-term estimates of the heat or salt transports based on a single CTD survey can be strongly misleading.

The transports obtained and their variability are all significantly larger than earlier estimates given in the literature. However, the discrepancy from values obtained using direct current measurements is smaller than that from estimates made using hydrographic data alone. The agreement in the East Greenland Current is better than that in the West Spitsbergen Current. This is possibly due to the stronger baroclinic currents relative to the barotropic flow, which results in rather small errors if the geostrophic current velocities are calculated relative to bottom. The barotropic currents obtained from the moored instruments and the derived sea level elevation (Fig. 5a and b) suggest that appropriate monitoring of the sea level might result in useful information on transport fluctuations if the array is carefully calibrated.

For the time being, the evaluation of the available measurements can be summarized as follows: 1). The high variability and the nonlinear character of the transports through Fram Strait require time series of sufficient time-resolution to eliminate high frequency effects such as tides, eddies and seasonal variations. 2). The measurements have to include both branches of the West Spitzbergen Current, the one on the north Spitsbergen slope and the other west of the Yermak Plateau. 3). The horizontal extent and the resolution of the measurements have to cover the recirculation in the Strait and the flow on the East Greenland shelf. 4). The strong barotropic component of the West Spitsbergen Current might allow detection of transport fluctuations by bottom pressure recorders. 5). The strong contribution of the upper ocean layers requires the use of ADCPs and profiling CTDs which are not affected by sea ice.

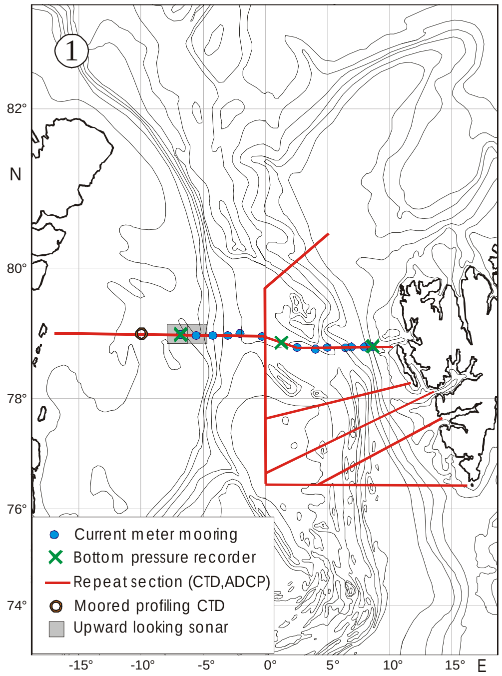
Costing (US Dollars)

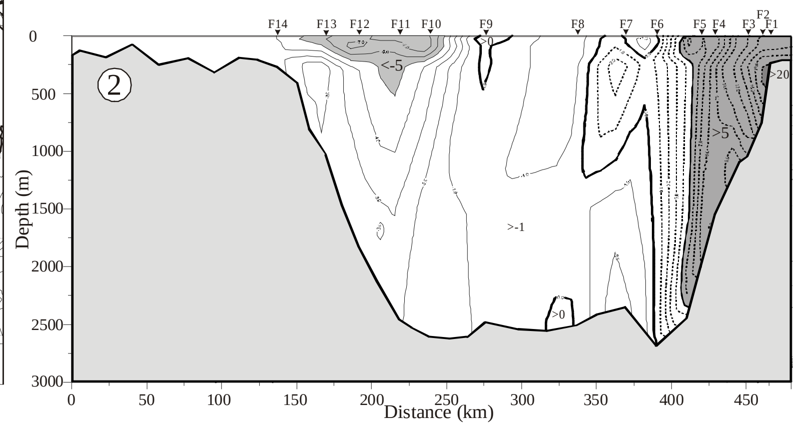
1. Initial investment	
41 current meters	348.500
28 Seabird TS-recorders	170.000
5 ADCPs	120.000
28 Acoustic releases	210.000
4 Sea level recorders	55.000
	903.500
2. Initial mooring material	220.000
3. Annual mooring refurbishment	200.000
4. Annual ship time (14 days)	420.000
5. Personal (support/evaluation pa)	140.000

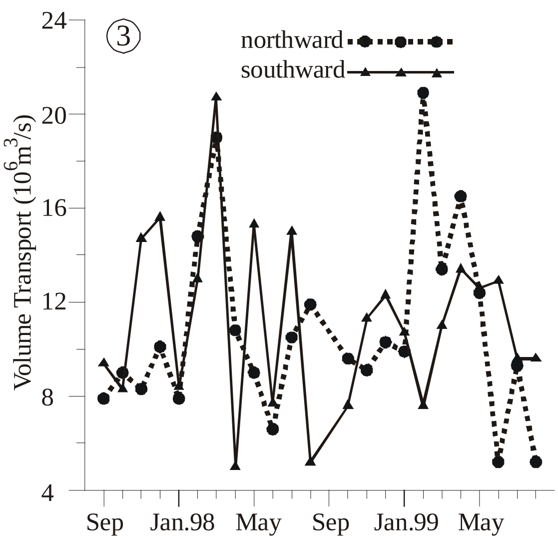
The initial costs might decrease after an initial phase of array calibration when the information from the sea level recorders might be used for transport estimation.

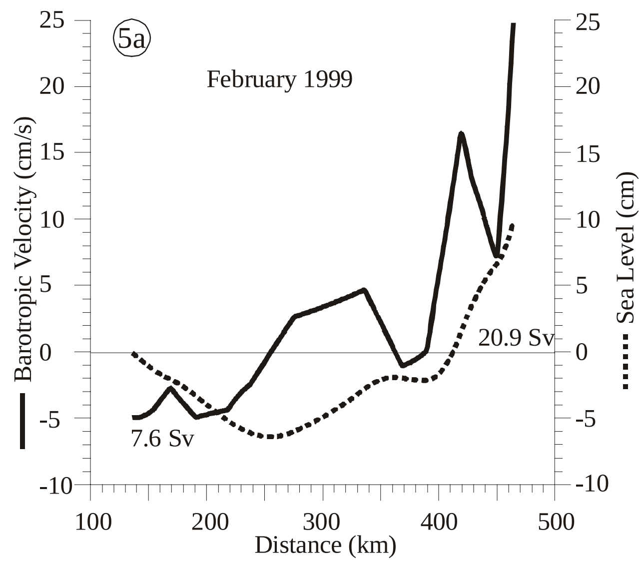
Figure captions

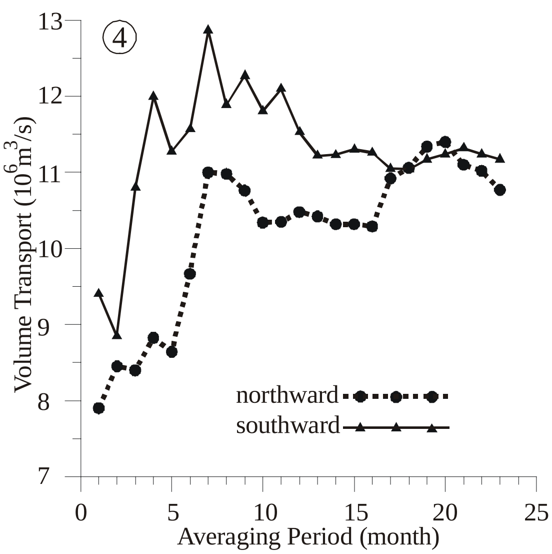
Fig 1: Map with the positions of CTD-sections and moored instruments to be deployed in Fram Strait, as suggested in the OPEC proposal.
Fig. 2: Vertical transect of current velocities through Fram Strait averaged over the time period from September 1997 to September 1999.
Fig.3: Monthly averages of the volume transports through Fram Strait (1 Sv = $10^6 m^3 s^{-1}$).
Fig. 4: Cumulative averages of the volume transports through Fram Strait.
Fig. 5: Monthly averages of the barotropic velocities and sea level determined from the moored instruments in (a) February and (b) August 1999 and the southward and northward transports.

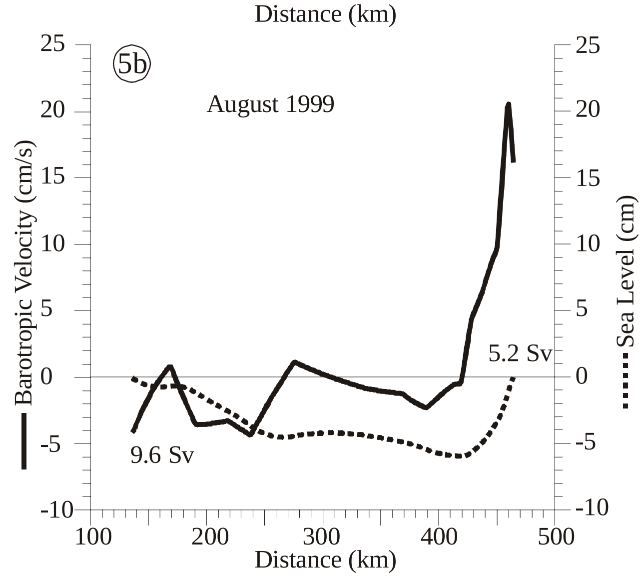

1
82°
N
80°
78°
76°
74°
Current meter mooring
Bottom pressure recorder
Repeat section (CTD,ADCP)
Moored profiling CTD
Upward looking sonar
-15°
-10°
-5°
0°
5°
10°
15°
E


2
F14 F13 F12 F11 F10 F9 F8 F7 F6 F5 F4 F3 F2 F1
<-5
>0
>-1
>5
>20
Depth (m)
Distance (km)


3
northward
southward
Volume Transport ($10^6 m^3/s$)
Sep
Jan.98
May
Sep
Jan.99
May


5a
February 1999
Barotropic Velocity (cm/s)
Sea Level (cm)
20.9 Sv
7.6 Sv
Distance (km)

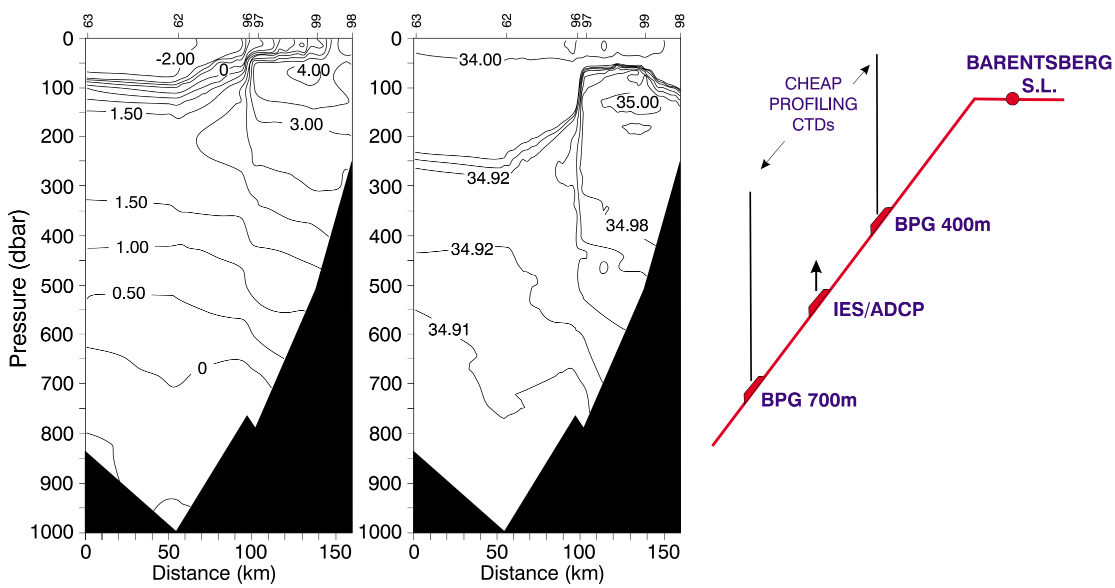

4
Volume Transport ($10^6 m^3/s$)
northward
southward
Averaging Period (month)


5b
August 1999
Barotropic Velocity (cm/s)
Sea Level (cm)
5.2 Sv
9.6 Sv
Distance (km)

Addenda: [inserted by Editor].

A. To supplement the existing moored array (Figure 1 above), the Tromso Workshop recommended a small additional observing effort north of Svalbard to help identify that part of the flow which will enter the Arctic Ocean from that which will recirculate southwards without entering. A moored array of bottom-mounted sensors running northwards across the Arctic Slope from the NW tip of Spitzbergen would cross the warm, saline Atlantic inflow at the earliest point after it has actually entered the Arctic Ocean, where the ice cover is likely to be less problematic than further east and where the warm, saline current core is still well confined against the upper Slope (Figure 6). There, providing equipment is protected against heavy shellfishing activities, both the baroclinic and barotropic components of inflow to the Arctic Ocean could be monitored with a limited array of gear. There are two development aspects to this task ---(a) to design, construct and test a novel low-cost, bottom-parked, profiling CTD system based on fishing reel technology, and (b) to fit these units and other existing equipment (2x Bottom Pressure Gauges, 2x Inverted Echo Sounders @ 12 kHz, and one Acoustic Doppler Current Profiler @ 150 kHz) into trawl-proof seabed mounts. The long term sea-level station at nearby Barentsberg is already available to help with the barotropic transport estimate.

Proposed Atlantic inflow array, North Spitzbergen



B. Ideally, the colder, fresher (Barents Sea) branch of inflow to the Arctic should also be measured close to its point of entry to the Arctic Ocean for the same reason (elimination of the recirculating component). A Norwegian /Russian team has already how this branch may be monitored close to its point of entry to St Anna's Trough in their successful recovery of a pioneering long-term current meter array from waters between Franz Josef Land and Novaya Zemlya, and from their results we know where the inflow core is located (towards the south side of this passage). Thus the array itself is practicable in technique, location and physical access.

13. Measuring the Bering Strait Throughflow

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Background

The influence of Pacific waters entering the Arctic Ocean through Bering Strait can be traced across the Polar Basin into the northern extensions of the North Atlantic. A particularly important dynamical aspect of the Pacific presence in the Arctic Ocean is its contribution to stabilizing the upper ocean, and thereby its influence on the maintenance of the ice cover and on upper ocean mixing. In addition to the direct effects of the Bering Strait flow on the stratification and properties of the Arctic Ocean, the strait represents an essential link in the global freshwater cycle by helping to balance the water budgets of the North Pacific and the North Atlantic [Wijffels et al., 1992]. Calculations also suggest that the Bering Strait flow significantly augments the global wind-driven circulation through its role in the Goldsbrough-Stommel haline circulation [Huang and Schmitt, 1993]. Furthermore, the strait transmits the time-dependent but spatially integrated physical and biogeochemical output of the northern Bering Sea system, and it is therefore an efficient observing site for that large system [Roach et al., 1995]. Note that portions of the Bering and Chukchi seas are among the most biologically productive areas of the world ocean [Walsh et al., 1989; 1997; Springer et al., 1996]. The strait is also the migratory gateway for a remarkably rich and diverse annual movement of marine mammals and birds over distances that bridge polar, temperate, and tropical waters [Ainley and DeMaster, 1990; Tynan and DeMaster, 1997]. Finally, the strait delivers to the Arctic Ocean a burden of anthropogenic contaminants deposited in the North Pacific over an extended time [Macdonald and Bewers, 1996].

An accurate assessment of conditions and fluxes in Bering Strait, and in particular of their variability, is therefore essential to assessing and understanding the state and health of the Arctic ecosystem, as well as the changing contribution of the region to Pan-Arctic and global issues of ocean structure and circulation and of

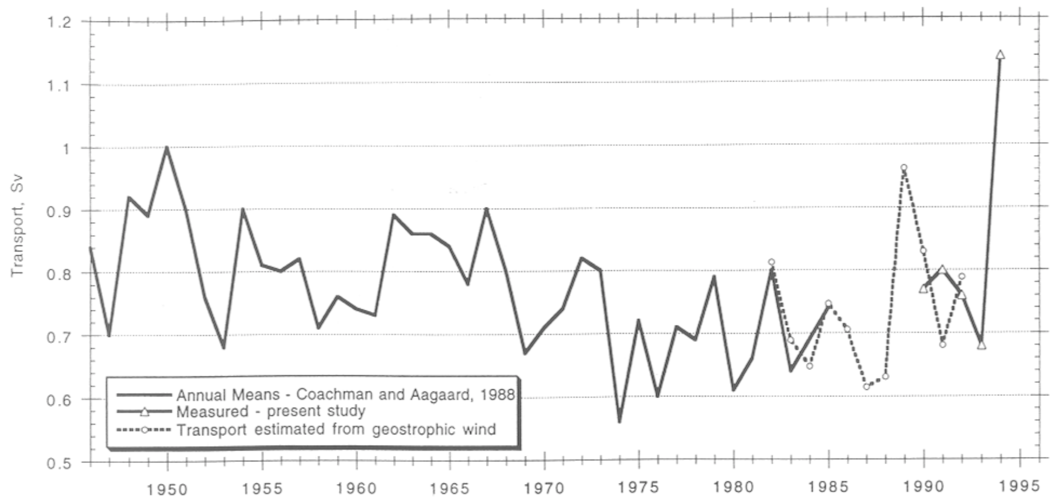


Figure 1. Time series of observed and estimated annual mean transport estimates for Bering Strait, 1946-1994 (from Roach et al., 1995).

biogeochemical cycling. There is mounting evidence of large variability in the Pacific inflow (e.g., Figure 1), including its salinity and temperature, based on the nearly continuous time series of velocity, temperature, and salinity in Bering Strait that have been acquired during the past decade [Roach et al., 1995, Weingartner et al., 1998]. The measurements show that both the transport and the salinity of the flow have large annual cycles, and that interannual variability significantly influences the water mass products that are exported to the Arctic Ocean [Weingartner et al., 1998].

Approach

While the strait is 85 km wide, it is extremely shallow (about 50 m), as is the shelf for hundreds of kilometers north and south (see Figure 2, from Roach et al., 1995).

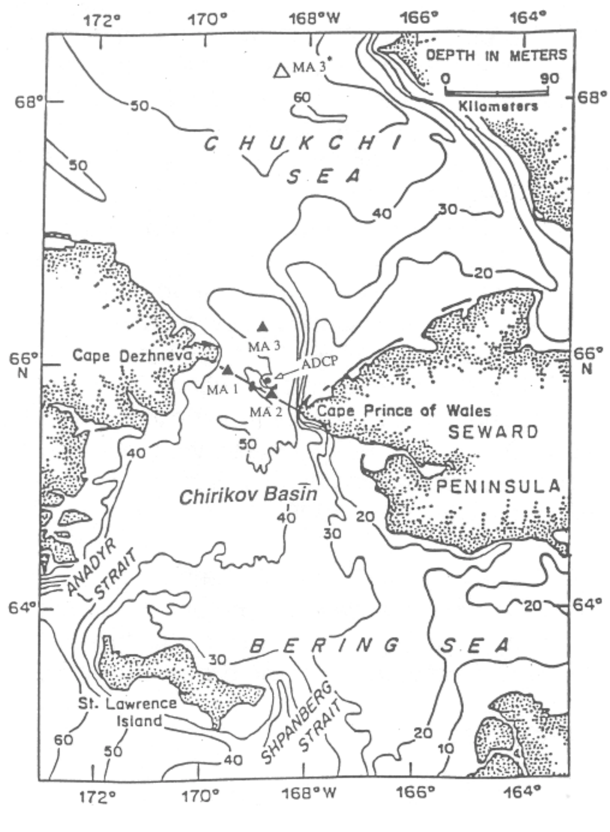


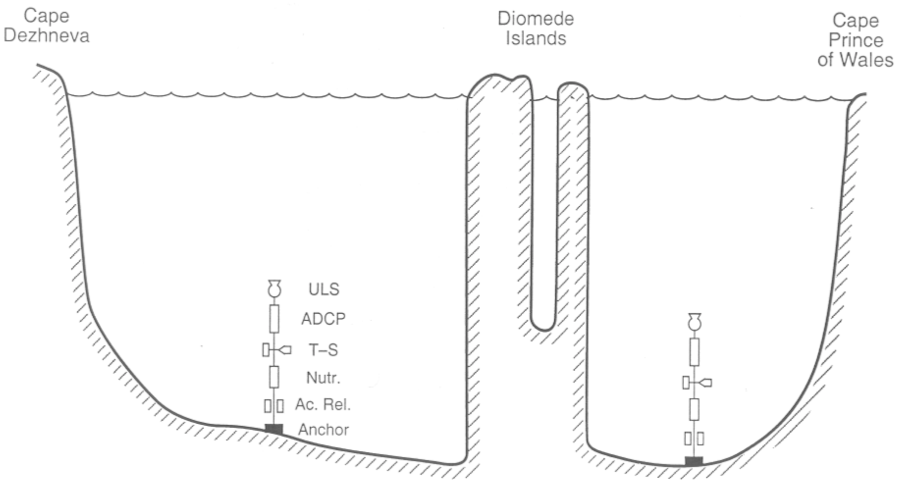
Figure2.BeringStrait mooring sites and bathymetry, from Roach et al., 1995. Solid triangles indicate conventional moorings, solid circle indicates ADCP.

The low-frequency flow through the strait is largely barotropic, and the water column tends to be well mixed vertically, but there are horizontal gradients in both velocity and water properties. Existing measurements suggest that a single mooring in each channel may be adequate for monitoring the low-frequency flow and the water properties, but a full calibration of this procedure has never been attempted. The latter could likely be completed in a single year, summer-to-summer.

Field work is complicated by the demarcation line between the Russian and U.S. Exclusive Economic Zones that bisects the strait, passing between the Diomede Islands. Arranging reliable access for oceanographic research moorings in both channels of the strait is therefore an important requirement. The eastern channel of Bering Strait is presently being monitored in mid-channel directly, while the western one is monitored at a surrogate location north of the Diomede Islands, just east of the Russian Exclusive Economic Zone and north of the western channel proper. This work is being done by investigators from the University of Washington.

Gear requirements and costs

Velocity, temperature, and salinity are presently included in the core physical measurements at each mooring, supplemented with ice thickness measurements using upward-looking sonar. In addition, selections from the growing array of



biogeochemical sensors and sampling devices are being added, including automated water samplers and in situ nutrient recorders.
A cross section of Bering Strait with an appropriately instrumented array is shown in Figure 3.
Figure 3. Schematic representation of Bering Strait instrumented for time series measurement of ice thickness, ice and water velocity, temperature and salinity, and nutrients. With the ADCP in a bottom-tracking mode, ice velocity can be measured directly.

Typical costs for two physics-oriented moorings, i.e., without biochemical instrumentation, can be estimated as:

Upward-looking sonar, 2 ea -	$ 40,000
ADCP, 2 ea -	$ 52,000

T-S recorder, 2 ea -	$ 10,000
Acoustic release, 4 ea -	$ 36,000
Flotation and mooring hardware -	$ 5,000
	Total $143,000

Existing instrument inventories will reduce these expenses. Additional costs, however, largely in salaries, derive from mooring manufacture, deployment, and recovery; calibration and data processing; and analysis.

The strait is ice-free for about half the year, so that a conventional research vessel can service the moorings each summer.

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14. Measuring the Fram Strait Ice and Freshwater Flux

By
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Introduction

Measuring the magnitude and variability of the ice and freshwater flux through the Fram Strait is an important element in understanding the climate variability in the Arctic. Since the majority of the ice and freshwater that leave the Arctic Ocean pass through the Fram Strait, figure 1, this passage can be considered the key area for estimation of the net production of ice in the Arctic Ocean. As this ice export in turn represents the major part of the ice production in the Northern Hemisphere, it becomes an important climate signal. In addition the ice and liquid freshwater export from the Arctic Ocean represent the major input of freshwater to the Nordic Seas, where a variable input of melt water may effect the stability, and thereby be of crucial importance for the local convection. Since 1990 the Norwegian Polar Institute (NPI) has monitored the ice thickness and the ice transport through the Fram Strait, figure 2, most years by means of two moorings. For the period 1990-96 the mean annual ice export was about 2850 km^3 pr year. This efflux shows significant variation from year to year, nearly 130%, mainly caused by variation in the atmospheric forcing and to a lesser degree by variation in the annual mean ice thickness. Since 1997 Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI) and NPI have operated fourteen moorings across the Fram Strait as a part of the EU founded project VEINS (Variability of Exchanges in the Northern Seas). Monitoring the Fram Strait flux of ice and freshwater is a key CLIVAR/ACSYS variable.

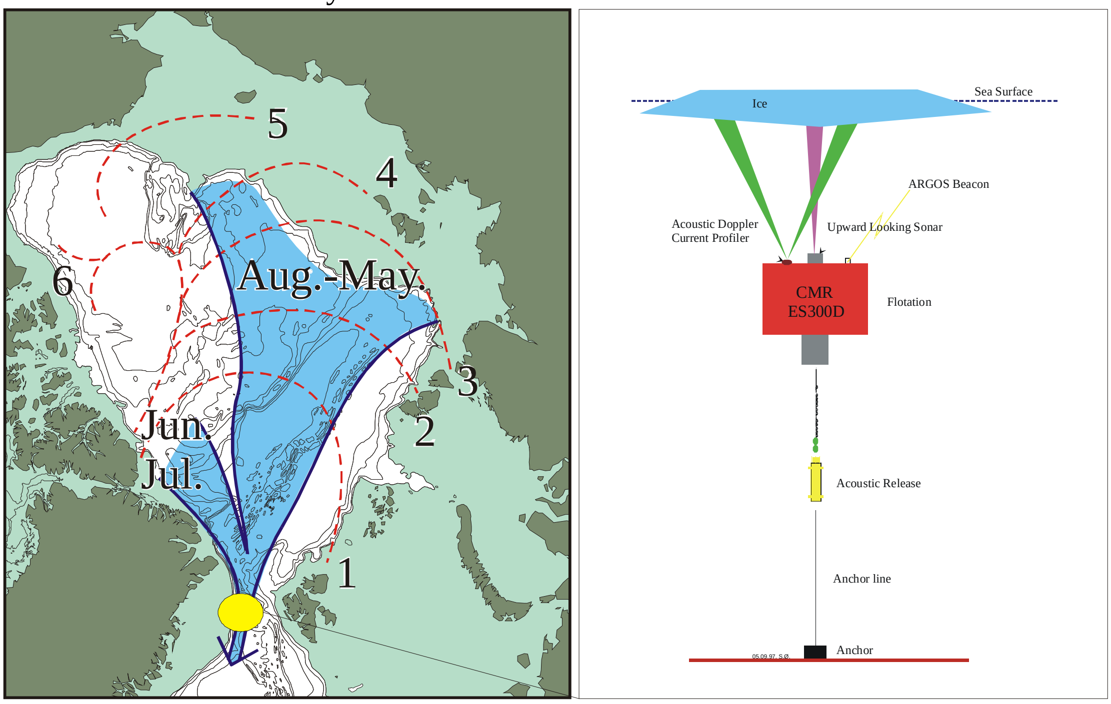


Figure 1
The ice and liquid freshwater in the Arctic Ocean is transported by the Transpolar Current through the Fram Strait. The yellow dot marks the monitoring position and the right a sketch of the mooring configuration.

Methods

The ice thickness has been measured using upward looking sonar from Christian Michelsen Research (CMR), Bergen. CMR has combined the ES300 ULS with an acoustic Doppler current profiler (DCM12) from Aanderaa Instruments. The instruments are placed at the top of a mooring underneath the drifting sea ice, figure 1. The CMR-ES300 has been used for ten years in the Fram Strait. The ice draft is measured by emitting four 300 kHz sound pulses every three minutes. With an aperture angle of 2° and a nominal depth of 50 m, the sonar beam covers a footprint on the underside of the ice of radius 1.75 m. The ES300 is equipped with a pressure transducer to monitor the depth of the sonar head. The Doppler current profiler, DCM12, works at 600 kHz and has three beams. The speed and direction are measured for the ice and in five levels beneath the ice. The DCM12 also measures the wave height.

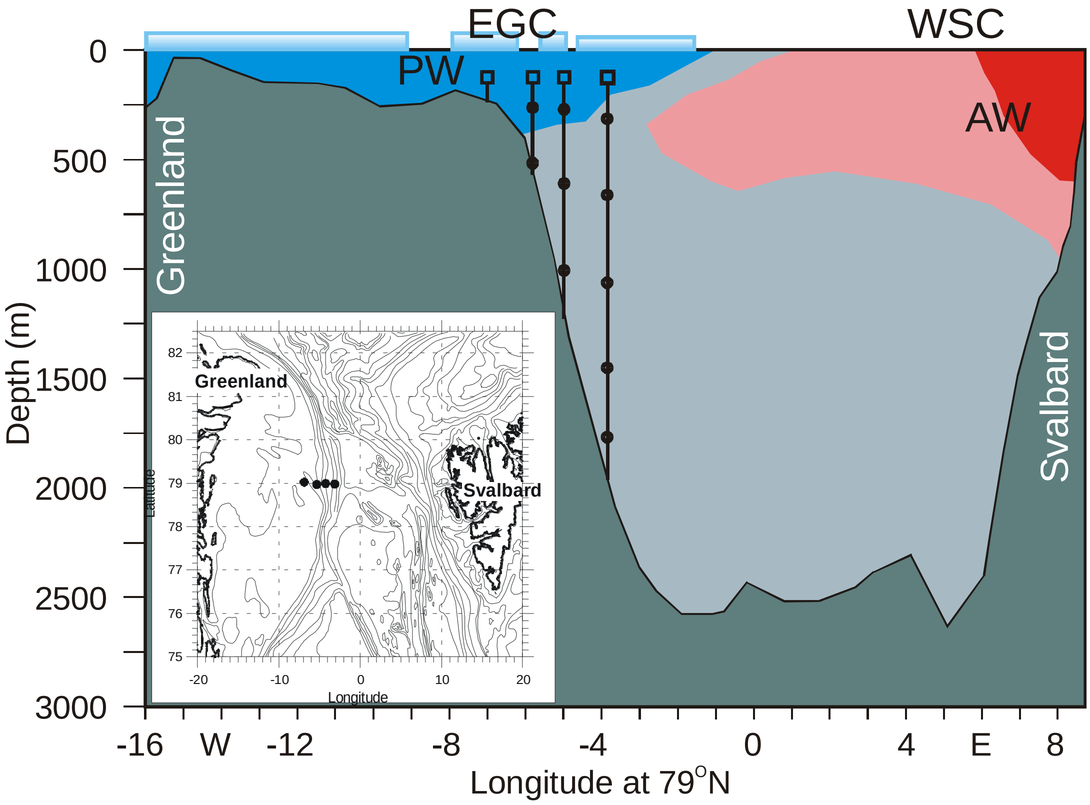
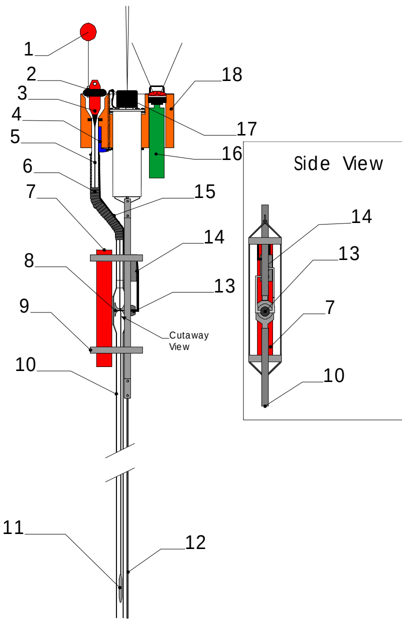


Figure 2. A section across the Fram Strait at 79° N. The moorings positions are shown on the inset map. To the east the West Spitsbergen Current (WSC) carries relatively warm Atlantic Water (AW) to the Arctic Ocean. The East Greenland Current (EGC) carries cold Polar Water (PW) from the Arctic Ocean to the Greenland Sea.

Future development

Existing instruments and methods are sufficient to measure ice volume efflux from the Arctic Ocean through the western Fram Strait, but these instruments are not developed to measure the liquid part of the freshwater transport. The liquid part of the total freshwater transport has been estimated to about 20% (Aagaard and Carmak, 1989), but more recent estimations indicate that the liquid part may be about one third. It is not clear if the liquid part has increased or the older estimates were wrong. To measure the liquid freshwater flux is a challenge and new instruments are needed. CMR is in the process of developing an extension to the ES300 instrument. The new system will in addition to measuring the ice thickness and flux also be capable of measuring the salinity and temperature in the upper layer. A somewhat artistic view of the system is shown in figure 3. The system operates as follows: at pre-set time intervals, controlled by a real time clock the system goes into profiling mode. The control electronics located inside the ES 300 start the electro–hydraulic pump (14) which drives the hydraulic motor (13). The hydraulic motor turns the capstan (8), causing the CTP sensor (2) to ascend, driven by the buoyancy (1). The counterweight (11) reduces the power required to turn the system. As the CTP ascends, data are collected via the inductive sensor head (4) at an approximate rate of .5 Hz. Data are transferred into the ES 300 and stored. When the buoyancy (1) reaches the surface or the ice, the inverted bottom alarm (2) gives a signal to the controller, which in turn reverses the hydraulic pump. Data collection is also stopped. The CTP will descend as the capstan turns the other way, still with a balance between the buoyancy (1) and the counterweight (11). A stop detector (in practice a magnet switch) located within the inductive communication head (4), detects the presence of a magnet beneath the CTP when the CTP is docked. The hydraulic pump is stopped and locked and the data collects cycle ends. If the necessary funding is obtained the instrument will be in operation from the 2001 season.



1	Buoyancy 3-4 kg	10	PVC pipe, 60 mm
2	Inverted bottom alarm		
3	CTP Sensor	11	Counterweight, balanced
4	Inductive Co-munication head	12	Mooring line
5	Cable 3-4 mm	13	Hydraulic Motor
6	Flexible, inner form stable pipe.	14	Electro-hydraulic pump
7	Battery Pack, 300 Ah@12V	15	Control cable for pump.
9	Protective frame	16	Aanderaa DCM 12

Figure 3

Sketch of the inverted CTP profiler, combined with the CMR ES300 and Aanderaa DCM 12. This instrument will in addition to measuring the ice thickness and speed also profile the water column about the instrument and map the salinity and temperature.

Future of the monitoring moorings

The four NPI moorings were deployed in August 2000 as a part of the fourteen moorings AWI and NPI have operated since 1997. The moorings are deployed for a two years period and will be recovered in 2002. The NPI moorings are partly funded by the Research Council of Norway until 2002. NPI intention is to keep the four moorings in operation as long term monitoring stations, but no funding is obtained after 2002.

Budget

To build and test the new CTD system is calculated to the cost of NOK 955940 (100.000 USD). It does not include the CMR-ES300 ULS (NOK 250.000), its flotation collar, the Aanderaa DCM 12 (125.000) or any parts of the mooring. A summary of the budget is given in table 1. The cost of a complete system is estimated to NOK 700.000, after the initial investment in developing the CTD system. Upgrading the old system with automatic inverted CTD profiler is estimated to cost NOK 400.000 for each system.

The main running expensive is the ship time, which presently is made available by NPI and AWI. The approximate cost of keeping the four moorings running each year is summarized in table 2. A service time of two years will reduce the yearly running cost.

Description	Sum in NOK
Mechanics – Man hours	195460
Mechanics – Direct Costs	98680
Electronics Hardware	212080
Electronics Software	318720
Electronics - Direct Costs	15000
System Tests	116000
Sum Project	955940

Table 1. Summary of the budget for the automatic inverted CTD profiler.

Description	Sum in NOK
Maintenance for 4 systems pr year	200.000
Maintenance for 4 moorings pr year	100.000
Replenishment of one complete system each year	700.000
Replenishment of one complete mooring each year	100.000
Sum pr year	**1100.000**

Table 2. Running cost of the four NPI moorings in the Fram Strait. Instrumentation for the deepwater monitoring is not included.

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15. The East Greenland Current at 75°N - Indicator of low frequency variability in the output of the Arctic Ocean/Nordic Seas to the Atlantic

By

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In a longer-term study by the University of Hamburg and the Alfred-Wegener-Institut for Polar- and Marine Research in Bremerhaven, the variability of watermass-transport in the East Greenland Current (EGC) will be measured. The water mass components and their principal paths are shown in Figure 1: (*a*) The Polar Water and Ice (PW), which is the fresh water run-off from the Arctic Ocean, (*b*) the Arctic Atlantic Water (AAW), which is Atlantic Water recirculating through the Polar-basins along various routes, (*c*) the recirculating Atlantic Water (rAW), which is Atlantic Water of the West Spitsbergen Current directly recirculating in Fram Strait and (*d*) the Arctic Intermediate Water (AIW), which is the product of convection in the Greenland and Iceland Seas.

With this water mass composition, the EGC has a doubly-important impact on the Atlantic thermohaline circulation: Whereas the intermediate and deeper components provide the advective source for the deep Overflows which cross the Greenland-Scotland Ridge and thus determine the intensity of North Atlantic Deep Water formation (Willebrand et al, 2000), the upper fresh component exerts a major control on the convectively-formed watermasses of the Greenland, Iceland and Labrador Seas (Rahmstorf, 1996).

From the literature there is widely inhomogeneous information on transports and relative water mass composition in the EGC. For the liquid freshwater content in the PW, there are only scarce measurements from hydrographic sections, and the published estimates are mainly based on budget considerations for the Arctic Ocean (Goldner, 1999). For the transport of freshwater as sea ice, numbers have been provided by Kwok (1999) and Vinje et al (1998). Estimates for the AAW were given by Rudels et al (1999), and the contributions of rAW and AIW to the ECS can be found in Mauritzen (1996) and Strass et al (1993). Depending on the data used and the assumptions made about mixing and the pattern of the ocean circulation, the authors provide for differing proportions of watermasses in the composition of the EGC. Taking into account the recent findings of considerable low frequency variability in the availability and circulation of water masses within the Arctic Ocean/Nordic Seas (Dickson et al, 1999, Dickson et al, 2000), it seems reasonable to state that the different results on the transports and the composition of the EGC are a reflection of the low frequency variability in the system. There are strong indications that the NAO-related variability in atmospheric forcing is linked to changes in the advective pattern of the Greenland Sea, and that this explains relevant changes in the water mass composition of the EGC.

Therefore, by measuring the longer-term changes of the EGC-water mass composition and transports within the Nordic Seas, we expect to gain insight into the dynamics of this variability. Without this information, we will not be able to verify model results adequately, and there will be a continuing lack of understanding about how to install an optimised long--term observing system.

A strategic location for these measurements is the East Greenland shelf and slope at 75°N. There, repeat hydrographic sections have been worked across the Greenland and Lofoten Basins since 1986, and there have been several years of current measurements over the East Greenland Slope (Woodgate et al, 1999). Moreover, 75°N is the point where both the outflow from the Polar Basins and the major convective contribution from the Nordic Seas pass south before splitting to supply the Denmark Strait and Iceland-Scotland overflows.

Figure 2 shows the planned array of current meters & temperature and salinity sensors over the East Greenland Slope. For the freshwater fluxes over the ice-covered shelf, a combination of bottom-mounted ADCPs and specially-designed moorings with vertically-spaced, ice-sheltered temperature-salinity recorders will be deployed. There will also be upward looking sonars in the array to estimate ice thickness variations and deduce freshwater transport as ice.

Cost (US Dollars)

1.	Initial investment	
	20 Current meters	170.000
	32 Seabird TS-recorders	190.000
	4 Upward looking sonars	96.000
	1 ADCP in bottom frame	115.000
	8 Acoustic releases	80.000
		651.000
2.	Initial mooring material	150.000
3.	Annual mooring refurbishment	150.000
4.	Annual ship charter (14 days)	170.000

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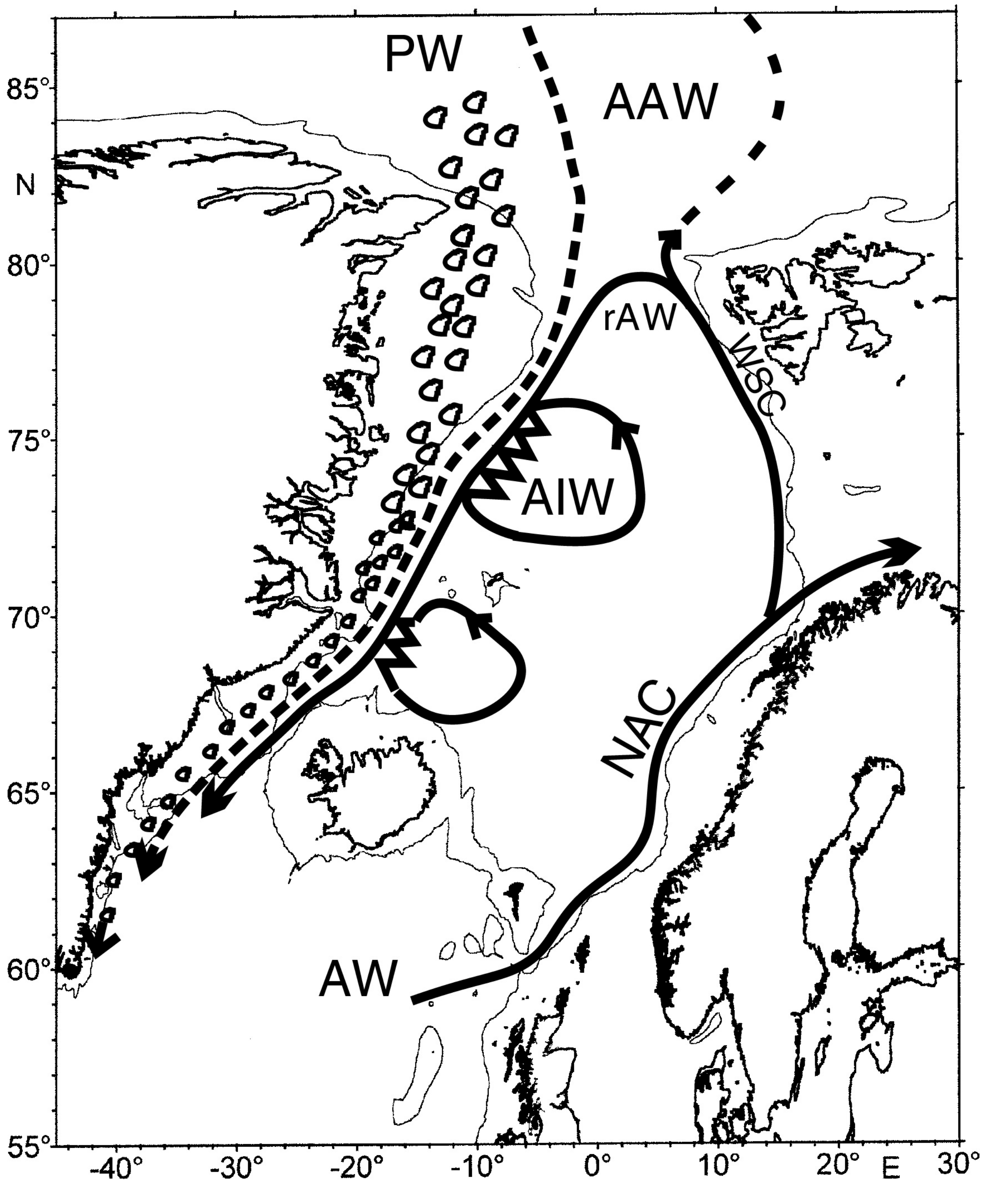

Figure 1: Schematic presentation of water mass circulation between the North Atlantic and the Nordic Seas/Arctic Ocean

AW	=	Atlantic Water
rAW	=	recirculating Atlantic Water
NAC	=	Norwegian Atlantic Current
WSC	=	West Spitsbergen Current
PW	=	Polar Water
AAW	=	Arctic Atlantic Water
AIW	=	Arctic Intermediate Water

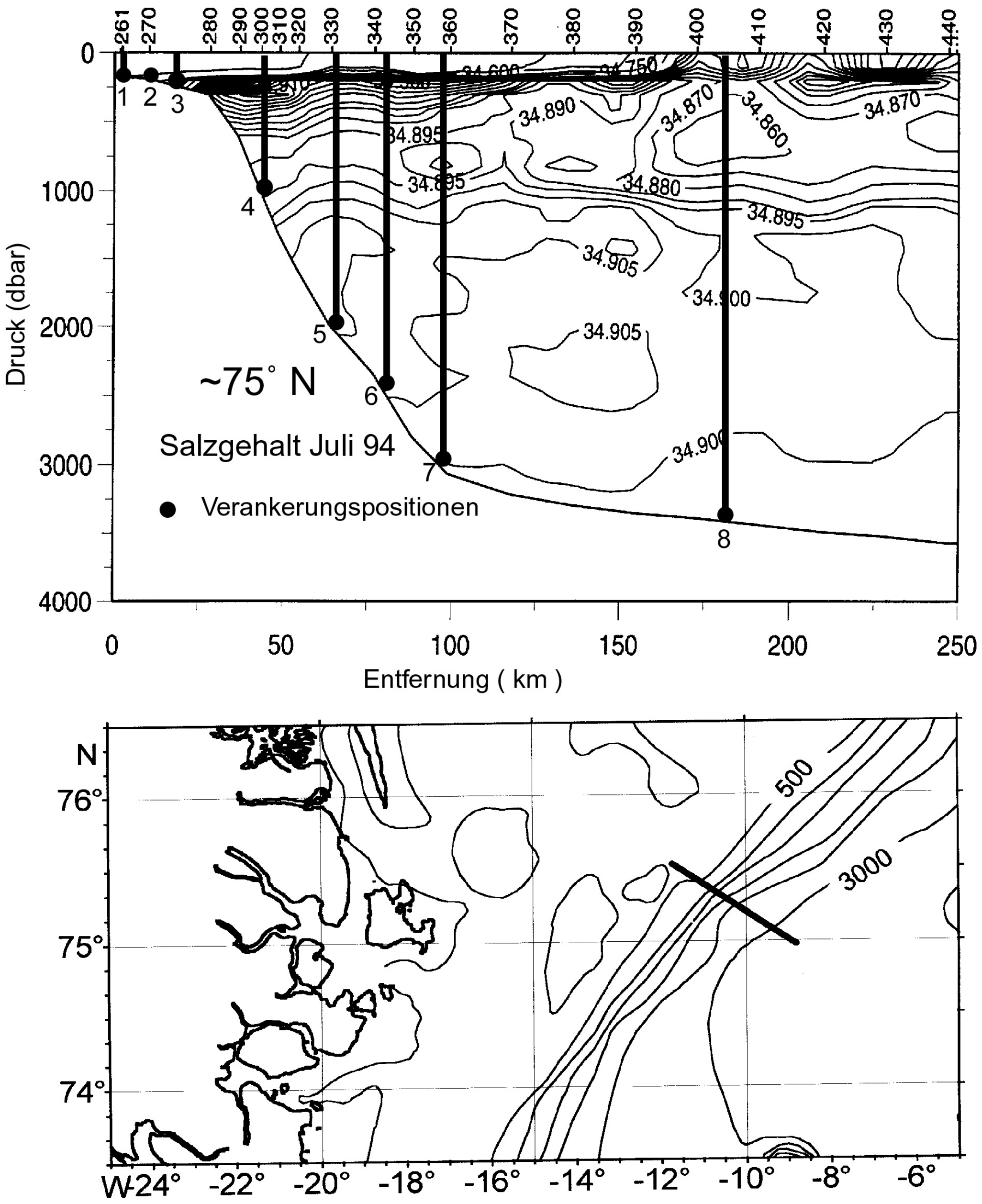

Figure 2: Salinity distribution over the East Greenland continental slope at 75°N (Woodgate et al, 1999) and location of planned moored array.

Details:

Moorings 1+3: Full depth moorings for TS-profiles with ice protected TS-recorders
Mooring 2: Bottom mounted ADCP and ULS
Moorings 4+6+8: Full depth moorings with current meters, TS-recorders and ULS
Moorings 5+7: Full depth moorings with current meters and TS-recorders

16. Lagrangian measurement of freshwater distribution along the East Greenland shelf.

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An ice/oceanography buoy for meteorology and sub-ice oceanography

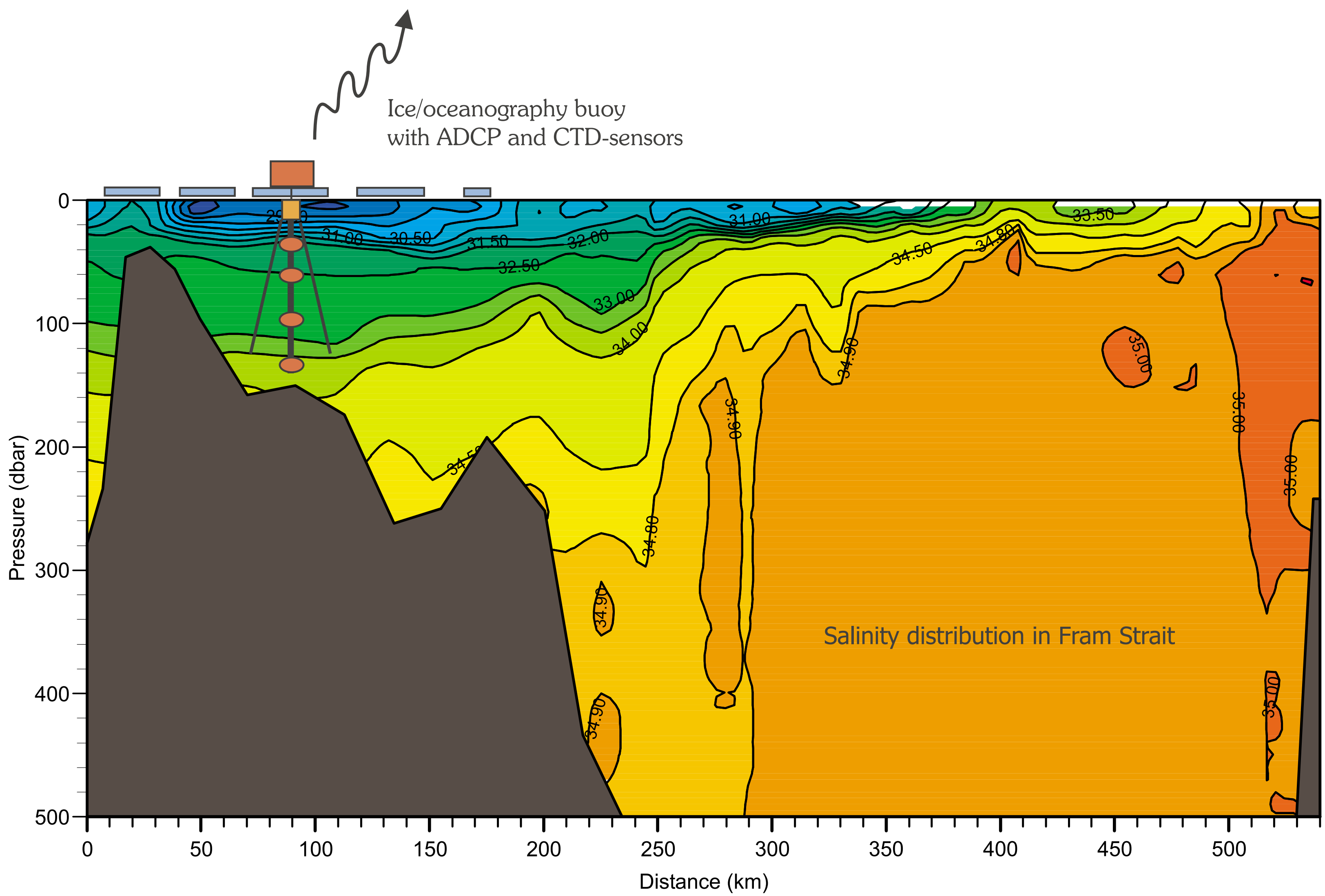
Most of the fresh water exchange between the Arctic Ocean and Nordic Seas occurs in the upper layers which are difficult to access with conventional moorings. A large part exits the Arctic Ocean on the East-Greenland shelf which is ice-covered in Fram Strait and along most of its length making mooring work even less appropriate. We therefore propose to use ice drifting buoys to give us Lagrangian information on the near-surface vertical salinity structure immediately beneath the East Greenland marginal sea-ice, if possible from Fram Strait to SE Greenland .

These buoys consist of a drifting body which will be deployed on an ice floe. They are buoyant, however, so that they can survive periods of open water during their southward transport. The upper part is equipped with sensors for air temperature and air pressure, and to measure the subsurface stratification and current profile, they carry a 200 m long subsurface chain with sensors for temperature, pressure, conductivity and velocity (e.g. ADCP and Microcats). The subsurface data will be transmitted inductively to the cable and to the buoy. From there, the data and the position of the buoy (GPS) will be transmitted ashore with the aid of the ARGOS or comparable systems. Absolute water velocity can be calculated from the buoy drift and the water velocity measured relative to the buoy drift. The choice of manufacturer for the buoy and its sensor system has not yet been made.

Costs

Annual cost of data-capture & data-reduction technician.	= 50 k Euro
Unit capital cost per buoy (met sensors,1 ADCP, 5 microcats)	= 95 k Euro
Argos data link per buoy per year	= 5.1 k Euro.

For a long term program of deployments, we consider it necessary to deploy 2 buoys every second year. The buoys will not be recovered, unless by chance: the ship cost associated with deliberate recovery of buoys is probably more expensive than a new buoy.


Ice/oceanography buoy
with ADCP and CTD-sensors
Salinity distribution in Fram Strait
Pressure (dbar)
Distance (km)
0
100
200
300
400
500
0
50
100
150
200
250
300
350
400
450
500
31.00
30.50
31.50
32.00
32.50
33.00
34.00
34.50
34.80
34.90
33.50
35.00

17. Measuring arctic freshwater flux in Icelandic waters.

by

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The freshwater fluxes from the Arctic split to flow either side of Iceland and the Marine Research Institute has been involved in several international research projects (Greenland Sea Project, WOCE, ESOP and VEINS) involving the measurement of both components. The sections on figure 1 were worked during the VEINS project up to four times a year.

East Iceland Current.

Mooring station LNA 1 on figure 1 is situated in the fresh East Icelandic Current over the slope. This mooring consisted of three current meters at 80, 200 and 650 m depths. Figure 2 shows the temperature, salinity and density profile at this station on the 3rd of June 1998 and the current meter depth is approximately at the cold core of this current. Over one year, the progressive vector diagram (figure 3) shows the current at 80m flowing to the southeast with a mean speed of approximate 10 cm/s . The current at 200 m depth is much less consistent in direction with a mean current of around 2 cm/s. So the East-Icelandic Current at this location appears to be highly baroclinic and figure 4 illustrates the vertical section of absolute velocity calculated as the geostrophic current adjusted to the current meter measurement. A preliminary estimate of the freshwater transport in March 1998 above 150 m depth and referred to the salinity 34.93 is about 0.0052 Sverdrup, which is roughly 4 % of the freshwater transport through Fram Strait, (Aagaard and Carmack, 1989). However, some seasonal and interannual variability has been observed in the amount of fresh water present at this section; figure 5 illustrates the stronger velocity distribution observed in June 1998.

Denmark Strait.

The Marine Research Institute has also been concerned with improving the estimate of fresh water fluxes to the NW of Iceland. The mooring positions and locations of the current meters on the Kogur Section across the approaches to the Denmark Strait are shown in vertical section in figure 6 (the northernmost section on figure 1). The salinity distribution on this section in September 1997(Figure 7) illustrates the fact that the main body of freshwater extends over the Greenland shelf, and a progressive vector diagram in the fresh water flow at IS6 over the East Greenland slope (not shown) indicates a generally southward flow. The Kögur section has been repeated almost annually since 1987 (GSP) at the time of year (September) when the sea-ice extent is at minimum extent. The estimated freshwater thickness relative to a salinity of 34.93 for each year at same positions is shown on figure 8. Time variability of freshwater over the shelf is considerable and it is clear that to be able to estimate the fresh water flux through this section thoroughly some type of continuous measurement on the Greenland shelf has to be obtained. At the same time it may be pointed out that the southernmost section in figure 1, the Faxafloi section, is a coast to coast section and in connection with a mooring on the Greenland shelf, would be adequate for monitoring purpose.

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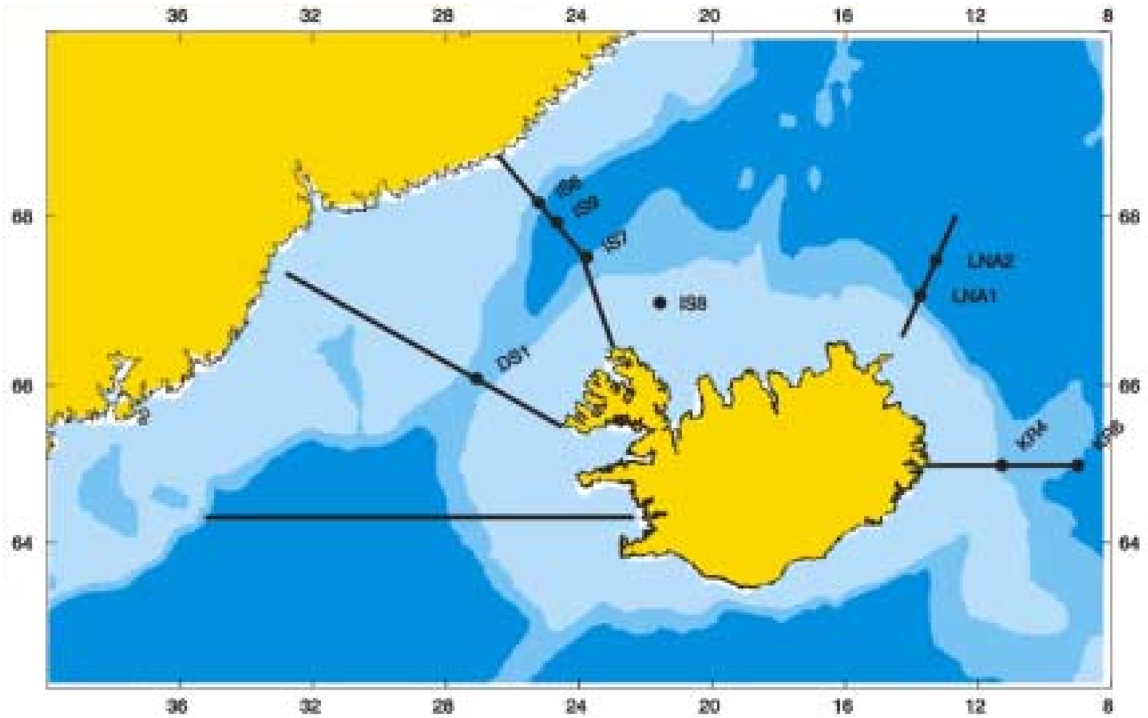

Figure 1. Location of some of the sections and current meter moorings of the Marine Research Institute, Iceland.

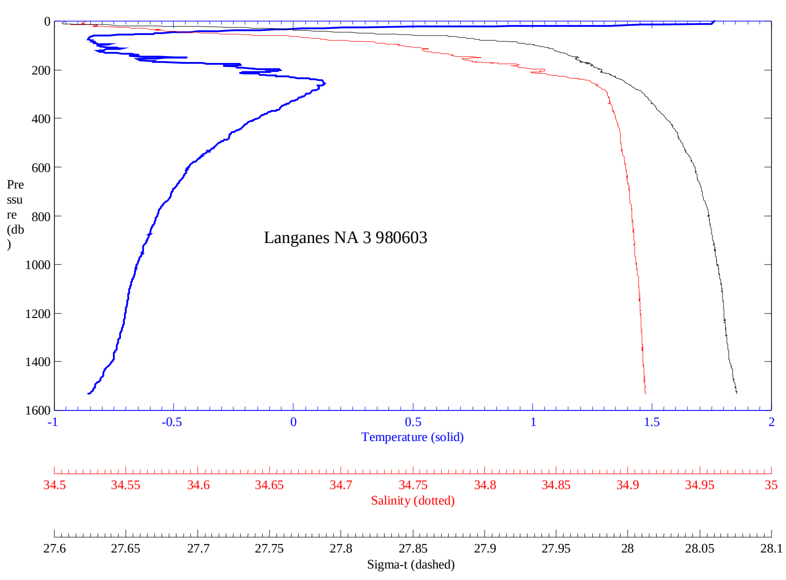

Figure 2. Temperature, salinity and density at station LNA1.

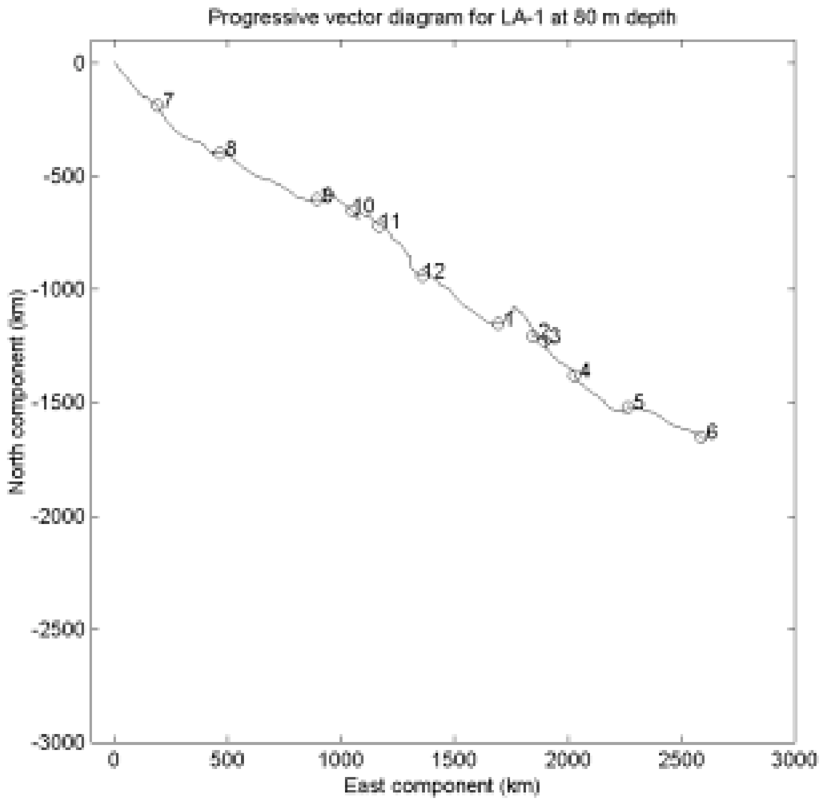

Figure 3. Progressive vector diagram from LNA1, 80 m depth, 1997 to 1998. Numbers indicate the beginning of each month.

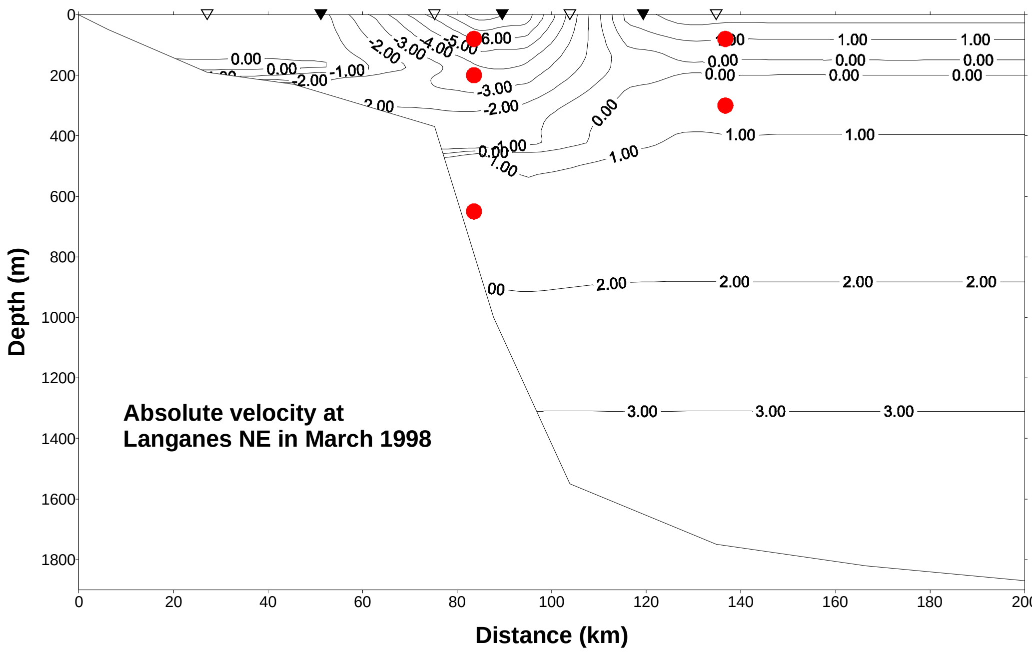

Figure 4. Absolute velocity at Langanes NE in March 1998. Open triangles at surface are CTD stations. Location of current meters as round dots. Data only from the four southernmost stations, so the section for the last 60 km is extrapolated.

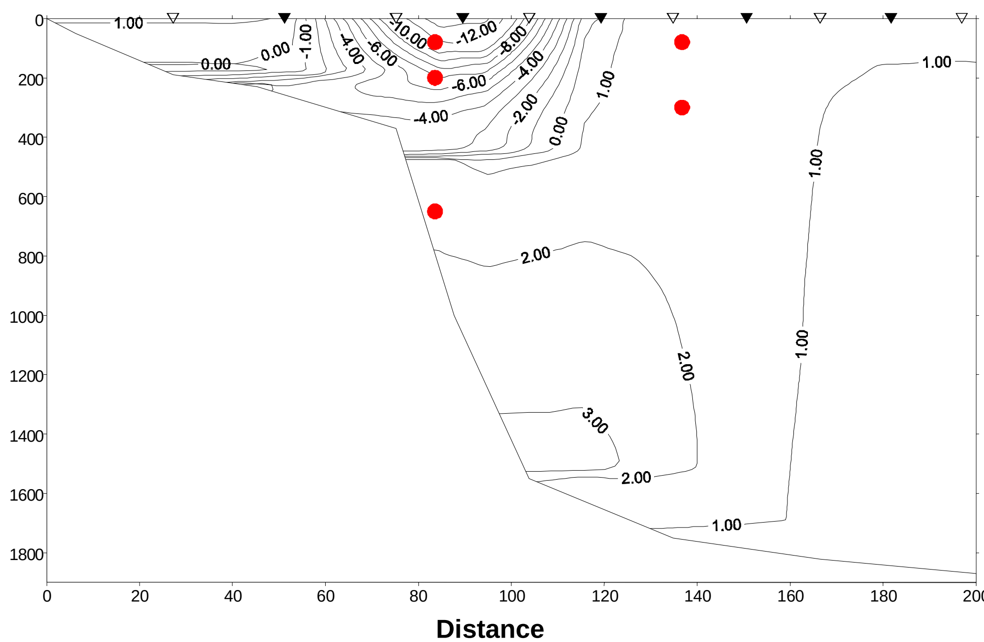

Figure 5. Absolute velocity at Langanes NE in June 1998. As in figure 4, except that CTD data from six stations is used.

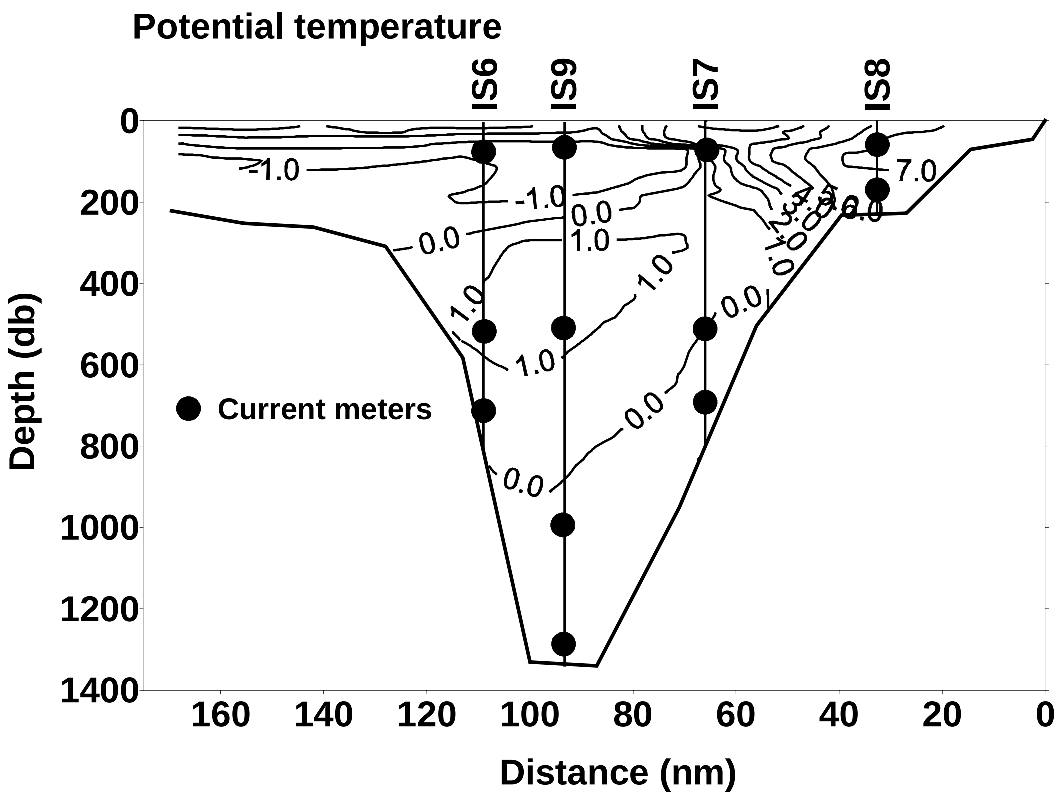

Figure 6. Location of current meters and current meter moorings on the Kögur section during the last decades.

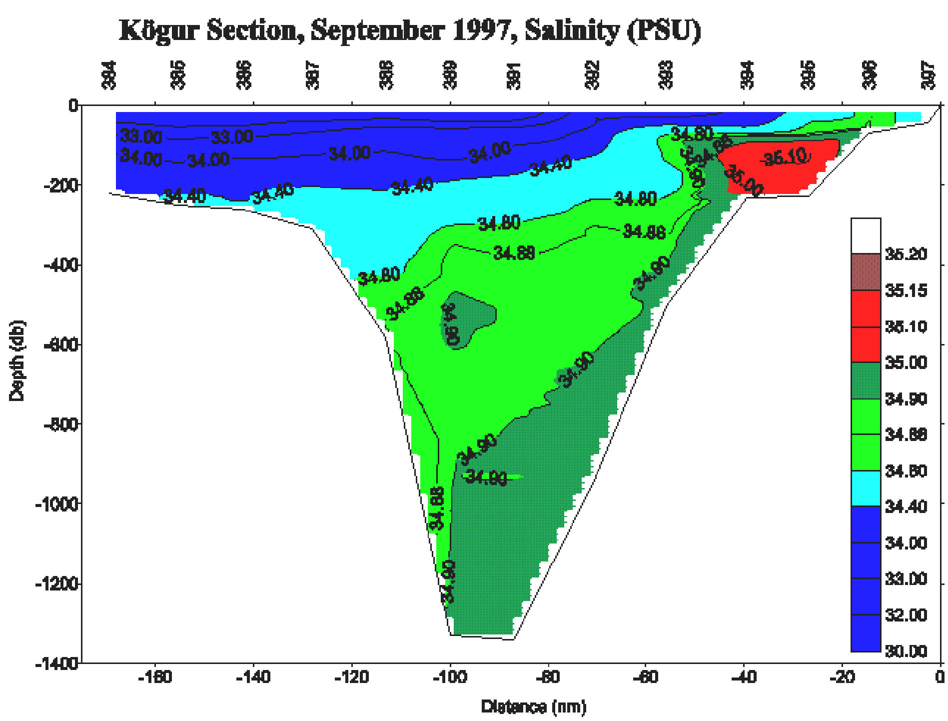

Figure 7. Salinity at the Kögur section in September 1997. Iceland is to the right.

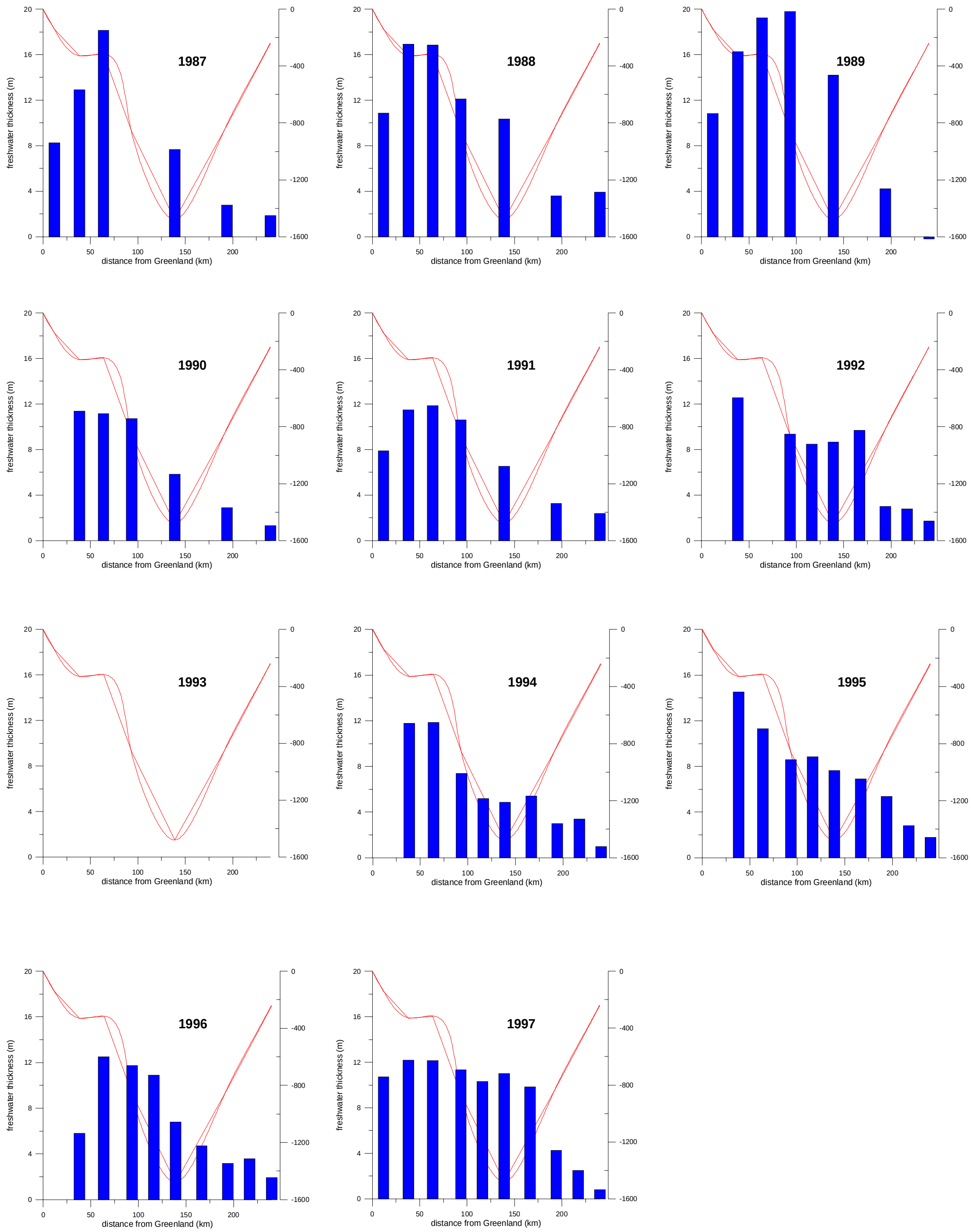

Figure 8. Variability of fresh water as estimated from CTD data from the Koegur section, between Iceland and Greenland. Thin line denotes the bottom. Iceland is to the right.

18. Measuring the Freshwater Flux through the Canadian Arctic Archipelago.

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The plumbing behind the Arctic's freshwater budget is extremely complex, and nowhere is it more complex than in the Canadian Arctic Archipelago (CAA). Roughly the size of India, study of this region presents both spatial and temporal challenges: spatial because of the maze of channels and sub-basins that comprise the plumbing; temporal because the time scales of throughflow (from months to decades) allow recycling of freshwater through seasonal melting and freezing. That said, both observations (Aagaard and Carmack, 1989; Melling, 2000) and modelling (Holloway, personal communication) suggest that freshwater fluxes through the Archipelago may be equal to those through Fram Strait, and thus cannot be ignored.

Prior to proposing a monitoring program, some thought must be given to the *real* objective of the measurement program. Is it to measure total freshwater fluxes for the purpose of supplying a boundary condition to global climate models? If so, this task is formidable indeed. Is it to acquire a measure of low-frequency flow variability for comparison to various teleconnection indices? Then a different and perhaps less formidable challenge is presented. Or, is it to understand the various forcing elements and water-mass transformation processes associated with freshwater throughflow? The latter may be both attainable and useful in understanding the Arctic's role in a changing climate. Such questions should be addressed by this workshop.

Our existing information suggests that the bulk of freshwater moving from the Arctic Ocean to the North Atlantic exits through five main channels: Nares Strait, Cardigan Strait/Hell Gate, Wellington Channel, Barrow Strait and Bellot Strait. Additional freshwater fluxes from Hudson Bay and Foxe Basin may enter the Labrador Sea directly through Hudson Strait. However, to concentrate only on freshwater outflow via selected passages is to "two-dimensionalize" the CAA system and thereby ignore upstream effects and processes that occur during the long transit from the Arctic Ocean to these selected "choke points".

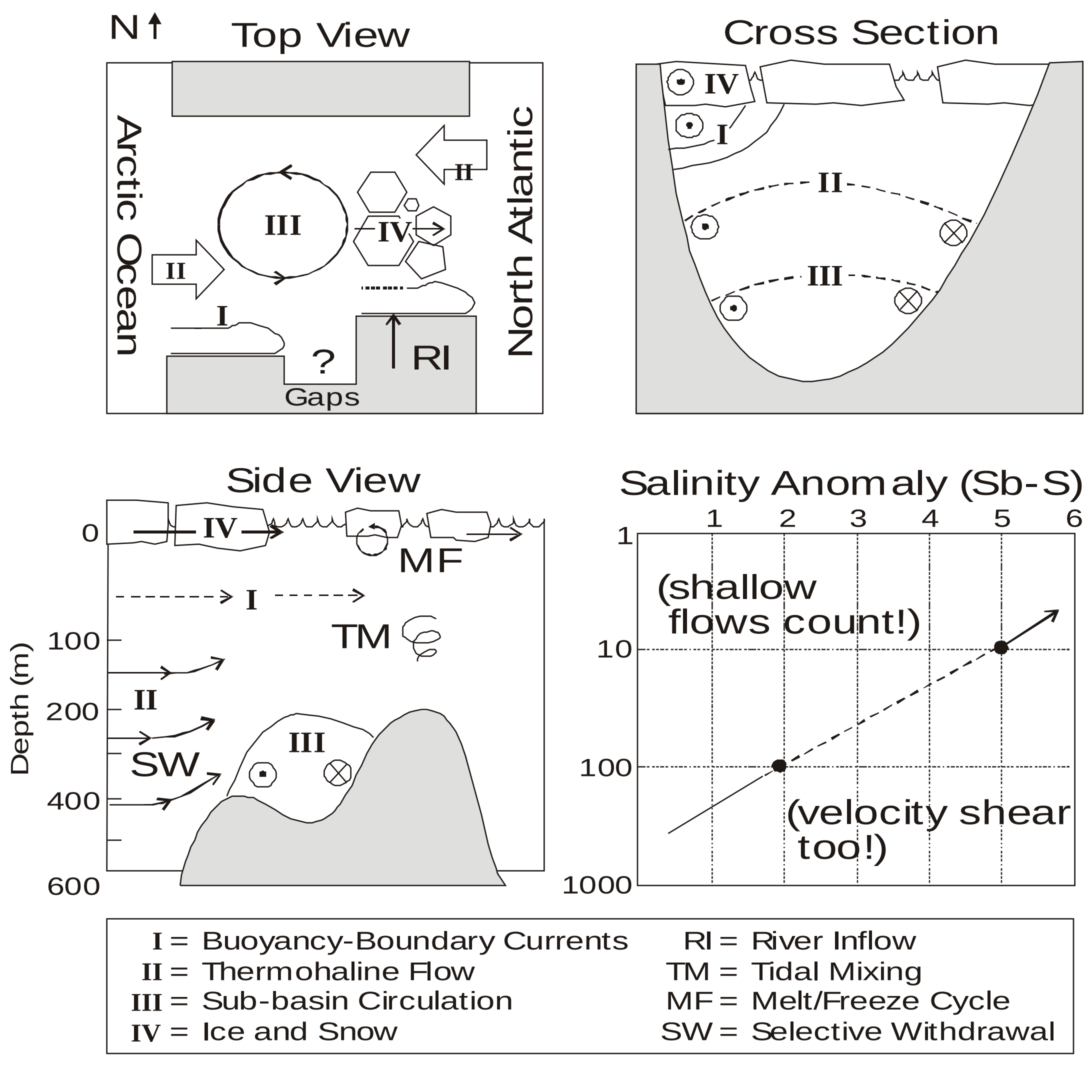
There are many features of the CAA that make it unique in comparison to other inflow/outflow regions (Bering, Fram and Barents; cf. Melling 2000). This note identifies a number of issues that must be addressed to understand the characteristics of such throughflow and to quantify the components, both water and ice, that comprise freshwater flux through the CAA; these include (see Figure 1):

- The pathways of flow are complex, with over a dozen possible routes through the CAA
- The channels themselves are wide (of order 10 or more Rossby radii) and deep (e.g. the limiting sill depth in Barrow Strait is over 100 m, Nares Strait over 350 m)
- The flow is a poorly known mix of barotropic and baroclinic components, likely with strong seasonal variability in their ratio
- The baroclinic component of flow includes the general thermohaline throughflow, episodic buoyancy-boundary currents, and quasi-stationary sub-basin circulation (Figure 1)
- The freshwater flux includes both solid and liquid phases and is driven by both wind and thermohaline forcing
- A residence time that is long, thus allowing water mass modification *en route*
- Severe logistical and technical challenges; for example, to measure flow year-round in the upper 20-40 m of a water column which is ice-covered is practically impossible with conventional technology

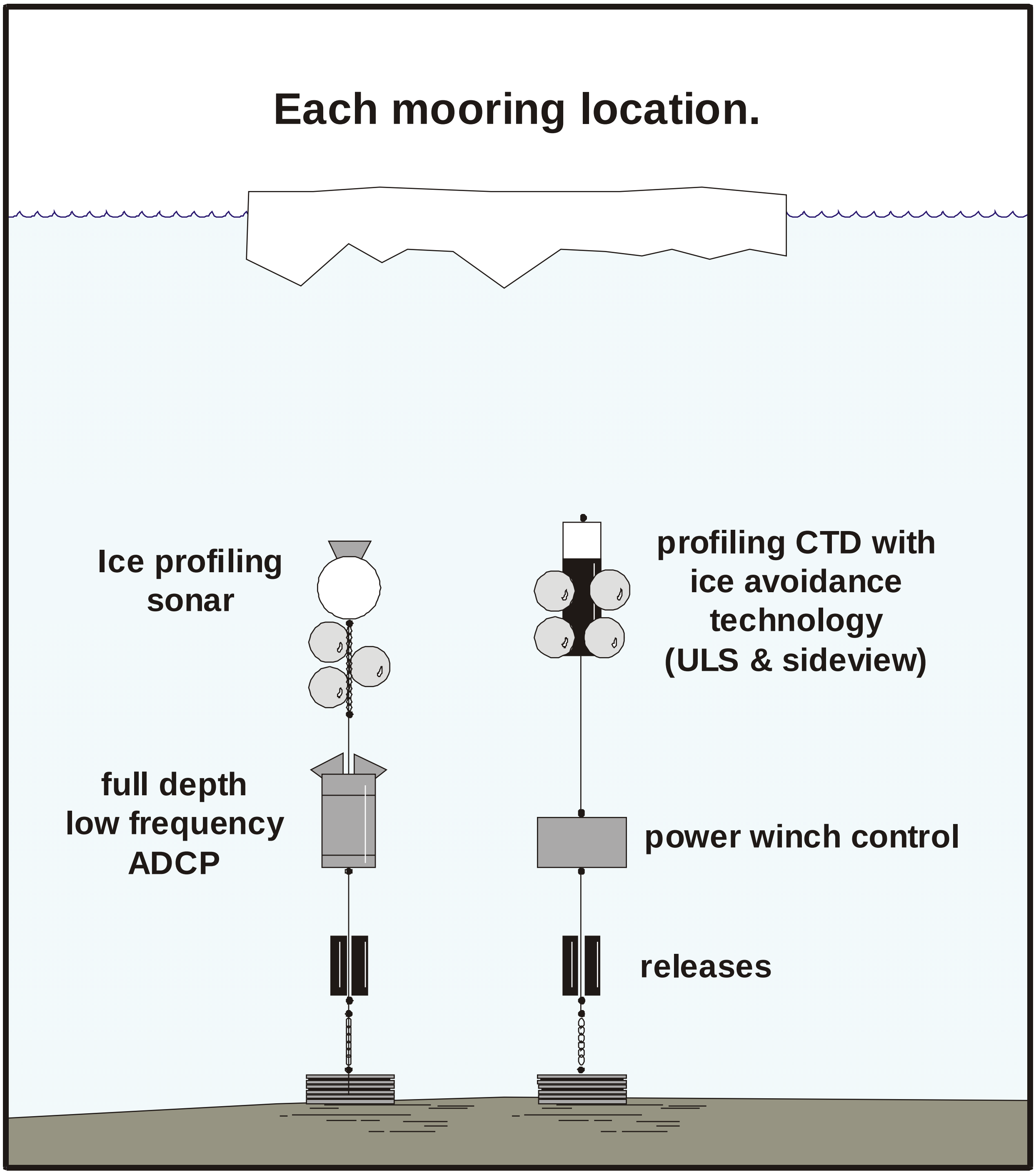
With these limitations in mind, and in an attempt to resolve the importance of time-dependent forcing (e.g. seasonal, decadal) on water and ice transport through the CAA in the light of climate variability, the following (idealistic) suggestions are made:

- Complete a reconnaissance of water mass distributions along the various pathways of flow in both summer and winter to identify sources and water mass modification *en route*
- Establish a network of water-level stations throughout the CAA to monitor fluctuations in relative pressure gradients
- Utilize a combination of remote sensing and upward-looking sonar moorings to estimate time-dependent sea-ice transport
- Deploy a sufficient number of moorings (current meter and recording salinometer) across each of the main exit routes to resolve transport.
- Resolve on a seasonal basis the relative contribution of buoyancy-boundary currents using a combination of hydrography and moored/towed current profiling instruments
- Resolve the various sources of freshwater and their residence times throughout the CAA using geochemical tracers

Figure 1. Conceptual Model of Archipelago Throughflow



We provide two options to cover the cost of observing the freshwater flux through the Canadian Arctic Archipelago, using a standard array design shown in Figure 2.



The first option is to deploy **the full array** necessary for the task, which would require a total of 24 moorings at 5 km spacing across the 122 km combined span of Bellot Strait, Barrow Strait, Wellington Channel, Cardigan Strait/Hell Gate and Kennedy Channel (for locations see Figure 3): ie

Moorings 24 at $150,000 USD each	*3.6 Million USD*
Components for redeploying	*1.5 Million USD*
Shiptime	*0.2 Million USD*
Data processing and analysis	*0.3 Million USD*
Total	*5.6 Million* USD

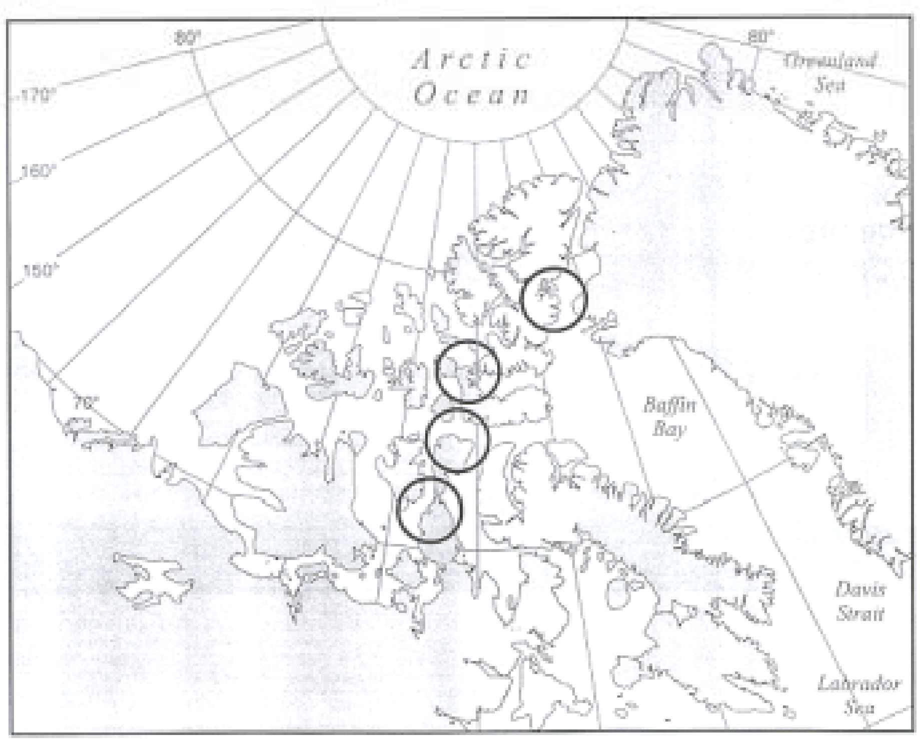
[Of which 4.1 Million represents the 1st year cost and 2.0 Million is the annual cost thereafter].

The second option would focus on **studying a single section** to learn about the system - for example, to investigate questions of whether there is a relationship between the amounts of freshwater transported by ice and transported by the water column, whether the bulk of the transport occurs in boundary currents etc. If one channel could be studied for several years, enough might be learned to judiciously locate a smaller number of moorings in the other channels, with considerable potential savings. For this purpose and option, we would instrument Barrow Strait, about 50 km across, at the following annual cost for an initial period of 3 years.

Moorings 12 at $150,000 USD	*1.8 Million USD*
Components for redeploying	*0.9 Million USD*
Shiptime	*0.1 Million USD*
Data processing and analysis	*0.1 Million USD*
Total	*2.9 Million USD*

[Of which 2.0 Million represents the 1st year cost and 1.1 Million is the annual cost thereafter].

Fig 3.Freshwater outflow monitoring locations in the Canadian Arctic Archipelago



19. Advances in measuring and modelling the fluxes of heat and freshwater through the Canadian Arctic Archipelago.

S Prinsenberg, J. Hamilton, G. Fowler and D Greenberg, BIO, Dartmouth, N.S. Canada

The program has collected two years of velocity, salinity and temperature data east of Resolute in the eastern Barrow Strait (1998-2000; Fig 1). Figure 2 shows a compilation of ice-drift, current velocity, temperature and salinity data over the one-year period, August 1998-August 1999 from a site on the south side of the Eastern Barrow Strait and over a range of depths between 31 and 170m.

The velocities were measured using upward looking ADCPs. To do this required solving the problem of measuring direction close to the north Magnetic pole, now achieved with the use of the Watson Compass (see Fig 3; some results now on DFO/BIO Web site: http://www.maritimes.dfo.ca/science/ocean/seaice/home.htm).

The fact that a CTD module moored at 30m in 1998/99 was recovered whereas the top CTD module moored at 20m in 1999/2000 was lost may indicate that the limit of safety of subsurface moorings may be in the 30m range at this site. A prototype ICYCLER system has however been developed that can measure temperature and salinity to the base of the ice every six hours for a year, and some sea-trials have taken place. In winter 2001, it is planned to test the system under ice in Northumberland Strait.

A finite-element model that includes the Canadian Arctic Archipelago has been developed (Fig 4). This modelling effort was made possible by a new compilation of recent and unpublished records of bathymetry. While little data are available for comparison, the model predictions agree with what is known about flow and tides in the area. At present the flow is driven by an arbitrarily chosen 10 cm elevation gradient. It is hoped to obtain funding to install permanent tide gauges at Alert and at some site in the western part of the Archipelago to measure the gradient of sea-surface height across the outer (Arctic Ocean) edge of the Archipelago as the ultimate forcing function for the throughflow. Eventually, the output of this model may be helpful in optimising the siting of current meter moorings and so minimising the need for direct measurements and moored equipment.

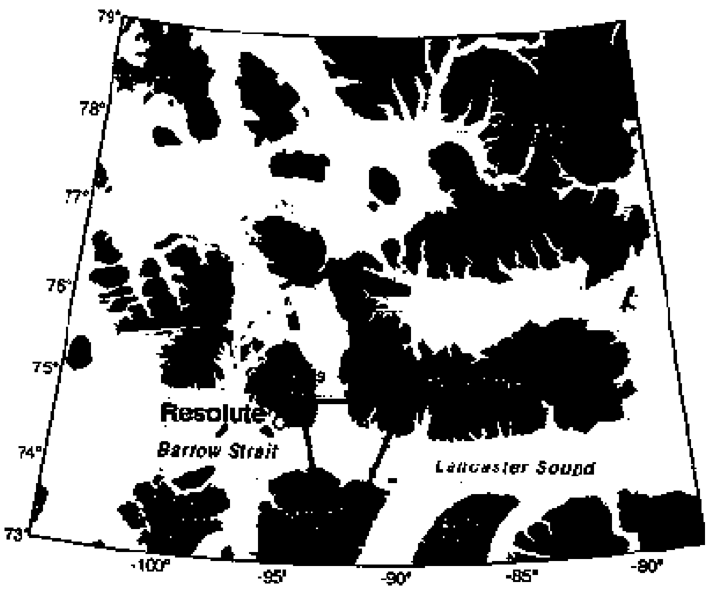


Figure 1.

Work area for the Barrow Strait Flow-through Study. The X's denote the northern and southern mooring sites. The lines represent the CTD sections completed.

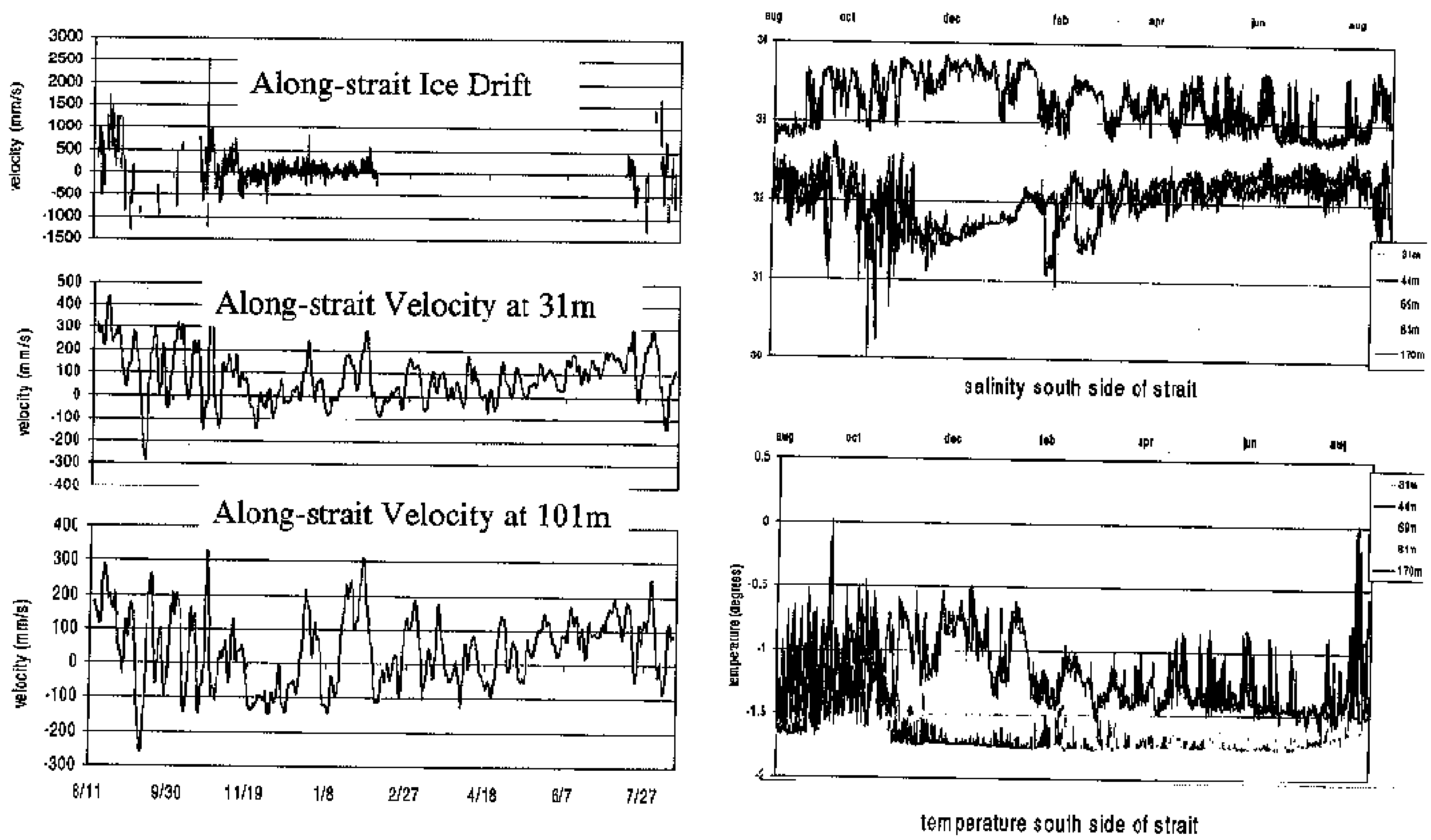

Along-strait Ice Drift
Along-strait Velocity at 31m
Along-strait Velocity at 101m
velocity (mm/s)
8/11
9/30
11/19
1/8
2/27
4/18
6/7
7/27
aug
oct
dec
feb
apr
jun
salinity south side of strait
temperature south side of strait
temperature (degrees)
31m
44m
69m
81m
170m

Figure 2

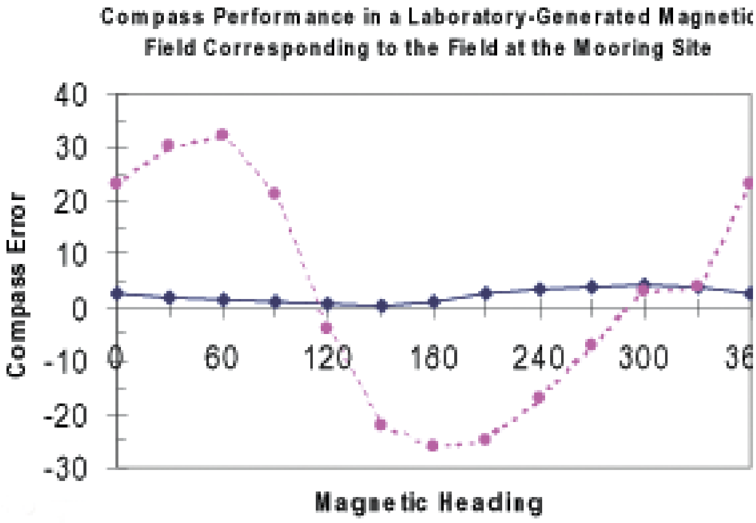


Figure 3

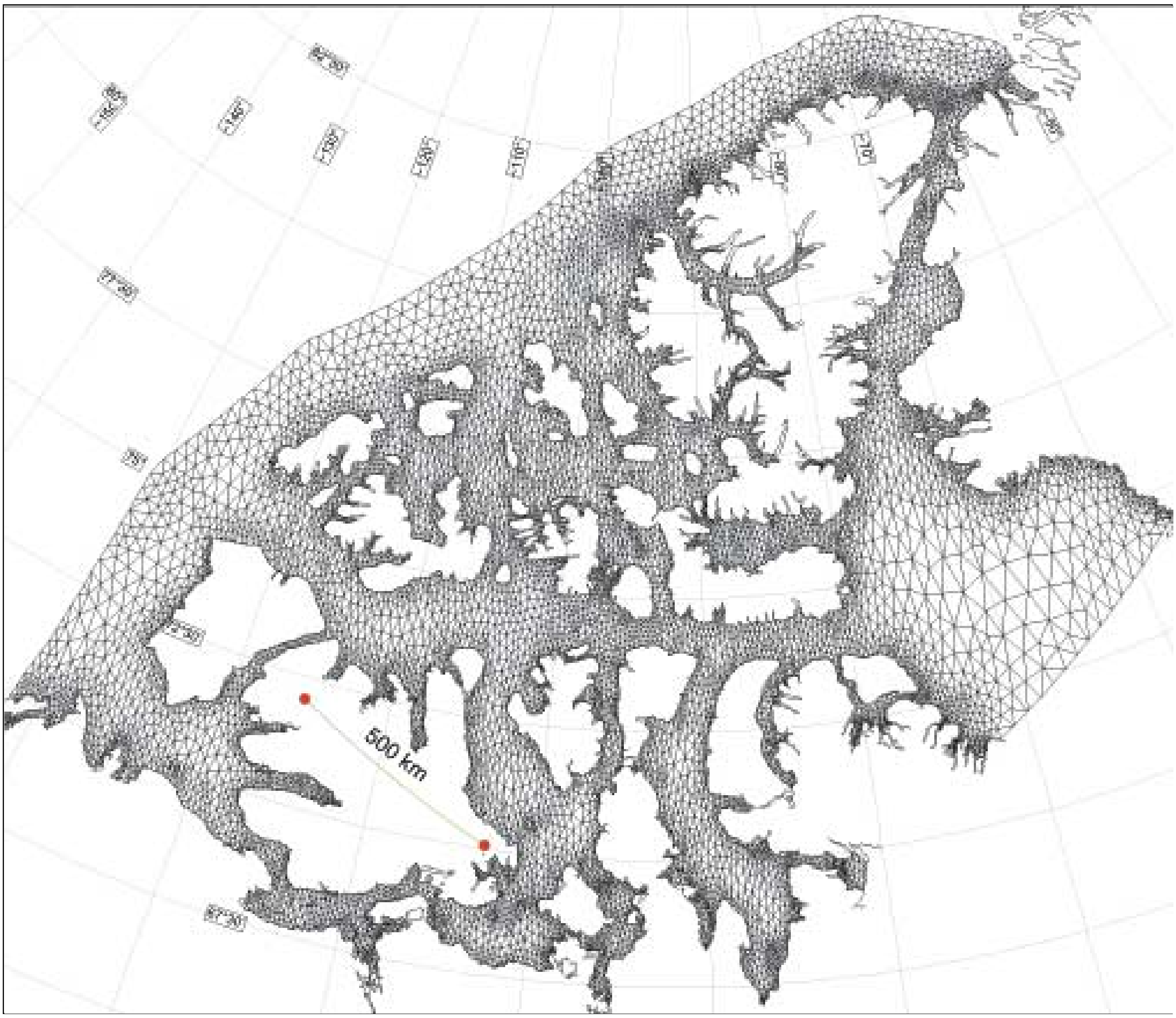


Figure 4

20. The combined measurement of the Denmark Strait Overflow and the freshwater flux off SE Greenland.

by

Bob Dickson, CEFAS, UK, Ian Vassie, POL UK, Jens Meincke, IFMH Germany and Pentti Maelkki, IMR Finland

1) The Denmark Strait Overflow.

The overflow and descent of cold dense water from the Denmark Strait sill is a principal means by which the deep ocean is ventilated and one of the key elements that drive the meridional overturning circulation of the North Atlantic. For this reason, it is of central importance to measure the long-term variability of overflow and explain & model its causes. Long but non-continuous direct current measurements in the overflow core off Angmagssalik, SE Greenland since 1986 (Dickson et al 1990; Dickson and Brown 1994) describe a vigorous, topographically-steered, near-bottom current, some 300m thick, with maximum speeds of up to 100 cm s^{-1}, a mean speed of around 25 cm s^{-1}, a large-amplitude fluctuating component with dominant time scales of 2 to 12 d, but with surprisingly little evidence of variability in flow-speed over longer periods (months, seasons, years; Figure 2, top).

However a clear decadal signal *has* been identified in the temperature (hence density) of the overflowing watermasses (Figure 2, lower panel), apparently in lagged response to NAO forcing in the eastern Fram Strait some 2500km upstream and 3 years earlier (Dickson et al 1999). This temperature signal can also be traced a further 2000 km downstream to the abyssal layers of the Labrador Sea. Our recent arrays have therefore provided evidence that the effects of climatic variability may pass rapidly (over 3-4 years & = 5000 km) from the ocean surface to abyssal depths ----a direct demonstration of climatic effects on the abyssal limb of the Thermohaline Circulation. It is planned to continue these measurements in an extended 8 mooring array across the East Greenland Slope (location, Figure 1) to achieve decadal measurements of overflow transport, temperature & thickness and (by adding Microcat sensors and water samplers) pentade measurements of salinity and other tracers cabable of describing the changing composition and varying upstream origins of the flow.

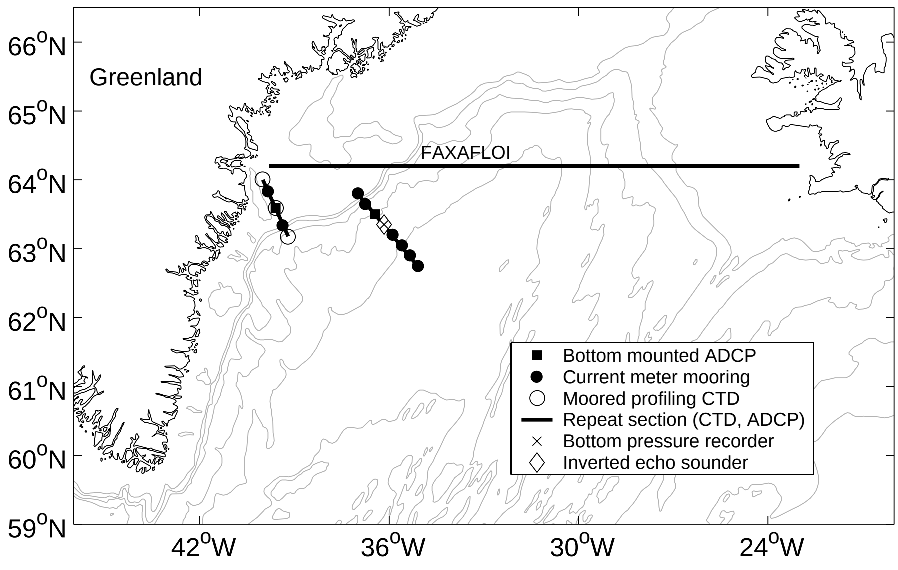


Figure 1. Location of the two arrays.

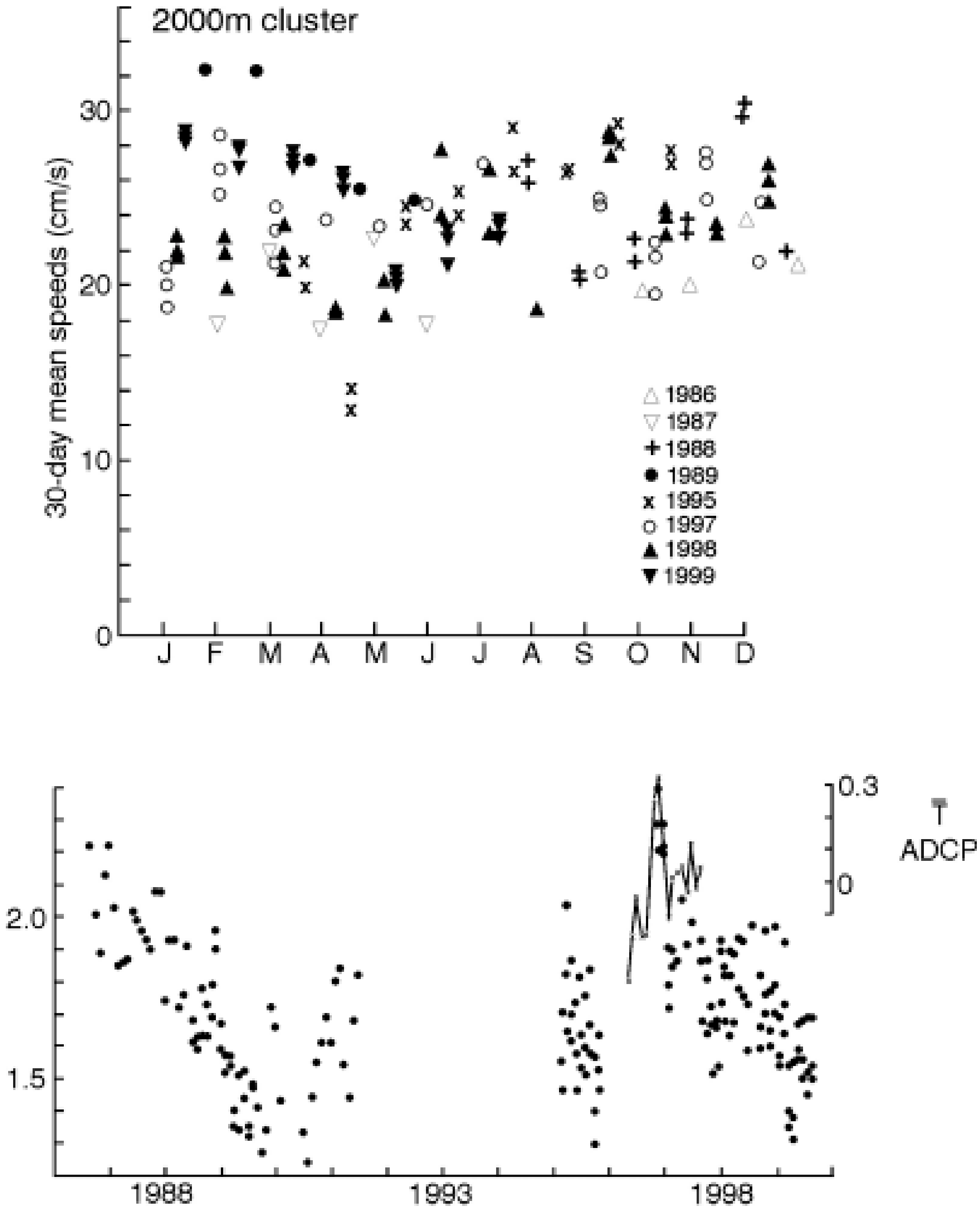


Figure 2. Updated 30-day mean characteristics from the current meter mooring set at 2000m depth in the core of the Denmark Strait Overflow off Angmagssalik SE Greenland. The 30-day means of near-bottom current speed (upper panel) represent almost all the direct measurements that have been made in the overflow core. They continue to show little sign of any systematic seasonal or longer-period variation in speed. The equivalent 30-day means of temperature from the same depth and height above bottom (lower panel; H = 20-100m) show growing evidence of decadal variability, with temperatures undergoing a second long period of cooling to the spring of 1999. This signal appears to be the lagged response to temperature changes in the Eastern Fram Strait, some 2500 km upstream and three years earlier, which in turn appear to be linked to interannual changes in NAO forcing (Dickson et al, 2000). If confirmed, this remote control on overflow variability may permit some predictability of overflow characteristics.

2) The freshwater flux on the East Greenland Shelf.

Achieving a better measure of freshwater flux from the Arctic is justified by the global importance that coupled models currently assign to relatively minor changes in freshwater distribution at high latitudes (e.g. Rahmstorf and Ganopolski, 1999). Hitherto, the important component of freshwater flux under the East Greenland ice-pack has proved elusive and this may be the major component of the southward flux. The southward flux of ice from the Arctic through western Fram Strait is now well monitored by Norway (see Østerhus text above) and in that location, the ratio of ice to liquid freshwater is approximately known (about 50:50). However this flux is only of global importance once it passes south of Denmark Strait to affect the global thermohaline circulation, and we have evidence from EC-VEINS that much can recirculate back into the Nordic Seas en route. The East Greenland Shelf south of Denmark Strait is therefore the critical location for monitoring the net transport and phase of the freshwater flux, and is an area where both are almost totally unknown. We need a new array designed to provide such a measure under the ice of the SE Greenland shelf. Basing the sensor deployment on summer and winter salinity transects during the IGY (Figure 3 top), the suggestion is that this could now be achieved using two new types of mooring.

a) Microcat "pipe" moorings with deflectable tops. Since the freshwater over the East Greenland shelf lies mostly in the uppermost layers of the watercolumn, immediately below the ice (Figure 3 top), the business of providing a full assessment of the freshwater flux passing south along the East Greenland Shelf will depend critically on being able to extend instruments into the near-surface layer, as close as possible to the base of the sea-ice. Hitherto this has been impractical using moorings since it meant running the risk of having moored equipment snagged and destroyed by passing ice. It is intended to get over this problem in a simple but novel way by having the near-surface buoyancy and instrument packages enclosed in 45m-long, rigid, freely-flooding, PE plastic shells, designed to deflect on impact with deep ice floes, then return to the vertical. By this technique, we plan to deploy and maintain strings of Microcat salinity sensors throughout the watercolumn, together with current meters of two types, to make the first measurements of the freshwater flux reaching the North Atlantic. PE is chosen because it can be cut and welded but does not become brittle at low temperatures, and the knockdown is monitored by placing a high-accuracy pressure sensor in the topmost instrument string. A trial mooring of this type was deployed by F/S Poseidon on the East Greenland shelf in August 2000.

b) First use of a cheap bottom-moored profiling CTD (HOMER). We intend to supplement or substitute the Microcat moorings using a new type of mooring which employs an undulating CTD capsule to measure conductivity, temperature and pressure during repeated (pre-programmed) vertical excursions from the bottom (Figure 3, bottom). Initially, it is planned to perform such a profile once each day for a period of a year and to limit the vertical excursion to 300m above the bottom as this seems reasonably achievable and covers most of the watercolumn over the East Greenland shelf. The totally-new element is the Undulating CTD Capsule “Homer”, which confers several advantages over any current alternative technique. Profiling CTDs exist but are not yet reliable and cost around £100k per unit, whereas the approach adopted here achieves the same result based on cheap and simple fishing reel technology at one tenth of that cost, making it possible to deploy in the multiples required. The technique also has advantages over more-conventional arrays of fixed gear. It is cheaper to use a single CTD to profile though the watercolumn than to place 5 such units at fixed depths on a mooring; also, by rising up to the ice and down to park on the bottom for most of each day, there should be a much lesser risk of the gear becoming towed off and destroyed by passing ice. The system has the following characteristics: A self contained buoyancy capsule will be released from the bottom frame on a fishing line and reel system. The capsule will contain the necessary measurement electronics, logging system and power supplies to sample conductivity, temperature and pressure throughout a 300m bottom layer of the water column. The resolution will be sufficient to make a measurement every 10 cm during the vertical excursion. The drive mechanism to rewind the capsule will be mounted in the bottom frame. This places little restriction on the battery payload. The operational life of the device will be targeted as being one-year sampling with a complete profile once per day. The design of such an undulating capsule has been simulated by computer program under conditions similar to those that might be expected on the East Greenland shelf, has passed initial tests in a 10m aquarium tank, and is being prepared for sea trials in autumn 2000. If successful, the prototype may be available for field trials under the ice off East Greenland as early as August 2001. A future development of the system would concentrate on increasing reliability by transferring the measured data to the bottom-mounted part of the instrument. An optical link developed at POL and already used for 4 years in the Drake Passage could form a suitable basis for the telemetry link. Since the most advanced Arctic Ocean models now anticipate that the freshwater flux through the Canadian Arctic Archipelago may be linked in its time-dependence to that passing south along the East Greenland shelf, it makes good sense to make coordinated measurements of both components of the freshwater flux at the same time.

3) Combined costs of the proposed arrays.

a) The Extended Slope Array

The existing VEINS array consists of 6 current meter moorings (F1, F2, UK1, G1, UK2, G2), each carrying 3 Aanderaa instruments to a height of 120m above the seabed, and 2 bottom mounted sensors for the acoustic measurement of overflow layer-thickness at F2 (ADCP) and UK1 (IES). We plan to extend this array in two ways to achieve a more complete coverage of the overflow plume. To measure the distribution of current speeds through the plume and into the surrounding watercolumn, each mooring will be extended to a height of 380m above the sea-bed with 4 instruments at heights of 20, 100, 200, and 350m. One additional mooring will be added at either end of the array (O1 and O2), to span the full width of the overflow. Four Micro-cat CT loggers will be distributed across the array.

b) The freshwater flux array on the East Greenland shelf.

A new array is planned to make the first long term detailed measurements of the freshwater flux passing south under the ice of the East Greenland Shelf. A total of 6 moorings of three types would span an area close to the overflow array where the shelf narrows (see Figure 1) to measure the speed and salinity distribution throughout the watercolumn to the base of the ice. Two “Tube” moorings each with 4 Micro-cats, 1 Aanderaa RCM8 and 1 acoustic release would largely employ conventional technology. These would be alternated on the array with 3 “Homer” Undulating CTD packages being developed for the purpose by POL. The array would be completed with a further mooring in which a bottom frame fitted with a 150khz ADCP (plus two acoustic releases) would relate the spot measurements by conventional current meters to the velocity distribution throughout the watercolumn.

c) Unit Mooring Costs	initial set up cost	annual
(a) tall c/m mooring (380m, 4 Aanderaas +1 a/r)	£42368	£2375
(b) As above with Micro-cat sensor	£45868	£2525
(c) ADCP in Frame + 2 a/rs	£100592	£1150
(d) “tube” mooring complete	£43776	£1600
(e) IES mooring complete	£17296	£1500
(f) “Homer” undulating CTD	£8000	£800

d) Total array costs:

- *Denmark Strait Overflow Array* : [4 type (a)+ 4 type (b) + 1 type (c) + 1 type (e)] = £470,832 plus a recurrent annual cost of £22250
- *Freshwater flux array, East Greenland Shelf*: [2 type (d) + 1 type (c) plus 3 type (f)] =£212,114 plus a recurrent annual cost of £6750
- *Not included* : transport, shiptime, or staff time

4). References.

Dickson, R. R., Gmitrowicz, E. M. and Watson, A. J. 1990.. Deep-water renewal in the northern North Atlantic. Nature (Lond.) 344 (6269): 848-850.
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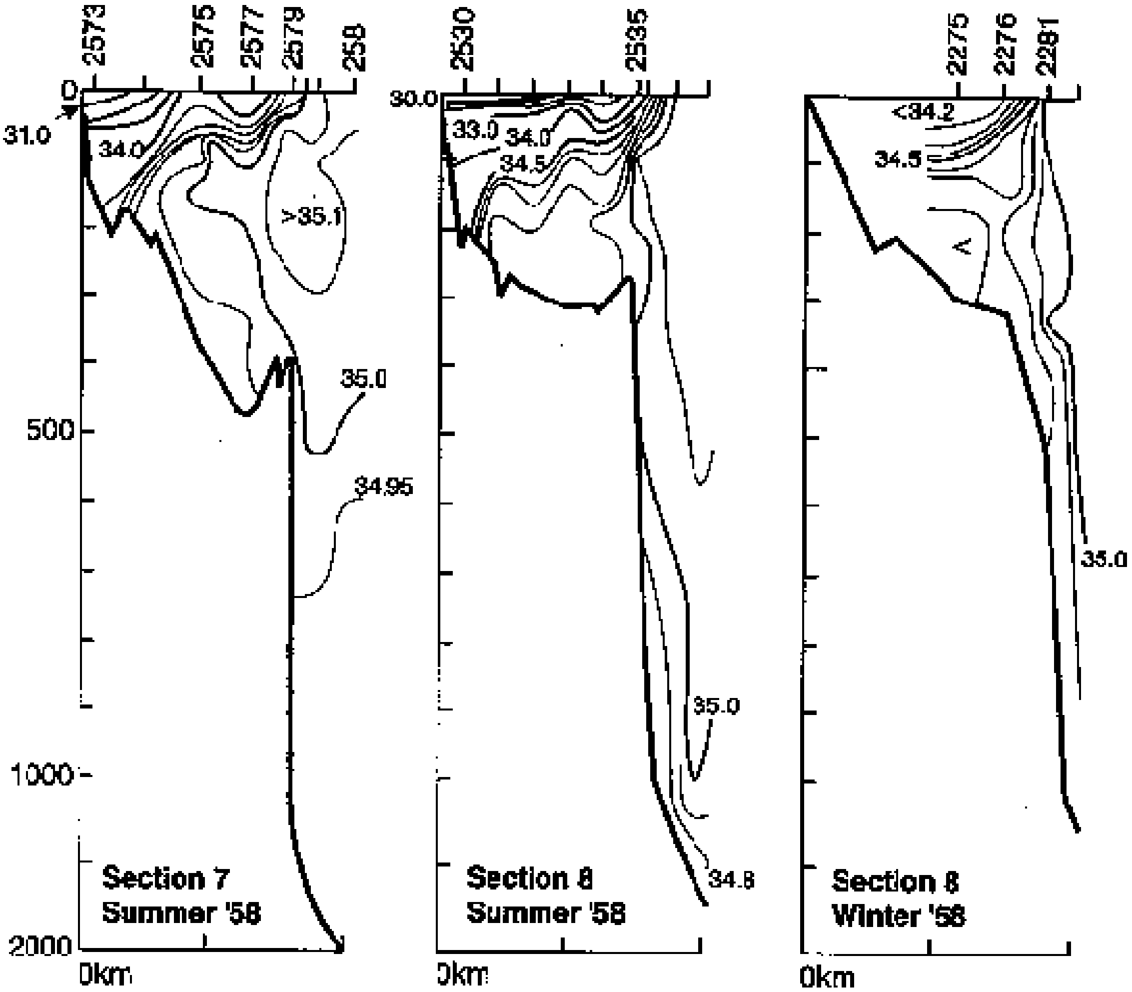
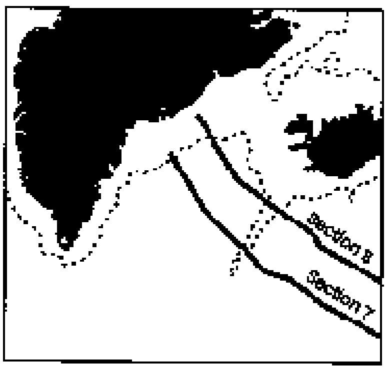
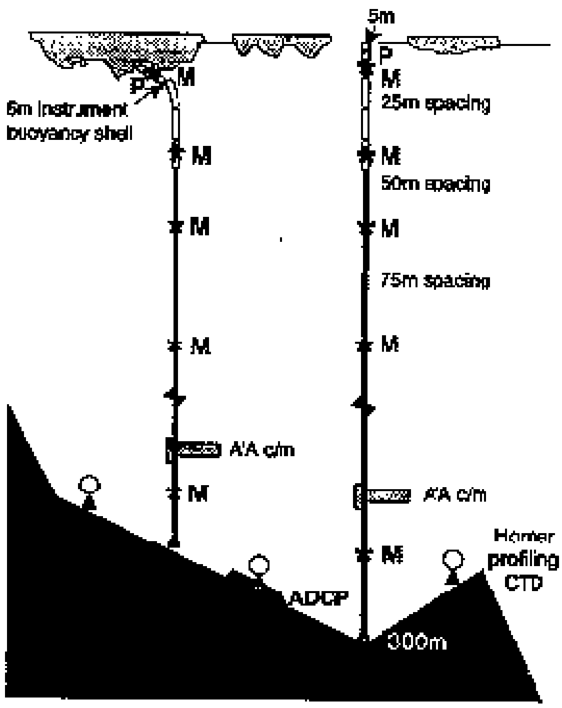
Dickson, R.R., J. Meincke, I.M Vassie, J Jungclaus and S. Osterhus. 1999 Possible predictability in overflow from the Denmark Strait. Nature lond. 397, 243-246.
Dickson, R.R., T. J. Osborn, J. W. Hurrell, J. Meincke, J. Blindheim, B. Adlandsvik, T. Vinje, G. Alekseev, and W. Maslowski. 2000. The Arctic Ocean Response to the North Atlantic Oscillation. J. Clim **13**, (15), pp 2671-2696.

A freshwater flux array for the SE Greenland Shelf





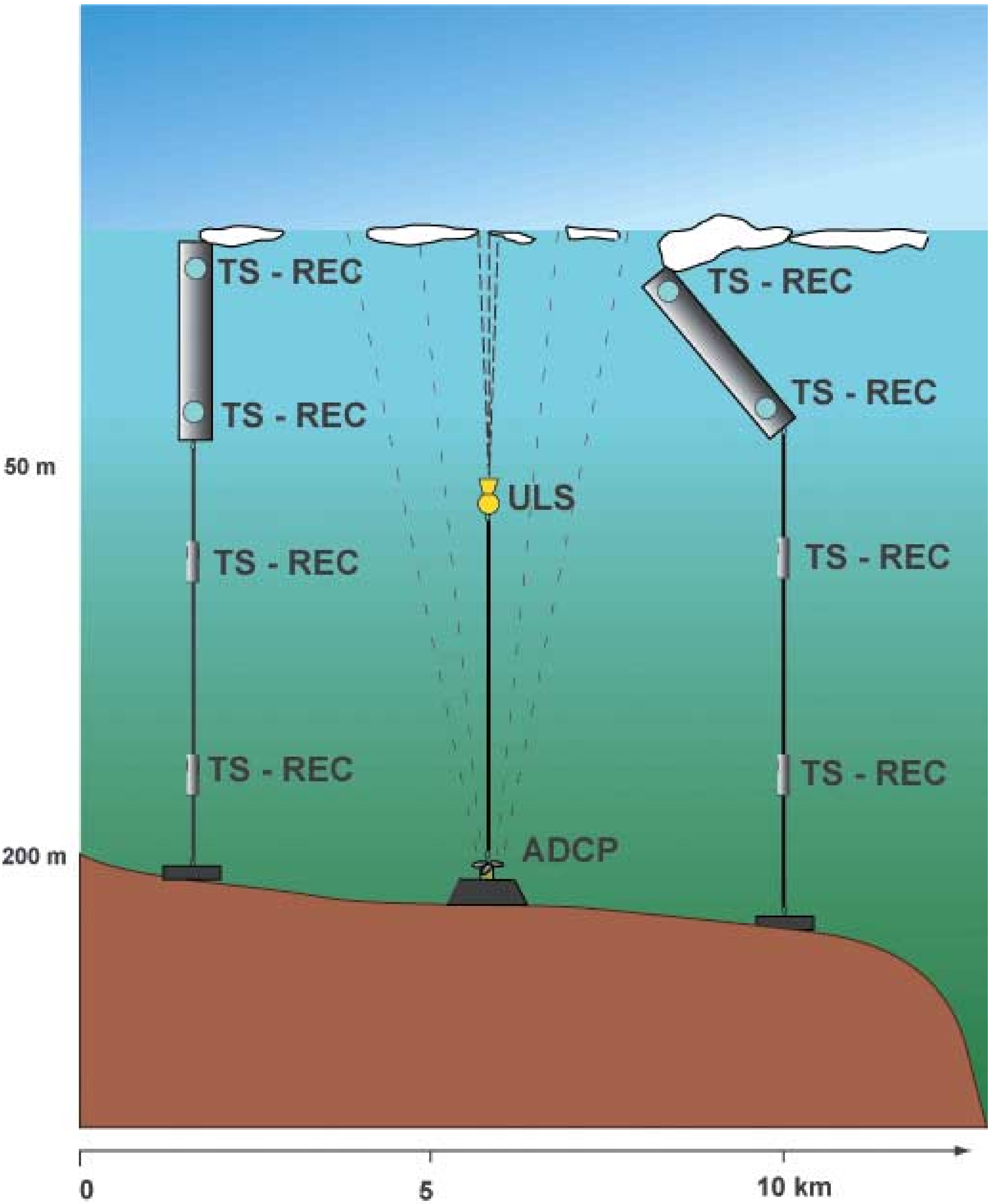


★M Microcat sensor

◆P Pressure sensor

Homer profiling CTD

Figure 3 (left) and detail (below)



FRESHWATER - FLUX
MOORED ARRAY

21. Monitoring Inflow and Outflow Across the Iceland-Scotland Ridge

Bogi Hansen, Fisheries Laboratory, Faroe Islands; Svein Østerhus, Geophysical Institute, Bergen, Norway; Bill Turrell, Marine Laboratory, Aberdeen, Scotland.

The Faroe monitoring network was designed to quantify fluxes crossing the Iceland-Scotland Ridge, and their variability. Observations along three sections monitor 88% of the inflow to, and 33% of the outflow from the Arctic Mediterranean, including the main path for overflow of Deep water. The system has the advantage of long term hydrographic data (12 to 100 years) which are able to set the more recent transport measurements into a climatic context.

Flux Measurements Around Faroe: Three standard hydrographic sections north, south-east and south-west of Faroe monitor temperature, salinity, nutrients and tracers. These sections cross the inflow of Atlantic water to the north of the Iceland-Faroe Ridge, the Atlantic inflow through the Faroe Shetland Channel (FSC), and the outflow through the Faroe Bank Channel (FBC). Since 1994 transport and flux estimates using semi-permanent ADCP moorings have been added to the hydrographic monitoring , which spans periods of decades to a century (Figure 1).

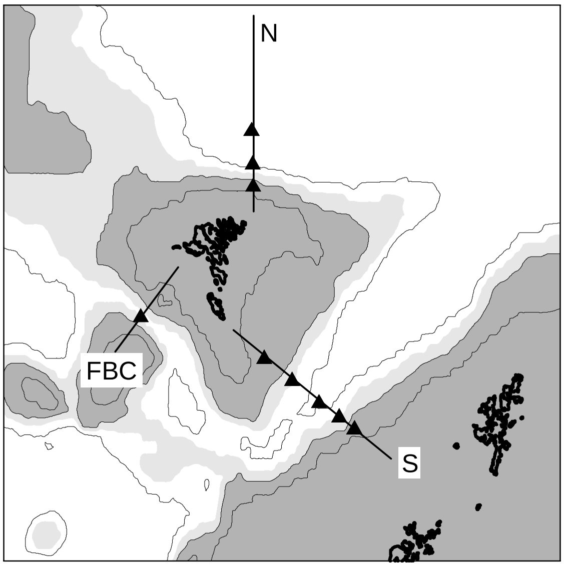


Figure 1. The Faroe monitoring network, consisting of three standard hydrographic sections, north of Faroe (N), across the Faroe Shetland Channel (S) and across the Faroe Bank Channel (FBC). ADCP locations are marked by triangles.

Based on the latest estimates from the Faroe monitoring network (Figure 2), the network monitors 88% of the Atlantic inflow across the Greenland–Scotland Ridge (3.7Sv south Faroe, 3.3Sv north Faroe, 1Sv west Iceland), and 92% of the heat flux (Hansen *et al*, 1999). It also monitors 33% of the deep water outflow from the Arctic Mediterranean, as 2Sv flows through the FBC (Østerhus *et al*, 1999), 1Sv crosses the Faroe-Iceland Ridge and 3Sv leaves through the Denmark Strait. The ADCP network has quantified these mean transports, and indicated that there is little seasonality in either the warm water inflow or the cold deep water outflow across the GSR (Hansen *et al*, 2000).

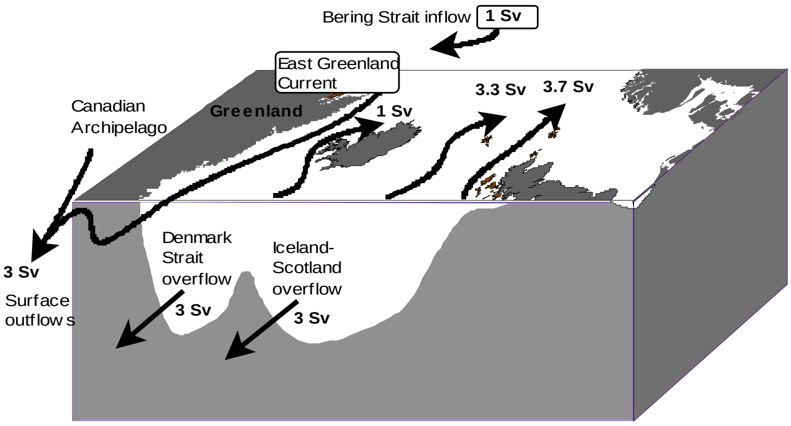


Figure 2. Water budget for the Arctic Mediterranean with fluxes of the main inflow and outflow branches in Sverdrup (Sv).

When combined with observations from the other gaps, the network has given a consistent budget for the exchanges between the Arctic Mediterranean and the rest of the World Ocean.

Decadal Change in Outflow: Although the direct monitoring of transports by the ADCP network is yet to reveal interannual variability, the hydrographic monitoring has shown that since the late 1970s the outflow through the FBC has been altering. The salinity of overflow water is decreasing by 0.01 per decade (Figure 3) as Norwegian Sea Deep Water (NSDW) is replaced by lower salinity intermediate water. It is estimated that the overflow consisted of approximately 60% NSDW in 1970-1985, which reduced to 40% NSDW by 1990. This result is confirmed by the deepening of the -0.5°C isotherm in the FBC (Figure 4). The 3°C isotherm, delimiting the Intermediate water, in the FBC did not change depth in this period, however.

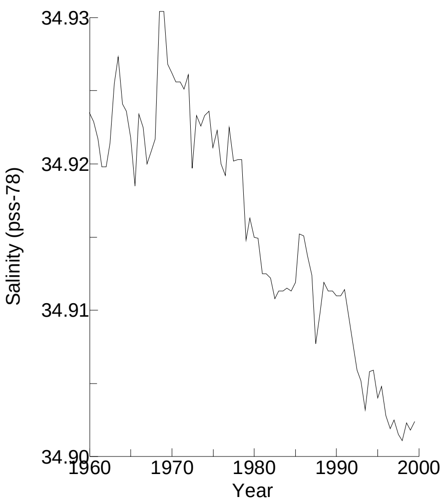


Figure 3. The decline of salinity at 800m (depth of Faroe Bank sill) in the outflowing cold bottom water, monitored by the southern Faroe network monitoring standard section (S). From Turrell *et al* 1999.

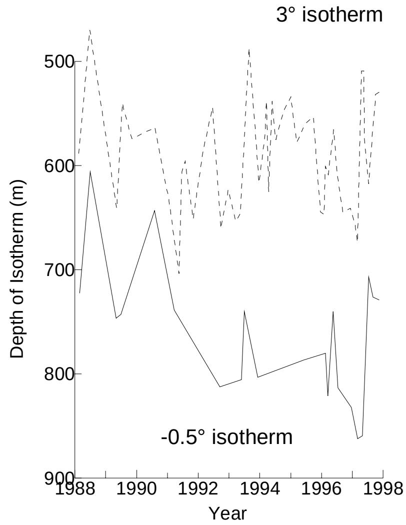


Figure 4. The deepening of the upper boundary of the overflowing deep water (-0.5°C isotherm) in the Faroe Bank Channel compared to the upper boundary of the outflowing intermediate water (3°C isotherm). From Hansen and Østerhus 2000.

The changes observed by the Faroe monitoring network during the last 4 decades are consistent with a reduction in the production of deep water in the Greenland Sea, and confirms that these changes are affecting the overflow areas and propagating into the Atlantic. The observations also indicate, however, that the reduced overflow of Deep water has been compensated by increased overflow of Intermediate water.

Future of the Monitoring Network: The hydrographic observations along the three standard sections have been undertaken by the fishery institutes in Faroe and Scotland, with central Government funding for most of this century as regards section S (Fig. 1) and since 1988 for the other two. It is envisaged that these observations will continue. The flux observation network, based on moored ADCPs, around Faroe commenced as the Nordic WOCE program (1994 - 1997). The period 1997-1999 was partly funded by the EU program VEINS. 2000-2001 will be funded by the EU program MAIA. Figure 5 illustrates the present system. Beyond 2001 it is hoped that further funding may be obtained for the network of ADCPs, but their long term future is not certain.

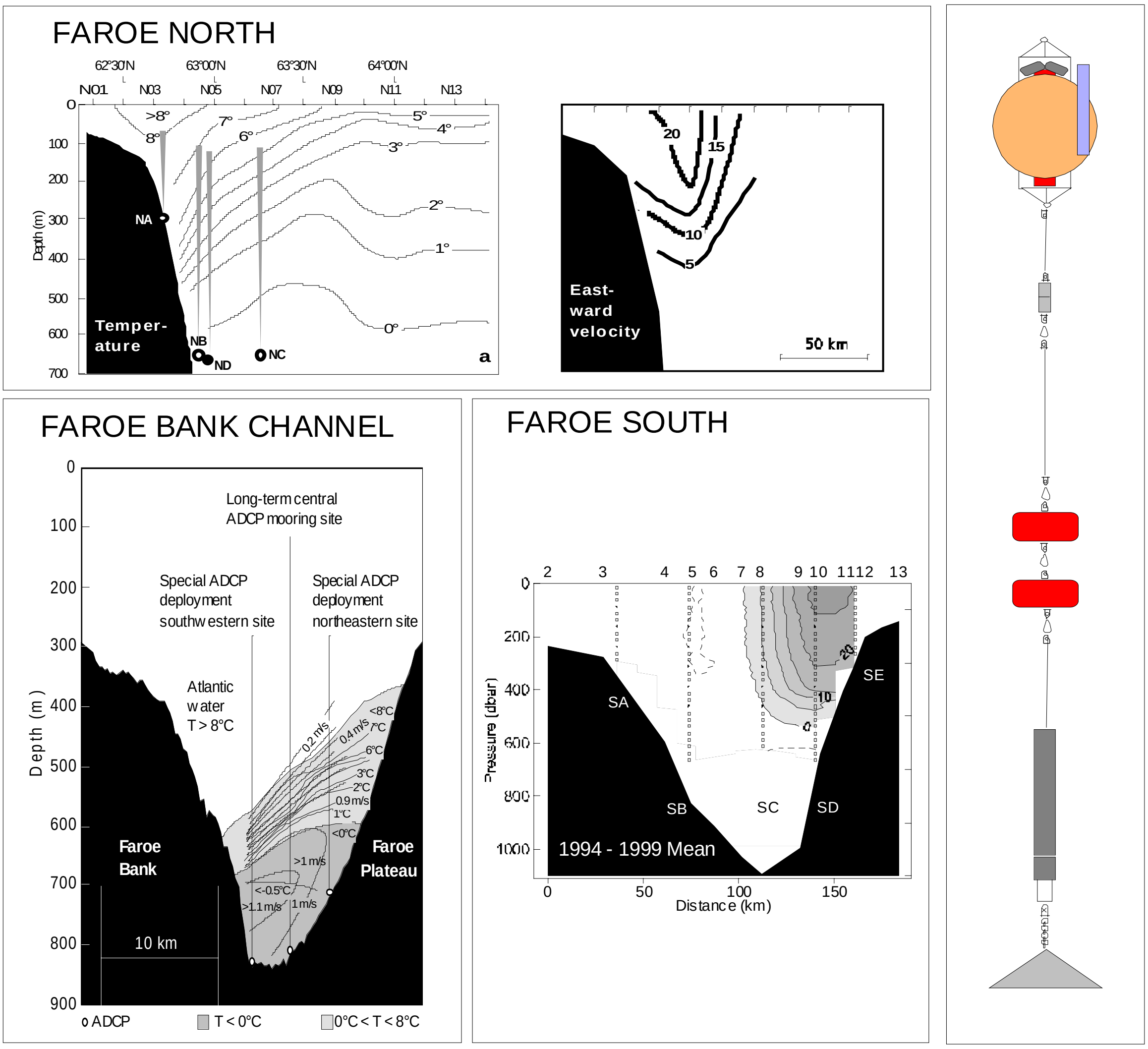


Figure 5. Examples of products from the Faroe monitoring network of combined hydrographic sections and semi-permanent ADCP moorings. **Faroe North** – Sections of mean temperature and eastward velocity, with location of ADCP moorings indicated by shaded areas, showing the Faroe Current Atlantic water inflow. **Faroe Bank Channel** – combined section of mean isotachs and isotherms showing the deep outflow. **Faroe South** – mean along channel speeds showing the Faroe Shetland Channel Atlantic inflow. All deep water ADCP moorings are similar to the standard layout shown. Shallow water moorings are deployed in trawl proof housings.

The approximate cost of keeping the Faroe network running each year is summarised in Table 1:

North Faroe				
Hydrographic Monitoring	T and S of Atlantic Water, Intermediate waters	4 surveys / year. 2 days per survey.	Ship = $6,000 per day	$48,000
ADCP Monitoring	41 % of Atlantic Inflow	4 ADCPs.	Maintenance = $1000/ADCP/year Replenishment = 1 ADCP/year @$70,000	$74,000
South Faroe				
Hydrographic Monitoring	T and S of Atlantic Water, intermediate and deep overflow water	4 surveys / year. 4 days per survey.	Ship = $10,000 per day	$120,000
ADCP Monitoring	44 % of Atlantic Inflow	4 ADCPs.	Maintenance = $1000/ADCP/year Replenishment = 1 ADCP/year @$70,000	$74,000
Faroe Bank Channel				
Hydrographic Monitoring	T and S of overflow water	4 surveys / year. 1 days per survey.	Ship = $6,000 per day	$24,000
ADCP Monitoring	33 % of overflow	1 ADCP.	Maintenance = $1000/ADCP/year	$1,000
Shiptime cost: $192,000		**Additional required Cost of Faroe Monitoring Network / Year**		**$149,000**

Summary of Funding Situation:

While in the past decades hydrographic monitoring along standard sections around Faroe has been undertaken by the fishery institutes in Faroe and Scotland, with central Government funding, since 1994 added value has been obtained from this work by the addition of direct measurements of transport using ADCP moorings funded externally. After the initial investment in equipment, the added-value component of the Faroe monitoring network, which supplies transport measurements within 88% of the inflow to, and 33% of the outflow from the Arctic Mediterranean, costs approximately $150,000 per year. This is required in addition to the $192,000 per year of ship time, which presently is made available by the participating institutes.

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Turrell WR, Slesser G, Adams RD, Payne R, Gillibrand PA (1999) Decadal variability in Faroe Shetland Channel Bottom Water. Deep-Sea Res 46:1-25

22 & 23. Observing Large-scale Thermohaline Changes in the Labrador Sea.

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1. Rationale

The Labrador Sea (Location chart, Figure 1) is a critical site for observing large-scale and long-term change in the Atlantic overturning circulation. This follows from the fact that the intermediate, deep and abyssal water masses which contribute to the deep limb of the thermohaline circulation all originate in or pass through the Labrador Sea, and the freshwater outflows from both the Canadian Arctic Archipelago and the Nordic Seas pass around its margins. Put differently, the basin of the Labrador Sea contains both the water masses that “drive” the Meridional Overturning Circulation (MOC), and the fresh surface outflows that are supposed to shut it down. It also is the site of some of the most intense air/sea interaction of the North Atlantic, and the temperature/salinity history of the water column records the influx of heat and fresh water with useful accuracy.

Five water masses can be distinguished in the salinity and CFC transects of Fig. 2. In the upper 150 m is a low salinity surface layer (S < 34.80 psu typically) derived from melting ice and river runoff, and concentrated on the shallow Labrador and Greenland continental shelves. In contact with the atmosphere, it contains high concentrations of CFCs. Just below the surface layer to about 500 m are boundary currents in deep water near the respective continental rises. These have higher salinity (S>34.88 psu typically)/lower CFC Irminger Water (IW) that has been transported into the area by the from the Irminger northern boundary current. The large vertically-homogeneous mode water between 500 and 2300 m in the central region is the Labrador Sea Water (LSW), formed during severe winters by open ocean deep convection ($S\sim34.85$, $\theta\sim2.9^{0}C$). Beneath the LSW, a warm, salinity maximum/CFC minimum layer at 2300 to 3300 m identifies the North East Atlantic Deep Water (NEADW) which originates in the eastern basin of the North Atlantic as the deepening, dense outflow from the Faroe Bank Channel and flows into the western basin through gaps in the Mid-Atlantic ridge. Its salinity exceeds 34.90 psu. The deepest layers of the basin are occupied by Denmark Strait Overflow Water (DSOW) with a slightly lower salinity (~34.88 psu) and higher CFC. DSOW originates in the deep dense overflow from the Denmark Strait sill and is the densest water in the northern North Atlantic. It is also the dominant dense-water mass of the global merdional overturning circulation.

2. Large-scale changes in watermass characteristics.

Multi-decadal changes of large amplitude have been observed in the three main watermasses of the Labrador Sea.

a) In the case of the LSW at *intermediate depths*, the observed changes are thought to be largely the result of local variations in the depth and intensity of deep convection due to long-period changes in NAO forcing. A strongly positive NAO is associated with anomalously strong and chill northwesterly winds over the region in winter leading to unusually large heat losses and intense & deep-reaching convection in the central region of the Labrador Sea. During the negative phase of the NAO, winter storm activity tends to be minimal over the Labrador Sea, air temperatures are relatively warm and both convection and LSW production are suppressed. [The passage of the Great Salinity Anomaly around the Basin in the late 1960s-early 70's may further have helped to suppress Labrador Sea convection and LSW formation during these NAO-minimum years].

Over the past 35 years, we have observed the largest low-frequency shift of record in the NAO as its Index amplified from its most extreme and persistent negative phase (generally) in the 1960s to its most extreme and persistent positive phase in the late 1980s-early 1990s. The accompanying increase in the depth and intensity of convection resulted in a progressive cooling, freshening and deepening of the LSW, culminating in 1993 in the coldest, freshest "vintage" of LSW ever observed and the deepest homogeneous layer (2300 m). All three of these changes are evident in Figure 3 which shows the changes in potential temperature and salinity of the entire watercolumn as a function of depth and time, and in Figure 4 which shows the median values of these variables for the three main watermasses over the past five decades. [Note that the divergence of LSW θ and S trends between 1990 and 1995 marks the penetration of the underlying higher salinity/lower CFC and higher density layer as convection developed to its maximum intensity].

b) and c) Underlying the convectively-formed mode water, the *deep and abyssal watermasses* of the Labrador Sea (NEADW and the DSOW) have also undergone remarkable long-term variations in their temperature and salinity, of lower amplitude than LSW but perhaps steadier in trend (Figures 3 and 4). In particular, the salinity of *both* watermasses has decreased steadily by around 0.01 per decade for the past 3.5 decades (Figure 4). Since these layers lie beyond the reach of the deepest convection, these variations are unlikely to be locally forced. A more-likely origin lies upstream. Over the past 3-4 decades and largely in response to NAO forcing, the upper waters of the Nordic Seas have undergone a dramatic, extensive and protracted freshening to depths of 1000-1500m (Blindheim et al, 2000). At 700 – 900m, the sill depths of the Denmark Strait and Faroe-Shetland Channel are appropriately placed to tap this freshening layer and transfer it to the deep Atlantic via the two main overflows which cross the Greenland-Scotland Ridge at intermediate depths. We already have temperature evidence to connect conditions in the upper layers of the

Nordic Seas with the DSOW layer of the Labrador Sea (Dickson et al 1999). However the long salinity series from the Faroe-Shetland Channel (see Turrell, this volume) show that at sill depth, the deep dense overflow there has undergone almost exactly the same rate, amount and timing of freshening as that observed in the NEADW layer of the Labrador Sea downstream (Figure 5). Since the one is the source of the other, this coincidence of trend seems compelling evidence of cause and though we have no equivalent salinity series from the Denmark Strait Overflow, the fact that NEADW- and DSOW-derived layers in the Labrador Sea show parallel freshening suggest that both overflows are implicated in transferring the freshening of the upper Nordic Seas to the deep and abyssal layers of the NW Atlantic.

In the present context, this connection is important: it offers compelling new evidence that climatic forcing at the ocean's surface in high northern latitudes can be transferred south via the intermediate-depth overflows to affect the characteristics of the deep & abyssal layers of the Labrador Sea which form the headwaters of the THC.

Because the the THC is driven by density differences it is important to quantify their change over decade-to-century periods; it is found that Labrador Sea Water indeed experienced a densification by about 0.05 ppt between 1970 and 1993-95, then relaxing as milder winters returned. Consequently, an outpouring of LSW has been observed extending southward along the western Atlantic boundary, particularly in CFC measurements (Pickart and Smethie (1997). NEADW, the layer beneath LSW, has however seen very little change in density while experience great change in salinity and temperature. DSOW, the crucial watermass for the global overturning circulation, has also seen rather smaller density change (~.02 ppt) despite its long-term decline in salinity between 1965 and 2000. The CFC signal suggests two lobes of enhanced southward transport: LSW, which contributes to Upper North Atlantic Deep Water, and DSOW which largely drives lower North Atlantic Deep Water. It is important to develop improved monitoring of this dynamical signal.

3. Observational history and method.

During the WOCE period, Canada committed itself to an annual occupation of a hydrographic/tracer section across the Labrador Sea. This section passed close to the old OWS BRAVO site (Figure 1) and was also similar but not identical to a standard section established by NAFO in the 1950s. A partnership with University of Washington allowed this section to be augmented by moorings near the OWS BRAVO site and across the deep Labrador Slope. Canada occupies the section in spring or early summer (mid May to early July) in order to be able to identify the properties of the previous winter's convection in the Labrador Sea, and this work has been supplemented by irregular reoccupations at other times of year by BIO and others. The hydrographic and tracer data along the section have shown how the properties of the principal components of the

NADW have changed over the 1990's on interannual time scales, though the frequency of these observations means they are probably tracking changes over 2-3 years rather than year to year. These sections are planned to continue as part of Canada's commitment to CLIVAR and GOOS.

Bravo mooring

There are diverse important reasons for maintaining extended time-series observations at fixed sites in the high latitude oceans. The heat-storage, fresh-water storage and potential energy of the water column are net expressions of climate change, observed independently of atmosphere/ocean fluxes derived from the weather network. The same measurements record decadal variability of the major water masses, particularly if the site is carefully chosen. In addition to changes in properties, the volume fluxes of major water masses can be observed at sites within major boundary currents and at sills. There is some tension between the desires to observe both property changes and transports of major water masses. Bravo is particularly valuable, because of the rapid out-mixing of waters from the neighboring boundary currents, as described above: we can see watermass variability right through the stack of water masses: shallow low salinity water, LSW, NEADW and DSOW at a single site (Figures 2-4).

The mooring near the Ocean Weather Station BRAVO site was intended to repeat the high frequency observations of T and S profiles that were obtained by the ocean weather ships in 1964-1974. This mooring was first set in May 1994, catching the peak of the current cycle of strong, cold winters. Since then it has provided coarse records of the deepening mixed layers through the fall and winter and the rapid restratification in April in spite of some mooring losses (Lilly, Rhines, Visbeck, Lazier, Schott and Farmer 1999; Lilly and Rhines 2000). In combination with an ambitious effort involving German moorings in the region, Bravo has described the decadal variability of LSW and NEADW, and time-intensive view of the remarkable restratification of the water column seasonally and interannually. Mesoscale eddies have themselves changed dramatically in properties with coming and going of intense, cold wintertime atmospheric forcing. Geographical maps of wintertime convective depth have been obtained from the PALACE and other profiling floats deployed in 1996/97.

New technologies are being "beta-tested", which may greatly improve our ability to observe the region: among these are full-depth profiling ctd/cm moorings (Doherty et al. 1999), acoustic tomography from the IFM group and gliders (e.g., Eriksen *et al.* 2000, see Section 5. below).

Deep-water boundary current moorings in the Labrador Sea

The encircling boundary currents in the Labrador Sea communicate the watermasses described above to the global deep circulation. Direct transport measurements in the globally important water masses are an important goal at many sites, as discussed in other chapters of this volume. Yet only at sites like the ends of the AR7/W section shown of Figure 1, are the currents stacked with the 'parfait' of water masses, all observable at a single mooring. The velocity has a strong barotropic mode, thus being very difficult to estimate from hydrography (Figure 7). Transport measurements here will be extremely useful in diagnosing changes in the THC. A BIO mooring under the shelf-break front, between the shallow Labrador Current and deep system of boundary currents on the 1000 metre isobath has been limited to a single near-bottom current meter because of iceberg interference, but it has recorded one of the longest nearly continuous series in the northern Atlantic, from 1979 to 2000. Remarkably, convective penetration reaches this instrument in all but the mildest of winters, and the site tracks the decadal shifts of LSW rather well, despite being distant from the center of the Sea.

A more comprehensive set of boundary current moorings spanned the deep boundary currents from 1000m isobath out to the Bravo mooring beginning in 1996. This involved BIO, University of Washington and German Institut fuer Meereskunde (IFM); it has largely tied down the transport of that deep stack of boundary currents at 40 to 42 Sverdrups during 1996-1998 (in IFM calculations). The IFM group is continuing observations here and at other downstream sites (Fischer et al., 1999). A more permanent effort like this would be needed if we are to estimate the mass, heat and salt transport of the deep circulation in relation to what water flows from the Arctic through the Archipelago. CTD sections alone cannot reliably determine the transport, even with lowered adcp velocity data, because of a strong 7 to 30 day oscillation of the top-to-bottom boundary current transport, documented by these moorings. While we do not put forward a detailed plan for deep boundary current moorings in this document, the evolution of mooring and glider technology suggests deployments for the near future.

Shallow-water moorings at the margins of the Labrador Sea

The global precipitation/evaporation/runoff balance for freshwater historically involves net evaporation from the Atlantic and net precipitation into the Pacific. A return circuit is the Bering Strait-Arctic pathway, much of it through the Labrador Sea, and much of that on the Labrador continental shelf. The shallow Labrador Current on the continental shelf transports some 7.6 Sverdrups southward, water of very low salinity and ice (see Figures 1 and 8); with salinities of 31 to 34.8 psu, temperatures of –1 to 3 C. Annual range of the transport is roughly 4 Sverdrups (Lazier and Wright, 1993). While this is less than the ~40 Sverdrups in the deep boundary current system, it is a significant part of the low salinity, low density fluid transport in the region. The southward shallow transport originates (1) in the West Greenland Current that branches and partially crosses the open Sea to the Labrador Shelf, (2) directly from the Davis Strait, which is the dominant pathway for flow from the Arctic, and (3) from Hudson's Bay.

Additionally there are local run-off and ice-melt sources of fresh water. Pacific and Atlantic waters are distinguishable by their nitrate/phosphate content, showing that flow from the Arctic has a strong component from the Pacific (and Hudson's Bay contains nearly pure Pacific water (Jones, 2000).

Transport of the Labrador Current diminishes greatly by the time it rounds the Grand Banks of Newfoundland, to 3.6 Sverdrups, then to 0.6 by Halifax. and thus it is actively communicating with the deeper-water boundary currents. The estimated freshwater transport is 210 milliSverdrups (mSv, referenced to 34.8 psu salinity), Figure 8. Of this transport it is estimated that 120 mSv come in the Baffin Island Current through the Davis Strait, and only 29 mSv from round Cape Farewell and the Greenland shelf. Roughly 35 mSv of 210 mSv total are suspected to be in sea-ice (All numbers are from Loder, Petrie and Gawarkiewicz, 1998). Decadal variability in the entire shelf-water system has been observed (e.g., Petrie and Drinkwater 1993), and it is the enhancement of these observations, particularly relating to transports, that is suggested here.

Moorings on the shelf are scoured by icebergs and trawlers. However, BIO has developed hardened bottom adcp moorings to withstand this interference. For hydrography, the BIO 'Icycler' winched ctd is in the prototype stage, and is being deployed also in the Canadian Archipelago passages.

In winter and spring, ice motion can be estimated from analysis of remote imagery or by the deployment of ice drifters onto the pack. Without measurements of ice thickness as well as T/S profiles across the shelf, it will be impossible to estimate changes in mass, heat and salt transport over the Labrador shelf. A bottom-mounted upward looking sonar and adcp in a hardened shell has been proposed by Prinsenberg at BIO, for the narrow shelf region near Nain, Labrador. Radarsat imagery is available to provide the context for the mooring.

Canadian runoff, sea-ice cycling and transport from the Arctic are all significant in producing the Labrador current freshwater transport. Interaction of this shallow circulation with the deep THC is of great interest, particularly given the sensitivity of sinking regions to capping off with buoyant fresh water.

Davis Strait

The Davis Strait, about 650m deep at 67^0 N west of Greenland, carries much of the Arctic outflow west of Greenland, and feeds the Labrador shelf (described above). Water masses observed there seem well-defined, cleanly dividing between northward flowing warm, saline Irminger Water (in the west) and southward flowing low-salinity waters (in the east) for Arctic (and largely Pacific) origin. In addition a shallow residual of the low-salinity West Greenland Current makes its way northward along the eastern boundary. A 5 mooring/ 17 instrument current meter/temperature/salinity program by C.Ross of BIO (unpublished document) estimated 3.1 Sverdrups southward and 0.7 Sverdrups northward transport, for a net of 2.4 Sverdrups southward. This was a 3-year deployment beginning in 1987. The array did not sample the upper 150m, nor on the narrow shelves, nor the ice. Future work in this area could involve profiling moorings and gliders (at least in ice-free months of the year). This site could be extremely fruitful in supplementing the observations of CAA throughflow discussed by McLaughlin and Carmack (this volume, section 9). Ice draft measurements with ADCPs could augment the sub-surface, profiling or fixed-instrument moorings.

Modelling issues

A significant motivation for these observations lies in the central importance of computer models of the ocean/atmosphere. These climate models, in order to be global in coverage, must limit their spatial resolution; yet the ocean is known for its great diversity of length scales. In doing so the models have limited representation of key processes like deep convection, boundary currents, especially in sinking regions, complex topography and sills, upper mixed layer dynamics, fronts and sea-ice dynamics. Only by making high resolution observations of key sinking, convection and through-flow sites will be able to support the ongoing improvement of these models.

There has been observed salinity and temperature variability in overflows, which subsequently appears to propagate downstream. Theory and models show that such changes propagate as topographic waves cyclonically round ocean basins, with tracer properties catching up more slowly. When significant density variability is involved, the signals can restructure the entire top-to-bottom circulation. The subpolar Atlantic gyre is in part driven by these overflows, and responds to their variability. In a word, cooling the Denmark Strait can warm the upper subpolar ocean by spinning more warm water up from the subtropics. Events like these are at the heart of the major climate ‘oscillators’ being discovered in climate models, and their reality needs to be tested.

4. Costs:

a) Shiptime: The Labrador Sea CTD line takes about a week to work with full physical, chemical and biological sampling. To work only the physics would take about 4 days plus 1 day for the mooring work. The steaming time from St. John's is roughly 1.5 days to the southern end of the line and 3.0 days back from the northern end. The annual total requirement is for 9.5 - 11.5 days at $20k per day = $190000 - $230000.

b) Bravo mooring and boundary current mooring unit costs. The approximate capital and maintenance costs of a 3500 m mooring carrying 6 Seacats and 6 current meters (US$) are as follows:

Capital equipment (USD)

6 Aandara RCM8 Current Meters at 20 k	120000
6 Seacats @ 6 K	36000
Acoustic release	20000
15 Backup up buoyancy packages @ $1000	15000
Main Float	40000
Total Capital	$230000

Annual recurrent costs of mooring maintenance.

3500 m wire @ $2.00/m	7000
Prep. of 6 current meters @ $1k ea	6000
Prep. of 6 Seacats @ $1k ea	6000
Acoustic Release	2000
Main Buoyancy	500
Back up buoyancy 15 @ 100	1500
Hardware including anchor	2000
Total Annual Maintenance	$35000

c) Labrador Shelf mooring costs. Estimated unit hardware cost for a 'hardened' shelf mooring are:

long-range ADCP	32000
upward looking sonar	26000
releases (2)	26000
mooring hardware	8000
Total Capital	$92000

***5. Future Options*.**

1). GLIDERS. The Eriksen Seaglider (Figure 6) is a gliding PALACE device that has had very successful early trials off Monterey. The Seaglider platform has the versatility to imitate a mooring, by profiling in place for a year, to perform trans-ocean sections at a typical speed of 20 km day-1, or to make dense, repeated surveys across boundary currents or across sills. All of these have daily satellite communication of the full dataset, and strategic changes in sampling (course and depth range) based on these data. The current low-production cost of the instrument is $65K, and this will improve with economies of scale. Turnaround of a glider between missions will cost ~$10K. Little or no ship-time is involved. The design suggests that one-year deployments should give 6,000 km horizontal travel with 600 profiles to 2 km depth and at an average speed of about 20 cm/sec. The current trials involve 4 sensors (Seabird conductivity, temperature, a new Seabird O_2 sensor and a fluorometer). With this sensor load, it runs at about 2 watts average power consumption in shallow water, or 1/2 watt in deeper dives. Communication near shore is by cell phone, but the intention is to use the Globalstar satellite network whose footprint covers the entire North Atlantic. This development is of interest since it may be one of the only ways to monitor key parts of the northern Atlantic with a sufficient observational density.

A future program combining profiling moorings with Seagliders could be a very effective complement to ship work. One glider could work 2 transatlantic sections per year, at an average profile-spacing of 20 km from shore to shore at 50N. In summer or other ice-free times it could visit overflows. The glider may learn how to deal with ice. At present it misses the deep branches of the circulation, but technology will continue to develop. It is also uniquely able to sample boundary currents, crossing them and even riding with them to speed through a survey pattern. Several alternative uses of the Seaglider are shown in Figure 9. We note that the important, and relatively ice-free Atlantic inflow to the Norwegian Sea/Arctic could be well-sampled (with sill depths of order 800m) by a glider, repeatedly occupying sections as shown on the figure.

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Pickart R. S., and W. M. Smethie, Jr., 1997: Temporal evolution of the deep western boundary current where it enters the sub-tropical domain. Deep-sea Research, *45,* 1053-1083.

Figure captions

1. The subpolar Atlantic, showing the location of the Bravo mooring and AR7/W hydrographic section of Bedford Institute of Oceanography in the Labrador Sea.

2. Salinity and CFC sections at the AR7/W line for 1993, 1995 and 1997. This period proceeds from the coldest, densest, deepest Labrador Sea Water of the past half century in 1993, to a restratified state after weak wintertime cooling subsequently. The boundary current system is visible at the left (Labrador slope) and right (Greenland slope) and its properties have mixed efficiently to the Bravo site in the central part of the section.

3. Depth/time history of salinity (above) and potential temperature (below) at Bravo.

4. Time history of the salinity and potential temperature of the three major deep water masses at Bravo.

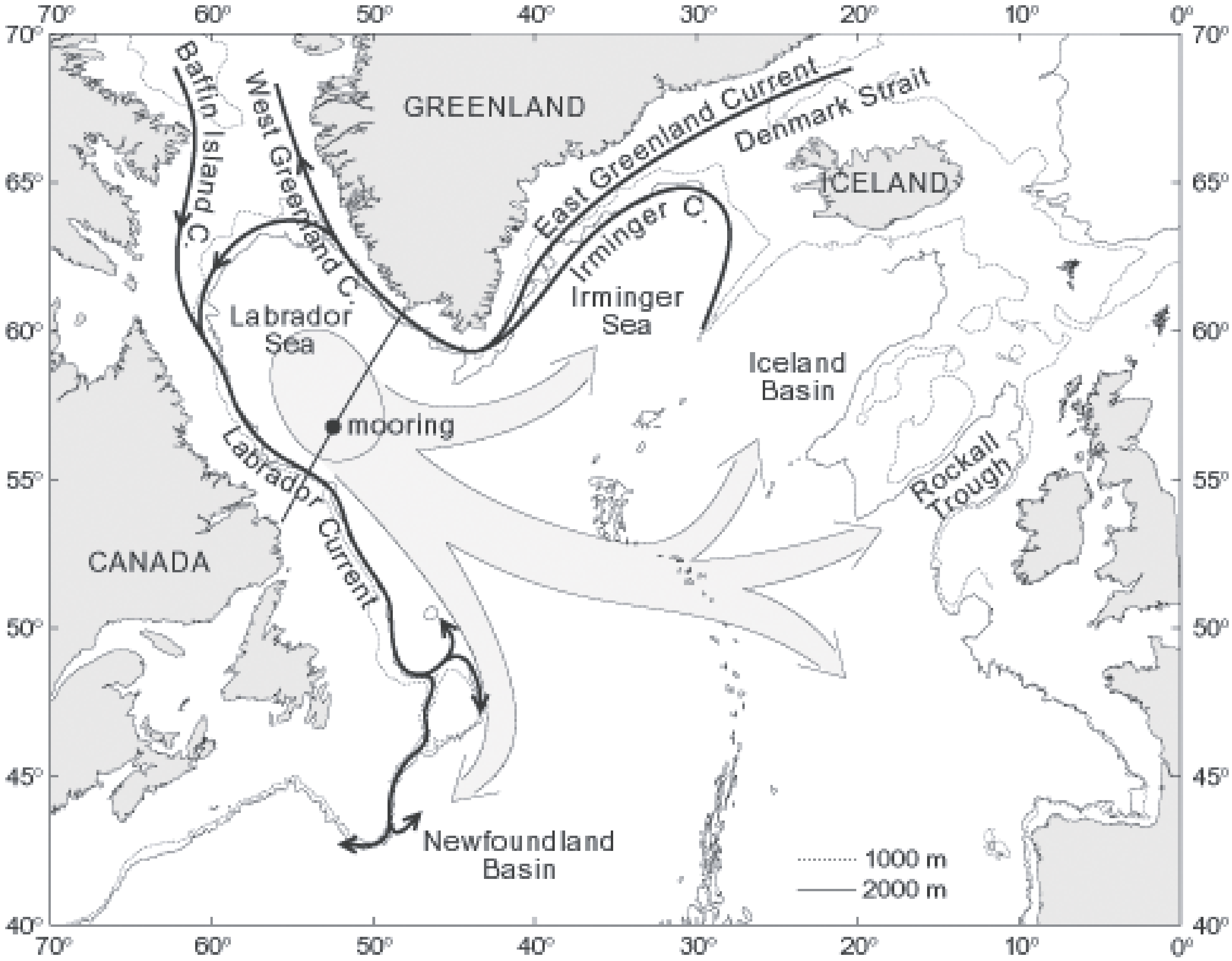
5. Comparison of long-term salinity trends at sill depth (800m) in the deep outflow from the Faroe-Shetland Channel (Turrell, personal communication) with those of the deep and abyssal layers of the Labrador Sea downstream (Yashayaev, personal communication).

6. Three Seagliders waiting for deployment (Eriksen, personal communication).

7. Boundary current mooring velocity record at the 2800m isobath (the soutwest end of the line shown in Figure 1), from Oct. 1996 to June 1998. There is a strong depth-independent component of velocity, plus maxima at top and bottom. The deep maximum is the core of the Denmark Strait Overflow Water. Strong 7 to 30 day oscillations make transport estimates from individual hydrographic/adcp sections unreliable.

8. Fresh-water transport on the shallow continental shelves in the western subpolar Atlantic (referenced to 34.8 psu). A dominant component flows through the Davis Strait along the Labrador Shelf, and then mixes with the deep ocean boundary currents (Loder *et al.* , 1998).

9. Possible paths of Seagliders in the subpolar Atlantic; (1) a 150 day survey of the Labrador Sea boundary currents round the rim that Sea (individual profiles show as circles); (2) a transAtlantic section requiring 6 months, or a dogleg to the north requiring slightly longer; (3) sections on the Iceland-Scotland Ridge and in the Norwegian Sea.



70°
60°
50°
40°
30°
20°
10°
0°
65°
55°
45°
GREENLAND
ICELAND
CANADA
Baffin Island C.
West Greenland C.
East Greenland Current
Denmark Strait
Irminger C.
Irminger Sea
Labrador Sea
Iceland Basin
mooring
Labrador Current
Rockall Trough
Newfoundland Basin
1000 m
2000 m

Fig. 1

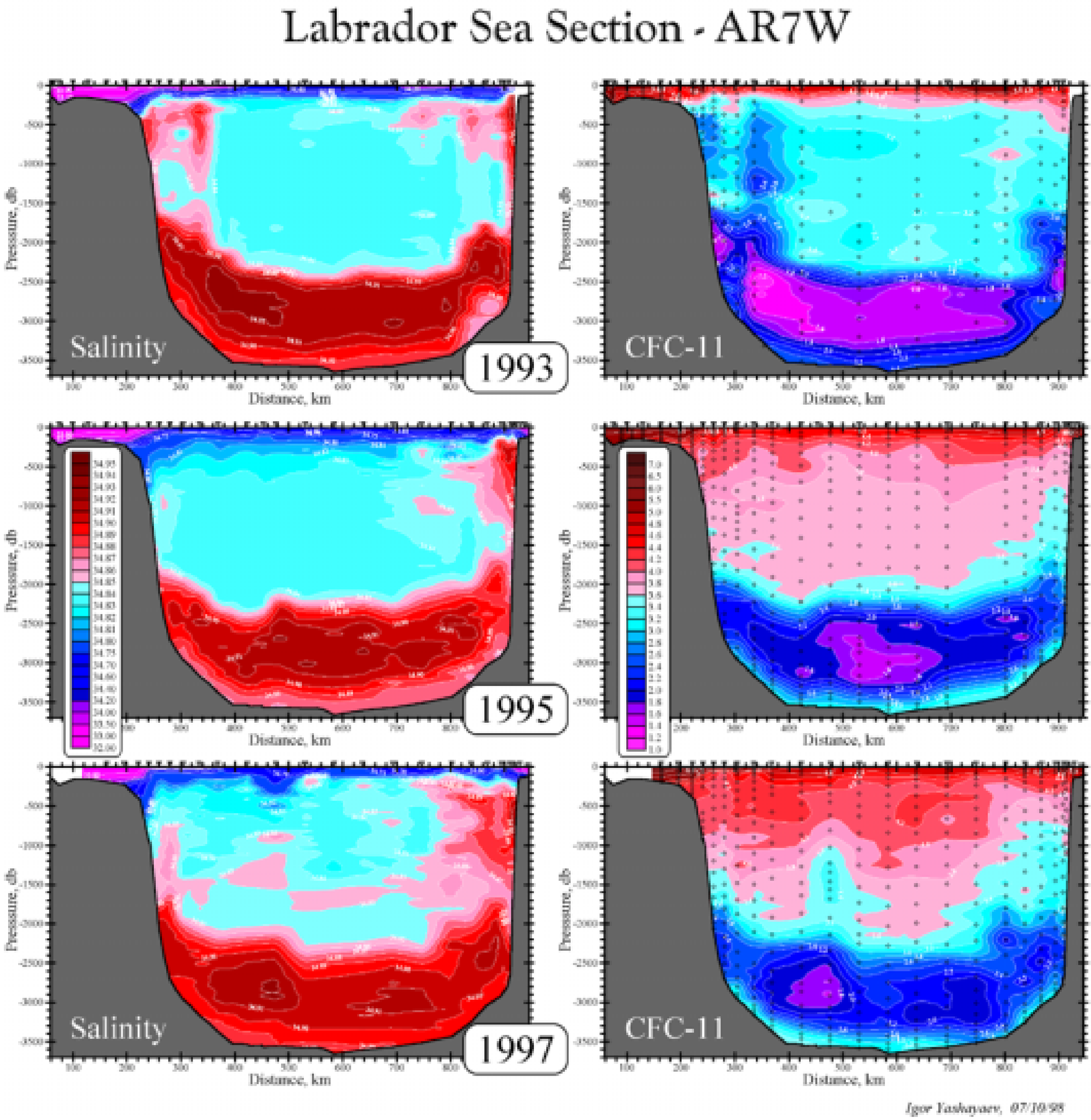
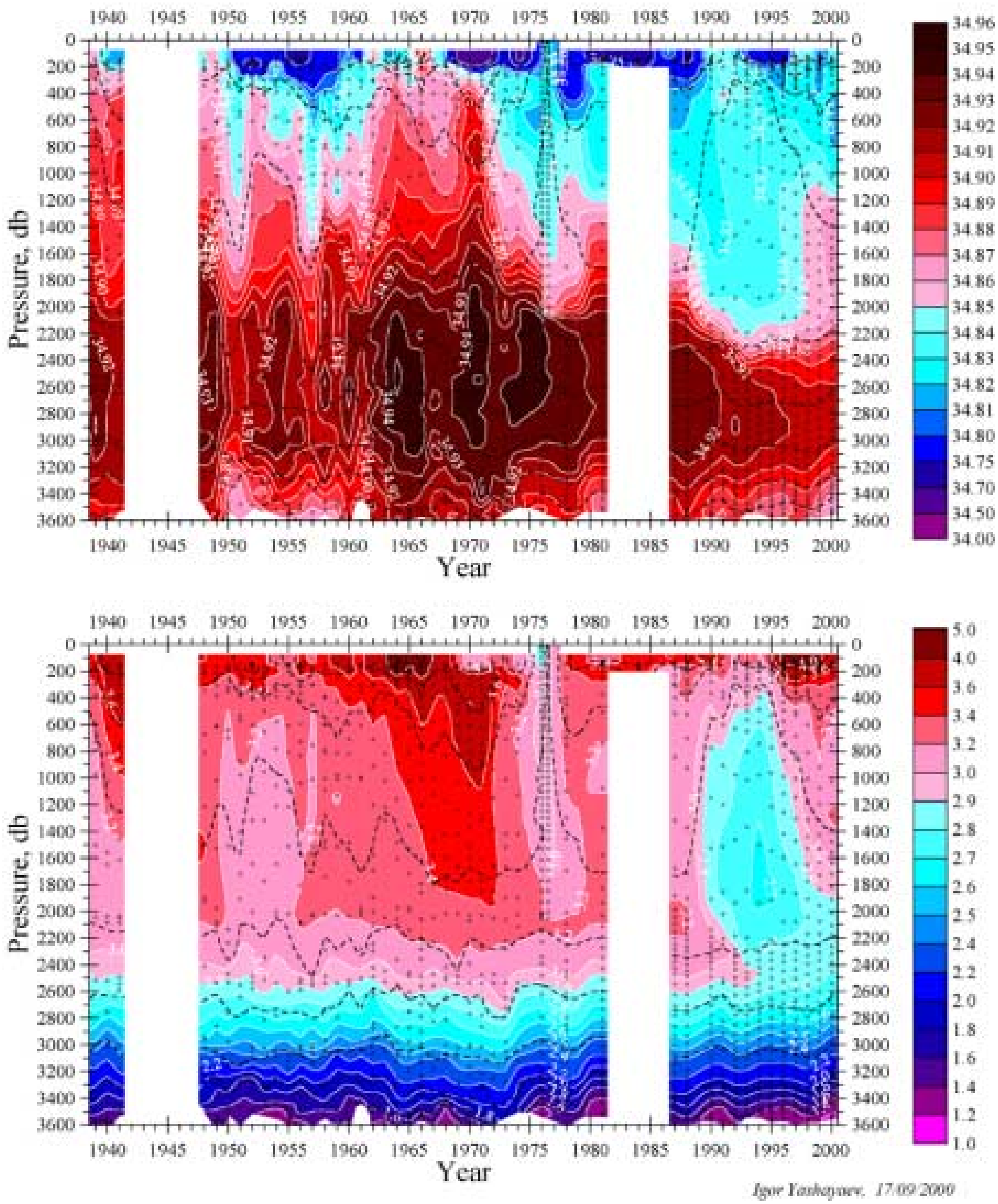

Labrador Sea Section - AR7W
Salinity
CFC-11
1993
1995
1997
Salinity
CFC-11
Pressure, db
Distance, km
Igor Yashayaev, 07/10/98

Fig. 2


Pressure, db
Year
34.96
34.95
34.94
34.93
34.92
34.91
34.90
34.89
34.88
34.87
34.86
34.85
34.84
34.83
34.82
34.81
34.80
34.75
34.70
34.50
34.00
Pressure, db
Year
5.0
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3.6
3.4
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2.8
2.7
2.6
2.5
2.4
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1.8
1.6
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1.2
1.0
Igor Yashayaev, 17/09/2009

Fig. 3

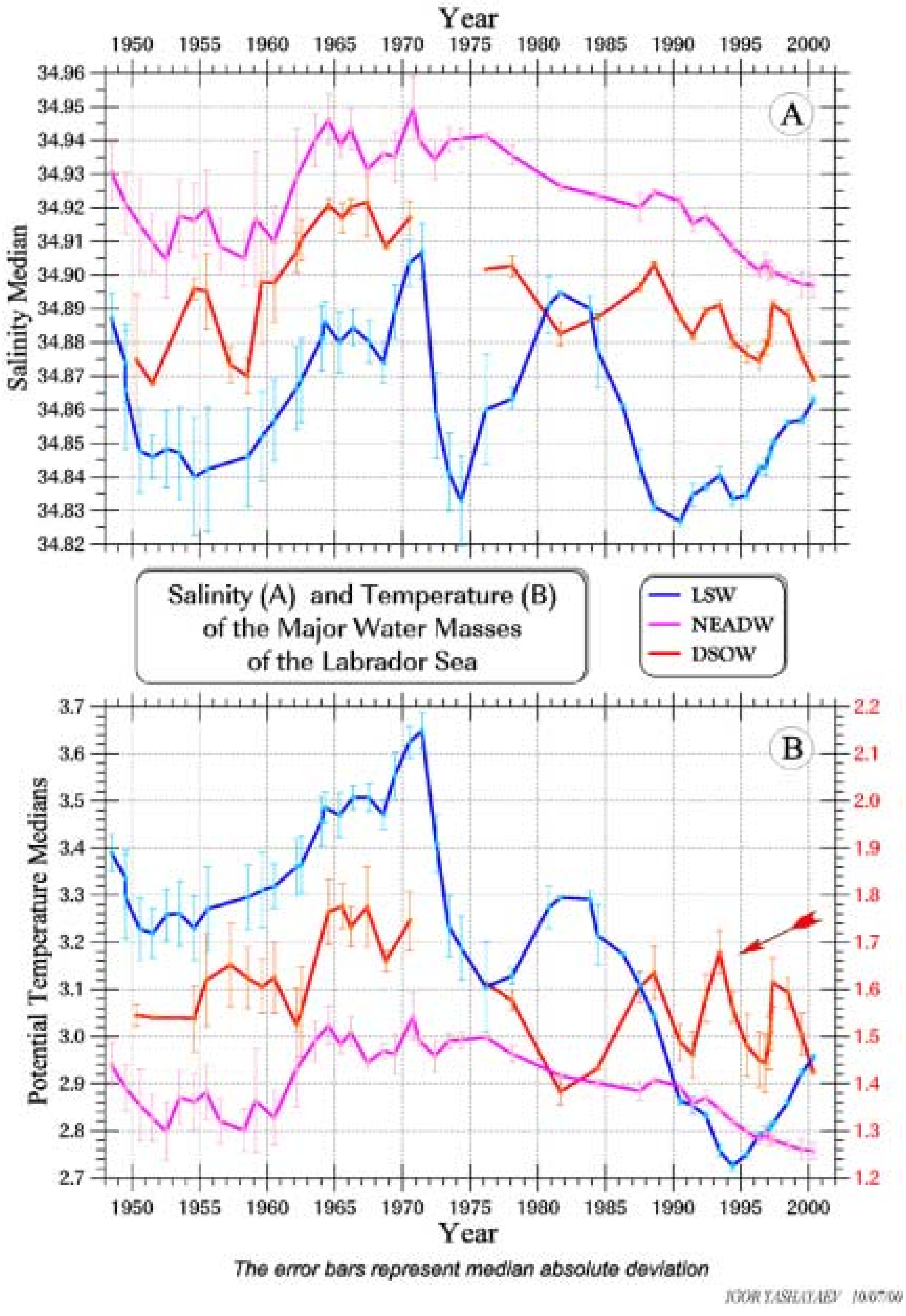
Year
Salinity Median
A
Salinity (A) and Temperature (B)
of the Major Water Masses
of the Labrador Sea
LSW
NEADW
DSOW
B
Potential Temperature Medians
Year
The error bars represent median absolute deviation
IGOR YASHAYAEV 10/07/00

Fig. 4

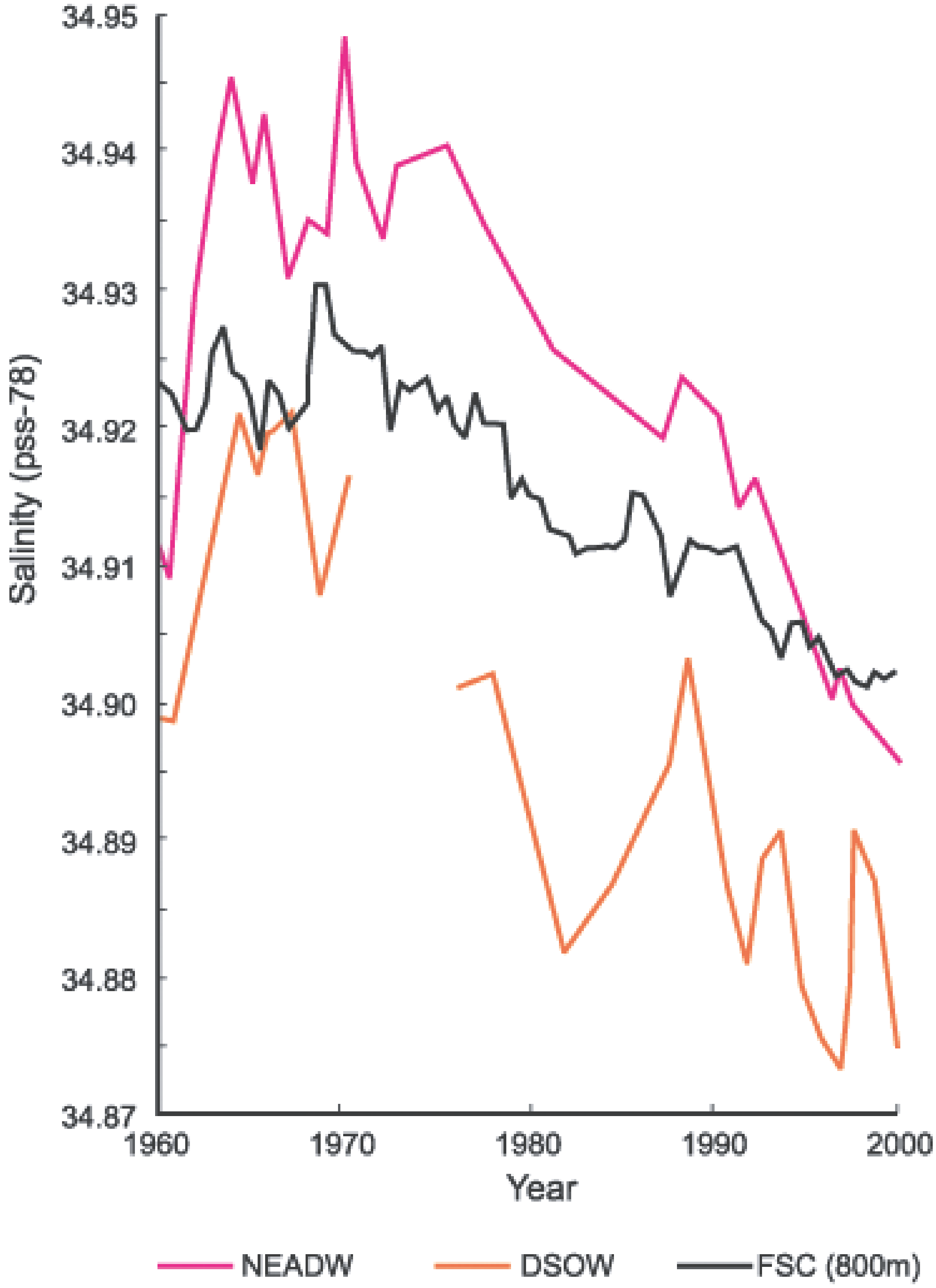

Fig. 5

Comparison of long-term salinity trends at sill depth (800m) in the deep outflow from the Faroe - Shetland Channel (Turrell, pers.comm.) with those of the deep and abyssal layers of the Labrador Sea downstream. (Yashayaev pers.comm.)

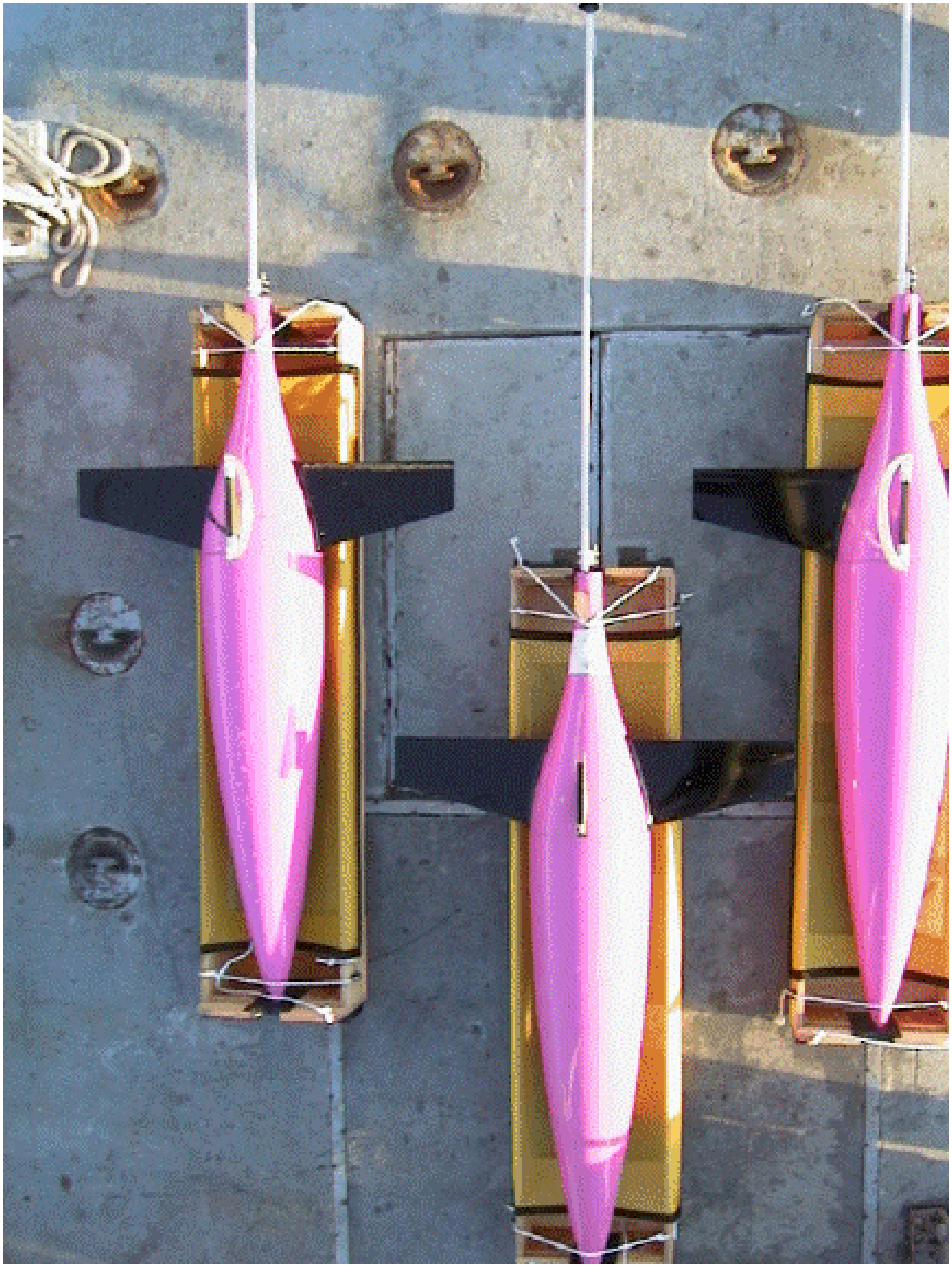

Figure 6. Gliders

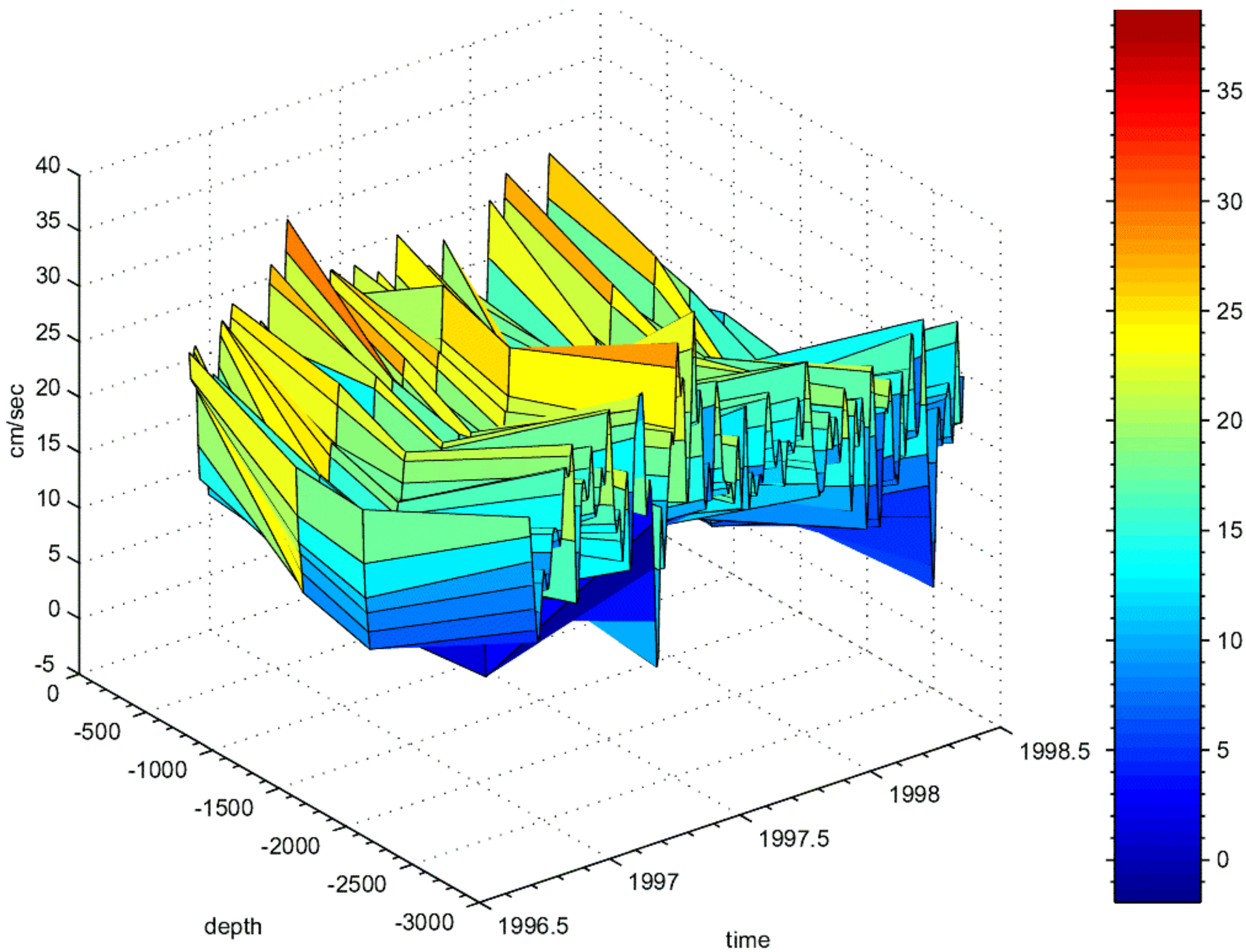
40
35
30
25
20
15
10
5
0
-5
cm/sec
0
-500
-1000
-1500
-2000
-2500
-3000
depth
1996.5
1997
1997.5
1998
1998.5
time
35
30
25
20
15
10
5
0

Figure 7

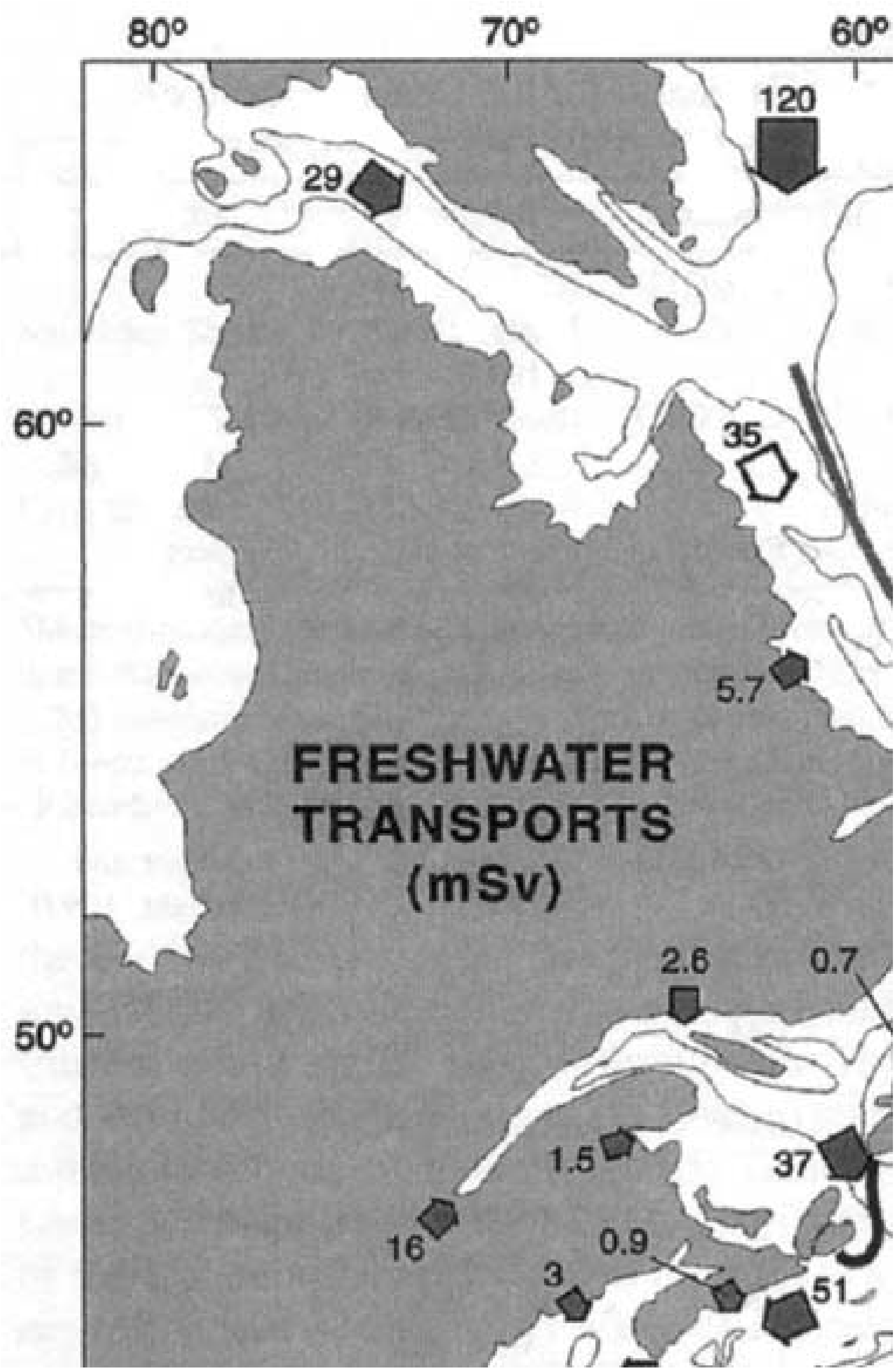
80°
70°
60°
120
29
60°
35
5.7
FRESHWATER
TRANSPORTS
(mSv)
2.6
0.7
50°
1.5
37
16
0.9
3
51

Figure 8

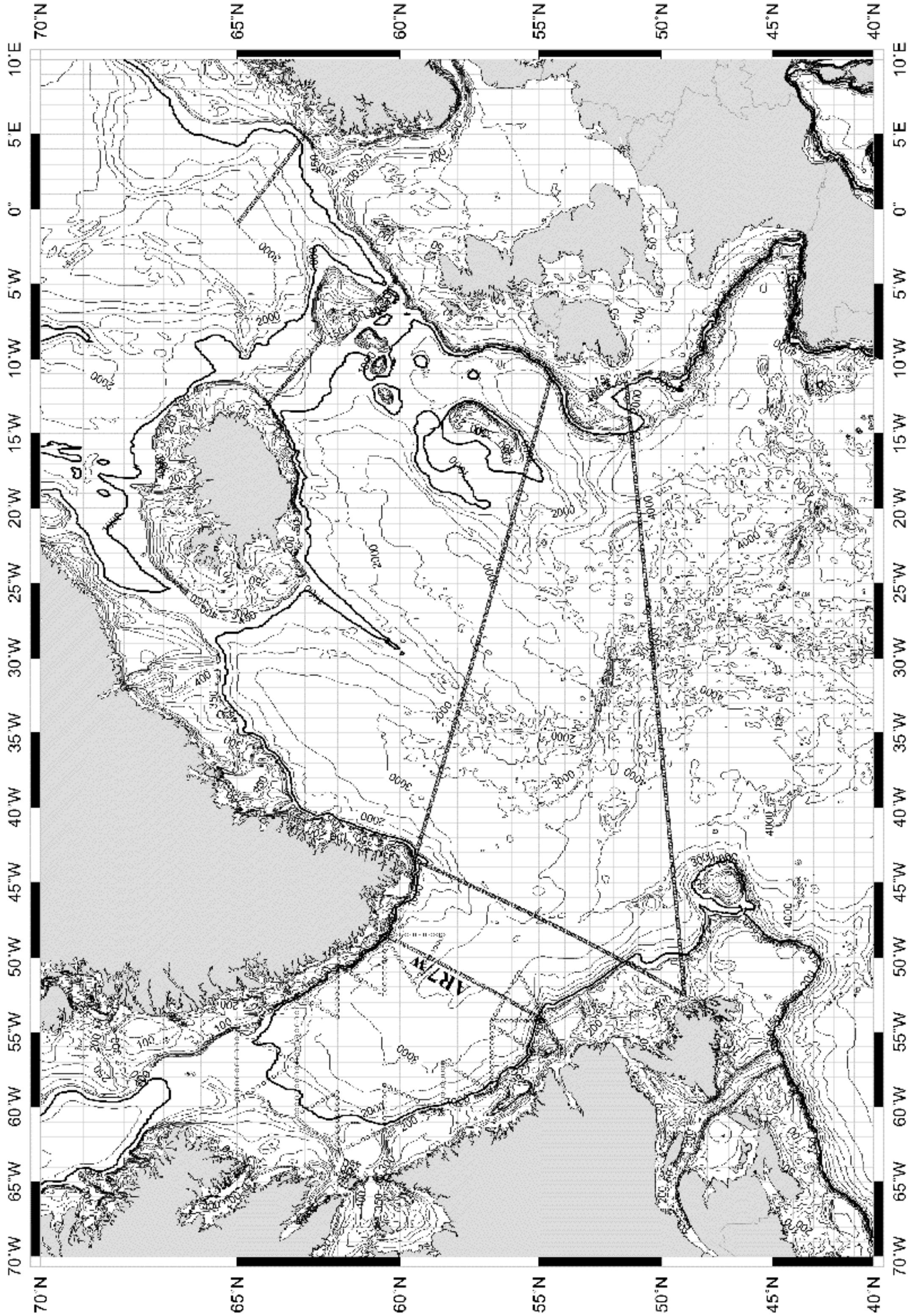

Figure 9

24. A Scenario for a Meridional Overturning Circulation Observing System

Jochem Marotzke, Stuart Cunningham, Harry Bryden (SOC)

1) Rationale for observing the THC at low-to-middle latitudes:

While much of this programme is focussed on the high latitudes, it is ultimately the ocean energy transport around 25°-35°N that is most relevant for climate; hence, the basic monitoring of the THC itself should occur there. Much of the energy transported northward in the Atlantic is given off to the atmosphere over the Gulf Stream extension, from where it is transported north-eastward toward Europe by the atmosphere. Hence, a THC observing array should not be situated too far northward. The basic strategy relies on simple dynamic height considerations: Mass transport between any two points depends only on the pressure difference between these points; to estimate the meridional mass transport (or meridional overturning circulation, MOC, including both buoyancy- and wind-driven components) across the entire Atlantic thus would require the continuous observation of density at eastern and western boundaries. Simple and straightforward as this idea might be, it has been implemented to limited extent only. Whitworth (1983) monitored Drake Passage transport over 20 years ago; more recently, Lynch-Stieglitz et al. (1999) estimated Florida Strait transport during the Last Glacial Maximum. Marotzke et al. (1999) did tests in their GCM, while Kanzow (2000) performed array design studies for moorings dedicated to monitoring integrated transports in the western North Atlantic. In part based on Kanzow's findings, U. Send and co-workers (2000, pers. comm.) deployed 3 moorings at 16°N to observe the deep integrated flow west of the Mid-Atlantic Ridge, as a pilot study to an observing system for the entire MOC.

We propose that a continuous observing array for the MOC should be supported. Important specifics have to remain flexible at this stage; the following illustrates some of the existing possibilities. The choice of latitude is principally between 25°N or (nominally) 30°N; the choice of temperature and salinity measurement platforms between moored and bottom-mounted ones. The 25°N section has the fundamental advantage that the western boundary current (flow through Florida Strait) can be measured relatively straightforwardly by cable (existing long-term programme by the US, e.g., Larsen, 1992) and regular calibration cruises. This leaves observing the relatively quiescent interior section, to be accomplished with a series of moorings on the western end (off the very steep drop east of the Bahamas, which makes bottom-mounted platforms difficult to deploy) and either moorings or bottom-mounted systems on the eastern end. The disadvantage of the 25°N section is the very same geographic peculiarity, making it highly unrepresentative of the ocean, which is likely to permit only limited inference of the dynamical connection between observed high-latitude processes and changes in 25°N MOC. In that respect, a more northerly array would be an advantage.

Which mooring design should be applied depends in part of future technological developments. A tall mooring should be equipped with a CTD profiler taking roughly one profile per day. This technology appears to just have reached maturity (J. Toole, 2000, pers. comm.). Over relatively gentle topography, several of these moorings, over differing water depths, would be required. Another option is pure bottom-mounted systems, allowing a significantly greater number of moorings to be deployed, which gives a more robust estimation of non-geostrophic eddy-noise in the density field. All moorings should be equipped not only with CTD but also pressure sensors and current meters. This gives added information for estimating the part of the MOC that is not in thermal wind balance but is rather dominated by high-frequency barotropic dynamics (e.g., Lee and Marotzke, 1998). To test the boundary array, at least two transoceanic sections would be required, toward the beginning and the end of the deployment period. Whichever latitude and basic design is chosen, international collaboration will help to make the system cost-effective. Miami appears as the ideal base for mooring deployment and recovery, and also for cable measurements. A UK-funded continuous observing system is likely to be a strong incentive for the US to support and participate in the effort. If outside support cannot be secured, a purely UK-funded effort could concentrate on 30°N and deploy instruments on both the eastern and western margins.

2) A concrete example:

The system described here assumes that the US cable measurements will continue. At this early stage of designing an observing system for the MOC, sufficient redundancy must be built into the system so that it can be ascertained from the data that indeed the sought-after signal can be picked up. Moreover, a pilot experiment with very intense sampling would be limited in time (one year), to allow the system to be evaluated. The following elements would be included (figures describing details of this scenario and a detailed budget follow in the end):

a) Western array at 26°20', eastern array at 26°35', both locations based on bathymetry. Each end array would include:

- 3 profiling moorings (CTD + profiling current meter), pressure gauge and current meter at bottom of each mooring; each mooring in deep water (> 4000m)
- 2 shallow profiling moorings (Vassie-style), CTD + current meter
- 2 current meter moorings in shallower water (20 current meters altogether)
- 10 bottom mounted systems (CTD, pressure gauge, current meter) distributed between deep and shallow systems,

The instruments on the profiling moorings would have to be dedicated, while the current meters could come out of the available pool and return to it after the first year. The profiling moorings would be maintained for 5 years, in the first instance.

The bottom-mounted systems should allow us to get a handle on bottom triangle problem (e.g., Whitworth and Peterson, 1985), but it also offers a strategy to obtaining density profiles different from the profiling moorings. Sampling density along the topography is, in principle, what Lynch-Stieglitz et al. did with measuring oxygen isotopes in foraminifera.

Density differences relate to zonally integrated thermal wind shear only if the bottom is not intersected. The mid-Atlantic ridge (MAR) represents a major deviation from this guiding principle, therefore, we propose

b) Two profiling moorings (CTD + profiling current meter) to the east and west of the MAR in water depth > 4000m. During deployment, swath bathymetry should be taken.

c) For calibration purposes, two "standard" hydrographic sections will be taken, one at the beginning and one at the end of the observing period.

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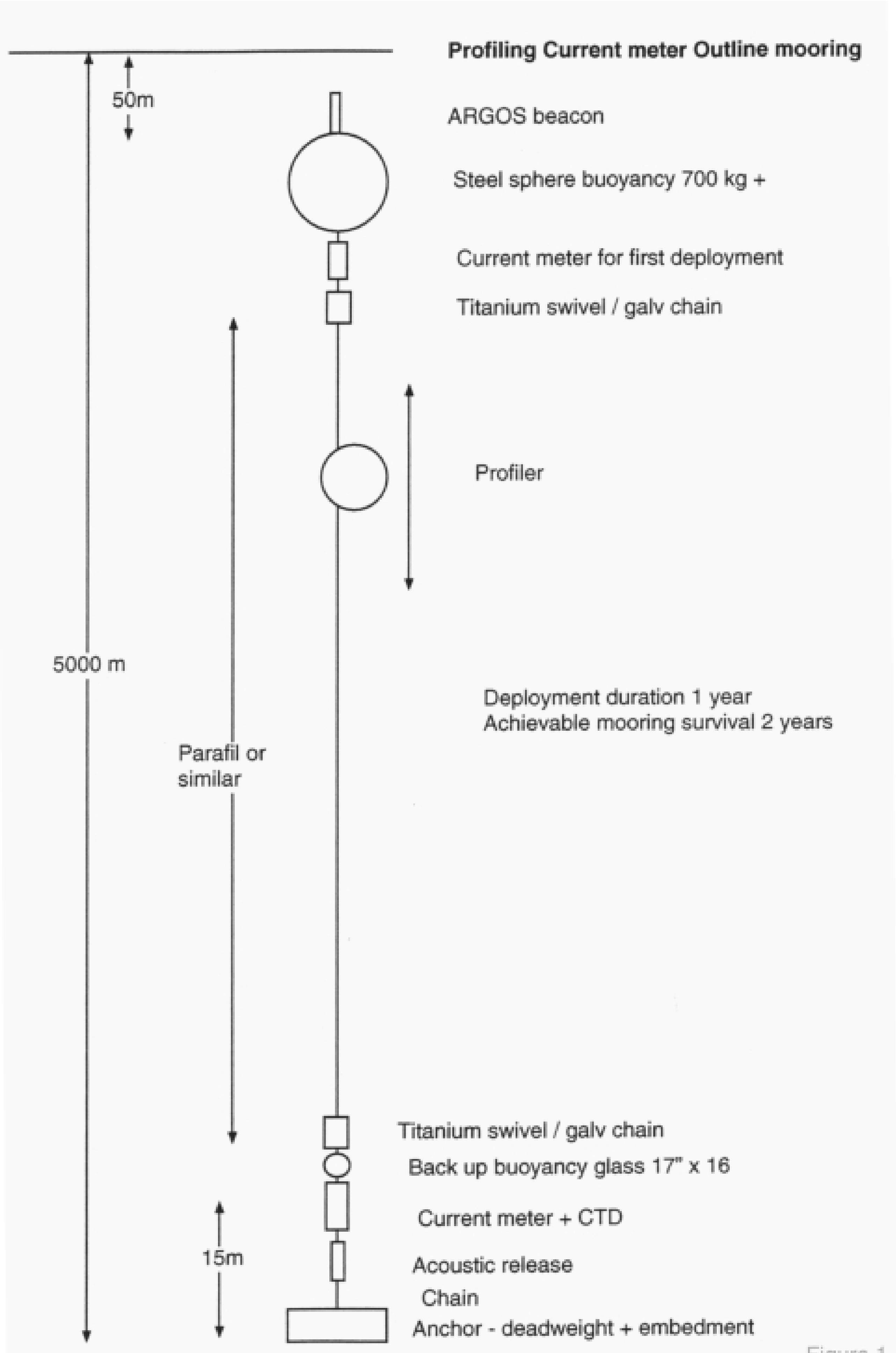
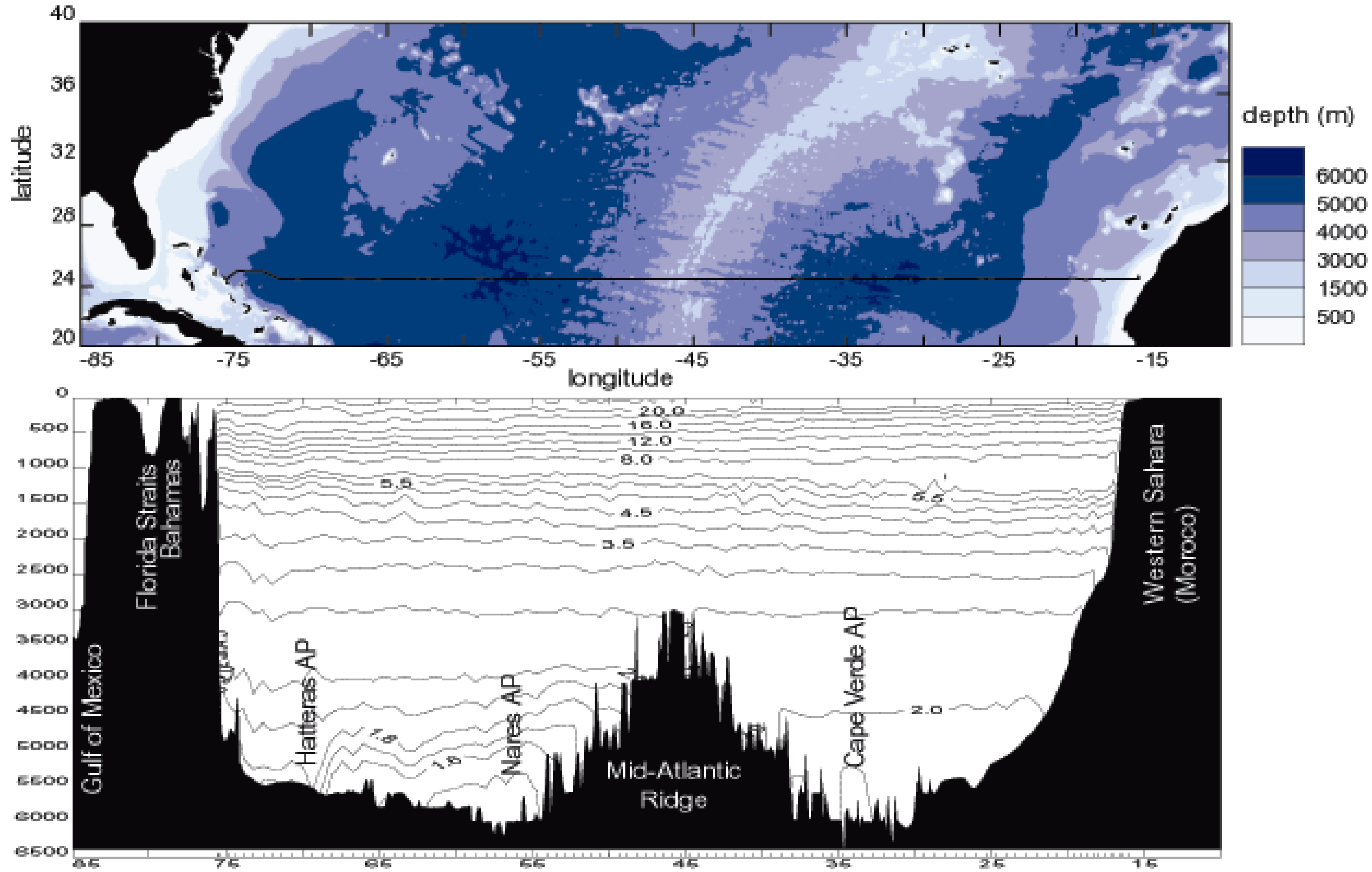
Five year budget for 24°N mooring array

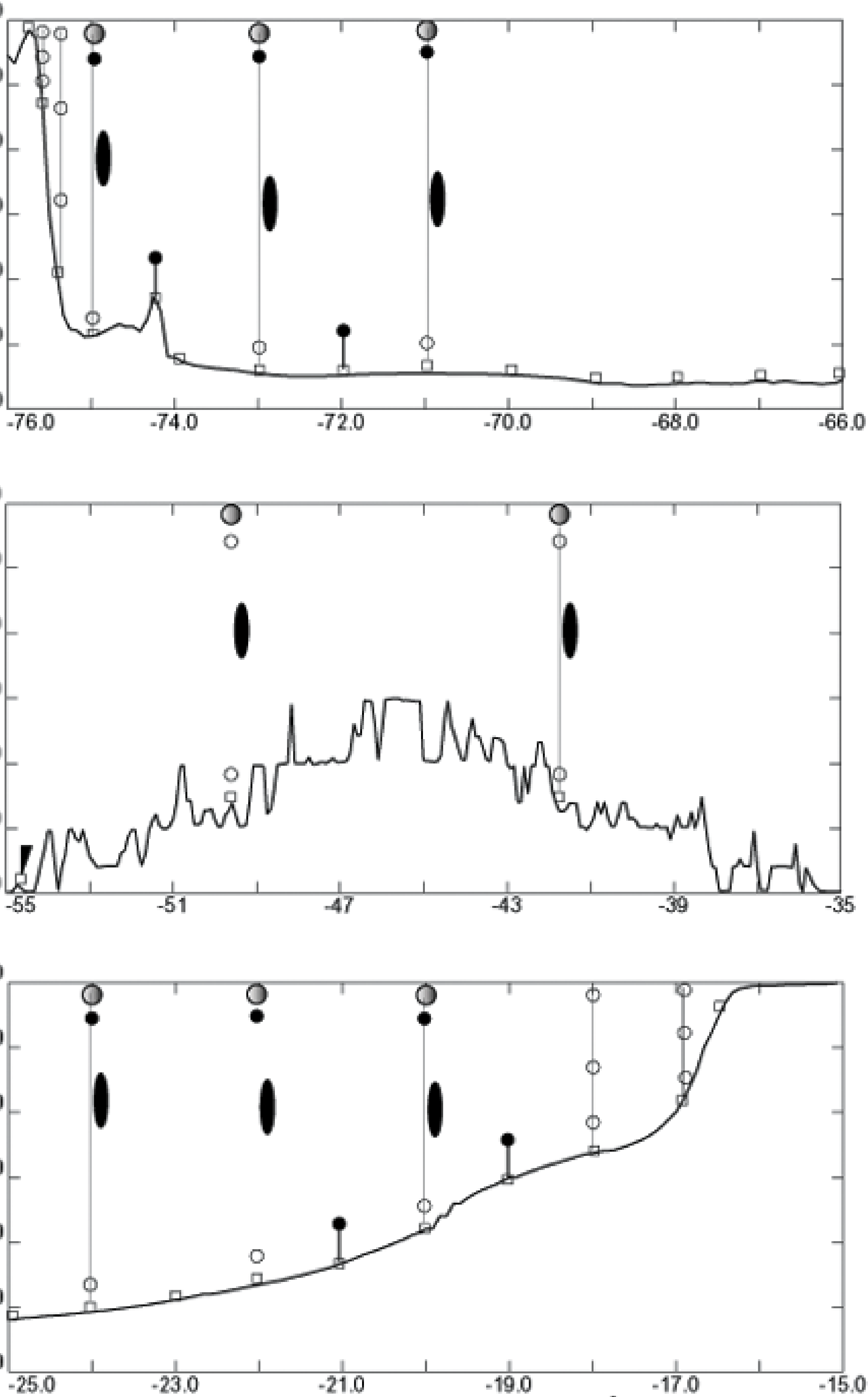
Year	**Item**	**Unit cost (k£)**	**Number**	**Total (k£)**
1	profiling mooring	140.6	8	1124.4
1	dedicated mooring equipment	23.0	1	23.0
1	bottom pressure recorder, CTD and current meter	25.0	10	250.0
1	1500 m mooring	58.3	4	233.0
1	300 m mooring	42.1	4	168.4
1	POL Near bottom profiler	12.0	4	48.0
1	Ship/staff cost	172.8	1	172.8
2	profiling mooring (duplicate set of moorings as year 1)	140.6	8	1124.4
2	bottom pressure recorder, CTD and current meter	25.0	10	250.0
2	1500 m mooring	6.5	4	25.8
2	300 m mooring	4.5	4	18.0
2	POL Near bottom profiler	12.0	4	48.0
2	ARGOS SSM costs	2.0	24	48.0
2	Ship/staff cost	172.8	1	172.8
3	profiling mooring	9.4	1	9.4
3	BPR, cm and CTD servicing	1.5	10	15.0
3	1500 m mooring	6.5	1	6.5
3	300 m mooring	4.5	1	4.5
3	POL Near bottom profiler	1.0	4	4.0
3	Ship/staff cost	172.8	1	172.8
4	profiling mooring	9.4	1	9.4
4	BPR, cm and CTD servicing	1.5	10	15.0
4	1500 m mooring	6.5	1	6.5
4	300 m mooring	4.5	1	4.5
4	POL Near bottom profiler	1.0	4	4.0
4	Ship/staff cost	172.8	1	172.8
5	profiling mooring	3.6	1	3.6
5	BPR, cm and CTD servicing	1.5	10	15.0
5	1500 m mooring	4.7	4	18.8
5	300 m mooring	3.8	4	15.2
5	POL Near bottom profiler	0.5	4	2.0
5	Ship/staff cost	172.8	1	172.8
	Total Cost of moorings over 5 years			**4185.4**
1	24N transatlantic hydrographic cruise			**490.0**
5	24N transatlantic hydrographic cruise (year 1 + 2.2% / year)			**546.3**
	Total cost of 24°N monitoring programme over 5 years including 2 transatlantic hydrographic sections			**k£ 5221.7**


Profiling Current meter Outline mooring
50m
ARGOS beacon
Steel sphere buoyancy 700 kg +
Current meter for first deployment
Titanium swivel / galv chain
Profiler
5000 m
Deployment duration 1 year
Achievable mooring survival 2 years
Parafil or
similar
Titanium swivel / galv chain
Back up buoyancy glass 17" x 16
Current meter + CTD
15m
Acoustic release
Chain
Anchor - deadweight + embedment
Figure 1



A. North Atlantic bathymetry from ETOPO5 (5 minute resolution) with the Hesperides 1992 cruise track at 24N. B. Vertical section of the ETOPO5 batymetry at 24.5N from North America to Africa with the main bathymetric features named (Abyssal Plain AP). The monitoring array at the western boundary will include 3 profiling CTD and current meter moorings with bottom pressure recorders (see Figure 3), 2 Proudman Oceanographic Laboratory near bottom profilers, 2 shallow water moorings, and 10 bottom mounted pressure recorders with CTD and current meters. This array is replicated at the eastern boundary. Density differences across the mid-Atlantic ridge will be measured by a pair of profiling CTD moorings on either flank in depths <4000m and , and one bottom mounted upward looking ADCP.

Figure 2



24N monitoring array: profiling mooring buoyancy; profiling CTD/3D acoustic current meter; current meter (filled with CTD); bottom pressure recorder with CTD and current meter; POL near bottom profiler; bottom mounted ADCP.

Figure 3