

iAOOS: An ocean-observing system for Northern Seas during the legacy phase of the International Polar Year



A Report of the Arctic Ocean Sciences Board written by Bob Dickson (CEFAS) with Bert Rudels (FMI), Craig Lee (UW-APL), Tom Haine (JHU) and iAOOS PIs

Araon in the Chukchi Sea, July - August 2010; photo by Dr. Kyungho Chung, Korea Polar Research Institute.

iAOOS: An ocean-observing system for Northern Seas during the legacy phase of the International Polar Year.

Introduction and antecedents: This is the fourth in a series of Reports written at the behest of the Arctic Ocean Sciences Board (AOSB), the Marine Working Group of the International Arctic Science Committee (IASC). Taken together, these form an extended essay on a common theme:— *how might we design an effective international ocean-observing plan for Northern Seas in the 'Legacy Phase' of the International Polar Year, based on what we have learned?* Already, there is a need to define terms. Though 'iAOOS' does signify an *integrated* Arctic Ocean Observing System, this is not meant to imply that the plan is integrated across disciplines ---the Report deals largely with physical oceanography --- but instead, that it attempts to piece together a large-scale context against which individual projects might be set and to which individual PIs might contribute. As such, it might more properly be called an *integrative* ocean observing system. It uses the phrase 'Northern Seas' rather than Arctic because it is now entirely demonstrable that the two-way oceanic exchanges that connect the Atlantic and Arctic Oceans through subarctic seas as well as the changes in the Polar Seas themselves are of fundamental importance to climate. In fact, from the time that the hydro-climatology of the Arctic deep basins was first properly established in the late-1990s (Arctic Climatology Project, 1997), the first accounts of large-scale departures from that climatology were descriptive of a changing balance between Atlantic and Pacific inputs to the Arctic Ocean (Morison et al 1998, 2000). So change may certainly be imposed on the Arctic Ocean from subarctic seas, and it is also now accepted that the signal of Arctic change may have its major climatic impact by reaching south through subarctic seas, either side of Greenland, to modulate the Atlantic thermohaline 'conveyor'. Finally, the new ideas and new observing techniques developed during the intensive observing period of the International Polar Year provide the justification for developing an observing plan with an outlook of the next 5 to 10 years --- the so-called 'Legacy Phase' of the IPY. In summary then, this report is intended to provide the Arctic research community—scientists, policy makers, funding agencies, and those interested in the Arctic—with a sustainable post-IPY physical oceanography observing plan to better understand the role of the Northern Seas in climate.

The first two iAOOS reports, written during the IPY itself, (Dickson 2007, 2008) were largely descriptive, detailing some of the main advances that were made in the difficult business of observing the Arctic and subarctic seas during the special focus period of the IPY, and describing some of the main results and new ideas that were emerging from these observations (see also Dickson 2009). A third report used these results and ideas to begin the task of establishing what was the rational mix of observations to sustain into the future (Dickson and Fahrback, 2010). The reason for attempting such a forward look is clear. If we are to develop the predictive skills and utility of climate models, we will need to observe, understand and 'build in' a list of processes that are not yet represented realistically (or at all) in climate models. In fact, the list is quite long (Dickson, Meincke and Rhines, 2008, p6). It is also clear that it will be the 'legacy phase' of the IPY, sustained over years to decades, rather than the two-year project itself that will develop our understanding of these processes, their changes, their feedbacks and their likely climatic impacts to the point where they can be of practical use to climate models.

At the Arctic Science Summit Week (ASSW) in Bergen in March 2009, the AOSB determined that the task of developing such a legacy phase plan should focus on the

role of northern seas in climate, and to achieve that focus, the plan was structured around the following questions: 1) *Following the IPY, what questions should we be testing to help us understand the role of the Northern Seas in Climate?* 2) *How should we design an ocean observing system to test these questions?* The report concluded by listing 18 questions that appeared to reflect the present ideas of the Community on the role of Arctic-subarctic seas in climate (see <http://aosb.arcticportal.org/> under iAOOS Annex A). Though the list makes no claim to be exhaustive, and may certainly expand or alter as our ideas develop, the 18 questions listed there all appear testable over a 5-10 year period, and whichever way they turn out, seem capable of advancing our ideas as to how the ocean-atmosphere- cryosphere system of the Arctic-subarctic might function.

It is the task of the present (fourth) report to piece together an ocean observing system that is capable of testing these questions. Though it would be impractical to investigate our question-list as 18 distinct research projects, in practice the essence of the list can be distilled down to 3 main issues:

- Issue 1. *Sorting out the (Atlantic Water) inflows. (PI Bert Rudels, U.Helsinki/FMI)*
- Issue 2. *Coping with change in the Arctic watercolumn (PI Craig Lee, UW-APL)*
- Issue 3. *Revitalising our ideas about Greenland, freshwater and the MOC (PI Tom Haine, JHU).*

The design of an appropriate observing plan for each ‘issue’ forms the basis for the remainder of this Report. Since the tasks differ widely in character, no attempt is made to standardise their solution.

Issue 1: Sorting out the (AW) inflows. *What is the relative importance of the two main Atlantic inflow branches—the Fram Strait Branch and the Barents Sea Branch---, in carrying ocean climate ‘signals’ from the Nordic Seas into, around and through the Arctic deep basins? (with PI Bert Rudels, U. Helsinki)*

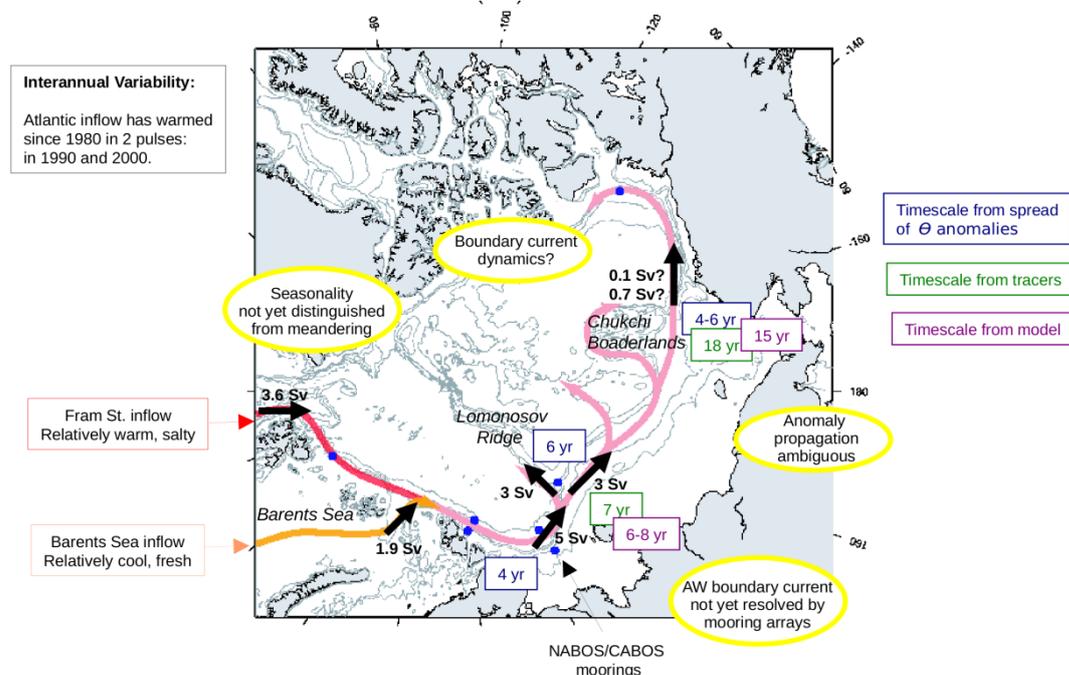


Fig 1.1 Summary of the paths, transports and transit times for Atlantic water circulation in the Arctic (adapted from a graphic kindly supplied by Bob Pickart, WHOI, pers comm.)

The basis for this as a focus question was the suggestion put forward by Bert Rudels (Univ. Helsinki) at the Arctic Science Summit Week, Bergen 2009, that the colder fresher Barents Sea inflow branch may be the one that dominates the Arctic Ocean beyond the Nansen Basin, with the Fram Strait branch seldom penetrating beyond the Lomonosov Ridge. Dmitrenko et al (2008b) would seem to agree. If so, the source of the recent warming along the boundary of the Laptev Sea and Canada basin (Polyakov et al 2005, 2007; Dmitrenko et al 2008a,b; Carmack pers comm.) will effectively have been reassigned.

Fig 1.1 describes the basic geography of inflow to the Arctic, while the various panels of Figure 1.2 provide a basis for Rudel's contention. The essence of Rudel's argument is that beyond the Gakkel Ridge the θ -S characteristics of the Atlantic-derived sublayer are closer to those of the Barents Sea Branch (BSB in Fig 1.2) than the Fram Strait Branch (FSB). Testing Rudel's idea will be an important task for the legacy phase to resolve, but the tools to do so seem well-proven: detailed ship-borne hydrography, sustained flux measurements through the northeast Barents Sea, and continued or intensified coverage of the boundary currents along the Eurasian margin of the Nansen basin from the point where both branches first flow together to their supposed points of separation at the Lomonosov Ridge.

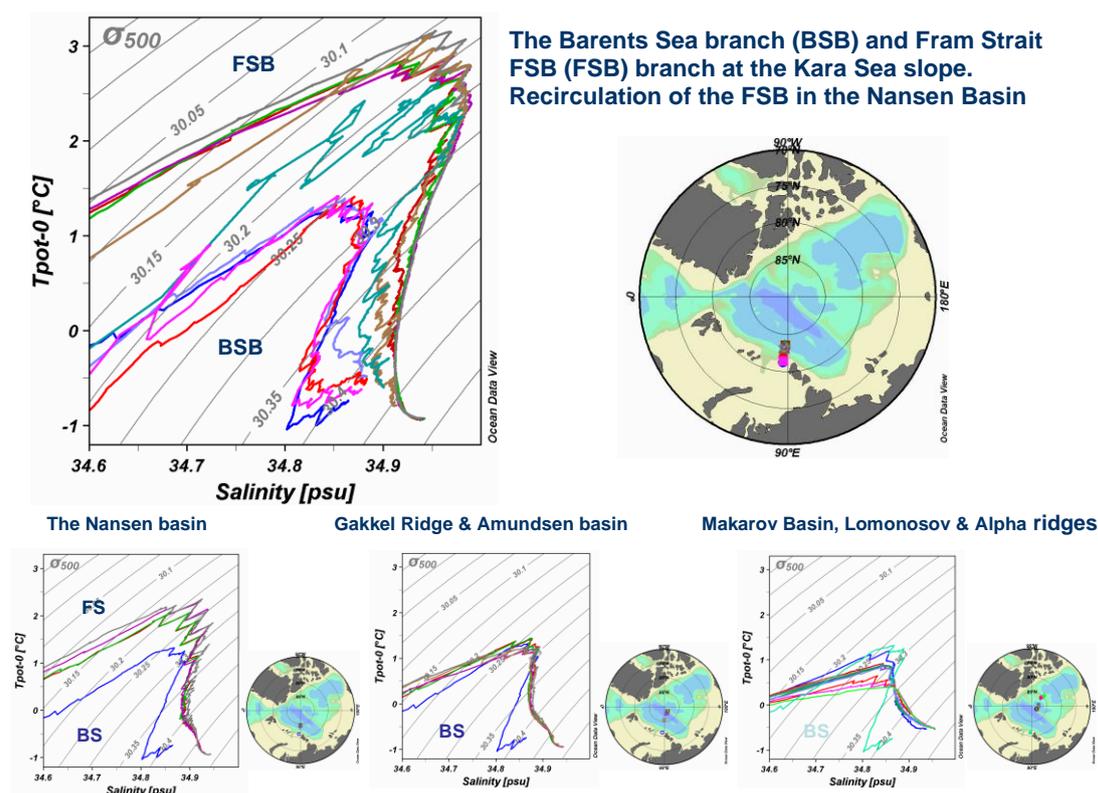


Figure 1.2: θ -S curves from the Fram Strait Branch (FSB) and the Barents Sea Branch (BSB) north of the eastern Kara Sea (upper panel). The lower panels show θ -S curves from the interior Nansen Basin, the Gakkel Ridge & Amundsen Basin, and the Lomonosov Ridge & Makarov Basin compared with the θ -S characteristics of BSB water from the Kara Sea slope. Data are from the SPACE cruise 2007.

1b. What are the elements of the problem? Both branches of Atlantic Water (AW) inflow to the Arctic originate from the Norwegian Atlantic Current, which splits at the Barents Sea opening. One part continues northward as the West

Spitsbergen Current, while the shoreward part, together with the Norwegian Coastal Current, enters the Barents Sea. As the AW of the Fram Strait branch enters the Arctic Ocean, its upper part interacts with sea ice north of Svalbard to generate ice-melt, resulting in a ~100m thick, low salinity upper layer that is homogenised by convection in winter. Capped by this upper layer, the AW flows eastward as a boundary current along the Eurasian continental slope. Ice melt in summer creates a shallow and even-less-saline surface layer that is subsequently removed by freezing and convection in winter. The fresh upper layer isolates the warm AW from the sea surface so that it retains a fairly high temperature and salinity as it passes east, at least as far as Severnaya Zemlya.

The Barents Sea branch, by contrast, experiences strong cooling along its path across the Barents Sea shelf and its temperature and salinity are reduced. Direct heat loss to the atmosphere causes the largest transformation, but here also ice melt on top of the inflowing warm water creates a low salinity upper layer, similar to but more saline than that formed in the Fram Strait branch north of Svalbard. Furthermore, cooling and ice formation over shallow areas induce brine rejection and result in the accumulation of dense shelf water at the bottom. This water eventually sinks into the Arctic Ocean, either as a denser part of the main Barents Sea inflow in St. Anna Trough, or as dense boundary plumes across the Barents Sea and Kara Sea shelf break. The Norwegian Coastal Current follows the southern coast of the Barents Sea and continues eastward, mainly south of Novaya Zemlya, to the Kara and Laptev seas. This low salinity coastal current receives and incorporates the runoff from the large Siberian rivers Ob, Yenisei and Lena, creating the low salinity shelf water that eventually crosses the shelf break to supply the Polar Mixed Layer and the halocline in the Arctic Ocean.

The Barents Sea branch is often associated with an intermediate-depth salinity minimum (in the Eurasian Basin) and lower intermediate-depth salinities (in the Canadian Basin). This is not fully correct. The Barents Sea branch occupies a large density range and supplies water to the Atlantic layer as well as to the intermediate waters and to the halocline. Fig 1.2 compares the theta-S characteristics of the two AW branches where they flow side by side along the continental slope west of Severnaya Zemlya. In the smaller panels the characteristics of the Barents Sea branch are compared with the watermasses observed in CTD profiles through the Nansen Basin, over the Gakkel Ridge, in the Amundsen Basin, and over the Lomonosov Ridge and in the Makarov Basin.

The two branches of inflow come into contact in and east of the St. Anna Trough and thereafter flow eastward side by side along the continental slope with the Barents Sea branch located closer to the shelf (Fig. 1.2). The two branches remain distinct as far east as Severnaya Zemlya and are separated by a narrow, sharp front, where isopycnal mixing takes place, probably influenced and perhaps also induced and driven by double-diffusive processes. Farther east, north of the Laptev Sea, no "undisturbed" Fram Strait AW is observed. In fact, the AW of the boundary current is dominated by intrusions and the maximum temperature and salinity have been considerably reduced, showing characteristics similar to the initial Barents Sea branch.

Several explanations are possible for the changes in the boundary current that are observed between the eastern Kara Sea and the Laptev Sea: a) a possible *strong vertical heat transfer from the Atlantic water to the mixed layer and to the sea ice and atmosphere north of Severnaya Zemlya*, leading to heat loss and a reduction in the Atlantic Water temperature; b) *Isopycnal mixing between the two inflow branches* resulting in a single, cooler and less saline Atlantic core in the boundary current east

of Severnaya Zemlya. The heat will remain in the AW, and the reduced temperature is compensated by the larger volume; c) *dense boundary plumes from the area around Severnaya Zemlya entrain warm Atlantic water and displace it towards deeper levels*. The AW temperature would be reduced but the heat is still stored in the water column; d) *the major part of the Fram Strait branch recirculates within the Nansen Basin north of the Laptev Sea and returns to Fram Strait*, so that only the cooler Barents Sea branch of AW enters the Amundsen Basin and the Canadian Basin. By this scenario, the warm Fram Strait branch is largely confined to the Nansen Basin and the return flow will also carry some Barents Sea branch water, cooling the AW (Fig. 1.2). Beyond the Nansen Basin the observed reduction of the AW temperature is small when compared with the Barents Sea branch AW (Fig. 1.2). Heat is transferred upward to the lower halocline and downward to the intermediate layer below, but little heat is lost to sea ice and the atmosphere.

The exchanges across the front between the two inflow branches may vary in time so that occasionally the Fram Strait branch water is forced into the Barents Sea branch stream and advected into the Amundsen Basin and the Canadian Basin. The warm AW observed in the Makarov Basin in the 1990s (Carmack et al., 1995) and now being traced through the Canada Basin may partly have been the result of such a disruption of the flow pattern. The source of temperature variability in the Arctic deep basins is an important issue since this will influence the heat loss to sea ice, the atmosphere and the Arctic as a whole. If the Barents Sea branch supplies the AW to most of the Arctic Ocean beyond the Nansen Basin, the temperature variability of the North Atlantic may prove to be less influential on the Arctic Ocean water column than the local forcing conditions in Barents Sea. How much advected oceanic heat is actually released in the Arctic?

1c. What observations are necessary? The observations needed to determine the relative importance of the two inflow branches for the ventilation of the Arctic Ocean and the oceanic impact on the heat balance of the Arctic have already started within long-term programmes such as VEINS, ASOF, DAMOCLES and NABOS, providing time series of salinities, temperatures and transports. Much new information has also been supplied by hydrographic observations in the interior of the Arctic Ocean from icebreaker expeditions and from ice-tethered platforms, especially during IPY. To fully study the circulation and variability of the two inflow branches, it will be necessary to continue these observations and to add some crucial observation-sites (*those printed in blue are underway or planned, in whole or in part; see Section 1d below*):

- i) *The 'upstream' observations at the Svinøy section should be continued to determine the variability of the characteristics and the transport of water advected from the south. They should be maintained at a high enough resolution to capture the structure of the current from the shelf across to the front between the AW and the Norwegian Sea interior.*
- ii) *The section across the Barents Sea opening should be regularly occupied and the existing current meter array maintained to estimate the inflow of AW, and should be extended to also monitor the inflow of Norwegian Coastal Current water to the Barents Sea.*
- iii) *The volume and temperature of the inflow of AW in the West Spitsbergen Current have to be observed and the close recirculation and the spatial and temporal variability in the strait have to be better estimated than today.*

- iv) Because of the difficulties in determining the recirculation and variability in Fram Strait, a better position for a monitoring array would be at the continental slope east of Svalbard. However, this has been tried and found difficult to maintain due to severe ice conditions. An array in this position nevertheless has a high priority in spite of the high risk of losing instruments.
- v) **An array in the passage between Novaya Zemlya and Franz Josef Land.** Such an array would catch the outflow of the Barents Sea branch as it enters the Arctic Ocean via the St. Anna Trough. Since part of the AW from the Fram Strait branch may penetrate the Trough, this may be the last point before the two branches mix.
- vi) North of the eastern Kara Sea the two branches are clearly separated and their cores distinct (Fig 1.2). **An array across the continental slope west or north of Severnaya Zemlya** would capture the characteristics, the transports and the variability of the two branches before the major transformations take place north of Severnaya Zemlya.
- vii) North of the Laptev Sea the NABOS programme has for several years maintained an array which has revealed large temperature variations and the passage of pulses of warmer and colder water along the Laptev Sea slope. With observations from the passage between Franz Josef Land and Novaya Zemlya and from north of Severnaya Zemlya it will be possible to estimate how much of the variability observed north of the Laptev Sea is due to the variations of the individual inflow branches and how much is from the mixing and/or from the dominating presence of one or the other of the inflow branches. This in turn would provide a better foundation for estimating how much heat is lost by the AW between the Kara Sea and the Laptev Sea, how much the temperature is lowered by mixing between the branches and how much is due to recirculation of the Fram Strait branch before the section north of the Laptev Sea.
- viii) To test the hypothesis of a recirculation of the Fram Strait branch in the Nansen Basin **hydrographic sections in the Eurasian Basin from the continental slope to the Lomonosov Ridge should be combined with ADCP surveys.** This could be done by ship-based hydrography but perhaps also from gliders. Gliders would, in addition to hydrographic data, also give information about the currents and thus indicate if a recirculation takes place and provide information about the overall current field between the northern Nansen Basin and the Lomonosov Ridge. Further information on the current field in combination with hydrographic properties should be obtained by Ice-Tethered Platforms equipped with CTDs and current meters.
- ix) The oceanographic observations have to be related to observations of the forcing fields, the atmospheric circulation and to the radiation balance as well as to the runoff. A parallel modelling activity is also necessary, including both process modelling and regional modelling.

In Summary, in order to obtain reliable Arctic Ocean heat and fresh water budget estimates, the flux measurements in the inflow passages have to be used in combination with Arctic-wide high-resolution surveys which capture the temperature and salinity distribution. By this means the oceanic heat transport estimates derived from the flux arrays can be used to distinguish between the heat transport contribution to temperature changes in the Arctic Ocean vs. the heat loss to the atmosphere and/or to melt ice.

Given that resources will be limited, these surveys do not need to have a high temporal resolution. The focus should be on getting a maximum of synoptic (i.e.

within a season) measurements over a wide region rather than getting the same number of measurements spread over a long time period. Therefore icebreaker surveys should be carried out in the same year and a fleet of ITPs should be deployed to further increase the spatial range and resolution. Gliders should also be used to extend the observations in ice-free areas. Such multi-ship surveys need only be undertaken every four or five years.

The resulting data sets will permit us to determine the differences in large-scale temperature and salinity distributions, and thus allow us to quantify the regional and Arctic-wide content of heat and fresh water. These numbers should be combined with the fluxes that have to be measured *between* these surveys. Combined with models, the data can be used to understand the processes driving such variability. This kind of combined effort requires a very high (and thus far unattained!) co-ordination of international research activity.

1d. What observations are already planned or proposed?

Most of the fieldwork proposed for the 5-10 year outlook period covered by this report is still undecided by the funding agencies so the content of this section is bound to be inexact. The attempt is made however simply because the fieldwork currently proposed and the PIs who proposed it are our main means of adding realism and hence feasibility to the task in hand. We are grateful to PIs for allowing their plans to be listed below.

(i) The NABOS arrays across the circum-Arctic Boundary Current (PI Igor Polyakov, IARC) have hitherto been our main source of information on the Atlantic inflow branches once they enter the Arctic Ocean. During the IPY years, the cruises of the RV *Viktor Buynitsky* in 2007 and of the *Kapitan Dranitsyn* in 2008 (see Dickson 2008, 2009) were the 6th and 7th in an annual series designed to service an increasingly international array of instruments set across the circum-Arctic boundary current. The program has had major successes, notably the recovery of 2yr-long datasets from at least two of the moorings (M4, M6; Fig 1.3, 1.4), which confirmed the presence of strong seasonal oscillations in the Atlantic Water, and the hydrographic cross-sections which confirmed the continuation of warming along this boundary.

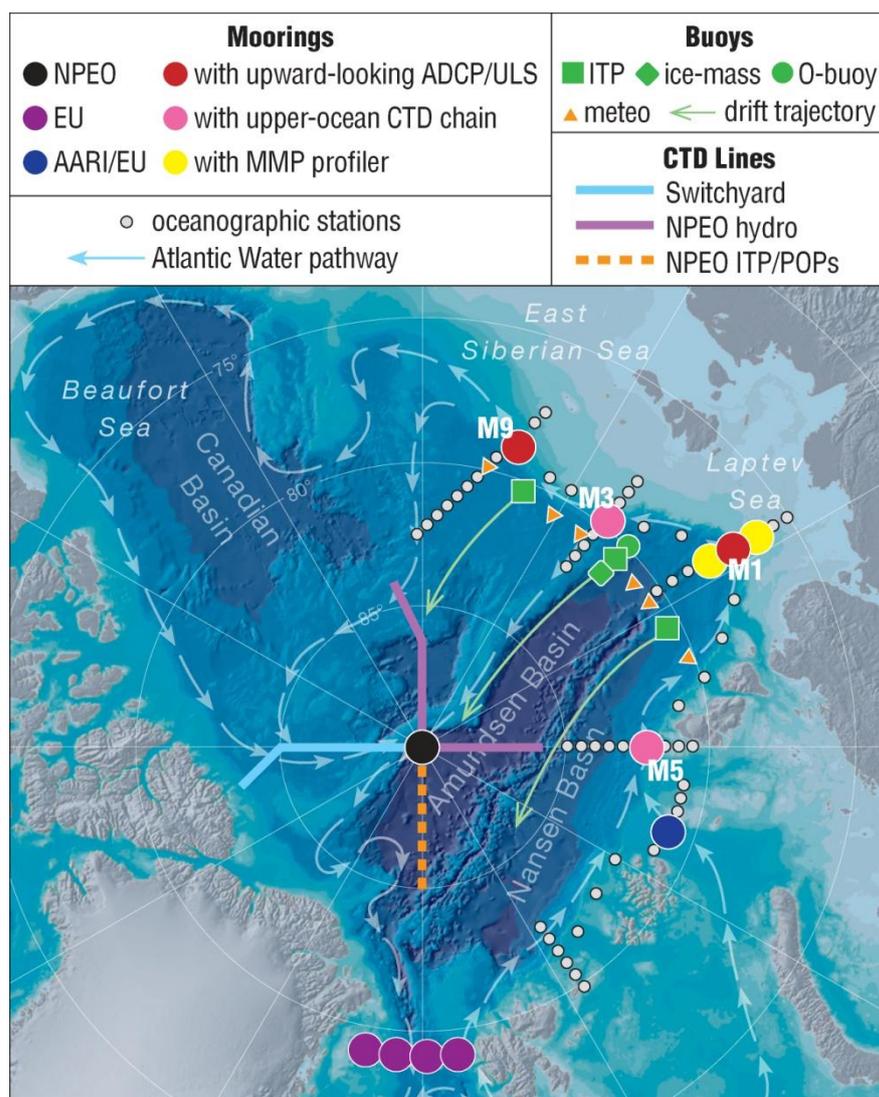


Figure 1.4. Locations of proposed moorings, cross-sections, and Lagrangian drifters. Igor Polyakov (IARC Fairbanks) is lead PI, with Jamie Morison (AW-APL) as co-PI for the planned collaboration on the 'NPEO/Switchyard' elements of the plan. The mooring in St. Anna trough is planned as a collaborative with AARI and follows a successful deployment with them in 2009, recovered by AWI in summer 2010. The signing of an MOU in summer 2010 formalized a relationship between UAF and AWI; AWI (Ursula Schauer) will recover the mooring next summer from *F/S Polarstern*. (Graphic courtesy of Igor Polyakov, IARC),

In the most recent development of this study, a Eurasian and Makarov Basins (EMB) observational network is currently proposed as an element of the Arctic Observing Network (AON). Three August-September cruises, one every two years, will make extensive measurements from Svalbard to the East Siberian Sea, thus tying together oceanographic, chemical, and ice observations using moorings, repeated oceanographic sections, and Lagrangian drifters to provide vital information about Arctic Ocean changes (Figs 1.4 & 1.5). The collaborative international and multidisciplinary nature of the proposal will be evident from the detail of its three main observational **targets**:

Target #1: *Along-slope AW transport by the boundary currents.* Continuing the records initiated in the early 2000s (Polyakov et al. 2010a), the along-slope transports will be evaluated using T and S observations complemented by a range of direct and indirect measurements of the flow. Geostrophic currents will be calculated using densities from repeated cross-slope sections. These estimates will be supported by direct observations from LADCP measurements and continuous moored current-meter

records. Sea-level gradients based on measurements at the NPEO and M1 and M9 moorings combined with satellite-based observations (Morison et al. 2007) will permit the evaluation of the barotropic components of flow. Comparison of these with density-driven currents will allow us to evaluate the relative contribution of barotropic and baroclinic forces governing along-slope transports.

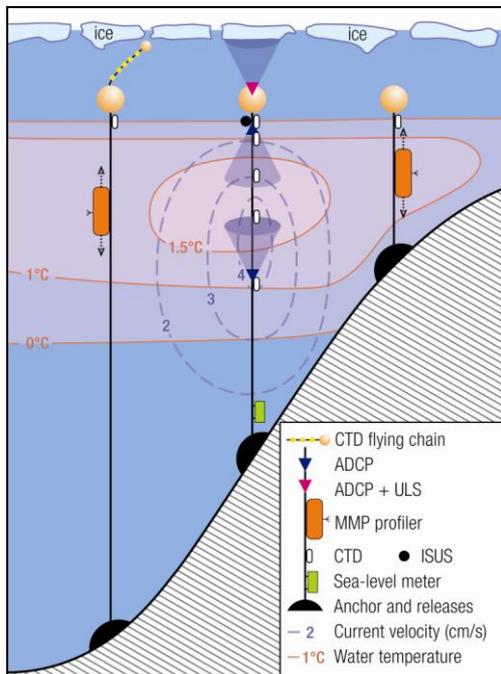


Figure 1.5: Mooring-based element of the proposed observational network. Conventional moorings (centre) will be maintained spanning from Severnaya Zemlya to East Siberian Sea (Fig. 1.4). These moorings are designed to capture changes in the AW, halocline, and upper ocean. McLane Moored Profiler (MMP)-based moorings will be deployed in proximity to the conventional mooring M1 (central Laptev Sea) and will form a section. Note that the vertical scale is distorted in order to emphasize observations proposed for the AW and overlying layers. (Graphic courtesy of Igor Polyakov, IARC),

Target #2: Interaction of AW branches with shelf waters and the deep basin interior. The role of shelf-basin interactions in modulating variability of the AW properties will be assessed by a combination of biannual CTD & water sampling with continuous ITP and mooring data. A water-mass census will be carried out (volumetric T-S plots), and the statistical significance of the estimates will be provided. Geochemical analysis will establish the balance between meteoric water (primarily river runoff) and sea-ice meltwater in shelf waters, will separate the Atlantic and Pacific water masses and will determine the individual contributions of the two AW branches. The rate of heat exchange between AW branches and the basin interior may be quantified using a combination of CTD data from cross-slope sections, MMP-based moorings, and ITPs. This synthesis of various types of data and methods of analysis will allow us to evaluate whether shelf-basin interactions enhanced by reduced arctic ice coverage could lead to AW cooling resulted in reduced lateral AW heat fluxes into the basin interior. Modelling and data assimilation will be powerful complementary tools [Polyakov et al. 2010c; Ivanov and Golovin 2007]. This target will thus provide regional estimates of the rate of AW and halocline lateral ventilation, will identify the source waters for this ventilation, and will estimate the lateral spreading rates of AW heat into the basin interior.

Target #3: Upward spread of AW heat will be estimated from repeat CTD measurements and microstructure snapshot measurements provided by UK colleagues (S. Bacon). These measurements may be used to evaluate both turbulent and double-diffusive fluxes. Lack of spatial and temporal coverage of microstructure observations will be partially compensated by data provided by continuous measurements using Lagrangian drifters (ITPs and IMBs) and upper-ocean mooring-based CTD observations. Data with high vertical resolution (ITP and mooring/survey CTD data) will be the key to evaluating the spatio-temporal patterns of double-diffusive heat fluxes, the major part of upward AW heat fluxes in the eastern Eurasian Basin (Lenn et al. 2009; Polyakov et al. 2010d). Atmospheric and IMB data complemented by mooring-based measurements in the upper ocean (including data from ADCP/ULS and CTD chains) will evaluate year-round heat fluxes in the upper ocean and atmosphere and distinguish between oceanic heat from below and radiative summer warming entering through openings in ice cover (Perovich et al. 2008; Toole et al., 2010). One- and three-dimensional modelling will complement these observation-based estimates, (eg Polyakov et al. 2010c) and envisage that data from meteorological buoys will be of growing importance to this study.

(ii) TransArc: AWI deployments in the Nansen-Amundsen basin from F/S Polarstern, 2011-12. Though mooring support by *Polarstern* in the Nansen-Amundsen Basin is mentioned in the NABOS plan (see Fig 1.3 above), these plans by AWI have now

moved beyond the proposal stage towards implementation in 2011-12 (the *Polarstern* TRansArc cruise).

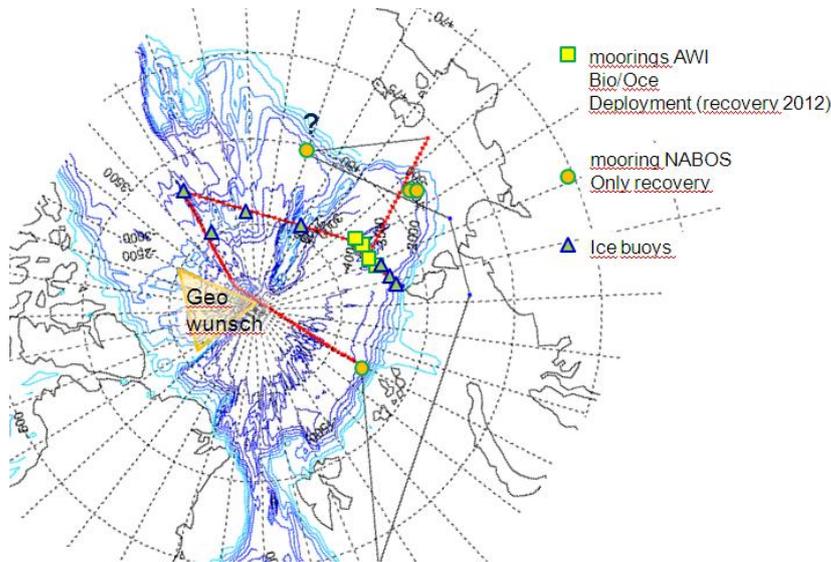


Fig 1.5. The present state of the *Polarstern* TRansArc deployment plan for summer 2011, (Ursula Schauer, AWI, pers comm., December 2010).

Fig 1.5 shows the intended release positions of 7 ITP profilers and the locations of the 3 (possibly 4) NABOS recoveries referred to above, but ---of great significance to the present discussion ----it also indicates the locations of 4 biophysical moorings in the vicinity of Gakkel Ridge (squares in Fig 1.5). The four full-depth moorings are more properly described as two mooring pairs, each pair featuring a conventional mooring carrying current meters, SEACATS, T & S sensors, and sediment traps, and the other carrying a profiling instrument similar to the McLane profiler, perhaps with a top profiling winch to cover the freshwater layer in the uppermost 100m of the watercolumn. As we will conclude below (see Section 1g and fig 4.1), these four moorings will occupy part of a transect of the Basin that is vital to the present task.

(iii) The Researcher Project: The Atlantic Water boundary current in the Arctic Ocean. This project aims to measure the Atlantic Water (AW) inflow in a detail never previously achieved by moorings, quantifying the volume, salt and heat transports and assessing the associated impacts on ocean circulation and Arctic ice cover by combining the observed mooring data with numerical modelling.

The rationale is as follows. Hitherto, the few moored measurements of the AW boundary current have been from small numbers of moorings sparsely located over a wide geographical area; no direct observations have actually resolved the AW boundary current, and the current's transport, structure, and dynamics are virtually unknown. Equally, although our limited observations to date suggest that climate anomalies circulate through the Arctic in this current, and (from models) that potential vorticity dynamics are crucial to this propagation (see Section 1e below), the necessary time series to establish the rate and mechanisms by which climate signals invade and impact the Arctic have never been collected. The mechanisms by which the warm water gets fluxed to the deep basin from the boundary current are probably dictated by mesoscale processes such as baroclinic instability, eddy formation, and wind-driven events; so in order to quantify the lateral flux of AW from the boundary current to the basin, it is necessary to measure the boundary current at high spatial and temporal resolution.

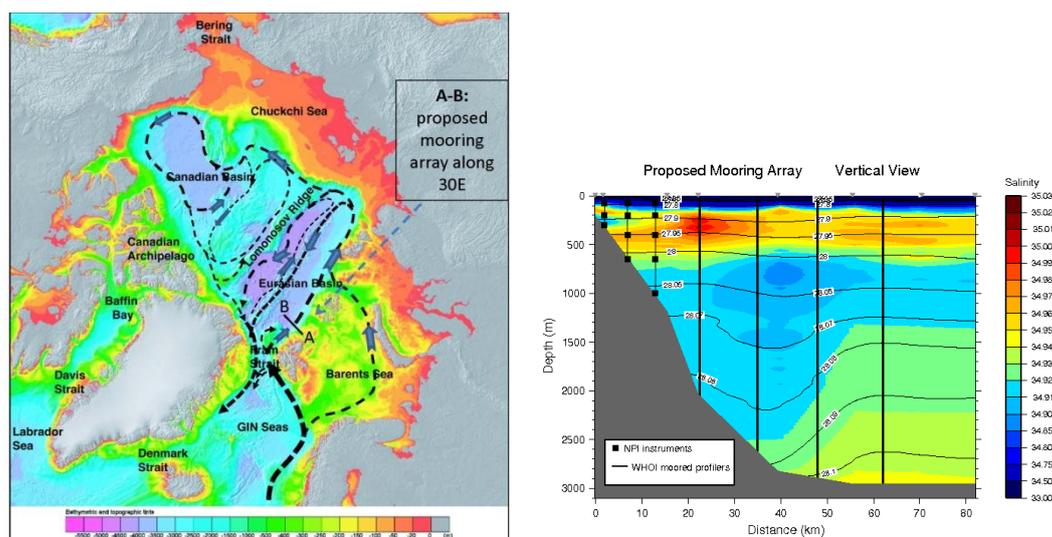


Figure 1.7. Schematic diagram showing the inferred circulation of Atlantic Water (AW) in the Arctic Ocean based mainly on water mass analyses from hydrographic data (left panel). The proposed mooring array near 30°E (labeled A-B in the figure) is designed to measure the AW downstream of the complex choke point at Fram Strait. The location of the mooring array operated by IMR in the Barents Sea is also shown. The right panel shows a vertical view of the proposed 7-mooring array. This configuration of instruments will provide multiple vertical sections of hydrographic properties and velocity per day, resulting in the first high-resolution description of the primary boundary current of the Arctic Ocean. The salinity (color) and potential density (contours, referenced to the surface, kgm^{-3}) are from a shipboard section through the current occupied in 2001 (Cokelet et al., 2008).

The primary collaboration will be between FRAM, the High North Research Centre for Climate and the Environment, Tromsø, and scientists from the Woods Hole Oceanographic Institution (WHOI) who will contribute moorings and technicians. Project management will be by IMR and principal PIs are Randi Ingvaldsen (IMR) & Bob Pickart (WHOI) together with Harald Loeng (IMR).

Altogether, 7 moorings will be deployed across the AW boundary current for a full year from summer 2012 to summer 2013, in a configuration that will resolve the relevant dynamical scales of the current. Deployment will be made from a Norwegian ice-strengthened vessel, with WHOI providing four of the moorings as well as technicians to carry out the deck work (see Fig 1.6). The location of the proposed array is downstream of Fram Strait in the first location along its path where the AW boundary current flows along well-behaved bathymetry and is free of recirculations, so providing an unambiguous interpretation of the data. The vertical coverage of the moorings is also shown in Fig 1.6, overlaid onto one of the very few (2?) high-resolution hydrographic sections of salinity and density ever worked near this location. The three IMR moorings are situated on the upper slope and consist of current meters and temperature/salinity sensors. The four WHOI moorings are McLane moored profilers providing continuous vertical traces of temperature, salinity, and velocity. The lateral spacing of moorings is on the order of the Rossby radius of deformation (10-15 km), so the relevant dynamical scales of the current will be resolved, and the array extends far enough offshore to capture any meandering of the high-salinity core of the current. With this configuration, the array will provide multiple high-resolution CTD/velocity cross-sections of the current each day. The synoptic hydrographic section shown in the figure provides an example of why such high-resolution coverage is needed, since the section revealed a deep perturbation in the current (i.e. the bending of the deep isopycnals just offshore of the high-salinity core of AW). Mooring data from the Barents Sea opening (provided by a separate

ongoing program) will provide a means of assessing the relative importance of the two branches of AW entering the Arctic Ocean.

The overall goal of the project is to obtain a quantitative description of the AW boundary current in the eastern Arctic Ocean over an annual cycle to elucidate the role of the current in regulating the Arctic system. Five specific targets are planned:

Target #1 . To quantify the mean and seasonally-varying transport, structure, and kinematics of the AW boundary current. The high vertical and cross-stream resolution of the mooring array will allow quantitative determination of the current's velocity and hydrographic structure and volume transport.

Target #2 . To determine the nature and cause of the mesoscale variability of the AW boundary current and investigate its impact on cross-stream fluxes of mass, heat, and salt. It is believed that the current will be unstable and form eddies (Schauer et al., 1997). Wind-driven exchange is also likely to occur. The proposed array will measure these processes and allow estimation of the resulting cross-stream fluxes.

Target #3 . To examine the flux of potential vorticity in the AW boundary current in the context of AOMIP model solutions to assess its impact on the sense of circulation in the Arctic Ocean. Different numerical models in the AOMIP consortium predict cyclonic versus anti-cyclonic AW circulation, which is tied to the potential vorticity structure of the flow (see below Section 1e). The proposed array will measure this structure and provide critical guidance to the models.

Target #4 . To use the high-resolution results from this array to design a sparser, long-term program for monitoring the AW boundary current. This approach was successfully used by WHOI to set up a long-term monitoring system for the Pacific Water boundary current as part of the Arctic Observing Network (AON) downstream of Bering Strait (Nikolopoulos et al., 2009).

Target #5. To investigate the relative importance of the two AW inflow branches to the Arctic Ocean. As the project will have measurements of AW flow available from both the Fram Strait and the Barents Sea branches, comparative analysis of the two branches will be made.

Collaboration with the long-standing Arctic Ocean Model Intercomparison Project (AOMIP) is seen to be of great importance in broadening our understanding of the role of warm AW in regulating the Arctic system. Andrey Proshutinsky (WHOI), as a lead PI of AOMIP, will organize coordinated numerical experiments specifically designed to investigate the dynamics and evolution of the AW boundary current employing different high-resolution AOMIP models. This includes models from LANL (Los-Alamos National Laboratory), NPS (Naval Postgraduate School), NOCS/ORCA25 (National Oceanography Centre Southampton) and others (see www.whoi.edu/projects/AOMIP).



(iv) *The Observatory Programme of Norway*, currently comprises two main elements, both of which are of potential or actual value in monitoring the flow of Atlantic Water passing north to the Arctic gateways. First, is the **COSMOS** proposal submitted to the Norwegian Research Council 13 October 2010 (Fig 1.7, left). The Norwegian Ocean Observatory Network (NOON) is the consortium behind this application for establishing cable-based ocean observatories infrastructure in Norway. The NOON was established in 2007 with seven Norwegian research institutions and industry as partners www.oceanobservatory.com. NOON is running the pre-project Cable-based Ocean Observatories (COO) with

Research Council and own funding 2009-2011. The vision for COSMOS is to establish the next generation infrastructure for a permanent interactive presence in

the ocean to enable sustainable monitoring and management of earth and life processes in the marine environment. The planned COSMOS shelf observatory west of Svalbard forms part of the Svalbard Integrated Arctic Earth Observing System (SIOS; see www.sios-svalbard.org), and is one of the sites selected as a European Multidisciplinary Seafloor Observatory (EMSO; see www.emso-eu.org). The second main element is the Norwegian Atlantic Current Observatory (NACO) in which SeaGliders will be used to continue the long-established programme of current meter moorings across the NwAC off Svinøy; this proposal has already been funded, and gliders are expected to be operational in 2011 (Peter Haugan, Geophysical Institute Bergen, pers comm., December 2010).

1e. What does theory contribute? *Potential vorticity as a control on the sense of the Atlantic Water circulation in the Arctic Ocean, with implications for an observing system; input from Jiayan Yang (WHOI, jyang@whoi.edu)*

The Arctic Ocean can be treated, on the 0th order, as a two-layer ocean, i.e., a highly stratified upper layer from surface to the base of the halocline layer and a less stratified layer beneath the halocline. Wind-driven circulation is confined primarily in the upper layer. The lower layer circulation is forced in part by water-mass exchanges through Barents Sea, Fram Strait and deep passages in the Canadian Archipelago, and thus could be considered as a source- and sink-driven circulation. The dynamics of such flows is best elucidated in terms of potential vorticity (PV). Observations (e.g., Woodgate et al., 2001) indicate that the circulation in the lower layer is highly barotropic and strongly steered by bathymetry. Therefore, the PV distribution and fluxes are strongly influenced by topography.

Yang and Price (2000; 2007) derived an integral constraint of PV budget for a general semi-enclosed basin bounded by a lateral boundary C:

$$\oint_C (\vec{U} \cdot \vec{n}) \frac{f}{H} ds = \oint_C (\vec{F} \cdot \vec{l}) ds \quad (1)$$

where \vec{n} is the unit vector perpendicular to the lateral boundary C, H is the thickness of the $\vec{U} = H\vec{u}$ is the transport velocity vector and \vec{F} is friction. The left hand side is the net PV transport through connecting passages (Barents Sea, Fram Strait and deep passages in Canadian Archipelagos) and must be balanced by PV production generated by boundary currents (the right hand side term).

$$f \left(\frac{Q_{Barents}}{H_{Bering}} + \frac{Q_{Fram}}{H_{Fram}} + \frac{Q_{archipelago}}{H_{archipelago}} \right) \approx \oint_C \vec{F} \cdot \vec{l} ds \quad (2)$$

The mass conservation requires that $Q_{Barents} + Q_{Fram} + Q_{archipelago} = 0$.

For a net positive PV flux, the boundary current must be cyclonic so that the frictional PV production is negative and vice versa. Yang (2005) argued that the net PV advection into the Arctic is positive because one of the inflow branches (Barents Sea) carries a high PV due to the thin layer of inflow. So the overall AW-Layer circulation must be cyclonic. This was supported by reanalyses of PV budgets diagnosed in 5 Arctic Ocean GCMs (Karcher et al., 2007).

Implications for an observing system: The PV study described above is purely theoretical and remains to be tested in observations. If this PV control mechanism is confirmed, it could help future observational programs by identifying the key variables and locations that may have greater impacts on the AW-Layer circulation in the Arctic Ocean. This theoretical idea is linked to our observing plan in the following ways:

(1) The two inflow branches, i.e., Fram Strait and Barents Sea, carry very different PV into the Arctic Ocean which could significantly affect the AW circulation in the Arctic Ocean. The high-PV branch through Barents Sea is likely to promote stronger cyclonic rim currents, possibly reinforced by cyclonic recirculations in sub-basins within the Arctic, and would more likely overcome the topographic PV barrier over the Lomonosov Ridge into the Makarov and Canada Basins. The low-PV branch through Fram Strait into the Arctic Basin would primarily affect the circulation in the Eurasian Basin. So a better understanding of the dynamical mechanisms that determine the partitioning of transport between these two branches should directly help us understand and predict the circulation changes in the Arctic AW Layer.

(2) The transport of PV outflow affects the overall PV integral over the Arctic Basin. **Monitoring the layer thickness (and thus PV) in key outlets is important.** In cases with thin layer outflows, the PV transport can be large even if the mass transport is small. The impact on the dynamics can be large.

(3) OGCM models have shown that wind stress forcing could contribute to the PV budget in the AW-Layer (Karcher et al., 2007; Zhang & Steele, 2007). But the downward flux of wind stress to the AW-Layer in models depends on the vertical mixing coefficients used. With the presence of a strongly stratified halocline layer, the mixing in the real ocean is probably too shallow to penetrate into the AW-Layer. **Observations that help us quantify the magnitude of vertical mixing are valuable.**

1f. What do models contribute? In summary, a recent submission by Aksenov et al (in review 2010) provides the most complete observationally-supported modelling results to date to clarify the structure of what they term the Arctic Circumpolar Boundary Current (ACBC). They demonstrate that the ACBC consists not of two but of three cores: the Fram Strait and Barents Sea Branches, plus a third, newly- identified feature, the Arctic Shelf Break Branch (ASBB) which transports halocline waters from the Barents and Kara Seas and has a velocity core located next to the shelf break.

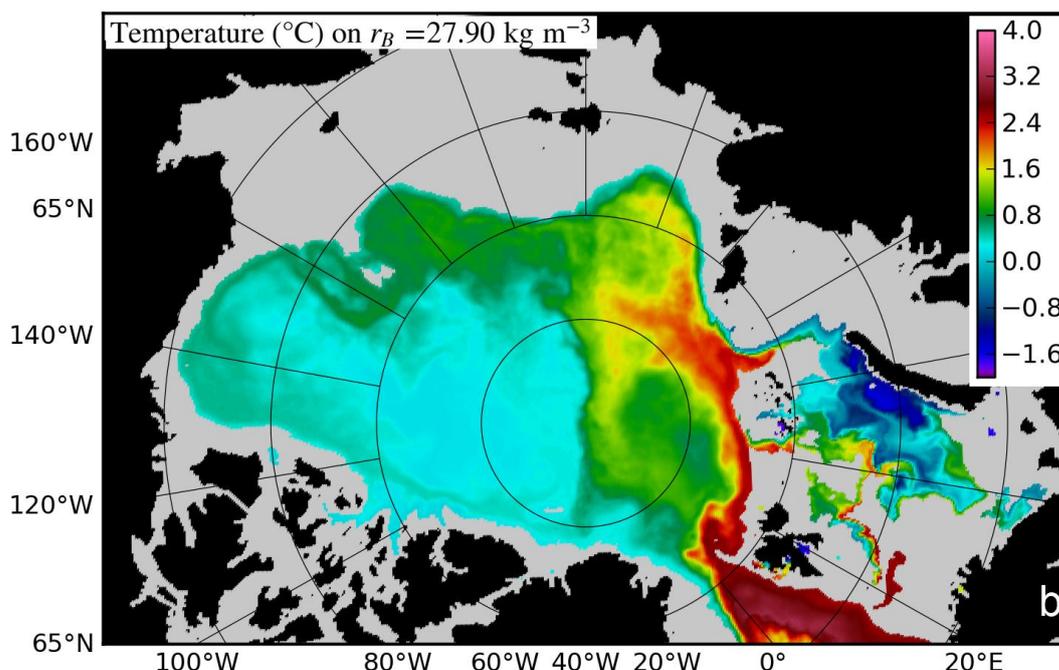


Fig 1.8. Temperature (°C) on the $r_B = 27.90 \text{ kg m}^{-3}$ surface of the Arctic Ocean in August, simulated by the high resolution Ocean Circulation and Climate Advanced Model (OCCAM) kindly provided by Yevgeny Aksenov, NOC. (see Aksenov et al 2010, 2011).

Aksenov et al show that the ACBC is continuous throughout the Arctic Ocean when all of its constituents are considered (ASBB, FSB and BSB). Individually, the FSB is a continuous current throughout the Arctic Ocean, entering and leaving through Fram Strait but continuous throughout its circuit around the Arctic. The ASBB takes a shorter path. It enters the Arctic via St Anna Trough, leaves via the Fram Strait and is continuous between these locations. The BSB is also continuous between St. Anna Trough and Fram Strait; while flowing around the rim of the Arctic Ocean it entrains waters cascading from the Arctic shelves and makes detours around seabed topography.

Aksenov et al also comment usefully on the characteristics and forcing of these flows. They suggest that the forcing mechanism for the ASBB is a combination of buoyancy loss and wind acting through non-local Ekman convergence, creating an upstream pressure head in the Barents Sea. The potential vorticity influx through the St. Anna Trough (see Section 1e above) dictates the cyclonic direction of flow of the ASBB, which is the most energetic large-scale circulation structure in the Arctic Ocean. It plays a substantial role in transporting Arctic halocline waters, and exhibits a robust seasonal cycle with a summer minimum and winter maximum. The Alaskan Shelf break Current is the analogue of the ASBB in the Canadian Arctic. It is forced by the local winds and pressure head in Bering Strait, caused by the drop in sea surface height between the Pacific and Arctic Oceans. The simulations show the continuity of the FSB all way around the Arctic shelves and the uninterrupted ASBB between the St. Anna Trough and the western Fram Strait. The BSB flows continuously along the Siberian shelf as far as the Chukchi Plateau, where it partly diverges from the continental slope into the ocean interior.

At first sight the results of the Aksenov et al simulations appear to show points of dissimilarity from the circulation schemes put forward by Rudels – the same circulation schemes that form the basis of ‘Issue One’ in the present Report. In fact the halocline formation-areas and circulations shown by Aksenov in his Fig 1 and are similar to those mapped by Rudels (2009; not shown here). The main point of dissimilarity lies in the fact that in Rudels’ account, it is the Barents Sea Branch water that reaches the western Arctic (dark blue in Fig 1.9) while in the simulations, it is the Fram Strait branch that forms a continuous circuit of the Arctic Slope.

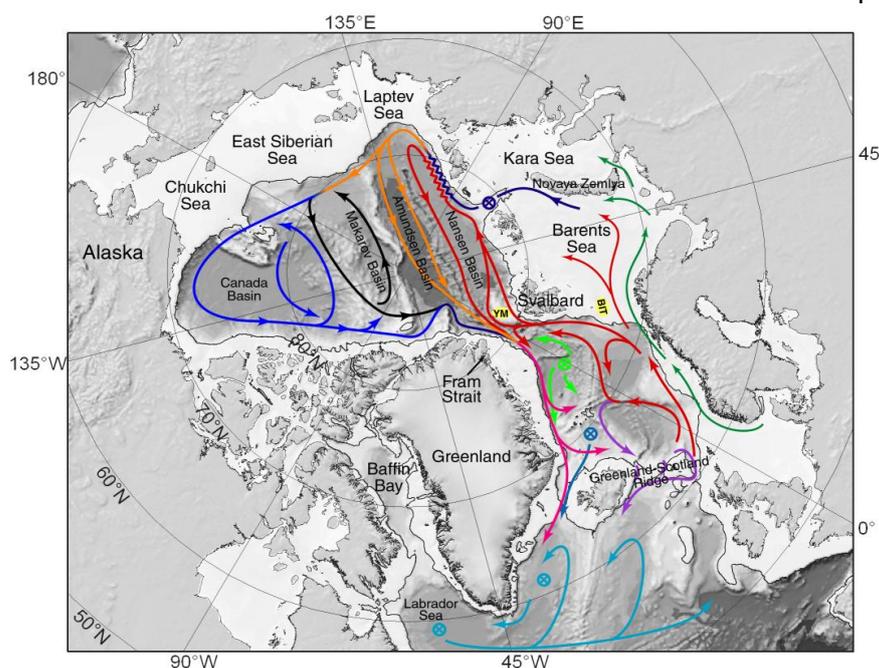


Fig 1.9 Schematic showing the circulation in the subsurface Atlantic and intermediate layers in the Arctic Mediterranean Sea. The interactions between the Barents Sea and Fram Strait inflow branches north of the Kara Sea as well as the recirculation and different inflow streams in Fram Strait and the overflows across the Greenland – Scotland Ridge are indicated. The isobath shown is 500m. (Adapted from Rudels et al., 1994).

In fact the density surface of 27.90 kg m^{-3} that Aksenov ascribes to the Fram Strait Branch of inflow is characterised by a relatively rapid cooling towards the eastern part of the Nansen basin (see Fig 1.8 above), which, realistically, can only be due to an admixture of cooler water from the Barents Sea, implied in both sets of schemes. In fact this point and its interpretation form the principal conclusion of Lenn et al, cited earlier (NABOS Target 3, p10 above), and are worth quoting in full: *‘The upper-ocean microstructure and hydrographic observations on the Arctic East Siberian continental slope region in summer 2007 reveal the cooling and freshening of the boundary current as it approached and crossed the L[omonosov] R[idge]. In this weakly turbulent environment ($\epsilon < 10^{-6} \text{ W m}^{-3}$), molecular diffusion controls vertical mixing. However, the doubly-diffusive convection heat fluxes ...failed to account for the significantly larger along-stream differences in upper-ocean heat-content observed. This implicates flow patterns of the boundary and recirculation currents, and lateral mixing with dense water convecting off the continental shelves and other fresher shelf waters in causing the observed evolution of the Arctic boundary current water properties’.* Put differently, both inflow branches contribute to what is observed on the 27.90 kg m^{-3} surface in Fig 1.8, and the question posed by Rudels and discussed here is still an appropriate subject for test in the Legacy Phase of the IPY.

Knowing the work proposed, it remains to establish what additional observational elements would be required to test Issue 1 to a conclusion. These are described under Section 4 below, where the outstanding requirements of all three issues form the ‘Summary and Conclusions’ of this report.

Issue 2: Coping with change in the Arctic watercolumn (with PI Craig Lee, UW-APL).

Unlike Issue 1, which essentially sets out to test a single key question (Annex A, Q1 in <http://aosb.arcticportal.org/>), the observing system that we set up to detect and explain change in the Arctic watercolumn and to assess its likely impacts needs to be given sufficient scope to explore and test a whole diversity of questions, often with little more in common than a general relevance to ‘the role of the Northern Seas in Climate’. At least 11 of the 18 questions listed in Annex A fall into this category. It will also be plain that over a period of 5-15 years, the system we put in place to detect change will itself be subject to dramatic changes:- a likely drastic reduction of sea ice cover (with some models predicting the almost total loss of sea-ice cover in summer by 2035; Wang and Overland 2009); improvements in the technical capability of ocean observing systems; a varying effectiveness of satellite remote sensing (losses as well as gains; Fig 2.2 below); changes in the state and ‘scale’ of the climatically important sublayers of the upper watercolumn that form our principal focus, and advances in understanding that lead to refocusing the observations.

Here it is not the intention to describe *all* present plans for observing the Arctic watercolumn, even if this were possible, though all such deployments will undoubtedly encounter change and have something to contribute to our understanding of it. Instead, following Dickson and Fahrback (2010) we order the task by drawing out the observational needs of four specific questions that seem to hold important and perhaps different keys to the ways in which the Arctic seas may impact climate:

- 2.1 What is the state, fate and drivers of the changing freshwater content of the Beaufort Gyre/Canada Basin?
- 2.2 What continued coverage of the upper watercolumn would be needed to keep track of ocean-atmosphere heat exchange as the sea-ice dwindles away?
- 2.3 What is the potential climatic impact of accessing the warm Pacific Summer Water layer in the Canada Basin through an increased depth and intensity of turbulent mixing as the sea-ice retracts?
- 2.4: Where can we expect the recent extreme warmth of the Atlantic-derived sublayer of the Arctic Ocean to have its main climatic impact?

Q 2.1: What is the state, fate and drivers of the changing freshwater content of the Beaufort Gyre/Canada Basin?

Until relatively recently, the Arctic Deep Basins were among the least-measured places in the world ocean (Arctic Climatology Project (1997)). That has now changed. The WHOI Beaufort Gyre Exploration Project [later Beaufort Gyre Observing System (BGOS)] led by Andrey Proshutinsky and employing a suite of new observing techniques has since 2003 gradually transformed the data desert of the Beaufort Gyre into what is now one of the best-covered regions of our northern seas. The elaboration of that effort into a BGOS/C3O/JOIS collaboration and the intensive survey of its borderlands by other collaborative ventures such as JWACS (Joint Western Arctic Climate Studies between JAMSTEC and Canada DFO/IOS since 2002), and CHINARE (the Chinese National Arctic Research Expedition with EC-DAMOCLES aboard *Xue Long* in 2008) have continued to intensify the scientific focus on the Beaufort Gyre, Canada Basin and Chukchi Sea so that our ideas of what drives change through this region and the significance of these changes for climate have developed rapidly. As a result, we would now regard the Beaufort Gyre-Canada Basin as ‘The Flywheel of the Arctic Climate’ (the subtitle of the WHOI BGOS project) and as one of the key sites in the World Ocean from the viewpoint of the Ocean’s role in climate (see ‘Beaufort Gyre Climate System Exploration Studies’: Special volume of JGR Oceans 115, C1, 2010).

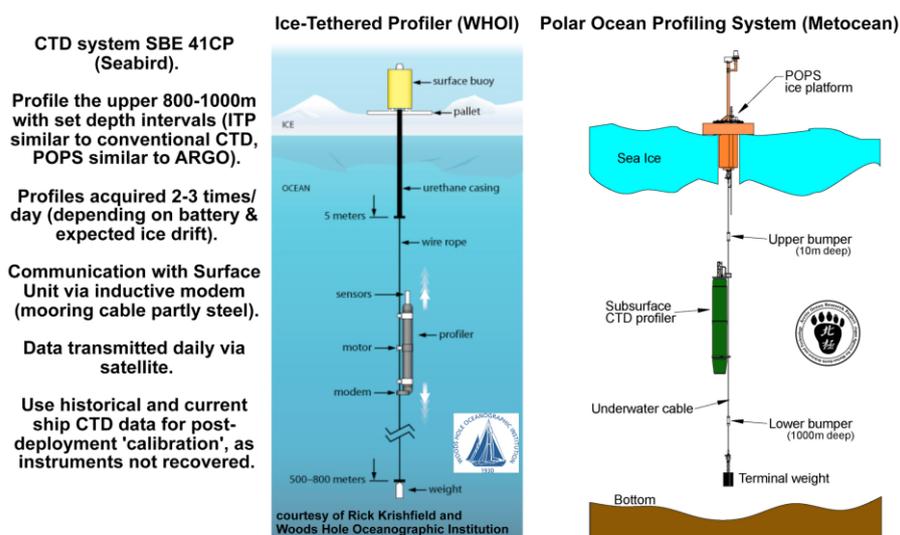


Figure 2.1. The two ice-tethered profiler systems that have revolutionised CTD data-density across the Arctic Ocean during the IPY ---the WHOI ITP system (left) in which a Seabird CTD crawler unit profiles along a taut wire 2-3 times per day, and the JAMSTEC POPS system (right) in which the same CTD unit is used essentially as an ice-tethered Argo float.

Informing our knowledge of the Beaufort Gyre but also setting a broadscale pan-Arctic context for the changes observed there, a principal success has been the rapid expansion of CTD coverage throughout the Arctic deep basins, provided largely by the autonomous use of ice-tethered profiler systems. The two main types, --- the WHOI ITP system (Krishfield et al 2008) and the JAMSTEC POPS (Inoue & Kikuchi, 2007; Kikuchi et al 2007) --- are illustrated in Fig 2.1. Altogether, the ITP array has now returned something in excess of 28,000 CTD profiles between ~7 and ~750 m depth from a growing range of international collaborations since the first unit was deployed in 2004 (information from John Toole WHOI October 2010), and with a ~90% good data return (Rick Krishfield, WHOI, 2009, pers comm.).

Present understanding: The presence of a salinity minimum at the centre of the Beaufort Gyre has been known about since the 1950s (Proshutinsky et al 2009b), but was not convincingly explained until 2003 when the BGOS program began applying its suite of observing techniques to the task. We now know that the Beaufort Gyre is the largest marine reservoir of freshwater on Earth (Carmack et al 2008), and that the major cause of its large freshwater content (FWC) is the process of Ekman pumping, generated by the climatologically anticyclonic atmospheric circulation centred there (Proshutinsky et al, 2002, 2009); we know in some detail how the thermal regimes of atmosphere and ocean modulate the liquid FWC according to the seasonal cycle of sea ice melt and growth; and through BGOS, we have become aware that the Beaufort Gyre freshwater content is a field in rapid transition, with strongly increasing trends in FWC between 2003-2008 (Proshutinsky et al, 2009). By this account, the spatially-integrated FWC of the Gyre increased by $>1000 \text{ km}^3$ post-1990 relative to climatology. This important finding naturally prompts questions about the wider context of this change; specifically whether the freshwater loading of the Arctic or the freshwater efflux from the Arctic might have altered in response. Direct observations are sparse, though a decade of mooring-based and ship-based observations in the western Fram Strait suggest that the export of LFW from the Arctic Ocean has remained approximately constant between 1998 and 2008 (de Steur et al., 2009).

The unprecedented summer-season sampling of the Arctic Ocean by ITPs, POPS and ship-based CTD during the intensive observing period of the IPY (~2006-8), and the recent use of seafloor-, sea surface- and satellite remote sensing techniques *in combination* have provided glimpses of a possible answer. The former has permitted quasi-synoptic estimates to be made of the liquid freshwater inventory right across the Arctic Ocean (Rabe et al, in press). Using objective analysis to estimate not only the large-scale spatial distribution of LFW and LFW content but also to quantify the error associated with these estimates, Rabe et al find that in 2006-8 compared to 1992–1999, the liquid freshwater content relative to a salinity of 35 in the layer from the surface to the 34 isohaline increased by $8400 \pm 2000 \text{ km}^3$ across the Arctic deep basins (water depth greater than 500m), roughly equivalent to the reported annual export of freshwater (liquid and solid) from the Arctic Ocean. Significantly, Rabe's analysis revealed that regional variations in LFW were due both to changes in the depth of the lower halocline, often forced by regional wind-induced Ekman pumping, and to a mean freshening of the water column above this depth, associated with an increased net sea ice melt and advection of increased amounts of river water from the Siberian shelves. In the later work (Morison et al submitted), we see for the first time the use of satellite altimetry (ICESat), satellite gravity (GRACE), ocean hydrography (ships and autonomous platforms) and ocean bottom pressure (moorings) to link and explain the recent observed changes in terms of both circulation and hydrography across a broad sector of the Arctic. The combined use of these techniques suggests that freshwater storage generated by the climatologically anticyclonic circulation of the Canada Basin (Proshutinsky et al, 2009), has been supplemented by Russian runoff carried in an S-shaped path into the Canada Basin by the opposite counterclockwise

circulation over the Eurasian Arctic). According to this account then, the total freshwater content of the Arctic Ocean did not change.

Future observing: With the largest marine reservoir of freshwater on Earth in a state of rapid transition, the continuation of the Beaufort Gyre Observing System to the point where we understand these changes and their drivers is clearly a priority for any sustained prospective observing system. In fact, NSF OPP has recently agreed to continue the BGOS and ITP programs for another 5 years (2009-14). Under the aegis of the Arctic Observing Network (AON), the BGOS project will measure time series of temperature, salinity, currents, geochemical tracers, sea ice draft, and sea level using bottom-tethered moorings and shipboard measurements. Three moorings will acquire precise data on the variations of the vertical distribution of seawater properties, bottom pressures and sea ice draft at 3 sites: 75N,150W; 78N,150W; and 77N, 140W (mooring sites A, B and C of the initial program). Ship-based sampling covering the entire Beaufort Gyre will be performed in collaboration with scientists from Canada and Japan with shared logistics expenses, to augment the year-round mooring measurements. Temperature, salinity, oxygen, nutrients, barium and delta-18O will be measured and analyzed at 30 standard locations along 140W, 150W, ~75N and ~78N sections using shipboard CTD/rosette to extend the long-term time series started in 2003. Samples that provide information on longer time-scales, such as CFCs and carbon tetrachloride, alkalinity, total CO₂, dissolved inorganic carbon and tritium/³He, will be collected less frequently. Between CTD/rosette casts, expendable CTDs that profile to 1100 m depth will be used to increase spatial resolution of the temperature and salinity fields.

Beyond the Beaufort, we are coming to realise that the Makarov Basin should be a second site for concentrated observations, particularly its undersampled southern part. A decade of evidence (eg Morison et al 2000, 2011) now suggests that this Basin is the pivotal location (literally!) for movements of the Atlantic-Pacific Front and of Transpolar Drift boundaries on interannual and decadal time-scales. To extend hydrographic coverage beyond the Beaufort, a total of four new systems or techniques are available or are in contemplation within the time-span covered by this Report (5-10 years).

First, to achieve the prospect of having ITPs sweep through a large fraction of the Arctic over the next few years, the surface buoy of has been redesigned to better survive thin ice, melt-out, open-ocean drift and freeze-in, and from 2009-10 the WHOI system has operated with just a conical float [note that measurements of velocity structure in the water column under Arctic ice from an Ice-Tethered Profiler (the 'ITP-V') are described under section 2.3 below, where the technique has its greatest scientific relevance].

Second, it would seem self evident that the combined use of satellite altimetry (ICESat), satellite gravity (GRACE), ocean hydrography (ships and autonomous platforms) and ocean bottom pressure (moorings) to link and explain Arctic Ocean changes in terms both of ocean circulation and hydrography (Morison et al submitted) must be continued across as broad a sector of the Arctic Deep Basins as practicable. Satellite altimeters observe the total sea level variation, including the signal caused by temperature and salinity fluctuations (the steric effect) and non-steric barotropic and mass variations. Separately, gravity satellites like GRACE measure temporal changes in the Earth's gravity field caused by the movement of water masses. A well-designed in-situ hydrographic sampling network – with judiciously deployed ocean instrument technologies – would ensure the most

accurate quantification of the sea level, circulation and mass changes of the Arctic Ocean.

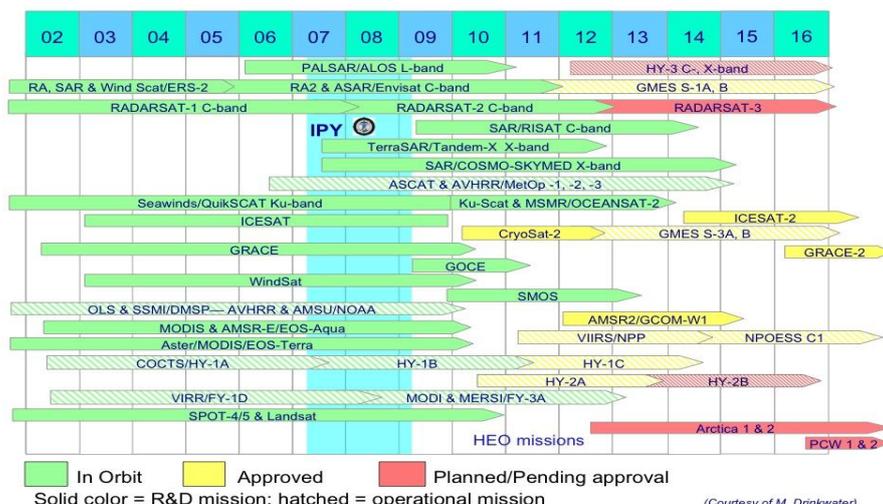


Fig 2.2 Planned cryosphere satellite missions (courtesy of Mark Drinkwater, ESA)

Together with an optimally designed bottom pressure array* for resolving shorter time scale processes, the steric (halosteric and thermosteric) and non-steric effects can be separated for quantifying changes in circulation and variability in Arctic sea level. Furthermore, sea surface heights from altimetry when differenced with the mean Arctic satellite geopotential constrain the geostrophic circulation [*Observing System Simulation Experiments (OSSE) will be necessary to optimise cost & benefit of an expanded and sustained in-situ bottom pressure array, providing guidance on mooring locations and defining the measurement accuracy and frequency needed]. Though the time-line of satellite availability suggests otherwise (Fig 2.2), in fact GRACE experts predict that the system will last until at least 2015 and maybe longer, barring unforeseen component failure, and CryoSat 2 should provide the necessary altimetry. A proposal for the combined use of GRACE and CryoSat2 has therefore been submitted to NSF (information from Jamie Morison 19 January 2011).

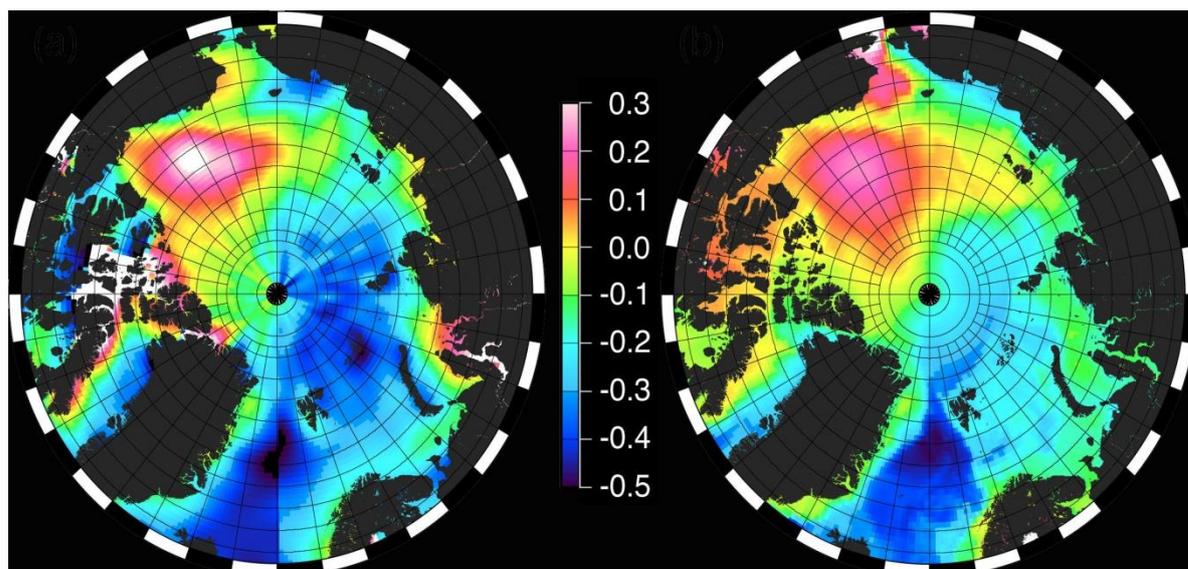


Fig 2.3 Comparison of Arctic Ocean mean topography from satellites and model. Both are exciting new results: *left* is the Observed Arctic Dynamic Ocean Topography (DOT) in 2010 from the CryoSat and Envisat radar altimeters; the main features of the Arctic circulation, including the Beaufort gyre, transpolar drift and the east Greenland current are clearly visible. The DOT is

calculated by subtracting the EGM-08 geoid from a combined CryoSat and Envisat mean sea surface. The CryoSat data are preliminary and show some artefacts at small scale above 81.5°N (the latitudinal limit of Envisat). *right* is the mean sea surface height (SSH) from the NEMO-CICE ice-ocean GCM for March 1979, with global mean resolution of 1/10° but with local Arctic resolution of ca. 1/30° or ~3km (so genuinely Arctic-eddy-resolving) and with an embedded interactive sea ice model. 1979 is used here because when this figure was assembled, the NEMO run had only just begun, and 1979 was the first available complete year clear of spin-up. (images kindly supplied by Seymour Laxon UCL-CPOM and Sheldon Bacon NOC).

Third, as CryoSat enters the field to extend the remotely sensed radar altimeter coverage almost to the pole, our first pan-Arctic comparisons with models reveals a growing capability in OGCMs of the Arctic. Fig 2.3 for example, compares Arctic Dynamic Ocean Topography (DOT) in 2010 from the CryoSat and Envisat radar altimeters with mean sea surface height (SSH) from the NEMO-CICE ice-ocean GCM for March 1979. Allowing for the different durations and time periods, the similarities are remarkable: eg, the SSH and DOT differences between the Beaufort Gyre and Nansen / Amundsen Basins is ~0.5m in both.

Fourth, autonomous platforms (in the Arctic context, floats and gliders) can contribute scalable, cost-effective, flexible elements to the Arctic Observing Network, enabling persistent, sustained sampling and broad spatial coverage of the deep basins, frontal regions and boundaries. These technologies have seen extensive use in lower-latitude environments, where they have dramatically altered the community's approach to ocean observing by providing the ability to collect broadly distributed measurements over extended time scales, as well as a variety of early successes in the Arctic itself. Recent IPY successes with autonomous technologies place the community on the threshold, ready to contemplate wider adoption.

Autonomous gliders provide the ability to resolve deformation-scale (~10 km) lateral variability (e.g. sharp fronts, eddies, filaments) and to characterize salinity structure near the ice-ocean interface. Sustained support from NSF-OPP and ONR led to the successful development and implementation of long-endurance autonomous Seagliders capable of extended (many months) operation in ice-covered waters (Fig. 2.4). In this regional scale (hundreds of kilometres) system Seagliders navigate by trilaterating from a 7-element array of mid-frequency (780 Hz) acoustic sources. Because under-ice gliders operate without human intervention for extended (weeks to months) periods, they incorporate enhanced autonomy, including algorithms for navigation, emergency response (if lost or experiencing system failure) and identifying and exploiting leads in the ice to telemeter data back to shore. For example, during a mission in 2009 that included 51 days under the ice, a glider made repeated sections across ice-covered Davis Strait while finding and exploiting 8 leads (in 33 attempts) for communication through the ice. Although open-ocean endurance has reached 11 months (in weak stratification and slow background flow), the stronger stratification and currents in the Arctic limit missions to 6-8 months. Current designs allow dives to 1000 m, but recent Deepglider development (Eriksen, personal communication) promises to extend profile range to 6000 m, albeit with corresponding degradation in lateral and temporal resolution. In addition to providing full water column profiling, the deeper, less frequent dives should greatly extend endurance. Ongoing efforts also focus on extending endurance of the 1000-m Seaglider beyond the 12-month mark.

Broad, easy access to satellite-based geolocation (GPS) and communications (Iridium) allowed autonomous approaches to scale efficiently in the ice-free oceans. Within the Arctic, ice often blocks access to the sea surface, forcing autonomous operations within AON to rely on acoustic navigation and communications. A basin-scale acoustic navigation system, the equivalent of pan-Arctic underwater GPS, is needed for Arctic observing to fully exploit the capabilities of floats and gliders.

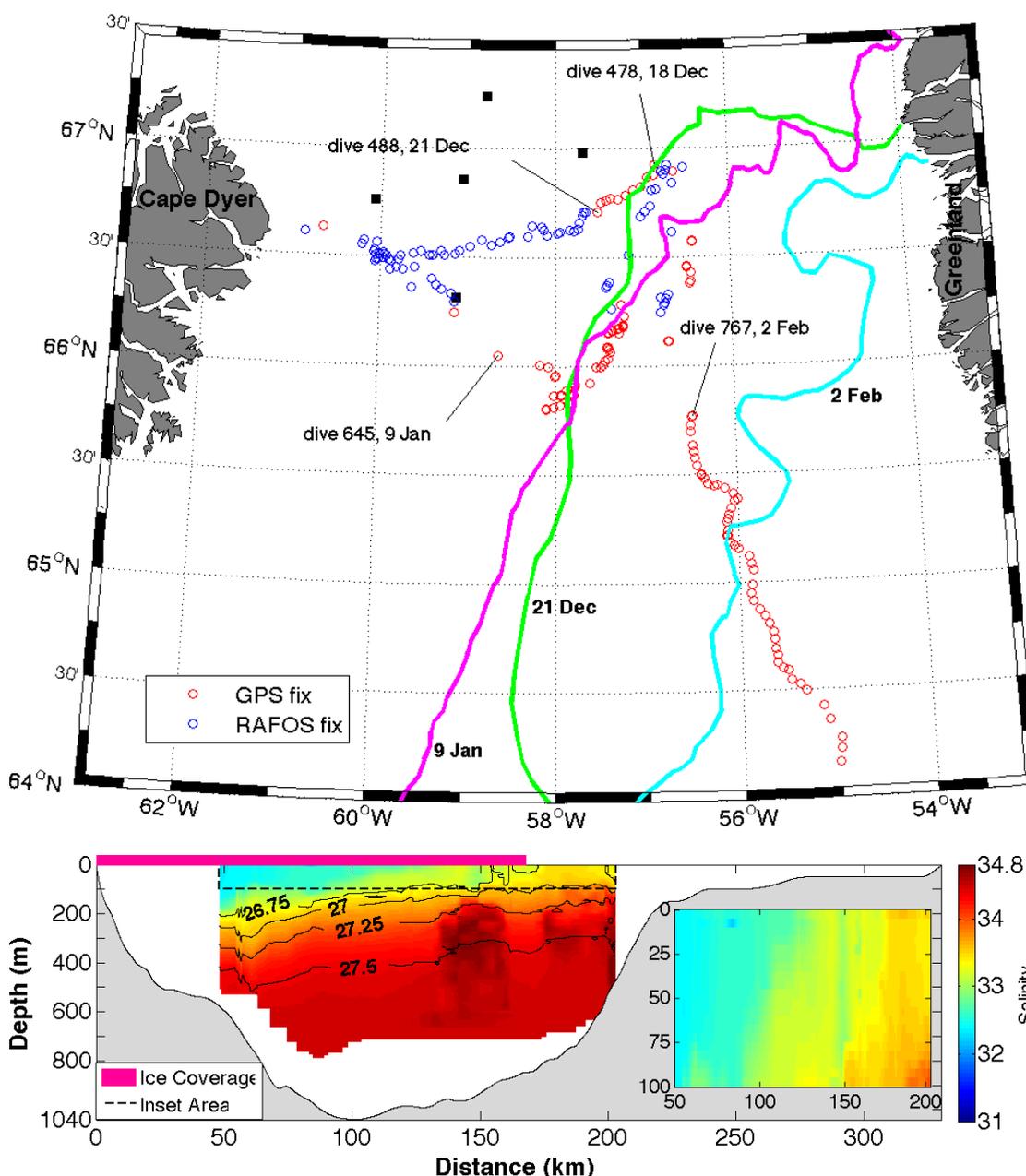


Fig 2.4 Example of a glider excursion under the ice. Colored lines mark the ice edge on various dates in late 2008 and early 2009. Red circles mark GPS positions, blue circles mark real-time positions derived from the acoustic navigation array, with red symbols in regions of ice cover indicating times when the glider surfaced through leads. The section depicts salinity across the ice-covered Strait. The pink bar marks ice extent and the enlargement depicts the upper 100 m. The mixed layer has deepened and become more saline (due to brine rejection during ice formation) relative to that observed 2 months earlier in ice-free conditions (Lee, 2009)

Surface ducting and the resulting reflection off the ice bottom limits mid-frequency acoustics (such as that successfully implemented in Davis Strait) to $O(100\text{ km})$ ranges in ice-covered waters, restricting such systems to regional applications. Previous experiments (e.g. Mikhalevsky et al., 1999; Gavrilov and Mikhalevsky, 2006) demonstrate trans-basin ranging at frequencies of $O(10\text{ Hz})$, indicating that an acoustic navigation system operating at 40-100 Hz could provide pan-Arctic navigation from an array of ~ 10 sources (Fig. 2.5, Gavrilov and Mikhalevsky, 2006). Implementation of such a system faces many challenges (see Lee and Gobat, 2006; Anchor WG 2008; Lee et al 2010), including design of an efficient source, mitigation of marine mammal impacts, siting in the EEZs of the nations bordering the Arctic and costly maintenance that will require international collaboration.

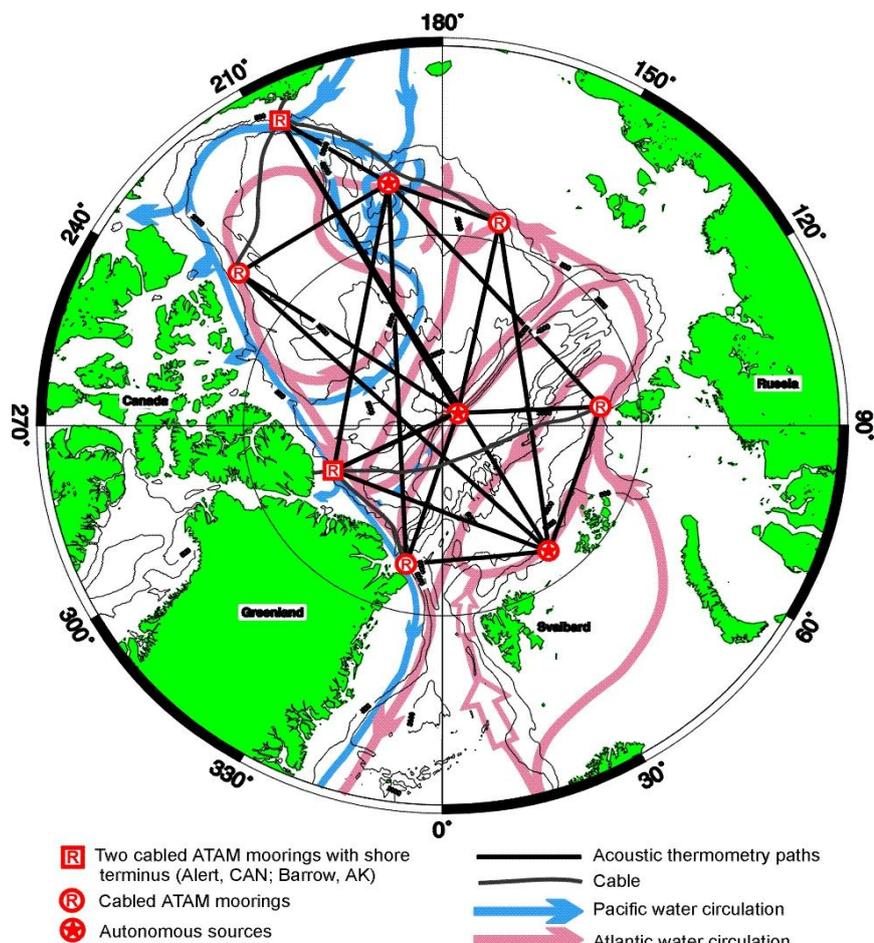


Fig 2.5 Notional low-frequency (10–100 Hz) acoustic navigation and thermometry array. Black dashed lines indicate paths for acoustic thermometry. Array geometry and assumed transmission ranges were informed by low-frequency results stemming from the ACOUS program. A network such as this could supply acoustic navigation for the entire Arctic basin. (Gavrilov and Mikhalevsky, 2006)

That said, by opening the Arctic to highly scalable autonomous observing technologies, such as the ability to conduct low-cost, decadal scale distributed measurements with acoustically-navigated ARGO floats and sustained, repeat occupations of critical sections across fronts and boundary currents with gliders, Pan-Arctic acoustic navigation would provide enormous scientific returns (see SEARCH, 2008; AON 2010 for ‘next steps’).

Q 2.2: How might we observe the effects of an ice-free polar ocean on the regional atmospheric circulation? *(input from Jim Overland, NOAA-PMEL and Michael Tjernström, Stockholm University)*

Present understanding: We now know that the Arctic climate is sensitive to multiple amplification mechanisms and is thus especially responsive to external forcing (Miller et al 2010; Overland, Wood and Wang, 2011). As the ice in the Pacific sector of the Arctic melted back to its record minimum in summer 2007, and the heat storage of the underlying ocean increased, the release of this heat in autumn was indeed found to erode the stratification of the atmosphere to progressively higher levels, leading to a clear change in the regional atmospheric circulation. As Fig 2.6 reveals, the retraction of sea-ice cover from the western Arctic in summer 2002-8 was

accompanied by a warming throughout the Arctic troposphere and to an increase in geopotential height anomaly in fall leading to a weakening of the poleward geopotential gradient. It is this weakening of the thermal wind that reduces the jet stream winds, according to Overland and Wang, 2010. The point is the *delay* implied in this process. Rather than just an *ice albedo* feedback, that would be most active in summer in response to insolation, Overland and Wang and Overland et al 2011 suggest that this mechanism is evidence of a late summer early autumn *ice insolation* positive feedback due to additional heat storage in newly sea-ice-free areas.

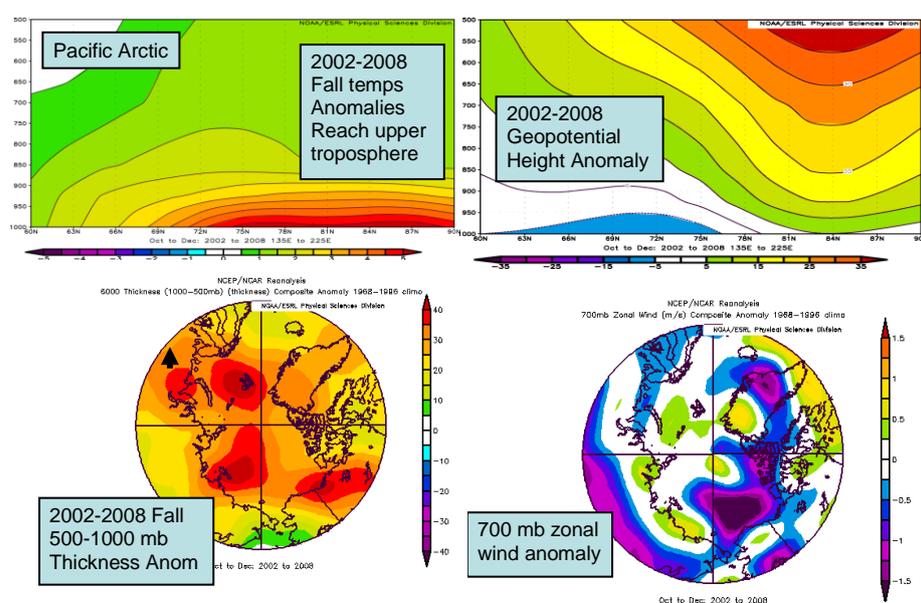


Fig 2.6 Composite changes in the polar troposphere in October-December 2002-8 as the ice retracted from the western Arctic. Top left: vertical section of air temperature anomalies ($^{\circ}\text{C}$) from the Bering Strait to the Pole. Top right: corresponding plot of geopotential height anomalies (dynamic metres). Lower left: the 500-1000 hPa thickness field anomaly showing, in particular, the band of greater thickness from the E. Siberian Sea to N Alaska, the main region of diminished sea-ice cover. Gradients in this field are the baroclinic contribution to the flow field. Lower right: the zonal wind anomaly field (ms^{-1}) at 700 hPa showing the reduction in zonal wind component north of Alaska and western Canada. All from Overland and Wang, 2010.

At the same time we must also enquire about the **role of the atmosphere** in setting up the conditions necessary for such drastic reductions in sea-ice as we have seen in for example 2007-08. It is insufficient to treat either the heating of the ocean by the atmosphere or the autumn release of heat to the atmosphere as forcing elements in isolation; the upper ocean/sea ice/atmosphere must be considered as a continuum. Unfortunately, present atmospheric measurements over the Arctic Ocean are insufficient to pin down the energy fluxes either in the atmosphere or between the atmosphere and the ocean or to determine how these fluxes might vary due to vertical stratification, changes in water vapor and clouds, or aerosol concentrations. For this reason we rely heavily on so-called reanalysis data. Reanalysis is a method of optimally constraining model calculations with observations inherited from the numerical weather forecasting community. Figure 2.7 from Graversen et al., 2010, shows one example taken in the summer of 2007, showing the energy-flux anomalies during the summer season of 2007 over the area in the western Arctic that experienced the largest reduction in sea ice. While the convergence of the meridional atmospheric heat flux (thin solid black) fluctuates around zero until about May, it becomes consistently positive through the summer. At the same time the anomaly in the surface net longwave radiation becomes positive; this is a consequence of an anomaly in clouds probably as a consequence of the anomalous

water vapor transport (which is part of the energy flux), and it is not until the anomaly in ice concentration (difference between thick solid and dashed black lines) begins to increase that the anomaly in the surface net shortwave radiation (the ice-albedo feedback) becomes positive.

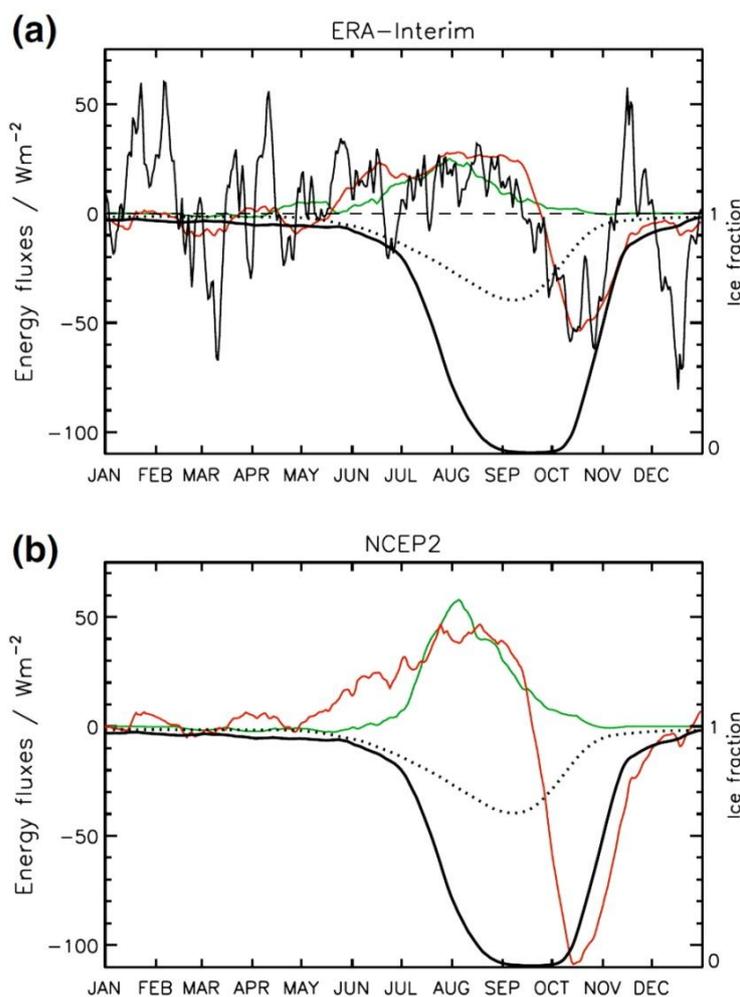


Figure 2.7: Ice coverage, convergence of atmospheric energy transport, and energy fluxes at the surface during 2007 over the region 74°–82° N and 135° W–165° E. Solid and dotted thick black curves indicate ice cover in 2007 and its average over the preceding 18 years, respectively. Green curve shows net shortwave-radiation anomalies at the surface, while the sum of the net longwave radiation, latent, and sensible turbulent flux anomalies is given by the red curve. The thin, solid curve indicates atmospheric energy transport convergence. Anomalies are relative to the climatology with monthly resolution from the years 1989–2003. Daily data are smoothed with a 30 day running-mean filter. Upper panel (a) is based on ERA-Interim data, whereas in the lower panel (b), the surface fluxes are from NCEP2, while the ice fractions are from the ERA-Interim. From Graversen et al. (2010), with kind permission of Springer Science+Business Media

The problem with results such as these is that while reanalysis works well in areas with a dense network of observations, the Arctic Ocean is severely lacking in all atmospheric observations except those from polar-orbiting satellites. These are particularly poor for the lower troposphere, thus in essence we have very little to no information on the lower troposphere vertical structure, clouds and their properties (which in the Arctic to a large extent are lower troposphere features) or surface energy fluxes. Thus there are insufficient observations to support reanalysis in the first place and those that are cannot be used to evaluate different reanalyses since they were all used, albeit differently, in the associated data assimilation. Long-term observations of the surface energy balance components over the Arctic Ocean are essentially non-existent and comparisons of current climate models (e.g. Sorteberg et al., 2007) with the few existing data sets (e.g. SHEBA) reveal significant problems, especially with the surface latent heat flux.

Figure 2.8 (from Jackson et al 2010) is our startpoint in describing the **role of the polar ocean** in these processes. It will be a key figure in the remaining three sections of 'Issue 2' below since it neatly illustrates the several ways in which this part of the western Arctic may affect climate. In its left-hand panel, Fig 2.8 shows the presence in summer of three distinct subsurface temperature maxima in the Canada Basin:

deepest, at a depth of ~ 400 m, sits the warm Atlantic-derived sub-layer whose remote origins and likely remote/delayed impact on climate will be described in Section 2.4. Above it at ~ 60m and 25m (respectively) lie a layer of warm Pacific Summer Water (PSW; to be discussed in Section 2.3 below) deriving from inflow through Bering Strait, and a Near Surface Temperature Maximum (NSTM) arising locally (or at least regionally) as the end-point of the ice-albedo feedback mechanism (Jackson et al, op cit). It is the NSTM that concerns us here.

Though we have known for more than a decade of the existence of a narrow temperature maximum just below the surface (~25m) of the Canada Basin in summer (Maykut and McPhee 1995), Jackson et al (op cit) have pieced together a modern CTD record from ice-tethered and ship-borne profilers (WHOI, C3O-JOIS and JWACS mainly) to reveal much of what is important about this seemingly-delicate but in fact extensive and rather robust layer. The NSTM that they describe is first formed in June-July when sufficient solar radiation enters the upper ocean through narrow leads and melt ponds to warm the near-surface waters. Ice melt from these warmed surface waters then accumulates to form a strengthening near-surface halocline (see Fig 2.8 b,c), effectively capping-off the NSTM and trapping solar radiation in the ocean until late September when sea ice begins to form once again, allowing penetrative convection (from brine rejection) and air-ocean or ice-ocean stresses to deepen the surface mixed layer. This is not an unvarying process. During the so-called 'Arctic Warm Period' (Overland et al, 2008), the temperature of the NSTM in the Canada Basin has increased north of 75°N at a rate of 0.13°C per year since 2004.

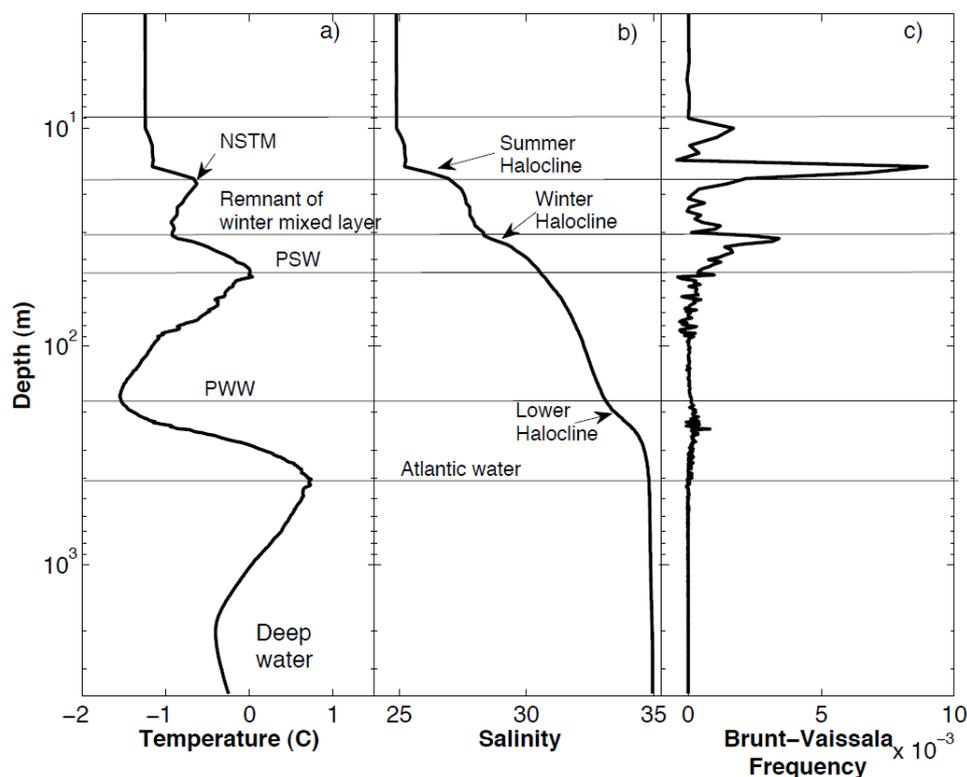


Fig 2.8. Water mass structure of the Canada Basin as characterized by a) temperature, b) salinity and c) Brunt-Väisälä frequency profiles, from Jackson et al, 2010. Note the depth axis is log scale. In summer, there are up to 3 temperature maxima [the near-surface temperature maximum (NSTM), Pacific Summer Water (PSW) and Atlantic Water], 2 temperature minima [the remnant of the previous winter's surface mixed layer and Pacific Winter Water (PWW)], and 3 haloclines (the summer halocline, the winter halocline and the lower halocline).

Future observing: In planning an observational legacy phase for the IPY, it makes sense to enquire what continued coverage of the upper watercolumn would be needed to keep track of this whole cycle of heat input, storage and delayed release that will determine ocean-atmosphere heat exchange as the sea-ice dwindles away. While the present (Section 2.1) and future (Section 2.3) variants of the ITP system will provide a valuable record of the heat stored in the upper watercolumn of the western Arctic, the task of assessing its time-dependent exchange with, and effect on, the lower troposphere will demand more. Fortunately, a prototype system is under development by iAOOS France that will provide the necessary triple profiles of the upper ocean-, the sea-ice, and the lower atmosphere from the same surface platform and for the first time (Fig 2.9).

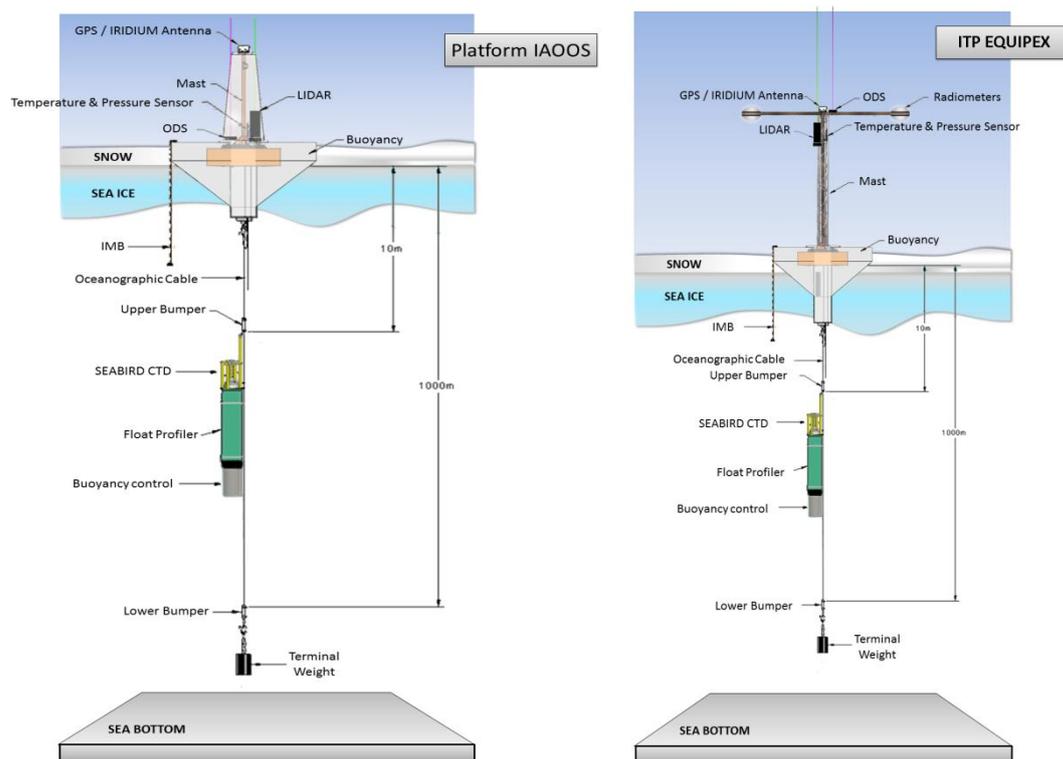


Fig 2.9 The two versions of the new system being developed by iAOOS France for profiling the upper polar ocean (CTD), sea-ice (IMB) and lower atmosphere (LIDAR & ODS) for the first time from the same surface platform. 50 platforms over 7 years are envisaged.

Fig 2.9 shows the variants of the two new ocean-ice-atmosphere observing systems recently proposed by iAOOS-France, whose funding was confirmed in January 2011. This 10-year project with a total budget of ~7 M euros will provide a total of ~50 platforms, with 15 platforms to be maintained continuously for 7 years. To achieve this, after a first deployment of 15 platforms, it is anticipated that around half will need to be replaced every year for 5 years. Individual Platforms would have a planned lifetime of 2 years. Each would be equipped with a CTD profiler (ARGO type), an Ice Mass Balance (IMB) string for the temperature profiling of sea ice and snow (SAMS type), a Laser Imaging Detection and Ranging (LIDAR) and Optical Depth Sensor (ODS; French type) for atmospheric sounding and, in one version, up/down radiometers. Platforms would be deployable on water or on sea ice. The LIDAR and ODR soundings will comment on atmospheric constituents and processes conditioning radiation fluxes (ozone, humidity, aerosols, haze and clouds). (Input from Jean-Claude Gascard, UPMC Paris).

Obtaining lower atmosphere soundings as well as upper ocean profiles *from the same surface platform* will not only ease the general (and major) lack of atmospheric observations over the Arctic Ocean but it will specifically improve coverage in the near-surface layers ----- the layers of critical importance to the present study. Looking down from space, satellite-borne radiation sensors are able to penetrate to different depths in the atmosphere to recover temperature profiles, but satellites have greater difficulty with vertical resolution for retrievals closer to the surface. As Liu et al (2006) have also shown, the weighting functions used mean that the retrieved temperature for a certain height may be somewhat influenced by temperatures through the lower half of the troposphere rather than from one level. For this reason, satellite data is best used as an input to reanalysis where, with modern (so-called 4-dimensional variational) data assimilation, it can be utilized without retrieval assumptions. This lack of resolution near the surface is a particular problem since it is well known (e.g. Serreze et al. 1992, Tjernström and Graversen 2009, Devasthale et al. 2010) that the Arctic atmosphere often has strong low level temperature inversions with strong vertical gradients that are not well resolved by most satellite retrievals. Also TOVS surface temperatures show large errors (Francis et al. 2002; TOVS = Television and Infrared Observation Satellite Operational Vertical Sounder). In their study, TOVS temperatures were compared to direct surface observations, and areas with large differences (4 to 6 K) are found in both winter and summer. Schweiger et al. (2002) found RMS errors in TOVS of ~2 to 3 K at the 850 mb level compared to radiosondes temperature profiles during the SHEBA experiment.

That said, while we can readily agree that ocean-ice-atmosphere profiling by the French iAOOS platforms will provide something quite new and essential to the task under discussion here ---- tracing out the delicate atmospheric impacts of and feedbacks from the newly open polar sea, ----- their surface based instruments too will require development. While some of the platforms will be able to measure some aspects of clouds and aerosols, and other platforms the radiative energy balance at the surface, the calibration and maintenance of the unattended sensors in the Arctic is far from a trivial task. Several problems with atmospheric in-situ observations in the Arctic need engineering development attention. One of the most serious, but seemingly trivial, problems is that of deposition of ice on the sensors, either from riming of fog droplets or sea spray, or from direct sublimation of water vapor to form frost. Not only does this render the observations useless, in several cases it is not even possible to detect, from the observations themselves, if they are affected or not and to what degree. Several avenues seem open for the alleviation this problem ---- heating (which requires power), treating the instruments (by some chemical), development of resistant material surfaces or protection of the instruments by some mechanical housing ---but these have still to be explored.

As these technique are developed, tested and implemented it is also very important to realize that while the properties of clouds and aerosols and the components of the surface radiation budget are indeed key parameters to measure in the context of this report, neither of these new platforms will provide surface heat fluxes, temperature or wind speed profiles for the lower troposphere, nor will cloud information beyond cloud-base height and properties of the very lowest cloud be observed since the lidar attenuates rapidly in clouds. Techniques to accomplish this from the surface do exist today: sensible and latent heat flux by sonic anemometers, temperature profiles by scanning microwave radiometer, winds by Doppler lidar or radar and clouds by radar. Today these techniques, while reliable and useful, require too much power for remote unattended usage, are too large, heavy and expensive for buoy deployment or require continuous attendance. However, engineering and miniaturization of sensors and electronics have developed tremendously even over the last decade alone and efforts to develop existing technologies for remote unattended deployment as well as

developing new measurement technologies should be strongly encouraged. *In all of this development it is of great importance that the scientific community sees this development as an opportunity to achieve something new rather than focusing on the difficulties. Only in this way can we provide the incentive to the engineering community to push for the necessary development.*

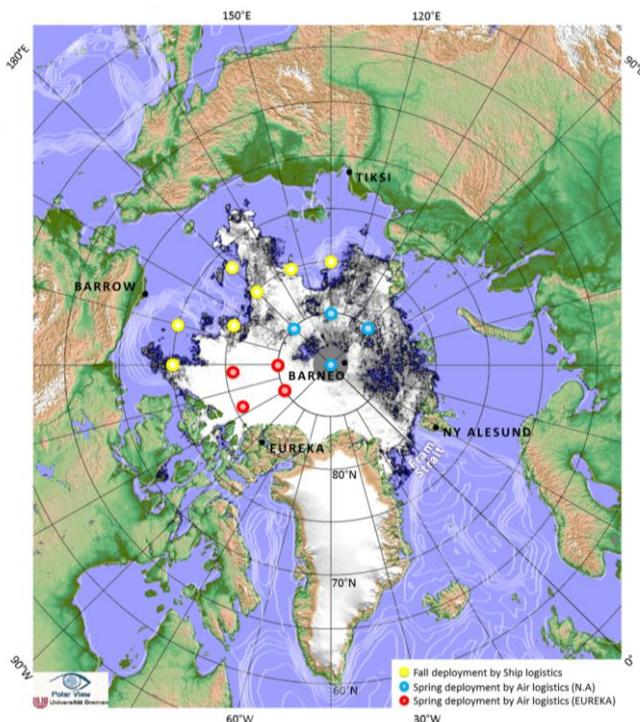


Fig 2.10 Intended release positions of the first 15 platforms being developed by iAOOS-France to provide profiles of the upper ocean-, sea-ice, and lower atmosphere from a surface platform for the first time. Colour coding describes the origins of each deployment, yellow by ship, cyan from Ny Ålesund, red from Eureka. (Graphic from Jean-Claude Gascard, UPMC, pers comm)

Fig 2.10 illustrates the intended locations of the first 15 platforms, to be deployed from Eureka (Canada), Ny Ålesund (Norway) and from icebreakers, beginning with a first planned use of lidars and ODS in summer 2011 during an icebreaker summer cruise in the Beaufort Gyre. Radiosoundings with stratospheric balloons equipped with Vaisala instruments will be launched on each deployment to measure a complex of atmospheric variables in vertical profile (temperature, humidity, winds, ozone etc) and should be a priority throughout each deployment cruise. While these soundings will be too infrequent to contribute to reanalysis results, they may serve as data that can be used to evaluate reanalysis results, since they will be independent. Infill met data and upper ocean data will be available from the long established platforms of the International Arctic Buoy Program (since 1979; see Rigor et al 2000, 2002, 2004), now designed to be deployed onto sea-ice or open ocean as Airborne eXpendable Ice beacons (AXIB; see Dickson 2009), together with any continuing deployments of the original Ice Mass Balance Buoys (Richter-Menge et al 2006; Perovich et al 2008) that led the field in revealing the extraordinary amount of basal ice-melt that can take place in the western Arctic in summer (2m of bottom melt in the Beaufort Sea in August 2007, ----11cm per day in the last week of that month!).

Q 2.3: What is the potential climatic impact of accessing the warm Pacific summer water layer in the Canada Basin through an increased depth and intensity of turbulent mixing as the sea-ice retracts?

Present understanding: The component parts of this problem are set out by Toole et al (2010) and our focus is on the Pacific Summer Water (PSW) layer that forms the second of the three temperature maxima shown at ~ 60m depth in Fig 2.8. The analysis of 5800 ITP profiles of temperature and salinity from the central Canada basin in 2004–2009 reveals a very strong and intensifying stratification that greatly impedes surface layer deepening by vertical convection and shear mixing, and limits the flux of deep ocean heat from the PSW sublayer to the surface that could influence sea ice growth/decay. At present, the intense pycnocline sets an upper bound on mixed layer depth of 30-40 m in winter and 10 m or less in summer, and consistent with the analyses of Maykut and McPhee (1995) and Shaw et al. (2009), Toole et al find these stratification barriers effectively isolate the surface waters and sea ice in the central Canada Basin from the influences of deeper waters. However while PSW heat appears not to be currently influencing the central Canada Basin mixed layer and sea ice on seasonal timescales, it is conceivable that over longer periods that heat-source could become significant. After all, as Toole et al point out, the PSW heat now entering the central Canada Basin can't simply disappear; it is presently being stored in the ocean as intrusions in the 40-100 m depth range of sufficient magnitude to melt about 1 m of ice if its heat were somehow to be introduced into the mixed layer. It is not yet obvious what physical mechanisms might allow the mixed layer to rapidly tap that heat. Winter 1-D model runs initialized with profiles in which the low-salinity cap in the upper 50 m was artificially removed failed to entrain significant PSW heat, even when more than 3 times the ocean cooling rate and 10 times the mechanical work of the standard winter model runs were applied to the mixed layer. It thus seems most likely to Toole et al that if PSW heat is vented upwards in the central Canada Basin in the near future, that flux will be accomplished by a relatively weak, small-scale turbulent diffusive process. Thus the driving question underlying this issue is *'what are the intensities and the physical mechanisms supporting turbulent diapycnal heat and fresh water fluxes between the Arctic surface mixed layer and the waters immediately underlying, and how might those fluxes change in future if we transition to a seasonal ice pack?'* (John Toole, WHOI pers comm.)

Future observing: apart from the CTD profiles provided by the ITP program, continuing until at least 2014, two new approaches seem to be helpful to solving this question and are commended here.

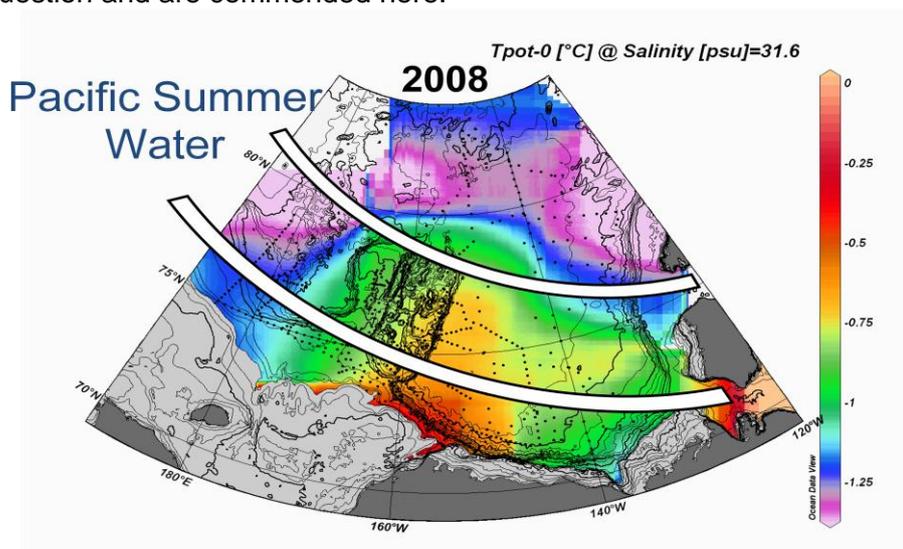


Fig 2.11. Zonal hydrographic sections in the Pacific Sector of the Arctic Ocean designed to cover interannual variations in PSW distribution due to the changing dominance of wind and buoyancy forcing (Koji Shimada pers comm., January 2011; see also Shimada et al 2006.)

The *first* and more conventional approach is to keep track of the spreading pathway of the Pacific Summer Water (PSW) in the western Arctic. The long-sustained (since 1990) moored arrays maintained by the University of Washington but augmented and elaborated in complexity during the IPY (Woodgate et al, 2006, 2010) already provide evidence of changes in the flux and characteristics of the inflowing watermasses through Bering Strait and since at least part of this array (A3) has been proposed as a 'climate site' (Woodgate et al 2007), we may assume that this valuable coverage will continue. Downstream, in the western Canada Basin-Chukchi Cap, detailed hydrographic surveys by Koji Shimada (Tokyo University of Marine Science and Technology) have shown by that the spreading area of PSW may fluctuate according to the dominance of wind- or buoyancy-forcing in a given year. Shimada therefore recommends the annual working of two zonal hydrographic sections occupying the full span of the southern Canada Basin (Fig 2.11), and an annual campaign to do so using the new Korean icebreaker *ARAON* (front cover) is now planned.

The *second* approach is to find some direct way of assessing the subtle changes in upper-ocean mixing under the retracting ice-cover. Through a development of the ITP system, measurements of the velocity structure in the water column under Arctic ice are now possible using a WHOI Ice-Tethered Profiler (ITP) with an acoustic point-measurement current meter, MAVS (Modular Acoustic Velocity Sensor). This new 'ITP-V' profiler, containing a Seabird CTD, MAVS, batteries, an inductive modem, and a wire crawling engine, integrated by McLane Labs, is deployable through a 24" diameter hole drilled in the ice (Fig 2.12), and the profiler is linked to a satellite transmitter fixed to a drifting but GPS-tracked location on the ice. While the profiler descends to 800m, velocity is thus measured relative to the moving mooring and the climbing profiler. An inertial sensor, Analog Devices ADIS 16355 is used to remove platform motion from the current measurement. The instrument exists, with a first ITP-V deployment in fall 2009 and a second in fall 2010. Both had/have telemetry problems but data from the first was recovered along with the instrument in fall 2010. A further deployment is planned for Fall 2011 using a 2nd unit which has been further developed to sample bio-optical parameters (information from John Toole, WHOI, 18 January 2011; see also Williams et al 2010, Thwaites et al 2011).

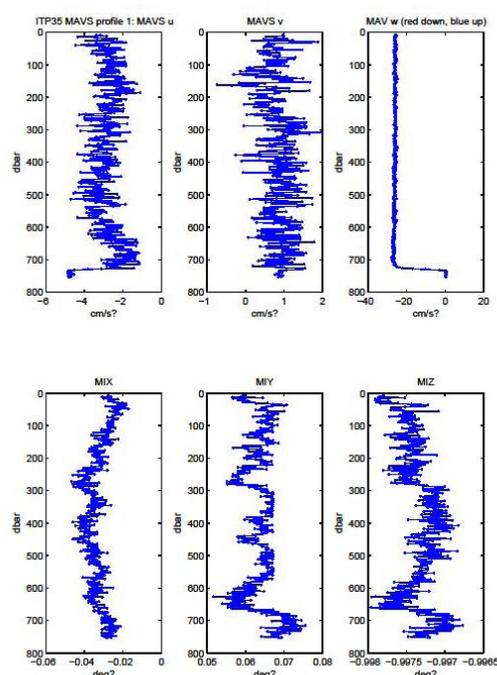
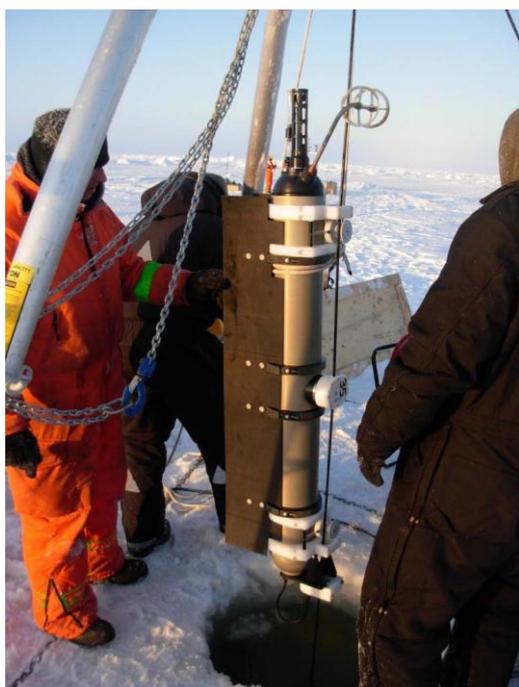


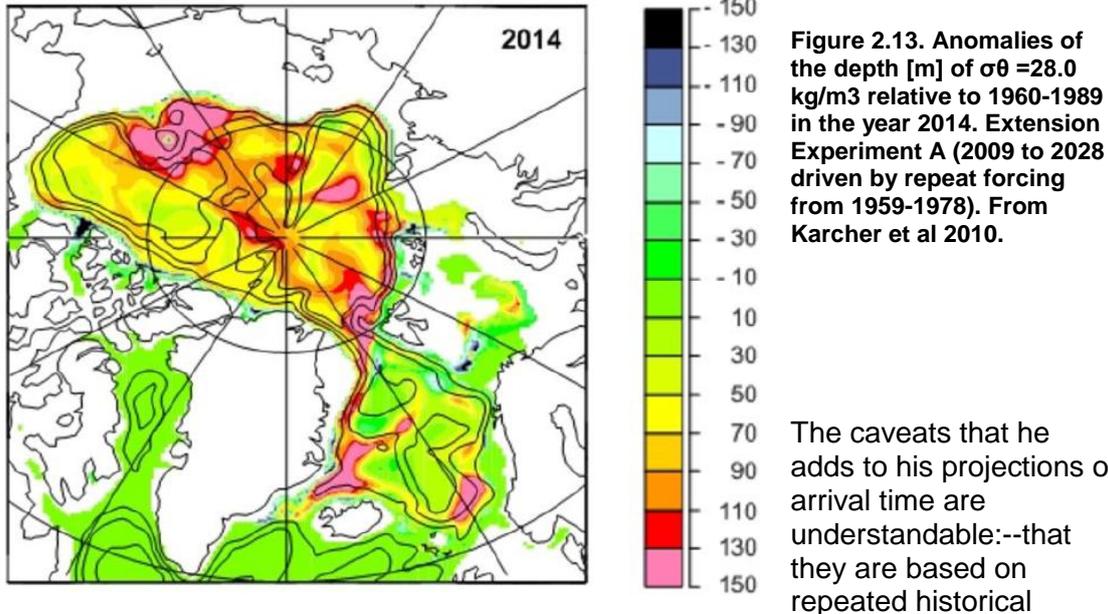
Fig 2.12. Left hand side: the new Ice Tethered Profiler with Modular Acoustic Velocity Sensor (ITP-V) being lowered into a hole in the ice along the mooring line. The short split fin to reduce swinging and Strouhal oscillation has been clamped to the housing. All systems for the profiler are inside the aluminum housing except the crawler motor and roller and the inductive modem transformer. Right hand panels: MAVS data from the first up profile of the ITP-V under the ice. The top row shows velocity into the sensor, velocity across the sensor and vertical velocity. The lower row shows three components of earth magnetic field direction cosines. Both from Williams et al 2010.

Q 2.4: Where can we expect the recent extreme warmth of the Atlantic-derived sublayer to have its main climatic impact?

Present understanding: This section highlights the potential remote and lagged climatic impact of the deepest of the three temperature maxima shown at in Fig 2.8 ---the Atlantic-derived layer at ~400m depth. Very recently, the Atlantic waters flowing into the Norwegian Sea and passing north through the Barents Sea have reached a 100-year maximum in temperature (Holliday et al 2007). The onward spread of this warmth has been documented along the Eurasian boundary of the Arctic Ocean from Fram Strait to the New Siberian Islands (Polyakov et al, 2005, 2007 and in press; Dmitrenko et al 2008 a, b), and the JOIS/C30 transects of the Beaufort Sea (McLaughlin et al 2009) confirm the arrival of an earlier warm wave along the southern margin of the Canada Basin around 2007. To do what exactly?

The answer is unclear. When the IPY began in March 2007, it would probably have been the consensus view that a 100-year maximum in the warmth of Atlantic inflow to the Arctic must in some way be bound up with an increased melting of sea ice, and such claims are still advanced (see Polyakov et al 2010; also commentary by Carmack and Melling, 2011). Or, -----not quite the same thing----- that future accessions of warmth to the western Arctic might simply be removed by increased turbulence associated with the removal of ice cover. McLaughlin et al (op cit) however suggest that the heat input to the Canada Basin, amounting to ~30% of the Eurasian Basin input, will ultimately exit to modify the East Greenland Current, and this third possibility now seems the more likely as a result of new simulations by a group from the Alfred Wegener Institute, Bremerhaven (Karcher et al 2007, 2008 and 2010). These suggest that as the warm Atlantic-derived layer spread at subsurface depths through the Arctic deep basins, it did so at a significantly greater depth and with a significantly lower density than normal. Though the increased warmth may thus be too deep to have much effect on sea ice, the intriguing suggestion is made that, as and when this layer circuits the Arctic and drains south again into the Nordic seas, its changed depth and density now seem capable of altering the two factors, the density contrast across the sill and the interface height above the sill, that together determine the strength of the Denmark Strait Overflow (Whitehead, 1998), hitherto regarded as largely unchanging (Dickson et al 2008). By this reasoning the climatic impact of the recent inflow of warmth to the Arctic may have less to do with local effects on sea ice than on the Atlantic's thermohaline 'conveyor', far to the south and many years later (in 2016-18 by present estimates, or 15 – 25 years after the entrance of the original signal through Fram Strait into the Arctic Ocean; Michael Karcher, AWI, pers comm. 2009).

Future observing: Maintaining surveillance on an evolving change of this magnitude taking place throughout the length and breadth of our Arctic and subarctic seas on a timescale of decades is likely to prove highly instructive to our understanding of the role of our northern seas in climate, although detecting and following such decadal transient signals is likely to impose a need for new tools in observational network design. Karcher identifies three key areas in the Arctic in the approaches to Fram Strait and in the area upstream of the Overflows, which are suggested to be of importance for intercepting the outflowing anomalies in the AW sublayer.



The caveats that he adds to his projections of arrival time are understandable:--that they are based on repeated historical forcing rather than on the (unknown) actual forcing; that the changes we believe we see in the Arctic Ocean circulation in recent years [eg a strengthened Beaufort Gyre (Giles 2011); a much reduced AW flow from the Eurasian to the Makarov Basin; an intensified recirculation inside the Eurasian Basin and along the Lomonosov Ridge etc], might well result in a very different route and rate for these anomalies in the 2000s compared to the 1990s; that the anomalies we are tracing are calculated relative to long term means (eg in interface height) that are not known with any great precision from observations. The only way to cope with this imprecision is if course to deploy our 'receiving array' well before the event, but since the two 'hypothetical' experiments described in Karcher et al 2010 suggest that the arrival of these low-density signals north of the Denmark Strait may be as early as 2014 (Figs 2.13 and 2.14) , we have little enough time to prepare.

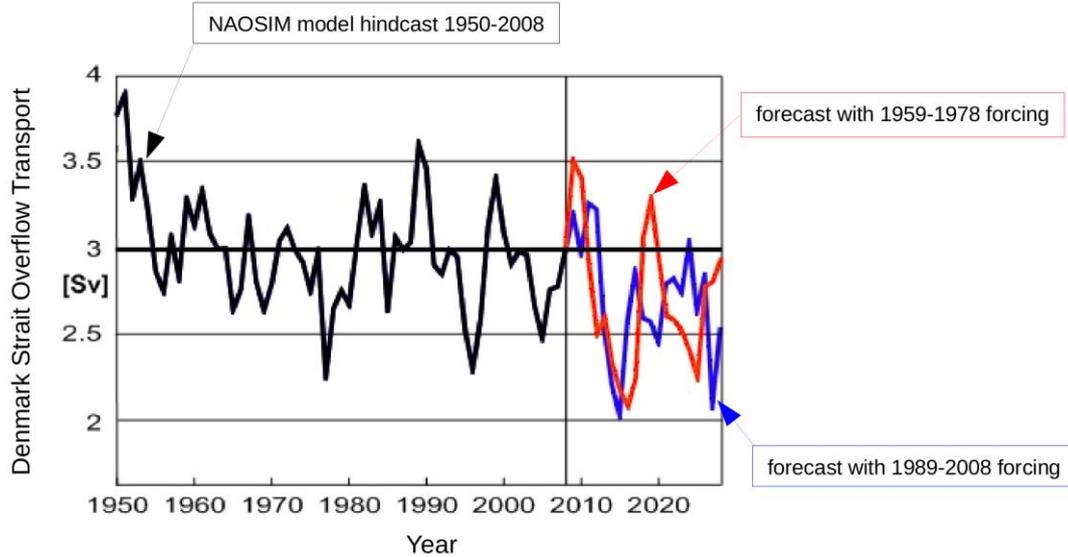


Figure 2.14. Timeseries of Denmark Strait overflow transport, adapted from Karcher et al. (2011). The black line for 1950- 2008 shows the NAOSIM model hindcast. The red and blue lines show plausible forecasts for 2008-2028, depending on different air/sea forcing scenarios, and show diminished overflow transport as buoyant anomalies drain out of the Arctic.

Experiments already planned for the area in this ‘ramping-up’ phase must necessarily reflect what we already know of overflow variability. New observations to detect the low-density anomalies flushing through Denmark Strait must capture the overflow properties and transport and must also cope with the 2-4 day overflow transport variability at the exit to Denmark Strait.

The transport variability is similar to the mean transport itself. The variability is associated with equivalent-barotropic cyclones that are nearly geostrophic and correlate with sea-surface height (SSH; upper left panel in Figure 2.15). Existing satellite altimeter observations of SSH have adequate space/time sampling to reconstruct the transport fluctuations using a regression developed from model results, but measurement error overwhelms the signal (Haine 2010). Three potential directions to monitor Denmark Strait overflow transport exist: First, the pending Surface Water and Ocean Topography (SWOT) wide-swath altimeter appears accurate enough, and with good-enough coverage, to allow the transport fluctuations to be reconstructed. Second, bottom pressure recorders at the exit of the Denmark Strait can also reproduce the transport variability. Finally, it may be possible to use extant SSH data and data assimilation (DA) to reconstruct the time-series of DSOW variations at section DSS (see the upper right panel in Figure 2.15 for the location of section DSS). Observing system tests with TOPEX/Poseidon and Jason SSH data are encouraging in this regard (Lea, Haine & Gasparovic 2006; lower panel in Figure 2.15), and tests with real data are in progress. On periods longer than $O(100)$ days, DSOW variations exhibit hydraulic control and correlate with upstream SSH (Köhl et al. 2007). This relationship should be exploited in any practical scheme to monitor DSOW, as should the current observations at the sill.

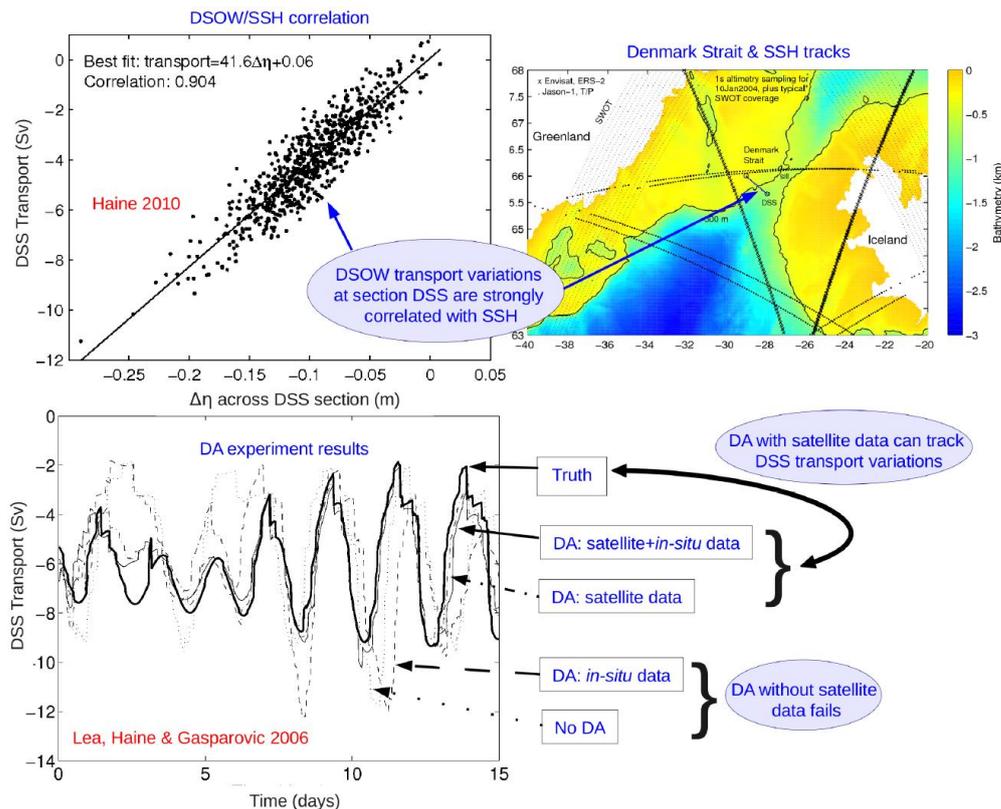


Fig 2.15 Denmark Strait Overflow variability can be monitored with SSH and data assimilation. See text for details.

Observing change: At present in the run-up to the arrival of the unusual and instructive events of Fig 2.13 and 2.14, a design for a comprehensive DSOW monitoring system, exploiting all these themes, is now urgently required. The most important existing projects to build on are illustrated in Fig 2.16a. (i) In the EU-THOR project, two overflow moorings will be in place at least until the end of THOR (summer 2013) and the project leader Detlef Quadfasel (UHH-ZMAW pers comm. January 2011) anticipates that these will continue at least until 2016. (ii) Fig 2.16 a,b also shows the location and instrumentation of an intended US-Icelandic-Dutch-Norwegian ‘Kogur line’ of moorings to be deployed across the current to the north of the sill between August 2011 and August 2012 (graphic and information from Bob Pickart WHOI, January 2011).

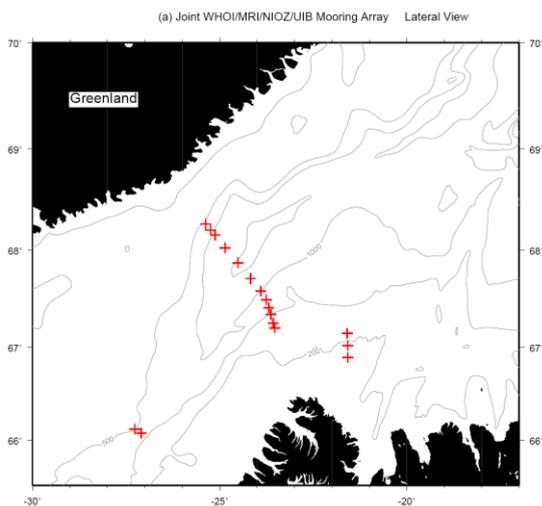
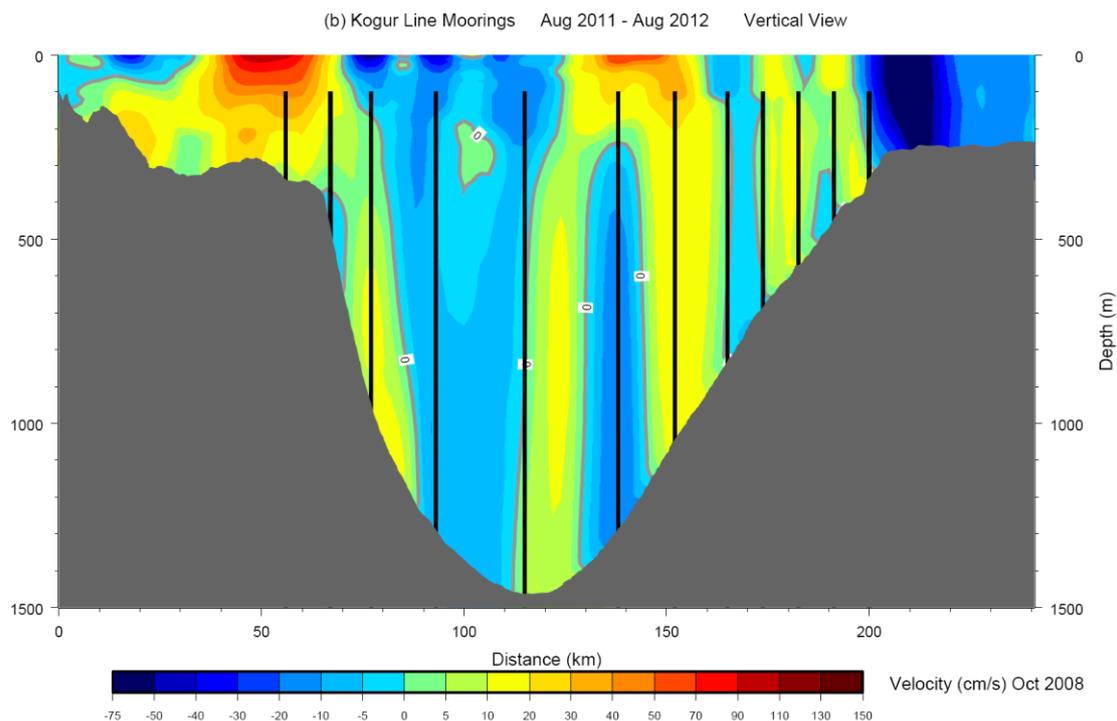


Fig 2.16a. Present and planned current meter arrays covering the dense water overflow through Denmark Strait: (left) the presently deployed THOR moorings at the Denmark Strait sill and in the North Icelandic Irminger Current, together with the to-be-deployed Kogur Line moorings. Fig 2.16b. The vertical view (below) shows the Kogur Line moorings overlaid on a section of absolute geostrophic velocity. PIs are Bob Pickart (WHOI), Hedinn Valdimarsson (MRI), Steingrímur Jonsson (MRI), Laura de Steur (NIOZ), Kjetil Våge (UIB) and Svein Østerhus (UIB)



Simulating Shelf-Basin Exchange south of Denmark Strait: Although the overflow through Denmark Strait sill is likely the main conduit to drain the low-density anomalies, the shallower flow on the East Greenland shelf should not be overlooked. That flow is not well observed, yet it is an important influence on the deep ocean via shelf-basin exchange. Shelf-basin exchange is a process that is also not well-observed, or understood. One current project focuses on this issue however. Under NSF support, $O(0.1\text{--}1)$ km resolution numerical simulations of shelf-basin exchange south of Denmark Strait are being performed (Magaldi et al. 2011). The focus is on the East Greenland Spill Jet, an intense cascade of shelf waters into the deep Irminger basin (Pickart et al. 2005). Model results compare well with the sparse field data and suggest that the Spill Jet is a permanent feature subject to strong variability. The model Spill Jet transport is around 5 Sv equatorward in summer 2003, similar to the primary overflow through Denmark Strait after it has entrained some ambient water. Two distinct types of spilling events are identified, of roughly equal frequency: Type I spilling is a local perturbation that results in dense waters descending over the shelf break. Type II spilling occurs in the presence of surface instabilities associated with the Denmark Strait overflow variability described above. Future work includes a detailed comparison of the model results with 2007—2008 mooring data (from Bob Pickart) and an investigation of the dynamics of the spilling process. It is crucial that the importance of shelf/basin exchange for DSOV should be assessed, and a strategy on how it might be monitored must be devised. With luck, shelf-basin exchange south of Denmark Strait exemplifies shelf-basin exchange off West Greenland, Labrador and Newfoundland, where it is also important (see section 4.3.1). In any event, the southeast Greenland case study must be extrapolated to these other locations, and further studies conducted where necessary. At its Workshop in WHOI in October 2010, the ASOF-2 WG under Tom Haine accepted this task.

Issue 3: Revitalising ideas about Greenland, freshwater and the MOC (with PI Tom Haine, JHU).

The global thermohaline circulation, driven by fluxes of heat and freshwater at the ocean surface, is an important mechanism for the global redistribution of heat and salt and is known to be intimately involved in the major changes in Earth climate. Thus a partial shutdown of this world-wide overturning cell appears to have accompanied each abrupt shift of the ocean-atmosphere system towards glaciation (eg Broecker and Denton, 1989), and since the pioneering modelling work of Bryan (1986) and Manabe and Stouffer (1988), most computer simulations of the ocean system in a climate with increased greenhouse-gas concentrations predict a weakening thermohaline circulation in the North Atlantic as the subpolar seas become fresher and warmer.

Today, despite major advances in simulating the system, we remain undecided on many of the most basic issues that link change in our northern seas to climate. The need to develop a future observing plan on the freshwater passing Greenland lies at least in part in the fact that there are robust plans for observing the MOC further south that will require this input. The study of the Atlantic Overturning Circulation (AMOC) was identified as a near-term priority in the U.S. Ocean Research Priorities Plan, by the U.S. Joint Subcommittee on Ocean Science and Technology. This led to the formation of US AMOC, a program sponsored by NSF, NASA and NOAA, that includes the design and implementation of an AMOC monitoring system. **O-SNAP** is a to-be-proposed international program that focuses on the AMOC variability in the subpolar North Atlantic and is led by Susan Lozier (Duke). The main objectives of O-SNAP are to measure the fluxes of mass, heat and fresh water in the subpolar region and establish their link to changes across the Greenland-Scotland Ridge (as observed by European PIs including the recent EU-Thor Project) and the 24°N array in the N. Atlantic maintained by the UK-US RAPID program. The straw man plan for the O-SNAP system includes moored boundary current arrays at the 53°N location occupied by the German SFB-460 program until a few years ago. Gliders and floats will also be proposed to monitor the basins' interior along two lines – roughly across the Labrador Sea and from Cape Farewell to Scotland. Though there are issues still about 'which line' and whether their workings should be separated in time, the fact remains that there will be AMOC arrays further south that will require advice on Arctic –subarctic changes passing south to their area of interest.

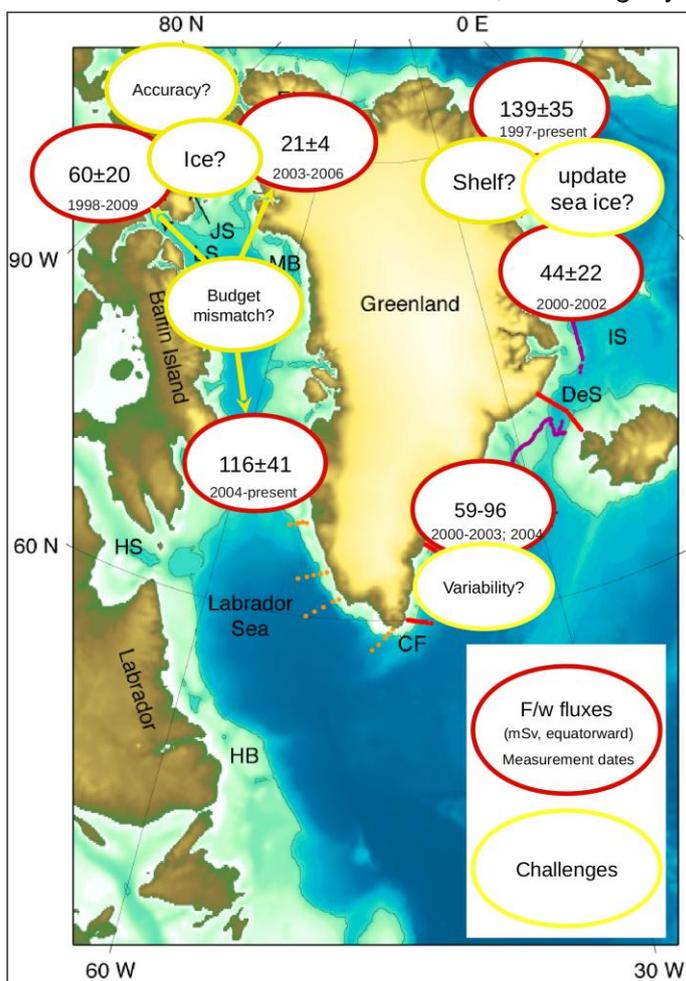
Present knowledge: In the final section of this report, we attempt to pull together four apparently disparate aspects of the freshwater flux passing Greenland to show that they are in fact intimately related and perhaps capable of solution through observations. They take the form of 4 questions, debated at an AOSB - ASOF workshop in Woods Hole on 18 October 2010:

- Q 3.1** what are the freshwater fluxes either side of Greenland and how can we monitor them effectively in the long term?
- Q 3.2** Which side of Greenland will be favoured by the freshwater efflux in future, and how can we resolve model inconsistencies on this point?
- Q 3.3.** Is the future freshwater production of Greenland capable of making significant impacts on CAA Outflow (path; transport), and what/where should we monitor to test for this?
- Q 3.4.** How might we evolve a long-term observational strategy to observe the expected impact of these changes on the MOC?

Q 3.1 How much? What are the freshwater fluxes either side of Greenland and how can we monitor them effectively in the long term? Inputs from Laura de Steur (NIOZ), Craig

Lee (UW), Andreas Münchow (U Delaware), Simon Prinsenberg (BIO), Humfrey Melling (IOS), Kelly Falkner (OSU)

There are two major freshwater pathways from the Arctic Ocean to the subpolar North Atlantic, namely Fram Strait and the passages through the Canadian Arctic Archipelago (CAA). Fram Strait today carries roughly equal amounts of freshwater in liquid and solid form while the export through the CAA is mostly liquid freshwater. Figure 3.1 provides a modern overview on estimates of freshwater and volume fluxes, including sea ice, whenever possible, around Greenland (compilation by Laura de Steur, NIOZ pers comm). All estimates, except in the southern EGC, are based on moored current meter observations carried out under different observational programs in the 2000s. The programs in Fram Strait (NPI/AWI) and Lancaster Sound (BIO) have been carried out since the late 1990s. Continuous moored measurements in Nares Strait (U. of Delaware/IOS/OSU) were collected during 2003 to 2006 and the moored array in Davis Strait (APL/UW) has been in place since 2004. The liquid freshwater flux in Fram Strait has shown a small (but not significant) increase from 2005 up to 2008. The freshwater flux in Lancaster Sound appears to decrease from 2001 up to 2009. The latter estimate is loosely related to the net volume flux while for the former it is less clear. A preliminary estimate of fluxes in Davis Strait shows a slight decline from 2004 to 2008. Despite the fact that several years' data have been recovered, the time series are still too short, and uncertainties are still too large, to make conclusive statements about significant trends in freshwater fluxes. Also, the time series show large annual and inter-annual variability which makes it hard to interpret observed changes. In addition, there are still some unknown contributions to the freshwater fluxes around Greenland. These challenges include: updating the estimate of sea ice flux in Fram Strait, obtaining a year-round flux estimate on the



East Greenland Shelf between 74° and 80°N, estimating the annual average fluxes in the EGC and on the shelf in southeast Greenland (60-66°N), and reducing uncertainties in sea ice flux in the CAA, as well as the liquid freshwater flux in Nares Strait. Baffin Bay volume and freshwater budgets (Curry et al, 2011) close to within the somewhat large uncertainties in the constituent estimates, with imbalances of 26% (volume) and 4% (freshwater) of the net 2004-2005 Davis Strait fluxes. In all the mooring records, it remains very hard, and very important to obtain accurate current measurements near the surface.

Figure 3.1. Freshwater fluxes east and west of Greenland and outstanding challenges. The freshwater fluxes are referenced to a salinity of 34.9 east of Greenland, north of Denmark

Strait and 34.8 otherwise. The base map is courtesy of Bacon et al. (2008). A flux of 1mSv corresponds to 31.5km³/yr. (Laura de Steur, NIOZ, pers comm.)

There are some indications that freshwater is poised to exit the Arctic Ocean. For example, the freshwater content has clearly increased in the Beaufort Gyre up to 2008, with Proshutinsky et al. (2009) and McPhee et al. (2009) finding freshwater anomalies of +1000 km³ and +8500km³, respectively, relative to climatology. A more recent study of freshwater storage in the Beaufort Gyre and Eurasian Basin by Rabe et al. (2010) shows an increase by 8000 ± 2000km³ over the whole Arctic Ocean during the IPY (2007-2009) compared with hydrographic data from the 1990s (1992-1999). More recently still, the first combined use of satellite altimetry, satellite gravity, ship-based hydrography and ocean bottom pressure (Morison et al submitted) suggests that freshwater storage generated by the climatologically anticyclonic circulation of the Canada Basin (Proshutinsky et al, 2009), has been supplemented by Russian runoff carried in an S-shaped path into the Canada Basin (see p 20 above).

It is of direct climatic interest to know by which pathway this freshwater will pass to lower latitudes but we remain uncertain on this point. McPhee et al. state that the additional freshwater content is associated with increased transport toward the CAA, while de Steur et al. (in preparation) show that the freshwater accumulated in the Beaufort Gyre has started spreading towards the Lincoln Sea, north of Greenland, in the late 2000s, associated with a change in Arctic Ocean circulation from anticyclonic between 1997 and 2008 to cyclonic in 2009 associated with a shift from low Arctic Oscillation Index to high. The continued monitoring of the freshwater, volume and heat fluxes at the gateway sections around Greenland (the CAA, Davis Strait, Fram Strait, and Denmark Strait) seem critical to understanding if, how, and when Arctic Ocean freshwater is released to lower latitudes.

3.2 What do models contribute? What trends in freshwater balance do they suggest? How robust are their conclusions? Which side of Greenland will be favoured by the freshwater efflux in the future, and how can we resolve model inconsistencies on this point? Input from Rüdiger Gerdes (AWI), Alexandra Jahn (NCAR) and Laura de Steur (NIOZ). There is a developing consensus on how on climate models project the future development of freshwater in Arctic. The phase and pathways of freshwater exported from the Arctic Ocean to the subpolar North Atlantic do matter from the point of view of impact on the large scale oceanic circulation. Liquid freshwater is more constrained by ocean dynamics to follow boundary currents around Greenland and Labrador while sea ice is more sensitive to driving by the local wind. Liquid freshwater is vertically distributed in the water column while sea ice melt water is concentrated near the surface. Because of the nonlinearity of vertical mixing processes in the ocean, the impact on deep water formation is greater for sea ice melt. Observed freshwater export events have consisted of both phases: sea ice (mainly) in the case of the Great Salinity Anomaly, and liquid freshwater (mainly) in the case of the mid-1990s export event. Projections of future liquid freshwater export from the Arctic suffer from several uncertainties. Apart from model bias, uncertainties in the scenario assumptions are most important for projections until the end of the century.

Nonetheless, all climate projections agree that in future we can expect increasing atmospheric moisture transport to high northern latitudes and thus more precipitation and run-off to enter the Arctic Ocean. In equilibrium, the Arctic Ocean will return the additional freshwater to lower latitudes. Since sea ice thickness in the Arctic Ocean will decrease, most of the additional freshwater export will occur as liquid freshwater through both the Canadian Archipelago and Fram Strait. During a transitional period, changes in the freshwater storage in the Arctic Ocean can be important.

Reference Model	Arctic Ocean freshwater storage	Fram Strait liquid freshwater	Fram Strait sea ice	CAA liquid freshwater	CAA sea ice
Holland et al. 2006 CCSM3	↑	V ↑ & S ↓	↓	V ↑ & S ↓	—
Holland et al. 2007 all 10 model	↑	V x & S x	↓	x	x
Koenigk et al. 2007 ECHAM5/MPI-OM	↑	V ↑ & S ↓	↓	V ↓ & S ↓	↓
Arzel et al. 2008 IPSL	↑	V ↑ & S ↓	↓	V ↓ & S ↓	↓

Table 3.1: Direction of changes in the Arctic freshwater storage and export in 21st century simulations performed with different climate models. Changes are shown as increase (↑), decrease (↓), and no significant change (—), compared to 20th century simulations. If no information is available, this is indicated by “x”. The direction of changes in the volume transport (V) and in the salinity of the export (S), which cause the changes in the liquid freshwater export, is also shown. (From Gerdes, Jahn and de Steur, see iAOOS Support docs. Q10; <http://aosb.arcticportal.org/>).

Details of the projected freshwater balance and the future development of salinity are model dependent. One reason for such differences is the different representation of ocean passages connecting the Arctic Ocean with the subpolar seas. Because of the narrow straits and shallow passages, the CAA poses an extreme challenge for the under-resolved ocean components of coupled climate models. Nevertheless, although the rates of increase in the freshwater export through the CAA and Fram Strait vary between models, [a shift in total freshwater transport \(sea ice plus liquid freshwater\) from Fram Strait to the CAA, and an overall increase in total freshwater transport from the Arctic Ocean seem inevitable](#). In the opinion of group under Rüdiger Gerdes who conducted this study, [the freshwater fluxes around Greenland will increasingly take the western route through the CAA](#).

Alex Jahn (AOMIP Meeting, WHOI October 2010) has compared the simulated Arctic freshwater export variability from different models to ask how robust are their conclusions --- important if we are to base our observing plan on them. ‘Semi-robust’ (7 of 10 models) is the conclusion that CAA liquid FW export is generally larger than Fram Strait liquid FW export. The ‘robust’ findings are especially informative on the CAA itself: that CAA liquid FW export variability is mainly dominated by volume flux variability (as opposed to Fram Strait where it is affected by both salinity and volume flux changes); that there has been a decreasing liquid FW export in the CAA since ~1990; that Barrow Strait liquid FW export makes up most (~56% to 76%) of the total CAA liquid FW export (Nares Strait makes up 26% to 44%).

Q 3.3. What does theory contribute? What is the impact of Greenland ice-melt on the freshwater flux from the Arctic? Is the future freshwater production of Greenland capable of making significant impacts on CAA Outflow

(path; transport), and what/where should we monitor to test for this? Input from Bert Rudels, FMI.

Whether its effects on the Atlantic Meridional Overturning Circulation are in train or merely in prospect, the Arctic freshwater outflow that passes south either side of Greenland is of acknowledged climatic importance, as are the causes of change in its sources, rates and pathways. The Greenland ice cap is one such source under change. Net mass loss from the Greenland Ice Sheet (currently about 30 mSv) has increased rapidly over the last decade, primarily as a result of the acceleration and retreat of outlet glaciers in western and southeast Greenland. In a recent analysis, Rudels (2011, submitted) tries to assess the importance of the Canadian Arctic Archipelago and Baffin Bay for the mass and freshwater transports between the Arctic Ocean and the North Atlantic, both at present and in a future situation when a smaller Arctic Ocean sea ice export is expected and an increased melting of the Greenland icecap might occur. The controlling mechanisms in the coupled Canadian Arctic Archipelago – Baffin Bay system form his focus, and even in its early stages, the results of this study seem instructive from the viewpoint of designing an effective observing system.

Baffin Bay connects the Arctic Ocean and the Labrador Sea, receiving Polar water through the Canadian Arctic Archipelago and via the West Greenland Current. The Polar water is, after transformation, exported in the Baffin Current through Davis Strait. With control sections both upstream and downstream, Baffin Bay invites the use of an idealized hydraulic approach to estimate the transports, and Rudels (2011, op cit) describes the steps of this approach. First the baroclinic transport, driven by the density differences between the Arctic Ocean and Baffin Bay, is determined; the density and upper layer depth are assumed the same in Lancaster Sound, Nares Strait and the West Greenland Current. Once the baroclinic transports are estimated the sea level difference is computed. Next the upper layer depth in Nares Strait and the West Greenland Current is reduced while the sea level slope is kept constant. This allows for deep inflows through Nares Strait and the West Greenland Current. To establish a deep outflow through Davis Strait a “barotropic” sea level slope between the Arctic Ocean and the Labrador Sea is estimated from two “ideal” stations. The transports are determined for different salinities in the Polar water and the most reasonable transports are found for $S = 33$ (see Rudels 2011 for further details).

The effects of increased melting of the Greenland icecap were then examined, according to two scenarios. In the first case (not illustrated here) freshwater was added only to Baffin Bay, corresponding to the situation when for example the discharge from the Jacobshavn breen increases drastically. The freshwater export through the archipelago stays almost constant while the freshwater transport through Davis Strait increases due to the freshwater added to Baffin Bay. In the second scenario, an increased input from the glaciers was added all around Greenland, feeding both the East Greenland Current and the West Greenland Current and reducing the salinity of the water entering Baffin Bay in the West Greenland Current. In contrast to the first case, the freshwater export through Davis Strait increases as the Baffin Bay upper layer salinity decreases (x-axis) but the freshwater derives more and more from the West Greenland Current inflow and less and less from the transport through the Canadian Arctic Archipelago (Figure 3.2). The input directly to Baffin Bay also increases with this parameterization of the freshwater input. [In both scenarios, the export of sea ice through Davis Strait is kept constant and equal to that obtained for the prescribed PSW salinity]. These estimates only affect the baroclinic transports of the Canadian Arctic Archipelago – Baffin Bay system. The

barotropic flow between the Arctic Ocean and Labrador Sea, driven by the sea level difference between the Arctic Ocean and the Labrador Sea, is still present.

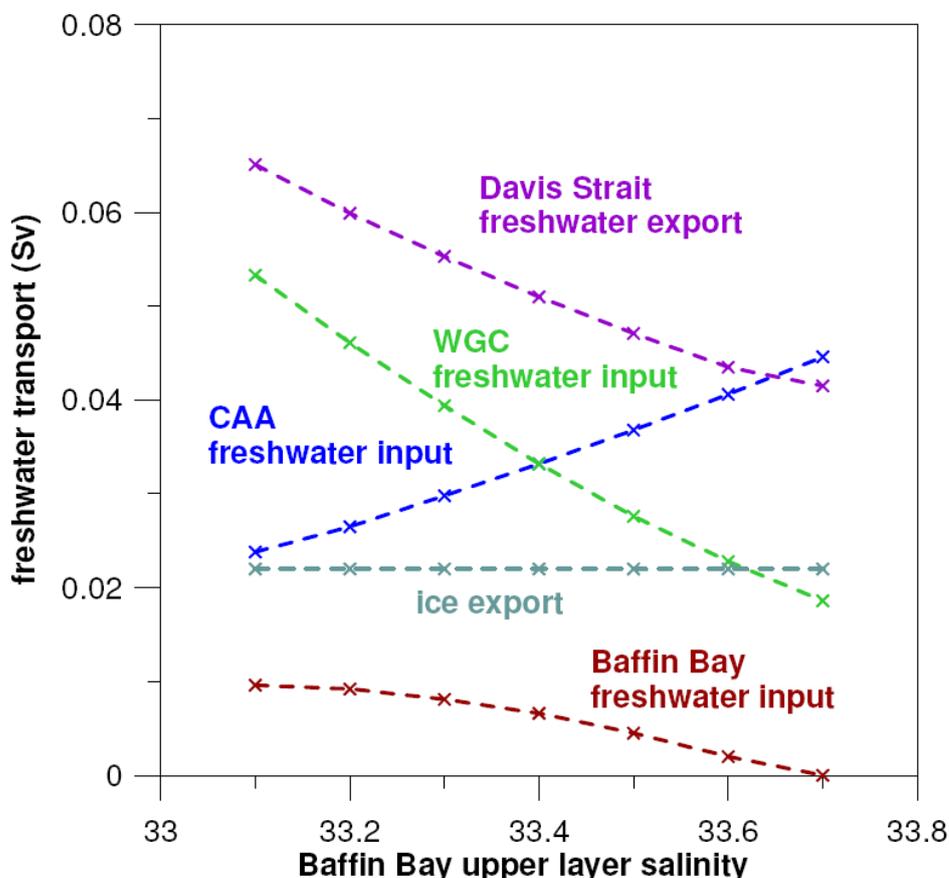


Fig 3.2 Freshwater transports through CAA, in WGC, the ice export and the Baffin Bay freshwater input as functions of the Baffin Bay salinity. In this scenario, freshwater is added along the Greenland coast, as might occur, for example, through an increased melting of the Greenland icecap (from Rudels 2011, submitted).

At its most basic then, the study suggests that if freshwater is added directly to Baffin Bay the effects are small, but if freshwater is incorporated in the East and West Greenland Current a reduction of the Polar outflow through the CAA by 25% might take place.

Naturally as Rudels points out, there are many caveats and assumptions underlying this conclusion. The TS characteristics and stratification in Baffin Bay are assumed to modulate, and ultimately dominate, the effects of short-term forcing such as wind induced pressure differences and sea level slopes between the Arctic Ocean and Baffin Bay and between Baffin Bay and the Labrador Sea; the TS characteristics are from an ideal Baffin Bay stratification and are assumed to be fixed. Rotationally controlled baroclinic flows are assumed in all passages. The sea level difference between the Arctic Ocean and Baffin Bay is kept unchanged, while using different depth of the upper layers in Lancaster Sound and in Nares Strait and in the West Greenland Current [Rudels describes it as 'crucial' to find a reasonable relation between the sea level slope and the upper layer depth if his approach is to be developed further].

Nevertheless, the justification of this work as it stands is that it explores and illuminates the driving mechanisms and balances of the Canadian Arctic Archipelago – Baffin Bay system. The results obtained are acceptable within the range of existing

observations (e.g. Melling et al., 2008; Curry et al., 2011). And it alerts us to the possibility that a freshwater input distributed along the east and west coasts of Greenland ---eg through an increase in the melting of the Greenland icecap----might lower the outflow of volume and freshwater through the Canadian Arctic Archipelago, perhaps by 25%. Finally, from the viewpoint of designing an ocean-observing system for climate, it clearly suggests that monitoring and analyzing changes in the upper layer salinity in Baffin Bay might be 'useful and perhaps critical' for estimating variations in the transports through the Canadian Arctic Archipelago and Baffin Bay.

3.5 What impact on the MOC? How do we interface with existing plans for MOC monitoring further south? How might we evolve a long-term observational strategy to observe the expected impact of these changes on the MOC? Tom Haine, (JHU):

Following on from the simulations of future freshwater export from the Arctic (above), it remains an open question how much these changes in freshwater export will affect the formation of deep water in the North Atlantic. Freshwater exported through the CAA or Fram Strait can have different impacts on the subpolar deep water transformation areas. Specifically, freshwater exported via the CAA tends to remain in the Labrador Current, or inshore of it, and is isolated from the Labrador Sea deep convection areas. However, it remains concentrated at the surface as a relatively strong density anomaly. Freshwater exported via Fram Strait can impact the overflows across the Greenland-Scotland ridge. For this export pathway, the pertinent question is: how much is the freshwater anomaly diluted through the water column, and does it remain intense enough to modify the overflow. These questions need to be addressed by higher resolution models that can resolve eddies and thin surface layers of freshwater.

At the ASOF Science Meeting in October 2010, discussion centred on the ways in which a subarctic observing scheme might recognise the passage of Arctic change as it spreads to lower latitudes and, for the benefit of AMOC observing systems in existence or in prospect further south, how ASOF might prepare advice on the impact of Arctic buoyancy anomalies on the subpolar North Atlantic. Buoyancy was targeted because the projected Arctic freshening and warming both increase buoyancy, and because buoyancy is conserved away from the sea surface. The Labrador Sea was proposed as the place where buoyancy changes may first be clearly distinguished from background noise. Labrador Sea hydrographic structure has been reasonably well-monitored for several years now, mainly due to Canadian efforts at OWS Bravo and on the AR7W section. Knowledge of the full-depth circulation in the subpolar North Atlantic, including the Labrador Sea, is arguably more-complete than anywhere else in the global ocean, due to data from repeat hydrographic sections, floats, and altimetry. There are also some indications from climate models that Labrador Sea Water formation is the most sensitive part of North Atlantic Deep Water (NADW) formation to exported high-latitude anomalies.

After considering overflow transport (underway, continuing) and the total export from the subpolar Atlantic, including all LSW and NADW at say 53°N, (much fewer data; declining support), the ASOF Meeting explored what would be involved in adopting LSW formation rate as a metric to monitor the impact of Arctic outflow anomalies on the MOC. A number of key issues were identified. *First, a consensus on the exact definition of LSW formation rate is required. Second, consensus on how best to measure LSW formation rate is needed.* To date, there have been divergent definitions and divergent techniques to estimate LSW formation rate. This lack of agreement likely explains much of the variability seen in published estimates of LSW

formation rate (see Figure 27.5 of Haine et al. 2008, and the associated discussion). These challenges notwithstanding, the conceptual framework on how to proceed is in place, and future estimates will converge. Maintaining annual AR7W occupations, continuing subsurface float deployments in the western subpolar Atlantic, and periodic CFC surveys are the most important activities to accelerate this convergence. **Third, the pathways and rates connecting Arctic export to the Labrador Sea deep convection areas need to be identified.** Shelf/basin exchange is a particularly hard issue because it determines where buoyancy anomalies are injected into the subpolar flow but it occurs on small scales ($O(1)$ km) with intense dynamics (e.g., see Magaldi et al. 2011 on the East Greenland Spill Jet). Further process studies in the field are needed, but very high-resolution numerical modeling will also yield insight. **Finally, the connections between LSW formation rate and “the MOC” need to be clarified.** Typically, people understand “the MOC” to mean the magnitude of the overturning streamfunction at 30°N (e.g., the IPCC AR4 report). The links between NADW variations in the subpolar gyre and this MOC metric are unclear, however: they need to be elucidated in GCMs, but a satisfactory explanation will require simultaneous resolution of the large-scale North Atlantic circulation, and the details of shelf-basin exchange on much shorter scales. Such calculations will be available in the next few years.

Future observing: To summarise, the future observing of freshwater passing Greenland might reflect the following points:

From models. Although the projections of climate models remain highly uncertain, some robust results seem to be emerging (see Gerdes, Jahn and de Steur, docs in support, Q10; <http://aosb.arcticportal.org/>):- namely the virtual disappearance of sea ice in the exports from the Arctic Ocean, and the increasing relative importance of fresh water transports through the CAA. As the liquid freshwater transport east of Greenland does not intrude into the interior basins easily, the part of the freshwater transport east of Greenland that is most likely to influence deep water formation will decrease with the sea ice export. The liquid freshwater is distributed over a relatively large depth interval, further reducing its impact on deep water formation. On the other hand, the freshwater transport west of Greenland with an immediate and strong impact on deep water formation in the Labrador Sea will gain in importance in the future. *“The recommendation would thus be to focus observational programs on the CAA and Davis Strait because the models indicate that the largest and most consequential changes for the large scale ocean circulation will happen there. However, we believe that continuous measurements of the EGC should be maintained for a substantial amount of time, to monitor whether or not the liquid freshwater export is changing as we expect it to do. Even if these observations do not cover the whole East Greenland shelf, the time evolution of salinity in the EGC can provide important information on how the freshwater transport changes east of Greenland”.* [Gerdes, Jahn and de Steur, op cit].

From theory. The theoretical analysis of Rudels (2011, submitted) carries much the same message, clearly suggesting that monitoring and analyzing changes in the upper layer salinity in Baffin Bay might be ‘useful and perhaps critical’ for estimating variations in the transports through the Canadian Arctic Archipelago and Baffin Bay. It also suggests where these measurements might be made. Rudels’ treatment begins to alert us to the idea that the freshwater flux through Davis Strait and the Canadian Archipelago may not necessarily be simply related and provides motivation for beating down uncertainties in the constituent flux estimates to levels that allow investigation of more subtle effects. For example, the possibility that **an increase in the input of ice/freshwater along the east and west coasts of Greenland, arising through increased melting of the Greenland icecap, might lower the outflow of volume and freshwater through the Canadian Arctic**

Archipelago while at the same time increasing the freshwater flux through Davis Strait. If an ocean-observing system *for climate* is to have the scope to capture this possibility, a sustained series of transport measurements in *both* the CAA and Davis Strait seem vital.



Fig 3.3 The four main continuing elements of Canada's Arctic-subarctic ocean-observing programme in 2011, including the long sampling lines of 'Turbo-C30' (a 2011 development of the Canada 3 Oceans program of the IPY), the JOIS stations in the Beaufort being worked with US (WHOI) and Japanese collaborators, the three key sites of the Canadian Arctic Throughflow study (CATS; yellow dots) and the Canadian Rangers Ocean Watch study ---a downscaling exercise in Cambridge Bay (white dot). (kindly provided by Bill Williams, DFO pers comm.).

From the viewpoint of cost and benefit. [Input principally from Craig Lee (APL-UW), Humfrey Melling (DFO-IO) Simon Prinsenberg (DFO-BIO) & Andreas Muenchow (U Del)]. The reality of limited resources, especially given the goal of maintaining these observations over decadal timescales, will force difficult decisions about what and how to measure and, ultimately, focus efforts toward a limited number of issues. The community cannot afford to instrument the straits with moorings at deformation scale, and will need to optimize resource use across a range of tasks, rather than optimizing on a per-site basis. Such an exercise will depend on a careful assessment of goals: To what accuracy must fluxes be quantified in order to resolve signals of change? How much uncertainty can be tolerated, and in which parts of the estimates? What biological and biogeochemical parameters should be characterized, and at what spatial and temporal scales? Which of these goals are even practical? Are some entirely out of reach? Arguably, we still do not know how to measure ocean fluxes across the Canadian polar shelf to an accuracy that can yield a meaningful measure of inter-annual variability. Three initiatives are underway at the same time, two to measure volume flux through gateways within the Canadian Archipelago, and the third to measure that through Davis Strait. Although Curry et al. (2011) find that Baffin Bay volume and freshwater budget balance to within constituent uncertainties, these errors are large and the closure thus does not provide information useful for exploring more subtle questions. A similar problem has been encountered when attempting to balance total "measured" Arctic volume outflow against "measured" inflow (B Rudels, pers. com.). Clearly, the appreciable uncertainty in the accuracy of measured volume fluxes precludes a meaningful discussion of covariance estimates such as the fresh-water or heat fluxes, which are much more challenging to measure.

Quantitative criteria that specify acceptable uncertainties are needed to guide the difficult choices that must be made to create a sustained observing system. Different methods of volume-flux measurement are used in different gateways, each of which is subject to different sources of error. The value for flux through Lancaster Sound is derived from measurements of current at one or two reference locations; the scaling factors yielding volume flux are based on a year-long calibration period with four installations across the 67-km wide section. Though intriguing, this extrapolation is highly model-dependent, and such empirical models are likely to change with the dramatic changes observed in the Arctic and subpolar seas. These strategies may thus prove problematic if the goal is to quantify Arctic change. The values from Cardigan Strait, Hell Gate and Nares Strait are derived from measurements of current at locations no more than 5 km apart (approximately the internal radius of deformation); the section widths are 8, 4 and 35 km respectively. Here, Doppler ice

tracking has permitted interpolation of flow velocity through the upper 35 m of the ocean, wherein a large fraction of the volume flux here is apparently carried, although direct observations cannot be made. The values from Davis Strait are derived from an appreciable number (15) of moorings, but motions on the internal Rossby scale are not resolved because the section is 330-km wide. This shortcoming has been relieved in part by highly resolved (in space, with ~weekly temporal resolution) hydrographic transects acquired by Sea Glider across the deep part of the strait, but not on the shelves. So, if we do not know volume flux to useful accuracy or the origin or statistical properties of the errors, how can we monitor ocean fluxes effectively in the long term? As Melling concludes, 'we are probably not yet in a position to design an observational system for effective long-term monitoring of volume flux across the Canadian polar shelf', if "effective" is taken to mean "affordable", "unbiased" and "accurate". And 'being stumped by the "easy" variable, namely volume flux, means that prospects for useful monitoring of fresh-water and heat fluxes are even less achievable'. Prinsenbergh is also correct to advise against generalisation: the CAA is a large region 'where one process may occur in one strait and not in the other'.

Nevertheless, Canada's Arctic-subarctic ocean-observing programme continues to include CATS arrays at three sites (Fig 3.3). and although the science return could not be described as certain, intriguing results continue to emerge from the data sets that we have in hand. To name just two: (i) Andreas Muenchow (pers comm. October 2010) reports a linear regression of along-channel pressure gradients against estimated volume flux that explains 70% of the volume flux variance at time-scales longer than 20 days. Despite the caveats and assumptions that Muenchow also describes, this seems a valuable measurement to establish in the long-term and quite affordable relative to other options. (ii) Arctic ice-ocean models are developing rapidly (larger domains; higher resolution) and are on the edge of becoming tools to complement proposed monitoring arrays. In particular such models may be a vital element in the estimation of freshwater fluxes. However, continued relatively comprehensive observations are needed in the short term (5 years) in order to prove such models.

As more general motivation for the CATS arrays, the need to develop a basic understanding of the freshwater budget of the Arctic Ocean, its dynamical forcing and controls and the role of its variability (possibly trends) in the climate of the Northern Hemisphere is growing. We can accept that we have not yet reached that goal, and that it is premature to be designing a long-term monitoring system until we know how to do it properly. But the goal itself remains, and though the effort that ASOF-2 will coordinate will still largely be concerned with developing our capability towards that end (to be described in Section 4.3 below), the attempt is still justified: Arctic freshwater storage has recently increased; at present, this freshwater seems poised to exit the Arctic Ocean; in future, the atmospheric moisture transport to high northern latitudes is robustly expected to increase in all climate projections; and the freshwater production from Greenland is already on the rise. In these circumstances, developing ---by any means---our understanding of the rates, trends and pathways by which this freshwater will pass to lower latitudes is a crucial step towards understanding the impact of these changes on the MOC. The question remains: *How accurate must observational estimates of volume, heat and freshwater flux be to be useful?*

4. Summary and Conclusions

The final part of this Report centres on the observing systems that are needed to complete the tests of Issues 1, 2 and 3 compared with the observing systems that are proposed.

4.1 Sorting out the Inflows

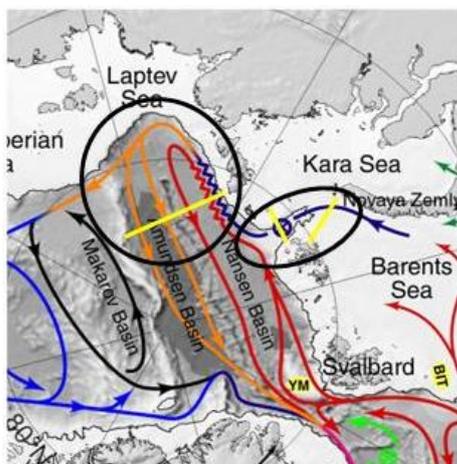


Fig 4.1 Expanded view of the Nansen-Amundsen Basin from Fig 1.9, detailing in yellow the three main sections/arrays that are important to the solution of 'Issue 1'.

In Section 1c above, which listed the required observational components of the problem according to Rudels (pers comm.), we find that many important elements of that list are already proposed or are in prospect (printed in blue). Here we have to presume that the proposals already submitted, such as NABOS, will be successful. No amount of urging in this report will make these proposals more convincing or more complete. The remaining elements that are critical yet for which no plan exists are listed in black in section 1c and are now circled in black in Fig 4.1. The three yellow sections shown in Fig 4.1 break down to the following observational requirements which can be regarded as the *sine qua non* for the solution of this problem:

In the area close to **St. Anna Trough** two tasks remain. 1) To obtain an estimate of the strength and the characteristics of the water from Barents Sea into the Kara Sea. How much does the Barents Sea inflow branch contribute to the different density intervals in the Arctic Ocean water column--- the halocline, the Atlantic layer and the deeper water masses? 2) In the St. Anna Trough the interaction between the Fram Strait branch and the Barents Sea branch needs to be studied. Does warm Atlantic water from the Fram Strait branch 'jump lanes' and join the Barents Sea branch on the upper <500m part of the slope? These two tasks can be studied by deploying two mooring arrays, one between Franz Josef Land and Novaya Zemlya and the other across the northern part of the St. Anna Trough. The first array has previously been deployed twice, in 1992 (Loeng et al 1993) and in 2007. Although the instruments have been recovered from the later (IPY) array, no data are yet available. The suggested array *across* the St. Anna Trough has never yet been attempted. If and when it is attempted, CTD surveys should also be carried out, at least during deployment and recovery operations.

The second critical requirement circled in Fig 4.1 is the need to study the circulation, interaction and possible separation of the two main AW inflow branches where they flow together through the **eastern Eurasian Basin**. Observationally, their study requires a high resolution mooring array running normal to the Slope north of Severnaya Zemlya, similar to the US-Norwegian array planned upstream (section 1d (iii) above and Fig 1.6). Farther offshore on the same transect, realism would suggest a much more sparse moored array, ideally comprising a pair of moorings either side of the Gakkel Ridge and a further pair in the Amundsen Basin, one at the centre and one close to the Lomonosov Ridge. These would be placed to determine whether the suggested return flow of the Fram Strait Branch actually occurs. As already described (Section 1d (ii), fig 1.5), moorings already planned for deployment by F/S *Polarstern* in summer 2011 are well-placed to form part of this array (Ursula Schauer, pers. comm.). To investigate whether the apparent rapid cooling of the Fram Strait Branch in the eastern part of the Eurasian Basin ----- the largest transformation of the Arctic Ocean boundary current in its entire circuit of the Arctic ----- is due to vertical heat exchange with the atmosphere or horizontal exchanges between the two

main inflows, we rely on detailed CTD observations by both ships and by autonomous profilers. Again a number of ITPs and detailed hydrography are already planned by *Polarstern* in 2011 (Fig 1.5).

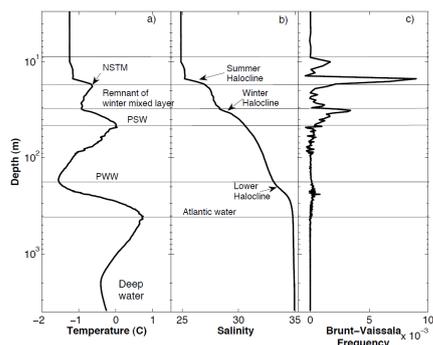
A third general observational requirement devolves from the apparent role of [vorticity dynamics](#) in determining the circulation of the AW-Layer through the Arctic Deep Basins. As Yang points out (p15), the PV study he describes is purely theoretical and remains to be tested in observations in the Arctic Ocean. His suggested implications for our observing system are these: (i) since the two inflow branches carry very different PV into the Arctic Ocean, a better understanding of the dynamical mechanisms that determine the partitioning of transport between these two branches should directly help us understand and predict the circulation changes in the Arctic AW Layer, with the high-PV Barents Sea branch the more likely to overcome the topographic PV barrier over the Lomonosov Ridge into the Makarov and Canada Basins ----the very essence of our study. (ii) Monitoring the layer thickness (and thus PV) in key outlets; the PV transport and the impact on dynamics can be large even if the mass transport is small. (iii) Observations that help us quantify the magnitude of vertical mixing are valuable. Models suggest that wind stress forcing could contribute to the PV budget in the AW-Layer, but are the vertical mixing coefficients used appropriate to the real Arctic Ocean with its strongly stratified halocline layer?

4.2. Coping with change in the Arctic watercolumn

4.2.1 General. In determining its 'driving questions' for this report, iAOOS-Norway suggested that '*What are the heat and freshwater contents of the Arctic Ocean and Nordic Seas this year?*' should be the 'no-matter-what' question for iAOOS' (Cecilie Mauritzen, pers comm). iAOOS-Norway is right. Three complex elements of our observing system go a long way to providing this capability and at least two are already in prospect.

First, With the largest marine reservoir of freshwater on Earth in a state of rapid transition, [the continuation of the Beaufort Gyre Observing System](#) to the point where we understand these changes and their drivers is clearly a priority for any sustained prospective observing system. A 5-year continuation of the WHOI BGOS and ITP programs from 2009-14 is already in hand, with intensified ship-based sampling and shared logistics with Canada and Japan augmenting the year-round measurements from three of the original four BGOS moorings (sites A, B and C; see earlier discussion). Widening our focus beyond the Beaufort, we are coming to realise that the [Makarov Basin](#) should be a second site for concentrated observations, particularly its undersampled southern part, though plans for this are less certain. Justification lies in a decade of evidence (eg Morison et al 2000, 2011) which shows that this is the Basin through which the Atlantic-Pacific Front and the boundaries of the Transpolar Drift tend to shift on interannual and decadal time-scales. Third, the brand new [combined use of satellite altimetry \(ICESat\), satellite gravity \(GRACE\), ocean hydrography \(ships and autonomous platforms\) and ocean bottom pressure \(moorings\) to link and explain Arctic Ocean changes in terms both of ocean circulation and hydrography](#) (Morison et al submitted) must be continued across as broad a sector of the Arctic Deep Basins as practicable. Satellite altimeters observe the total sea level variation, including the signal caused by temperature and salinity fluctuations (the steric effect) and non-steric barotropic and mass variations. Separately, gravity satellites like GRACE measure temporal changes in the Earth's gravity field caused by the movement of water masses. A well-designed in-situ

hydrographic sampling network – with judiciously deployed ocean instrument technologies – would ensure the most accurate quantification of the sea level, circulation and mass changes of the Arctic Ocean. GRACE is predicted to last until at least 2015 or maybe longer, and CryoSat 2 should provide the necessary altimetry. (A proposal for the combined use of GRACE and CryoSat2 for this purpose has been submitted). Observing System Simulation Experiments (OSSE) will be necessary to optimize the cost & benefit of an expanded and sustained in-situ bottom pressure array, providing guidance on mooring locations and defining the measurement accuracy and frequency needed, but a small scattering of bottom pressure gauges from other projects will already be in place (eg on the three continuing BGOS moorings, and on the NPEO).

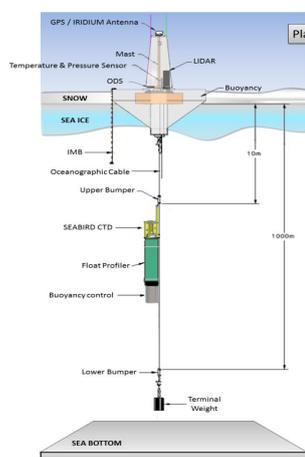


In the body of this report, these more-general remarks were followed by three studies that were much more specifically targeted at three of the questions submitted by the Community (Annex A, questions 7, 15 and 2). Though not the only questions directed at the Arctic watercolumn, these three combined importance and diversity with some new technical or modelling advance that had recently raised their likelihood of achievement from ‘desirable’ to (or towards!) ‘feasible’. Though the climatic importance of all

three derived from individual warm layers in the upper watercolumn of the Canada Basin, so that they might each be illustrated on a single CTD profile (**Fig 4.2** left; from Jackson et al 2010), in fact the origins of these layers (Arctic, Pacific, Atlantic) and their likely climatic impacts (immediate, potential, remote/lagged) are as diverse as could be imagined.

4.2.2 The Near Surface Temperature Maximum (NSTM).

How might we observe the effects of an ice-free polar ocean on the regional atmospheric circulation? Recap: Overland and his co-workers conclude from model results and from the recent unusual nature of atmospheric conditions over the Arctic that the continued reduction of sea ice in summer and other arctic climate changes are not simply due to natural chaotic and anthropogenic processes. The ‘Arctic climate feedback loop’ that they describe (Overland and Wang 2010) is mediated by heat provided from the ocean surface, and they further suggest that this heat provision may be lagged, the result of subtle changes in the upper ocean between summer and fall. Specifically, heat entering the ocean in summer becomes capped-off and preserved beneath a fresh upper layer (ice-melt) so that its release is delayed



until mixing resumes in fall. The effects of the newly open Polar Sea on the regional atmospheric circulation, and the element of predictability implied by this delayed response, both argue the importance of tracking the end-of-summer ocean heat content on a yearly basis. While all types of upper ocean sensors would be useful here, ranging from autonomous profilers (ITP) to ship-based CTD and (conceivably in future) gliders and floats, the newly funded amphibious platforms to be provided by iAOOS France (**Fig 4.3**, left) will clearly provide something quite new and essential to the task under discussion. Their promise of linking, *from the same platform*, the subtleties of

change in ocean heat storage, ocean stratification and ice state with the properties of the lower troposphere must represent a major step forward in our understanding of the impacts on climate of the newly open polar sea. As our earlier discussion suggested (p 28), the critical path will lie not so much in the provision of platforms and sensors, already funded, so much as in the calibration and maintenance of its unattended sensors; so this non-trivial aim becomes a primary task of the legacy phase. In addition to the IAOOS drifting platforms themselves, the system will rely on regular and extensive multiple atmospheric soundings from four shore stations almost equally distributed around the periphery of the Arctic: Barrow, Eureka, Ny Alesund and Tiksi. The continuation of the so-called "Pearl station" at Eureka --- probably one of the most advanced of these integrated systems---is particularly important.

4.2.3 The Pacific Summer Water sub-layer. *Will the warmth of the PSW layer in the Canada Basin become accessible through an increased depth and intensity of turbulent mixing as the sea-ice retracts?* Recap: the analysis of ITP profiles of temperature and salinity from the central Canada basin in 2004–2009 (Toole et al 2010) reveals that intense stratification sets an upper bound on mixed layer depth of 30-40 m in winter and 10 m or less in summer, greatly limiting the flux of deep ocean heat from the PSW sublayer to the surface. However as that report points out, it is conceivable that over longer periods this heat-source could become accessible. And if it could and does, the PSW heat presently stored as intrusions in the 40-100 m depth range is of sufficient magnitude to melt about 1 m of ice (the 'ticking time-bomb of the Canada basin' as John Toole, not unnaturally describes it). The question at issue then is 'What are the intensities and the physical mechanisms supporting heat and fresh water fluxes between the Arctic surface mixed layer and the waters immediately underlying, and how might those fluxes change in future if we transition to a seasonally ice-free Arctic?'. Apart from the CTD profiles to be provided by the ITP program, continuing until at least 2014, two new approaches were suggested above (p 30-31) to be helpful in solving this question, both of them already planned or are under development. The first and more conventional approach is to keep track of the spreading pathway of the Pacific Summer Water (PSW) itself in the western Arctic. For this purpose, the [UW moored array in Bering Strait will continue](#), and Koji Shimada (Tokyo University of Marine Science and Technology) and colleagues from the Korean Polar Research Institute plan the [annual working of two zonal hydrographic sections occupying the full span of the southern Canada Basin](#) (Fig 2.11), using the new Korean icebreaker *ARAON*.

The second approach is to use new technology to directly assess the subtle changes in upper-ocean mixing under the retracting ice-cover. In a development of the ITP system, [direct measurements of the velocity structure in the water column under Arctic ice](#) are now possible using a WHOI Ice-Tethered Profiler with Modular Acoustic Velocity Sensor ---the so-called ITP-V. The instrument exists, with data recovered from first deployments in fall 2009 and fall 2010, and with a further deployment planned for Fall 2011 using a 2nd unit with new bio-optical sensors.



Fig 4.4. Ice Tethered Profiler with MAVS entering the hole in the ice. From Williams et al 2010.

4.2.4 The Atlantic-derived Sublayer. *Observing and modeling of transient signals connecting the Arctic Ocean and the Nordic seas.* Recap: unlike the period from the 1950s to the 1980s, the warm episodes of AW inflow that entered the Arctic in two separate phases after 1990 were not compensated in density but were associated with density decreases of around 0.1 kgm^{-3} (Karcher et al. submitted). We may presume that these low density and rather deep anomalies, currently circulating through the Arctic, will drain south through Nordic Seas to decrease the dense water overflow through Denmark Strait, hitherto regarded as relatively unchanging. The overflow is hydraulically controlled, and the volume flux depends linearly on the density contrast across the sill, and quadratically on the upstream interface height. Model experiments by Karcher's group at AWI suggest that a 30% decrease in baseline overflow transport will occur over several years as the anomalies drain from the Nordic Seas.

Fig 4.5 repeats the 'target event' and its timing from our earlier discussion, as simulated by Karcher's group. Four main groups of tasks seem sensible if we are to capture the impact of this rare and climatically-important event (see earlier text). First, though a lack of repeat sections over long periods (decades) means that the detection of propagating AW anomalies is very difficult with existing data, [repeat hydrography in the Lincoln Sea and the southwest Eurasian Basin](#) would still be of value in capturing these signals as they exit through Fram Strait.

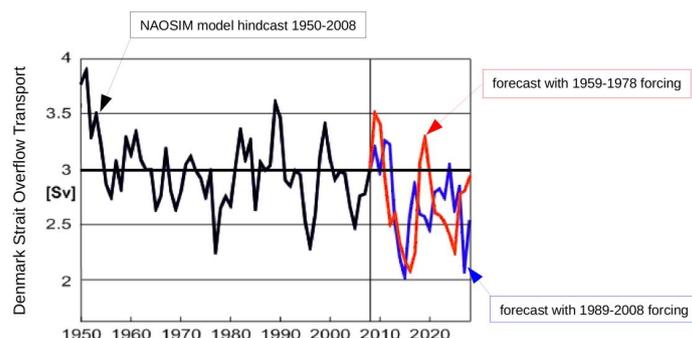


Figure 4.5. Timeseries of Denmark Strait overflow transport, adapted from Karcher et al. (2011). See earlier discussion in Section 2.4 and Fig 2.14. The red and blue lines show diminished overflow transport as buoyant anomalies drain out of the Arctic.

Second, a [synthesis of hydrographic and tracer data and different modeling approaches \(including hindcasts, forecasts, data assimilation, and idealized models\)](#) is recommended to fully document and understand the transient AW signals in the Arctic and their influence on the overflow. Third, Karcher proposes an “[all hands on deck](#)” approach to observe the anomalies, particularly in the northern approaches to [Denmark Strait](#), building upon the existing moorings of the EU-THOR program (expected to be maintained until 2016) and the 13-mooring US (WHOI)-Icelandic (MRI) - Dutch (NIOZ)-Norwegian (UiB) array planned for the ‘Kogur Line’ in August 2011 – August 2012 (see Fig 2.16). Fourth, [novel quantitative network design methods](#) may help to develop the best observational strategy for the deployment of that ‘all hands’ effort. The ASOF-2 WG under Tom Haine and Michael Karcher will coordinate these approaches.

4.3. Revitalising our ideas about Greenland, freshwater and the MOC. As already discussed, we have not yet achieved the ASOF goal of providing a balanced set of freshwater flux measurements for all Arctic gateways. Designing a long-term monitoring system is not yet feasible. Instead, pragmatism suggests a field program aimed at developing our capability towards the ASOF

objective. Based on current evidence, four tasks in particular seem relevant and though our ideas are bound to change as our data, theory and modeling develop, these four tasks are likely to be of lasting importance to the issue of 'freshwater passing Greenland'. Even at our present basic understanding of that system, these four development tasks seem linked. Freshwater passing around the Greenland shelves is larger than we thought (4.3.1; Holliday, NOC) and is likely to field increasing contributions from the expected increase in the calving and melting of the Greenland ice cap. If Rudels analysis proves valid, the introduction of an increasing injection of freshwater along the eastern side of Baffin Bay *may* ultimately bring about trends of opposite sign in the freshwater flux through the CAA and through Davis Strait. If so then the task list must include developing affordable observing systems at both the CAA (4.3.2; Prinsenberg & Melling, IOS) and Davis Strait (4.3.3: Lee, APL-UW). And whatever freshwater volume is delivered by this complex system of exchanges, there is a developing AMOC observing community further south which will need to know what that number is, how it is changing, how its sources are partitioned and how (depth? path?) it is delivered to the North Atlantic circulation. Establishing an effective metric for that delivery is our fourth task (4.3.4; Haine, JHU). ASOF-2 under Haine (JHU) and Karcher (AWI) will coordinate these approaches.

4.3.1 Developing our knowledge of the freshwater flux on the Greenland shelf & shelf-break. *Input from Penny Holliday, NOC.*

Analysis of high resolution hydrographic and velocity sections taken around southern Greenland in 2008 revealed the detailed structure of the currents carrying Arctic freshwater into the North Atlantic (Holliday et al, 2011). All of the contemporary freshwater export was captured by the sections from the east Greenland coast across the Irminger Gyre, and from the coast of Labrador to southwest Greenland. The results highlight the fact that most of the freshwater is concentrated in narrow (75-150 km) and shallow (100-250m) currents on the shelf and shelf-break. The currents are highly variable seasonally and interannually but in Aug-Sep 2008, to the east of Cape Farewell, 42 mSv of freshwater were transported southwards in the upper layers, and 23 mSv in the overflows. In the Labrador Sea an additional 68 mSv from Davis and Hudson Strait flowed southward in the upper 200m. The summer 2008 data, ongoing freshwater flux data from arrays in Davis and Fram Straits and output from a high resolution ocean-ice model suggest a recent reduction in freshwater transport west of Greenland, while export via the eastern route has not changed.

The implication of these results is that monitoring the highly variable, shallow, narrow boundary currents on, or close to, the continental shelves is essential if we are to understand the flow of Arctic freshwater into the North Atlantic. The southern Labrador and Irminger Seas are good locations for monitoring because they capture the combined freshwater from many routes and sources as they enter the subpolar North Atlantic. Holliday suggests two suitable sections for these observations (set into the larger observational context in Fig 4.7 below), the one close to AR7E and the other coincident with the German Labrador Sea exit array to match the developing plans for a subpolar MOC monitoring array (OSNAP). The key requirement lies not so much in the exact location (the southern section might equally well be sited along AR7W) but in the fact that observations need to extend right across the shelf from the coast to the deep water, and to extend to the surface. The observations need to be frequent enough to define the seasonal cycle properly, so a combination of ice-proof moorings and frequent glider sections would be ideal. Certainly hydro/LADCP sections are not sufficient. Some technological development is clearly required.

4.3.2 Developing the Canadian Arctic Throughflow Study (CAT). *Input from Simon Prinsenberg & Humfrey Melling, DFO Canada, and Andreas Muenchow, U Del.*

As already discussed, climate projections agree that the freshwater fluxes around Greenland will increasingly take the western route through the CAA. Rudels' study underlines the importance of maintaining and comparing the transport estimates through the CAA *and* the Davis Strait since there are reasons to do with an increased melting of the Greenland ice-cap, why their trends may diverge. While they remain written into the Canadian arctic programme, there are good reasons to monitor the total transport and freshwater flux through all three of the present straits (see Fig 3.3). "One process may occur in one strait and not in the other"; ideally, it is the total CAT that is of greatest interest; and although the less costly and more practical logistics would seem inevitably to favour Barrow Strait (a CCG vessel is already there on standby without interrupting its primary mission), in fact the use of a one-year cycle for operations in Lancaster Sound but a three-year cycle in Cardigan & Nares Straits has tended to even out this difference. What we recommend here, of course, will have little or no bearing on whether choices based on affordability have to be made; that will be a national decision. But we can usefully discuss the means of optimizing the observing plan for the Barrow Strait, the location of the longest time-series (since 1998) and easiest logistics.

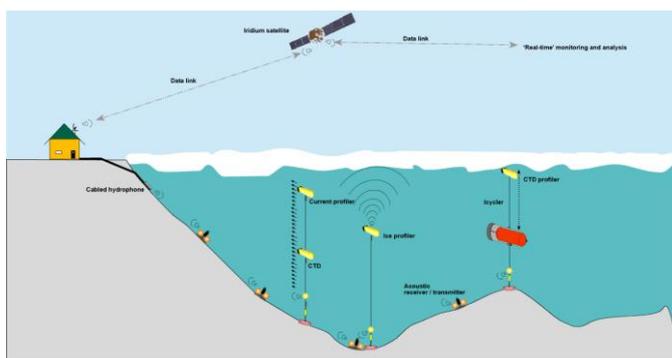


Fig 4.6. A potential means of achieving a difficult but climatically-important measurement at modest cost through the use of an acoustic/cable/satellite link to provide oceanographic data from Barrow Strait in real time.

The optimization of the Barrow Strait array(s) might take place in four steps (Simon Prinsenberg, BIO pers comm): (i) in cooperation with the Canadian Defence Research Development Corporation (DRDC), a plan is already underway to use an acoustic/cable/satellite system to provide oceanographic data from Barrow Strait in real time (Fig 4.6); (ii) with limited annual ship time (~10 days per annum) but with *two-year* moorings, one might double the number of sites occupied by the monitoring program, thereby better tracking the changes in Lancaster Sound; (iii) moorings might also be introduced for the separate task of obtaining real-time ice drift/draft data to assimilate into forecast models, mainly for marine transportation safety but also useful for monitoring the marine ecosystem. A week-long trial mooring has already been successful, reporting directly to BIO, and instrumentation is being prepared to provide histograms of ice drift/draft in real-time from summer 2011; (iv) though regression models only predict a fraction of the variance, Ingrid Peterson's success in linking transport to the large-scale windfield (not shown) is sufficiently intriguing to check its continued applicability in the light of environmental change by reoccupying the mooring line periodically with the full array.

4.3.3 Developing the Davis Strait Array *Input from Craig Lee (APL-UW), Brian Petrie and Kumiko Azetsu-Scott (BIO).*

The long-term observing system in Davis Strait characterizes the integrated CAA outflow after it has undergone pathway transformation during the transit through Baffin Bay, immediately before it

exits into the Labrador Sea. It also documents changes in the (relatively) warm, north-flowing Irminger and West Greenland Currents, which have been implicated in the accelerated melt of the Greenland icecap. The Davis Strait array, in operation since 2004, includes 12 moorings across the deep Strait and over both the Baffin and West Greenland shelves, complete with upward looking sonar to quantify ice draft and ICECATs, instruments designed as part of the Davis Strait program expressly to sample the region near the ice-ocean interface. Because the moored array cannot resolve deformation-scale variability in the dynamically wide strait, autonomous Seagliders, designed for extended (many months) operation in ice-covered waters, are being employed to collect repeated high-resolution sections at timescales of roughly one week. Gliders have executed two 6-month missions under the wintertime Strait, revealing large structural changes in the upper ocean and providing a sense of the important lateral scales. Neither could have been accomplished with any reasonable number of moorings. These data are being combined with the coarser moored measurements to refine flux estimates, and reduce uncertainties, while also providing finer-grained information about composition- a much improved ability to examine the fluxes by watermass class. An extensive marine chemistry program, including nutrients, oxygen isotopes, total alkalinity and total organic carbon, provides critical measurements that integrate over large spatial and temporal scales, while acoustic monitoring of marine mammals documents changes in cetacean abundance alongside measures of environmental change.

With recent funding from NSF-OPP and additional support from DFO Canada, the Davis Strait observing system will continue through 2015 to provide an 11-year time-series at this critical gateway. In addition to adjusting mooring locations to optimize coverage, most elements of the new array will move to a 2-year service interval. The lighter, riskier shelf installations will be serviced annually from a chartered Greenlandic vessel. Gliders will also be serviced using local charters. Bottom pressure gauges will likely be added to the array during the coming years. Analysis efforts focus on quantifying fluxes and investigating possible mechanisms for driving observed variability. Given that collection of extended time series and reducing uncertainties are top priorities, lowering costs and improving efficiency become important goals. The current analysis seeks identify a process-based (as opposed to empirical) model that could be used to infer fluxes from glider-based sections and a greatly reduced moored array.

4.3.4 Developing an interface with AMOC. Input from Tom Haine.

Coordinating these efforts to observe the northern seas with programs that focus on the Atlantic MOC will define their mutual success. We cannot prescribe how this interface will work in detail, but we can identify essential aspects of the observing system that should be considered during AMOC program planning. They are as follows:

First, **annual occupations of the AR7W section**, with hydrographic and tracer chemistry measurements (including CFCs), must continue. The AR7W timeseries, now extending more than 20 years, is critical to reveal the properties and volumes of LSW water being formed each winter. Cessation of LSW formation may be the best way to diagnose a slackening MOC, and AR7W is the best place to watch LSW formation. Expanding the AR7W observing program is desirable. This could be achieved in several ways, but the most obvious and cost-effective are to increase the deployment of Argo floats in the Irminger and Labrador Seas, and to commence a rolling program of glider measurements in the Labrador Sea to sample AR7W throughout the year. Resuming the Ocean Weather Ship Bravo mooring observations is another good way.

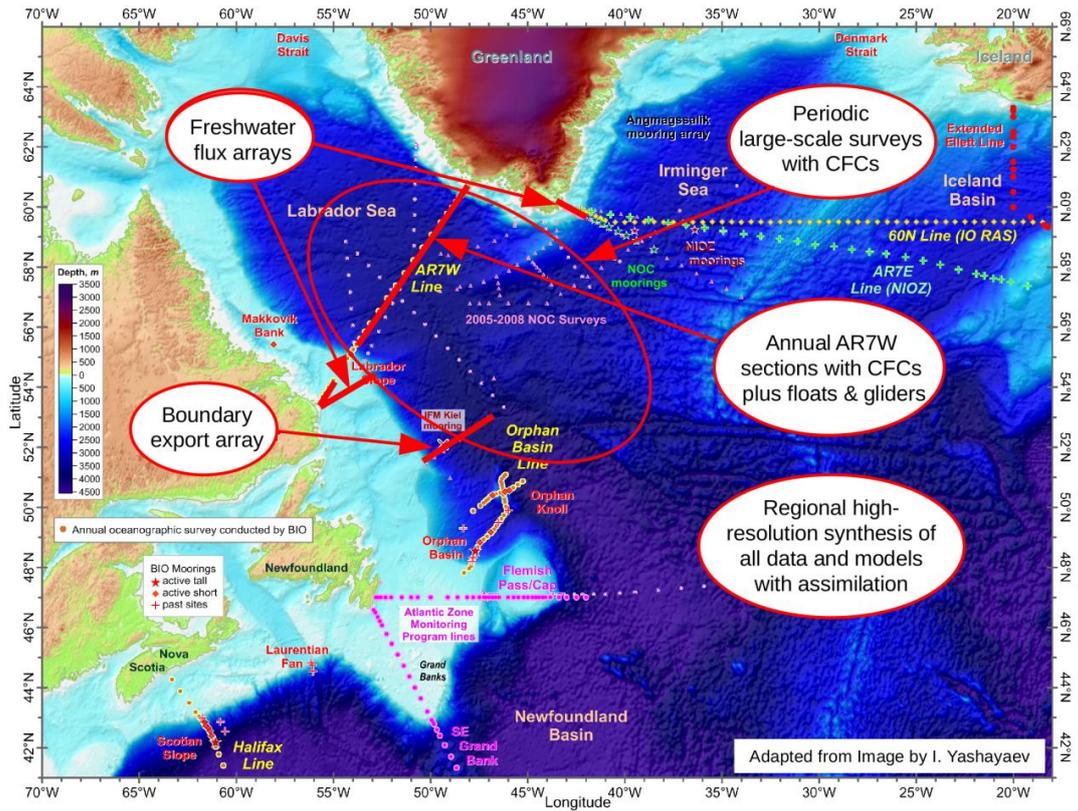


Fig 4.7. Suggested observing plan for interface with AMOC/OSNAP (Tom Haine). For explanation see text

Second, **NADW flux measurements are equally important**. Multiple options exist. Most useful is a section that captures the export from the subpolar gyre, including overflow waters and LSW. The 53°N velocity/hydrography section targeted by OSNAP is an excellent choice, although the existing timeseries there is short, and distinguishing between exported and recirculated waters is challenging. A dense moored current meter array with hydrographic profilers and gliders is the best approach at this time. Continuing overflow velocity/property measurements is desirable, especially at the 63°N section off southeast Greenland which intercepts overflows east and west of Iceland. Third, **periodic large-scale surveys of the western subpolar gyre** are needed to quantify the volume and character of LSW and overflow watermasses and their changes (Kieke et al. 2006 have shown the value of such surveys). Tracer chemistry measurements (CFCs) are required. Surveys every 5 years would be ideal. **Freshwater fluxes on the shelves** need to be measured, as discussed in section 4.3.1. In addition, we need to understand how Arctic freshwater on the shelves is exported offshore, to what depths, and in what concentrations. These questions are ideally addressed by a process study on the Labrador or Newfoundland shelves, and high-resolution numerical modeling has an important role to play in understanding, interpolating, and extrapolating the field data.

Finally, the subpolar North Atlantic sustains a multitude of diverse observing efforts. Although not primarily aimed at Arctic export impact on the AMOC, these efforts must not be overlooked. Three examples are the Canadian Atlantic-Zone Monitoring Program sections on the Newfoundland shelf, the mooring timeseries in the southern Irminger Sea, and altimetric sea level measurements of the strength of the subpolar gyre circulation. **Synthesizing** all these data sources with high-resolution regional circulation models **and data assimilation** is critical to obtain a complete picture. Elements of this effort are being developed (e.g., the MIT Arctic/Subpolar Gyre State

Estimate) but they need to be improved and expanded. Indeed, synthesizing all the available data this way is the best way to interface with AMOC programs further south.

5. Coda. Looking back on this exercise and attempting to summarise, it is probably easiest to define what this report is not. *It is not a repeat of other attempts to define the future of Arctic observing.* Though there are data sets that will be needed from our Northern Seas every year --- for example the ‘no-matter-what’ questions posed by iAOOS-Norway (p 48) --- we have no particular requirement for sustainability *per se*. Instead we have largely concentrated on identifying questions that might be tested to a conclusion during an IPY ‘Legacy Phase’ of 5-10 years duration, with effort switching to other issues (presumably) as these tests conclude. *The Report is not particularly ‘Arctic’ either.* If there is one conclusion that emerges from the sequence of four iAOOS Reports, it is that we can’t understand Arctic change just by studying the Arctic. Two of the three ‘issues’ that form the basis of this report concern the ways and means by which subarctic change is imposed on the Arctic deep basins from Nordic Seas, and the rates and pathways by which Arctic change may reach south through subarctic seas to impact the MOC. *It is not complete.* Though the questions that we seek to answer seem among the most important from our present understanding of the role of Northern Seas in climate, there are and will be others as that understanding deepens. *And it is not yet achievable.* Issues of ‘access’, cost and or technical capability still remain, though it is remarkable and heartening how many times in the course of this report some unforeseen new observing technique or some new source of funding or some new international collaboration has emerged just in time to meet some newly-defined scientific need. However, *the report is up-to-date*, reflecting the very many times that PIs have contributed their results and ideas before publication --- before submission even! As a result, an exercise that might have seemed, at its start, uncomfortably like compiling a ‘wish list’, turns out to have point. Remarkably few of the tasks described would now seem beyond us, and since the need to understand the processes, changes, feedbacks and climatic impacts of the ocean–atmosphere-cryosphere system of the high Arctic has certainly not diminished, these ideas for action are now commended to the IASC for implementation under the aegis of its new Marine Board (AOSB).

Bob Dickson, Cefas, March 2011

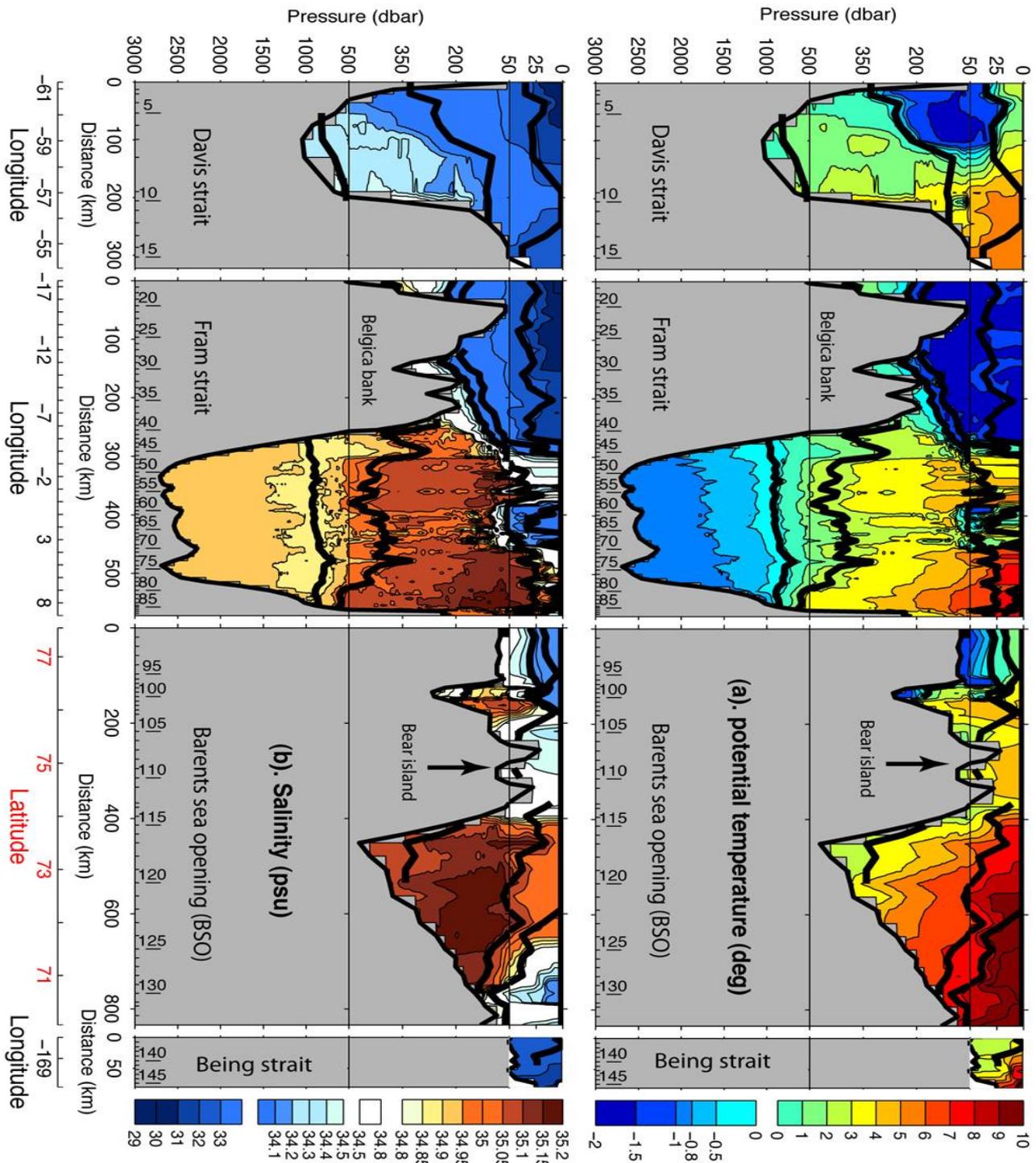
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