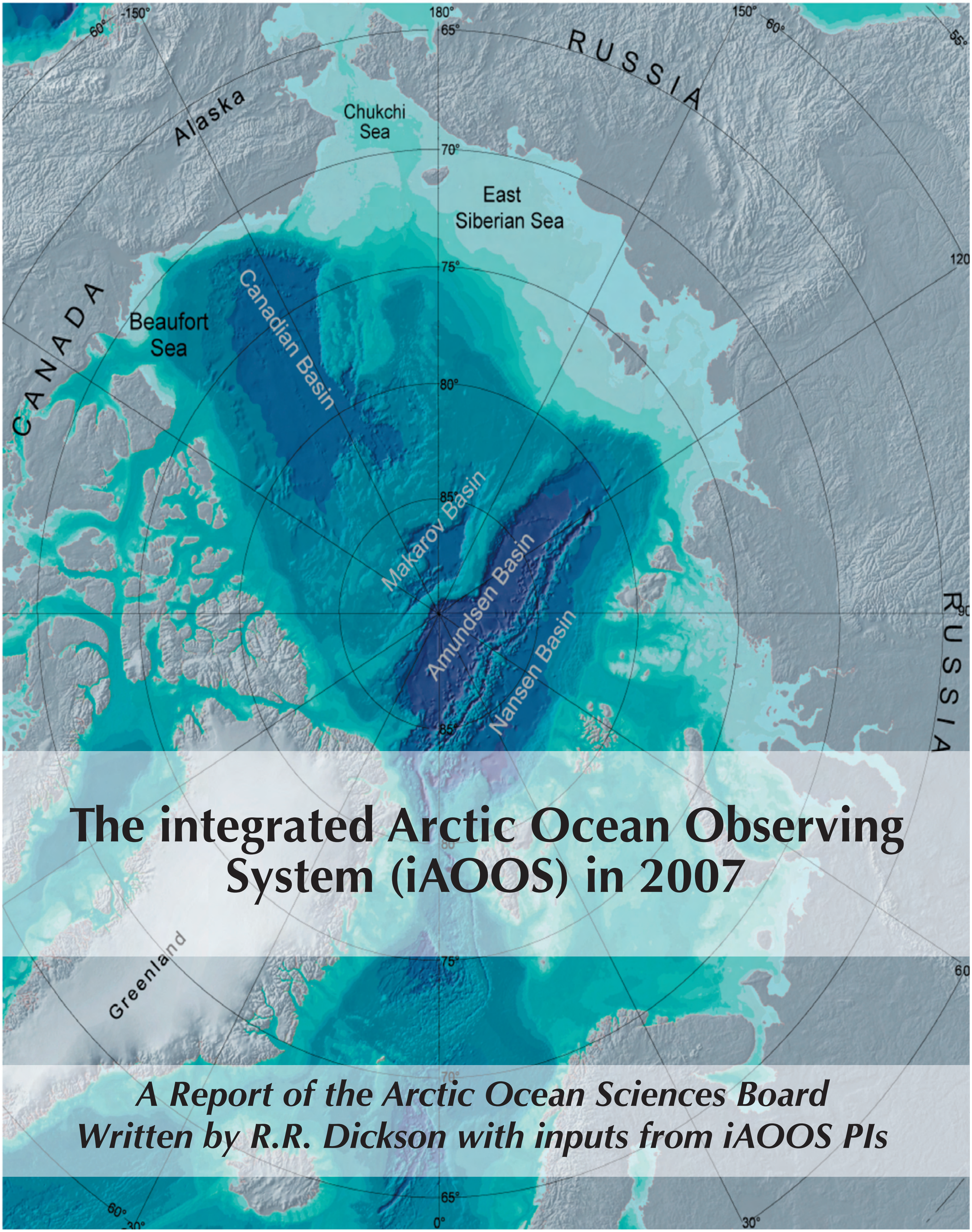


The integrated Arctic Ocean Observing System (iAOOS) in 2007

A Report of the Arctic Ocean Sciences Board

Written by R.R. Dickson with inputs from iAOOS PIs

1. Introduction

The integrated Arctic Ocean Observing System (iAOOS), originally conceived and sponsored by the Arctic Ocean Sciences Board (AOSB), is one of around 110 'Coordination Proposals' approved by the Joint Committee for the International Polar Year, designed in this case to optimise the cohesion and coverage of Arctic Ocean Science during the IPY. As such, iAOOS is not a funded programme in its own right but a pan-Arctic framework designed to achieve optimal coordination of funded projects during the IPY. It has a Science Plan (see Dickson, 2006) based on the >1150 Expressions of Interest received by the IPY; reflecting these proposals, its main concern is with Arctic change, including all aspects of the role of the Northern Seas in Climate, and it draws its primary focus on the present state and future fate of the Arctic Ocean perennial sea-ice.

2. Aim

The present report concentrates largely on the physical oceanography of iAOOS and has two main aims. First to provide a concise account of the ***activities*** of the main iAOOS flagship projects during 2007---cruises taken, instrumentation deployed, measurements made and models being developed. The report will also include a summary schedule describing the additional work planned in 2008 and (where evident) a brief assessment of what remains to be done to maximize the effectiveness of iAOOS coverage in either year. With the cooperation of PIs, a second component of the report will describe ***first results***, concentrating in particular on cases which demonstrate the validity of an iAOOS programme for the IPY: for example, cases where the emerging science (observations and modelling) could only have been achieved by a particularly close international coordination, those where long-awaited results are now being achieved by a novel or enhanced observing effort, or those which provide the Community with advanced warning of extreme or climatically-interesting events passing through our northern seas to which PIs might contribute while they are still evolving. These two aims overlap in the text of this Report, partly to avoid repetition, but also to attempt a coherent description of scientific activity and achievement across large sectors of our northern seas in a relatively-few pages.

3. Scope

The full-latitude scope of iAOOS may be surprising to the Reader who may expect this Report to be confined to the High Arctic. However as it evolved, it became clear to the AOSB and to the PIs involved that the scope of iAOOS could not be restricted to the Arctic Ocean. We now know from major studies such as the Arctic-Subarctic Ocean Flux Study (ASOF; http://asof.npolar.no) that the two-way oceanic exchanges that connect the Arctic and Atlantic oceans through subarctic seas are of fundamental importance to climate; that change may certainly be imposed on the Arctic Ocean from subarctic seas, including a changing poleward ocean heat flux that is central to determining the present state and future fate of the perennial sea-ice; and that the signal of Arctic change is expected to have its major climatic impact by reaching south through subarctic seas, either side of Greenland, to modulate the Atlantic thermohaline 'conveyor'. Reflecting this fact, and despite its main preoccupation with Arctic change, the iAOOS study necessarily spans the ***Arctic Ocean***, ***Canadian subarctic***, and the ***Nordic Seas*** to the northernmost north Atlantic, and these form the main geographical divisions of this Report.

4. Observing the Northern Seas in 2007. A brief summary of Projects and Progress

In the space available we cannot attempt to record every observation across the Northern Seas. We are forced to be both *succinct* and *selective*. Here, in keeping with the AOSB mission to foster international collaborations in the Arctic Ocean and surrounding seas, we place emphasis on cases where emerging results (observations and modelling) in the principal projects could only have been achieved by a particularly close international coordination, or those where long-standing observational gaps are now being filled by a novel or enhanced observing effort (Section 5 below will attempt to summarise the observing system on a more system-wide scale).

4.A Arctic Ocean

4.A.1. DAMOCLES in 2007; the voyages of R/V *Akademik Fedorov* and F/S *Polarstern:* The principal field effort of the EC-DAMOCLES integrated project in summer 2007 consisted of two main research cruises aimed at understanding past and present environmental changes in the Arctic Ocean, and at improving projections of future change: The first, by *F/S Polarstern* in August-September was led by an A-W-I team under Ursula Schauer, but with scientists from Germany, Russia, Finland, the Netherlands, Spain, US, Switzerland, Japan, France and China. The main tasks were to re-work historic sections, to follow the warming layer of Atlantic Water in the Eurasian Basin, to trace the spread of shelf water offshore, and to deploy a range of autonomous instruments including ITPs and POPS (see below), which will drift freely while collecting data on currents, and on T & S distributions. During the second, DAMOCLES scientists continued this effort, deploying more autonomous observing platforms while

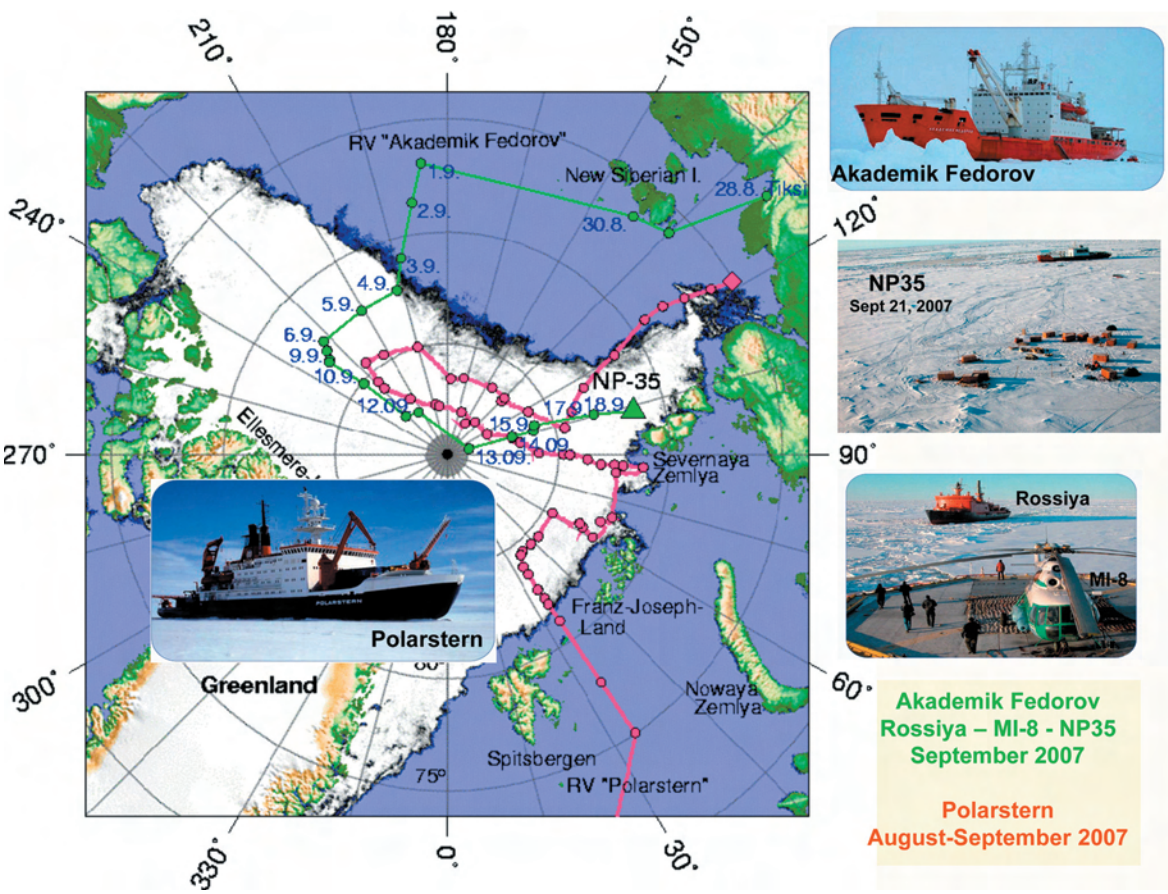


Figure 1. Cruise tracks of F/S *Polarsten* and R/V *Akademik Fedorov* in summer 2007

participating aboard the Russian-led *Akademik Fedorov* expedition in August-September 2007 whose main business was the installation of the new Russian drifting station NP35 (Section 5.7).

4.A.2. Progress of emergent sub ice systems in DAMOCLES & partners during 2007; the new family of instruments: To provide the necessary step-change in the provision of data from the Arctic watercolumn, a considerable effort has been devoted in DAMOCLES and its partner projects to the use of new autonomous observing systems. Five types of new system have been developed for that task:

- **AITPs (UPMC, Martec, Aquatec/UK, Seascan/USA):** Unlike the standard ice-tethered platform, which is not designed to communicate with other sub-ice systems, the acoustic ice-tethered platform (AITP) forms the vital link between sub-surface underwater vehicles and satellite transmission. It operates as a SOFAR sound source at 780 Hz with acoustic transmissions 4 times a day + telemetry encoded latitudes and longitudes with 12 total transmissions per day. The system operates via a RAFOS receiver at 1560 Hz. Acoustic modems are incorporated for short range navigation (10kms to 10 miles), including homing capability and high speed communication (100 kbits/s) between Gliders, Floats and AITPs. Satellite communication is achieved via Iridium and GPS positioning. The DAMOCLES plan calls for 10 AITPs and after first trials aboard *Akademik Fedorov* in 2007, the 1st deployment of 8 units is planned for spring 2008 to be air-landed using twin-otter aircraft, initially to 'talk' to ULS floats. The remaining two AITPs will be deployed by R/V (*Xue Long*?) in Summer 2008.
- **POPS (Metocean and Martec):** The Polar Ocean Profiling System (POPS) is an observation system using Argo floats that has been extensively used in the Arctic Ocean by JAMSTEC, Japan. A platform for POPS is installed on sea ice and a cable equipped with Argo floats is dropped into the ocean. The float measures water temperature, salinity, and pressure in the range of 10 m and 1,000 m depth.
- **MOPS (UPMC and Martec):** In July 2007, the first mooring of the DAMOCLES Moored Ocean Profiling System was deployed by R/V Hakon Mosby on the Yermak Plateau in 744m depth [80°36'N, 715.7'E] in cooperation with the Geophysical Institute Bergen (PI Ilker Fer). The mooring is equipped with two main devices: 1) a long range 75 kHz ADCP fixed at the lower end of the mooring looking upward and 2) an ARGO float profiling along the cable above the ADCP from 500m depth up to 50m beneath the surface once a day to explore the T-S characteristics of the Atlantic layer in particular, as well as current speed and direction in all depth layers. The CTD is a Seabird sensor of the same type as MMP, POPS and ITPs; recovery is planned for July-August 2008.
- **ULS Float (UPMC, Martec, ASL/Canada, Aquatec/UK, Seascan/USA).** Now completed (see Fig 2). Will drift beneath the Arctic ice at 50m depth for up to 2 years to provide information on ice keel-depth using Upward Looking Sonar. Will act as SOFAR transmitter and RAFOS receiver and will include an acoustic modem to provide homing navigation for gliders. Satellite communications will be by iridium/GPS when surfacing. The DAMOCLES plan calls for 8 ULS floats, the first 2 to be deployed in spring 2008, air-landed by Twin Otter aircraft, the remaining 6 by R/V in summer 2008.

Figure 2. DAMOCLES ice-profiling float based on the MSI Provor system

4.A.3. Sub ice systems in DAMOCLES; the 2007 deployment and first results: In such a data-poor region as the Arctic Ocean, the collaborative deployment of new, functioning, autonomous instrumentation must represent the central achievement of DAMOCLES in 2007. By contrasting the ***actual*** with the ***planned*** deployments, Fig 3 illustrates the effect of the dramatic thinning and retraction of the Arctic sea-ice on the DAMOCLES ice-based observatory. The ***planned*** array is shown in light blue; AITPs as circles and ITPs as double triangles. The array ***actually deployed*** is shown in colour; 5 POPS plus 1 ITP (orange symbols) had already been deployed [3 POPS with Tara in September 2006 and 2 POPS plus 1 ITP (at NPEO) in April 2007]; 5 ITPs were deployed independently by the *Louis St Laurent* in the Beaufort Gyre (green symbols); to these, DAMOCLES added the following in summer 2007 (yellow symbols) -- a further 3 ITPs + 1 ITAC by *Polarstern*, and 5 ITPs +3 IMBs by *Akademik Fedorov*. The *Fedorov* also established the ice-camp NP 35 (yellow triangle).

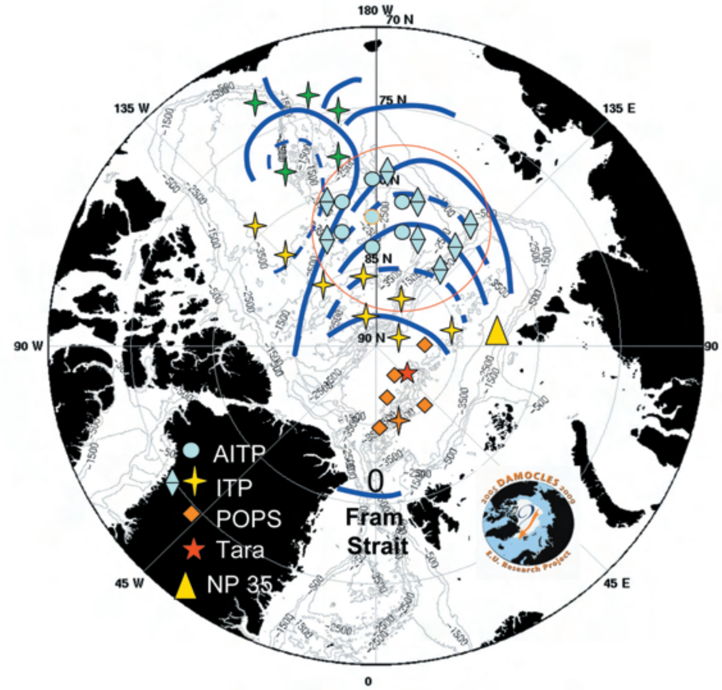


Figure 3. Planned and actual ice-based instrument deployments in summer 2007. For explanation see text.

In a single deployment, a current-profiling ITAC, an AOFB turbulence sensor, a profiling ITP and an Ice Mass Balance buoy (see NSF-AON* IPY Award #0612391: an 'Ice Mass Balance Buoy Network: Coordination with DAMOCLES') were launched from *Polarstern* on 13-14 October 2007 to form a Super Buoy Array on the Lomonosov Ridge at 86°40'-87°24'N (**illustrated on back cover**). And already the first maps of salinity at 10 and 26m are being traced out by the ITP system as proof of concept (Fig 4 from Benjamin Rabe and Ursula Schauer A-W-I).

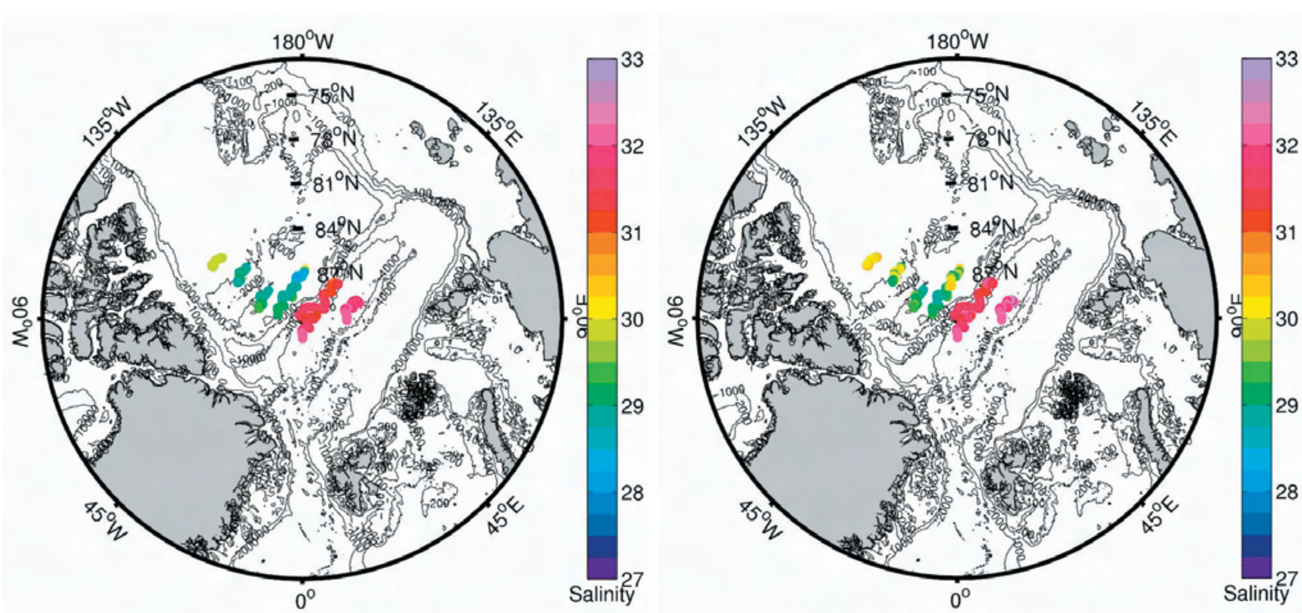


Figure 4. First salinity distributions from DAMOCLES drifting ITPs, at 10m (left) and at 26m (right). Graphic by Benjamin Rabe (A-W-I, pers comm.)

4.A.4. The NABOS-ASBO Collaboration (NSF/NOAA; PI Igor Polyakov, IARC): Fig 5 illustrates the 2007 cruise track aboard RV *Viktor Buynitsky* and main activities of this international NABOS Cruise. A total of 10 moorings under various 'ownership' (IARC/NABOS, Laval Canada, A-W-I/OSL, DAMOCLES), including 5 set this year, are now in place across the boundary current of the Eurasian Basin; those double-ringed on Fig 5 are the multi-year moorings that have already proved successful in documenting the entry and spread of extreme warmth along this boundary in recent years (see section 5.2 below). In addition, the UK-ASBO project contributed research on nutrients (NOC) and on upper-ocean (top ca. 800m) turbulent dissipation (Bangor University).

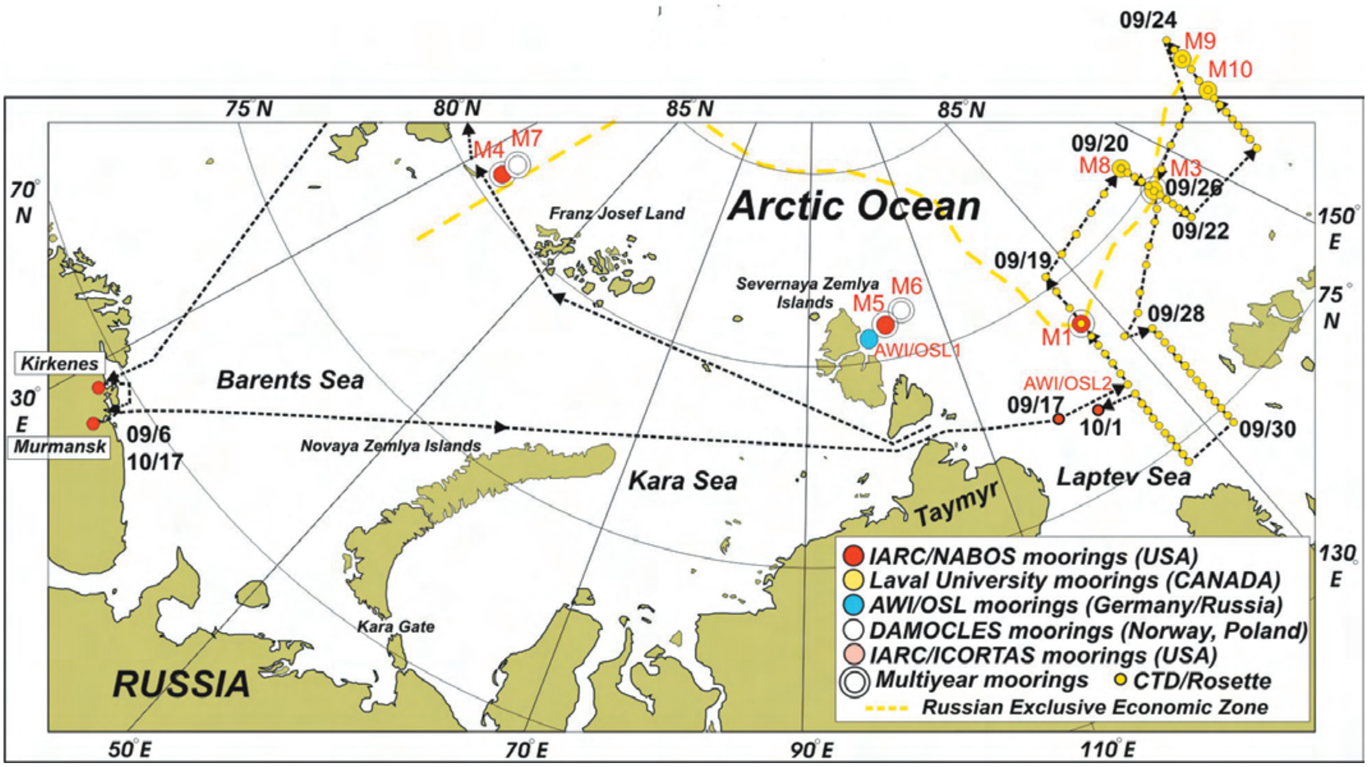


Figure 5. NABOS 2007 cruise map

Table 1 shows NABOS mooring locations deployed in 2007 (bold). In addition, it shows moorings which were deployed in 2006, but left in water for the second year. (Source: Igor Polyakov November 2007)

Region		Latitude	Longitude	Depth	Years	Owner	Funding
Laptev Sea slope	**M1**	78°26'N	125°49'E	2700	2002-08	IARC/NABOS	NSF/NOAA
Severnaya Zemlya slope	M5	81°01'N	105°18'E	2400	2006-08	IARC/NABOS	NSF/NOAA
	M6	80°45'N	103°30'E	1500	2006-08	IOPAS	DAMOCLES
New Siberian Islands slope	**M3**	79°56'N	142°19'E	1400	2004-08	LU-IARC/NABOS	Canada/NSF
	M8	80°47'N	138°47'E	2500	2007-08	LU	Canada
East Siberian Sea slope	**M9**	80°21'N	161°16'E	2500	2007-08	LU	Canada
	M10	79°45'N	159°20'E	1500	2007-08	LU	Canada
Svalbard slope	M7	81°40'N	31°11'E	2500	2004-08	IARC/NABOS	NSF/NOAA
	M4	81°34'N	30°51'E	1000	2006-08	NMO	DAMOCLES

Table 1. List of moorings. LU = Laval University, IOPAS = Institute of Oceanology, Polish Academy of Science, NMO = Norwegian Meteorological Institute. Moorings deployed in 2007 are shown in bold, moorings deployed in 2006 are shown in regular font

Once again, a primary result of NABOS lies in its news of the further eastward spread of the recent warm pulse along the boundary of the East Siberian Sea as well as a warming of the upper watercolumn there that might have quite a different cause (discussed in Section 5.2). Specifically, it is not yet clear how the causes of this upper-ocean warming should be partitioned between insolation, upwelled warmth from below and advected warmth from the Pacific via Bering Strait.

From the UK team, an early result of general interest is the confirmation by measurement of near-zero turbulent mixing rates in the deep waters of the Arctic Ocean. Fig 6 shows a section from the Makarov Basin, between the Lomonosov and Alpha-Mendeleev Ridges, kindly provided by Phil Wiles and Ben Powell of Bangor University. Turbulent mixing rates are an order of magnitude lower than world-ocean "background" rates of 10^{-5} m^2s^{-1}, tending towards the instrument's noise floor.

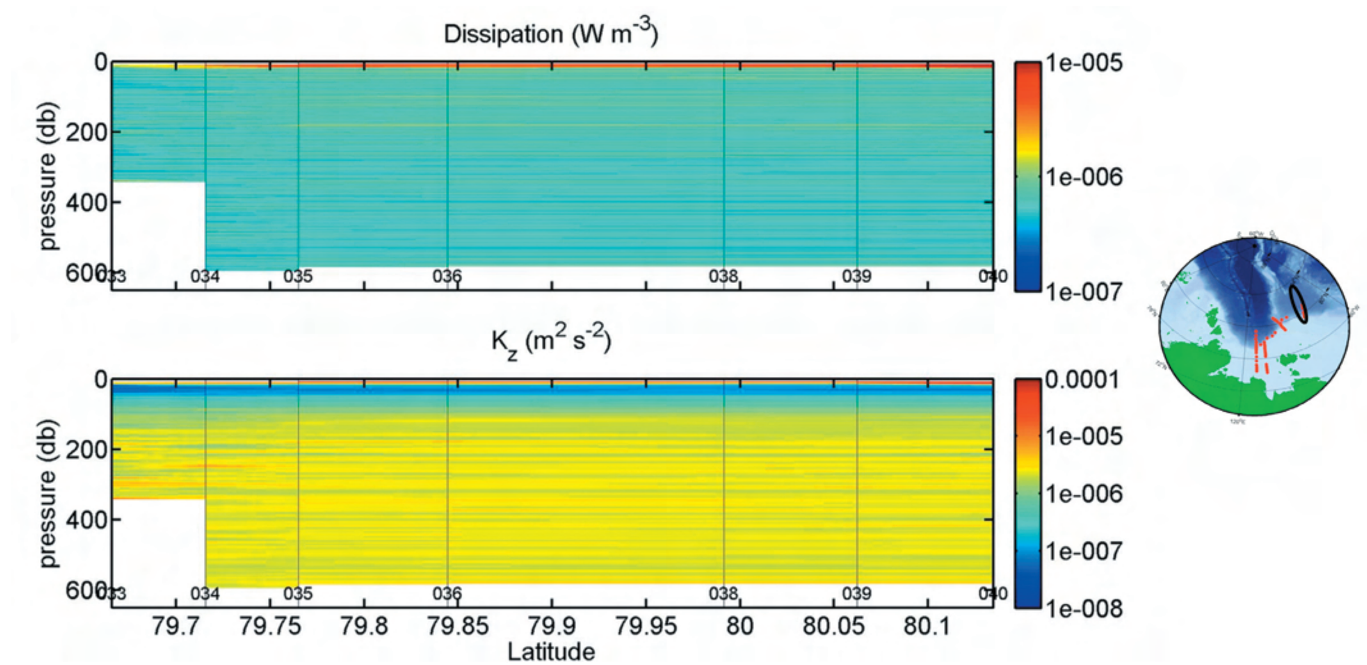


Figure 6. First direct turbulence measurements by Phil Wiles and Ben Powell (Bangor University) on the eastern section of the NABOS 2007 cruise to the Siberian margin aboard the *RV Viktor Buynitsky*

4.A.5. iAOOS on the Russian Shelf; the Kara Sea Observing System. (PI Michael Flint, Shirshov Inst. Of Oceanology, Moscow). The 54th cruise of the R/V *Akademik Mstislav Keldish* carried out extensive multidisciplinary studies of the Kara Sea ecosystem in September-October 2007, a Russian contribution to the circum-Arctic Shelf-Basin Exchange (SBE) effort for the IPY (The corresponding US SBE program led by Grebmeier is discussed below in Section 4.C.2).

4.A.6. The Beaufort Gyre Observing System (Andrey Proshutinsky, Richard Krishfield, WHOI in collaboration with Eddy Carmack, Fiona McLaughlin, IOS, Sidney, Canada; Koji Shimada, Motoya Itoh, JAMSTEC, Japan); (NSF-AON* IPY award #0424864: the Beaufort Gyre System: The Flywheel of the Arctic Climate?). The major goal of the Beaufort Gyre Observatory is to investigate basin-scale mechanisms regulating freshwater content in the Arctic Ocean and particularly in the Beaufort Gyre (BG) of the Canada Basin. The major hypothesis under test (Proshutinsky et al., 2002) is that the Gyre accumulates a significant amount of fresh water under anticyclonic wind forcing and then releases it when the forcing weakens or changes to cyclonic rotation. This accumulation and release mechanism could be responsible for the observed salinity anomalies in the North Atlantic and for a decadal-scale variability of the Arctic system as the BG may both filter annual river inputs and pulse freshwater outflows. ***[*note that throughout this Report, projects labelled 'NSF-AON' are the initial***

NSF contribution to the development of an Arctic Observing Network and are integral to the implementation of the US Study of Environmental Arctic Change (SEARCH)].

The major objective of the observational program is to determine freshwater content and freshwater fluxes in the BG during seasonal, interannual and longer cycles. Beginning in August 2003, time series measurements of T, S, currents, geochemical tracers, sea ice draft, and sea level have been acquired by the international team (see title) using 3-4 moorings, drifting buoys, shipboard, and remote sensing measurements (see Fig 7 for primary locations). The moorings have precisely measured the variations of the vertical distribution of freshwater content, sea level variability, and sea ice draft at representative locations. The repeated hydrographic sections have examined the variation by radius from the center of the Gyre. The remote sensing program has characterized the variability of the sea ice thickness and the sea surface height horizontal structure (See Section 4.A.7 below).

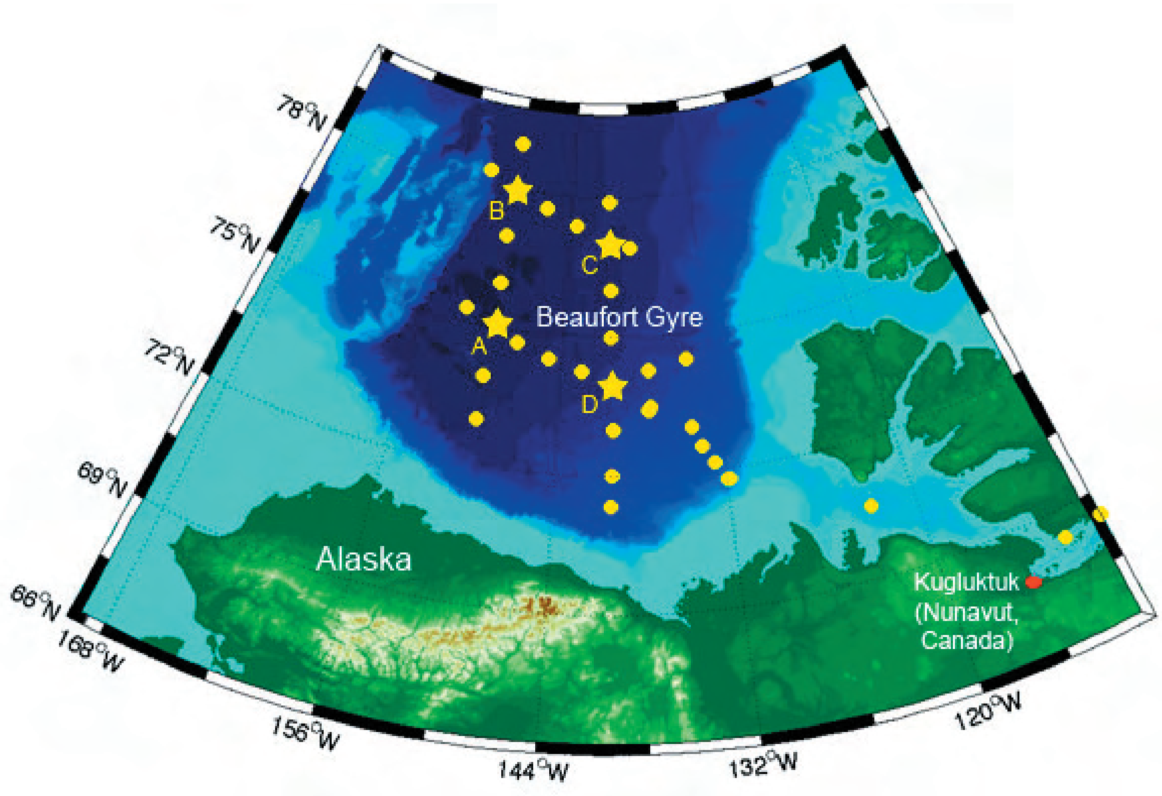


Figure 7. Main moorings and stations of the WHOI-led Beaufort Gyre Observing System, 2003 to date. Locations of CTD stations conducted in August-September are shown by yellow dots and moorings by yellow stars. For details, see Proshutinsky et al, 2007 submitted.

In 2007, the full-scale observational program was repeated at the standard program locations; 107 CTD casts were completed (inter alia for salinity, nutrients & dissolved oxygen, Chlorophyll A, DOC, and CDOM); bulk seawater samples were recovered for suspended particles; radiotracer sampling was conducted for ^{129}I (13 stns), Cs (8 stns), and Pu & Am (2 stns); 99 X-CTDs and 10 XCPs were launched; 4 ice cores longer than 2 meters were recovered and sampled; and the four moorings starred in Fig 7 were recovered and redeployed.

From being a relative data 'desert', the Beaufort Gyre is thus becoming one of the best-sampled areas in the high-latitude ocean. Already, summer data reveal significant changes there over the past two decades (Proshutinsky et al submitted and in prep), manifested in a shrinking, a southeastward shift and an intensification of the gyre and an increase in its freshwater and heat content. The particular mechanisms of these changes remain to be understood however and additional research and new theories continue to be needed to fully explain the role of the Beaufort Gyre in Arctic climate variability.

During 2007/2008 a total of 5 MMPs (T, S, currents), 6 sediment traps, 17 temperature sensors, 4 bottom pressure recorders, 4 upward-Looking sonars, 3 current meters, 3 Ice-tethered Profilers, 2 Ice-mass balance buoys, and one ocean flux buoy will record the changes in the Beaufort Gyre. Three of the four moorings will also be redeployed for recovery in 2009, subject to funding.

4.A.7. New ground truth for satellite remote sensing. Sea surface height (SSH) retrievals from radar altimetry have been available for ~10 years from Laxon's team at CPOM (University College London) but have had almost no ground truth to control them. The comparison between satellite-derived SSH (Laxon) and bottom pressure data from the Beaufort Gyre (Proshutinsky) has now proved so close (Fig 8) as to show that retrievals of ocean dynamic topography at the cm level are now possible even in the presence of ice.

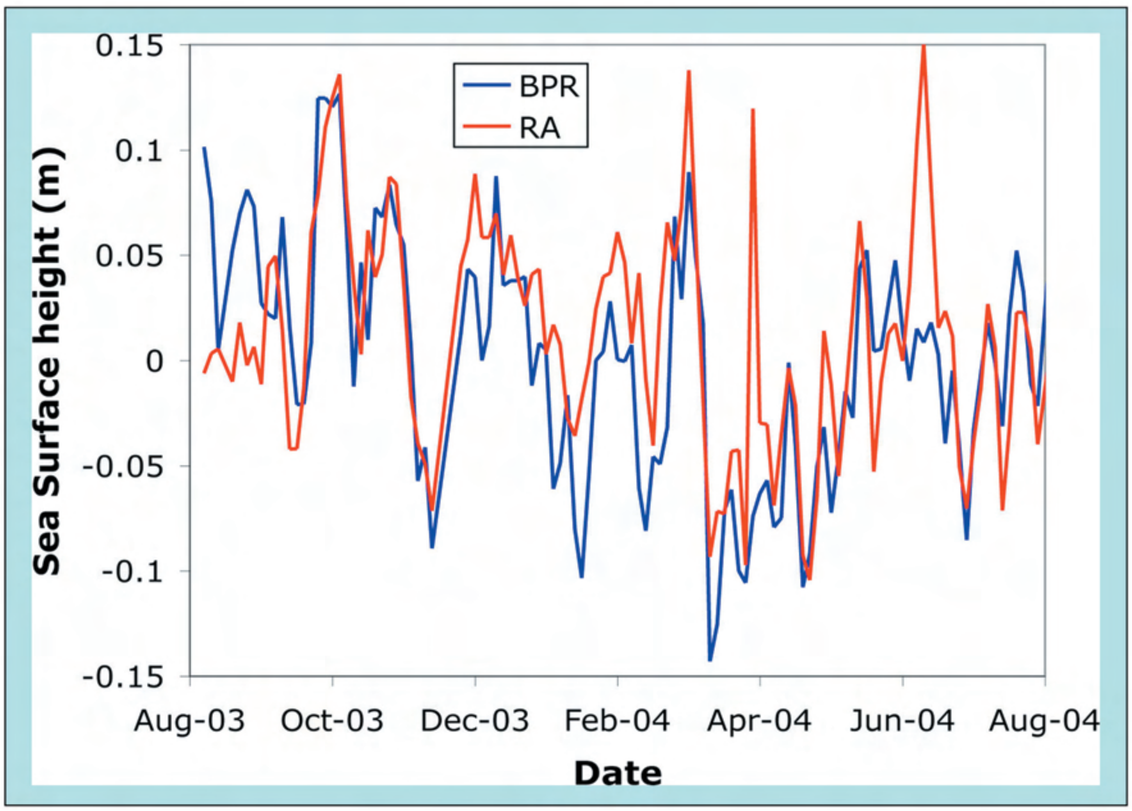


Figure 8. Ground truth from Bottom Pressure Recorders (BPR) in the Arctic Ocean is now becoming available. Shown is the first comparison of SSH inferred from BPR data in the Beaufort Sea (Andrey Proshutinsky WHOI) and as measured by ENVISAT RA-2 (Seymour Laxon CPOM-UCL and UK-ASBO).

4.A.8. North Pole Environmental Observatory (NPEO); NSF-AON IPY awards #0352754 and #0634226: The NPEO (PI Jamie Morison, APL-UW) was first established in 2000 as means of tracking long-term change in the central Arctic Basin from the surface to the sea floor. It is not limited to a single location, but is a distributed observatory consisting of three parts: an **automated drifting station** installed near the Pole that samples air-ice-ocean conditions as it drifts across the Amundsen and Nansen basins to Fram Strait, a **deep ocean mooring** approximately 25 km from the Pole; and repeated airborne hydrographic surveys that track changes along key **sections radiating from the Pole** (Fig 9; NSF-AON Award #0634226). The North Pole region is sensitive to a changing Arctic climate, recording a strong increase in upper ocean salinity during the 1990's and a large increase in Atlantic Water temperatures at depth, suggesting a close connection of the interior ocean with the boundary current that rings the Eurasian Basin. NPEO is scheduled to continue through 2008. The automated drifting station and its installation provide opportunities for others to test new models (see Section 4.A.9 below), instrument designs and automated platforms in the presence of a wealth of background observations at minimal incremental logistics cost. The hydrographic sections provide opportunities for added sampling and drifting buoy deployments. In keeping with its project title (Collaborative Research: North Pole Station: A Distributed Long-Term Environmental Observatory), data from NPEO is made available to the research community as rapidly as possible.

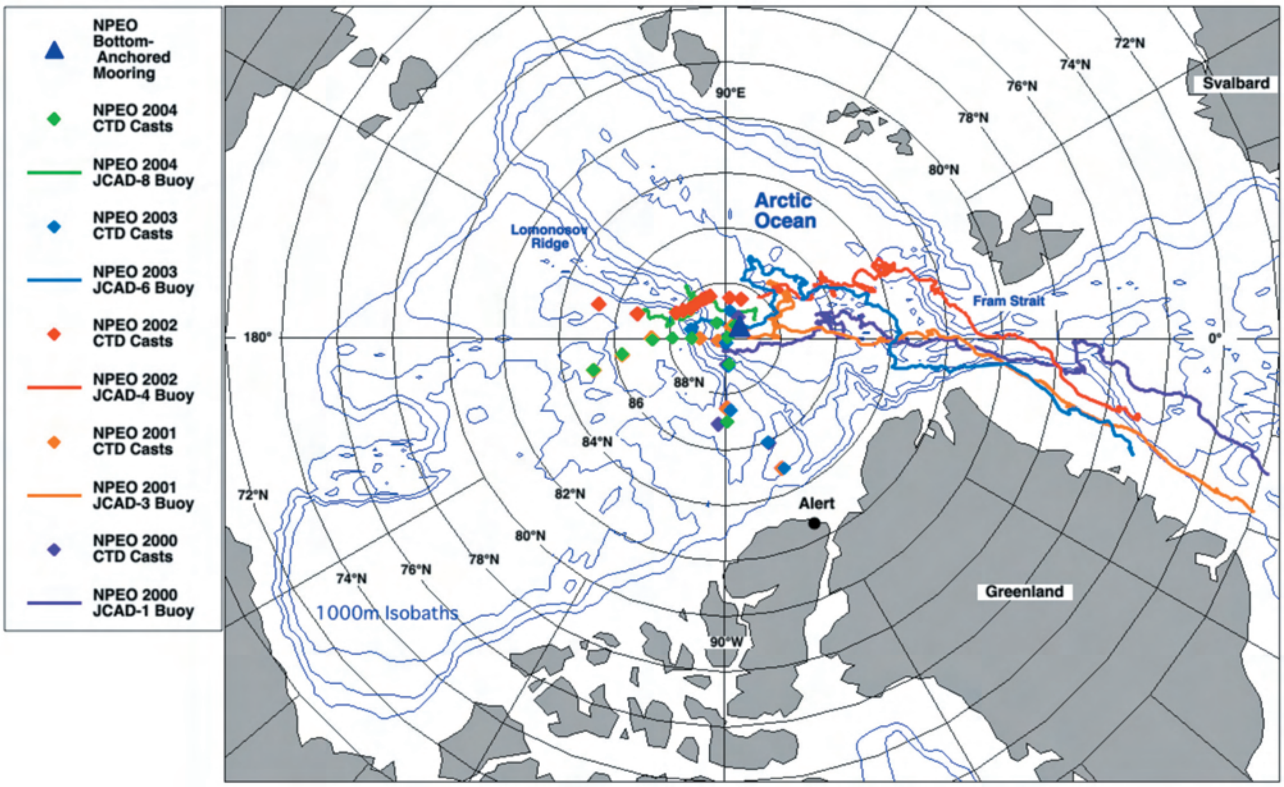


Figure 9. Continuation of Jamie Morison's (UW) well-established North Pole Experimental Observatory (NPEO), with the main mooring supplemented by airborne CTD and a succession of JAMSTEC Compact Arctic Drifters (J-CAD) and POPS

4.A.9 TOPAZ Modelling: TOPAZ is, since January 2003, the first ocean and sea-ice forecasting system based on advanced data assimilation methods (the ensemble Kalman filter), and a coupled ocean and sea-ice model (based on HYCOM and the EVP sea-ice rheology). In addition to assimilating ocean data (sea surface heights, sea surface temperatures) in the open ocean, it assimilates ice concentration from the NSIDC and ice drift products from IFREMER. Within the MERSEA European project, the system is validated for 1) consistency against temperature and salinity climatology; 2) accuracy against non-assimilated data (an example of the fit with NPEO data is shown in Fig 10), or the drift of the Tara expedition; 3) forecasting skills, with respect to the trivial "persistence" predictor. This information is updated each week on http://topaz.nersc.no. TOPAZ is developed and operated by the Mohn-Sverdrup Center at the Nansen Environmental and Remote Sensing Center, Bergen, Norway.
See also http://www.mersea.eu.org.

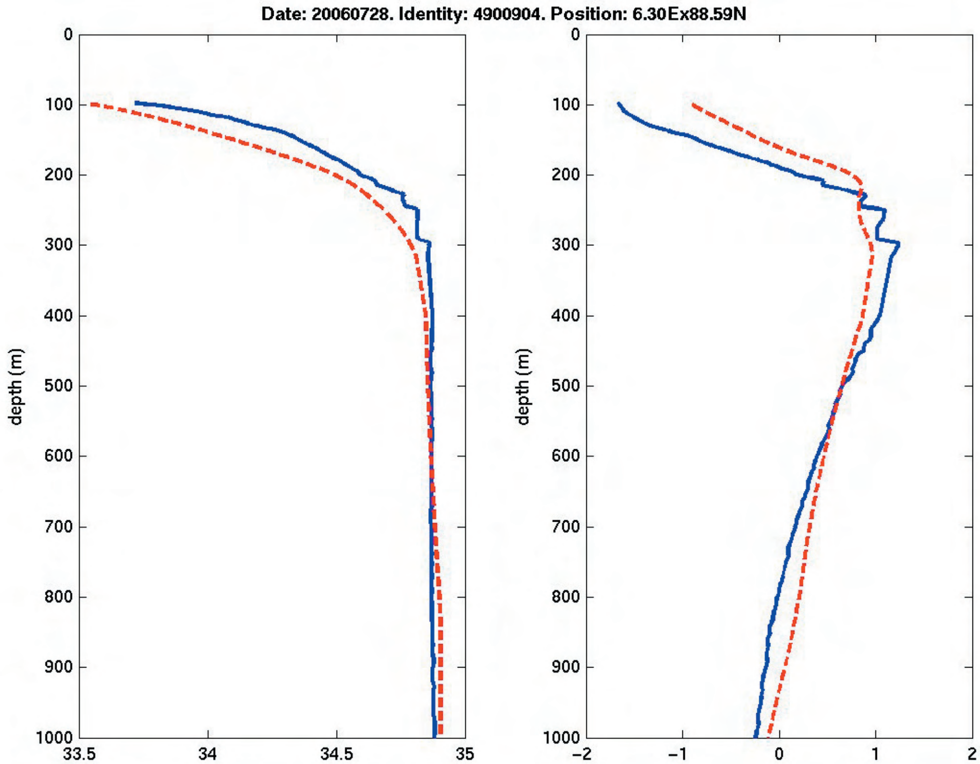


Figure 10. Comparison between observed profiles of salinity (LHS) and temperature (RHS) at the North Pole Environmental Observatory (solid lines) on 28 July 2006 and TOPAZ simulations (dashed line). Courtesy of Laurent Bertino, NERSC

4.A.10. First CTD coverage North of Greenland: The special nature of the Swedish LOMROG expedition in August –September 2007 (Lomonosov Ridge off Greenland) lay in the fact that in its western section, the *Oden* was charting a virtually unexplored region of the Earth — the ʻrootʼ of the Lomonosov ridge in the heavy ice zone of the Artic Ocean to the North of Greenland. Since ice thicknesses of up to 5 metres are expected here with pressure ridges up to 20 metres thick, the Russian nuclear icebreaker *50 let Pobedy* (50 Years of Victory) ---the most powerful icebreaker class available--- was in support to ensure that the area of interest could be reached. As Fig 11 shows, a series of 25 CTD casts formed part of the suite of measurements; the subsurface S-maximum encountered at ~2000 m may be new evidence of a persistent leakage from the Makarov Basin via a 1870m deep channel in the central Lomonosov Ridge (Göran Björk & Leif Anderson, pers comm.).

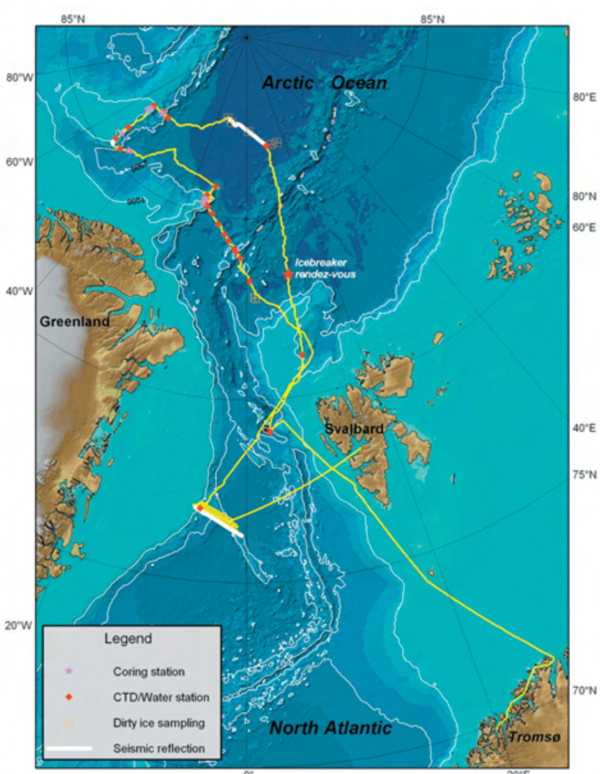


Figure 11. Swedish LOMROG expedition route and scientific station work (hydrography: Björk - Anderson)

4.B Nordic Seas

4.B.1. Introduction of UW Seaglider support for the study of exchanges across the Greenland-Scotland Ridge: The oldest time-series that we have relied on in iAOOS, the hydrographic transects of the Faroe-Shetland Channel begun by HN Dickson aboard HMS *Jacka*l on 4 August 1893, have provided soundly-based estimates of the inflow of heat, mass and salt to Nordic Seas and have described the variability of inflow over many decades (eg Østerhus et al 2005). The task of attributing cause to these changes requires us to distinguish (for example) the effect of quite-local changes in the inflow 'switchgear' (Hatun et al 2005) from more-remote changes in the hydrography of the source-waters (eg, those due to changes in the global water cycle; see Curry et al 2003), requiring a more sustained coverage and higher space-time resolution than normally provided by seasonal or annual survey.
It is therefore of importance that from March 2006 - March 2009, the historic coverage has been supplemented by repeat deep SeaGlider patrols across both the Ridge and Faroe-Shetland Channel (Fig 12), the plan being to maintain 3 gliders in the water at all times over the 3 years. This technique and this application of it were jointly funded by ONR, NOAA and NSF. The rapidity with which these Seaglider transects have confirmed and extended the findings of classic hydrography has provided a clear endorsement of the technique.

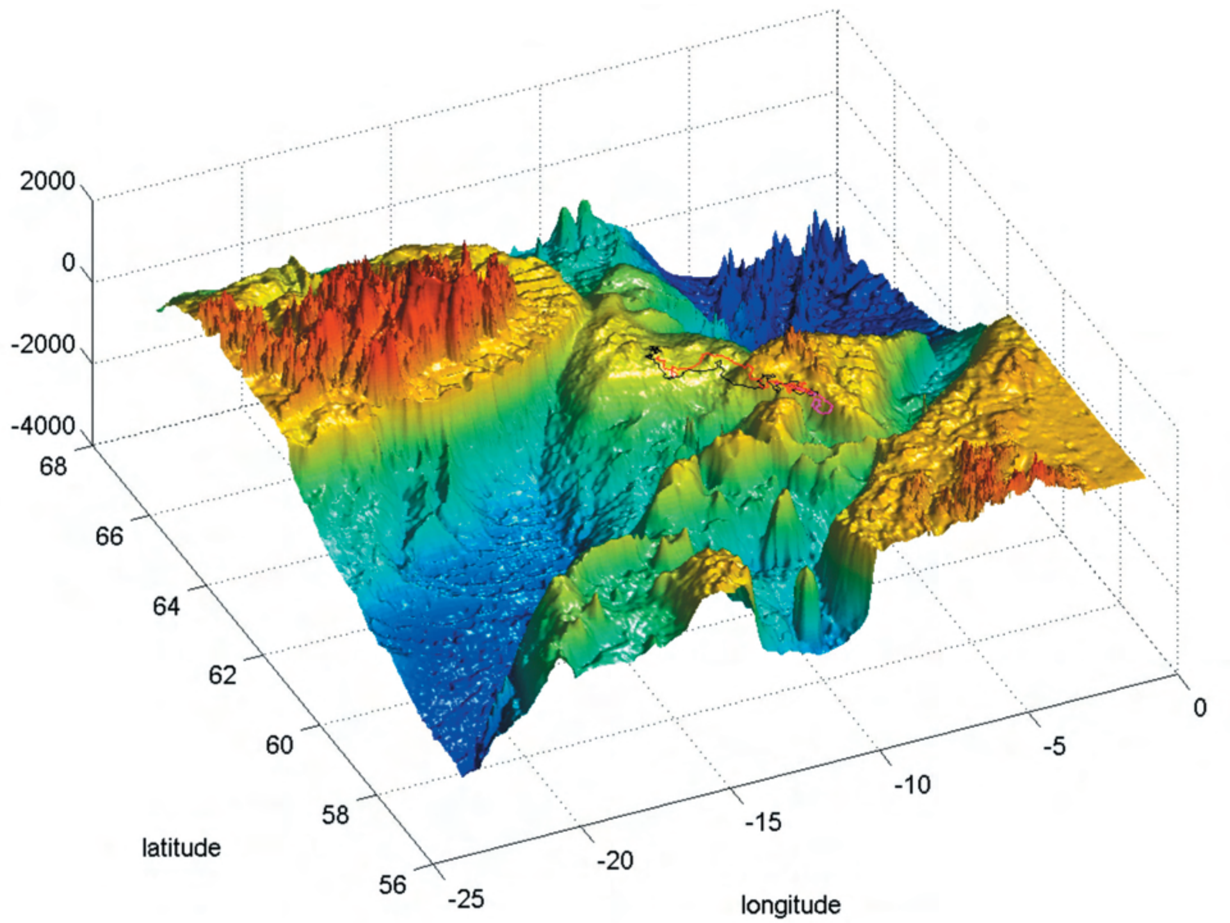


Figure 12. Three UW SeaGliders patrolling the Iceland-Faroe-Shetland Ridge/Channel in 2007, providing for the first time a sustained, high-resolution space-time coverage of both the dense-water overflows and the warm saline inflows to the Nordic seas. (Courtesy of Peter Rhines and Charles Eriksen UW, 2007 pers comm). http://iop.apl.washington.edu/seaglider/ or http://iop.apl.washington.edu/seaglider/sections.php?glider=101&mission=Faroes_Jun07

4.B.2. iAOOS for Norway; first concerted attack on the 'other half' of the northward ocean heat flux west of Norway: Though we tend to describe the Norwegian Atlantic Current in the singular, in fact *two* main branches of warm, saline Atlantic water enter and pass north through the Norwegian Sea, of approximately equal magnitude. Yet although 12-year time-series of transport have been recovered from the inshore branch against the Norwegian Slope, so that we now have some sense of its local and remote forcing (see Orvik and Skagseth 2003; also Skagseth et al. 2008), the offshore branch, passing north through the Norwegian Sea as a free jet, has remained unmeasured. Both branches are involved in the spread of warmth to the Barents Sea and Arctic Ocean, and the issue of determining what might control this warm, saline flux and its characteristics (flux, variability, forcing, fate and degree of covariance with the inshore branch) is of the first importance in quantifying the role of the Northern Seas in climate. A 3-pronged attack on this critical but difficult measurement is underway. First, Mork and Skagseth of GFI Bergen (in press, 2007 and pers comm) have combined satellite altimetry with hydrography and modelling to calculate the volume, heat and salt transports of both branches between 1993 and 2004. Total transport is 7 Sv in summer and 10 in winter, equally shared between the two branches (see Fig 13). Second, Orvik (also GFI) has supplemented his two conventional moorings on the Svinøy line (SE1 and SE3) by deploying 3 Pressure Inverted Echo Sounders (PIES) in the vicinity of the western branch in November 2007, to be joined by a 4th PIES mooring and a McLane Moored CTD profiler (MMP) in spring 2008. And third, since OWS M straddles the offshore free jet, Østerhus and Gammelsrod of GFI will deploy a further complex mooring there in the late spring of 2008, incorporating an ADCP (RDCP-600) at 75m depth, five Aanderaa RCM9 current meters, Microcat T-S sensors at 9 standard depths (75, 100, 150, 200, 300, 400, 600, 800, and 1000m) and oxygen sensors, and with data downloaded weekly aboard the Weathership via acoustic link. With these measures in place, the comprehensive 'capture' of the offshore free jet will finally have been achieved, and iAOOS-Norway will have achieved its aim of 'developing the Svinøy Section into a complete, sustainable, simple and robust upstream reference system for monitoring Atlantic inflow towards the Arctic Ocean during the IPY'

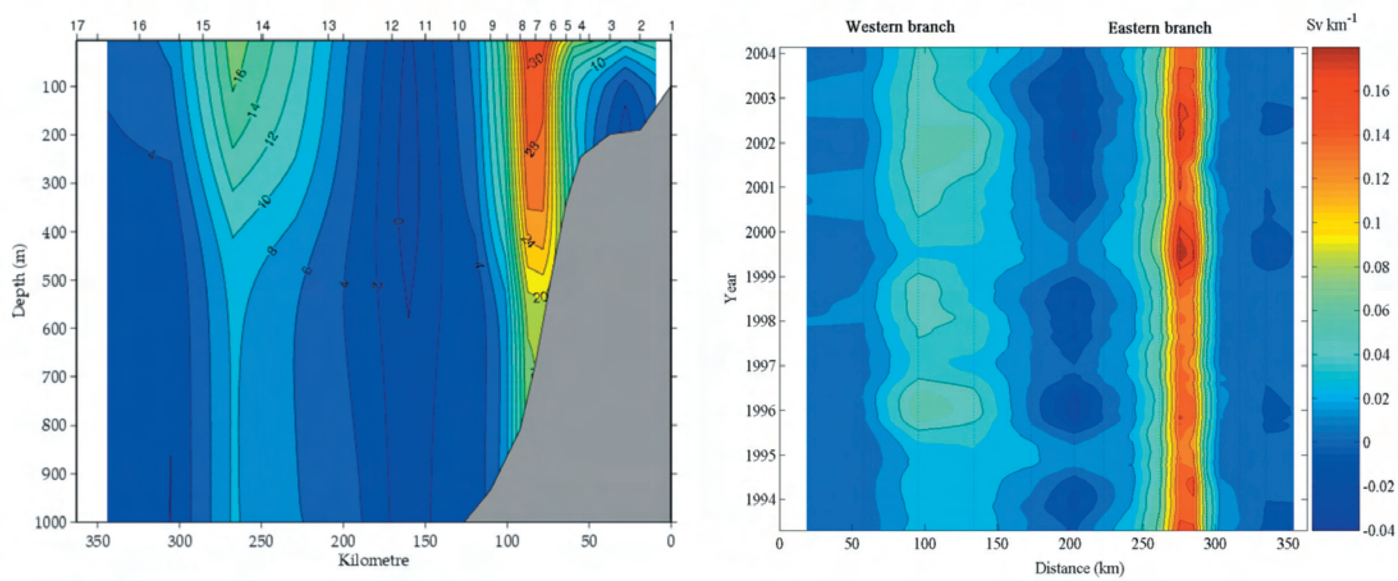


Figure 13. First complete description of the Norwegian Atlantic Current west of Svinøy. Shown is the distribution of annual mean geostrophic transport (LHS) and one-year moving averages of volume transport (RHS) for the two branches of this Current, derived by Kjell Arne Mork and Øystein Skagseth of GFI Bergen (in press and pers comm) using a combination of satellite altimetry, modelling and hydrography. Though the unstable, meandering western branch appears weaker than the topographically-trapped eastern branch, in fact the fluxes of mass, heat and salt are almost equivalent (table 2).

Inflow branch	Volume transport (Sv)	Heat transport (TW)	Salt transport (kTs^{-1})
eastern	4.2	132	153
western	4.3	121	155
total	8.5	253	308

Table 2. First estimates of volume, heat and salt transports for the two branches of Norwegian Atlantic Current west of Svinøy. Kjell Arne Mork and Øystein Skagseth pers. comm. 2007

4.B.3. iAOOS for Norway; new investigation of bifurcation in the NwAC: The long-term monitoring of heat, salt and mass flux through the Barents Sea Opening (BSO), begun during EC-VEINS and EC-ASOF, has continued (Skagseth et al. 2008) but is now augmented with two upstream/downstream moorings by Skagseth on the Gimsøy and West Bear Island Sections which are the start of a new study of the causes of bifurcation in the NwAC (positions shown in Fig 29, below).

4.B.4. BIAC of Norway & Russia; Reinstatement of a key current meter array in the northeastern Barents Sea: The current meter array that Loeng and Ozhigin deployed between Novaya Zemlya and Franz Josef Land by in 1992 (Loeng et al 1993) was of historic importance, providing the first direct measure (Fig 14 left) of the warm water transport that crosses the Barents Sea shelf to enter the Arctic Ocean through the Sankt Anna Trough. Apart from our general need for direct measures of this exchange-pathway, there is a growing realization that the vorticity dynamics associated with this outflow from the shelf to the Trough may play a wider role in controlling the circulation of the Atlantic water layer in the Eurasian Basin.

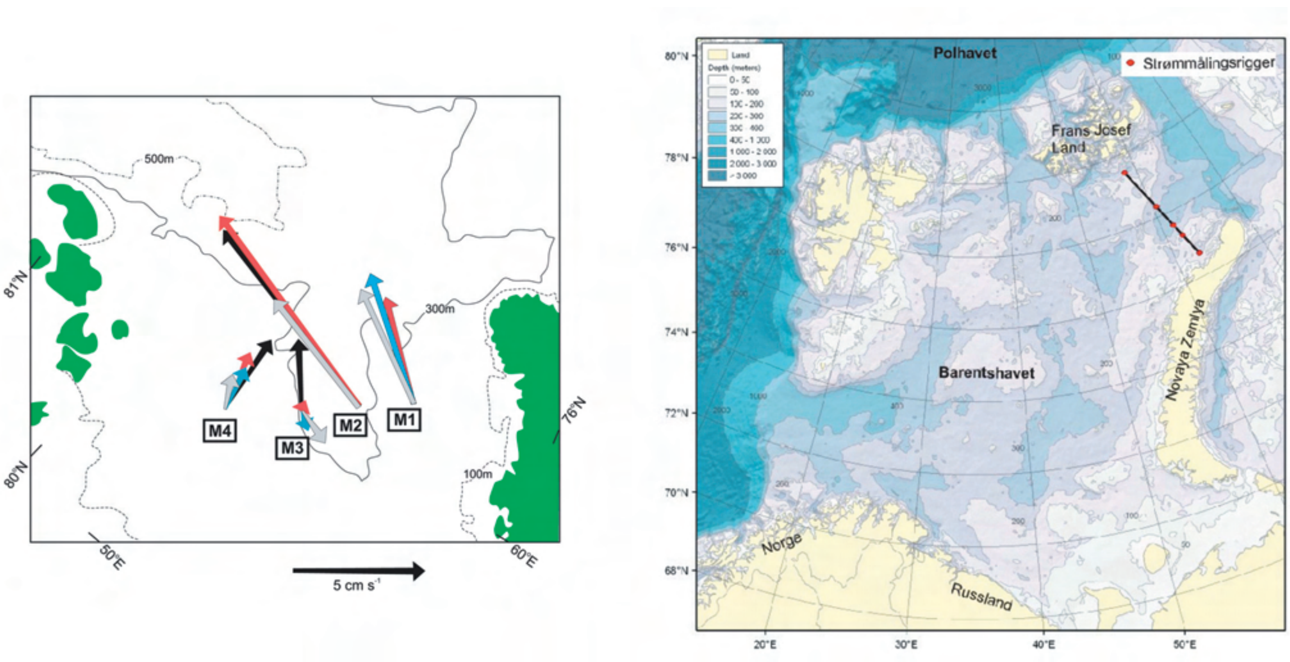


Figure 14. Exercise-mean current vectors from the Norway-Russia array of 1992 (left) and the location of the equivalent BIAC array in 2007-8 (right).

It is therefore important that fifteen years after its first deployment, this key array has been reinstated (Fig 14b). During 12-15 September 2007, 5 moorings incorporating 10 RCM-7 Current meters and 2 Nortek-Continental 190 kHz ADCPs were deployed by the Russian *R/V Fritjof Nansen* as part of the IPY-project BIAC, to be recovered in autumn 2008. The Norwegian PI for this part of BIAC is Harald Loeng and the Russian PI is Andrey Pedchenko of PINRO, Murmansk. A new modelling initiative will model the Barents Sea throughflow to 4km resolution.

4.B.5. DAMOCLES; Introduction of tomography in support of the conventional 'picket fence' current meter array in Fram Strait: Though a major long-term effort of ASOF, DAMOCLES and iAOOS (see Schauer et al. 2008), the conventional array in Fram Strait has limitations in its ability to resolve the effect of meso-scale features, the recirculation pattern, and to sample the cold freshwater flux. This may cause errors in flux estimates of 50 -100 %. The DAMOCLES objective is to augment the conventional picket fence array of current meters in the Fram Strait with a range of new systems designed to improve the monitoring of volume, heat and freshwater transports, including a) the building, testing and use of an ocean acoustic tomography system across both the West Spitzbergen Current and the East Greenland Current (Fig 15), b) establishing and validating a high resolution (2 km) ice-ocean model and c) combining acoustic thermometry, satellites, sub-surface moorings and coupled ice-ocean modelling through advanced assimilation techniques. The lead is NERSC, Norway (Hanne Sagen and Stein Sandven), but includes major input by FORTH, Crete, Scripps, USA, WHOI, USA, and Webb Research.

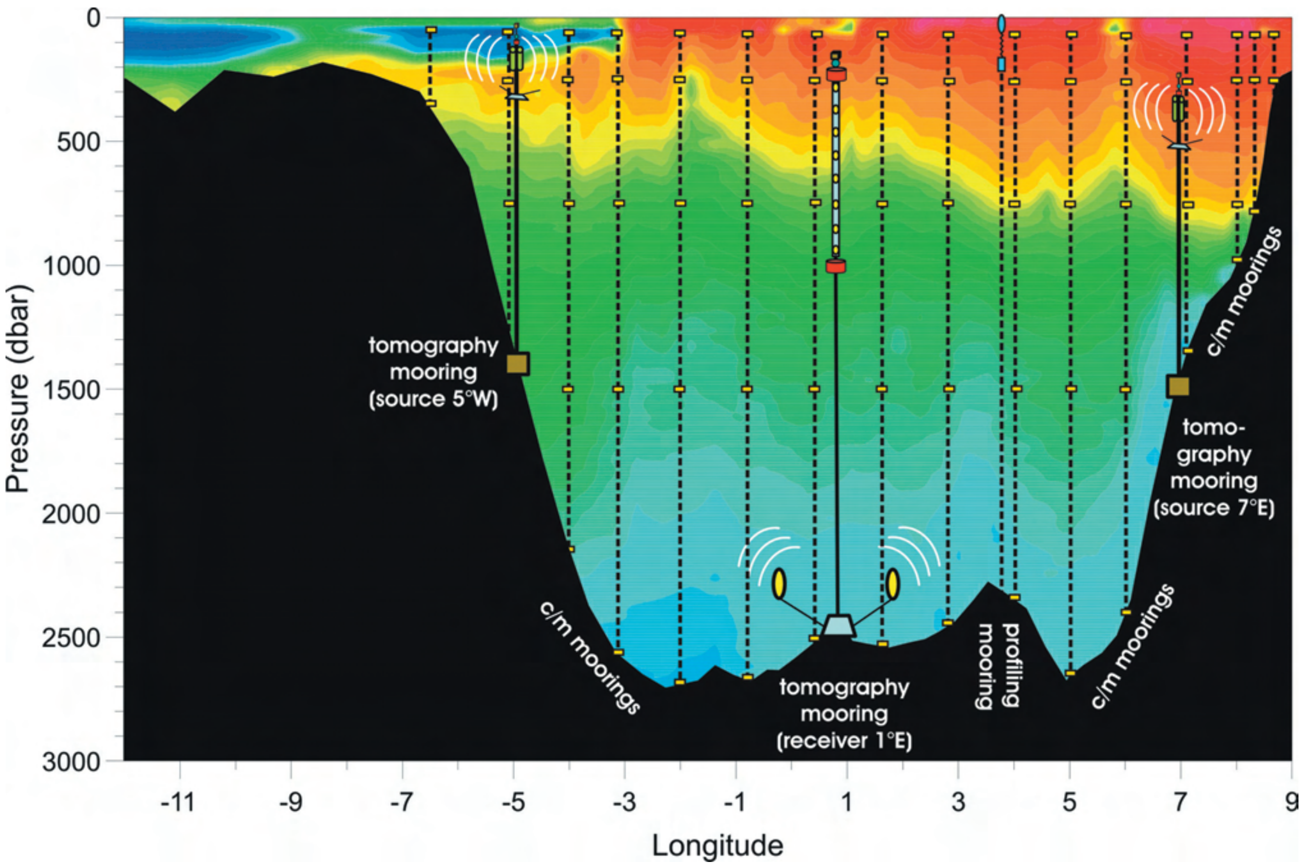


Figure 15. Temperature distribution in Fram Strait with the moorings of the existing ASOF Current meter array and those of the intended DAMOCLES tomography array superimposed. (Figure courtesy of Agnieszka Beszczynska-Möller, A-W-I and Stein Sandven, NERSC). Though the components of the tomography array are assembled, bad weather has forced postponement of its deployment till 2008. Other improvements will follow (illustrated in Section 6 below)

4.B.6. WHOI-JHU; first comprehensive array across the East Greenland Current south of Denmark Strait: Because of its climatic significance, the dense water overflow through Denmark Strait has been measured for more than a decade off Angmagssalik and since 1998 at the sill (see Dickson et al. 2008), and these elements of our observing system continue, with contributions from Germany, Iceland, Finland and UK. The vigorous East Greenland Current, flowing south along the East Greenland shelf and upper Slope, is of equivalent climatic significance, carrying the major component of the freshwater flux between the Arctic and the North Atlantic, but hitherto the EGC has proved very much harder to observe. Now for the first time a modern array has been deployed across the EGC south of the sill by Robert Pickart of WHOI. Each of the 7 moorings (Fig 16) carry CTD profilers and Microcat C-T sensors, plus ADCPs and/or Acoustic Current Meters, so that the array will effectively return two CTD/velocity sections per day.

An associated modelling component led by Tom Haine (JHU) will enhance the interpretation of the in-situ measurements, and investigate the broader impacts of the shelf-basin exchange in terms of the North Atlantic subpolar gyre and the MOC. This too will be novel, involving regional models of the Denmark Strait and Irminger Sea with roughly 2-km horizontal resolution and 100 vertical levels.

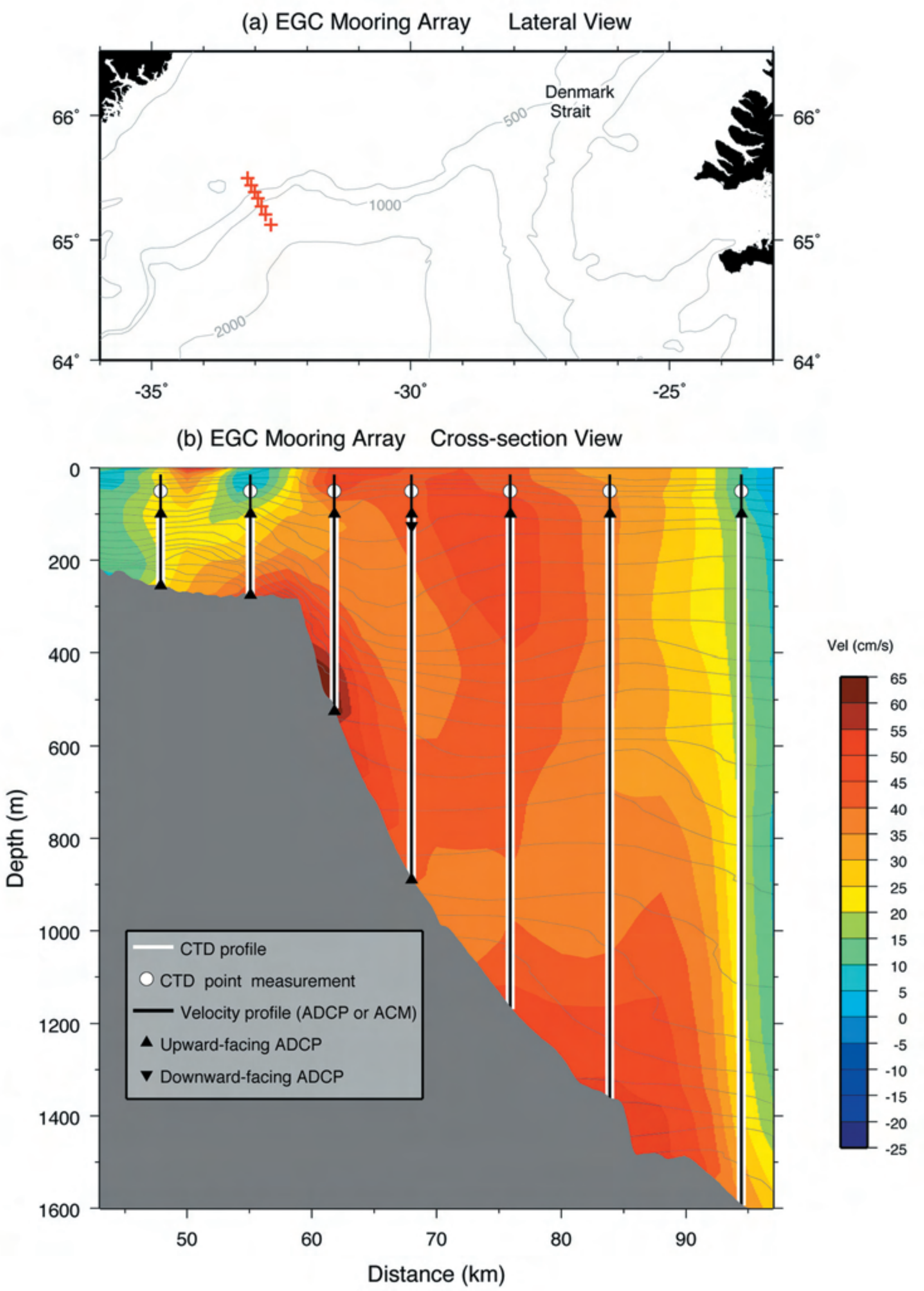


Figure 16. The new WHOI East Greenland Current Array, laid by R/V *Arni Fridriksson* in September 2007 across the outer shelf and upper Slope off SE Greenland, and scheduled for recovery in September 2008. (Robert Pickart, 2007 pers comm.)

Dynamical simulations will be carried out of the circulation, stratification, property distributions and sea-ice in this region, permitting a more quantitative understanding of the dynamics of the shelf-basin exchange, including its sensitivity to various factors such as atmospheric forcing, mixing, and double-diffusive processes.

4.C North American Subarctic Shelf

4.C.1. Canada's Three Oceans (C3O) study (Carmack, Vagle, McLaughlin, Melling) and Collaborators: Exploiting the fact that Canada's coastline spans Pacific, Arctic and Atlantic waters and that two science-capable icebreakers CCGS *Sir Wilfrid Laurier* and *Louis St-Laurent* already work these waters extensively on an annual basis, C3O is designed to integrate these efforts in physical, chemical, biological and geological oceanography to produce a comprehensive view of the changing conditions along a section some 15,000 km in length (Fig 17).

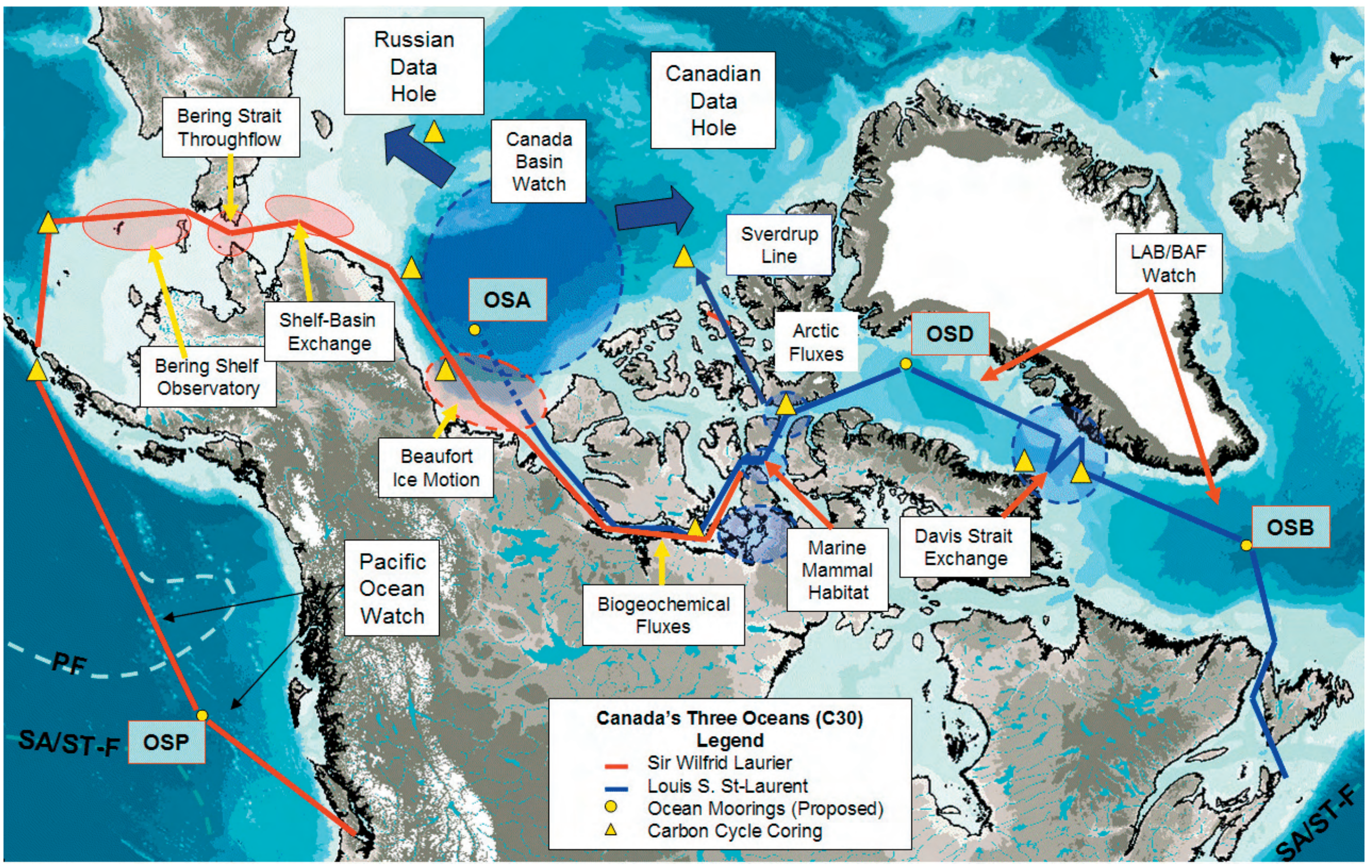


Figure 17. The 15,000 km section through Pacific, Arctic and Atlantic waters whose regular re-workings by two science-capable icebreakers will act as Canada's 'climate change antenna' through her northern waters.

Supplementing these *long lines*, a series of site-specific *regional studies* will focus on specific eco-domains, with moorings recording the more-detailed space-time scales of variability. Fig 18 describes the location and explains the research focus of regional study-sites clockwise from Victoria to Halifax in relation to the 0-200m distributions of temperature, salinity, oxygen and fluorescence along the main long section. As shown, **A** captures interannual variability in BC coastal waters; **B** passes near Ocean Station "P"; **C** crosses the Polar Front into the Gulf of Alaska gyre; **D** crosses the Alaskan Stream (AS) and Alaska Coastal Current (ACC); **E** follows the flux of fresh water (FW) from the Pacific into the Bering Sea and the upwelling of nutrient-rich waters onto the shelf; **F** crosses the Bering Sea shelf and near-bottom 'cold pool'; **G** is Bering Strait and the flux of freshwater into the Arctic Ocean; **H** is the Chukchi Sea

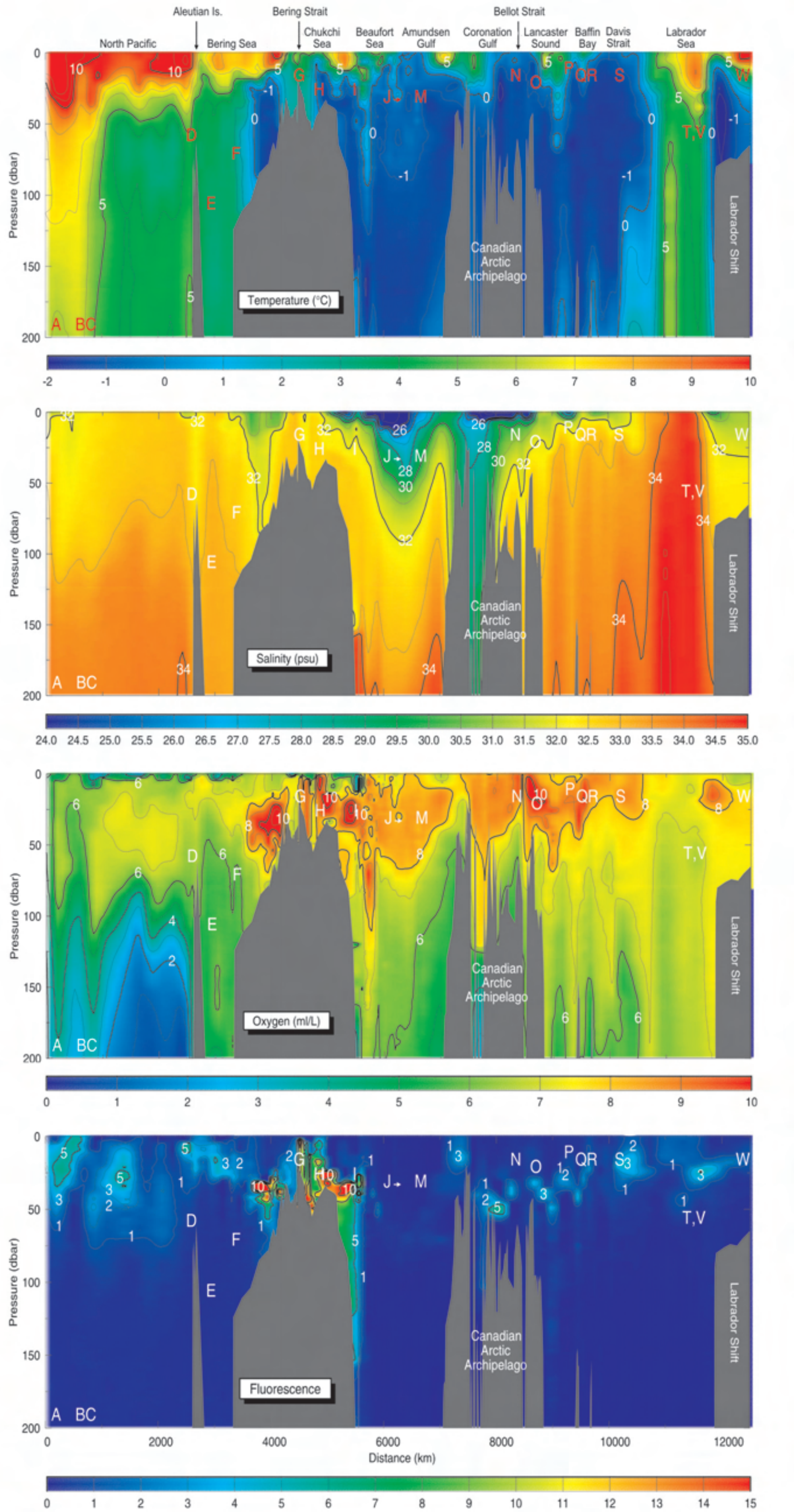


Figure 18. First results from the C3O Section worked in summer 2007 from Victoria BC to Dartmouth NS through the Canadian Arctic. Though the Section was worked over much of the watercolumn, we show here only the detailed distributions of T, S, oxygen and fluorescence in the 0-200m layer, collected on 5 separate legs by >90 scientific personnel aboard the icebreakers CCGS *Sir Wilfrid Laurier* (July 1 to July 21, September 11 to September 20, September 22 to October 15) and *Louis St-Laurent* (July 3 to July 26 and July 26 to August 30).

Though created as an IPY effort (2007-11), the C3O Section will realize its full scientific and social value as the basis of a National Monitoring Program for Canadian waters. Spanning Arctic and subarctic waters, regular repetition through to 2050 would reveal the expected redistributions of oceanic boundaries and biomes (eg Carmack and McLaughlin, 2001; Grebmeier et al 2006) and allow scientists and policy makers to access the time-scales of change that have the greatest societal relevance and impact.

Unpublished data, kindly provided by Eddy Carmack, IOS Sidney BC, January 2008.

and the production of cold halocline waters (HC) that drain into the Arctic Ocean via Barrow Canyon; **I** is the Alaskan North Slope coastal current; **J** is Arctic Ocean Station "A"; **K** is the Beaufort Gyre and freshwater storage; **L** is the monitoring of ice thickness and drift on the Canadian Beaufort Shelf;

M is the Canadian Beaufort Shelf & Amundsen Gulf; **N** represents various biological 'hotspots' *en route*, such as Bellot Strait, Gulf of Boothia and Barrow Strait where physical process produce and concentrate food for top predators; **O** represents physical and biogeochemical changes as ice and seawater (residence time ~ 5-10 years) transit the Canadian Arctic Archipelago; **P** is the Arctic outflow water exiting through northern archipelago passages in support of CATS and ASOF objectives; **Q** is the assembly in northern Baffin Bay of Arctic outflow waters from Nares Strait (NS), Lancaster Sound (LS) and the West Greenland Current (WGC); **R** is Baffin Bay and its isolated deep water; **S** is Davis Strait and the bifurcations in the Baffin/Labrador and West Greenland currents, and the passage of Arctic outflow water; **T** is deep convection in the Labrador Sea; **U** is the proposed ecological work in tidally-mixed Frobisher Bay; **V** passes near Ocean Station "B"; **W** represents the influence of arctic-derived waters on the physical habitat of the North Atlantic fisheries. Not shown above but proposed are hydrographic lines extending into the Sverdrup Basin of the Canadian Arctic Archipelago (**X**), the Canadian Hole (**Y**) and the Russian Hole (**Z**) where very little data exists. Though C3O was initiated as an IPY effort (2007-11), its full potential as a National Monitor for Canadian Waters will be realized by extension to 2050 and beyond, when it will be able to describe conditions out to the multi-decadal scale of climatic and macro-ecological change.

4.C.2. The C3O-SBE Collaboration; US and Canadian Shelf-Basin Exchange (SBE) studies within the IAOOS System in 2007 (Grebmeier/Cooper/Lovvorn): In the Northern Bering Sea, field research aboard USCGC *Healy* (cruise HLY0702) was focused first on how sea-ice change and increased bottom temperatures might affect the very productive, benthic-dominated food webs on shallow arctic shelves through the expansion in ranges and numbers of mobile benthic predators. In addition, along a shelf-to-basin hydrographic line (SBE) in the northern Bering Sea, a CTD rosette system provided hydrochemical samples, including chlorophyll, nutrients, particulate organic carbon, dissolved organic carbon, zooplankton, benthic population measurements and sediment tracers; optical equipment (PAR and UV) lowered to 60-150 m provided measurements of variable light penetration in the water column; a vertical net was used to collect zooplankton for population measurements; benthic van Veen grabs and a HAPS benthic corer were used to collect benthic fauna and sediment samples for population, community structure, food web, sediment chemistry and metabolism studies; a beam and/or otter trawl was subsequently used to collect epifauna for population and stable isotope and lipid content measurements.Both bridge and helicopter operations were also used for seabird, marine mammal and sea ice surveys. A total of 118 stations were occupied in the northern Bering Sea, from south of St. Lawrence Island (SLI) to Bering Strait (Fig. 19).

Figure 19. Cruise map for USCGC Healy cruise HLY0702, with SBE line in northern Bering Sea

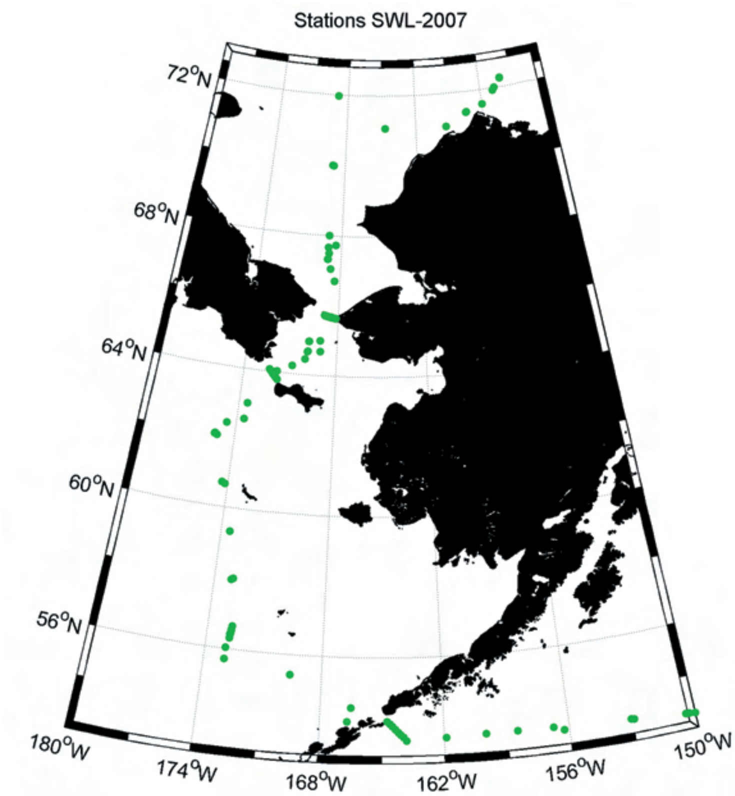


Figure 20. Leg 1 of the C30 project in the Gulf of Alaska and Bering/Chukchi Seas aboard *Sir Wilfrid Laurier* en route to the Arctic Ocean.

Annual hydrographic and benthic sampling at selected sites in the Gulf of Alaska and in the Bering Sea north and south of Bering Strait are part of collaborative time-series studies in the northern Bering and Chukchi seas between the University of Tennessee Knoxville and the Department of Fisheries and Oceans Canada. In 2007 and 2008 this research was embedded in the larger C3O effort (see previous Section) with participation by the CCGS *Sir Wilfrid Laurier* en route to its duties in the Canadian Arctic (Fig. 20).

4.C.3. Overwintering of the *Amundsen* in the Canadian Arctic; the Circumpolar Flaw Lead Study [Barber (U Manitoba), Stern (DFO), Deming (UW), co-leads, plus 200 collaborators from 15 countries]. The circumpolar flaw lead (CFL) is a perennial characteristic of the central Arctic, formed when the mobile central pack moves away from coastal fast ice, opening a flaw lead that occurs throughout the winter season. Due to a reduced ice cover these regions are exceedingly sensitive to physical forcing from both the atmosphere and ocean. ***Oceanographically*** the high ice production in the flaw lead system contributes significantly to brine fluxes from the continental shelves into the deep basins, drives biogeochemical fluxes on and off the continental shelves and controls many aspects of gas and mass fluxes across the ocean/sea-ice/atmosphere interface. ***Meteorologically***, the flaw lead system is expected to play a central role in the steering of cyclones within the region. ***Biologically*** with the early availability of light and increased availability of nutrients through advection and upwelling at the shelf break, the CFL encourages an ecosystem-wide enhancement of productivity.

Although the CFL is hemispheric in scale, this study focuses on the Canadian sector near Banks Island, NT (The Cape Bathurst Polynya). The central element of the field study is the overwintering of the NGCC *Amundsen* beginning in October 2007, continuing through August 2008. In January, as the ice encroaches on the flaw lead, the ship will enter into the landfast ice located immediately adjacent to the flaw lead, south of Banks Island. The study will continue with temporal measurements centred on an ice camp, while spatial measurements will be emphasized through flaw lead sampling by *Amundsen*. At regular intervals (monthly to bi-weekly) the *Amundsen* will break out from her 'landfast harbour' to conduct a 1-2 day survey of the evolving flaw lead system. Once melt ponds form (likely in mid-June), the ice camp will be disassembled and the study will proceed with continuous sampling from the *Amundsen* until August, 2008.

Through the fall of 2007, the CFL Study conducted several open-water transects throughout the Amundsen Gulf and Southern Beaufort Sea (Fig 21), with a science team of 40 sampling all elements of the physical and biological systems at fixed locations. During these sampling operations many ocean observatories were collected and re-deployed throughout the area, in collaboration with ArcticNet.

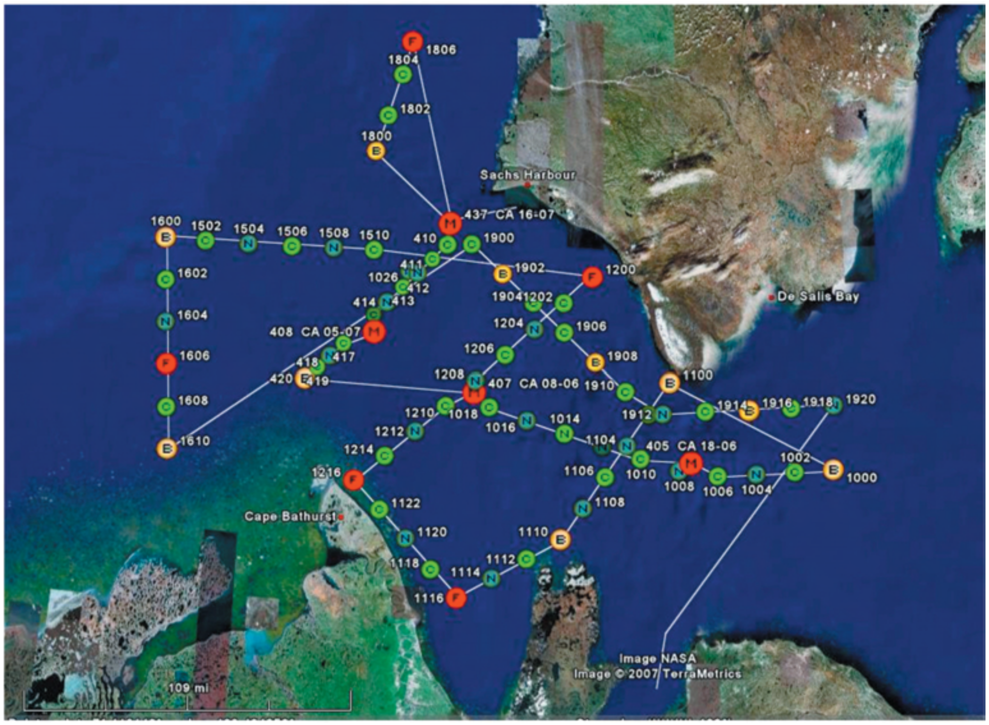


Figure 21. CFL sampling strategy for open water and new ice periods (fall 2007)

Since the beginning of December, the ship has been in drift mode, parked in an ice-floe for several days so that researchers can venture onto the ice to sample. The ice conditions in the southern Beaufort Sea have been unusually light (see Section 5.1) and surface mixed layer temperatures have been unusually high (Section 5.2). Full details of the project, including daily dispatches, are available at www.ipy-cfl.ca.

Figure 22. *Amundsen* penetrates heavily decayed polar pack to sample multiyear sea-ice in early December, 2007.

4.C.4. Ocean Currents of Arctic Canada; new insights on the Canadian Arctic Through-flow (PI Humfrey Melling, IOS Sydney). The Canadian Arctic Through-flow (CAT) study during the IPY is the culmination of ten years' of effort within Canada and the international community to measure flows of freshwater, saltwater and ice through the Canadian Archipelago, from Arctic to Atlantic (see Münchow et al 2008; Falkner et al 2008; Melling et al 2008). Beginning in 1998, the first moorings for year-round measurement were placed in western Lancaster Sound and in Cardigan Strait, and new techniques were developed, principally those of measuring the current direction near the geomagnetic pole and salinity within the hazardous 30-m zone beneath drifting ice pack. These early installations have been maintained and augmented ever since. In 2003, a large array of instruments was installed across the third principal path for Canadian Arctic through-flow, Nares Strait, with the support of US-NSF and with US collaborators – Dr Andreas Münchow (University of Delaware) and Drs Kelly Falkner and Roger Samelson (Oregon State University) and representing an important component of the international Arctic-Subarctic Ocean Fluxes Study (ASOF).

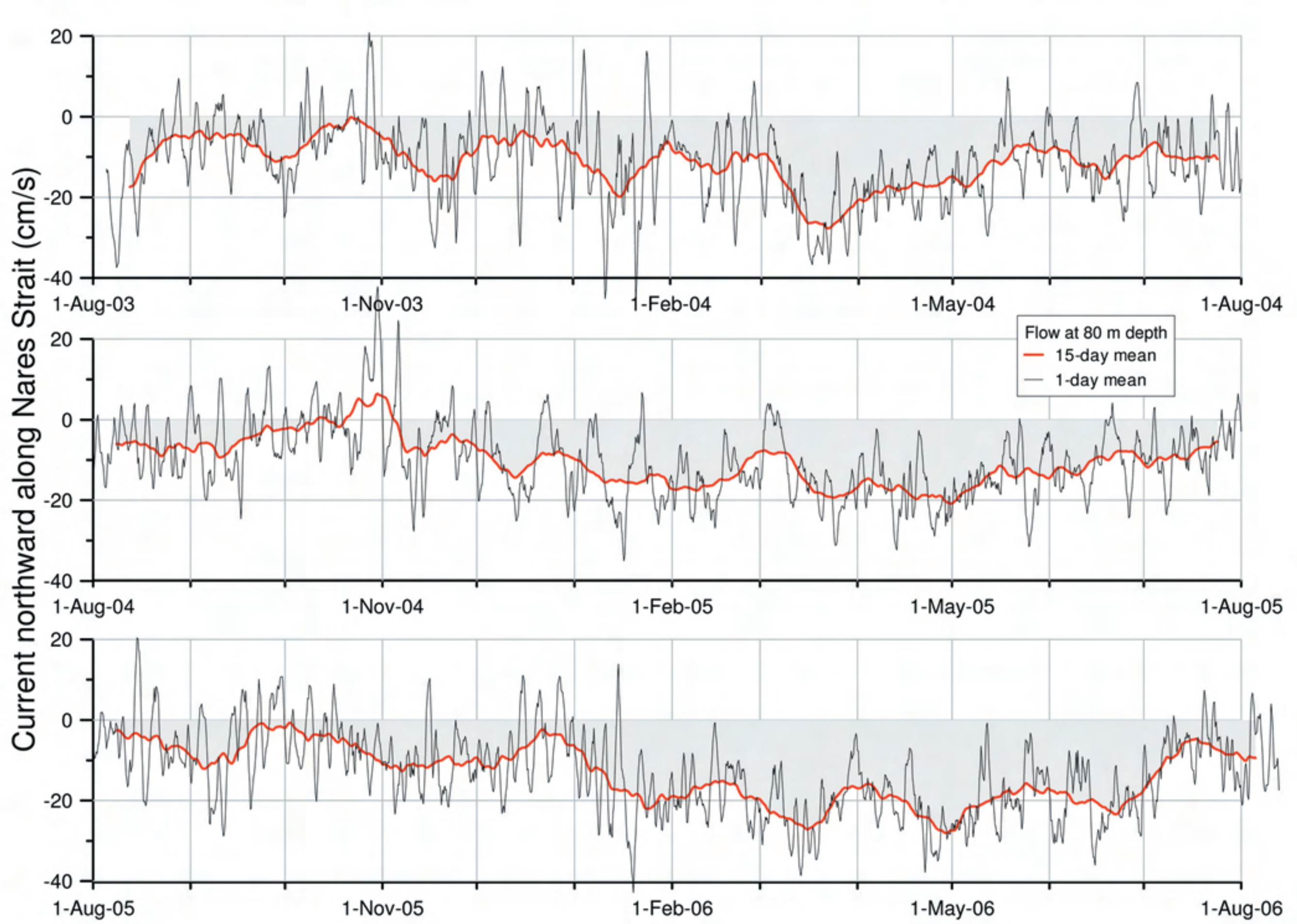


Figure 23. Three-year record of 1-day and 15-day mean flows at 80m depth on the western side of Nares Strait, 2003-6, close to the main southgoing baroclinic jet

Most of the instruments placed in Nares Strait in 2003 were retrieved using CCGS *Henry Larsen* in 2006, and though much work remains in analyzing the mooring data and integrating the analyses from the doppler-sonar and T-S moored arrays, new insights are already emerging. In Fig 23, a continuous record of flow-speed from 80m depth close to the high-speed southgoing baroclinic jet on the Canadian side of the Strait reveals almost continuous southgoing flow, some first signs of interannual variability and a strong seasonality with a maximum in Feb-April, 2-3 months earlier than the March–August maximum through Cardigan Strait and Barrow Strait (Melling et al op cit). Following a 1-year hiatus in 2006-7, a new array was established by *Henry Larsen* across the southern end of Kennedy Channel in August 2007 as part of a Canadian contribution for the IPY, while the long-standing installations in Cardigan Strait were also recovered and redeployed (Fig 24). Recovery is planned in Summer 2009.

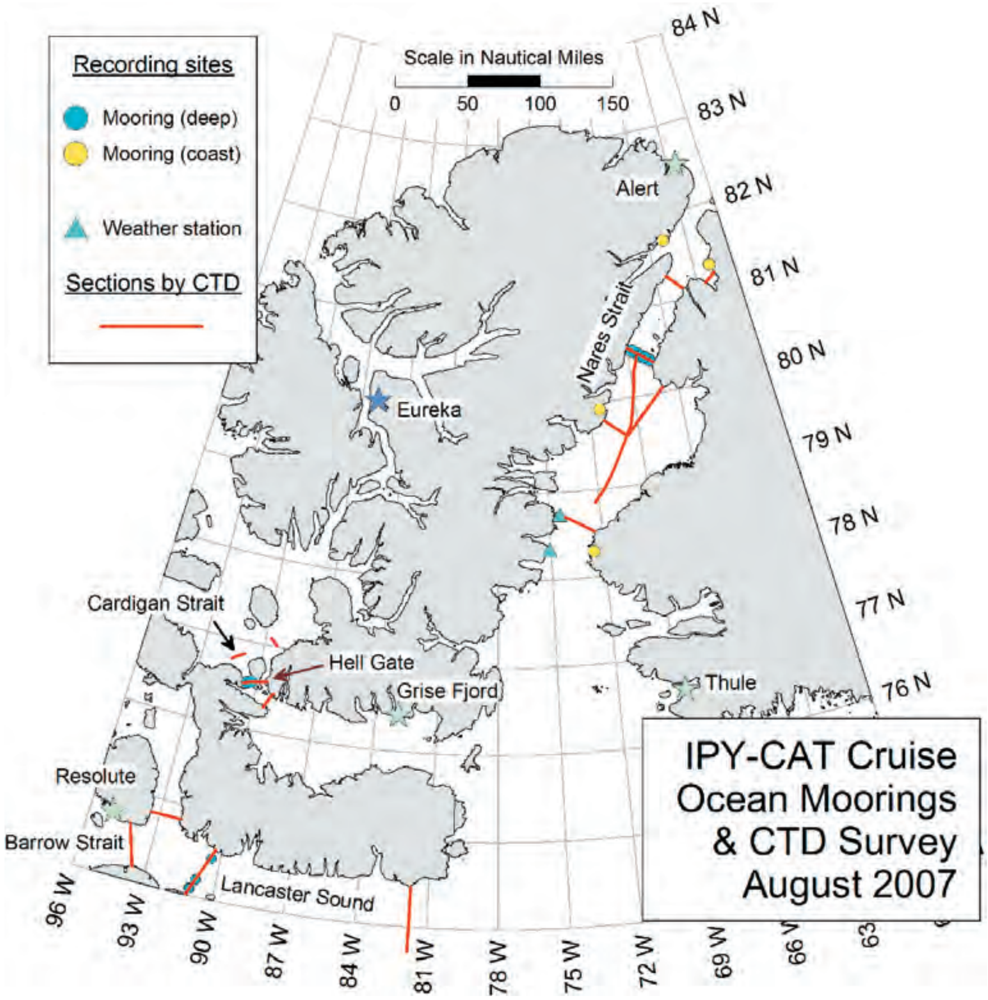
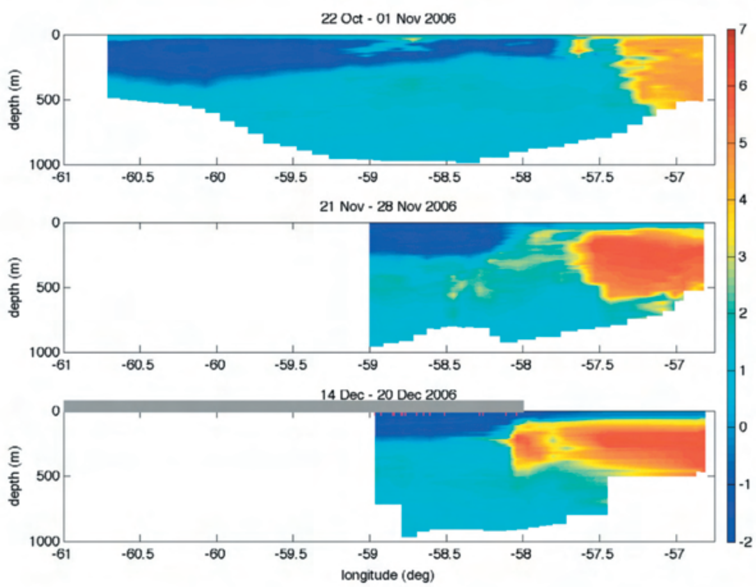
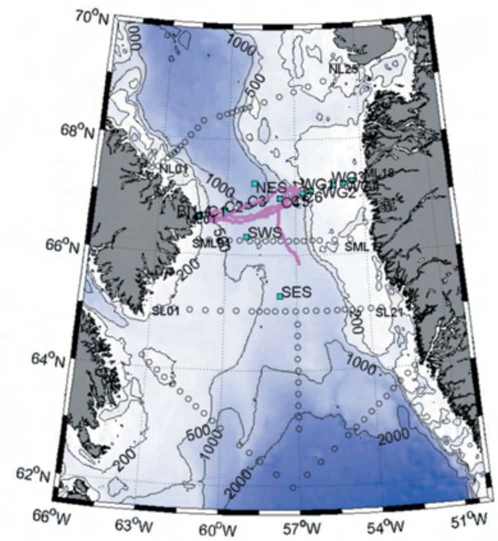


Figure 24. Sites of scientific activity conducted from CCGS Henry Larsen during August 2007. The principal centres of activity are in southern Kennedy Channel between Greenland and Ellesmere Island at 80.5°N and in Cardigan Strait between Ellesmere and Devon Islands at 091°W.

The IPY CAT project has during 2007 also supported maintenance of the Lancaster Sound array from CCGS *des Groseilliers* and installation of an oceanographic mooring in Bellot Strait from CCGS *Louis S St Laurent*. Bellot Strait is the least of the four constrictions for Canadian Arctic through-flow. The CAT study is now observing the flows of seawater, salt and heat through all the pertinent straits within the Canadian Archipelago. The two long-term goals of the project are 1) to understand the forcing and control of CAT, so that it may be represented more realistically in predictive climate models and 2) to develop sustained observations of seawater and ice movements through the Canadian Archipelago as an effective, affordable approach to monitoring for ocean climate.

4.C.5. A major advance in monitoring flow through Davis Strait; the first autonomous sub-ice glider profiles (see NSF-AON award #0632231,'An Innovative Observational Network for Critical Arctic Gateways: understanding Exchanges through Davis and Fram Straits') PI Craig Lee, with Jason Gobat, Richard Moritz & Kate Stafford, APL-UW, Brian Petrie, BIO Dartmouth N.S., and Marlene Simon, Greenland Nature Institute). A system consisting of moorings and extended-endurance (9-12 months) autonomous gliders deployed across Davis Strait characterizes exchanges of mass, heat and freshwater between the Arctic and the North Atlantic though the Canadian Arctic Archipelago and thus acts as a vital monitor of Arctic and subarctic change. This project began with the deployment of a moored array in autumn 2004, was supplemented with gliders in autumn 2005 and involves the on-going development of acoustically-navigated gliders that will be capable of operating year-round under seasonal ice cover. While the Davis Strait program has conducted numerous glider-based sections across the Strait during the ice-free autumn months, the project achieved a milestone in December 2006 with the successful operation of a glider beneath the ice-covered western Davis Strait (Fig 25).





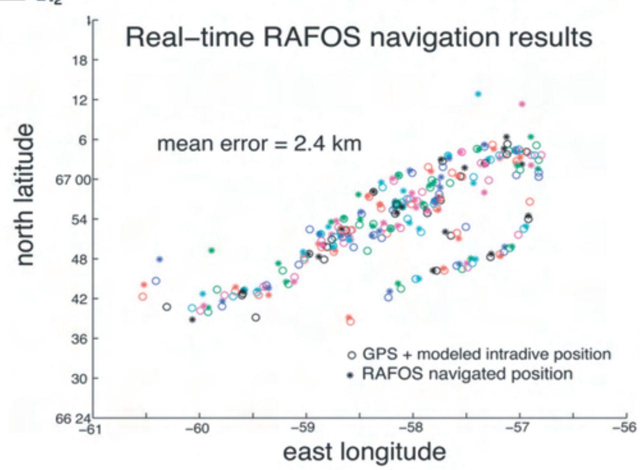


Figure 25. Three glider transects of Davis Strait including the first successful sub-ice section in December 2006 (3rd panel; grey tone indicates sea-ice). Gliders used the RAFOS array for navigation but were fully autonomous in operation, deciding where to go and when to attempt to surface, without human intervention.

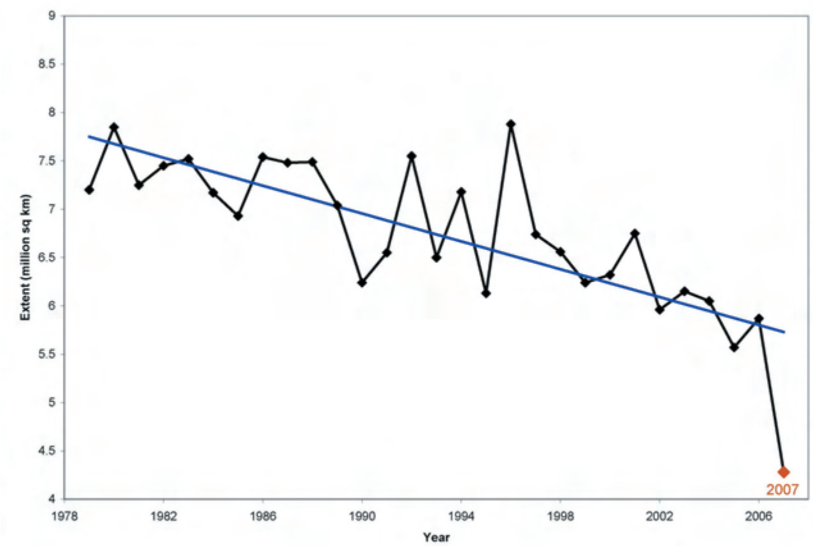
As illustrated in Fig 25, 3rd panel, a single seaglider successfully navigated from the ice-free eastern Strait westward to 59°W, shifting to fully autonomous behaviour, avoiding the surface and continuing its westward transit after encountering the ice-edge. Significantly, all aspects of the ice-capable glider system functioned properly, including acoustic navigation, ice sensing, autonomous decision making. The entire section was conducted without human intervention, with the glider making its own decisions and surfacing to report its data after navigating back to the ice-free eastern side of Davis Strait. By returning observations to within a few meters of the ice-ocean interface and at roughly 5 km horizontal resolution, the technique successfully resolved the south-flowing, surface-trapped Arctic outflow from the CAA. Unfortunately, a hydraulic failure (unrelated to the new ice functionality) resulted in the loss of this glider. More recently, faulty Iridium modems and Iridium/GPS antennas have caused UW to suspend under-ice glider operations for the 2007-2008 season. Davis Strait glider operations will resume in autumn 2008.

5. Drawing the strands together: the present state of the system

By 'system' we mean both the physical environment of the Arctic-subarctic seas that form the iAOOS domain, and the observational network deployed to observe it.

5.1 The present state of the Sea-ice

Though much of this Report has been concerned with its physical oceanography component, it is appropriate to begin this summary with the present state of the Arctic perennial sea-ice, the primary research-focus of iAOOS.



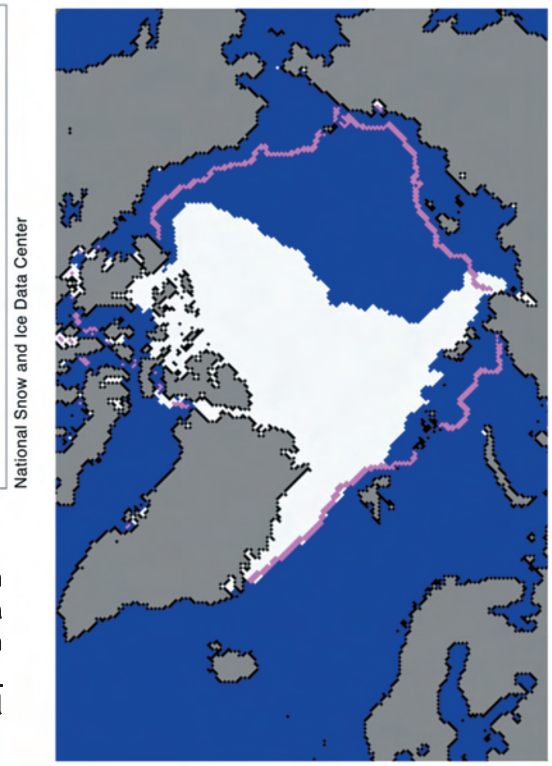


Figure 26. The new record minimum sea-ice extent* in September 2007. Data from NSIDC Boulder CO. The magenta line shows the median September monthly extent based on data from 1979 to 2000 (http://nsidc.org/news/press/2007_seaiceminimum/20070810_index.html). See also Stroeve et al 2008.

As the figures released by NSIDC show (Fig 26), the extent* of the Arctic perennial sea-ice dropped to a new record minimum of 4.20 million square km in September 2007, nearly 50% lower than during the 1950s (*defined by NSIDC as the total area covered by some amount of ice, including open water between ice floes). The absolute minimum extent of 4.13 million square km was achieved on September 16, 2007. Note that the new NSF-AON award #0632398 for the IPY (PI Hajo Eicken), will directly study 'The State of the Arctic Sea Ice Cover via an Integrated Seasonal Ice Zone Observing Network (SIZONET)'. The effect of a decrease in the albedo of the Arctic Ocean from 80% to 20% or less over an area the size of Europe is one effect of a dwindling sea-ice cover on climate that DAMOCLES will study. The effect of an increased Arctic freshwater efflux on the Atlantic MOC is another.

5.2. The present state of the Ocean; the poleward spread of extreme warmth

Very recently, the temperature and salinity of the waters flowing into the Norwegian Sea along the Scottish shelf and Slope have been at their highest values for >100 years (Bill Turrell, FRS, pers comm., 2006). At the 'other end' of the inflow path, the ICES Report on Ocean Climate for 2006 (ICES, 2007) shows that temperatures along the Russian Kola Section of the Barents Sea (33°30'E) have equally never been greater in > 100 years. Shorter records en route and beyond, on the Norwegian arrays off Svinoy (Skagseth et al. 2008) and on the moored array monitoring Fram Strait (Schauer et al in press) have all remarked the passage of this warmth; Holliday et al (2007) have described its continuity along the boundary. It forms part of the rationale for Overpeck's (2005) statement that *'a summer ice-free Arctic Ocean within a century is a real possibility, a state not witnessed for at least a million years.'* Most recently, Polyakov et al (2007 and pers comm) have documented the onward spread of the most recent pulses of warmth along the Eurasian boundary of the Arctic Ocean (Fig 27) using the records of his Mooring-based Arctic Ocean Observing System (MAOOS), an important element of iAOOS. The arrival of successive warm pulses at the Slope of the Laptev Sea (Polyakov 2005), its continued eastward spread beyond the Novosibirskiye Islands (Polyakov et al 2007) and the beginnings of its offshore spread along the Lomonosov Ridge [reported from survey data by IA Dmitrenko (in Polyakov et al 2007)] are neatly confirmed in simulations using the NAOSIM model (Karcher et al 2003, 2008a).

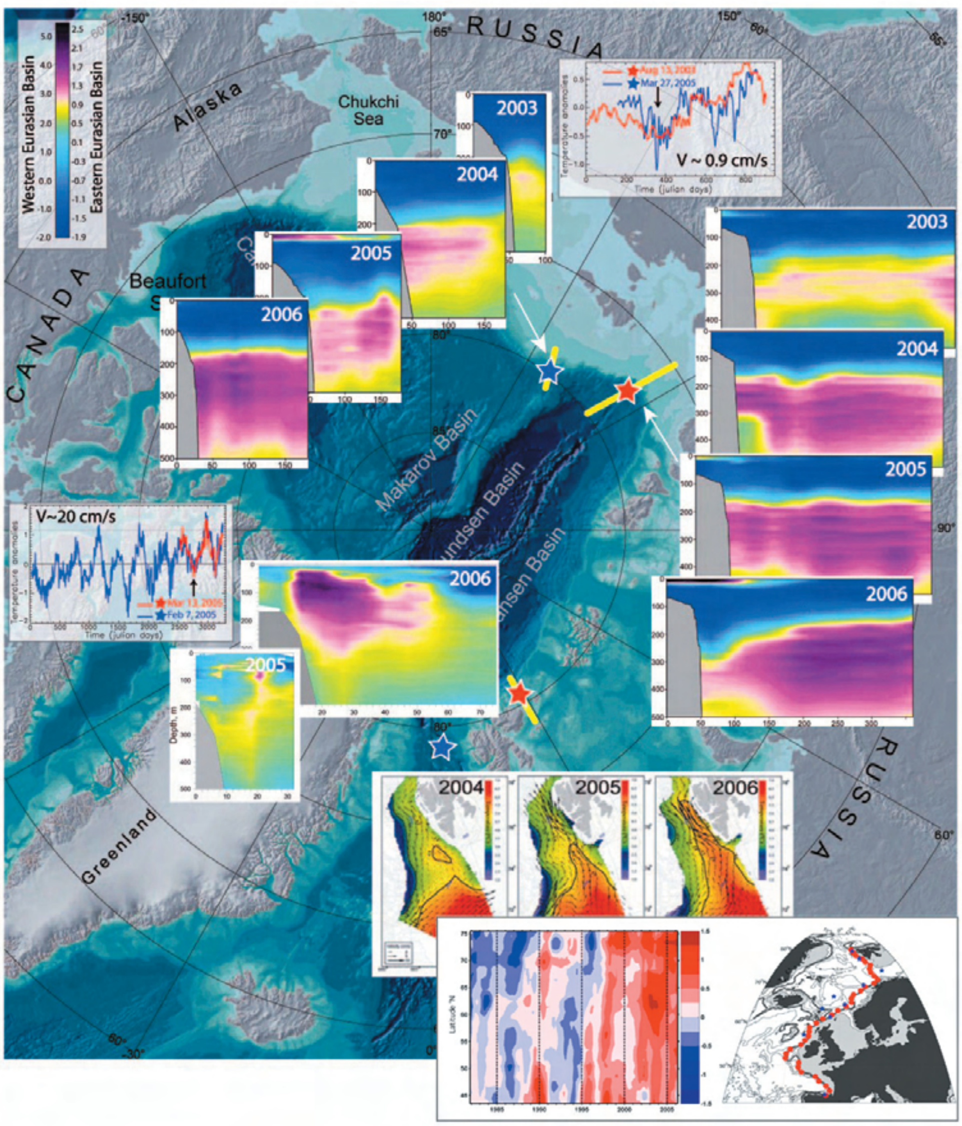


Figure 27. Vertical cross-sections of water temperature and mooring-based time series of water temperature anomalies (ºC) from the Laptev Sea slope (top) and vicinity of Svalbard (middle). From Polyakov et al 2007. These observations provide evidence of the spread of unprecedented warmth along the eastern boundary of the Nordic Seas to Fram Strait (lower panels) and its on-going propagation along the Eurasian boundary of the Arctic Ocean. The evidence of warming at the approaches to Fram Strait derives from a grid of about 220 CTD stations worked annually in June-July by the Polish Institute of Oceanology, Sopot, while the map at lower right gives locations of the time series of SST data (red dots) and approximate locations of the hydrographic sections (blue stars)

Though the spread of warming is far from complete, its depth, horizontal extent and magnitude plus evidence of new warm anomalies entering through Fram Strait suggest that 'spreading warmth' must form an important part of any description of the present state of Arctic and subarctic seas. The environmental impact of this warming may not be straightforward. The rapid drop in ice extent in summer 2007 (Fig 26) may partly reflect the remarkable strength of meridional airflow from the North Pacific and Bering Strait at that time (Overland et al 2008). Insolation may also help explain the warmth of the upper watercolumn on the East Siberian Shelf encountered by Polyakov's NABOS-07 cruise in September 2007 and confirmed in the SST distribution mapped by JAMSTEC for September 15 using AMSR-E (compare Figs 28 a and b below).

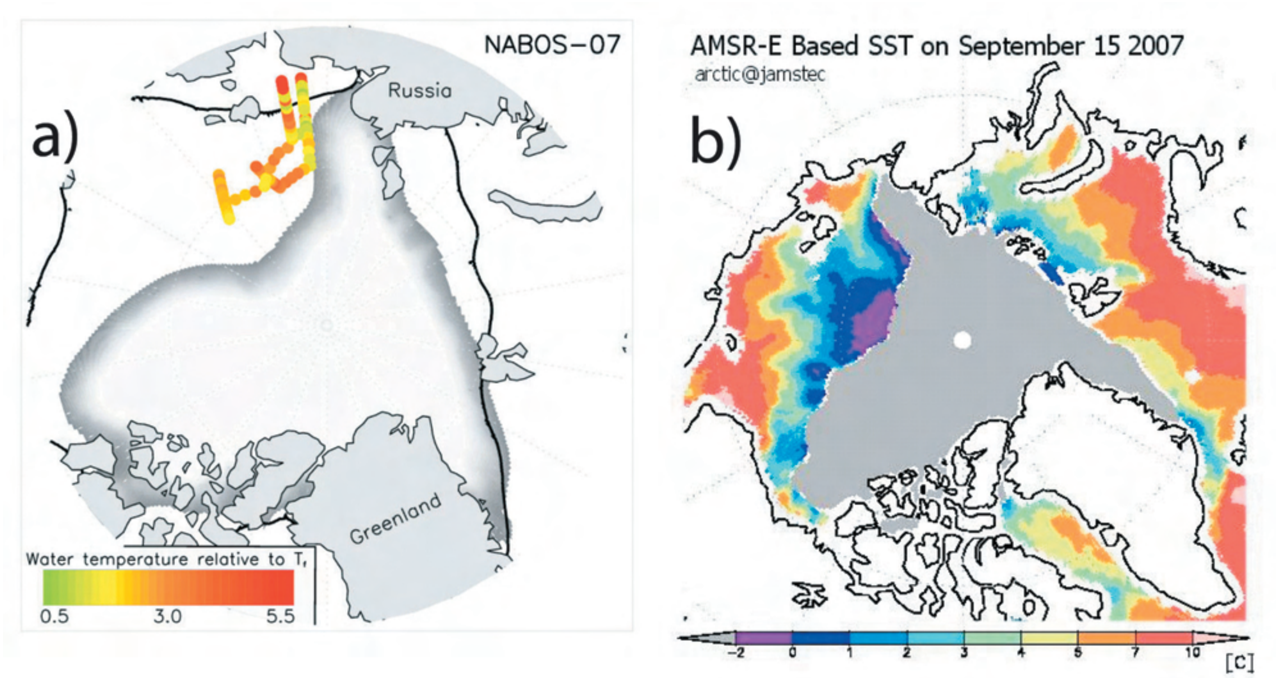


Figure 28. a) Against the mid-September 2007 ice cover (gray shadow) and mid-September ice edge climatology (solid thick black line), the colour circles show sea temperatures in the upper 20m relative to the freezing point encountered on the NABOS-07 cruise, (Igor Polyakov pers comm.); these are ~ 3-5C with slightly lower anomalies (as expected) near the ice edge. From such a large anomaly, Polyakov points out that strong impacts on sea-ice seem likely; freezing had not then begun despite the fact that in a "normal" year this area would be ice-covered and temperature would be close to freezing; b) confirms the warmth of the upper Arctic Ocean in mid-September 2007, showing the SST map for 15 September derived using AMSR-E imagery (Takashi Kikuchi, JAMSTEC pers comm., November 2007)

Fig 28a, based on the NABOS-07 expedition is our most recent information, kindly supplied by the NABOS PI, Igor Polyakov. This observation is consistent with the broad-scale distribution of SST in the ice-free area of the Arctic Ocean in mid-September 2007, as derived by JAMSTEC from AMSR (Fig 28b; Takashi Kikuchi, pers comm). Although the warming Atlantic sublayer may have had some role in 'preconditioning' this most recent and most rapid retraction of the Arctic sea-ice, it is possible that its core lay too deep to have significant influence on it, and instead, the climatic impact of the warming Atlantic layer may operate in quite a different way, through its projected effect on the Atlantic MOC, as Karcher (2008b, in prep) points out. His reasoning is that in contrast to earlier T-S changes, much of the recent warming of the Atlantic–derived layer in the Arctic basins since the late 1980s has not been density-compensated and that the layer with density >27.8 kg m^{-3} has significantly deepened; that due to decadal timescales of advection and small vertical heat loss, a large pool of anomalously light water has formed which will slowly drain back into the Nordic Seas; and that it may there influence the strength of the Denmark Strait Overflow ---hitherto largely unchanging (Dickson et al. 2008)---by altering the two factors, the density contrast across the sill and the interface height above the sill, that together determine the strength of overflow (Whitehead 1998). This is not of course the only potential climatic effect of the warming of our northern seas (see Section 5.1 above). But the fact that conditions now seem right for a weakening of the Denmark Strait overflow is certainly a third subject to challenge both our integrated monitoring system, and our new capability in understanding and modelling that overflow (eg Käse and Oschlies 2000; Wildenskjeld and Quadfasel 2005; Köhl, Käse, Stammer and Serra, 2007; Olsen and Schmith, 2007; Macrander et al 2007).

5.3. The present state of the mooring network

Fig 29, compiled by Humfrey Melling with additional input from Bob Dickson, describes the distribution of all 156 current meter moorings and arrays deployed across the iAOOS domain during 2007 whether or not they are primarily intended for the support of the IPY and its component programs. Although thinly spread in places, in fact the mooring network shown is a healthy advance on the situation of earlier years and conforms well with the iAOOS Plan (Dickson, 2006), with all the main choke-points of ocean exchange between Arctic and subarctic seas now covered, with the continuation of historical time-series moorings, and with long-standing 'gaps' at climatically-important sites now properly instrumented, many for the first time (offshore branch of the Norwegian Atlantic Current, flux to the Arctic Ocean from the NE Barents Sea, East Greenland Current, Davis Strait etc; Sections 4.B.2, 4.B.4, 4.B.6 & 4.C.5 above).

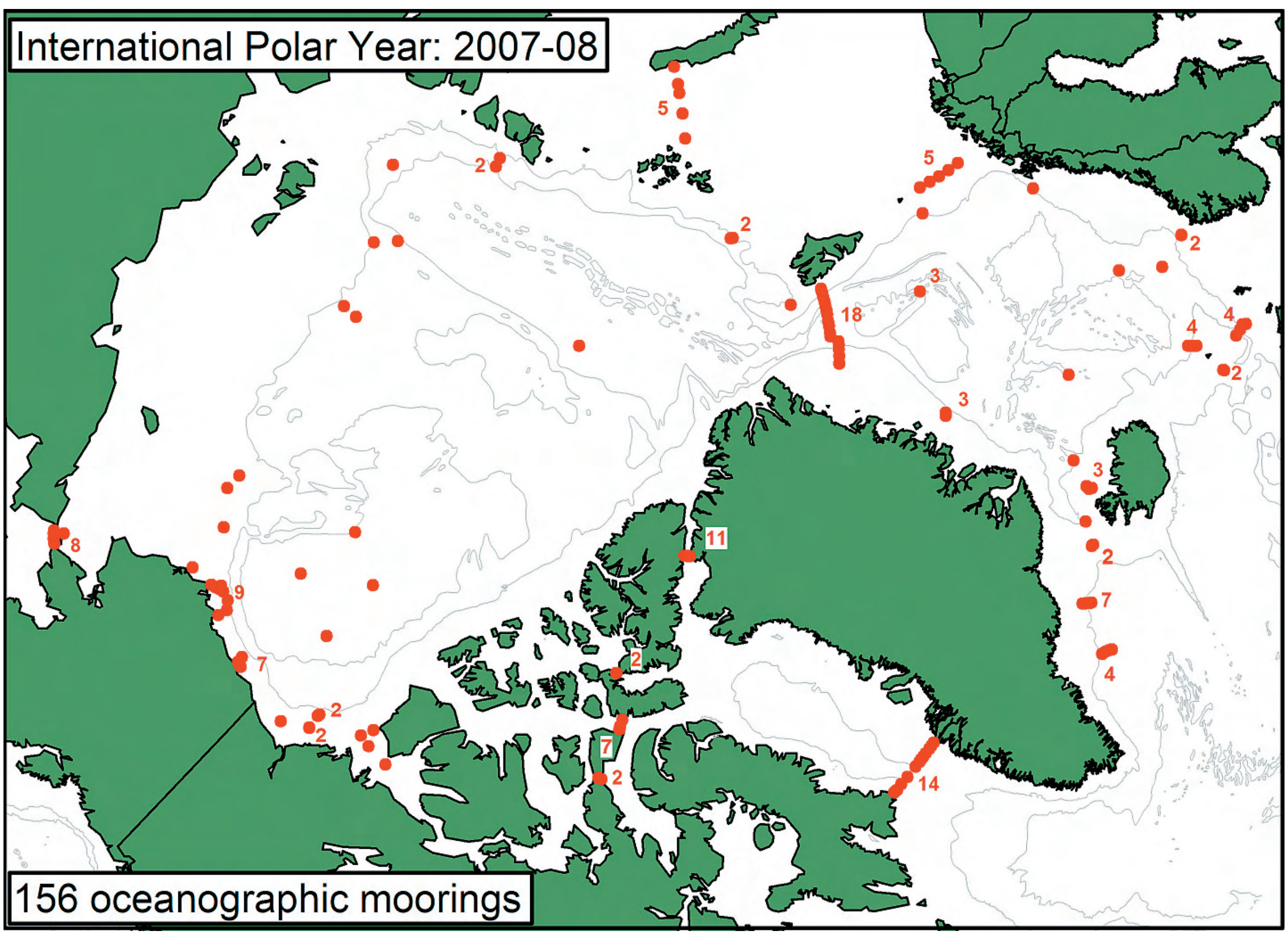


Figure 29. Distribution of all 156 current meter moorings and arrays across the iAOOS domain in 2007. Compilation by Humfrey Melling, IOS Canada and Bob Dickson CEFAS UK. Small numerals in red refer to the number of moorings in an array, where these are too numerous to distinguish individually. A spreadsheet detailing contact PIs for all 156 will be posted on the AOSB website http://www.aosb.org/

5.4. The present state of the Ice-Based Observatory. **[Co-PIs Toole, Krishfield, Proshutinsky, Timmermans, Ashjian (WHOI; see NSF-AON awards #0519899 and #0631951), Perovitch, Richter-Menge (CRREL; NSF-AON award #0612391), Stanton, Shaw (NPS; NSF-AON awards #0520328 & #0632041), Overland (PMEL), Rigor (UW; NSF-AON award #0520287), Hutchings (UAF), Kikuchi, Shimada (JAMSTEC), Gascard (LOCEAN), Schauer (AWI) Priamikov and others (AARI), & Laxon, Bacon, Meldrum UK (UCL, NOC, SAMS resp)]**

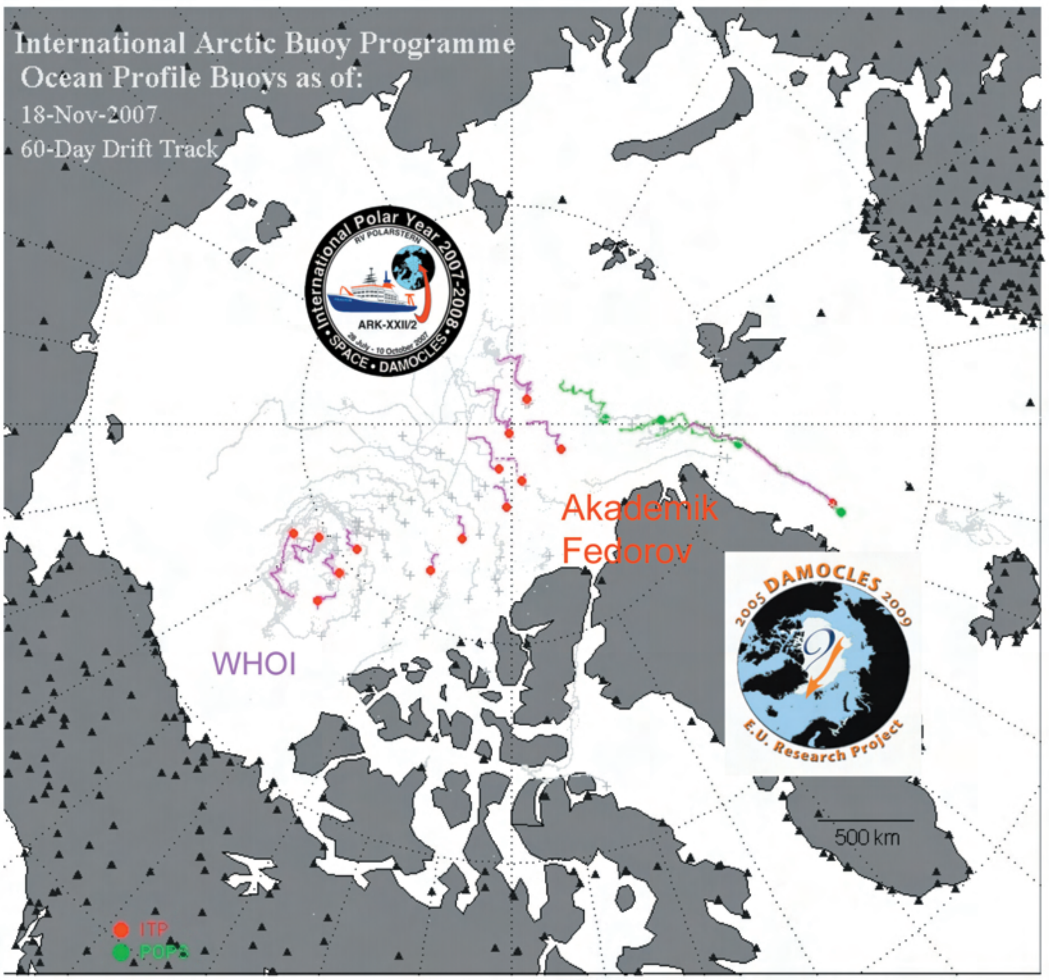


Figure 30. Location of the 18 ITPs and POPs at 18 November 2007, together with the drift track of each over the preceding 60d. From the website of the International Arctic Buoy Program http://iabp.apl.washington.edu/. Comparison with Fig 29 will show just how complementary in coverage are the ice-based and mooring-based observing systems

The presence of a well-integrated ITP-POPS grid is crucial to the modern measurement of the Arctic Ocean, gathering met data, making autonomous CTD profiles of the upper watercolumn and communicating data to and from satellites. Fig 30 illustrates the locations at 18 November 2007 of the 18 platforms that then made up the ITP grid. Shown are the 3 ITPs deployed by *F/S Polarstern* in summer 2007 (A-W-I SPACE Project), the 5 units deployed by DAMOCLES from *Akademik Fedorov*, the 5 platforms laid by Proshutinsky, Toole and Krishfield from the Canadian icebreaker *Louis S. St-Laurent* as part of their 2003-2008 Beaufort Gyre Observing System (BGOS; WHOI), plus 5 so-called POPS (Polar Ocean Profiler System of JAMSTEC; see below). John Toole (WHOI, pers comm., November 2007) estimates that since August 2004, ITPs have now returned a total of more than 9000 CTD profiles from the upper watercolumn (~8 to 760 m depth) of this historically data-poor Ocean.

At the level of the individual scientist, the projects employing ice-tethered instruments are also among the best integrated. Necessarily so, reflecting the relatively small number of systems in use and the expertise necessary for their operation. Thus, as just one example of effective coordination, the 5 ITPs (3 funded by DAMOCLES, 1 by AARI and 1 by WHOI) deployed from *Akademik Fedorov* in summer 2007 were installed by WHOI technicians with DAMOCLES in support, the three deployed from *Polarstern* (2 AWI, 1 DAMOCLES) were installed by AWI personnel after training in Woods Hole and with WHOI equipment on loan, one was installed with the NPEO in spring 2007 (see 4.A.8 above), and three were installed in the Canada Basin in conjunction with the BGFE cruise of the *Louis St. Laurent*.

As with ARGO, we can anticipate having to reseed the array annually to maintain the network in the face of instrument dropouts from exhausted batteries, physical destruction by ice, grounding, and from the loss of units carried out of the Arctic through Fram Strait (see Fig 30). So in 2008 a number of replacements are in prospect, still with the close involvement of the designers/main users of the systems (mainly WHOI and JAMSTEC). Thus WHOI will again deploy an ITP near the Pole in spring '08; a further 3 WHOI-type ITPs will be deployed on behalf of the UK-NERC ASBO project aboard the WHOI Beaufort Gyre cruise in summer 2008 with a fourth UK ice mass balance unit (surface and in-ice packages) "attached" to one of Proshutinsky's underwater units; at a number of sites it is hoped that WHOI ITPs will be combined with Ice-Mass Balance Buoys of Perovitch & Richter-Menge (CRREL; NSF-AON award #0612391), and with Tim Stanton's (NPS) Arctic Ocean Flux Buoy systems at a few sites (NSF-AON awards #0520328 & #0632041); approx 3 ITP systems will be provided by the WHOI team to the *Polarstern* for deployment east of the Chukchi Cap in summer 2008, and possibly a similar number to the *Akademik Fedorov* during her cruise to recover NP-35 (see below, Section 5.7). In fact, though not yet finalised, the A-W-I SPACE study in 2008 is in prospect of deploying a varied collection of 2(+1?) Polar Ocean Profilers (POPS; JAMSTEC), +1 ITAC from AWI, 1 ITP from WHOI, and 1 ITP (?) from DAMOCLES during *Polarstern* Cruise ARKXXIII-3, 12 Aug – 19 Oct 2008 (Ursula Schauer A-W-I pers comm., see below), again with JAMSTEC support. (The number and locations of JAMSTEC POPS buoy deployments from *Polarstern* will depend on the route to be taken to her main study area in the East Siberian Sea and Mendeleyev Ridge; Takashi Kikuchi pers comm., 2008). From spring 2008, these already diverse systems will have been joined by the first 8 (of 10) AITPs for DAMOCLES, air-landed on the ice (see Section 4.A.2) & with the remaining 2 following via R/V deployment later in the summer.

Thus the IBO effort is truly a pan-Arctic activity that ---at the scientist level--- spans individual research programs and/or cruises in a way that few components of the Arctic observing system are yet able to do. And the unprecedented high-horizontal resolution of the CTD data returned by ITPs is already paying dividends. Both Toole et al (2006) and Timmermans et al (2008, in press) showcase new features resolved by ITPs, the latter, for example, using ITP data to document a new class of halocline eddies in the Canada Basin [note also Timmermans NSF-AON award #0632201 'Observing the Dynamics of the Deepest Waters in the Arctic Ocean'].

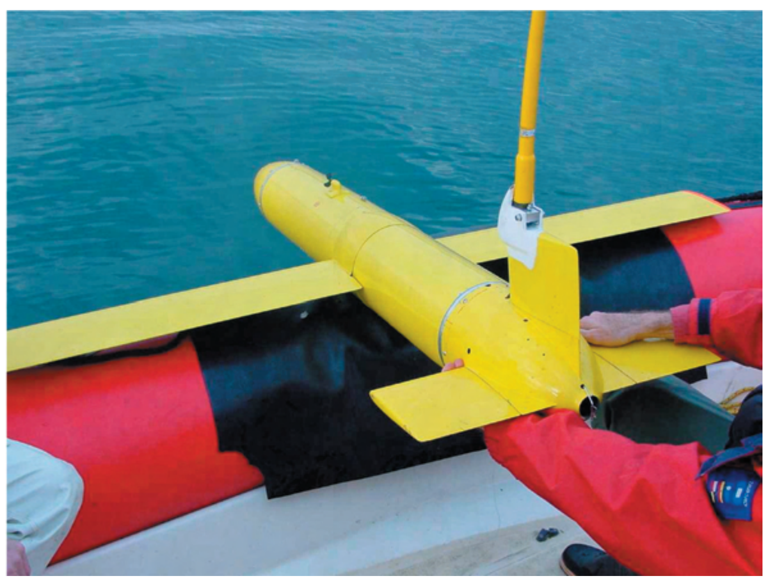
5.5 The present state of the international sea-glider & profiling-float effort in Arctic and subarctic seas

The technical advance represented by the evolution of the SeaGlider is one step further back than the ITP in its application and integration into the full range of subarctic and Arctic programs. As with ITPs, a heartening degree of project support has been made available to project PIs by the originators of the system --largely the APL-UW version in northern seas at present http://iop.apl.washington.edu/seagliders/ will show present locations of all SeaGliders). From its first uses on survey during ASOF, initially in waters west of Greenland, the SeaGlider has more recently added its fine-scale space-time resolution to the classic ship-based hydrography across the Faroe-Shetland

Channel and Iceland-Faroe Ridge by which we have long characterised the poleward ocean heat flux to the Arctic (see Eriksen and Rhines, 2008). It is a nice point that the oldest time-series that we have relied on in ASOF, the hydrographic transects of the Faroe-Shetland Channel begun by HN Dickson aboard HMS *Jackal* on 4 August 1893, are now supplemented by repeat deep SeaGlider sections from the cutting-edge of technical advance (Section 4.B.1). Its further development to a Deep Glider able to cruise the whole watercolumn of the Subpolar gyre has already been called for as a necessary aid to capturing the baroclinic adjustments that cause interannual changes in the transport of overflow from Nordic Seas (Dickson et al. 2008). Further north, SeaGliders are being brought to bear on the problems of the poleward heat flux passing to the west of Norway, (section 4.B.2); the bifurcation of the Norwegian Atlantic current at the Barents sea opening (PIs Mauritzen and Hoydalsvik, Section 6 below); the improved monitoring of the oceanic exchanges through Fram Strait in DAMOCLES (ditto; see Fig 39); and the actual monitoring of oceanic exchanges passing south to the west of Greenland through DAVIS Strait (Section 4.C.5). In addition to these uses, all of which employ the University of Washington SeaGlider with UW technical support, the EC- DAMOCLES project is preparing to use ENSIETA gliders under the Arctic sea-ice, and two WEBB-Research gliders, a deepwater version profiling to 1000m and a shallow version to 200m will be introduced to Skagseth's study of bifurcation in the Norwegian Atlantic Current in 2008.

In 2007-8, glider deployments did include both successes and setbacks.

- **Davis Strait.** The UW project (Craig Lee; Section 4.C.5 above) achieved a considerable technical milestone in December 2006 with the first successful operation of a glider beneath the ice-covered western Davis Strait. Gliders used the RAFOS array for navigation but were fully autonomous in operation, deciding where to go and when to attempt to surface, without human intervention. Faulty Iridium modems and Iridium/GPS antennas later caused UW to suspend under-ice glider operations for the 2007-2008 season. Davis Strait glider operations will resume in autumn 2008.
- **Fram Strait.** Postponed through communications failure in 2007, the Seaglider in Fram Strait will now also be deployed in summer 2008.
- **DAMOCLES gliders (ENSIETA).** The DAMOCLES gliders pictured right are intended for sub-ice navigation in the Arctic Ocean based on the acoustic information from moorings, and are independent of surface GPS information. Though the first gliders have been completed, an initial trial in the Baltic on 22 November 2007 (ENSIETA/FIMR) was unsuccessful and the glider was lost. Through the cooperation of Craig Lee (UW-APL), a second ENSIETA glider for DAMOCLES will be tested with the APL array in the Davis Strait in September 2008.
Because of such setbacks, it is likely that the first use of these gliders will be on the EC ACOBAR Project which will succeed DAMOCLES from 2009 (Section 6 below).



- **Polar Profiling Floats**: in a quite different technical development, but relevant here, Breck Owens and Peter Winsor (WHOI) have secured funding to build 8 Polar Profiling Floats and make them available for deployment in 2008. Because of their mode of operation, these are seen as key contributors to the pan-Arctic autonomous ocean observing system by accessing the growing areas that are seasonally ice-free, particularly round the periphery of the Arctic where there is significant open water, if not a total lack of ice, for much of the year. The Owens-Winsor polar profiling float is much like an Iridium Argos float with one major difference. If it finds its way blocked by ice when profiling to the surface to acquire a CTD cast and then telemeter its data, it sinks back down a few meters then tries again. After repeated attempts, if still unsuccessful, it sinks back to its rest depth to wait for the next scheduled profile time. Once they do surface, all data not yet transmitted are relayed over Iridium. These stored profiles do not provide exact position data since they are not tracked acoustically, but their cost is low, ---around $15k as with a standard Argo float. Owens presently has a number of these floats working in the Antarctic, and has made test deployments in the Arctic. Possible deployment regions being discussed for 2008 include the southern Canada Basin and east of the Chukchi Cap (Louis St-Laurent and Polarstern cruises). Interestingly, the Argo program now recognizes a need to extend sampling to polar latitudes; this increases the number of floats needed in the ARGOS array from ~3000 to ~3300, though the funding for this expansion is not yet clear. As the technology matures we can anticipate that Profiling Floats and Gliders will contribute increasingly to the effort of creating and sustaining a pan-arctic observing network.

5.6 The present state of ship-based CTD observations

Though incomplete, Fig 31 goes some way towards describing the distribution of CTD stations worked during 2007.

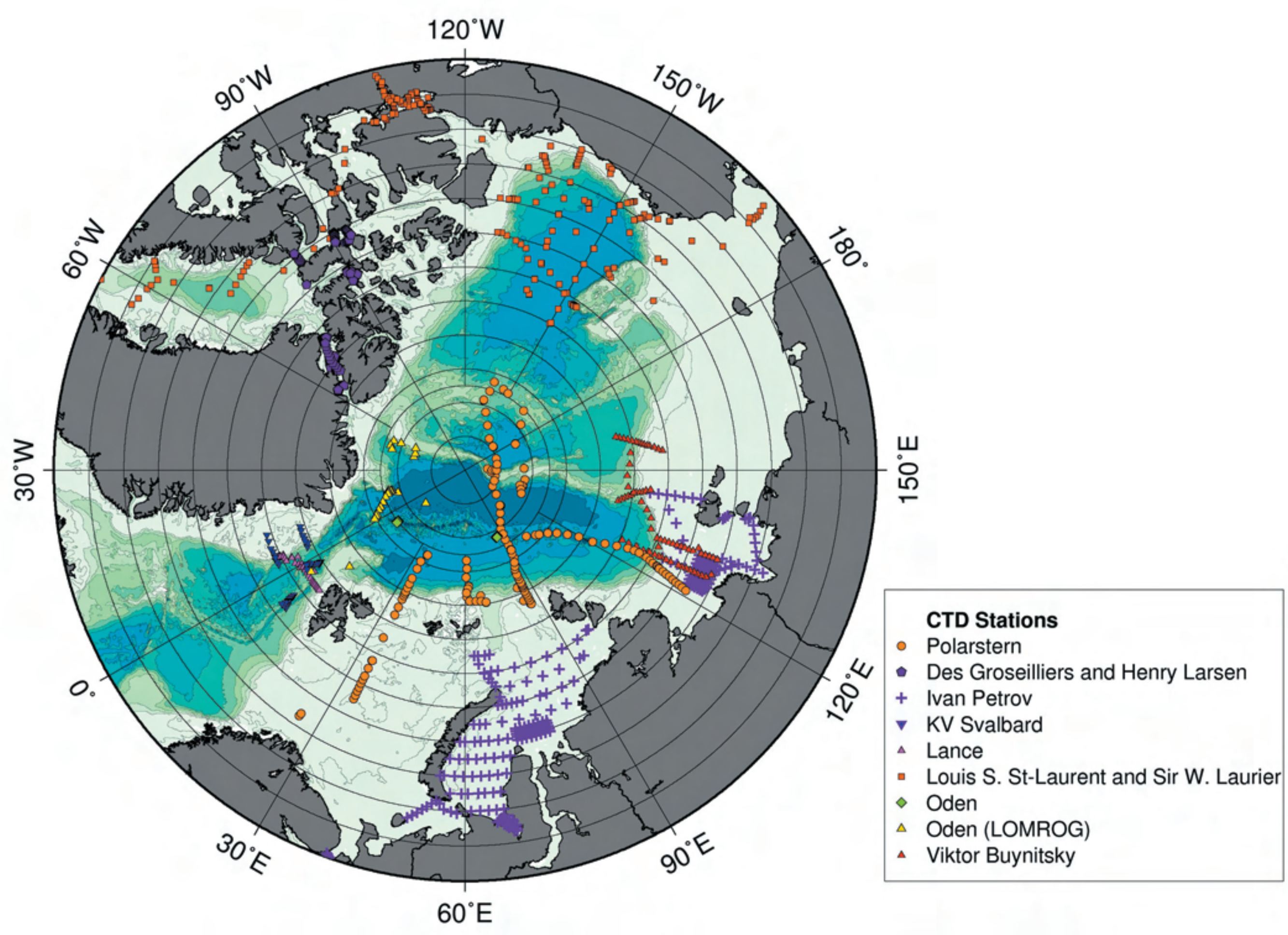


Figure 31. Distribution of ship-based CTD stations worked during 2007. (incomplete draft at 12 February 2008, from Ursula Schauer A-W-I, pers comm.)

Compiled by Ursula Schauer (A-W-I) and reproduced with her permission, Fig 31 represents a work in progress, still lacking stations from the *Academic Fedorov* cruise in 2007, the NPEO, and positions from drifting stations such as *Borneo, Tara*, and others. [ITP/POPs data are not included but are available via their websites, http://www.whoi.edu/science/PO/arcticgroup/projects/ipworkshop_report.html and http://www.jamstec.go.jp/arctic/index_2e.htm]

For the map in its present state, the contact addresses of responsible PIs are:
Polarstern: Ursula Schauer (Ursula.schauer@awi.de)
Ivan Petrov: Heidemarie Kassens (hkassens@ifm-geomar.de)
Lance: Edmond Hansen (edmond.hansen@npolar.no)
Louis S. St-Laurent and Sir Wilfrid Laurier : Fiona McLaughlin (McLaughlinF@pac.dfo-mpo.gc.ca)
Des Groseilliers and Henry Larsen: Humfrey Melling (MellingH@pac.dfo-mpo.gc.ca)
Oden, AGAVE (Green diamonds): Peter Winsor (pwinsor@whoi.edu)
Oden (LOMROG): Göran Björk (gobj@gvc.gu.se)
Viktor Buynitsky: Igor Polyakov (igor@iarc.uaf.edu)

5.7 The present status of Transpolar Drift Platforms; EC-DAMOCLES, Russia, iAOOS for Norway, NSF-SEARCH (Study of Environmental Arctic Change)

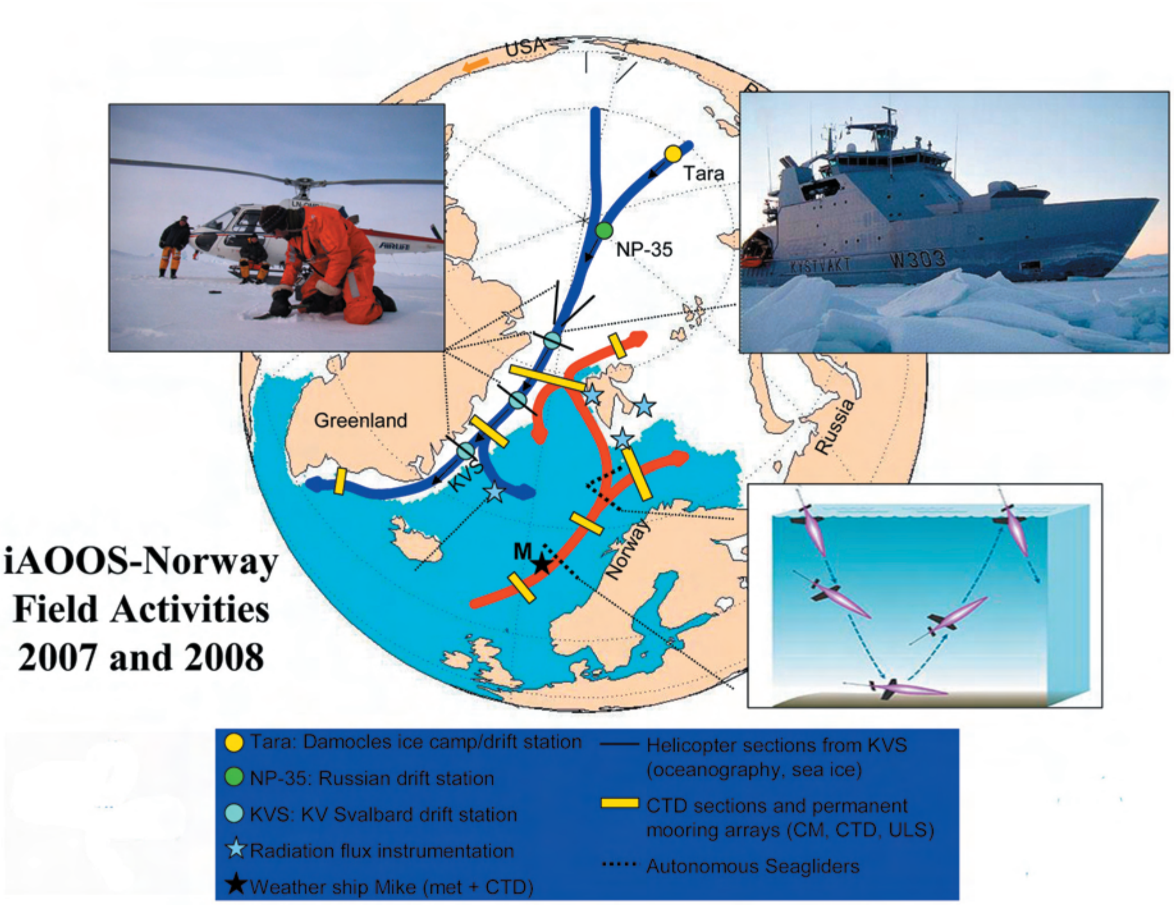


Figure 32. Pre-launch illustration of the various transpolar drift platforms for 2007, taken from the "iAOOS for Norway" project plan

- **TARA:** On September 3, 2007 the polar schooner *Tara* celebrated its first year in the polar ice. She was then embedded in ice and drifting in the style of *Fram* (see Fig 33), but drifting twice as fast as expected. Scientists on board were responsible for running ten different reseach programmes for DAMOCLES, collecting data related to sea ice, atmosphere and ocean. Its location in the heart of the Arctic Ocean permitted the servicing of a sophisticated web of autonomous buoys, spread within a 500 km range around the ship. IAOOS for Norway contributed installations of radiometers and optical measurements. *TARA* passed out of the Arctic Ocean through 80N in December, was picked up by the ice off east Greenland and was finally released into the western Greenland Sea, 300 km north of Jan Mayen on 21 January 2008, some 500 days and 5000 km since her drift began on September 3, 2006, north of the Laptev Sea. See Gascard et al, 2008.

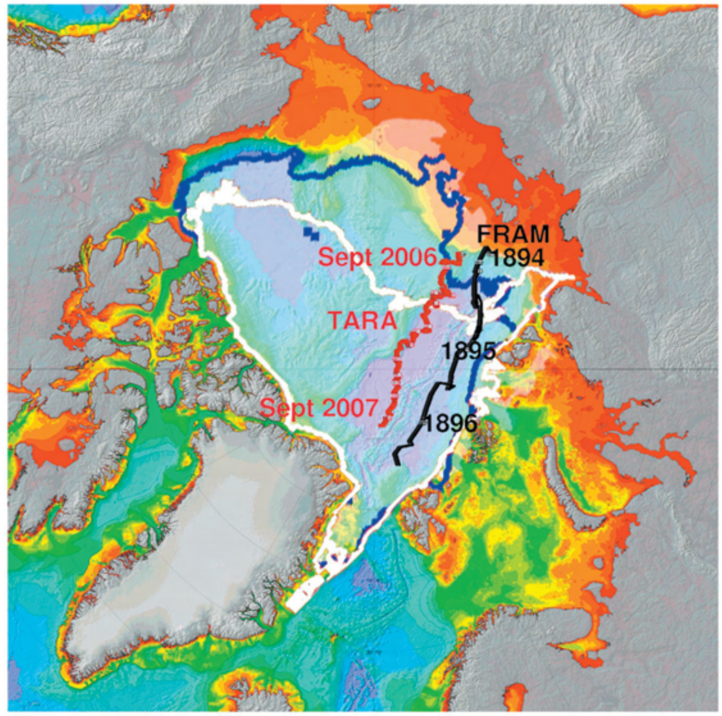


Figure 33. Comparison between the transpolar drift of the *Tara* in 2006-7 and the drift of the *Fram* in 1894-96

- **Russian drifting station NP35**: The part-time involvement of DAMOCLES in the cruise of *Akademik Fedorov* in September 2007 has already been described (Section 4.A.1); the principal aim of this cruise, led by the Arctic and Antarctic Research Institute (AARI) in St Petersburg, was concerned with locating a stable ice floe near Svernaya Zemlya as a base for establishing a trans-polar drift station (NP-35) as an observation platform for the IPY, following the long Russian tradition and expertise in this technique. The intention was to measure a comprehensive suite of climatic variables over an 8- to 12- month period of drift:-- the upper ocean, sea ice & snow cover, standard atmospheric variables plus trace gases such as carbon dioxide and ozone, a strong focus on the planetary boundary layer to a height of ~1500 metres, and for the first time, high resolution vertical profiles of ozone distribution in the central Arctic, north of 82ºN -- currently a blank spot on the global ozone distribution. IAOOS for Norway is due to add radiometers in April 2008 should the opportunity arise. Unfortunately, since its establishment, the floe has shown a tendency to turn back towards Russia rather than join the transpolar drift, so that the ice-camp may need to be re-located to meet its aims.
- **KV *Svalbard*; iAOOS for Norway (PIs Wassmann, Hansen):** the 1st intensive winter/spring field campaigns with KV *Svalbard* took place from 10-30 April 2007, covering the output end of the Transpolar Drift, the western Fram Strait and the headwaters of the East Greenland Current (EGC). 29 scientists from 8 nations took part, including Russia. Sampling for biology, oceanography and sea-ice-physics was concentrated on two drift-sites at 79°40' and 77° 40'N, each lasting 1 week, while a helicopter secured data collection along cross-shelf transects. In spite of periods with heavy ice-conditions and low temperatures, the field campaign was a success providing new data on stratification and high-resolution hydrography in wintertime. An extension in geographical coverage is planned for 2008 (Fig 34), aiming to cover latitudes 74-80 N across the EGC and outer parts of the shelf. As in 2007 there are three main components-- sea ice physics, oceanography, and marine biology/ carbon cycling---but now with the inclusion of oxygen isotope sampling to address Greenland runoff and the solid/liquid phase interchanges of the Arctic freshwater output. In addition it is hoped to get the A-W-I EM-bird on board in time; sections of ice-thickness mapping of the output end of the Transpolar Drift as it exits the Arctic will address the fate of the Arctic ice as it leaves the Arctic, and the coupling to oxygen isotope sampling and liquid/solid freshwater interaction is obvious.

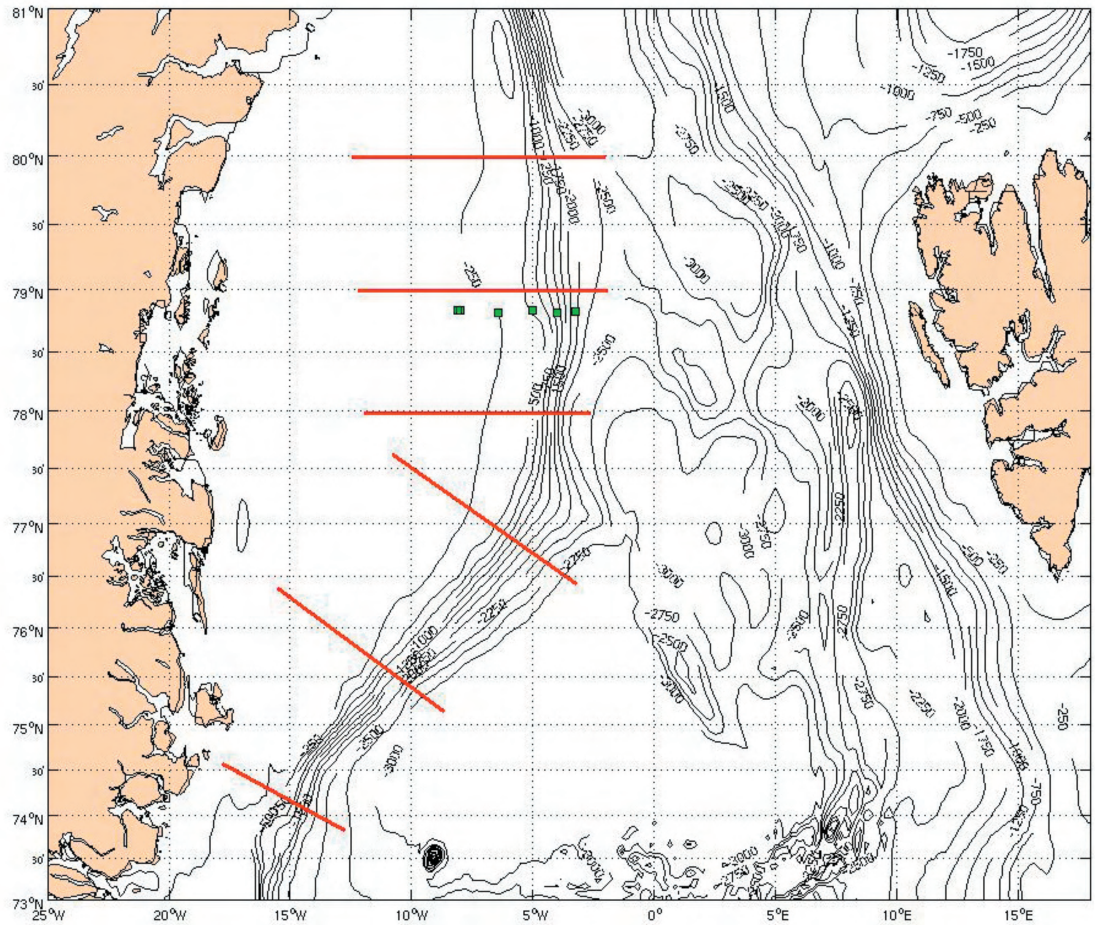


Figure 34. KV *Svalbard* sections and moorings planned for the East Greenland shelf in 2008 (Edmond Hansen, NPI, pers comm.)

6. Supplementing the Ocean Observing System in 2008

- **The NABOS Collaborations (ASBO-SBE-RUSALCA-PAG):** Fig 35 brings together two elements of the current NABOS-ASBO collaboration, currently under negotiation. The ship track and its start-point are not yet known but will include servicing of the boundary current moorings at their present locations and are likely to include the shelf-basin transects illustrated here. The option of connecting marginal transects A and G through additional deep-basin measurements on the return leg will depend on the ship and cruise duration and is thus undecided at present. The UK-Bangor turbulence team and the UK-NOC chemistry team will take part as before. Also under discussion is the aim

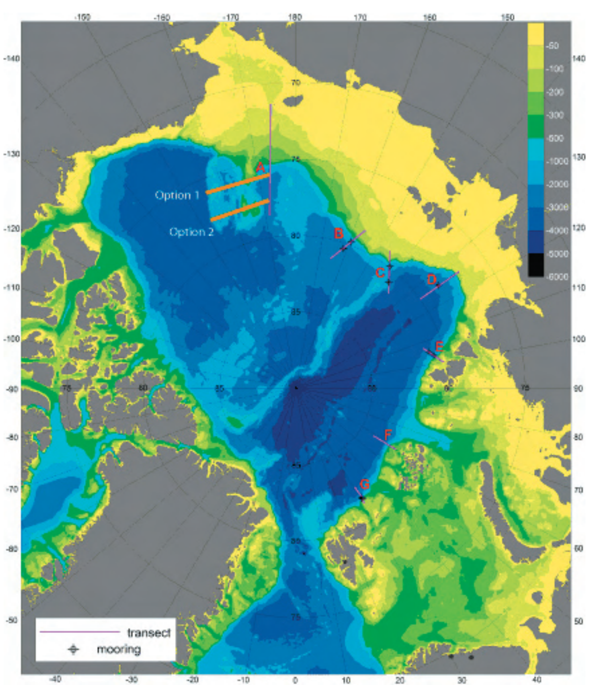


Figure 35. Moorings and off-slope transects proposed for Polyakov's NABOS study in 2008, together with hydro lines proposed by Bacon (UK-ASBO) to connect the Siberian Slope with Proshutinsky's (WHOI) Beaufort Gyre Exploration Study

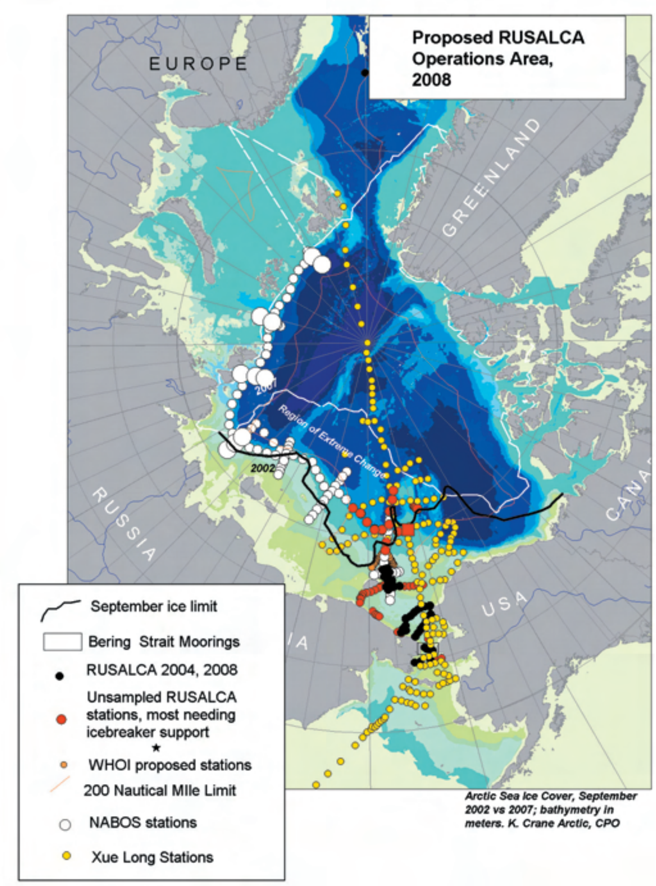


Figure 36. Proposed 2009 tracks for the Pacific Arctic Group (PAG), the joint US-Russia 2008 RUSALCA Expedition, the 2008 Chinese CHINARE Arctic Expedition aboard *Xue Long*, and NABOS

of UK-ASBO to make a hydrographic connection between the NABOS cruise and the WHOI Beaufort Gyre Observing System of Andrey Proshutinsky, by adding a zonal section to cross the Chukchi Plateau from the draft "A" section to the Canada Basin. Two possibilities for this interconnector section have been sketched on draft Fig 35 by Sheldon Bacon, co-PI of ASBO; either would enable ASBO to close off the Arctic into the 'boxes' it needs to conduct its conservative flux calculations for the whole Arctic Ocean. Since the job of 'quantifying the freshwater content of the Arctic Ocean' was the primary aim of ASBO, this is a significant addition.

Fig 36 describes plans to integrate NABOS with the *Xue Long* expedition and RUSALCA, using a nuclear icebreaker: Leg 1 with the *Xue Long* from Svalbard over the Pole to the Bering Strait, tending the North Polar Environmental Observatory in the process. In Leg 2, RUSALCA uses icebreaker escort to extend the RUSALCA region into areas with sea ice cover; on Leg 3 NABOS takes the nuclear icebreaker from the Chukchi Sea back to Murmansk. This plan is also designed to interface with the Pacific Arctic Group's plan for IPY 2008 (participants, will be U.S., Russia, China, Korea and EU). (Information from Kathy Crane, Arctic Research, Climate Program Office, NOAA, January 2008). Note that the complimentary Canadian plans are not yet included.

- **Swedish-Russia collaboration:** Though still under discussion, the major Swedish effort in 2008 is likely to be a collaboration with Russian scientists (Fig 37) to study the land-shelf-basin interaction in the area of the Chukchi-East Siberian-Laptev Seas from the coast to the continental slope, with a focus on the transformation and transport of carbon (in most of its forms). PIs will be Leif Anderson of Goteborg University and Igor Semiletov of the Pacific Oceanological Institute, Far Eastern Branch, Russian Academy of Sciences.

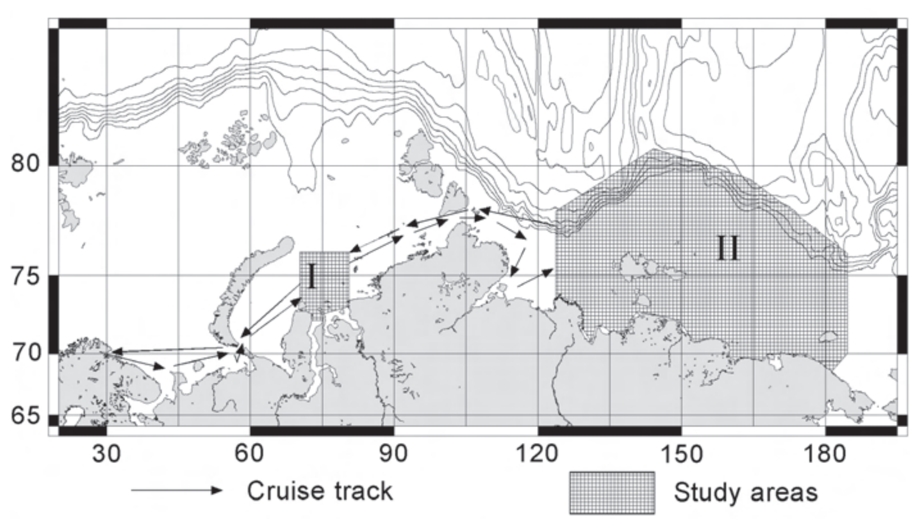


Figure 37. Planned track of Swedish-Russia cruise to the Chukchi-East Siberian-Laptev Seas in 2008. Some extensions from this track are planned across the continental slope and to the east, including Herald Trough (source: Leif Anderson, University of Goteborg)

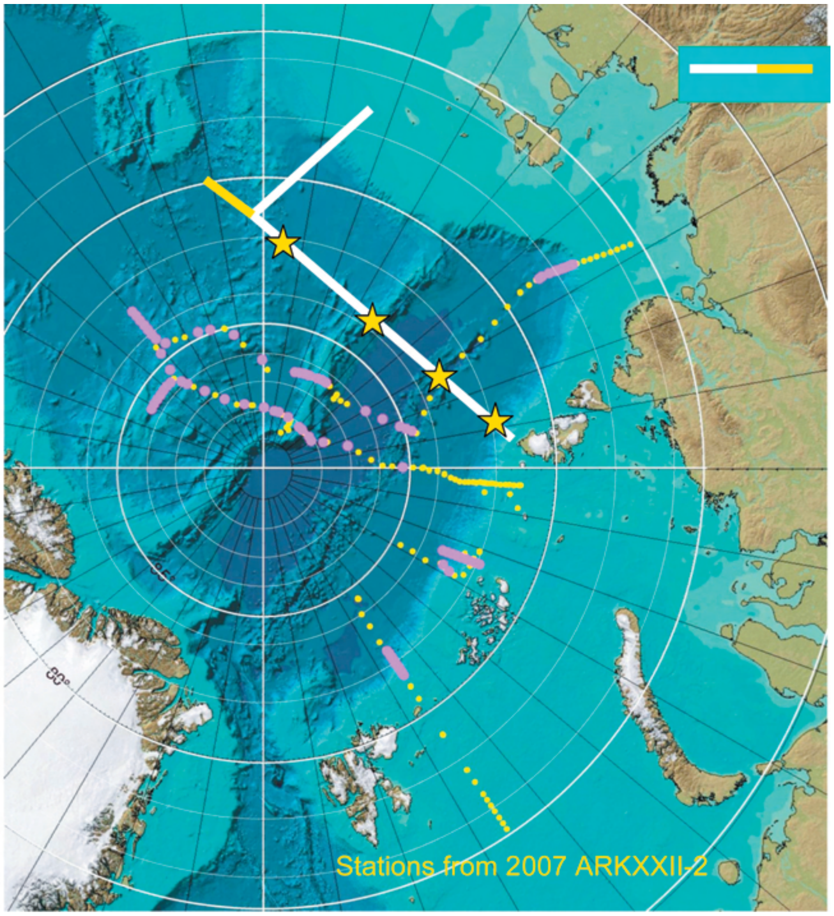


Figure 38. SPACE Plan for *Polastern* cruise 2008 ARKXXIII-3 relative to the 2007 station plan. Fahrbach/Schauer (AWI, Optimare) and Takashi Kikuchi (JAMSTEC)

- **Synoptic Pan-Arctic Climate and Environment Study (Space):** The A-W-I SPACE study led by Schauer and Fahrbach of A-W-I continues in 2008, in partnership with Takashi Kikuchi of JAMSTEC. As shown in Fig 38, its major elements will be (a) CTD/XCTD observations from the East Siberian Sea to Severnaya Zemlya and the East Siberian shelf slope with CTD every 20~30 nm and XCTD every 5~15 nm between CTD stations [*Helicopter XCTD operation (ice) for extending line and/or for saving ship time]; (b) buoy deployments (yellow stars in Fig 38) to include 2(+1?) Polar Ocean Profilers (POPS; JAMSTEC), 1 ITP from AWI?, +1 ITAC from AWI?, 1 ITP from WHOI?, 1 ITP from DAMOCLES? (question marks denote that plans are not final).

- **IAOOS for Norway:** Following testing in 2007 and deployment (planned) on Dec 1 from KV *Eigun*, the Svinoy monitoring line will be augmented by transects of the Norwegian Atlantic Current by UW SeaGliders (PIs Mauritzen-Høydalsvik). Skagseth's study of bifurcation in the NwAC will expand to include the use of two WEBB-Research gliders, a deepwater version profiling to 1000m and a shallow version to 200m. Conceptual modeling will begin on the 'inverted estuarine circulation' related to the circulation driven by Arctic freshwater (PI Tverberg). The KV *Svalbard* cruise in 2008 will be much larger in scope and geographical coverage, as described earlier (Fig 34).

- **DAMOCLES Fram Strait tomography:** delayed by weather in summer 2007 (see earlier) the tomography array will now be deployed in Summer 2008 from R/V *Håkon Mosby*. As Fig 39 describes, the further technical advances planned for monitoring this key interface with the Arctic Ocean will include the installation of modems for long-range and short-range data transfer, a profiling CTD mooring with satellite data transmission, the introduction of UW Seagliders on survey, and more-extensive use of Pressure Inverted Echo Sounders (PIES).

• **Further Trials of DAMOCLES gliders.** Through the cooperation of Craig Lee (UW-APL), the DAMOCLES ENSIETA glider will be tested with the APL array in the Davis Strait in September 2008. Postponed through a communications failure in 2007, the Seaglider in Fram Strait will now also be deployed in summer 2008.

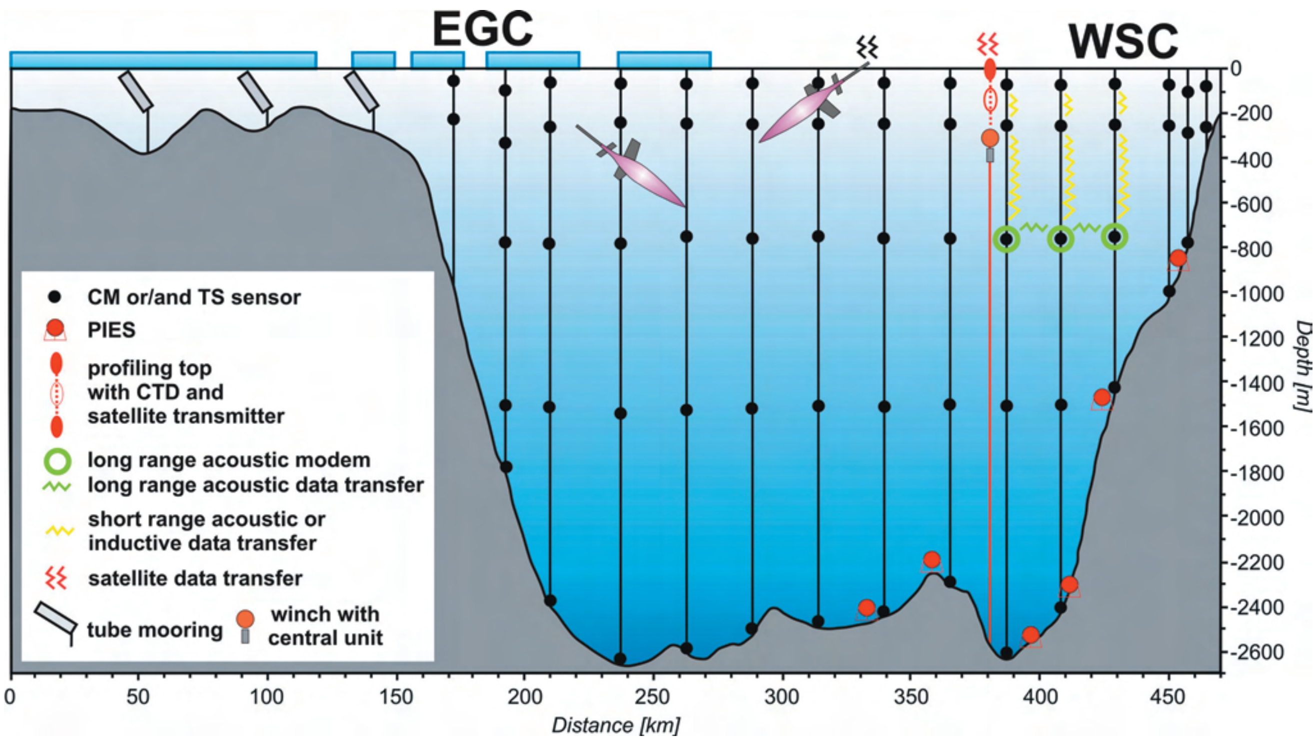


Figure 39. Illustration of the further new systems planned for the Fram Strait Array. (courtesy of Agnieszka Beszczynska-Möller, A-W-I)

• In the Canadian IPY project **'Investigation of the effect of Climate Change on Nutrients and carbon Cycles in the Arctic Ocean'**, the PI Roger Francois (UBC) aims to obtain a better understanding of carbon and nutrient cycling and their evolution in response to changes in ice cover and river discharge. The underlying goal is improved prediction of the effects of these changes on the productivity, ecosystem structure and carbon sequestration potential of the Arctic Ocean. Some preliminary watercolumn chemistry was conducted in October 2007, and additional measurements (trace gases) are planned for summer 2008. But the full coordinated multi-PI project (11 PIs covering the range of expertise required to meet the project's goals) has been postponed to summer 2009 in the Beaufort Sea to give PIs a suitable platform (*Amundsen*) to conduct their research.

• Between summer 2008 and summer 2009, **A National Ocean Partnership Program,** led by Tom Weingartner of University of Alaska, Fairbanks but with Co-PI input from JPL, WHOI & APL will study the Circulation, Cross-Shelf Exchange, Sea Ice, and Marine Mammal Habitats on the Alaska Beaufort Sea Shelf. Physical oceanographic measurements will include (Fig 40): five cross-shelf oceanographic moorings, high-frequency surface current mapping radars to determine shelf circulation between August and November 2008 and AUV operations in open water season to determine the hydrography of the shelf at high-resolution.

• **Hudson Strait:** the freshwater outflow from Hudson Bay is a not-inconsiderable 42 mSv. The pre-existing 3-mooring ADCP + Seacat + profiler array was recovered in August 2007 and the Strait is currently not monitored. Straneo (WHOI) and Saucier (UQAR) intend to redeploy an expanded 4-mooring array across Hudson Strait from August 2008 to August 2009 with the intention of

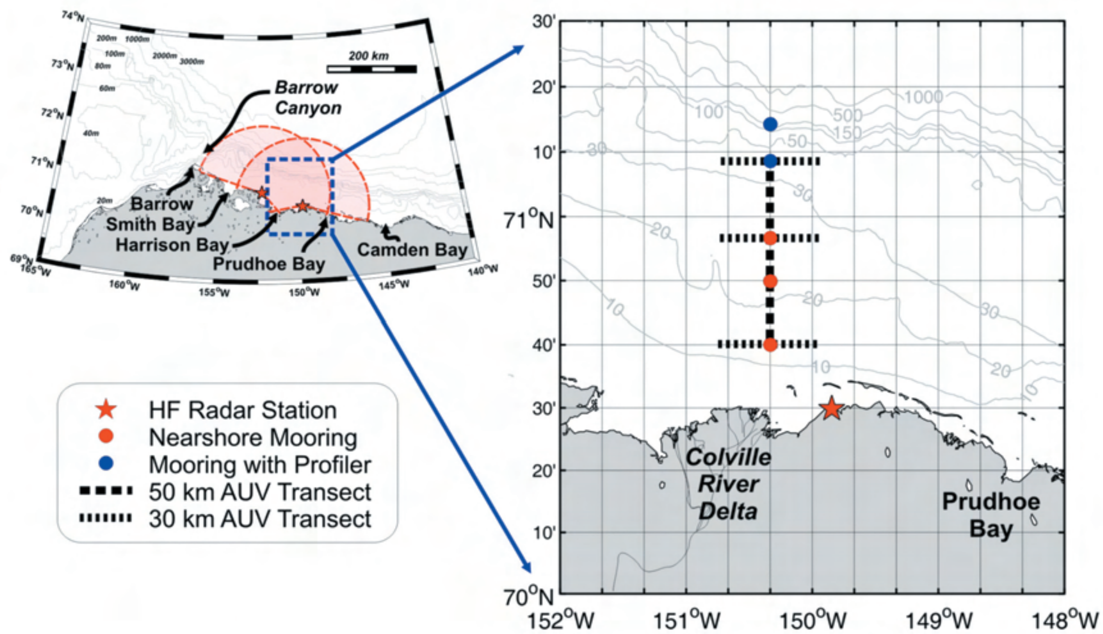


Figure 40. A National Ocean Partnership Plan for the Alaska Beaufort Sea Shelf in summer 2008 (Tom Weingartner, UAF pers comm)

distinguishing outflow from the inflowing Baffin Current. Partly funded by WHOI's Arctic Initiative, the approximate locations of the moorings will be:

	Latitude	Longitude	Bottom depth, m
1	N 62° 30'	W 70° 40'	340
2	N 62° 22'	W 70° 55'	350
3	N 62° 12'	W 71° 16'	340
4	N 61° 59'	W 71° 39'	180

• **THOR:** In the new 4-year (2008-2012) EC-FP7 Integrated Project THOR, recently accepted and currently in the negotiation stage before implementation, scientists from 26 Agencies in 11 nations will establish an operational system to monitor and forecast the development of the North Atlantic THC on decadal time scales and assess its stability and the risk of a breakdown in a changing climate. In addition to a heavy modeling effort (Hadley Centre, UHAM, MPI, ECMWF, NERSC, DMI), THOR will greatly reinforce our observational coverage across the southern boundary of the iAOOS domain, monitoring exchanges across the Greenland-Scotland Ridge, the outflow from the Labrador Sea and the total Overturning Circulation at 26.5°N.

• **ACOBAR; ACoustic technology for OBserving the interior of the ARctic ocean:** Also recently accepted by the EC and currently entering the negotiation stage is the Integrated Project ACOBAR. This study aims to develop a system for environmental monitoring of the interior of the Arctic Ocean by assimilation of data obtained with acoustical methods, including tomography, data transmission from underwater platforms, and communication and navigation of floats and gliders under the ice cover. ACOBAR is thus a follow-up of the acoustic side of DAMOCLES and helps extend the DAMOCLES study into its 'legacy phase'. ACOBAR is led by NERSC Norway (Sandven, Sagen) but with partner PIs from A-W-I, Université Pierre et Marie Curie, SIO, WHOI, OPTIMARE (Germany), Aquatec (UK) and ENSIETA & ACSA (France). ACOBAR is expected to start formally in summer 2008 but with its first equipment deployment in 2009.

7. Achieving a more coordinated approach to the understanding of Arctic change

Though it is perhaps difficult to distinguish when laid out piece by piece, there is considerable pan-Arctic 'system' and integration as well as real scientific achievement in the projects that have formed the bulk of this Report. However it remains to ask whether iAOOS as a concept has purpose, and if so, how its point might be improved. A range of issues are bound up with this question ---- issues that the present debates on a Sustainable Arctic Observing Network (SAON) and an Arctic Regional Ocean Observing System (Arctic-ROOS) will also be addressing. They are these: Have we correctly delimited the appropriate 'system' for study? Do we know the extent of the present effort that is being devoted to that study? Is the study of that system integrated and coordinated in an effective way? And if so, what is the most appropriate way of sustaining & safeguarding such a pan-Arctic coordinated study into the future?

7.1. Have we correctly delimited the Arctic 'system'?

iAOOS and Arctic-ROOS both include the word 'system' in their title and in SAON a large-scale Arctic coverage is implied. Yet all three may focus on different domains. Which is appropriate? The considerations that have defined the *Arctic-and-subarctic* scope of iAOOS are these:

The history of hydrographic observation in Northern Seas is a long one, exceeding 100 years in places, but even so, recent hydrographic observations from Northern Seas have described events that are extreme even for this great length of record. Connecting such extrema, it is relatively easy to justify the idea that subarctic change is an important driver of Arctic change ---for example, that the recent poleward spread of warmth along the eastern boundary of the Nordic Seas is a direct cause of extreme warmth along the Eurasian margin of the Arctic Ocean. In fact at this stage in our understanding, it appears that a whole complex of interactions between the polar and sub-polar oceans ---- near and remote, short-term as well as long-term controls ---- have been involved in providing the Polar Basin with a steady supply of increasingly warmer water through subarctic seas. The converse may also apply. A long sequence of simulations from Bryan (1986) and Manabe and Stouffer (1988) to the present day have suggested that the signal of Arctic change may have its major climatic impact by reaching south through subarctic seas to modulate the Atlantic thermohaline 'conveyor'. And very recently, our simulations have attained sufficient complexity to implicate the *two-way* oceanic exchanges between the Arctic and subarctic seas as controls on the thermohaline circulation; for example, from experiments using the Hamburg models ECHAM5 and the MPI-OM, Jungclaus et al (2005) conclude that while '*the strength of the (Atlantic) overturning circulation is related to the convective activity in the deep-water formation regions, most notably the Labrador Sea, …..the variability is sustained by an interplay between the storage and release of freshwater from the central Arctic and circulation changes in the Nordic Seas that are caused by variations in the Atlantic heat and salt transport*.' We take these indications to mean that we cannot understand Arctic change just by studying the Arctic; that iAOOS must address the whole, variable, full-latitude system of oceanic exchanges through Arctic *and subarctic* seas if we are to understand the full subtlety of the role of our Northern Seas in climate.

7.2. Do we know the extent of the present effort in this domain?

Much of the present report is a compilation of existing ocean-observing efforts throughout Arctic and subarctic seas. The rationale is simple. That to understand a complex and variable system, we need a reasonably complete and protracted view of it; and until we define the extent of the present pan-Arctic coverage, we cannot identify or plug its gaps. That at any rate is part of the reason for the present compilation. As the draft Report from the first SAON Workshop usefully explains, these 'gaps' or constraints on the adequacy of coverage may be of four different kinds, ranging from environmental constraints (thick ice?), geopolitical constraints (forbidden/ costly access?), logistical constraints (no icebreaker available?) and methodological constraints (no technique?). Identifying these types of constraint will itself argue the appropriateness of top-down or bottom-up solutions and inform the debate on the type of international body, long-term international coordination, and logistics planning that will be needed to minimise them. However, the second but perhaps the major reason for the present compilation ---in which we deliberately emphasise the major *scientific* advances being achieved through the new collaborative use of brand new techniques-----is a quite different one. With a full view only of the projects that they themselves have funded, the individual funding agencies may have a less-than-complete view of the scientific successes being achieved during the IPY across Northern Seas on the largest (pan-Arctic) scales. It has been the purpose of this Report to piece together at least some of these major successes and patterns of achievement. The hope is that evidence of scientific success will be the best catalyst for developing top-down solutions to some or most of the constraints listed above.

7.3 Is the study of the Arctic-subarctic system being coordinated in an effective way?

In some respects, it is. After many years of acting together to a common plan ----*'to measure and model the variability of fluxes between the Arctic Ocean and the Atlantic Ocean with a view to implementing a longer-term system of critical measurements needed to understand the high-latitude ocean's steering role in decadal climate variability*'--- the ASOF Subset of iAOOS is well-coordinated. Gaps in coverage certainly exist, of all four types, but by and large these constraints and their solutions are known. In fact many of the major scientific advances described above for subarctic seas (Sections 4.B and 4.C above) concern long-awaited solutions to long-existing problems in ASOF. The Arctic Ocean itself poses knottier problems of coordination, in which technology, access, politics and logistics all continue to play their part. Here, although top-down coordination is bound to be a built-in feature of EC 'integrated projects' such as DAMOCLES (with 12 nations and 45 agencies), it would be fair to say that at present, the integration *between* projects is much more active and effective at the level of individual scientists. Many of the most-effective instances have been spurred by technical advance; in Section 5.4 the willingness of the developers and experienced users of ITPs and POPS, at WHOI and JAMSTEC mainly, to deploy, train & loan these systems to others has been the stimulus for a rapid extension of coverage across the Arctic basins; it is worth repeating John Toole's comment (Section 5.4) that since 2004, ITPs have as a result returned a total of more than 9000 CTD profiles from the upper watercolumn of this historically data-poor Ocean. The spread of UW Seaglider technology across the iAOOS domain, from the Davis Strait, Iceland-Scotland Ridge, Norwegian Sea and Fram Strait is a further notable example and includes continuing UW assistance with the trialling of DAMOCLES ENSIETA gliders for sub-ice operations in the Arctic. Aside from such striking examples, there is currently much debate between scientists, agencies and organisations such as SAON on how best to acquire the well-organised, long-term and pan-Arctic ocean data set that they need to understand the environmental system of the Arctic. There would be little debate among scientists that the basic need is for a plan capable of integrating national efforts to provide a freely-shared, flexible, reliable and reasonably complete ocean data set, versatile enough to spread both established and emerging technologies across the available platforms, and to ensure both the compatibility of data sets and their widespread distribution. The fear would be that national issues of sovereignty, access and logistics might instead promote a dataset whose coverage, quality, cost and accessibility would be a variable function of the country responsible. An international approach to the solution of these key issues is currently underway in SAON, Arctic ROOS and elsewhere, but the appropriate top-down approach is not yet obvious or decided.

7.4. So what is the most appropriate way of sustaining & safeguarding such a pan-Arctic coordinated study into the future?

Most of the Arctic groups debating this issue are of finite duration. Despite its focus on 'sustainability', even SAON may not be a truly sustainable mechanism in the long run, and though projects like DAMOCLES will have a lengthy 'legacy phase', neither are they. One suggestion, and the one advocated here is to identify ISAC for this task as the pan-Arctic body with the largest geographic scope and intended longevity. Their task is not really to ask what can be measured. These days, and for the first time, we are in prospect of being able to measure almost any key environmental variable of interest almost anywhere and at almost any time, and the exceptions to this statement will surely dwindle with time. The task today is to define what subset of variables is of greatest scientific interest for sustained measurement, to match this subset efficiently to funding and platforms (with due allowance for binding-in new technologies as they emerge from their research institutions), and thereafter to act to minimise constraints on their sustained measurement. The current 'Modular Approach to Building an Arctic Observing System for the IPY and Beyond in the Switchyard Region of the Arctic Ocean' (PI Peter Schlosser, SEARCH; NSF-AON Award #0633878) is a regional example of such a process at work. By extending this process throughout the iAOOS domain, a strong, flexible and responsive ISAC Program (International Study of Arctic Change) would ensure that a sustainable and integrated ***international*** observing system was maintained across Arctic and Subarctic seas, available both for the benefit of the next generation of Arctic scientists and the global community.

8. References

Bryan F., 1986. High latitude salinity effects and inter-hemispheric thermohaline circulations. Nature 323, 301-304.

Carmack, E.C. and F.A. McLaughlin, 2001. Arctic Ocean Change and consequences to biodiversity: A perspective on linkage and scale. Mem. Nat.Inst.Polar Res.54, 365-375

Curry R., R.R. Dickson and I. Yashayaev, 2003. A change in the freshwater balance of the Atlantic Ocean over the past four decades. Nature, 426, 826-829.

Dickson R.R., 2006. The integrated Arctic Ocean Observing System (iAOOS): an AOSB-CliC Observing Plan for the International Polar Year. Oceanologia 48 (1) 5-21.

Dickson, R. R., S Dye, S. Jónsson, A. Köhl, A. Macrander, M. Marnela, J. Meincke, S. Olsen, B. Rudels, H. Valdimarsson and G. Voet, 2008. The overflow flux west of Iceland: variability, origins and forcing. Pages 443-474 in: R Dickson, J Meincke and P Rhines (Eds), *Arctic-subarctic Ocean fluxes: defining the role of the Northern Seas in Climate*. Springer, 734pp.

Eriksen C. and P. Rhines, 2008. Convective- to gyrescale- dynamics, the first SeaGlider campaigns, 2003-5. Pages 613-628 in: R Dickson, J Meincke and P Rhines (Eds), *Arctic-subarctic Ocean fluxes: defining the role of the Northern Seas in Climate*. Springer, 734pp.

Falkner, K.K., M.C. O'Brien, E.C. Carmack, F.A. McLaughlin, H. Melling, A. Münchow and E.P. Jones, 2007. Implications of nutrient variability in passages of the Canadian Archipelago and Baffin Bay for fresh water through-flow and local productivity. Journal of Geophysical Research, in revision.

Gascard J-C and co-authors, 2008. Exploring Arctic Transpolar Drift During Dramatic Sea Ice Retreat. EOS 89 (3), 21-22

Grebmeier, J.M., J.E. Overland, S.E Moore, E.V Farley, E.C Carmack, L.W Cooper, K.E Frey, J.H Helle, F.A McLaughlin and L McNutt, 2006, A major ecosystem shift observed in the northern Bering Sea. *Science*, 311, 1461-1464.

Hatun, H., A.B. Sandø, H. Drange, B. Hansen and H. Valdimarsson, 2005. Influence of the Atlantic Subpolar Gyre on the Thermohaline Circulation. Science, 309, 1841-1844.

Holliday N.P., S.L. Hughes, A. Lavin, K.A. Mork, G. Nolan, W. Walcowski, and A. Breszczynska-Moller, 2007. The end of a trend? The progression of unusually warm and saline water from the eastern North Atlantic into the Arctic Ocean. CLIVAR Exchanges 12, (1) pp 19-20 + figs

ICES, 2007. ICES Report on Ocean Climate 2006. ICES Cooperative Research Report No 289. 59pp.

Jungclaus, J.H., Haak, H., Latif, M., & Mikolajewicz, U., 2005. Arctic-North Atlantic interactions and multidecadal variability of the meridional overturning circulation. *Journal of Climate*, 18, 4013-4031.

Käse R, Oschlies A (2000) Flow through Denmark Strait. J. Geophys. Res. 10, 28527-28546

Karcher M.J., Gerdes R., Kauker F., Köberle C., 2003a. Arctic warming: Evolution and spreading of the 1990s warm event in the Nordic Seas and the Arctic Ocean. J. Geophys. Res. 108, doi:10.1029/2001JC001265

Karcher M., R. Gerdes and F. Kauker, 2008a. Long-term variability of Atlantic water inflow to the Northern Seas: insights from model experiments. Pages 111-130 In: R Dickson, J Meincke and P Rhines (Eds), *Arctic-subarctic Ocean fluxes: defining the role of the Northern Seas in Climate*. Springer, 734 pp.

Karcher M., 2008b. in prep. The Arctic Ocean as a buffer.
Köhl A., Käse R., Stammer D., Serra N., 2007. Causes of changes in the Denmark Strait Overflow. J Phys Oceanogr, 37, 6, 1678-1696
Loeng H., V. Ozhigin, B. Adlandsvik and H. Sagen, 1993. Current measurements in the Northeastern Barents Sea. ICES CM 1993/C:40 22 pp mimeo.
Macrander A., Send U., Valdimarsson H., Jónsson S., Käse R.H., 2007. Spatial and temporal structure of the Denmark Strait Overflow revealed by acoustic observations. Ocean Dynamics, DOI 10.1007/s10236-007-0101-x.
Manabe S and RJ Stouffer, 1988. Two stable equilibria of a coupled ocean-atmosphere model. J Clim. 1, 841-866.
Melling H., T. Agnew, K. Falkner, D. Greenberg, C. Lee, A. Muenchow, B. Petrie, S. Prinsenberg, R. Samelsen, R. Woodgate, 2008. Fresh-water fluxes via Pacific and Arctic Outflows across the Canadian Polar Shelf. Pages 193-248 in: R Dickson, J Meincke and P Rhines (Eds), *Arctic-subarctic Ocean fluxes: defining the role of the Northern Seas in Climate*. Springer, 734pp.
Mork K.A. and Ø. Skagseth, 2007. Northward transport of Atlantic water in the Norwegian Sea from Hydrography and Altimetry. GRL in press,
Münchow, A., K.K. Falkner and H. Melling, 2008. Spatial continuity of measured seawater and tracer fluxes through Nares Strait, a dynamically wide channel within the Canadian Archipelago. Journal of Marine Research. Accepted minor revision & resubmitted.
Olsen, S. M., and T. Schmith, 2007. North Atlantic-Arctic Mediterranean exchanges in an ensemble hindcast experiment, J. Geophys. Res., 112, C04010, doi:10.1029/2006JC003838.
Østerhus S., W.R. Turrell, S. Jonsson and B. Hansen, 2005. Measured volume, heat and salt fluxes from the Atlantic to the Arctic Mediterranean. Geophys Res Lttrs, 32, L07603,doi:10.1029/2004GL022188
Overland J.E., M. Wang and S. Salo, 2008. The recent Arctic Warm Period. Tellus, (in revision).
Overpeck J. and Co-authors, 2005. Arctic system on trajectory to new seasonally ice-free state. EOS, 86, 34, pp 309, 312, 313.
Polyakov I. V., Beszczynska, A., Carmack, E., Dmitrenko, I., Fahrbach, E., Frolov, I., Gerders, R., Hansen, E., Holfort, J., Ivanov, V., Johnson, M., Karcher, M., Kauker, F., Morrison, J., Orvik, K., Schauer, U., Simmons, H., Skagseth, Ø., Sokolov, V., Steele, M., Timkhov, L., Walsh, D., J. Walsh, 2005. One more step toward a warmer Arctic, Geophys. Res. Lett., 32, L17605, doi:10.1029/2005GL023740.
Polyakov I. , L. Timokhov, I. Dmitrenko, V. Ivanov, H. Simmons, F. McLaughlin, R. Dickson, E. Fahrbach, J-C. Gascard, P. Holliday, L. Fortier, E. Hansen, C. Mauritzen, J. Piechura, U. Schauer, and M. Steele, 2007. The International Polar Year under the banner of Arctic Ocean warming. EOS 88 (40) pp 398-9.
Proshutinsky A., R. H. Bourke, and F. A. McLaughlin, 2002. The role of the Beaufort Gyre in Arctic climate variability: Seasonal to decadal climate scales, Geophys. Res. Lett., 29 (23), 2100, doi:10.1029/2002GL015847.
Proshutinsky, A., J. Yang, R. Krishfield, R. Gerdes, M. Karcher, F. Kauker, C. Koeberle, S. Hakkinen, W. Hibler, D. Holland, M. Maqueda, G. Holloway, E. Hunke, W. Maslowski, M. Steele, and J. Zhang, 2005. Arctic Ocean Study: Synthesis of Model Results and Observations, EOS, 86 (40), 368-371.
Proshutinsky, A.,R. Krishfield, E. Carmack, F. McLaughlin, K. Shimada, D., V. Alexeev, Perovich, J. Richter-Menge, J. Overland, C. Guay, and R. Hopcroft. The Beaufort Gyre Observing System: Documenting key parameters to enhance understanding of Arctic Change (submitted to EOS)
Proshutinsky A. et al., Changes in the Arctic Beaufort Gyre, (in prep for GRL), 2007.
Schauer U., A. Beszczynska-Möller, W. Walczowski, E. Fahrbach, J. Piechura and E. Hansen, 2008. Variation of measured heat flow through the Fram Strait between 1997 and 2006. Pages 65-86 in: R Dickson, J Meincke and P Rhines (Eds), *Arctic-subarctic Ocean fluxes: defining the role of the Northern Seas in Climate*. Springer, 734pp.
Skagseth Ø., T. Furevik, R. Ingvaldsen, H. Loeng, K. A. Mork, K. A.Orvik and V. Ozhigin, 2008. Volume and heat transports to the Arctic Ocean via the Norwegian and Barents Seas. Pages 45-64 in: R Dickson, J Meincke and P Rhines (Eds), *Arctic-subarctic Ocean fluxes: defining the role of the Northern Seas in Climate*. Springer, 734pp.
Stroeve J, M Serreze, S Drobot, D Gearheard, M Holland, J Maslanik, W Meier and T Scambos, 2008. Arctic Sea Ice Extent plummets in 2007. EOS 89 (2), 13-14.
Timmermans, M. -L., J. Toole, A. Proshutinsky, R. Krishfield, and A. Plueddemann, 2008. Eddies in the Canada Basin, Arctic Ocean, observed from ice-tethered profilers, *Journal of Physical Oceanography,* in press.
Toole, J., R. Krishfield, A. Proshutinsky, C. Ashjian, K. Doherty, D. Frye, T. Hammar, J. Kemp, D. Peters, M.-L. Timmermans, K. von der Heydt, G. Packard and T. Shanahan, 2006. Ice Tethered-Profilers Sample the Upper Arctic Ocean. EOS, Transactions of the American Geophysical Union, Vol. 87, No. 41: 434, 438.
Whitehead J.A., 1998. Topographic control of oceanic flows in deep passages and straits. Rev. Geophys 36, 423-440
Wilkenskjeld S., Quadfasel D., 2005. Response of the Greenland-Scotland Overflow to changing deep water supply from the Arctic Mediterranean. Geophys. Res. Lttrs, 32, L21607, doi:10.1029/2005GLO24140

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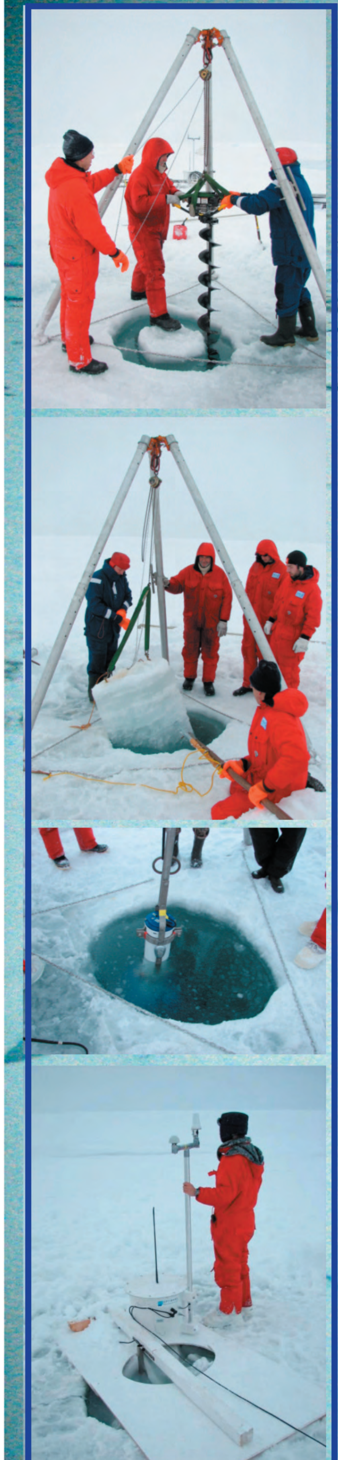
'Super Buoy Array' deployment 13/14.09.2007

around the Lomonosov ridge between 86º 40' to 87º 24' N, on the edge between the Amundsen and Makarov basins



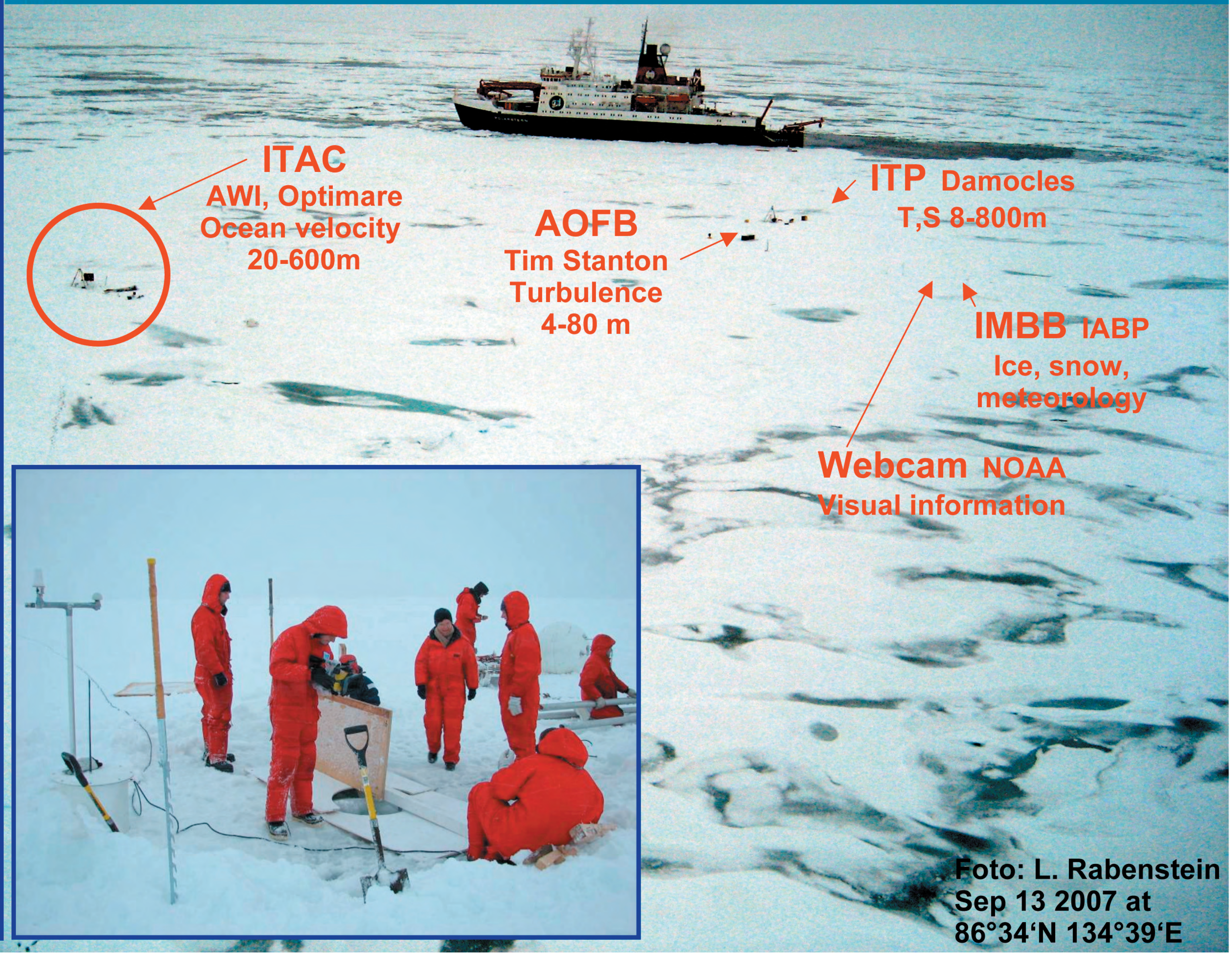


Foto: L. Rabenstein
Sep 13 2007 at
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