Report on AOSB-ASOF Joint workshop on the integrated Arctic Ocean Observing System (iAOOS)

Woods Hole Oceanographic Institution, 18 October 2010.

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5. January 2011

Summary

This proved to be an excellent and productive Workshop, preceding the ASOF-2 ISSG meeting under Tom Haine on 19 October 2010, the junior AOMIP meeting under Mike Steele also on the 19th, and the full annual AOMIP meeting under Andrey Proshutinsky on 20-22 October. Together these meetings provided the broadest possible range of Arctic-subarctic expertise, and in which as a result, the design of an effective and realistic iAOOS observing effort for the IPY 'legacy phase' was materially advanced.

This report is intended to set the background and context, to summarize the workshop content for the AOSB and to describe next steps for the Board's consideration and approval.

Though plans have yet to be finalised, the likelihood is that an Issue 1 Workshop under Bert Rudels will be held in Potsdam in January 2011 at the time of the IASC Marine Board meeting. Issue 2 will be designed over winter by correspondence between Craig Lee and Bob Dickson. Coupled with the essential points of Issue 3, the iAOOS Report will then be drawn together by Bob Dickson for submission to AOSB. The intention is to finish this in February with editing by Roberta Boscolo (WMO) late February, printing by UCAR early March, in time for the Arctic Science Summit Week in Seoul in late March.

0.0 Introduction.

It is now almost exactly 13 years since the comparison of SCICEX submarine data with climatology provided the first startling new evidence of Pacific-Atlantic change playing out across the deep basins of the Arctic Ocean (Morison, UW, November 1997 pers. comm.), and 2 years since the IPY approximately-doubled the spend on Polar Science. As Bob Dickson pointed out in his introduction, the latest of 3 Reports for AOSB had to do with designing an ocean observing system for the 'legacy phase' of the IPY, based on what we have learned. To establish a modern list of focus questions specific to the ocean and to the Arctic-subarctic, we had asked the following 3-part question of the Community: 'Following the IPY, how would we now define the role of the Northern Seas in Climate? What questions should we be testing to help us understand that role? How should we design an ocean observing system to test these questions?
We are now at the third stage of this exercise ----we have a list of 18 key questions (listed in Dickson 2010) and the present purpose of iAOOS is to design an integrated and international ocean observing system to test them. Though it would be impractical to attempt 18 separate projects, in fact the essence of the list can be distilled down to 3 main issues or themes that push the frontiers in subtly different ways:

- **Issue 1. Sorting out the inflows.** Precision ship-based oceanography and precisely-placed arrays focused primarily on the Eurasian Basin with the aim of distinguishing the transformations and interchanges between the Fram Strait and Barents Sea Branches of Atlantic water between their points of inflow and the Lomonosov Ridge (mainly). The aim is to learn which of the two Atlantic-derived branches is primarily responsible, most of the time, for carrying the ocean climate 'signal' from subarctic seas through the Arctic deep basins. Leader: Bert Rudels, FIMR.

- **Issue 2. Coping with change in the Arctic water-column.** Clever, adaptive observing systems capable of informing our present ideas on the roles of the Arctic water-column in climate (see Dickson 2010 for examples) while coping simultaneously with the 4 or 5 main types of change that are currently underway: the reduction of sea ice cover; the improvement in capability of our ocean observing systems; the varying effectiveness of satellite remote sensing; and the changes in the state and 'scale' of the climatically important target sublayers of the upper water-column throughout their individual domains. Leader: Craig Lee UW-APL.

- **Issue 3. Revitalising our ideas about Greenland, freshwater and the MOC.** Novel observing techniques, theory, modeling, designed to cover 5 sub-issues in particular:
  1. How much freshwater passes south and how can we monitor it effectively in the long term?
  2. Which side of Greenland will be favoured by the freshwater efflux in future, and how can we resolve model inconsistencies on this point?
  3. Is the future freshwater production of Greenland capable of making significant impacts on Canadian Arctic Archipelago (CAA) Outflow (path; transport), and what/where should we monitor to test for this?
  4. What is the ocean impact on Greenland freshwater production and how can field observations be improved?
  5. What is the future impact of the changing freshwater efflux on the MOC, and how might we evolve a long-term observational strategy to observe it?

  Leader: Tom Haine, JHU.

Though the primary aim of this workshop was concerned with resolving Issue 3, and dealt exclusively with that issue from the morning coffee break onwards, we took advantage of the venue and the expertise present to solicit three ancillary talks that were of significance to the other two issues also. The workshop agenda appears as the Appendix and the presentations are available at: http://asof.awi.de/en/outputs/reports_broshures/presentations_woods_hole_meeting_october_1819_2010/. The workshop deliberations were as follows:

1.0 Issue 1 Sorting out the Inflows

Bob Pickart: Measuring the flows along the Eurasian boundary of the Arctic Ocean
with input from Andrey Proshutinsky

One of the fundamental aspects of the Arctic Ocean is the circulation and transformation of relatively warm Atlantic Water (AW), which plays a critical role in Earth's climate system. AW carries a tremendous amount of heat into the Arctic, for example, and exerts a powerful influence on the mid-depth Arctic hydrography and on the shelf waters. The modification and conversion of AW in the Arctic Ocean also forms the headwaters of the global meridional overturning circulation (MOC). While oceanographers have been studying the AW in the Arctic for nearly a century, our understanding of the primary boundary current of the Arctic and the manner that it communicates with the interior basin is incomplete (Figure 1). For example, at present we do not know precisely how much AW flows into the Arctic nor do we know the precise seasonality of that inflow. Boundary current meandering may have a seasonal signal. The dynamics of the circulation, which determines how the water spreads and mixes into the interior, are largely unknown. Limited observations to date suggest that climate anomalies circulate through the Arctic in the boundary current, and models suggest that the potential vorticity dynamics may yield insight. But present mooring deployments are not dense enough to coherently resolve the propagating anomalies.

Bob's presentation discussed the feasibility of measuring the Atlantic Water boundary current in the Eurasian basin using a high-resolution mooring array. He argued that the highest priority should be placed on measuring the current at two locations: (1) downstream of Fram Strait where the topography is well-behaved, and (2) downstream of St. Anna Trough where the two branches of the Atlantic Water merge. He discussed the advantages of using a high-resolution array, as well as the challenges that exist in implementing such an array. Challenges include: the high cost of an array wide enough and dense enough to resolve the boundary current and its meandering, the availability of a suitable ice-breaker, and permission to operate the array in Russian national waters.

2.0 Issue 2. Coping with change in the Arctic water-column.

Michael Karcher: Observing and modeling of transient signals connecting the Arctic Ocean and the Nordic seas

During the period from the 1950s to the 1980s AW inflow hydrographic anomalies in the West Spitzbergen Current (WSC) at Fram Strait were compensated in density. Since 1990 warm inflow occurred in two separate phases and was associated with density decreases of around 0.1 kgm^{-3} (and around 1ºC; Polyakov et al. 2005, Karcher et al. submitted). The WSC anomalies peaked in 1992 and 2006, and each lasted about 5 years. As a consequence, large low-density pools formed and propagated around the cyclonic AW path shown in Figure 1. Isopycnal surfaces were depressed in association with the warm, light anomalies. The anomalies are presently circulating through Arctic and will presumably exit via Fram Strait and/or the CAA. If the anomalies reach Denmark Strait undiluted, they may exert a significant influence on the overflows.

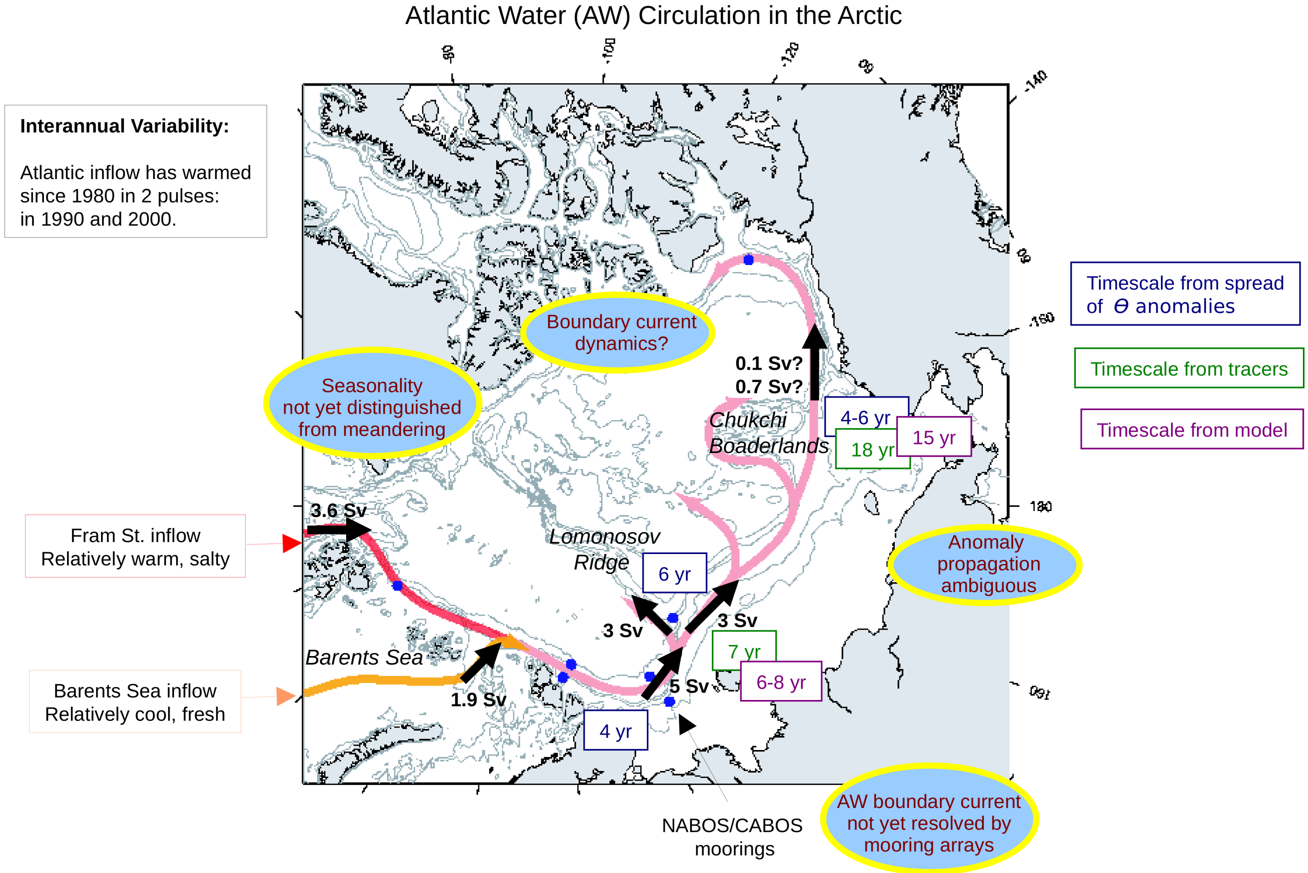

Figure 1. Atlantic Water circulation in the Arctic with estimates of transport and AW propagation timescales from the literature. Key challenges are noted in the ellipses. Adapted from Bob Pickart's presentation.

The reason is that the overflow is hydraulically controlled, and the volume flux depends linearly on the density contrast across the sill, and quadratically on the upstream interface height. From model forecasts, Michael projected the arrival of these anomalies at Denmark Strait to be in the range 2020-2025, although the AW circulation draining the Arctic is not known in detail, and it also depends on the phase of the Arctic Oscillation which is hard to predict. Nevertheless, the model

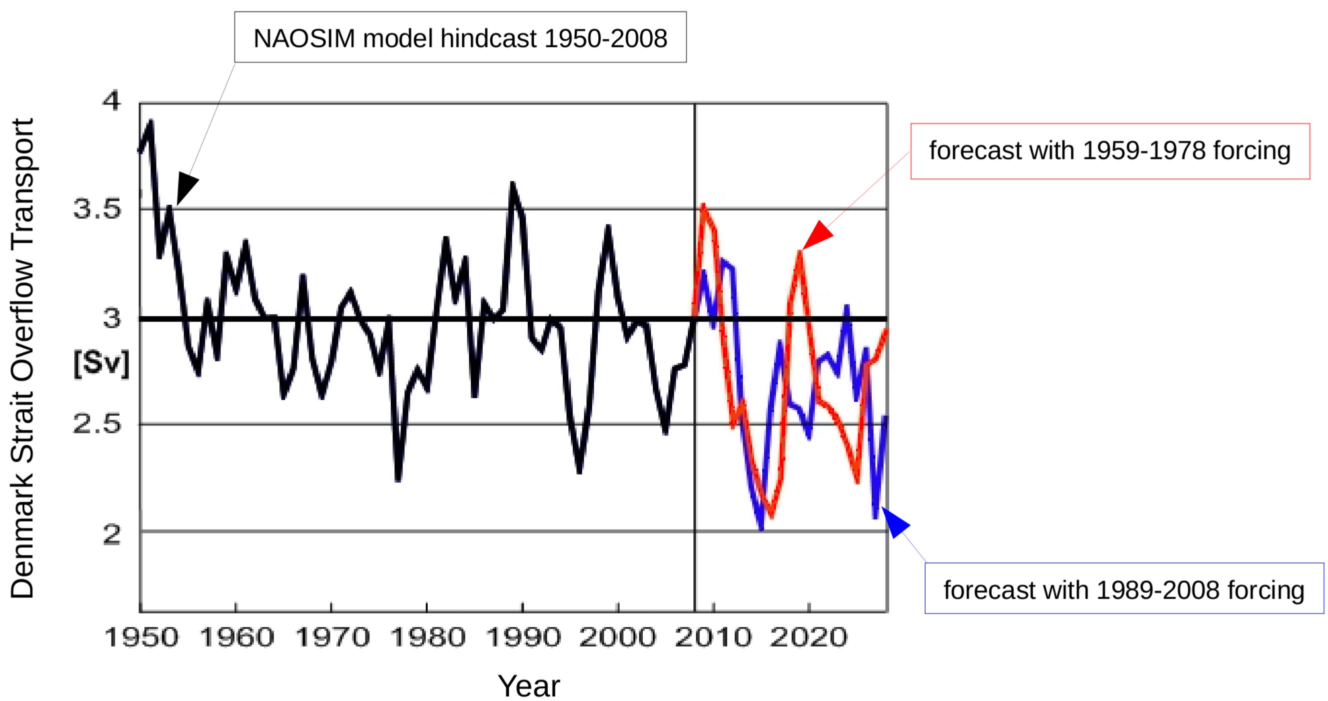

Figure 2. Timeseries of Denmark Strait overflow transport, adapted from Karcher et al. (2011). The black line for 1950-2008 shows the NAOSIM model hindcast. The red and blue lines show plausible forecasts for 2008-2028, depending on different air/sea forcing scenarios, and show diminished overflow transport as buoyant anomalies drain out of the Arctic.

experiments suggest a 30% decrease in baseline overflow transport for several years as the anomalies drain from the Nordic Seas (Figure 2).

Michael agreed with Bob Pickart's assessment that clear detection of propagating AW anomalies is very difficult with the extant data. The main reason is lack of repeat sections over long periods (decades). Michael advocated greater efforts to reoccupy sections in the interior Arctic to better capture the long term development and the occurrence of transient anomalies. To monitor the development of the density and interface anomalies which are currently moving through the Arctic Ocean, a reliable background (reference) state is needed. It may already be too late to make the necessary measurements, but targeting the area between the 1990s and 2000s anomalies would make most sense. Further monitoring of the current anomalies should also target the Lincoln Sea and the southwest Eurasian Basin to capture signals exiting through Fram Strait. Optimally, a synthesis of hydrographic and tracer data and different modeling approaches (including hindcasts, forecasts, data assimilation, and idealized models) is recommended to fully document and understand the transient AW signals in the Arctic and their influence on the overflow. Novel quantitative network design methods may help to develop the best observational strategy. To this end, Michael proposed an "all hands on deck" approach to coordinate efforts to track the anomalies.

3.0 Issue 3. Revitalising our ideas about Greenland, freshwater and the MOC.

Issue 3.1: How Much? What are the ocean fluxes either side of Greenland (including, but not confined to, freshwater) and how can we monitor them effectively in the long term?

Laura de Steur with input from: Craig Lee (UW), Andreas Münchow (U Delaware), Simon Prinsenberg (BIO), Humfrey Melling (IOS), Kelly Falkner (OSU)

Laura gave an overview on estimates of freshwater and volume fluxes (including sea ice, whenever possible) around Greenland (see Figure 3 and Table 1). Heat fluxes were not considered. The different pathways were considered, including Fram Strait, Nares Strait, Lancaster Sound, Davis Strait and the southern East Greenland Current (EGC). All estimates, except in the southern EGC, are based on moored current meter observations carried out under different observational programs in the 2000s. The programs in Fram Strait (NPI/AWI) and Lancaster Sound (IOS) have been carried out since the late 1990s. Continuous moored measurements in Nares Strait (U. of Delaware/IOS/OSU) were collected during 2003 to 2006 and the moored array in Davis Strait (APL/UW) has been

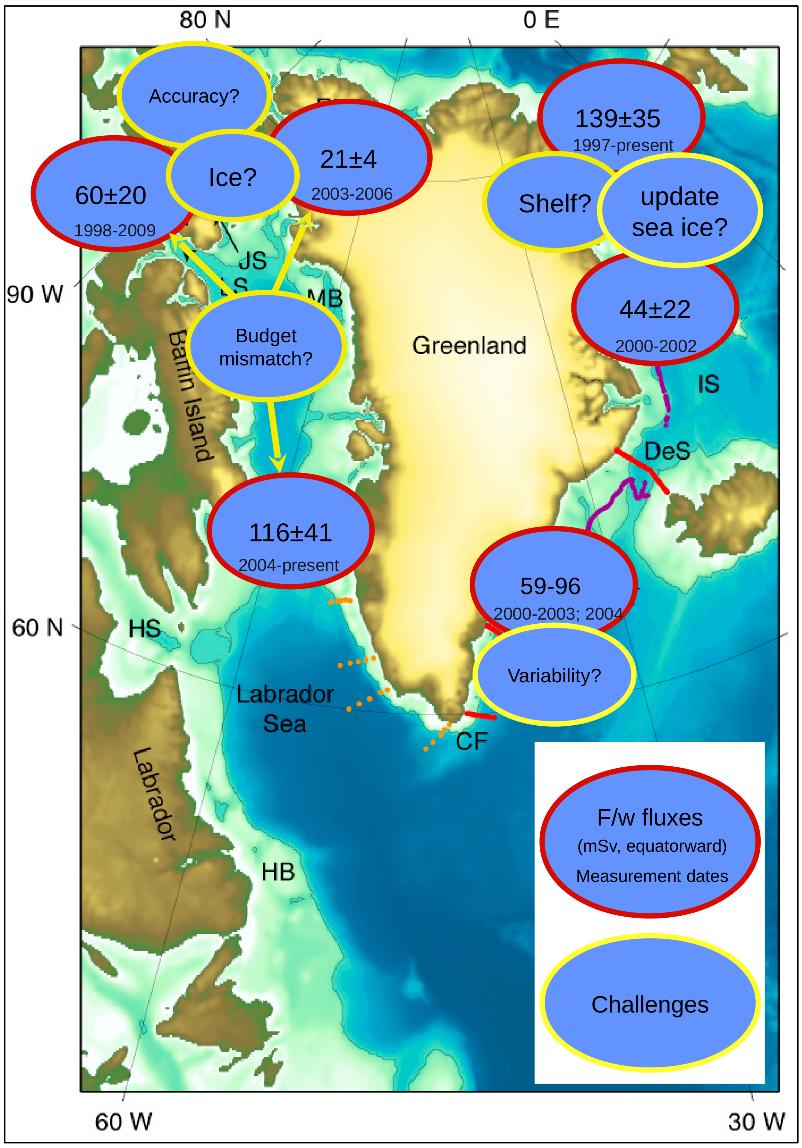

Figure 3. Freshwater fluxes east and west of Greenland and outstanding challenges. The freshwater fluxes are referenced to a salinity of 34.9 east of Greenland, north of Denmark Strait and 34.8 otherwise. The base map is courtesy of Bacon et al. (2008). A flux of 1mSv corresponds to 31.5km^3/yr. See Table 1. Adapted from Laura de Steur's presentation.

in place since 2004. The liquid freshwater flux in Fram Strait has shown a small (but not significant) increase from 2005 up to 2008. The freshwater flux in Lancaster Sound appears to decrease from 2001 up to 2009. The latter estimate is closely related to the net volume flux while for the former it less clear. A preliminary estimate of fluxes in Davis Strait shows a slight decline from 2004 to 2008. Despite the fact that several years' data have been recovered, the time series are still too short, and uncertainties are still too large, to make conclusive statements about significant trends in freshwater fluxes. Also, the time series show large annual and inter-annual variability which makes it hard to interpret observed changes. In addition, there are still some unknown contributions to the freshwater fluxes around Greenland. These challenges include: updating the estimate of sea ice flux in Fram Strait, obtaining a year-round flux estimate on the East Greenland Shelf between 74˚ and 80˚N, estimating the annual average fluxes in the EGC and on the shelf in southeast Greenland (60-66ºN), and reducing uncertainties in sea ice flux in the CAA, as well as the liquid freshwater flux in Nares Strait. There is also an apparent mismatch in the Baffin Bay freshwater budget that needs to be reconciled. In all the mooring records, it remains very hard, and very important to obtain accurate current measurements near the surface.

Table 1. Volume and freshwater flux estimates either side of Greenland. See Figure 1. Positive fluxes indicate equatorward transport.

Location	Period	Volume Flux (Sv)	Liquid Freshwater Flux (mSv)	Solid Freshwater Flux (mSv)	Comment
East of Greenland, relative to 34.9					
Fram Strait EGC	1997-2010	6.9±2.6	40±14	70	70mSv is an old estimate. de Steur et al. (2009)
Fram Strait Shelf	1997-2010	0.8-1	29±21	?	Based on model/data synthesis. de Steur et al. (2009)
74ºN EGC	2000-2002	1.9 combined	22-28	22	Little data. Holfort & Meincke (2004)
74ºN Shelf	2001-2002		22		Little data. Holfort & Meincke (2004)
63ºN	2000-2003	1	10-90 combined		Holfort et al. (2008)
East of Greenland, relative to 34.8					
South of Denmark Strait, EGC	2004	0.6-1.4	25-30 combined		From hydrography. Sutherland & Pickart (2008)
South of Denmark Strait, EGCC	2004	0.4-1.4	30-60 combined		From hydrography. Sutherland & Pickart (2008)
West of Greenland, relative to 34.8					
Nares Strait	2003-2006	0.9±0.1	21±4 combined		No extrapolation to surface or sides. Münchow et al. (2007)
Lancaster Sound	1998-2006	0.7	48±15	?	S. Prinsenberg, pers. comm.
	1998-2009	0.6±0.25	60±20 ?	?	Prinsenberg et al. (2009)
Davis Strait	2004-2005	2.3±0.7	116±41 combined		Data exist 2004-2010. Curry et al. (2011).

Craig Lee: Strategies for Sustained Observing

Efforts to characterize and understand both Arctic change and the meridional overturning circulation call for sustained, long-term quantification of volume, freshwater and heat fluxes at the handful of gateways (Fram Strait, Canadian Arctic Archipelago, Bering Strait and the Barents Sea opening) that link the Arctic and subpolar oceans. To advance understanding of the mechanisms that govern variability and distinguish cyclic from secular change, flux measurements and accompanying uncertainty estimates must: (i) provide sufficient accuracy to resolve anticipated signals of environmental change, (ii) resolve seasonal timescales, (iii) resolve lateral and vertical watermass structure, and (iv) collect sustained, consistent measurements that span decades. Although gateway observing systems experienced accelerated build-out during the

International Polar Year (IPY) 2007-09, the community now faces the difficult challenge of selecting strategies and developing designs that will facilitate sustained operation over decadal timescales. Fiscal realities will severely limit the scope of these systems, demanding highly efficient designs that focus on a small, critical subset of the desired observations. Optimization of gateway observing systems with respect to available resources rests on a clear definition of design targets. How much uncertainty is deemed acceptable in the various flux estimates? What temporal resolution is required? The community requires quantitative definition of these design requirements to inform network design efforts- without this there is no basis for network optimization exercises.

Gateway observing systems face a range of challenges that cast some uncertainty on what quantities can actually be measured. The critical straits sit in remote, difficult locations that are typically ice-covered most of the year. Gateway straits are dynamically wide (width much greater than the internal deformation radius) and thus admit small-scale recirculation features that are difficult to resolve given practical resource constraints. Freshwater moves preferentially in a thin layer near the ice-ocean interface. This region must be sampled to produce accurate estimates of freshwater flux, though instruments placed near the ice-ocean interface risk destructive interaction with the ice. The ice itself can carry a substantial quantity of freshwater, necessitating quantification of ice velocity and thickness at appropriate spatial and temporal scales. Proximity to the magnetic pole can render instrument compasses unreliable, thus requiring more sophisticated methods for reliable heading (and velocity) measurements. Moreover, networks must be designed for a period of accelerating environmental change. Effective systems will incorporate significant flexibility to adapt rapidly to both environmental change (e.g. changes in seasonal ice cover) and to changes in understanding (shifting measurement focus as new priorities are identified).

Both strong science outcomes and clear links to stakeholders will be needed to motivate the substantial resource commitment required for sustained observing. In addition to the ‘policy’ need to document and understand climate change, the observing system should feed planning for high-risk activities (e.g. extraction, commercial navigation) as well as ‘tactical’ support for day-to-day activities (Lee et al., 2010). This adds the burden of identifying and delivering useful products to agencies and stakeholders, but places the observations into a very practical context that may make it easier to garner support for consistent, long-term operations.

Existing gateway observing efforts offer examples of potential approaches. Fluxes though the Canadian Arctic Archipelago have been quantified using measurements collected at the narrow northern passages and at the wider Davis Strait, which integrates the smaller channels. The challenges observing at Davis Strait are being addressed using a system comprised of moorings augmented by long-endurance gliders capable of providing fine horizontal resolution and access to the region near the ice-ocean interface (Curry et al., 2011). At Nares Strait, data from high-resolution moored array are being used to explore correlations between transports and along-channel pressure gradient (ref) while, at Lancaster Sound, high-resolution measurements were used to develop correlates between individual moorings, winds in the interior Arctic and transport estimates (ref). The use of regression models to create transport proxies from less costly and/or extensive observations has great appeal, as this approach may allow sufficiently accurate flux quantification using greatly reduced arrays. However, during periods marked by environmental change, the regression models used to create these proxy transports may lose their applicability. Periodic assessment against high-resolution data might be required.

Craig also discussed specific cases. These included Davis Strait where a straight moored array works well. Correlation between freshwater flux and volume flux is high there, as is typical. The largest uncertainties are due to extrapolation to the surface and difficulty in resolving the sharp, mobile hydrographic front. At Nares Strait the along-channel pressure gradient (on timescales longer than 20 days, as measured using bottom pressure recorders) is well correlated with the transport and captures 70% of variance. At Lancaster Sound the useful regression model between remote sea level pressure and transport is a good example of how for other straits. It's unclear if the regression still applies under conditions of environmental change, however. Improved understanding of the physical processes behind the correlation will illuminate this question, although periodic reoccupation of the section with an intense array may still be needed. At Fram Strait the ACOBAR program is succeeding the earlier aray and includes acoustic tomography and ocean models.

Emerging technologies also offer valuable new options for monitoring the gateway sections. They include the Icecycler and Arctic winch (~$100k), ICECAT (ice sacrificial mooring, ~$10k, expendable), and gliders under ice (requiring acoustic arrays for navigation). Ideally, an Arctic acoustic array would provide a navigation system for the entire Arctic ocean.

3.2 Which Side? Which side of Greenland will be favoured by the freshwater efflux in the future, and how can we resolve model inconsistencies on this point?

Laura de Steur, with input from: M. Steele (PSC/UW), E. Hansen (NPI), J. Morison (PSC/UW), I. Rigor (APL/UW), C.

Lee (APL/UW), I. Polyakov (UAF), S. Olsen (DMI), and F. McLaughlin (IOS).

Laura gave an overview of observations of liquid freshwater in the Arctic Ocean and changes therein during the 2000s. Recalling the discussion of issue 3.1 above, she said that the freshwater flux in Fram Strait has increased slightly in the late 2000s while the flux in Davis Strait appears to have decreased relative to 2004. These trends are not significant with respect to the uncertainties related with the measurements, however. On the other hand. freshwater content has clearly increased in the Beaufort Gyre up to 2008. Proshutinsky et al. (2009) and McPhee et al. (2009) find freshwater anomalies of 1000 km^3 and 8500km^3, respectively, relative to climatology. For comparison, the Great Salinity Anomaly involved discharge of about 10000km^3 of freshwater in 5 years (Curry & Mauritzen, 2005). Proshutinsky et al. find that the mechanisms related with the freshwater increase are both dynamic (Ekman) and thermodynamic. McPhee et al. state that the additional freshwater content is associated with increased transport toward the CAA. A more recent study of Rabe et al. (in press) shows freshwater storage in the Beaufort Gyre, but also in the Eurasian Basin. Their estimate of the total accumulated freshwater anomaly is 8000±2000km^3 over the whole Arctic Ocean. This estimate is derived from ITP observations collected during the IPY (2007-2009) and is calculated relative to hydrographic data from the 1990s (1992-1999). Another recent study by de Steur et al. (in preparation) investigates hydrographic data collected in several large monitoring programs in the 2000s. They show that freshwater that accumulated in the Beaufort Gyre has started spreading towards the Lincoln Sea, north of Greenland, in the late 2000s. The increase in freshwater content was significant (equivalent to up to 3m extra freshwater) in 2009, followed by a small decline again in 2010. The redistribution was associated with a change in Arctic Ocean circulation from anticyclonic between 1997 and 2008, accumulating freshwater in the Beaufort Sea (low Arctic Oscillation (AO) index), to cyclonic in 2009 which released the freshwater anomaly eastwards to the Lincoln Sea and Fram Strait (high AO index; Proshutinsky et al., 2010). These changes suggest that freshwater is poised to exit the Arctic Ocean. In order to understand if, how, and when Arctic Ocean freshwater is released to lower latitudes continued monitoring of the freshwater, volume and heat fluxes at the gateway sections around Greenland (the CAA, Davis Strait, Fram Strait, and Denmark Strait; see issue 3.1) is critical.

Rüdiger Gerdes: How climate models project future development of freshwater in Arctic.

The phase and pathways of freshwater exported from the Arctic Ocean to the subpolar North Atlantic matter for the impact on the large scale oceanic circulation. Liquid freshwater is more constrained by ocean dynamics to follow boundary currents around Greenland and Labrador while sea ice is more sensitive to the local wind driving. Liquid freshwater is vertically distributed in the water column while sea ice melt water is concentrated near the surface. Because of the nonlinearity of vertical mixing processes in the ocean, the impact on deep water formation is greater for sea ice melt. Observed liquid freshwater export events consisted both mainly of anomalously large sea ice (Great Salinity Anomaly) and mainly of liquid freshwater anomalies (mid-1990s export event). Projections of future liquid freshwater export from the Arctic suffer from several uncertainties. Apart from model model bias, uncertainties in the scenario assumptions are most important for projections until the end of the century. For the upcoming decades, the phase of important natural low-frequency fluctuations, especially the Atlantic Multidecadal Oscillation, is to be considered.

Still, all climate projections agree on larger freshwater input into the Arctic Ocean in the future, a decrease in sea ice volume and sea ice export from the Arctic. Sea ice production is going to shrink and the Arctic freshwater export is going to shift towards the liquid freshwater phase. The large changes in the oceanic freshwater balance suggest that the greatest global salinity changes will occur in the Arctic Ocean.

However, details of the projected freshwater balance and the future development of salinity are model dependent. Models that perform well for the late 20th century deliver very different answers for the end of the 21st century. One reason for such differences is the different representation of ocean passages connecting the Arctic Ocean with the subpolar seas. Because of the narrow straits and shallow passages, the CAA poses an extreme challenge for the under-resolved ocean components of coupled climate models. Nevertheless, an increase in total freshwater transport, the sum of sea ice and liquid freshwater, from Fram Strait to the CAA and an overall increase in total freshwater transport from the Arctic Ocean seems inevitable.

Rüdiger summarized his talk by saying that freshwater fluxes around Greenland will increasingly take the western route through the CAA.

Alex Jahn: Future freshwater export from the Arctic according to CCSM3/4 and other GCM scenarios

Simulations from several GCMs for the 21st century all show an increase in the freshwater input into the Arctic Ocean, an increase in the liquid freshwater storage in the Arctic Ocean, and a decrease of the export of sea-ice from the Arctic, due to decreasing Arctic sea-ice volume. GCMs with at least one CAA channel show that the total freshwater export through the

CAA becomes more important in the 21st century, but rates of increase in the freshwater export through the CAA and Fram Strait vary between models. Nevertheless, most of the GCMs with at least one CAA channel agree that the volume export through the CAA will decrease in the 21st century, but the volume export through the Fram Strait will increase, while the exported water will become fresher both east and west of Greenland. How much these changes in the export will affect the formation of deep water in the North Atlantic, however, remains an open question. Freshwater exported through the CAA or Fram Strait can have different impacts on the subpolar deep water transformation areas. Specifically, freshwater exported via the CAA tends to remain in the Labrador Current, or inshore of it, and is isolated from the Labrador Sea deep convection areas. However, it remains concentrated at the surface as a relatively strong density anomaly. Freshwater exported via Fram Strait can impact the overflows across the Greenland-Scotland ridge. For this export pathway, the pertinent question is: how much is the freshwater anomaly diluted through the water column, and does it remain intense enough to modify the overflow. These questions need to be addressed by higher resolution models that can resolve eddies and thin surface layers of freshwater.

3.3 Greenland freshwater impact on CAA Outflow. Is the future freshwater production of Greenland capable of making significant impacts on CAA Outflow (path; transport), and what/where should we monitor to test for this?

Bert Rudels: Volume and freshwater fluxes through the Canadian Arctic Archipelago – Baffin Bay system.
Baffin Bay is an enclosed connection and reservoir between the Arctic Ocean and the Labrador Sea. It receives polar water from the Arctic Ocean through the narrow, shallow passages in the CAA as well as from the south by the West Greenland Current. The polar water is, after transformation, exported in the Baffin Current through Davis Strait to the Labrador Sea. The isolated nature of Baffin Bay with control sections both upstream and downstream makes it tempting to use an idealized hydraulic approach to estimate the transports. The transports are assumed rotationally controlled and driven by the difference in sea level and by the different stratifications in the Arctic Ocean, Baffin Bay and Labrador Sea. The only external forcing considered is the cooling in Baffin Bay that is responsible for the characteristic cold upper layer in Baffin Bay (-1.6ºC, 33.7). The work proceeds in three steps. First the baroclinic transport, driven by the density differences between the Arctic Ocean and Baffin Bay, is determined and where the density and upper layer depth are assumed the same in Lancaster Sound, Nares Strait and the West Greenland Current. Once the baroclinic transports are estimated the sea level difference is computed. Next the upper layer depth in Nares Strait and in the West Greenland Current is reduced while the sea level slope is kept constant. This allows for deep inflows through Nares Strait and in the West Greenland Current. To establish an outflow through Davis Strait in the deeper layer a “barotropic” sea level slope between the Arctic Ocean and the Labrador Sea is estimated from two “ideal” stations, one in the Arctic Ocean and the other in the Labrador Sea. The transports are determined for different salinities in the Polar water and the most reasonable transports are found to occur for salinities 33.0-33.2. Finally the effects of increased melting of the Greenland icecap on the transports are examined. It is found that if the freshwater is added directly to Baffin Bay the effects will be small, but if the added freshwater is incorporated in the East Greenland Current and the West Greenland Current a reduction of the Polar outflow through the CAA by 25% might take place.

3.4 What is the ocean impact on Greenland freshwater production and how can field observations be improved?

Fiamma Straneo, **Ice-Ocean Interactions in Greenland**
with input from: G. Hamilton, D. Sutherland, R. Curry, L. Stearns, C. Cenedese

Net mass loss from the Greenland Ice Sheet has increased rapidly over the last decade, primarily as a result of the acceleration and retreat of outlet glaciers in western and southeast Greenland. The Greenland Ice Sheet freshwater flux is about 30mSv now, and accounts for about 25% of sea level rise. The leading hypothesis is that the acceleration was due to an increase in ocean-driven submarine melting at the glaciers’ termini-which are typically grounded ~600 m below sea-level in Greenland’s deep fjords. Yet, our knowledge of the water masses present in the fjords and the circulation associated with the submarine melting is very limited.

Fiamma presented measurements from three glacial fjords in East Greenland obtained from synoptic surveys using an icebreaker, small local vessels and helicopters, as well as moored data. These show that the fjords are filled year-round with cold waters of Arctic origin, transported by the East Greenland Current, overlaying warm waters of Atlantic origin. These waters are continuously and rapidly replenished via exchange with the shelf. Melting is primarily driven by the Atlantic Waters but the presence of the Arctic layer above effectively limits the vertical reach of the upwelling meltwater plume at the ice edge. These results show that the large scale oceanic stratification has a strong impact on the melting of Greenland’s glaciers and that variability in either the Arctic or Atlantic water masses will drive variations in the submarine melt rate.

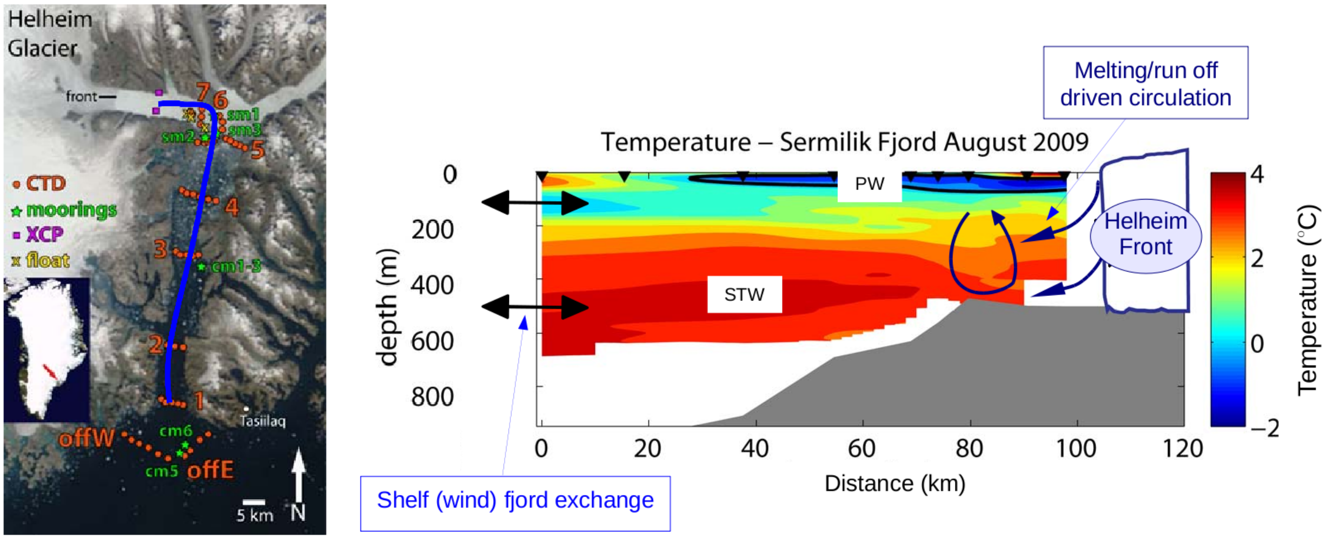

Figure 4. Temperature section through Sermilik Fjord, in August 2009 showing cold polar water (PW) overlying warm subtropical water (STW). Adapted from Fiamma Straneo's presentation.

3.5 How do we interface with existing plans for MOC monitoring further south? How might we evolve a long-term observational strategy to observe the expected impact of these changes on the MOC?

Tom Haine:

The impact of Arctic buoyancy anomalies on the subpolar North Atlantic were discussed. Tom advocated the importance of looking at integrated quantities to detect clear signals of Arctic change penetrating southwards. In particular, buoyancy should be targeted because the projected Arctic freshening and warming both increase buoyancy, and because buoyancy is conserved away from the sea surface.

The Labrador Sea was proposed as the place where buoyancy changes may first be clearly distinguished from background noise. Labrador Sea hydrographic structure has been reasonably well-monitored for several years now, mainly due to Canadian efforts at OWS Bravo and on the AR7W section. Knowledge of the full-depth circulation in the subpolar North Atlantic, including the Labrador Sea, is arguably better than anywhere else in the global ocean, due to data from repeat hydrographic sections, floats, and altimetry. There are also some indications from climate models that Labrador Sea Water formation is the most sensitive part of North Atlantic Deep Water (NADW) formation to exported high-latitude anomalies.

The overflows are obviously important for NADW formation too, and hence the MOC. But the overflows are likely more robust to upstream changes than Labrador Sea Water (LSW) formation. The reasons are that overflow transport is less variable in the limited available records. Overflow transport is less likely to change rapidly because buoyancy anomalies can either bypass the overflow (on the Greenland shelf), or are diluted over a large volume of Nordic Seas intermediate water which buffers their impact. The nature of the hydraulic control of the overflow transport also makes the overflows less susceptible to short-term variability because it sets a limit to the overflow flux. Nevertheless, the overflows are relatively easy to monitor with have relatively long timeseries already: clearly such efforts should continue.

Measuring the total export from the subpolar Atlantic, including all LSW and overflow waters is an attractive option too. For example, NADW export from the Labrador Sea at 53ºN, or round the Grand Banks at the ACM-6 mooring line, is a desirable quantity to measure. However, there are much fewer data at these locations, and the German activities that supported them have declined in recent years.

The discussion explored what would be involved in adopting LSW formation rate as a metric to monitor the impact of Arctic outflow anomalies on the MOC. A number of key issues were identified. First, a consensus on the exact definition of LSW formation rate is required. Second, consensus on how best to measure LSW formation rate is needed. To date, there have been divergent definitions and divergent techniques to estimate LSW formation rate. This lack of agreement likely explains much of the variability seen in published estimates of LSW formation rate (see Figure 27.5 of Haine et al. 2008, and the associated discussion). These challenges notwithstanding, the conceptual framework on how to proceed is in place, and future estimates will converge. Maintaining annual AR7W occupations, continuing subsurface float deployments in the western subpolar Atlantic, and periodic CFC surveys are the most important activities to accelerate this convergence. Third, the pathways and rates connecting Arctic export to the Labrador Sea deep convection areas need to be identified. Shelf/basin exchange is a particularly hard issue because it determines where buoyancy anomalies are injected into the subpolar flow but it occurs on small scales (O(1) km) with intense dynamics (e.g., see Magaldi et al. 2011 on the East Greenland Spill Jet). Further process studies in the field are needed, but very high-resolution numerical modeling will also yield insight. Finally, the connections between LSW formation rate and "the MOC" need to be clarified. Typically, people understand "the MOC" to mean the magnitude of the overturning streamfunction at 30ºN (e.g., the IPCC AR4 report). The links between NADW variations in the subpolar gyre and this MOC metric are unclear, however: they need to be elucidated in GCMs, but a satisfactory explanation will require simultaneous resolution of the large-scale North Atlantic circulation, and the details of shelf-basin exchange on much shorter scales. Such calculations will be available in the next few years.

Fiamma Straneo: Observing the Subpolar North Atlantic Program (O-SNAP)
The study of the Atlantic Overturning Circulation (AMOC) was identified as a near-term priority in the U.S. Ocean Research Priorities Plan, by the U.S. Joint Subcommittee on Ocean Science and Technology. This led to the formation of US AMOC, a program sponsored by NSF, NASA and NOAA, that focuses on the AMOC and includes the design and implementation of an AMOC monitoring system.

O-SNAP is a to-be-proposed international program that focuses on the AMOC variability in the subpolar North Atlantic and is led by Susan Lozier (Duke). The main objectives of O-SNAP are to measure the fluxes of mass, heat and fresh water in the subpolar region and establish their link to changes across the Greenland-Scotland Ridge (as observed by European PIs including the recent Thor Project) and the 24ºN array in the N. Atlantic maintained by the UK-US RAPID program. The straw man plan for the O-SNAP system includes moored boundary current arrays at the 53ºN location occupied by the German SFB-460 program until a few years ago. Gliders and floats will also be proposed to monitor the basins' interior along two lines – roughly across the Labrador Sea and from Cape Farewell to Scotland.

Sheldon Bacon, commenting on the choice of 53oN rather than the AR7W line, said that occupations of AR7W and AR7E are typically separated in time, which is inconvenient. A regional survey in 2005 showed detachment of the boundary current at Cape Farewell and maybe the DWBC is also not continuous at Eirik Ridge. The currents are very barotropic in the western subpolar gyre.

4.0 Conclusions.

Patrick Heimbach, State Estimation and adjoint sensitivity calculations in support for Arctic observing system design
Synthesis efforts which combine diverse observations in a coherent dynamical framework provide a description of the global ocean state and its temporal evolution, and enable access to "diagnostic" climate variables that cannot be directly measured, are essential for climate analysis and prediction. Patrick briefly reviewed the subject, drawing considerably from experience with MIT synthesis efforts as part of the Estimating the Circulation and Climate of the Ocean (ECCO) project, and describing beginning efforts of the development and production of a dedicated Arctic and Subpolar gyre coupled ocean sea-ice state estimate (Arctic/subpolar gyre State Estimate; ASTE, at 1/6º). Various state estimates of near-global extent and covering periods dating back several decades are available, but prior to the altimeter and Argo era, data is very sparse in space and time. Until the early 1990s, available estimates are thus very weakly constrained. Data thinning experiments suggest that observations in the modern period (Argo, altimetry) provide essential constraints for determining the ocean state. Even for the modern period, however, severe under-sampling remains, particularly at depth (> 2000 m), at high latitudes including most ice-covered areas, and most of the marginal and shallow seas. Most data sets are not dense enough to provide good constraints on the scales relevant for climate analysis, particularly in regions with large eddy energy.

Computing power and algorithmic challenges have prevented the production of global eddy-permitting state estimates until recently. This is now beginning to change, and the successful production of an eddy-permitting Southern Ocean State Estimate within ECCO has encouraged a similar development targeting the Arctic Ocean and the North Atlantic subpolar gyre. The heightened interest in high-latitude processes requires adequate treatment of sea ice, along with the use of sea ice and, where available, under-ice observations.

Besides their direct use in production mode, estimation systems also provide a quantitative framework for assessing the impact of various observing systems in constraining the state estimate. ECCO in particular is exploiting the availability of and adjoint model to quantify the sensitivity of key climate indices, such as meridional heat, freshwater, and volume transports, Arctic sea ice coverage or freshwater content, to remote perturbations in the ocean and atmospheric state. Dominant centers of action on various time scales may be identified with implications for observations required to describe the observed variability. In parallel, observation system withholding experiments (OSEs) enable the impact of various observations (different variables, spatial or temporal distribution) on constraining climate indices to be quantified, and may help the design of future observing systems through observing system simulation experiments (OSSEs). This design process is in progress now for the Arctic Observing Network.

References

Curry, B., C.M. Lee, B. Petrie, 2011: Volume, freshwater, and heat fluxes through Davis Strait, 2004–05. *J. Phys. Ocean.*, doi: 10.1175/2010JPO4536.1.

Curry, R., and C. Mauritzen (2005), Dilution of the northern 170 North Atlantic Ocean in recent decades, *Science*, **308**, 1772–1774.

Haine, T., C. Böning, P. Brandt, J. Fischer, A. Funk, D. Kieke, E. Kvaleberg, M. Rhein, and M. Visbeck, 2008, *North Atlantic Deep Water formation in the Labrador Sea, recirculation through the subpolar gyre, and discharge to the subtropics* , edited by R. R. Dickson, J. Meincke, and P. Rhines, pp. 653-701, Springer.

Holfort, J., and J. Meincke, 2005: Time series of freshwater-transport on the East Greenland Shelf at 74ºN. *Met. Zeitschrift.* **14(6)**, 703-710.

Holfort, J., E. Hansen, S. Østerhus, S. Dye, S. Jonsson, J. Meincke, J. Mortensen, and M. Meredith, 2008, *Freshwater fluxes east of Greenland, in Arctic-Subarctic Ocean fluxes,* edited by R. R. Dickson, J. Meincke, and P. Rhines, pp. 263–288, Springer.

Karcher, M., A. Beszczynska-Möller, F. Kauker, R. Gerdes, S. Heyen, B. Rudels, U. Schauer, 2011, Arctic Ocean warming and its consequences for the Denmark Strait Overflow, *J. Geophys. Res.*, in press.

Lee, C.M., H. Melling, H, Eicken, P. Schlosser, J-C. Gascard, A. Proshutinsky, E. Fahrbach, C. Maurtizen, J. Morison and I. Polyakov, 2010, Autonomous Platforms in the Arctic Observing Network. In Proceedings of OceanObs '09: Sustained Ocean Observations and Information for Society (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. and Stammer, D. Eds., ESA Publication WPP-306.

Magaldi, M. G., T. W. N. Haine, and R. S. Pickart, 2011, On the nature and variability of the East Greenland Spill Jet: a case study in summer 2003, J. Phys. Oceanogr., submitted.

McPhee, M. G., A. Proshutinsky, J. H. Morison, M. Steele, and M. B. Alkire, 2009. Rapid change in freshwater content of the Arctic Ocean. Geophys. Res. Lett., 36, L10602, doi: 10.1029/2009GL037525.

Prinsenberg, S., J. Hamilton, I. Peterson, and R. Pettipas. 2009. Observing and interpreting the seasonal variability of the oceanographic fluxes passing through Lancaster Sound of the Canadian Arctic Archipelago. Influence of Climate Change on the Changing Arctic and Sub-Arctic Conditions, J. C. J. Nihoul and A. G. Kostianoy (eds.), Springer.

Proshutinsky, A., et al., 2009. The Beaufort Gyre freshwater reservoir: State and variability from observations. *J. Geophys. Res.*, **114**, C00A10, doi:10.1029/2008JC005104.

Proshutinsky, A., et al., 2010. The Arctic, c. Ocean. [In: State of the Climate in 2009]. *Bull. Amer. Meteor. Soc.*, **91(6)**, S85–87.

Polyakov, I. V., A. Beszczynska, E. C. Carmack, I. A. Dmitrenko, E. Fahrbach, I. E. Frolov, R. Gerdes, E. Hansen, J. Holfort, V. V. Ivanov, M. A. Johnson, M. Karcher, F. Kauker, J. Morison, K. A. Orvik, U. Schauer, H. L. Simmons, Ø. Skagseth, S. T. Sokolov, M. Steele, L. A. Timokhov, D. Walsh, J. E. Walsh, 2005, One more step toward a warmer Arctic, *Geophys. Res. Lett.*, **32**,10.1029/2005GL023740.

Rabe, B., M. Karcher, U. Schauer, J. Toole, R. Krishfield, S. Pisarev, F. Kauker, R. Gerdes and T. Kikuchi (accepted) An assessment of Arctic Ocean freshwater content changes from the 1990s to 2006-2008, *Deep-Sea Res. I,* doi: 10.1016/j.dsr.2010.12.002.

de Steur, L., E. Hansen, R. Gerdes, M. Karcher, E. Fahrbach, and J. Holfort, 2009. Freshwater fluxes in the East Greenland Current: a decade of observations. *Geophys. Res. Lett.*, **36**, L23611, doi:10.1029/2009GL041278.

Sutherland, D.A., and R.S. Pickart, 2008. The East Greenland Coastal Current: Structure, variability, and forcing. *Progr. Oceanogr.* **78**, 58-77.

Appendix: Workshop Agenda

iAOOS Planning Workshop on the IPY Legacy Observing System for Greenland
Woods Hole Oceanographic Institution, Woods Hole, MA, USA
Fuglister Room, Room 201, Clark Laboratory
18 October 2010

We are holding a one-day meeting to discuss future observing of the Arctic and subarctic seas during the so-called 'legacy phase' of the IPY. The workshop is sponsored by the Arctic Ocean Sciences Board and follows a Report compiled on its behalf in 2009: 'Observing our northern seas during the IPY: what was achieved, what have we learned and where do we go from here?' [see AOSB.org under iAOOS] in which we explored three key iAOOS questions 1) Following the IPY, how would we now define the role of the Northern Seas in Climate? 2) What questions should we be testing to help us understand that role? 3) How should we design an ocean observing system to test these questions? We are now at step three and the aim is that by the end of the 2010, we might have an effective observing plan for the IPY Legacy phase to put before AOSB. [* the AOSB is now the Standing Science Committee on Oceans for the International Arctic Science Committee (IASC)].

In all, a total of 18 questions were put forward to us for testing, covering 3 main issues:

Issue 1- Sorting out the inflows. Bert Rudels has agreed to lead this one, with necessary input from a list of others currently being drawn up. This Group will probably meet under Bert towards the end of the year (November?), probably Helsinki.

Issue 2- Coping with change in the Arctic water-column. Craig Lee has agreed to take the lead here which is very good news since he is the current lead on the Observing Change panel of SEARCH and we thus not only get his expertise and that of his chosen team but avoid multiple plans to observe the same changes, often using mostly the same people, which would be pointless. As with Issue 1, Issue 2 will also be defined elsewhere, perhaps in association with the "Understanding Arctic Change" Workshop that is to be held in Seattle, Washington from 29 September-1 October 2010.

Issue 3 Revitalising our ideas about Greenland, freshwater and the MOC. This is the main activity of the WHOI Workshop, though we intend to lead off with a few selected talks to give a flavour of the other two issues.

The agenda is below, with the understanding that, in a meeting based on discussion, the timings will necessarily be led by that discussion. Very roughly, Issues 1 and 2 are intended to run to morning coffee, with Issue 3 taking the remainder of the morning and the whole of the afternoon. Bob Dickson will chair the morning discussion and Tom Haine will chair the afternoon. Lilian Schubert (AWI) kindly acted as the meeting rapporteur throughout.

Agenda:

8:45 AM Welcome, and brief summary of the Workshop's aims. Bob Dickson CEFAS

9:00 AM Issue 1 Sorting out the inflows

1. General introduction Bert Rudels FIMR.
2. Measuring the flows along the Eurasian boundary of the Arctic Ocean; what is desirable, what is practical, what remains problematic. Bob Pickart WHOI.
3. Inverse modelling of fluxes at the Arctic Ocean boundary Sheldon Bacon NOCS

Issue 2. Coping with change in the Arctic water-column

4. General introduction Craig Lee APL-UW
5. Observing and modelling of transient signals connecting the Arctic Ocean and the Nordic seas' Michael Karcher AWI

10:30 AM Coffee Break

11:00 AM Issue 3. Revitalising our ideas about Greenland, freshwater and the MOC

6. General introduction. Tom Haine JHU

Subhead 3.1 How Much? what are the ocean fluxes either side of Greenland (including but not confined to freshwater) and how can we monitor them effectively in the long term? Craig Lee UW, Andreas Münchow UDel, Simon Prinsenberg, BIO, Laura de Steur NPI, (Humfrey Melling IOS)

12:30 PM Lunch

1:30 PM Subhead 3.2 Which side? Which side of Greenland will be favoured by the freshwater efflux in future, and how can we resolve model inconsistencies on this point? Rüdiger Gerdes AWI, Alexandra Jahn UCAR, Laura de Steur NPI. Specific titles are:

	R. Gerdes: Uncertainties in climate scenario calculations regarding the freshwater fluxes around Greenland. A. Jahn: Future freshwater export from the Arctic according to CCSM scenario calculations L. de Steur: Observational strategies for monitoring freshwater fluxes on both sides of Greenland
2:30 PM	Subhead 3.3. Greenland f'w impact on CAA Outflow. Is the future freshwater production of Greenland capable of making significant impacts on CAA Outflow (path; transport), and what/where should we monitor to test for this? Bert Rudels FIMR Subhead 3.4 Ocean Impact on Greenland f'w production? What are the ocean Impacts on Greenland f'w production and how can field observations be improved? (Kelly Falkner COAS-OSU), Fiamma Straneo.WHOI
3:30 PM	Coffee/tea break
4:00 PM	Subhead 3.5. MOC impacts. Future impact on MOC How might we evolve a long-term observational strategy to observe the expected impact of these changes on the MOC? Tom Haine JHU, Fiamma Straneo, WHOI, Sheldon Bacon NOCS. Specific titles are : How do we interface with existing plans for MOC monitoring further south? Tom Haine The planning of OSNAP (Overturning in the Subpolar North Atlantic Program). Fiamma Straneo (Susan Lozier DUKE, John Toole WHOI) and UK-OSNAP Plans Sheldon Bacon. New Results on Arctic FW export & storage based on an analysis of the freshwater efflux from west and east of Greenland. (Penny Holliday), Sheldon Bacon NOC & Craig Lee (UW).
5:30 PM	General group discussion on when/where/what to observe, including: Adjoint sensitivity calculations in support for Arctic observing system design, Patrick Heimbach MIT
6:30 PM	Conclusions & Close

Workshop Attendees:
Bob Dickson (CEFAS)
Jean-Claude Gascard (LODYC)
Rüdiger Gerdes (AWI)
Charles Greene (Cornell)
Tom Haine (JHU)
Patrick Heimbach (MIT)
Alexandra Jahn (McGill)
Craig Lee (UW APL)
Michael Karcher (AWI/OASYS)
Marcello Magaldi (JHU)
Andreas Münchow (UDel)
Svein Østerhus (U. Bergen)
Gleb Pantaleev (IARC)
Bob Pickart (WHOI)
Simon Prinsenberg (BIO)
Andrey Proshutinsky (WHOI)
Bert Rudels (FIMR)
Lilian Schubert (AWI)
Laura de Steur (NPI)
Fiamma Straneo (WHOI)
Kjetil Våge (Bergen)
Waldemar Walczowski (IOPAN)
Rebecca Woodgate (UW APL)
Peili Wu (UKMO)
Øystein Skagseth (IMR)