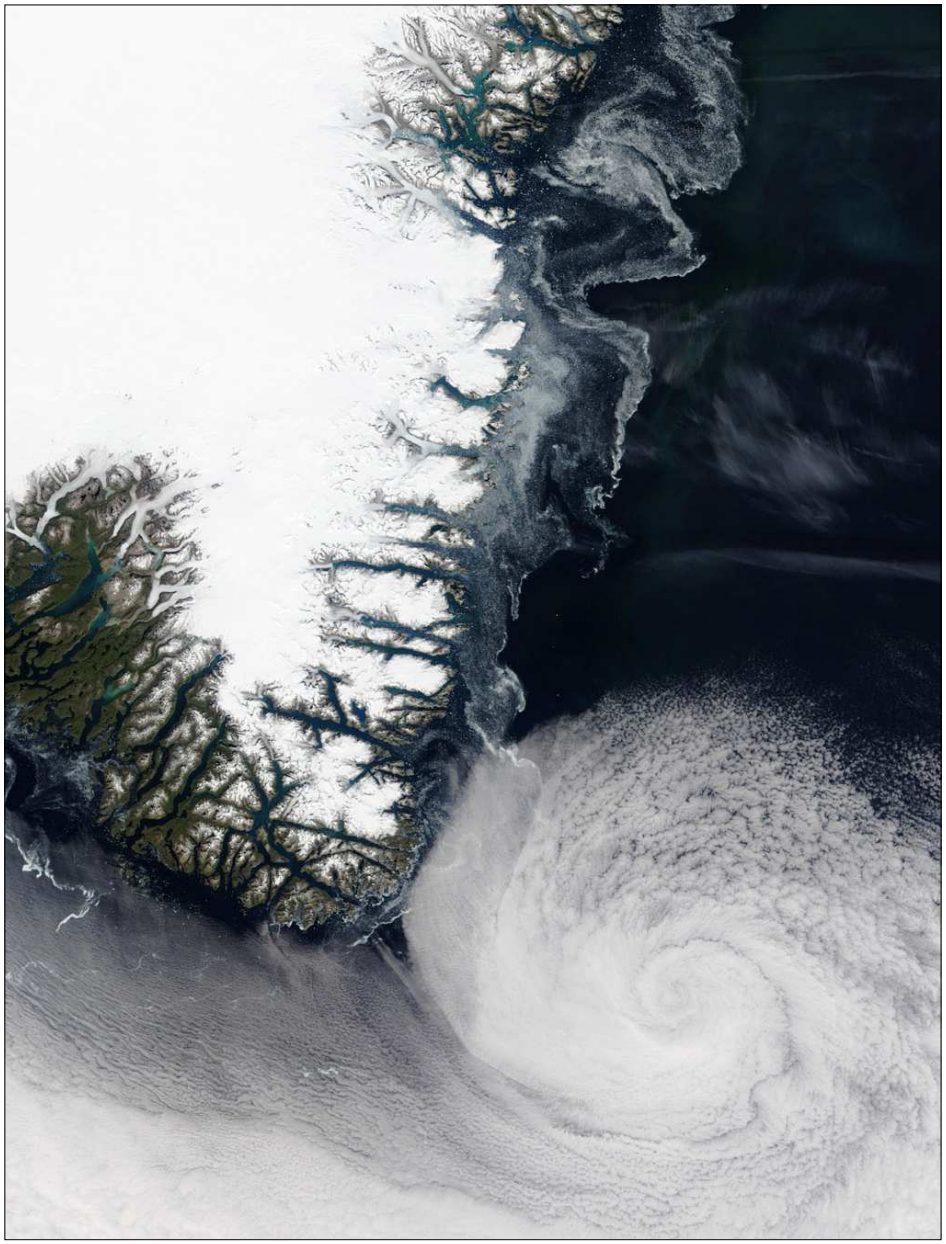
ASOF Status and Prospects in the Subpolar Gyre



Report on ASOF Task 5, Overflows and Storage Basins to Deep Western Boundary Current

November 2004

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[1]Cover figure: MODIS true-color image from July 27 2002 showing the interaction of a cyclonic weather system with the high topography of southern Greenland, represented in the image by the region of permanent snow cover. Such interactions can result in narrow high wind speed regions known as tip jets, represented in this image by fine scale structure in the cloud field, that are responsible for intense air-sea interaction, and possibly deep convection (*Pickart et al.*, 2003; *Doyle and Shapiro*, 1999). Meanders in the East Greenland Coastal Current are made visible in this striking image by variability in the sea ice. Courtesy of Kent Moore, University of Toronto

Status and Prospects for ASOF in the subpolar Atlantic. Report on ASOF Task 5, Overflows and Storage Basins to Deep Western Boundary Current

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1 Introduction

ASOF Task 5 concerns monitoring and understanding the import and modification of Arctic waters to the subpolar Atlantic ocean and their subsequent export south. The basins of this region - Iceland Basin, Irminger Basin, Labrador Sea, and Newfoundland Basin - are the last reservoirs for storage and mixing of the Arctic overflows. Vigorous water-mass conversion occurs there before the final products are discharged into the deep western boundary current of North Atlantic deep water. Key processes include: descent and entrainment of overflowing waters through Denmark Strait, Faroe Bank Channel, and across the Iceland-Faroe Rise; deep and abyssal flow through gaps in the mid-Atlantic Ridge, past Flemish Cap, and the Tail of the Grand Banks; diabatic transformation via deep convection in Labrador and Irminger Seas; shelf-slope interaction along the Greenland and Labrador shelves; storage of property anomalies in recirculations and exchange with boundary currents; sea ice formation, transport, and melting; and, interaction between southbound overflow waters and northbound subtropical waters. The relative importance of these mechanisms for the propagation of climate anomalies, via advection or waves, is unclear, but they form the context of the Task 5 working group.

In light of the overarching ASOF goal,

> "to measure and model the variability of fluxes between the Arctic Ocean and Atlantic Ocean with a view to implementing a longer term system of critical measurements needed to understand the high-latitude ocean's role in decadal climate variability" (*Dickson et al.*, 2002),

these issues motivate the following urgent questions for ASOF science to address:

1. What is the variability in large-scale stratification and circulation in these basins and how does it relate to changes upstream? What processes control this variability and how predictable are they?

2. What is the variability in fluxes of freshwater, ice, and heat through the region? How is this variability controlled? What compensation is there between anomalies from the Nordic Seas and the Canadian Archipelago?

3. How are stratification and property anomalies modified and transmitted through the subpolar North Atlantic? How do they propagate into the deep western boundary current? What are the mechanisms involved?

4. How is dissolved material exposed to, and sequestered from, the troposphere and what is the variability in these processes?

These overarching science issues provide the principal motivation for the Task 5 working group. Although much is known about them, much remains to be discovered.

This white paper serves two purposes. First, we report, briefly, on the status and plans of oceanographic and atmospheric research germane to ASOF in the subpolar Atlantic. Second, we identify gaps, and opportunities, in implementing ASOF for this area. The target audience includes the oceanographic research community actively investigating the subpolar North Atlantic, and a wider group of climate researchers and program managers working on the Atlantic circulation. The document is laid out as follows. In the next section we define and explain the scope of the Task 5 working group. In Section 3 we review the ASOF observing network in the subpolar Atlantic and discuss its prospects in the next few years. Section 4 contains a discussion

of key processes, and our ignorance of them, that are critical to understanding how high latitude climate anomalies propagate through the Task 5 area. In Section 5 we address liaison between Task 5 and other research programs, and finally, Section 6 concludes the white paper with a series of recommendations for ensuring that the ASOF goals are met.

This document is mainly based on discussion at a Task 5 working group meeting in June 2004. Support from NSF is appreciated in making that workshop possible.

2 Task 5 Scope

In October 2002, the ISSG agreed that implementation of the ASOF program would be delegated to six working groups split by natural oceanographic boundaries, and one working group to synthesize ASOF-relevant ocean circulation modeling projects. Task 5, Overflows and Storage Basins to Deep Western Boundary Current, concerns the deep subpolar North Atlantic ocean and adjacent continental shelves.

For scientific and practical reasons the primary focus of Task 5 is on monitoring and understanding the physics of the freshwater cycle in the ocean, including floating ice. Because of its disproportionate importance, the boundary current system on, and adjacent to, the Greenland, Labrador, and Newfoundland shelves is paramount. The gyre interiors in the Iceland, Irminger, Labrador and Newfoundland basins are also important in so far as they store and modify high latitude water masses. The warm limb of the meridional overturning circulation (MOC) passing through this area is not emphasized, however. Nominally, the geograpical boundaries of the Task 5 domain are the Greenland–Scotland Ridge, Davis Strait, and Hudson Strait to the north, and the A02 WOCE line between the British Isles and Newfoundland to the south (approximately 48°N).

The specific aims of the Task 5 working group are as follows:

1. Instrumental monitoring network:

    - Review the status of current and pending fieldwork in the western subpolar gyre relevant to ASOF. Compile and maintain a comprehensive list of activity.
    - Establish priorities in this list of field projects, based on relevance to permanent ASOF monitoring in the Task 5 area. Specifically, what are the critical quantities to measure at which critical places to monitor the MOC?
    - Identify gaps in the observing network. Discuss prospects to fill gaps and promote these opportunities.

2. Promote Task 5-relevant process studies: In particular, develop plans for a joint ASOF/CLIVAR process study on interaction and exchange between polar waters on the east Greenland shelf and the interior Irminger Sea.

3. Liaison: Discuss and foster collaboration between ASOF Task 5 and other programs such as CLIVAR, SEARCH, the International Polar Year, the UK/Norwegian RAPID program, the German SFB460 program, CLIC, THORPEX, and other ASOF working groups.

The Task 5 working group consists of 8 members from 5 countries (Appendix A), and met for the first time in June 2004 (agenda is at Appendix B). We anticipate meeting annually in the next few years.

3 Observations in the Subpolar Gyre

The central theme of ASOF is to observe and monitor the Arctic and sub-Arctic ocean freshwater cycle. Measuring the key fluxes is the greatest challenge because of the difficulty of mooring instruments in narrow rapid currents in remote, ice-choked places, or with substantial fishing pressure. These challenges exist in the subpolar North Atlantic ocean, as well as in the Nordic Seas and Canadian Archipelago, despite the long history of oceanographic research in this area.

It is appropriate, therefore, that the single most important duty for Task 5 is to review and promote the instrumental record of freshwater fluxes. Below, we identify and describe the important individual projects that contribute to this goal. The focus is on recent and future activity (since 2000), although long timeseries are identified where possible. Table 1 summarizes these efforts, and Figure 1 is a map showing their locations. Figures 2 and 3 show the coverage for the 1 year periods August 2003–August 2004 and August 2004–August 2005. We intend to maintain this database through the ASOF web site (http://www.asof.npolar.no), so corrections and additions are welcome (send details to Thomas.Haine@jhu.edu and/or rbos@iim.csic.es). The CLIVAR website (http://www.clivar.org/organization/atlantic/IMPL/index.htm) and *Busalacchi et al.* (2004)'s report on the CLIVAR Atlantic observing system are also useful resources.

3.1 Fixed Point Time series: Moorings

Moored instruments provide the backbone of the ASOF observing strategy. There are four principal areas of interest to Task 5:

3.1.1 Greenland/Scotland Ridge

The following projects are relevant to the southward overflows from the Nordic Seas into the subpolar North Atlantic (Note this area is also the focus of ASOF Task 4, Greenland-Scotland Ridge Exchanges. *Saunders* (2001) provides a good review prior to the year 2000.)

- Denmark Strait moorings. The German SFB460 subproject A1 (Overflow and Mixing Processes in the Irminger Sea, http://www.ifm.uni-kiel.de/fb/fb1/tm/research/sfb460/a1/sfb-a1.html) has been active in the Denmark Strait since 1996. Three upward-looking acoustic-Doppler current profilers (UL-ADCPs, in shielded housings to guard against trawlers), one inverted echo sounder and pressure sensor (PIES), and a thermistor chain were deployed at the sill between September 1999 and February 2000. Three ADCPs and two PIES were present for July 2000–May 2001 and two ADCPs and a PIES were there for July 2001–August 2002. One ADCP and one PIES were deployed between August 2002 and August 2003. Since that time a single bottom-mounted ADCP mooring at the deepest part of the sill has been present, operated by the Icelandic Marine Research Institute (MRI) as part of ASOF-EC(W). In addition, three high resolution ship-based surveys of the Strait and northern Irminger Sea were made in June–July 1997, September–October 1998 and July 2000 (including CTD, XCP, XCTD, VMADCP and LADCP observations). Future funding for measurements at Denmark Strait is not secure at this time.

- Faroe Bank Overflow, Wyville-Thompson Ridge, and Iceland-Faroe Ridge moorings. The ASOF-EC(E) project MOEN includes a work package to measure the dense overflows through the Faroe-Bank Channel and across the Wyville-Thompson Ridge (see http://www.-bjerknes.uib.no/research/MOEN/index.html). Upward-looking ADCP measurements of the Faroe-Bank Channel outflow - a more or less 2-layer system where outflow current

speeds typically exceed 1 ms^{-1} - have been made continuously since November 1995. A single instrument at the sill has been present at nearly all times while two brief experiments with an additional T, current instrument on either side and a central thermistor chain have also occurred. Ship-based CTD sections are also performed every three months. Two UL-ADCPs have been deployed in Wyville-Thompson Ridge since 2003. Two UL-ADCPs are to be deployed at various locations along the Iceland-Faroe Ridge for periods of about 6 months. Again, shallow UL-ADCPs are in trawl-hardened housings.

The MOEN project is funded until December 2005 and proposals to continue the observations are pending at the EC. See ASOF Task 4 and the ASOF ISSG reports for more details (*ASOF ISSG*, 2002, 2003).

In combination, these mooring arrays make an excellent network for monitoring dense overflows into the subpolar Atlantic. The long-term funding outlook for these mooring sites is unclear, however. If the mooring time-series are to continue beyond summer 2005 prompt action is needed to secure the necessary ship-time and resources. Also, note that a substantial part of the freshwater flux across the Greenland/Scotland Ridge is carried by the shelf currents off the wide Greenland continental shelf west of Denmark Strait. No direct measurements of this flux is underway or planned to our knowledge (although see section 4.1). This is a potentially serious shortcoming because significant shelf/basin exchange occurs downstream of Denmark Strait, but upstream of the ASOF-EC(W) shelf moorings at 63°N.

3.1.2 Iceland Basin

The dense overflows from the Nordic Seas rapidly sink below the ridge crest of the Reykjanes Ridge and are thus split into two components: one in the Iceland Basin to the east and one in the Irminger Sea to the west. The flow in the Iceland Basin is fed from the Faroe Bank Channel, the Wyville-Thompson Ridge, and the Iceland-Faroe Ridge which collectively form Iceland-Scotland Overflow Water (ISOW). Projects to measure ISOW in the Iceland Basin include SFB460 Subproject A3:

- Charlie-Gibbs Fracture Zone (CGFZ) moorings. Current meter mooring array at CGFZ (52°N, 30°W) were operated between June 1997 – July 1998 (at 3 sites) and June 1999 – July 2000 (at 4 sites). In addition, a mooring array on the eastern side of the Mid-Atlantic Ridge, south of CGFZ (at about 51.5°N) was deployed between July 1998 and June 1999 (at 4 sites) to monitor ISOW flow south.

- Reykjanes Ridge moorings. Current meter moorings on the eastern flank of the Reykjanes Ridge at 60°N, 20°W were operated between July 2000 and August 2002 (at 2 sites).

During deployment and recovery of these instruments detailed ship-based hydrographic transects were taken on 5 separate cruises. A RAFOS and APEX float program to study spreading of Labrador Sea Water in the Iceland Basin was also an important part of this project.

SFB460 Subproject A3 finished in 2003 and there are no known plans to reoccupy its mooring sites. This is an important gap in the ASOF observing array in the subpolar Atlantic because without measurements at CGFZ it is very hard to connect the Task 4 Faroe-Bank overflow measurements with changes in overflow waters in the western basins. Monitoring ISOW transfer through the Mid-Atlantic Ridge is a priority for Task 5.

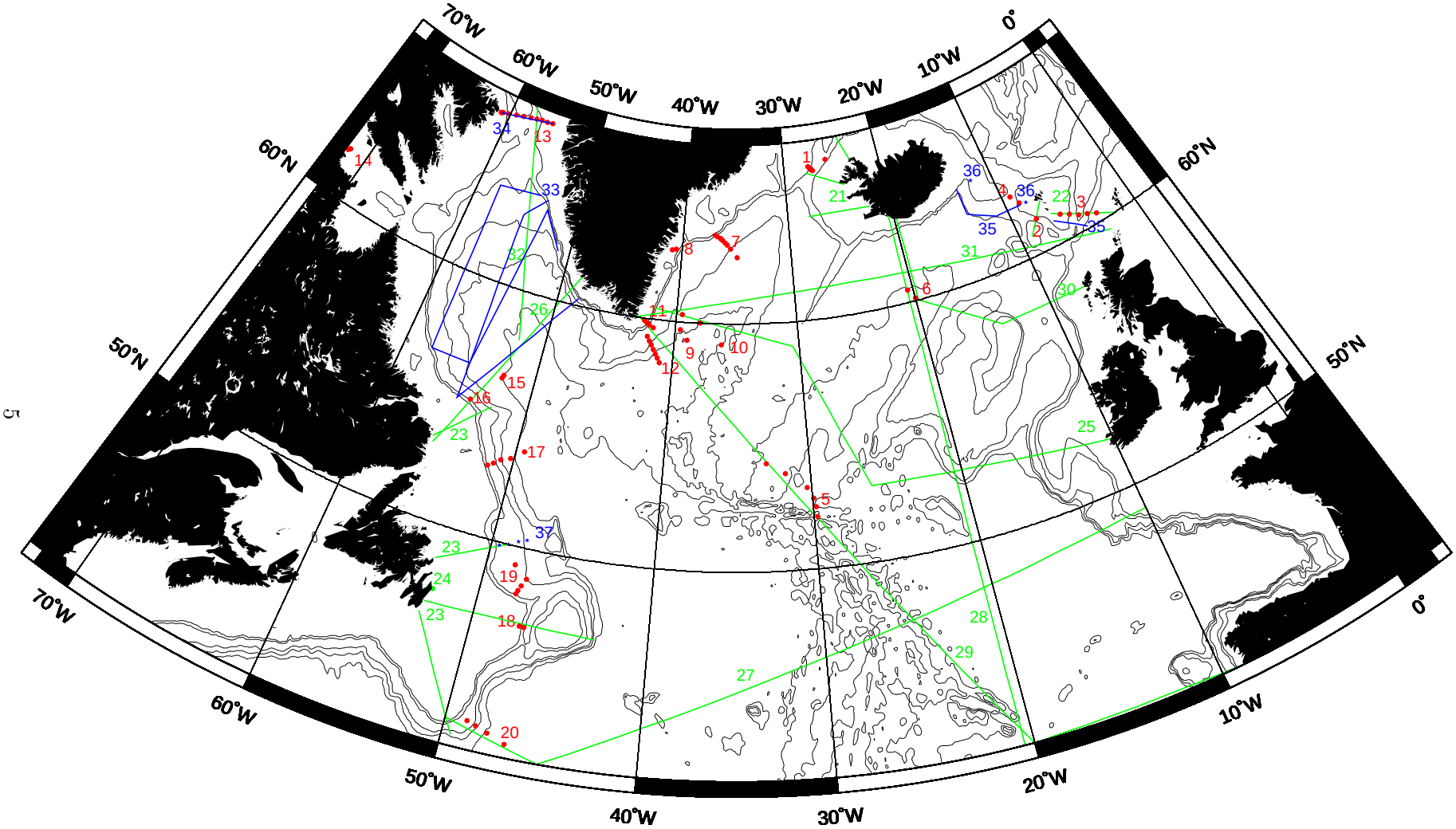

Figure 1: Map of fieldwork relevant to ASOF Task 5. See Table 1 for details on each numbered project. The 500, 1000, 2500, 3000, and 3500 m contours are shown.

Table 1. ASOF Task 5 relevant Observations in the North Atlantic Sub-polar gyre. See also Figures 1, 2, 3, and section 3.

ID	PI	Location	Lat	Long	Duration	Description
Fixed-Point Time Series: Moorings (section 3.1)						
Greenland/Scotland Ridge (section 3.1.1)						
1	Jonsson/Send	Denmark Strait	66-66.5N	22.5-27.5W	1997—2005	SFB460, A1: UL-ADCP, PIES, Thermistor chain plus 3 dedicated high-resolution ship-based T, S, and velocity surveys.
2	Osterhus/Hansen	Faroe Bank Overflow	61.5N	8.25W	1995—2005	ASOF EC-E (MOEN): 1 UL-ADCP
3	Osterhus/Hansen	Wyville-Thompson Ridge	59.5N	7W	2003--2005	ASOF EC-E (MOEN): 2 UL-ADCPs
4	Osterhus/Hansen	Iceland-Faroe Ridge	62.5N	9W	2003--2005	ASOF EC-E (MOEN): 2 UL-ADCPs will be placed at various sites for 6—8 month periods.
Iceland Basin (section 3.1.2)						
5	Zenk	Charlie-Gibbs Fracture Zone	52—54N	30-34W	1997—2000	SFB460, A3. T, S, current (4 sites)
6	Zenk	Reykjanes Ridge	60N	20W	2000—2002	SFB460, A3. T, S, current (2 sites)
Irminger Sea (section 3.1.3)						
7	Dickson/Meincke/FIMR	SE Greenland	63-63.5N	35.5-36.8W	1987 – 2006	ASOF EC-W: DSOW Current meters, T, S (8 moorings plus 1 HOMER)
8	Dickson/Meincke	SE Greenland	62.8N	40-41W	2003—2006	ASOF EC-W: EGC Current meters, T, S (3 tube moorings, 2 UL-ADCP).
8	Watson	SE Greenland	63N	36W	2004—2007	RAPID AquaMonitor transient tracer timeseries.
9	Pickart	S Irminger Sea	59.5-60N	38.5, 41W	2002—2004	Profiling T, S, UL-ADCP (2 sites)
9	Pickart	S Irminger Sea	60N	40W	2004 – 2009	Ultramoor. Profiling T, S.
10	van Aken	S Irminger Sea	59.5N	39, 36W	2003—2008	LOCO: Profiling T, S, current (2 sites)
9	Send	S Irminger Sea	59.7N	39.6W	21Aug02—7Feb03; 28Aug03—??	ANIMATE CIS T, S, current.
11	Lherminier/Mercier	S Irminger Sea	59.5-60N	42-43W	2004—2006	OVIDE: Current meters, T, S (5 sites).
12	Bacon	S Irminger Sea	59N	41W	2005—2007	RAPID CFER DWBC array: Current meters, T, S (5 sites), Profiling T, S
Labrador Sea (section 3.1.4)						
13	Lee	Davis Strait	66.6N	55-60W	2004—2007	ASOF W: Mid-strait: 6 sub-surface moorings (ULS, UL-ADCP, T, S); Greenland shelf: 2 UL-ADCP, 2 bottom T, S; Baffin slope: 1 UL-ADCP, 3 bottom T, S.
14	Straneo/Saucier/Pickart	Hudson Strait	62N	71W	Pending	3 moorings with T, S, UL-ADCP, ULS.
15	Clarke	OWS BRAVO	56.45N	52.30W	1960—2003, pending	T, S, profiles. Some currents.
15	Send	OWS BRAVO	56.33N	52.40W	1996—2002, pending	SFB460, A2: T, S, ADCP, acoustic tomography.
16	Clarke	Labrador Slope	55N	54W	1977—2003, pending	SLOPE; mooring (T, S, current?). No data 1990—1995.
17	Fischer	Labrador Sea Export	53N	51W	1997—2005	SFB460, A4: T, S, current meters (5 sites)
18	Loder	Flemish Pass	47N	47W	Nov2002—2005	Current moorings (2 sites).
19	Loder	Orphan Basin	48.5N	47.5W	Nov2002—2005	Current moorings (5 sites).
20	Schott	NADW Export	43N	49W	1999—2005	SFB460, A4: T, S, current meters (4 sites)
Fixed-Point Time Series: Ship-based (section 3.2)						
21	Jonsson/Valdimarsson	Icelandic shelf			1970--	Quarterly sections Flaxafloi, Latrabjarg, Kogur; T, S.
22	Hansen	Faroe Bank			?	Quarterly sections?
23	Therriaul/Clarke	Canadian shore to 3000m			1999--	AZMP: 7 bi-annual sections: T, S, nutrients.
24	Therriaul/Clarke	Near Canadian coast			1999--	AZMP Station 27: twice-monthly T, S, nutrients.
25	Bersch/van Aken	A01E; Greenland to Ireland			1990—2005	1990—2003, except 1993, 1998, 2000; T, S, VM-ADCP, some tracers.
26	Clarke	A01W; Labrador to Greenland			1990—2004	1990-- 2003; T. S. VM-ADCP, some tracers
27	Koltermann	A02; UK to Newfoundland	48N		1993—2004	1993—2003, except 1995, 2001, T. S. VM-ADCP, some tracers
28	(US PI)	A16N; Iceland south		20W	1988—2005	1988, 1989, 1993, 1997, 2003; T. S. VM-ADCP, some tracers
29	Mercier	A25; Iberia to Greenland			1997—2010	OVIDE: 1997, 2002, 2004; T, S, VM-ADCP, nutrients, CFCs, carbon, stable isotopes.
30	Holliday	UK to Iceland			1996—2005	1996—2003, T, S, VM-ADCP.
31	Rossby/Reverdin	AX01: Denmark to W Greenland	60N		1999--	Sections of: XBT, VM-ADCP, TSG, nutrients, CO2 every 3 weeks Apr- Jan.
32	Carmack/Shimada	Labrador Sea to Lancaster Sound			2001--	2001, 2002, 2003; XCTD
Lagrangian Instruments (section 3.3)						
33	Rhines/Eriksen	Labrador Sea	64N	54W	2Oct03—9Feb04; Oct04—May05	2 SeaGliders, T, S launched near Nuuk.
34	Lee	Davis Strait	66.6N	55-60W	2005—2007 (?)	ASOF W: 2 SeaGliders T, S, oxy.
35	Eriksen/Rhines	Iceland Faroe Ridge & Faroe-Shetland channel			Pending	2 SeaGliders, T, S to be launched from Torshavn for 6 month missions.
36	Rossby	Iceland Faroe Ridge			Sep04—Sep06	26 RAFOS floats at 200m SE of Iceland and 26 SW of Faroes, deployed in groups of 6 every 3 months.
37	Bower/Lozier	Newfoundland Basin	50N	49W	Jul03—2006	Export Pathways project. 72 RAFOS floats at 700 & 1500m on AZMP Bonavista line, deployed seasonally.
	Argo floats	Subpolar Atlantic				
Miscellaneous (section 3.4)						
Remote sensing						
	TOPEX/POSEIDON		to 66N		1992--	Altimetry
	Jason-1		to 66N		2001--	Altimetry
	ERS				??	Altimetry
	Pathfinder (AVHRR)				1985--	SST
	ERS2, ENVISAT (ATSR)				1995—1999, 2002--	SST
	TRMM				1997--	SST through clouds.
	NSCAT, QuikScat				1996—1997, 1999-	Windstress at 30km resolution.
	Radarsat, Envisat				1995--	Windstress at 1—100km resolution.
	AQUARIUS				2008—2011	SSS
	SSMI					
	AMSR					
	CryoSat					
Meteorological Products						
	NCEP/NCAR Renalysis					
	ERA-40, ERA-15					

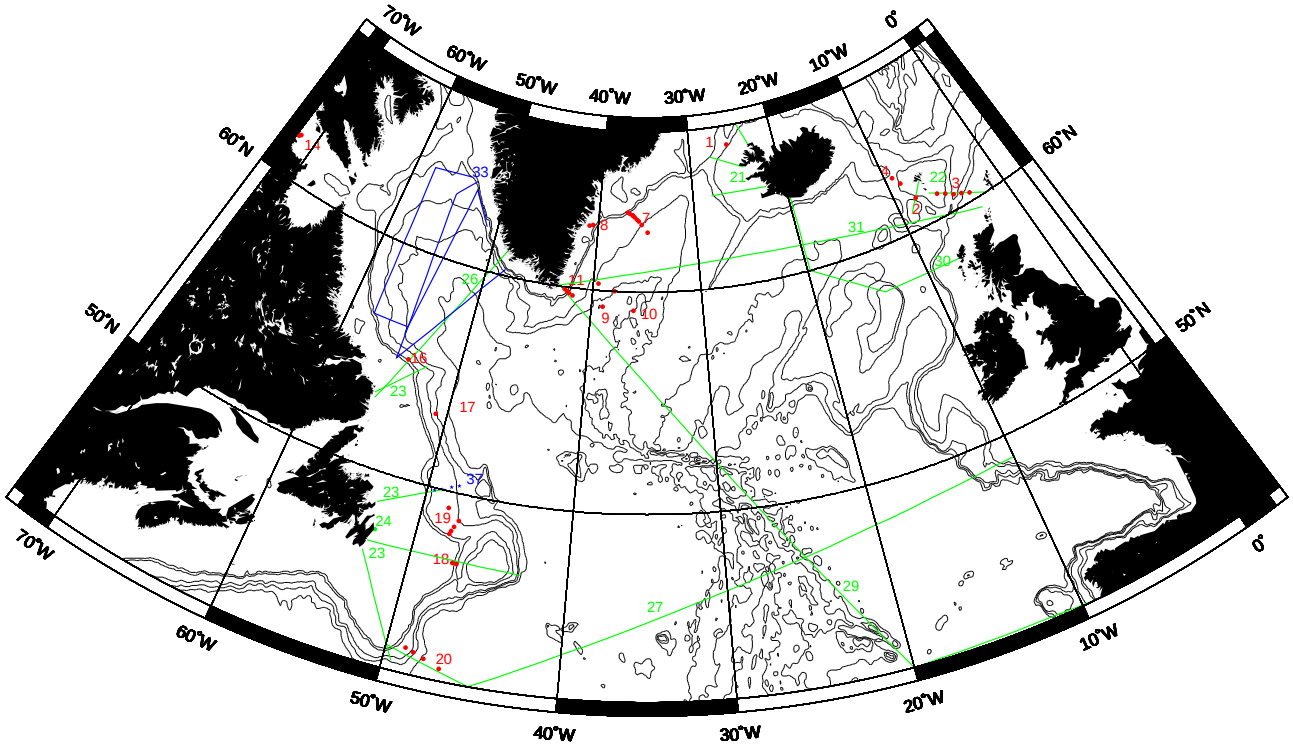

Figure 2: Fieldwork from Fig. 1 for, nominally, August 2003 to August 2004.

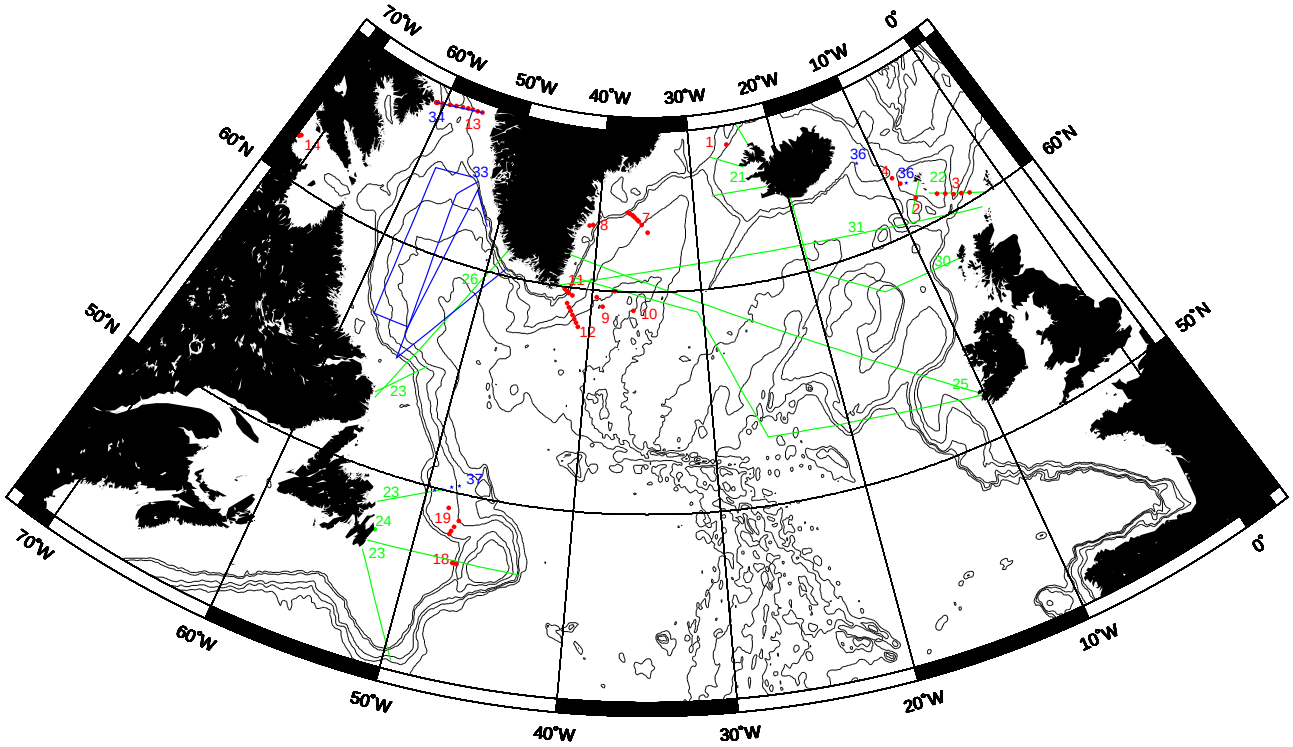

Figure 3: Anticipated fieldwork from Fig. 1 for, nominally, August 2004 to August 2005.

3.1.3 Irminger Sea

The principal southward flux occurs west of Iceland in the Denmark Strait Overflow (DSOW) and East Greenland Current (EGC). Measuring, and understanding, these currents on the east Greenland shelf and in the Irminger Sea is critically important. Several projects contribute to these goals:

- Southeast Greenland Denmark Strait Overflow moorings. Current meter moorings on the continental slope at 63°N have been monitoring DSOW more or less continuously since 1987. The present array consists of 8 current meter moorings with microcat temperature (T) and salinity (S) probes. An undulating HOMER CTD instrument has also been deployed to monitor the bottom 400m. This array lies in 1250–2750m water depth and is focussed on DSOW in the bottom few hundred meters. It is supported until 2006 under the ASOF-EC(W) program. There are also plans under UK's RAPID program to deploy a bottom-mounted Aquamonitor moored water sampler immediately inshore of mooring CEFAS UK1 at 2000 m in 2004. The water samples will be analyzed for CFCs, SF_6, $\delta^{18}O$, ^{129}I, and nutrients yielding weekly records for 2004–2007. This project is part of the ASOF-EC(W) program and is funded until the end of 2005. Proposals for continuation are pending at the EC.

- Southeast Greenland East Greenland Current moorings. Recently, a mooring array has been established on the shelf in 300m water at 63°N. To avoid damage from floating ice, a novel TUBE mooring has been used. It allows the mooring to be knocked down by ice without being destroyed and yields measurements within 30m of the surface. The moorings have current meter and microcat T and S probes. Deployment of two bottom-mounted UL-ADCPs is scheduled for 2004, plus another TUBE mooring inshore. This project is part of the ASOF-EC(W) program.

- South Irminger Sea moorings. Several independent groups have deployed moorings in the southern Irminger Sea. These instruments lie mainly along the A01E (also called AR7E) or A25 WOCE hydrographic lines approaching Greenland. Specifically,

  - Woods Hole Oceanographic Institution (WHOI) has deployed an ULTRAMOOR profiling CTD mooring in July 2004. This instrument should provide daily coverage of the upper 1500m until 2009. Data recovery is annual. This instrument extends the records of two close profiling CTD moorings with ADCP current observations for 2002–2004. These moorings focus on the upper 1500m.
  - WHOI has deployed a meteorological buoy in July 2004. This instrument should provide real-time data on the marine boundary layer and hence air/sea heat, freshwater, and momentum fluxes. It is designed to survive at least one winter.
  - The EU ANIMATE project maintains a mooring in the central Irminger Sea with current, T, and S measurements. The project is funded for 2001–2004.
  - The Dutch LOCO project has deployed two moored profilers in summer 2003 in the southern Irminger Sea. These will measure T, S, and current in the upper ocean until 2008.
  - The French OVIDE project has deployed 5 current meter moorings on the slope and shelf off Cape Farewell in June 2004. They will operate until 2006 (1 will be recovered in 2005).

- The UK RAPID CFER project plans to deploy 6 moorings on the continental rise and slope to measure DSOW current, T, and S off Cape Farewell. The anticipated duration is mid 2005 to mid 2006, with a possible extension for another year.

Overall, the network of stations monitoring the EGC and DSOW in the Irminger Sea is very good. Coordination and collaboration between the groups involved is essential to avoid unnecessary duplication of effort, however. This job is naturally handled by ASOF Task 5 and several of the PIs are members of the committee. Finally, it is important that exchange between the waters of the deep Irminger Sea and the East Greenland Shelf is not covered by this observing array. In fact, it appears that a substantial part of the Arctic freshwater export crosses the Greenland/Iceland Ridge on the Greenland shelf to be injected offshore before reaching Cape Farewell. Measuring and understanding this process is a challenge not to be overlooked. See section 4 below for details.

3.1.4 Labrador Sea and Newfoundland Slope

The Labrador Sea is, arguably, the most important place in the western subpolar Atlantic for ASOF Task 5. Here, the two branches of the Arctic outflows converge and mingle: the Greenland-Scotland overflows from the east and the Canadian Archipelago Throughflow from the west. Intense air/sea interaction also forms the densest and greatest of Atlantic subpolar mode waters, the Labrador Sea Water (LSW). The interaction between these water classes creates North Atlantic Deep Water (NADW) which forms the cold limb of the meridional overturning circulation in the Atlantic sector. With its properties set in the Labrador Sea, NADW leaves the subpolar Atlantic along the Newfoundland Slope passing Flemish Cap and Grand Banks. Its subsequent path through the abyssal ocean is relatively quiescent, lasting decades and stretching tens of thousands of kilometers, before being finally mixed away.

The projects most relevant to Task 5 in this area are:

- Davis Strait. The flow between Baffin Bay and Labrador Sea through the wide, deep, Davis Strait will be monitored by the University of Washington and the Bedford Institute of Oceanography (BIO) as part of the "High Resolution, Year-round Measurements of Volume, Freshwater, and Ice Flux Variability in Davis Strait" project. The array was deployed in October 2004 and will be maintained until autumn 2007 (Figure 4). It will consist of six subsurface moorings in the deep part of the strait (instrumented with T-C sensors (SBE Microcats), UL-ADCP, upward-looking sonar (ULS) and conventional current meters), four bottom-mounted instruments on the wide Greenland shelf (T, S, UL-ADCP), and four bottom-mounted instruments on the steep, narrow, Baffin Slope (T, S, UL-ADCP). The array also includes six 780 Hz RAFOS sound sources, which provide navigation signals for Seagliders during wintertime operations benneath the ice. Davis Strait glider operations will begin in 2005, with two Seagliders repeatedly occupying the section defined by the moored array to provide enhanced horizontal resolution (5 km) and measurements at the difficult ice-water interface. Hydrographic sections from the 2004 *Knorr* cruise are shown in Figure 5.

- Hudson Strait. WHOI has deployed a T, S, current mooring on the southern side of Hudson Strait in August 2004, where the tidal currents can reach 3 ms^{-1} (K. Falkner, pers. comm.). The mooring is equipped with a UL-ADCP, a McClean T, S profiler, and a ULS mounted on an "Arctic winch" that can profile up to the bottom of the ice 6 times per day. Two Canadian moorings are also nearby with UL-ADCP, T, and S sensors (from

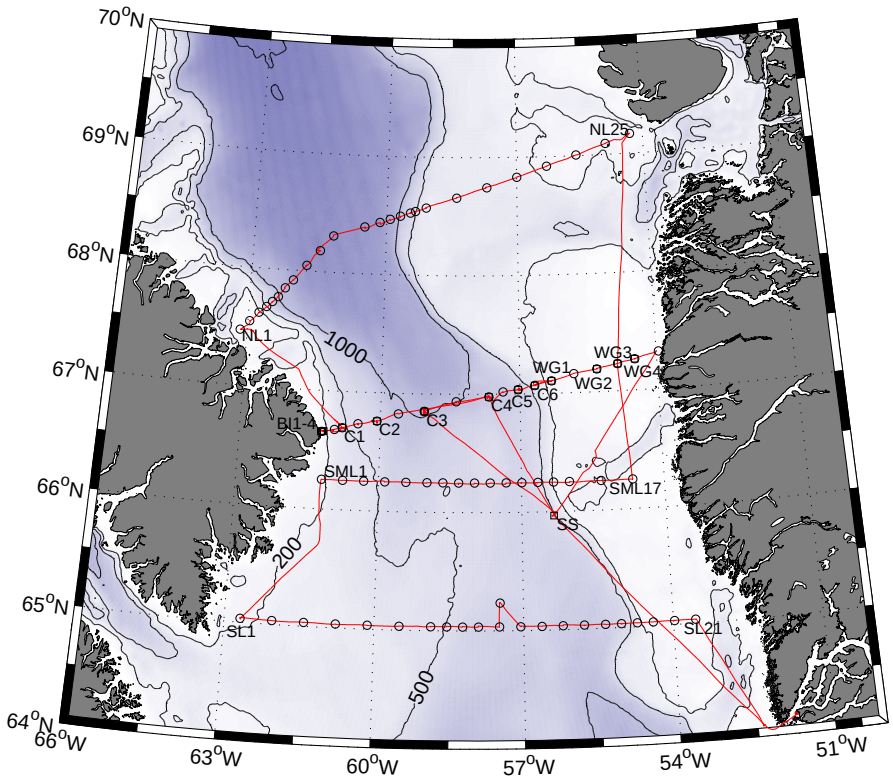

Figure 4: The 2004 R/V *Knorr* cruise track of the "High Resolution, Year-round Measurements of Volume, Freshwater, and Ice Flux Variability in Davis Strait" project. Squares mark six subsurface moorings (C1–C5), four Baffin slope landers (BI1–BI4), four Greenland shelf landers (WG1–WG4) and one off-axis RAFOS source (SS). Two gliders will be deployed in 2005 to make repeated, year-round occupations of the mooring section. Circles mark the locations of hydrograpic profiles conducted during the cruise. Courtesy of Craig Lee (Applied Physics Laboratory, University of Washington) and collaborators.

the Institute Maurice Lamontagne). Funding is insecure beyond summer 2005 for these instruments.

- Central Labrador Sea mooring. A monitoring site in the central Labrador Sea has been maintainted, initially with ship-based meteorological observations and hydrography and recently with moorings, for several decades. Ocean Weather Ship Bravo (OWS Bravo) was operated from the early 1940s until 1974. Since then, research vessels have continued the timeseries. From 1990, the WOCE repeat transect AR7W (also called A01W) through OWS Bravo has been occupied nearly every year (see section 3.2). Sub-surface moorings have also been deployed at various times in the last 15 years.

  Recently, there have been two moorings close to the OWS Bravo site, primarily to observe deep convection and LSW formation:

  - The long-standing Canadian effort at OWS Bravo has recently included a mooring for the period June 2002 – June 2003. There are no long-term plans for BIO to maintain a physics mooring there. Moored instruments to measure particle fluxes will likely be deployed at OWS Bravo in some years, however.
  - SFB460 Subproject A2 has maintained a densely-instrumented (T, S, UL-ADCP,

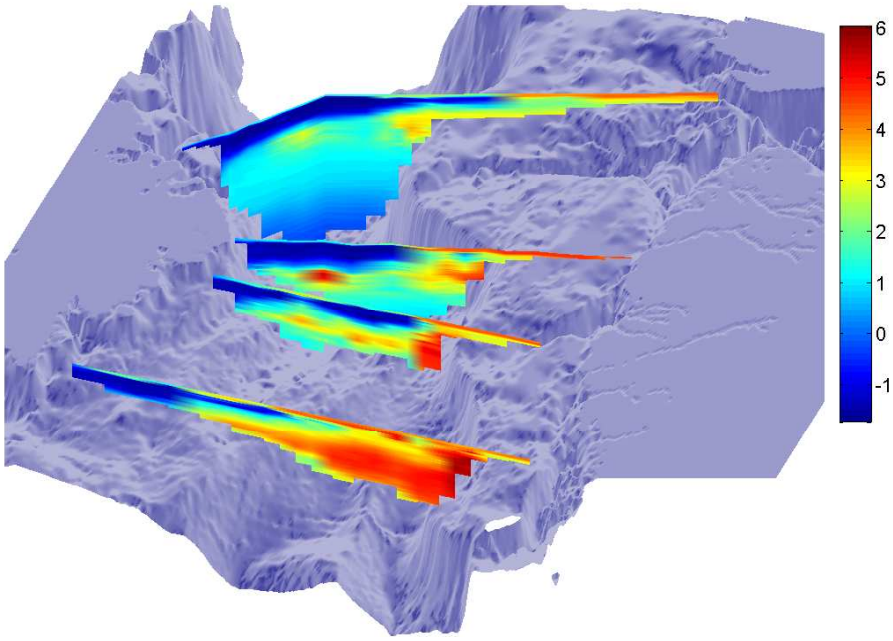

Figure 5: Temperature across the four hydrographic sections shown in Figure 4, looking northward over Davis Strait. The color scale to the right indicates temperature (°C). A layer of cold Arctic water extends from the Baffin coast in a 200 m thick surface layer. Warm Irminger water forms a subsurface layer over the Greenland slope and, in the northern sections, a narrow core over the Baffin slope.

acoustic tomography) mooring at OWS Bravo for the period 1996–2002. Again, a proposal for continuation is pending.

- Labrador Slope. A Canadian T, S, and current mooring was deployed in 1000m water depth off Hamilton Bank between May 1977 and 2003 (with a gap between 1990–1995). Funds for continuation are being sought, although, even if support is found, the mooring may not be re-deployed.

- South Labrador Sea. SFB460 subproject A4 has deployed a current meter array to monitor export from the Labrador Sea for the period 1997–2005. For 1997–1999 5 moorings were present, for 1999–2001 3 moorings were present, although just 2 were recovered, and for 2001–2003 3 moorings were present. There is 1 mooring currently deployed to be recovered in 2005 at the end of the project. Instruments included current meters (traditional and UL-ADCP), and T, S devices. See *Fischer et al.* (2004) for details on the first 2 years' deployment.

- Bedford Institute of Oceanography has deployed 5 current moorings in Orphan Basin (near 48.5°N, 47.5°W). They will operate for the period 2002–2005.

- BIO has also deployed 2 current moorings in Flemish Pass (near 47°N, 47°W) for 2002–2005.

- South Newfoundland Basin. SFB460 subproject A4 has maintained a mooring array off Grand Banks to monitor the export of NADW into the subtropics. It resumes the time-series made by BIO between 1993 and 1995. The array of 4 current meter, and T, S

instruments (including a profiling CTD) was deployed in summer 1999, then serviced in May 2001, and 2003. It will be recovered and removed in summer 2005.

In total, the present fixed-point mooring network in the Labrador Sea is very healthy. The German efforts during SFB460 and the US/Canadian Labrador Sea Project (*The Lab Sea Group*, 1998) in the mid 1990s have laid an exceptional foundation for understanding processes in the Labrador Sea and for monitoring change. That said, neither of these programs focussed on freshwater exclusively nor on long term secular variation. The pending addition of moored arrays at Davis Strait and Hudson Strait goes a long way to addressing this problem.

Of more concern, however, is the uncertain future strength of the moored network in the Labrador Sea. The SFB460 field program is in its final year and the Canadian mooring sites at OWS Bravo and Hamilton Bank are currently unoccupied, pending renewed support. It is critical that at least some parts of the mooring network in the south-east Labrador Sea and Newfoundland continental slope are continued. At this time, only the Davis Strait array has secure funding for in-situ observations beyond summer 2005. Clearly this effort is inadequate to monitor the whole Labrador Basin and Newfoundland Slope. Swift action is needed to avoid substantial disruption to these vital timeseries.

3.2 Fixed Point Time series: Ship Transects

Repeat hydrographic transects from ships is a key component of the Task 5 observing network. In addition to the hydrographic surveys that typically are carried out during deployment and recovery of the moorings listed in section 3.1, the following sections are particularly important:

- Iceland to Greenland section, Faxaflói, Látrabjarg, and Kögur. The Icelandic MRI runs a quarterly series of CTD transects on the Icealandic shelf radiating from Iceland. Of most relevance for Task 5 is the Flaxaflói section which heads west towards Greenland. Látrabjarg at Denmark Strait and Kögur north of the Strait are also relevant. Occasionally, these transects continue in deep water to the ice edge off Greenland.

- Faroe Bank Channel and Faroe Shetland Channel. The Faroese Fisheries Laboratory routinely (quarterly) runs hydrographic sections from the Faroe Islands since 1998. The lines crossing Faroe Bank Channel and Faroe Shetland Channel are most relevant to Task 5 (and Task 4).

- Canadian shore to 3000 m sections. The AZMP program at BIO runs 4 hydrographic sections to the 3000m depth contour every summer which are especially useful to Task 5. They are: Seal Island, Bonavista, Flemish Cap, and Southeast Grand Banks. The program begain in 1999.

- Canadian coastal stations. The AZMP program operates 8 coastal hydrographic stations on a twice-monthly basis. Of these, Station 27 in 180m off Newfoundland is the most useful to ASOF Task 5. The program began in January 1999.

- CLIVAR repeat hydrographic sections. Several WOCE hydrographic transects run through the subpolar Atlantic and will be continued as part of CLIVAR. The most important are:

  - A01E (AR7E) South Greenland to Ireland. Planned to be every 2 years. Funded for 2005.

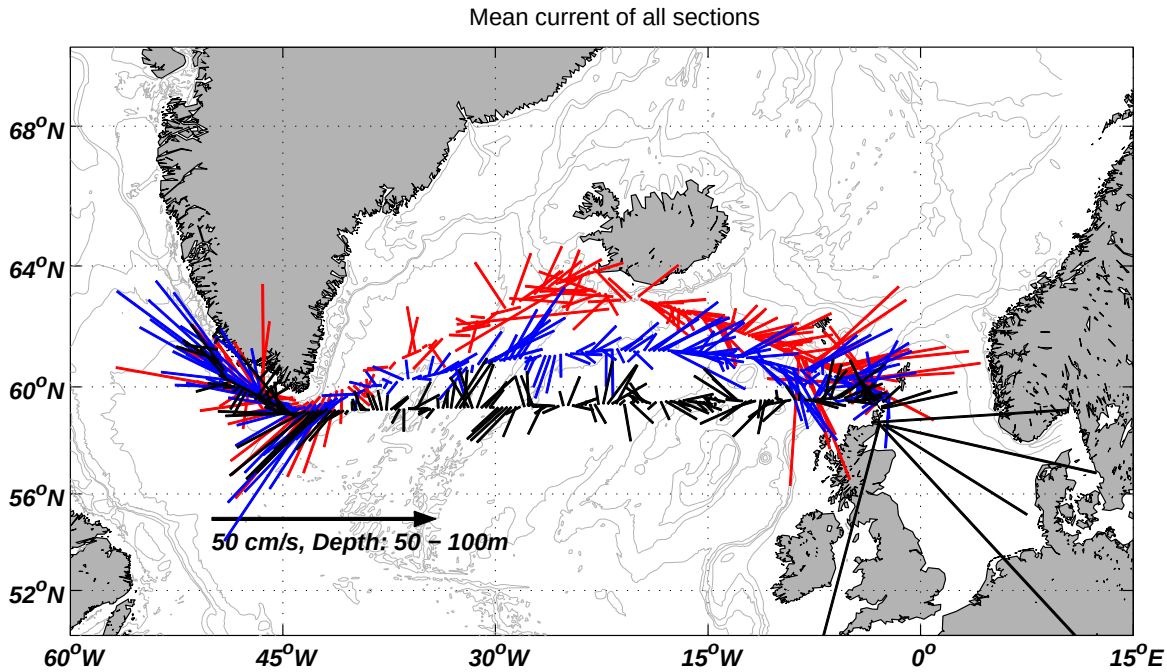

Figure 6: Mean currents at 52–100m from the *Nuka Arctica* ship of opportunity for sections taken between September 1999 and December 2002. There are 20 black transits (13 eastbound, 7 westbound), 13 blue transits (11 westbound, 2 eastbound), and 7 red transits (westbound). Courtesy Tom Rossby (University of Rhode Island) and Øyvind Knutsen (University of Bergen).

  - A01W (AR7W) Labrador to South Greenland. Planned to be every year. Canadian PIs are seeking long-term sustained funding for an annual spring occupation. Partial short-term funding is in place to support the line in May 2005.
  - A02 UK to Newfoundland. Planned to be every 2 years. Last occupied in 2004 with next probable section in 2006, but no secure funding beyond that time.
  - A16N Iceland south. Planned to be every 7 years. Last occupied in 2003.
  - A25 Iberia to South Greenland. Planned to be every 2 years until 2010 (the OVIDE program). Last occupied in 2004.
  - Scotland to Iceland. Planned to be every year (extending the Ellett Line from UK to Rockall which has been occupied several times each year since 1975: see http://www.soc.soton.ac.uk/GDD/hydro/nph/ellett/index.php). Funded until 2005.

- Denmark to West Greenland section, AX01. The container vessel *Nuka Arctica* operates between Denmark and West Greenland every 3 weeks for 9 months of the year, starting in April (Figure 6). The ice-strenghtened ship is equipped with a vessel-mounted ADCP (VMADCP), thermosalinograph for surface T, S, and instruments to measure nutrients and CO_2. There are some expendable bathythermograph (XBT) releases too. The program began in late 1999.

- Labrador Sea to Lancaster Sound section. XCTDs have been deployed from Canadian coast guard vessels under way from Labrador Sea through Davis Strait since 2001. Other vessels in transit to the Canadian Archipelago also have some data (e.g., VMADCP, surface hydrography from K. Falkner's cruises to Nares Strait).

These projects make a substantial contribution to Task 5. The MRI and AZMP fisheries surveys in shallow water have good time resolution, while the trans-ocean basin sections have excellent spatial resolution and full-depth coverage. The *Nuka Arctica* program has the advantage of very high frequency upper ocean velocity measurements, while the Canadian coast guard XCTD program gives access to some rarely sampled areas.

Commitment to sample the shelf-break jet systems at high resolution off Greenland and Labrador will greatly enhance the value of the CLIVAR repeat hydrographic transect. Sampling in sea ice fields is also of great benefit, whenever possible. It is an important priority that AR7W is occupied annually and adequate long-term support needs to be secured.

3.3 Lagrangian Instruments

Lagrangian instruments make an important contribution to monitoring the stratification and circulation in the western subpolar Atlantic. Of particular significance are:

- Labrador Sea SeaGliders. Two SeaGliders were deployed from Nuuk, Greenland (64°N, 54°W) in October 2003 (Figure 7). The instruments navigated south through the central Labrador Sea making daily T, S, profiles to 1000m with horizontal resolution of about 3 km. They were both lost in February 2004 after more than 1500 profiles in total. A software fault has been identified as the cause of the instrument loss (1 instrument washed ashore at Disko Island, Greenland, and has been returned to the University of Washington by the local police). Two new instruments will be deployed, again from Nuuk, in October 2004 for a 6 month mission. The intention is to retrieve and service them in May 2005 then redeploy, again for 6 months. SeaGliders are described in detail at: http://www.apl.washington.edu/projects/seaglider/summary.html.

- Davis Strait Seagliders. As part of the Davis Strait project, two Seagliders will operate along the moored array as described in section 3.1.4. Beginning in autumn 2005, they will provide year-round, full-depth T, S, and dissolved oxygen coverage north of the sill. The Applied Physics Laboratory, University of Washington, is developing a RAFOS-based navigation system and other glider enhancements to allow extended deployments beneath full ice cover. If successful, these systems could be employed in other environments where seasonal or permanant ice cover hinder direct measurements.

- Iceland/Faroe Ridge and Faroe-Shetland Channel SeaGliders. A proposal is pending to support SeaGlider operations along the Iceland/Scotland Ridge, staging out of Torshavn, Faroe Islands. If successful, two instruments will be supported for 6 month missions to begin operations in 2005.

- Iceland/Faroe Ridge RAFOS floats. A program is underway to deploy isobaric RAFOS floats along the Iceland/Faroe Ridge. The floats will circulate at 200m depth measuring T, S, and displacement. They will be deployed in groups of 6 every 3 months from both SE of Iceland and SW of Faroe starting in Fall 2004. A total of 52 floats will be released, and the project will end in September 2006.

- Newfoundland Basin RAFOS floats. The Export Pathways from the Subpolar North Atlantic project will deploy 72 RAFOS floats between July 2003 and May 2006 at the end of the AZMP Bonavista line (50°N, 49°W). Deployments will be, nominally, every 3 months. The floats will circulate at 700m and 1500m for 2 year missions.

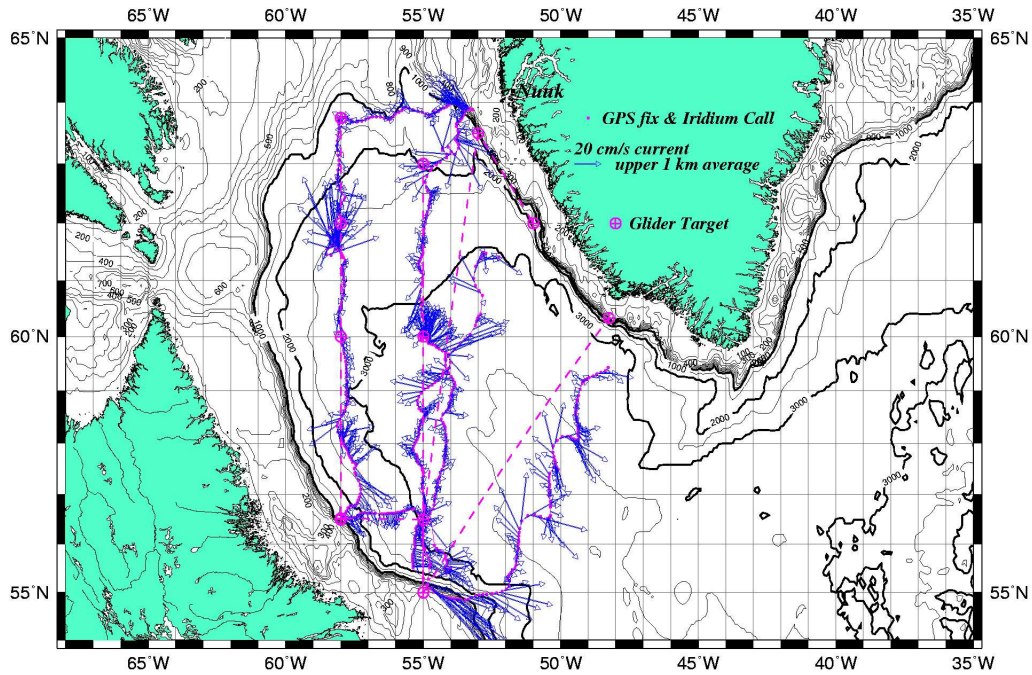

Figure 7: SeaGlider missions in the Labrador Sea, 2Oct2003 – 9Feb04. Two SeaGliders were launched from a small charter boat near Nuuk, Greenland and followed the tracks shown with daily CTD profiles to 1000m depth. Arrows show upper-1km-average currents which are accurate to O(1) cms^{-1} and may provide a reliable reference level for thermal wind calculations. Courtesy Charlie Eriksen and Peter Rhines (University of Washington).

- ARGO floats. The ARGO profiling drifter program will contribute to Task 5 by providing basic circulation and stratification information about the gyre interiors. There are typically 20–50 floats in the subpolar Atlantic at any given time. The program is described in detail elsewhere (e.g., at http://www-argo.ucsd.edu/).

Lagrangian instruments will make a valuable contribution to Task 5. SeaGliders yield hydrographic and displacement information in real time and can be remotely guided along a survey pattern, also in real time. The opportunity to monitor boundary current systems at high resolution in both space and time is unprecedented. Note that SeaGliders are most efficiently deployed and recovered from small boats. This makes reliable access to the east Greenland shelf and slope difficult without a large vessel or much greater risk of instrument loss. The RAFOS float programs will also likely yield interesting information about exchange across the Iceland/Scotland Ridge and LSW export pathways round Grand Banks. Other instumental technologies are poorly suited to address these questions. Overall, this collection of projects is in very good health and is reasonably well funded at this time.

3.4 Miscellaneous

In-situ oceanographic measurements are of most use to Task 5, but remote-sensing and meteorological reanalyses are also valuable (e.g., *Häkkinen and Rhines* (2004)). For data assimilation projects they are especially important (see section 5, for example). In particular, observations of the following parameters are relevant:

- Sea-surface height. TOPEX/POSEIDON and JASON altimetry data are of highest quality

but coverage ends near the Arctic circle. ERS altimeters extend further north. Altimetry retrieval algorithms tend to be unreliable in coastal seas and if sea ice is present.

- Sea-surface temperature. AVHRR, ATSR, and TRMM instruments give surface temperature data. Highest resolution data are only available in cloud-free skies (uncommon in the western subpolar Atlantic). Some lower resolution data are available through all but precipitating clouds.

- Sea-surface salinity. The AQUARIUS mission will measure sea-surface salinity with around 0.2pss accuracy. This is certainly adequate for the large salinity contrasts in the East Greenland, West Greenland, and Labrador Currents, although instrument sensitivity degrades as sea surface temperature falls. The instrument is scheduled to operate for 2008–2011 giving global coverage every 8–9 days.

- Sea-level wind. Scatterometer wind observations from QuikScat, NSCAT, and Synthetic Aperture Radars (Radarsat, Envisat) are valuable to resolve the small-scale atmospheric features in the Task 5 area.

- Sea ice concentration and extent. Several instruments are useful including: passive microwave sensors (SMMR, SSM/I, and AMSR), plus the optical imaging Landsat, and Radarsat satellites.

Atmospheric reanalysis products are also important, such as the NCEP/NCAR and ECMWF products. Significant errors in these syntheses have been identified for the subpolar Atlantic, however (*Renfrew et al.*, 2002). Improved climatologies based on the meteorological reanalysis data are now available (e.g., *Large and Yeager* (2004); *Taylor* (2000)), but they still exclude atmospheric processes on scales less than 100 km that cause intense air/sea interaction in this area. Success has been demonstrated with high-resolution regional atmospheric forecast models (*Pagowski and Moore*, 2001), but they are not routinely available. Satisfactory calibration of satellite retreivals at high wavenumbers and frequencies is also a significant obstacle for the Task 5 area. Dedicated efforts involving in-situ meteorological observations from buoys and research aircraft are needed. See also section 4.3.

4 Processes in the Subpolar Gyre

Understanding the processes that transfer and modify south-bound Arctic freshwater anomalies in the subpolar Atlantic is an essential objective of the Task 5 working group. Many of these processes occur throughout the world's high latitude oceans but they are often poorly understood and absent from current climate change models. A comprehensive attack on all the germane processes is obviously beyond our scope. Instead, we highlight here three interesting topics that are developing rapidly.

4.1 Freshwater exchange between the East Greenland Shelf and the Irminger Sea

A disproportionate part of the freshwater leaving the Nordic Seas for the subpolar Atlantic ocean occurs on the East Greenland continental shelf. The key phenomena include narrow, rapid jets, steered by bathymetry; sea ice formation, melting, and transport; and, intense air-sea interaction. None of these processes are understood in detail, and some are barely known

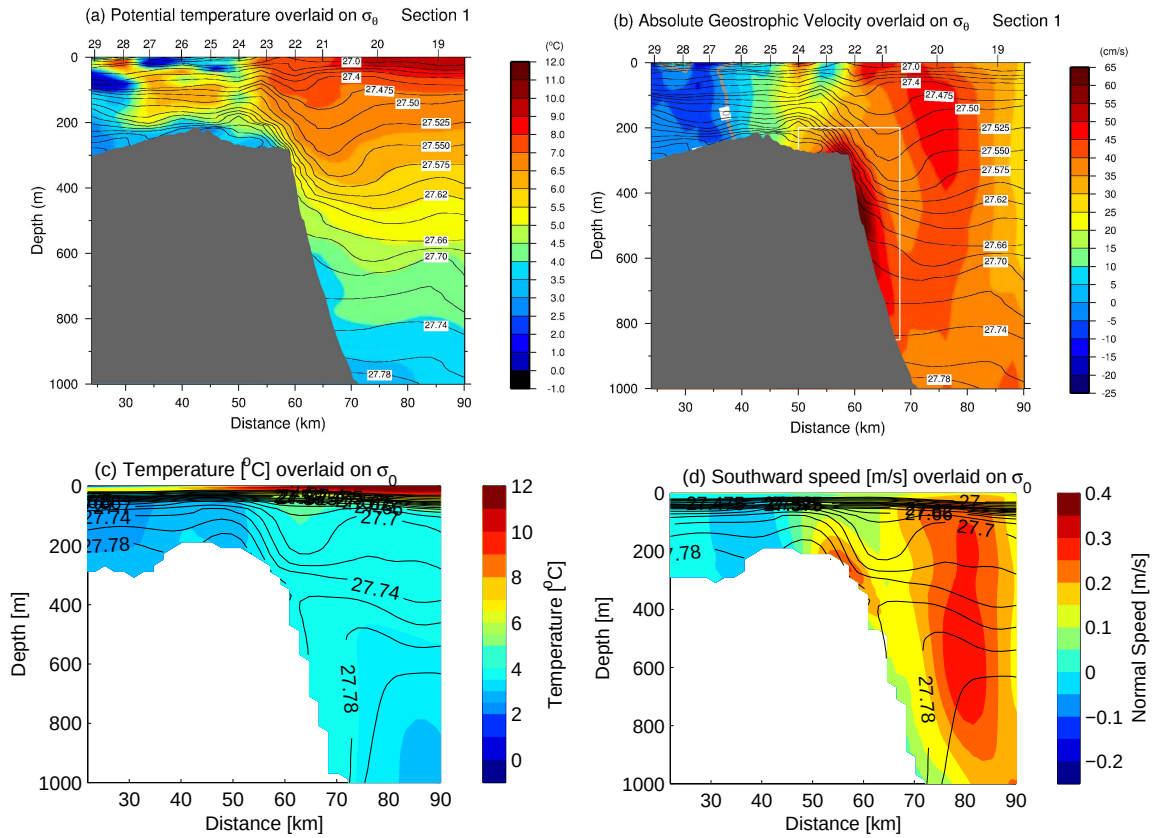

Figure 8: In-situ observations and numerical model results of the East Greenland Spill Jet. (a) Temperature (°C) overlaid on σ_0, and, (b) southward geostrophic current speed (m s^{-1}) overlaid on σ_0 for *Oceanus* 369 section 1 across the east Greenland shelf at 65°N in August 2001 (*Pickart et al.*, 2004). (c) Temperature (°C) overlaid on σ_0, and, (b) southward current speed (m s^{-1}) overlaid on σ_0 for the same section through the 1.75km, 97 level numerical circulation model developed by Tom Haine (Johns Hopkins University), nominally for 11 August 1999.

at all. Nevertheless, they seem to play a leading role in the freshwater balance of the western subpolar Atlantic, and, hence, in the variability and stability of the Atlantic MOC.

Access to study these processes year-round with moorings is difficult due to ice conditions and fishing pressure. Recently, an ice-immune mooring array has been deployed on the shelf at 63°N - near it's narrowest point on the East Greenland coast (UK/German/Finnish array, section 3.1.3). These measurements can be combined with the Denmark Strait Overflow observations: at 63°N and at Denmark Strait itself (if the timeseries started under SFB460 persists beyond 2005). The freshwater picture that will emerge will be valuable but it will neglect any shelf-basin exchange between Denmark Strait and 63°N. Yet between these two places the shelf narrows by a factor of 2 or 3, and exchange of mass and properties seems to be occurring all along the shelf break. Indeed, recent observations of the so-called East Greenland Spill Jet show that export of shelf water into the deep Irminger Sea is active and intense in this area (*Pickart et al.*, 2004). For example, Figure 8 shows data taken in August 2001 at the shelf break near 65°N (see *Pickart et al.* (2004) for details). The very-high resolution CTD and VM-ADCP survey resolves both the Irminger Current (surface-intensified, centered around a distance of 75km) and the spill jet (bottom-trapped at around 60km). The spill jet is very narrow (less than 10km wide) and fast (greater than 50cm/s), carrying 2Sv equatorward. It appears to be actively entraining

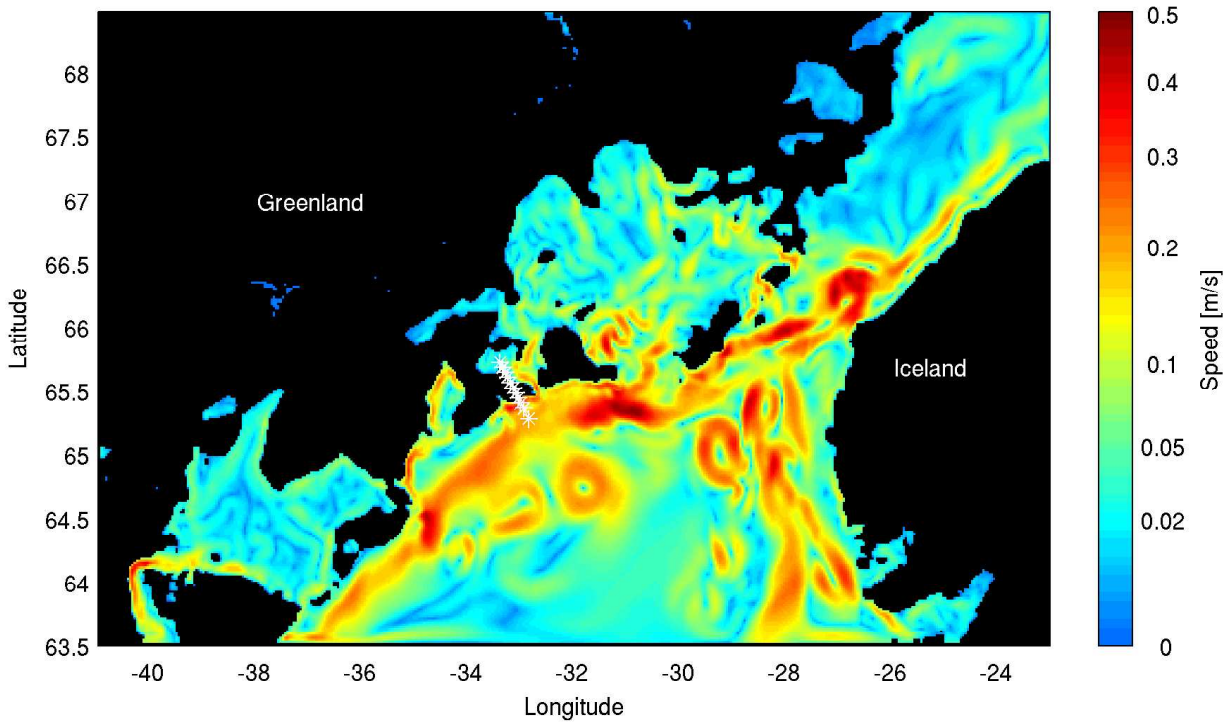

Figure 9: Numerical model results of the flow speed (ms^{-1}) at 330 m, nominally on 29 August 1999 (see section 4.1). The main Denmark Strait throughflow is clear, as is the Irminger Current, although both features are distorted substantially by eddies. The *Oceanus* 369 stations shown in Figure 8 are indicated by white stars. The spill jet is present at this time too, visible as a boundary intensified jet. It appears to be part of a current draining the Kangerdlugsuak fjord (the deep depression in the shelf centered at 31°W, 66.5°N). There exist other similar intense narrow shelf break currents at various places downstream of Denmark Strait.

ambient water at the time of the survey, based on Richardson number estimates (*Pickart et al.*, 2004). It is likely that the spill jet is responsible for substantial off-shelf freshwater flux, and is a ubiquitous part of the circulation there. Indeed, the feature has been seen on several other high-resolution transects at different locations along the East Greenland slope, and in different years.

Figure 8 also shows results from a very-high resolution regional circulation model of the northern Irminger Sea and Denmark Strait (courtesy of Tom Haine, Johns Hopkins University). The model has horizontal resolution of 1.75km with 97 vertical levels and 6-hourly air/sea forcing. The model thermocline is too shallow compared with the field data, probably resulting from deficiencies in the initial hydrographic fields. A moderately realistic spill jet and Irminger Current are present in the model solution, however, and are clearly distinct, as in the observations. The model peak current speeds are somewhat weaker than the data, probably because of the weaker model front arising from the shallow thermocline. Similar circulation models at coarser resolution do not capture these features (e.g., *Haine and Pickart* (2003)).

Figure 9 shows the model speed at a depth of 330 m. The spill jet is visible as a boundary-following current carrying water out of the deep Kangerdlugsuak fjord to the west of Denmark Strait. Interestingly, several similar jets are visible at various other places along the shelf break. It appears from this simulation that export of shelf water by narrow jets through shelf break gaps - such as the spill jet - is a ubiquitous feature of the circulation. Based on these results, we

speculate that the spill jet is a gravity-driven cascade basically like the Denmark Strait overflow itself, although on a smaller scale. Thus, it is presumably a more or less permanent circulation feature.

Measuring and understanding the spill jet in detail is clearly essential to clarify how Arctic freshwater impacts subpolar climate variability. We will propose a project that achieves these goals. Although the program is still being planned, possible components are:

- A high resolution mooring array to quantify exchange over the seasonal cycle. The field work will have a shelf-break focus, but will also include a regional component using ship surveys and/or autonomous instruments. The fieldwork will be coordinated with simultaneous high resolution atmospheric fieldwork with UK and/or Canadian colleagues.

- Diagnose and understand the spill jet and exchange dynamics using very high resolution (O(1km) grid spacing) numerical models, such as that shown above. We will identify the generic processes and their relationship to the entrainment occurring in the deep Denmark Strait overflow. Collaboration with the CLIVAR Process Team on Gravity Current Entrainment will help us extract key parametrizations so that the shelf-basin exchange can be represented in coarse-resolution climate models.

- Understand the relationship between the exchange and the local atmospheric state. Weather systems in the vicinity of Greenland that probably have large impact on shelf-break waters include: barrier winds, katabatic winds and gap winds. Understanding these phenomena and the intense, local air/sea interaction they likely cause will be an important part of the project. See section 4.3.

- Determine the impacts of the exchange on the freshwater budget of the subpolar gyre, convection, and water mass conversion. We will synthesize our results with the other ASOF observing efforts in the region to understand how Arctic freshwater impacts subpolar climate variability.

4.2 Sea Ice Processes and Interannual Variability

Sea ice plays a critical role in air-sea interaction over the sub-Arctic region. The growth, melt, and transport of sea ice exerts a strong influence on the exchange of heat, freshwater, salt, and momentum between the atmosphere and the ocean and on albedo. Much of the ocean deep convection in the northern hemisphere (NH) occurs within or near the sub-Arctic sea ice covered oceans, where sea ice has direct and/or indirect control on deep water formation. The sub-Arctic region also lies in close proximity to the storm track. Sea ice variability affects, and is affected by, the location and intensity of the storm track, shaping regional climate through coupled air/sea/ice interaction.

The Labrador Sea is one of four main areas of seasonal sea ice cover in the NH; the others are the Nordic Seas, the Bering Sea, and the Sea of Okhotsk. On one hand, the sea ice variations in these regions are closely linked. For example, an out-of phase relationship exists between the wintertime sea ice extents of the Labrador and Nordic Seas. To a large extent, this relationship is a sea ice manifestation of the NAO. However, from a hemispheric viewpoint it is just an Atlantic component of the leading NH sea ice mode that encompasses both the Atlantic and Pacific with action centers located exactly at the four regions of seasonal sea ice cover.

On the other hand, Labrador sea ice variability also has unique characteristics. It is the only sub-Arctic region in which wintertime sea ice extent anomalies persist significantly for several years. Multi-year persistence has also been observed in SST anomalies over the region (*Deser*

et al., 2002). These observations suggest the presence of a multi-year memory in the ice-ocean coupled system over the Labrador Sea and its vicinity. One possible mechanism that accounts for such a memory is the re-emergence of SST anomalies; SST anomalies initiated in winter are sequestered below the mixed layer in spring and re-emerge in the following winter (*Alexander and Deser*, 1995).

Observations also point to the importance of upstream atmospheric conditions. A new study proposes that a remote influence of ENSO extends to the Labrador Sea (*Ukita*, 2004). There is strong empirical evidence of a connection between the magnitude of the ENSO cycle and the strength of the North Atlantic storm track, which is mediated by North Pacific variability. This relationship is nonlinear in the sense that it prevails during both El Niños and La Niñas, but with different strengths. As positive and negative ENSO phases often succeed each other, the observed multi-year persistence of the Labrador Sea may result from this nonlinearity of the remote influence of ENSO over the region.

The relative importance of the re-emergence process versus remotely-coordinated atmospheric forcing for multi-year Labrador sea ice persistence is at present not well known. Other internal ocean mechanisms may also play an important role. Presumably, the multi-year Labrador Sea sea ice memory impacts freshening and cooling of the water column, however. Thus, understanding these mechanisms is important to the central theme of Task 5. Moreover, the interannual variations in upper-ocean, sea-ice, and the atmosphere over the western subpolar Atlantic have highly coherent spatial structures, which suggests strong coupling among these climatic components. Indeed, the sub-surface Labrador Sea may impact the mid-latitude atmosphere by controlling local sea ice variability and hence albedo: a much more direct feedback from deep subpolar ocean to atmosphere than usually postulated for the MOC. Understanding this coupling is thus also a priority. Studies that address it through reanalysis of the instrumental record, or simulations of the coupled air/sea/ice system are encouraged.

4.3 Air-Sea Interaction off Greenland

Air-sea interaction in the western subpolar Atlantic plays a vital role both in controlling mode water production, and in shaping the basin-scale circulation. The region lies directly under the primary synoptic-scale storm track. In consequence, intense buoyancy and momentum fluxes occur primarily at short spatial scales (O(1-100)km) and short periods (O(1 hr–1 day)) and are thus poorly represented in meteorological reanalysis products (see section 3.4). For example, interactions between cyclones and the high topography of Greenland - such as shown on the cover of this report - can result in high wind speed events that are barely resolved in the NCEP reanalysis (*Doyle and Shapiro*, 1999; *Moore*, 2003). *Pickart et al.* (2003) report that the large-scale wintertime NCEP reanalysis underestimates the true magnitude of tip jet wind stress curl by nearly one thousand times. It is likely that the rectified effects of these intense, intermittent weather systems is substantial. They probably exert significant control over deep convection, exchange across shelf breaks, flux through sills, boundary current instability, and sea ice conditions.

The Labrador Sea Experiment made notable progress in understanding, modelling, and forecasting cold-air outbreaks off Labrador (*The Lab Sea Group*, 1998). An aircraft-based observing campaign succeeded in estimating air-sea heat and moisture fluxes and observing cloud streets in January and February 1997 (*Renfrew and Moore*, 1999). Comparison with ship-based observations and reanalysis output revealed significant discrepancies in the NCEP fields at high wind speeds (*Renfrew et al.*, 2002; *Moore and Renfrew*, 2002). The project also provided accurate real-time weather forecasts for aircraft and ship operations using operational numerical

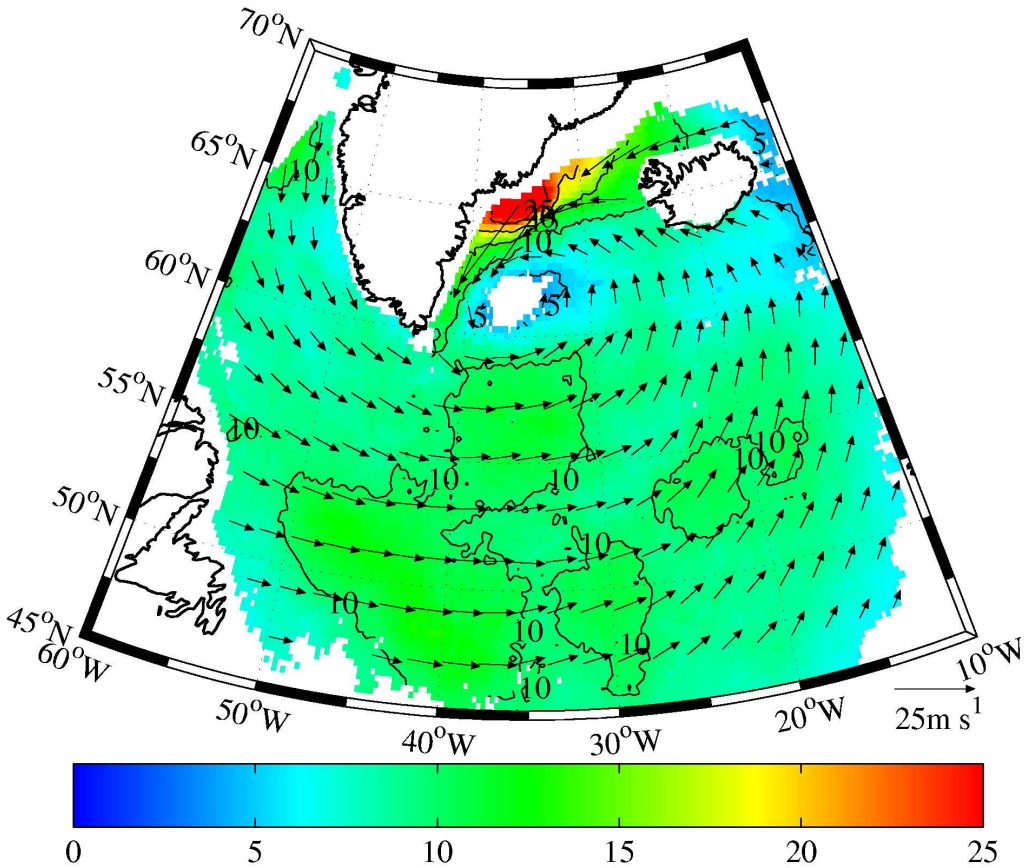

Figure 10: Barrier wind flow. Winter (DJF) 10 m composite windspeed (color; ms^{-1}) and velocity fields (every 6th gridpoint) from the 1999–2004 QuikSCAT dataset associated with barrier wind flow at the southern side of Denmark Strait. Fields shown are significant at the 99% level. A synoptic low pressure system lies east of Cape Farewell (uncolored region) causing cyclonic surface flow to converge against the Greenland plateau to the north. The north-easterly barrier wind results with peak windspeeds exceeding 50knots around 10% of the time. See *Moore and Renfrew* (2004) for more details.

weather models run in a specialized domain. Simulations with these models have shown success in simulating turbulent air-sea fluxes in a number of intense subpolar weather systems (*Pagowski and Moore*, 2001). Recently, a new generation of cloud-resolving numerical models has shown promise in capturing the significant variability in air-sea fluxes that result from cloud-scale motion and heterogeneity in sea ice cover in subpolar weather systems (*Liu et al.*, 2003).

Off Greenland, other phenomena also appear to impact air-sea interaction. Tip jets are poorly understood, especially aloft, although there seem to be two distinct classes: "forward" (as shown on the cover), and "reverse" (with the cyclone lying south of Cape Farewell). Barrier winds flowing parallel to the topographic contours, and hence parallel to the East and West Greenland Currents, presumably impact sea ice flow and maybe surface jets (Figure 10, *Thomas and Lee* (2004); *Moore* (2003); *Moore and Renfrew* (2004)). Katabatic winds and Gap winds are moderately well understood although the impact on the waters over the Greenland shelves is unclear (*Klein and Heinemann*, 2002). Finally, polar lows - small but intense cyclones that are driven by both dynamical instabilities and large air-sea fluxes - remain poorly observed. Just one polar low off Greenland has been sampled comprehensively (*Shapiro et al.*, 1987). Despite their

frequent observation in satellite imagery (for example, *Harold et al.* (1999)), their impact on the ocean is still unclear (*Moore et al.*, 1987; *Moore and Vachon*, 2002). All of these weather systems have precipitation associated with them and the effect that this highly localized freshwater flux has on the ocean is still poorly understood and modeled (*Moore et al.*, 2002; *Sathiyamoorthy and Moore*, 2002).

The high wind speed weather systems that are important in forcing the ocean are clearly also a hazard to shipping and other human activities in the vicinity of Greenland. Numerical modelling studies have shown that Greenland has an important downstream influence and affects forecasting capabilities over western Europe (e.g. *Petersen et al.* (2003, 2004)). Hence there are clear links to the current THORPEX/IPY initiative (see http://www.wmo.int/thorpex/), sponsored by the WMOs World Weather Research Programme. This project aims to improve short to medium term weather forecasts world wide, with the IPY intiative focussing on weather in the polar regions and weather systems originating, or influenced by, polar regions.

In light of their variety, their probable role in steering freshwater processes, and the present capability to both observe and model them, Task 5 would benefit from projects that study high-latitude intense weather systems, such as tip jets, barrier winds and polar lows. We promote process studies that investigate the structure, dynamics, and turbulent air-sea fluxes associated with them. Collaborative efforts that are coordinated with ocean process studies (e.g., section 4.1) are particularly valuable.

5 Liaison with other Programs

Liaison with other programs is essential for Task 5. We seek opportunities to collaborate with other projects that are working in the subpolar Atlantic, and also coordinate planning with those who are interested in wider issues. Only by doing this can ASOF really understand the factors that control the global MOC and its influence on global climate.

These issues are particularly important for Task 5 because several other programs are active in this area. They include: CLIVAR Atlantic, SFB460, SEARCH, CLIC, THORPEX, RAPID, and the International Polar Year (IPY). Some of these programs have objectives that are very closely related to the overall ASOF and Task 5 aims, stated in sections 1 and 2. We seek feedback from these programs in order to maximize the mutual benefit of the present and future observing network and process studies described in sections 3 and 4. Similarly, ASOF can contribute to other programs through its reports and online resources (e.g., this report and the proposed observing plan for the IPY by *Dickson et al.* (2004)). We intend to conform to the CLIVAR data management protocols (*Dickson et al.*, 2002).

A fitting legacy for ASOF would be an optimized long-term observing array that is managed by one or more operational agencies, not by the university research community. Transition to such a state requires early liaison and collaboration with likely agencies.

To reach this goal it is also important to collaborate with investigators working on the emerging field of ocean data assimilation. Data assimilation can serve in the design of an optimal instrumental strategy for a particular purpose, such as monitoring the flow through Denmark Strait. It also seems increasingly likely that data assimilation will become a routine part of physical oceanography as it is in atmospheric science. Many share the view that integrated quantities like mass transport, or freshwater flux, are best estimated by formally synthesizing the sparse and diverse direct measurements with ocean circulation models. Data assimilation can - in principle - achieve this goal. The methods required are either now understood or at an advanced stage of development. They will be implemented at eddy-resolving scales, and with sea ice, in the coming few years and we need to contribute to that development.

6 Conclusions

As described in section 2, the aims of ASOF Task 5 are to review and prioritize fieldwork, to identify gaps in coverage, to promote relevant process studies, and to foster collaboration with other programs. Section 3, Figure 1, and Table 1 give a detailed account of the current fieldwork in the western subpolar Atlantic and identify the prospects for future observations as far as can be presently discerned. At this time, it is premature to prioritize these projects in terms of relevance for a future long-term operational array. Nevertheless, there are some clear recommendations to maintain the integrity of the observational record:

The following are high priorities for maintaining the ASOF observing array in the Task 5 area:

- Continuation of the time-series at Denmark Strait, Faroe Bank Overflow, Wyville-Thompson Ridge, and Iceland-Faroe Ridge. See section 3.1.1.
- Estimates of the freshwater flux between Greenland and Iceland on the Greenland shelf. See sections 3.1.1 and 4.1.
- Re-establish Iceland-Scotland Overflow Water monitoring at Charlie-Gibbs Fracture Zone. See section 3.1.2.
- Coordinate mooring groups in Irminger Sea to maximize benefit and eliminate redundant resources. See section 3.1.3.
- Ensure that the excellent moored network in the Labrador Sea and Newfoundland Slope does not disappear after summer 2005. See section 3.1.4.
- Ensure that the AR7W transect is occupied annually with secure long-term funding. See section 3.2.

Direct physical observation of the western subpolar Atlantic is the primary implementation strategy for ASOF Task 5. It is clear that our understanding of the basic processes that cycle freshwater and heat in this area is still immature, however. To address this gap in knowledge we promote projects that study important, generic, processes that control freshwater and heat. Section 4 gives details.

In particular, the following are priorities for exploring processes that impact freshwater in the Task 5 area:

- Pursue process study to measure and model shelf-basin exchange south of Denmark Strait. See section 4.1.
- Encourage exploration of the impact of sea ice variability on upper ocean salinity. Seek to diagnose and understand the coupled interactions of the air/sea/ice system in the western subpolar Atlantic. See section 4.2.
- Promote and collaborate with process studies that investigate meso-scale atmospheric weather systems in the area and on their air-sea fluxes. See section 4.3.

Finally, liaison with other programs is essential for the success of ASOF Task 5 in particular. We must be actively involved in the transition to a long-term operational observing array with routine data assimilation. Section 5 gives details.

Appendix A: Task 5 Working Group Membership

Tom Haine (chair)	Earth & Planetary Sciences, Johns Hopkins University	Thomas.Hainejhu.edu
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Appendix B: Task 5 Working Group Meeting Agenda

ASOF Task 5: Overflows and Storage Basins to Deep Western Boundary Current

Committee Meeting 1

Earth & Planetary Sciences, Johns Hopkins University, Baltimore,

19 June 2004

Meeting Objectives:

The overlapping meeting goals are, tentatively,

1. Monitoring network:

- Review the status of current and pending fieldwork in the western subpolar gyre relevant to ASOF. Compile a comprehensive list of activity.
- Establish priorities in this list of field projects, based on relevance to permanent ASOF monitoring in the Task 5 area.
- Identify gaps in the observing network. Discuss prospects to fill gaps.

2. Process Study:
Discuss and advance plans for a joint ASOF/CLIVAR process study in the subpolar gyre.

3. Liaison:
Discuss interface between ASOF Task 5 and other programs.

Meeting Outcomes:

The ASOF steering committee has requested a “white paper” reporting the status of Task 5 activities and outlines a strategy for implementation in the subpolar gyre. Tom and Bob will compile this document based on discussion at this meeting.

Schedule

Morning:

8:30am	Introduction (Haine)
8:45am	Bob Dickson, *Review of Arctic/Sub-Arctic freshwater fluxes*
9:15am	Ian Renfrew, *Weather systems and air-sea interaction in the vicinity of Greenland*
9:45am	Kent Moore, *Climatology and High Resolution Modelling of Air-Sea Interaction over the Irminger Sea*
10:15am	Bob Pickart, *Components of the East Greenland Current South of Denmark Strait*
10:45am	Tea/Coffee
11:00am	Sheldon Bacon, *Cape Farewell and Eirik Ridge: Interannual to Millennial Thermohaline Circulation Variability*
12:00pm	Pascale Lherminier, *The OVIDE project and MOC variability, 1997-2002*
12:30pm	Tom Rossby, *URI's Nuka Arctica project and Faeroe/Iceland exchange program*
1:00pm	Lunch

Afternoon:

2:00pm	Daniel Lea, *Prospects for monitoring Irminger Sea circulation using data assimilation*
2:30pm	Craig Lee/Charlie Eriksen, *Davis Strait Monitoring and SeaGliders*
3:00pm	Discussion 1: Monitoring Network (Led by Haine)
4:00pm	Tea/Coffee
4:15pm	Discussion 2: Process Study (Led by Pickart)
5:15pm	Discussion 3: Liasion (Led by Dickson)

Close.

Attendees

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References

Alexander, M. A., and C. Deser (1995), A mechanism for the recurrence of wintertime SST anomalies, *J. Phys. Oceanogr.*, *25*, 122–137.

ASOF ISSG (2002), Report of the 2nd meeting of ASOF International Scientific Steering Group, 18–19 October 2002, Hamburg, *Tech. rep.*, available at `http://www.npolar.no/asof`.

ASOF ISSG (2003), Report of the 3rd meeting of ASOF International Scientific Steering Group, 25-16 October 2003, Seattle, *Tech. rep.*, available at `http://www.npolar.no/asof`.

Busalacchi, A. J., R. Boscolo, B. Dickson, A. Piola, J. Servain, and N. Zeng (2004), Climate Observing System for the Atlantic Sector, *Tech. rep.*, available at ??

Deser, C., M. Holland, G. Reverdin, and M. Timlin (2002), Decadal variations in Labrador Sea ice cover and North Atlantic sea surface temperatures, *J. Geophys. Res.*, *107*, 10.1029/2000JC000,683.

Dickson, R., J.-C. Gascard, S. Laxon, M. Meredith, J. Bamber, H. Loeng, L. Anderson, J. Greibmeier, and C. Ellis-Evans (2004), AOSB Observing Plan for the IPY, *Tech. rep.*, available at `http://www.npolar.no/asof`.

Dickson, R. R., J. Meincke, and P. B. Rhines (2002), Arctic-Subarctic Ocean Flux Study (ASOF) Implementation Plan, *Tech. rep.*, available at `http://www.npolar.no/asof`.

Doyle, J. D., and M. A. Shapiro (1999), Flow response to large-scale topography: The Greenland Tip Jet, *Tellus, Ser. A*, *51*, 728–748.

Fischer, J., F. A. Schott, and M. Dengler (2004), Boundary circulation at the exit of the Labrador Sea, *J. Phys. Oceanogr.*, *34*, 1548–1570.

Haine, T. W. N., and R. S. Pickart (2003), ASOF in the subpolar gyre: Recent results and future plans, *ASOF Newsletter*, *1*, 17–19.

Häkkinen, S., and P. B. Rhines (2004), Decline of subpolar North Atlantic circulation during the 1990s, *Science*, *304*, 555–559.

Harold, J. M., G. R. Bigg, and J. Turner (1999), Mesocyclone activity over the North-East Atlantic. part 1: Vortex distribution and variability, *Int. J. Climatology*, *19*, 1187–1204.

Klein, T., and G. Heinemann (2002), Interaction of katabatic winds and mesocyclones near the eastern coast of Greenland, *Meteorological Applications*, *9*, 407–422.

Large, W. G., and S. G. Yeager (2004), Diurnal to decadal global forcing for ocean and sea-ice models: The data sets and flux climatologies, *Tech. Rep. NCAR/TN-460+STR*, NCAR Climate and Global Dynamics Division.

Liu, A. Q., G. W. K. Moore, K. Tsuboki, and I. A. Renfrew (2003), A high-resolution simulation of convective roll clouds during a cold-air outbreak, *Geophys. Res. Lett.*, *31*, 10.1029/2003GL018,530.

Moore, G. W. K. (2003), Gale force winds over the Irminger Sea to the east of Cape Farewell, Greenland, *Geophys. Res. Lett.*, *30*, 10.1029/2003GL018,012.

Moore, G. W. K., and I. A. Renfrew (2002), An assessment of the surface turbulent heat fluxes from the NCEP-NCAR reanalyses over the western boundary currents, *J. Climate*, *15*, 20,202–20,237.

Moore, G. W. K., and I. A. Renfrew (2004), Tip jets and barrier winds: A QuikSCAT climatology of high wind speed events around Greenland, *J. Climate*, *submitted*.

Moore, G. W. K., and P. W. Vachon (2002), A polar low over the Labrador Sea: Interactions with topography and an upper-level potential vorticity anomaly, and an observation by RADARSAT-1 SAR, *Geophys. Res. Lett.*, *29*, 10.1029/2001GL014,007.

Moore, G. W. K., M. C. Reader, J. York, and S. Sathiyamoorthy (1987), Polar lows in the Labrador Sea - a case study, *Tellus, Ser. A*, *39A*, 272–306.

Moore, G. W. K., K. Alverson, and I. A. Refrew (2002), A reconstruction of the air-sea interaction associated with the Weddell Sea polynya, *J. Phys. Oceanogr.*, *32*, 1685–1698.

Pagowski, M., and G. W. K. Moore (2001), A numerical study of an extreme cold-air outbreak over the labrador sea: Sea ice, air-sea interaction, and development of polar lows, *Mon. Weather. Rev.*, *129*, 47–72.

Petersen, G. N., H. Olafsson, and J. E. Kristjansson (2003), Flow in the lee of idealized mountains and Greenland, *J. Atmos. Sci.*, *60*, 2183–2195.

Petersen, G. N., J. E. Kristjansson, and H. Olafsson (2004), Numerical simulations of Greenland's impact on the Northern Hemisphere winter circulation, *Tellus, Ser. A*, *56A*, 102–111.

Pickart, R. S., M. A. Spall, M. H. Ribergaard, G. W. K. Moore, and R. F. Milliff (2003), Deep convection in the Irminger Sea forced by the Greenland tip jet, *Nature*, *424*, 152–156.

Pickart, R. S., D. J. Torres, and P. S. Fratantoni (2004), The East Greenland Spill Jet, *J. Phys. Oceanogr.*, p. accepted.

Renfrew, I. A., and G. W. K. Moore (1999), An extreme cold-air outbreak over the Labrador Sea: Roll vortices and air-sea interaction, *Mon. Weather. Rev.*, *127*, 2379–2394.

Renfrew, I. A., G. W. K. Moore, P. S. Guest, and K. Bumke (2002), A comparison of surface layer and surface turbulent flux observations over the Labrador Sea with ECMWF analyses and NCEP reanalyses, *J. Phys. Oceanogr.*, *32*, 383–400.

Sathiyamoorthy, S., and G. W. K. Moore (2002), Buoyancy flux at Ocean Weather Station Bravo, *J. Phys. Oceanogr.*, *32*, 458–474.

Saunders, P. M. (2001), The dense northern overflows, in *Ocean circulation and climate*, edited by G. Siedler, J. Church, and J. Gould, pp. 401–417, Academic Press, San Diego, vol. 77 of the International Geophysics Series.

Shapiro, M. A., L. S. Fedor, and T. Hampel (1987), Research aircraft measurements of a polar low over the Norwegian Sea, *Tellus, Ser. A*, *39A*, 272–306.

Taylor, P. (2000), Final report of the Joint WCRP/SCOR Working Group on Air/Sea Fluxes: Intercomparison and validation of ocean-atmosphere energy flux fields, *Tech. rep.*, WCRP-112, WMO/TD-No. 1036, World Climate Research Programme, 303pp.

The Lab Sea Group (1998), The Labrador Sea deep convection experiment, *Bull. Amer. Meteor. Soc.*, *79*, 2033–2058.

Thomas, L. N., and C. M. Lee (2004), Intensification of ocean fronts by down-front winds, *J. Phys. Oceanogr.*, *submitted*.

Ukita, J. (2004), Intermodal structure of northern hemisphere climate variability, *Nature*, *submitted*.