ASOF in the Subpolar Gyre: Recent Results and Future Plans

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The subpolar North Atlantic is one of the best-studied oceans we know. Careful measurements over decades reveal intense water-mass transformation by both vigorous air/sea interaction and interior diabatic mixing. Through this reservoir pass the North Atlantic Current, yielding its heat to moderate Europe's climate, and North Atlantic Deep Water (NADW), a critical, but perhaps fragile, part of the global deep circulation. It also contains one antinode of the Atlantic-wide sea-surface temperature (SST) tripole pattern associated with the North Atlantic Oscillation (NAO) and has undergone large and sustained changes since 1950. Perhaps, nowhere else does such a small part of the ocean play such a large part in climate and its variability. Moreover, it continues to surprise us.

Most oceanographers believe that the central Labrador Sea is the formation site of the ubiquitous weakly-stratified waters of the mid-depth subpolar gyre - hence the name Labrador Sea Water (LSW). But recent work challenges this orthodoxy (*Pickart et al.* [2003a, b] - see also the commentary by *Dickson* [2003]). High-resolution, high-frequency meteorological data point to the southern Irminger Sea as another, maybe intermittent, region of LSW formation. Steered by the southern Greenland topography, frigid air periodically whips out across the Irminger Sea east of Cape Farewell - the so-called Greenland tip jet. The associated ocean-to-atmosphere heat flux reaches the extreme peaks seen in Labrador Sea winter storms, while the wind-stess curl exceeds the average winter subpolar value by one thousand times (*op. cit.*). The ocean responds, at least in a high-resolution primitive equation numerical model, by convecting to 2,000m, deep into the LSW layer. This evidence makes a strong case for LSW formation in the Irminger

Sea, but are there direct observations?

Resolution of this issue now seems to be in hand. The main task of a fascinating recent cruise of the R/V *Oceanus* was to recover, service, and re-deploy a pair of profiling CTD moorings in the Irminger Sea off Cape Farewell. These moored profilers have undulated through the upper 1,500m of the water column every day since August 2002. Although the measurements are yet to be analyzed, interrogation of the instruments on board *Oceanus* showed the data records are complete. If deep convection to LSW horizons occurred in the Irminger Basin last winter, these observations should prove it.

Labrador Sea Water formation in the subpolar gyre impacts the Atlantic meridional overturning circulation and poleward heat flux. Arguably, sub-surface diabatic conversion of water masses in transit through the region is less well understood and of greater interest to ASOF science, however. Here, too, we have made recent unexpected discoveries.

In particular, we completed an intriguing synoptic survey of the shelf-break circulation and hydrography southwest of Denmark Strait on *Oceanus*. Fair weather, and sea-ice cover that broke 50-year-record lows, permitted four CTD, ADCP, and XCTD transects near Dohrn Bank and the Kangerdlugsuak fjord. Remarkably, stations spaced by just 1km were needed to resolve the complex mingling of the Irminger and East Greenland Currents. The results confirm and expand the findings of a tantalizing section taken in August 2001 (Fig. 1). Immediately below the shelf-break, a bottom-intensified peak in equatorward speed (Fig. 1c) identifies a narrow plume of dense, fresh shelf water descending into the deep Irminger Sea. The feature has been named the "spill-jet." It appears to be a robust element of the shelf-break circulation (at least in summer) that is distinct from the Irminger Current and Denmark-Strait Overflow Water (DSOW). Preliminary calculations suggest the spill-jet exports a substantial volume of fresh, dense, water off the shelf. Understanding the importance of this shelf-basin exchange for regional circulation and NADW export is a critical challenge facing ASOF. So far, we have just a crude picture of the complex interaction.

One way to tackle this problem is to use high-resolution numerical general circulation models (GCMs). Our voyage on *Oceanus* was noteworthy in this respect too - the task of one of us on-board (Haine) was to run and explore a fine-scale (9km, 30 level) regional GCM of Denmark Strait and the Irminger Sea (see posters online for details: *Lea et al.* [2003a, b]). The results are very encouraging. For example, Fig. 2 shows a map of model circulation around 350m depth in the vicinity of Denmark Strait. White lines show the trajectories of simulated floats. Rapid flow through Denmark Strait, crossing the channel from east to west, is clear. The outflow vigorously entrains ambient Irminger water which the inter-woven float paths reveal (in common with many GCMs at this resolution, the model entrainment is too strong, although this does not seem to damage the accuracy of the basin-wide circulation). Strong topographic steering by the Kangerdlugsuak fjord is also clear, and is likely a robust feature of the flow. The spill-jet is too narrow to be captured at this grid-spacing. But its dynamics are an exciting topic which we are starting to investigate with similar models at higher resolution.

These calculations were made using a laptop computer on board *Oceanus*. The

GCM results were helpful in picturing the circulation and guiding the survey strategy. We also tested the possibility of performing variational data assimilation using remote-sensed and *in-situ* data while at sea. This systematic merging of field observation and GCM dynamics would be a major step toward a real-time state estimation that can monitor this area. It seems feasible. Next year we will be ready to stage a serious attempt.

The future prospects for ASOF in the western subpolar Atlantic are bright. A return cruise is scheduled on the RRS *James Clark Ross*, the British Antarctic Survey ice breaker, in August 2004. The southern Irminger Sea moored profilers will be retrieved and replaced with Ultramoor subsurface moorings which will monitor deep convection until 2009. The complete decade-long timeseries should resolve how deep convection induced by the tip jet is modulated by the NAO and break out of the string of recent mild winters. The relationship to the antinode of the SST tripole is unknown, but needs attention. Synthesizing other precious *in-situ* observations is also critical. British, Dutch, and German moorings are now deployed in the southern Irminger Sea, and on the East Greenland shelf and slope. Several of them are of innovative designs to dodge ice or fishing nets. The efforts of groups from several North Atlantic nations will sustain key hydrographic lines. Beyond that, we hope to mount a significant field program aimed at elucidating these subtle diabatic processes, probably as a joint ASOF/US CLIVAR initiative. We welcome your ideas and feedback.

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Figure Captions

1. Sections across the shelf-break and continental slope southeast of Kangerdlugsuak fjord in August 2001 [*Pickart et al.*, 2001]. (a) potential density, (b) potential temperature, (c) hull-mounted ADCP currents normal to section (positive equatorward). Station locations are numbered. Between stations 21 and 22 there is evidence of a rapid, narrow jet of shelf water trapped against the continental slope at 300–450 m depth. This feature, seen again in 2003, is the “spill-jet” and is distinct from DSOW. Although calculations need to be confirmed, the spill-jet seems to carry a substantial volume of dense, fresh shelf water into the deep Irminger Basin.

2. Results from a 9km-resolution regional model of Denmark Strait and the Irminger Sea. The colors show the 8-week-mean flow speed at 325–380m in mid-August. Black lines show bathymetry (every 500m). Float trajectories end at the circles and show the simulated path near 350m for the period 1 August–30 September. The location of the section shown in Fig. 1 is marked with stars. Kangerdlugsuak fjord is the deep basin centered at 31°W. Mixing of Denmark Strait Overflow waters with the Irminger Current is clear and the flow is strongly steered along the bathymetry of Kangerdlugsuak fjord. Only a small part of the model domain is shown. See *Lea et al.* [2003a, b] for details.

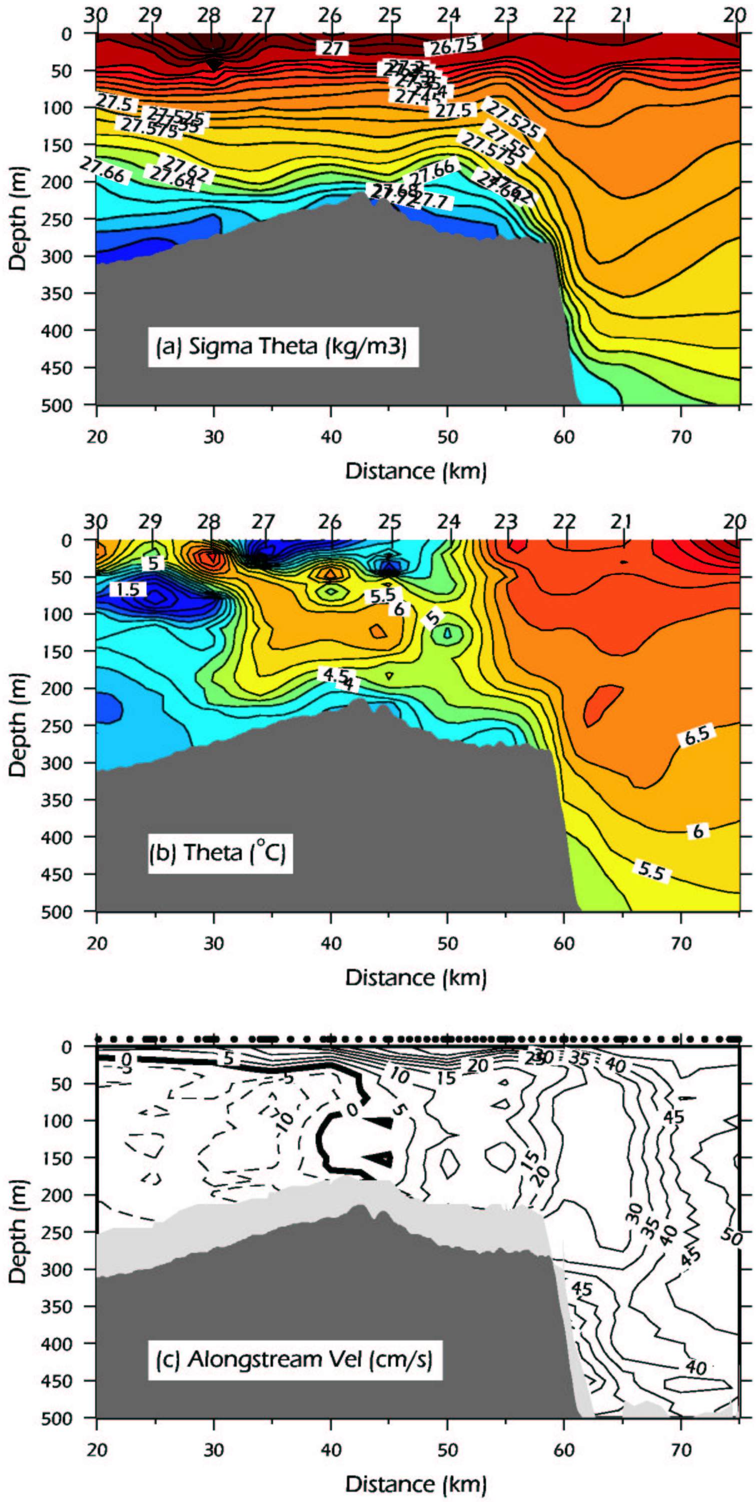
(a) Sigma Theta (kg/m3)
(b) Theta (°C)
(c) Alongstream Vel (cm/s)
Depth (m)
Distance (km)

Figure 1.

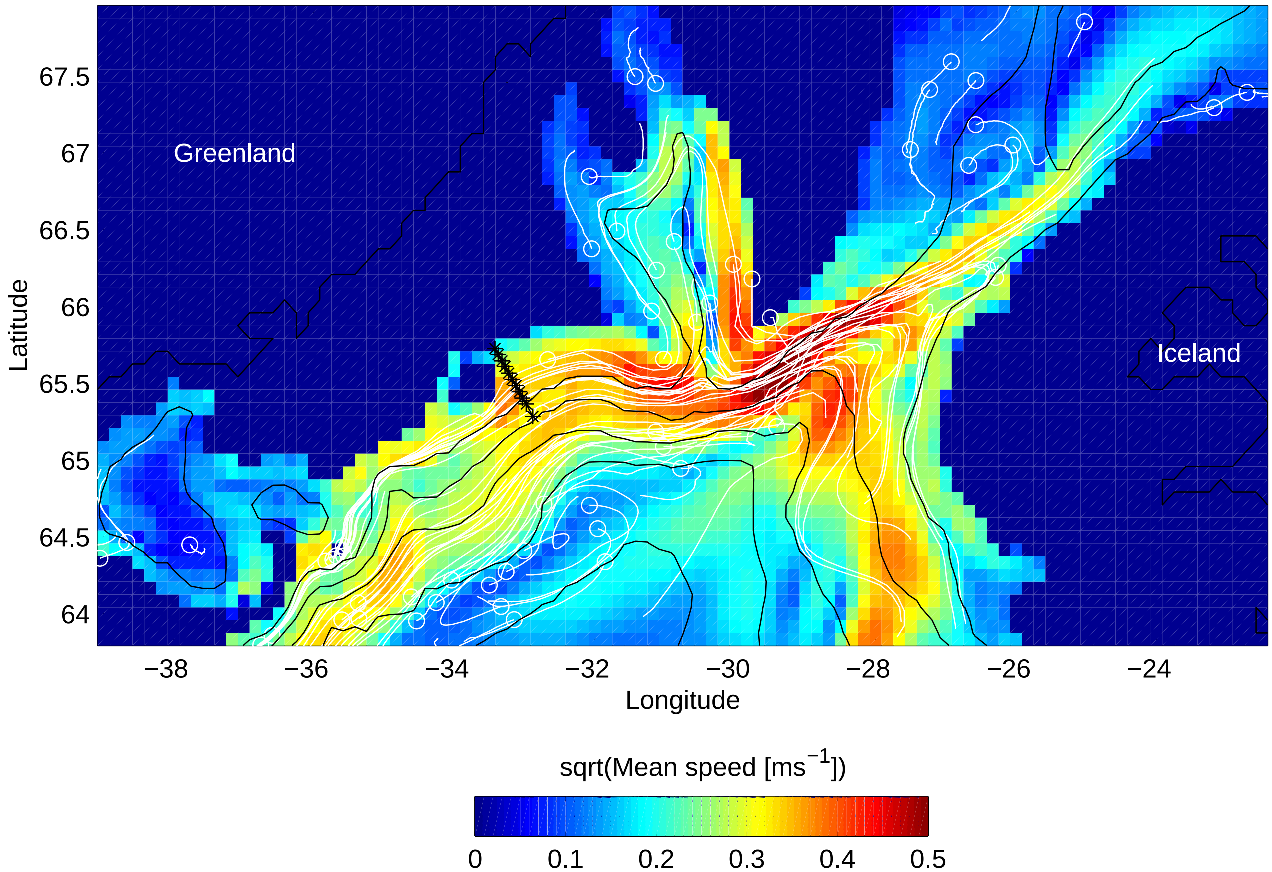
Greenland
Iceland
Latitude
67.5
67
66.5
66
65.5
65
64.5
64
−38
−36
−34
−32
−30
−28
−26
−24
Longitude
sqrt(Mean speed [ms−1])
0
0.1
0.2
0.3
0.4
0.5

Figure 2.