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Rapid change in freshwater content of the Arctic Ocean

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[1] The dramatic reduction in minimum Arctic sea ice extent in recent years has been accompanied by surprising changes in the thermohaline structure of the Arctic Ocean, with potentially important impact on convection in the North Atlantic and the meridional overturning circulation of the world ocean. Extensive aerial hydrographic surveys carried out in March–April, 2008, indicate major shifts in the amount and distribution of fresh-water content (FWC) when compared with winter climatological values, including substantial freshening on the Pacific side of the Lomonosov Ridge. Measurements in the Canada and Makarov Basins suggest that total FWC there has increased by as much as 8,500 cubic kilometers in the area surveyed, effecting significant changes in the sea-surface dynamic topography, with an increase of about 75% in steric level difference from the Canada to Eurasian Basins, and a major shift in both surface geostrophic currents and freshwater transport in the Beaufort Gyre. **Citation:** 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.

[2] Fresh water exiting the Arctic in both the upper ocean and the sea ice cover plays a major role in controlling convection in the North Atlantic, and consequently the global thermohaline circulation [*Aagaard and Carmack*, 1989; *Walsh and Chapman*, 1990; *Serreze et al.*, 2006; *Peterson et al.*, 2006]. Changes in the distribution and discharge of Arctic fresh water may thus figure prominently in the response of the world ocean to climate change: e.g., *Aagaard and Carmack* [1989] pointed out that a 25% increase in the freshwater discharge through Fram Strait maintained for two years (equivalent to freshwater excess of about 2,000 km^3) would account for the salinity deficit observed in the North Atlantic during the "Great Salinity Anomaly" (GSA) of the 1970s, considered by *Dickson et al.* [1988] to be one of the major ocean climate events observed in the 20th century. The single largest feature in freshwater storage in the Arctic is the Beaufort Gyre (BG), an extensive anticyclonic ocean circulation in the Canada Basin north of Alaska [*Carmack et al.*, 2008]. Here we report evidence from an International Polar Year (IPY) airborne hydrographic survey

executed in March–April, 2008, of both significant redistribution and net increase in volume of Arctic FWC compared with climatological values. The freshening is concentrated mainly in the BG, and appears to have accelerated in concert with recent dramatic reduction in minimum sea ice extent [*Maslanik et al.*, 2007]. Associated changes in sea-surface dynamic topography have modified Arctic ocean circulation, with a large increase in northward transport of freshened water in the Canada Basin, toward the Fram Strait and Canadian Archipelago passages to the North Atlantic.

[3] We report initial results from several sources: the 2008 springtime IPY airborne hydrographic survey that is a collaboration among the North Pole Environmental Observatory (NPEO, http://psc.apl.washington.edu/northpole); the Beaufort Gyre Exploration Program (BGEP, http://www.whoi.edu/beaufortgyre); the Freshwater Switchyard of the Arctic Project in the Lincoln Sea (http://psc.apl.washington.edu/switchyard); and the Ice-Tethered Profiler (ITP) Program based at the Woods Hole Oceanographic Institution (http://www.whoi.edu/itp/) [*Krishfield et al.*, 2008]. The IPY airborne survey used Twin Otter (TO) aircraft mounted hydrographic equipment of NPEO [*Morison et al.*, 2006] to make surface stations on the sea ice. The system is based on the Sea-Bird SBE-19+ internally recording CTD, with accuracies of 0.01 salinity units and 0.01°C, and includes water sampling. In the Canada Basin, additional stations for temperature and salinity were obtained using Airborne eXpendable CTD (AXCTD) probes dropped in open leads at locations farther north than were possible by surface landing. A more thorough description of the AXCTD approach is in progress, but based on repeat drops, AXCTD accuracies appear to be 0.02 salinity units and 0.02°C. The ITP program provided temperature and salinity profiles in near real time from six drifting ITP buoys most of which had been deployed the previous summer.

[4] We used the Polar Hydrographic Climatology (PHC 3.0) winter seasonal (March–April–May: MAM) climatology [*Steele et al.*, 2001] as context for interpreting the 2008 measurements. For obvious logistical reasons, there has been a paucity of winter hydrographic data over the deep basins of the Arctic Ocean, but the situation improved greatly with recent publication of data from extensive Soviet aerial surveys from the 1970s [*Environmental Working Group*, 1998], incorporated into PHC 3.0. Despite our use of the term "climatology," the winter database is heavily weighted toward the decades of the 1970s and 1980s. *Proshutinsky et al.* [2009] summarize changes that have occurred in the early part of this century.

[5] Following *Carmack et al.* [2008]

$$FWC = \int_{z_{\lim}}^{0} \left(1 - S(z)/S_{ref}\right) dz \qquad (1)$$

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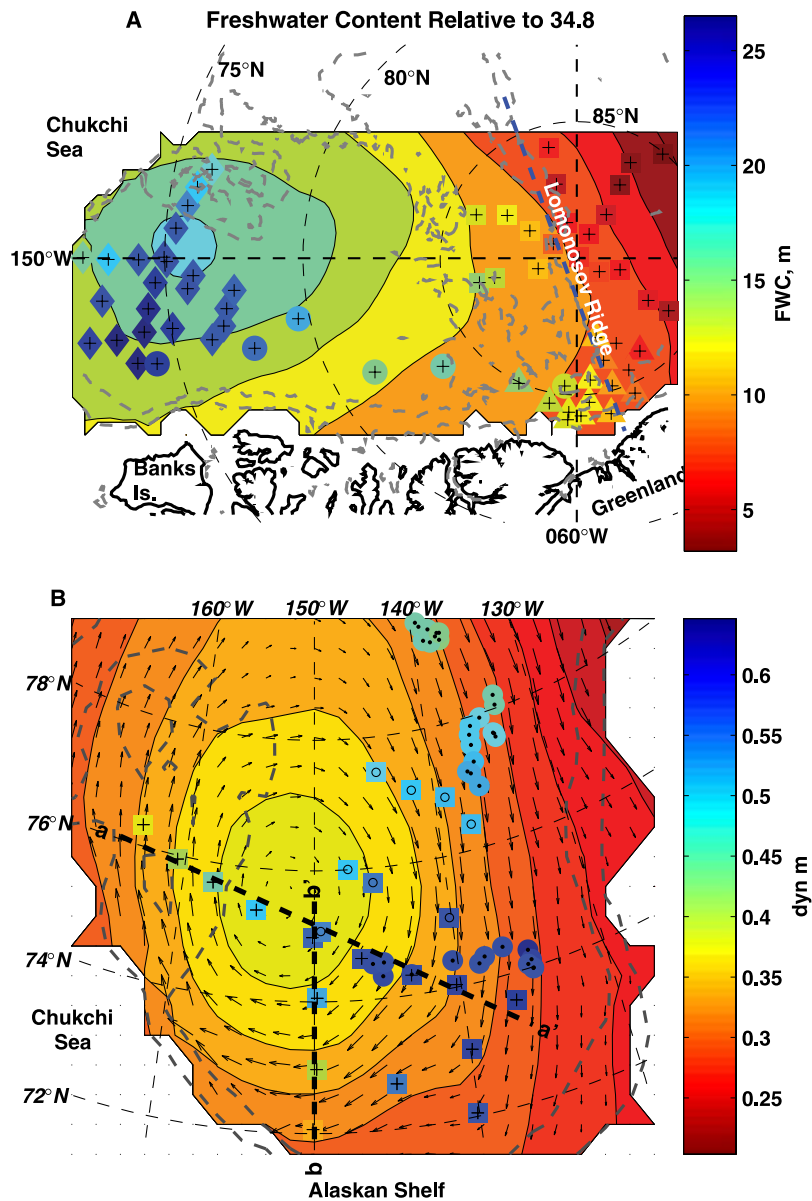
Figure 1. (a) FWC content in a measurement box encompassing 64 station locations (plus symbols) during the 2008 surveys. Color shaded contours show FWC from the late-winter climatological (PHC 3.0) database. Colored patches indicate FWC magnitude following the same scale for the different surveys: NPEO (squares); SWITCHYARD (triangles); IPY/BGEO (diamonds); and weekly (1−8 April, 2008) average ITP profiles (circles). The 2008 maximum FWC occurs in the SE part of the Canada Basin (lower left corner). The 500 and 1000 m isobaths are indicated by grey contours. (b) Detail of surface dynamic topography of the Beaufort Gyre (rotated from Figure 1a by 90°) with arrows indicating relative magnitude and direction of the associated surface geostrophic flow (magnitude range: 0 to 2.7 cm s^{-1}). Symbols indicate 2008 stations with colors corresponding to dynamic height: aerial survey TO surface landings (+); AXCTD (o); and weekly average ITP profiles from March through May, 2008 (diamonds). Section $a - a'$ indicates a line of 9 TO surface stations crossing close to the center of the traditional BG; section $b - b'$ is a south-to-north line of 4 TO stations along 150°W.

where S and S_{ref} are *in situ* and reference salinity, respectively, and z_{lim} is the uppermost level where S equals S_{ref} (34.8 on the practical salinity scale). For depths below z_{lim} (typically ∼400 m), variation in salinity is small. We considered a 2400 × 1200 km rectangular grid with the abscissa parallel to the 150°W meridian containing positions of the 2008 stations (64 in all) considered, which parallels approximately the shelf break running from Banks Island toward northern Greenland (Figure 1a). We then interpolated climatological values for temperature and salinity to a 50 × 50 km grid contained by the box, and calculated FWC at each grid point. The 2008 measurements confirm that the upper ocean in the western Arctic was extremely fresh compared with climatological conditions. At some stations in the SE Canada Basin (lower left in Figure 1a) FWC had increased by as much as 11 m, 60% above the climatological values. The freshening extends northward through the Canada and Makarov Basins to the Lomonosov Ridge (LR). On the

Eurasian side of the LR, the anomaly in FWC (i.e., FWC_{2008}-$FWC_{climatology}$) is negative, with minimum values of about -4 m. The overall magnitude of change in FWC from the Pacific to Atlantic sides of the observation box is almost 15 m. Although our emphasis here is on the 2008 results, we have looked at late winter ITP data from Canada Basin locations in 2006 and 2007, and find them consistent with a freshening trend identified in summer data by *Proshutinsky et al.* [2009]. ITP buoys deployed in the Canada Basin in 2008 again showed the upper ocean to be extremely fresh.

[6] We made a rough estimate of the total FWC in the area encompassed by the measurement box of Figure 1a by gridding the 2008 data via linear interpolation. We divided the box into regions on the Pacific side of the LR and a much smaller area toward the Eurasian Basin, as indicated by the dashed line in Figure 1a. Compared with winter climatological values in the same areas, freshwater volume on the Pacific side increased by approximately 8,500 km³ (26%) and decreased by about 1,100 km³ (26%) in the Eurasian area. From an earlier climatology, *Aagaard and Carmack* [1989] estimated the total FW volumes to be about 45,800 km³ in the Canada/Makarov Basins, and 12,200 km³ in the Eurasian Basin. By extending change ratios for the limited areas of the 2008 surveys to the entire deep basins that *Aagaard and Carmack* [1989] considered, we estimate that the western Arctic has gained in excess of 11,000 km³ of fresh water, while the Eurasian basin lost about 3,300 km³ for a net gain of 7,700 km³, equivalent to roughly four times the GSA salt deficit and comparable to total sea ice attrition (melt plus export) estimated by *Peterson et al.* [2006] for the period 1981–1995.

[7] Changes in FWC directly affect dynamic topography, i.e., the sea-surface elevation. We computed geopotential anomaly profiles, $\Phi'(p)$, [*Gill*, 1982] to the $p = 400$ dbar reference pressure surface for both the gridded climatological data and the individual 2008 stations. In the absence of other forces, current velocity at a particular pressure level is given by the geostrophic balance

$$f k \times v_g(p) = -\nabla \Phi'(p) \qquad (2)$$

where f is the Coriolis parameter and k the vertical unit vector. Over the deep basins of the Arctic, geostrophic velocity below the main pycnocline is small, so that surface geostrophic current is approximately

$$f k \times v_g(0) \approx \nabla \Phi'(p_{400}) \qquad (3)$$

and sea-surface dynamic height (relative to the reference pressure) is $-\Phi'/g$ (with units dynamic meters: dyn m) where g is the acceleration of gravity.

[8] When plotted in the same way as Figure 1a, dynamic height calculations for both the climatology and 2008 survey are barely distinguishable from FWC (except for numerical values for the color scale), with decreasing dynamic height from the Canada Basin north across the Lomonosov Ridge and beyond. Across the span of the gridded study area from the Canada to Eurasian Basins, in 2008 the difference in geopotential height was about 0.7 dyn m, an increase of roughly 75% from the climatological value of 0.4 dyn m.

[9] When viewed from the perspective of the BG, the recent sequestration of fresh water in the SE Canada Basin has appreciably changed the upper ocean circulation. The continuous shading and surface geostrophic current vectors of Figure 1b illustrate the traditional view of the BG, with doming of fresh water centered near 76°N, 150°W, and sluggish clockwise surface geostrophic current. In 2008, the locus of maximum FWC and sea-surface elevation had shifted several hundred kilometers SE, amplifying a trend beginning in the 1990s identified by *Proshutinsky et al.* [2009]. A section of 2008 surface-landing stations, stretching from the Northwind Rise nearly to the shelf break west of Banks Island (labeled $a - a'$), shows a continuous rise in surface dynamic height instead of the typical doming (Figure 2a). By considering finite difference approximations of horizontal geopotential gradient in each segment of section $a - a'$

$$\frac{\partial \Phi'(p)}{\partial x} \doteq \frac{\Phi'_2(p) - \Phi'_1(p)}{\Delta x} \qquad (4)$$

where subscripts denote adjacent stations, we calculated vertical profiles of geostrophic velocity relative to 400 dbar, transverse to $a - a'$. Surface components from the 2008 stations, $v_{\perp(p=0)}$ (Figure 2b, red arrows) are positive (i.e., heading ~20° from north) across the entire section, instead of the expected current reversal (blue). Along this line, our data showed no surface manifestation of the traditional BG.

[10] We estimated total freshwater transport (FWT) in each segment of section $a - a'$ by integrating the product of mean velocity and salt deficit:

$$FWT = \Delta x \int_0^{d_{400}} v_\perp(z) \left\{ 1 - \frac{S(z)}{S_{ref}} \right\} dz \qquad (5)$$

where $S(z)$ is the average salinity profile between adjacent stations and d_{400} is depth at the reference pressure. The calculation was repeated after substituting profiles from the PHC 3.0 climatology. Results for 2008 (Figure 2c) show a large net total NNE transport when summed over the entire section (red dashed line), versus a slightly negative sum for the climatology (blue dashed line). The difference is roughly half the total FWT (including sea ice) through Fram Strait estimated by *Serreze et al.* [2006]. In the easternmost segment of section $a - a'$ there is large southward FWT, despite small northward geostrophic surface current. We find there that only in the upper 50 m of the water column is the positive (northward) geostrophic shear sufficient to offset negative shear at lower levels. Southward current below that level carries relatively freshened water in the same direction as the traditional BG circulation, but at a higher rate.

[11] An analogous finite-difference calculation across the south-to-north section along 150°W, labeled $b - b'$ in Figure 1b, showed much enhanced westward FWT across the southern part of the Canada Basin: the total from 2008 stations is 1.72×10^5 m³s⁻¹ versus 0.45×10^5 m³s⁻¹ for climatology. In the central leg of section $b - b'$ (between 73° and 74°N) the westward geostrophic current component at 20 m depth is 8 cm s⁻¹, about five times the climatological value. By continuity, this is consistent with increased southward FWT at the eastern end of section $a - a'$ and
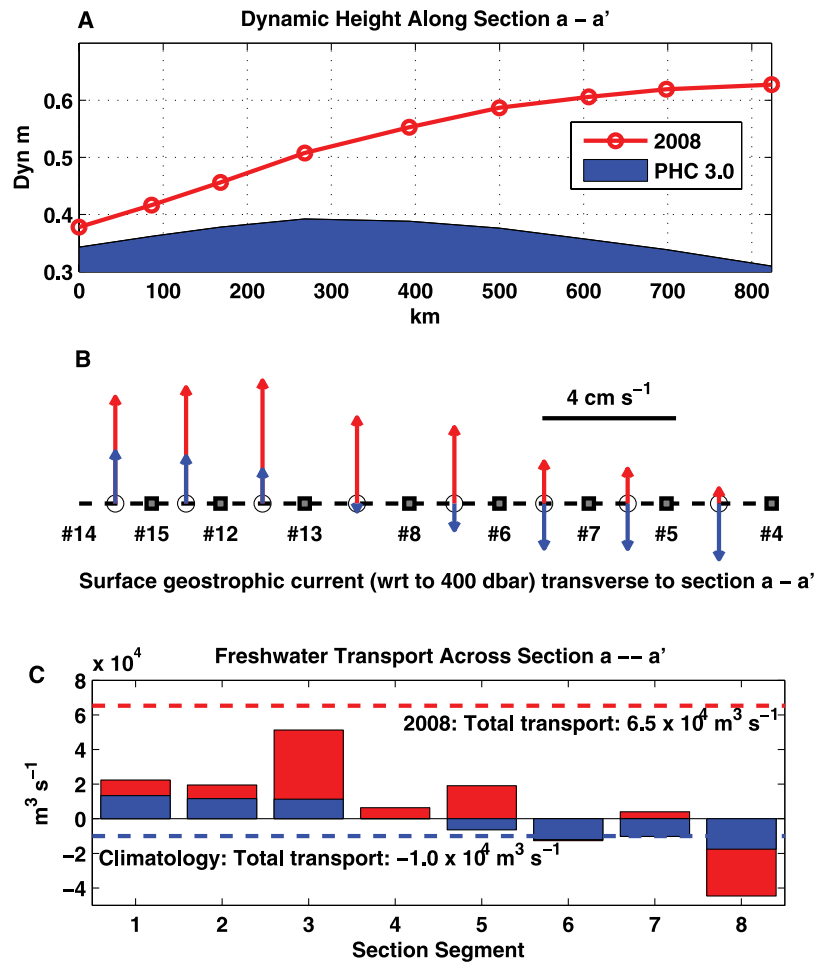
Figure 2. (a) Surface dynamic height along 2008 section $a - a'$ (solid curve with circles) compared with climatological values along the same line (shaded). (b) Corresponding surface geostrophic flow component perpendicular to the section (i.e., bearing 20° true at 150°W) for the 2008 survey (red vectors, numbers indicate station designation) and PHC 3.0 climatology (blue). (c) Total fresh-water transport perpendicular to the section in each segment. Sums for all segments are indicated by the dashed lines.

indicative of an overall increase in the circulation strength of the BG.

[12] Why has so much fresh water accumulated in the Canada Basin? The sheer volume of FWC change seems to rule out local melting of sea ice as a dominant source, even if accumulated over several years: e.g., a change in FWC of 11 m would require nearly 17 m of ice melt not balanced by ice formation and export. Preliminary chemical analyses conducted on water samples collected during the aerial hydrographic survey indicate meteoric water (river runoff plus precipitation) and Pacific water were the dominant sources of fresh water. We note that interannual variability in the relative contributions of Pacific water, ice melt, and meteoric water to the springtime freshwater inventory are difficult to determine, owing to the limited availability of data collected from this region during this time of year [Carmack et al., 2008]. Examination of ITP profiles from 2006 and 2007 at locations where the buoys have traversed the same region as selected stations in the 2008 survey, showed that while substantial freshening had occurred earlier, by 2008 it had penetrated deeper in the water column by tens of meters. We doubt that this can be attributed to surface driven turbulent mixing, which is

severely limited by the extreme density stratification now present.

[13] A plausible explanation for our findings derives from work by Proshutinsky et al. [2002, 2009], who have shown that seasonal and decadal variations of FWC in the Beaufort Gyre are associated with changes in atmospheric forcing: when anticyclonic conditions (high surface air pressure) dominate, FWC increases and spins up the BG, and vice versa. The essential mechanism, based on principles identified first by Ekman [1905], is that mass transport in the combined sea ice and ice-ocean boundary layer (IOBL) system is ideally 90° to the right (Northern Hemisphere) of the forcing wind stress, which in turn is typically 20–30° left of the geostrophic wind. Consequently, an anticyclonic wind pattern induces substantial mass transport toward the anticyclone center, and by continuity must induce a downward velocity (Ekman pumping) at the base of the IOBL, proportional to stress curl [e.g., McPhee, 2008]. Proshutinsky et al. [2002] liken this to a "flywheel" that stores potential energy and fresh water during periods of anticyclonic atmospheric circulation, and releases them when the regime is cyclonic.

[14] Ogi et al. [2008] have shown that cross-isobar sea ice drift, associated with anomalously high sea level pres-
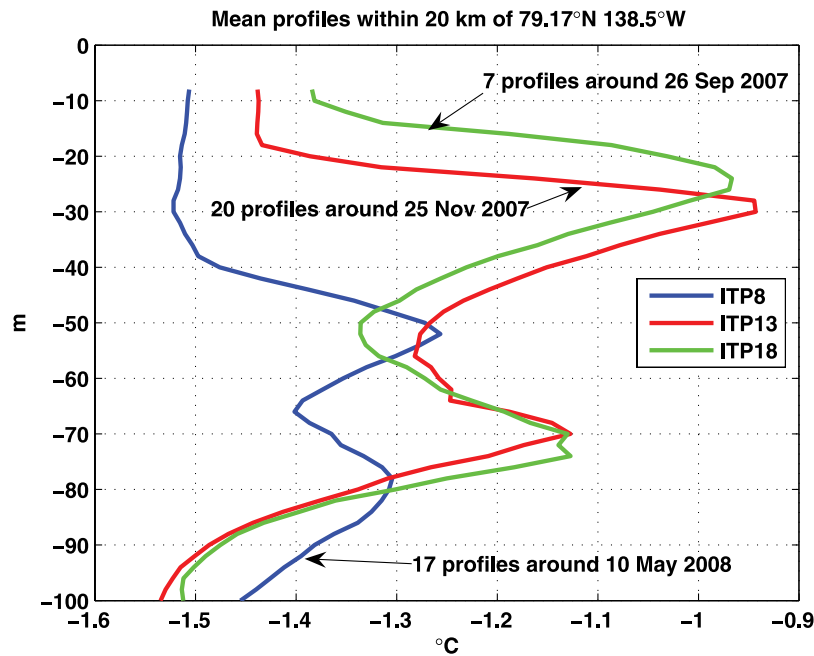
Figure 3. Mean temperature profiles when ITP trajectories crossed a common region in the Canada Basin at different times spanning the 2007–2008 winter.

sure during summer, 2007, contributed to the observed record low ice extent observed that year, by herding sea ice from the periphery toward the high-pressure center over the Canada Basin. Such conditions also favor freshwater convergence, with enhanced Ekman downwelling as illustrated by an example drawn from three different unmanned ITP buoys (Figure 3). All three had drifted at different times ranging from freeze-up (Sep, 2007), to late winter (May, 2008) within a 20-km radius of one location (79.17°N, 138.5°W) in the Canada Basin. Density of seawater near freezing depends almost entirely on salinity, with temperature often approximating a gravitationally passive tracer [*McPhee*, 2008]. In our interpretation, the upper temperature maximum on 26 Sep 2007 (green trace) marks heating from summer, 2007, insolation. By late winter (blue trace) the maximum is still present about 27 m lower, indicating a mean downward velocity of roughly 3.5 meters per month, consistent with the deepening observed from Sep to late Nov, 2007 (red trace). For comparison, an average perpendicular gradient in ice velocity of only 0.01 m s^{-1} per 100 km would provide sufficient stress curl to maintain the required downwelling velocity.

[15] Recent precipitous decrease in old, strong sea ice [*Rothrock et al.*, 1999; *Maslanik et al.*, 2007; *Nghiem et al.*, 2007] has contributed to the trends identified above in several ways. Reduction in ice strength has increased the direct coupling between wind and the IOBL [see, e.g., *McPhee*, 1980], enhancing the tendency for Ekman convergence and downward pumping. However, markedly increased stratification has decreased the capacity of the IOBL to directly mix fresh water downward by turbulence, tending to further decouple the relatively mobile fresh water in the upper layers from the deeper ocean, except by the Ekman pumping mechanism.

[16] The direction of total FWT for a given wind (visualize, e.g., northerly winds toward Fram Strait in the eastern

Arctic) depends critically on whether fresh water is mainly locked in sea ice, or resides instead as liquid in the IOBL. In the absence of internal ice forces, ice drift direction would typically be 10–20° right of the atmospheric isobars, whereas IOBL mass transport would be 65–70° degrees rightward. As a trend for ice melting earlier in the season continues, we anticipate substantial changes in FWC distribution from this effect alone.

[17] Our analysis suggests that in the Canada Basin, where the observed freshening has significantly increased potential energy in the water column, the system is adjusting by increasing FWT toward the Canadian Archipelago and Fram Strait. Across much of the deep Canada Basin, there is now a large northward FWT where previously there was none. Along its western, southern, and extreme eastern margins the clockwise circulation appears to have strengthened substantially. As described by *Proshutinsky et al.* [2002], a shift in atmospheric regime toward a more cyclonic state, lacking in recent summers [*Ogi et al.*, 2008], would "spin off" fresh water by IOBL divergence and upwelling. Combined with strengthened circulation across the Arctic, this would substantially increase freshwater import and stratification in the Nordic Seas and North Atlantic, as suggested by *Peterson et al.* [2006]. It will be fascinating to observe how this rapidly changing oceanic system evolves, and a clear challenge facing the climate community is adequately modeling the processes contributing to these changes in order to predict how and when this altered system will interact with the rest of the world ocean.