GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L07602, doi:10.1029/2006GL029016, 2007

Recent trends in Arctic Ocean mass distribution revealed by GRACE

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Received 6 December 2006; revised 24 January 2007; accepted 6 March 2007; published 4 April 2007.

[1] Measurements of ocean bottom pressure by the Gravity Recovery and Climate Experiment (GRACE) and new in situ bottom pressure measurements confirm the accuracy and utility of GRACE measurements in the Arctic Ocean. They reveal a declining trend in bottom pressure that corresponds to mass changes due to decreasing upper ocean salinities near the North Pole and in the Makarov Basin. The spatial distribution and magnitude of these trends suggest the Arctic Ocean is reverting from the cyclonic state characterizing the 1990s to the anticyclonic state that was prevalent prior to the 1990s. **Citation:** Morison, J., J. Wahr, R. Kwok, and C. Peralta-Ferriz (2007), Recent trends in Arctic Ocean mass distribution revealed by GRACE, *Geophys. Res. Lett.*, *34*, L07602, doi:10.1029/2006GL029016.

1. Introduction

[2] The 1990s saw major changes in the Arctic Ocean mass distribution and circulation. Results from many oceanographic studies [e.g., *Carmack et al.*, 1997; *Morison et al.*, 1998] showed that the boundary between the more saline Atlantic-derived upper ocean waters and fresher Pacific-derived waters swung counterclockwise from over the Lomonosov Ridge to roughly parallel with the Alpha and Mendeleyev ridges resulting in a more cyclonic circulation. These changes were manifest in the central Arctic near the North Pole as increases in upper ocean salinity and Atlantic Water temperature. Changes in the ocean occurred in concert with a decrease in surface atmospheric pressure, which was part of a change in atmospheric circulation of the Northern Hemisphere associated with a high Arctic Oscillation (AO) index [*Thompson and Wallace*, 1998]. An increase in the AO is associated with a cyclonic spin up of the Polar Vortex. *Morison et al.* [2000] hypothesize that the decadal-scale changes in the Arctic were related to the intensification of the AO. Like the ocean circulation, the ice drift in the 1990s was shifted counterclockwise 40°–60° from the 1979–1992 pattern [*Morison et al.*, 1998]. Reductions in sea-ice extent [e.g., *Parkinson et al.*, 1999] and thickness (43% over 25 years) [*Rothrock et al.*, 1999] can also arguably be related to this change in atmospheric forcing [*Rigor and Wallace*, 2004; *Lindsay and Zhang*, 2005].

[3] To track and understand changes in the circulation of the Arctic Ocean, we examine in situ and satellite observations of ocean bottom pressure. Variation of pressure distribution is central to variability in ocean circulation and can be thought of in two parts: variations in sea surface height (SSH) and variations in the density distribution (steric effects). Bottom pressure is the sum of both of these. Assuming the inverse barometer effect holds, changes in atmospheric pressure are balanced by a component of SSH change, with a combined contribution that does not affect bottom pressure.

[4] As the ocean is predominately hydrostatic, the time-varying gravity fields produced by the Gravity Recovery and Climate Experiment (GRACE) satellite mission can be used to estimate the fluctuating part of ocean bottom pressure [*Dickey et al.*, 1997; *Wahr et al.*, 1998; *Wahr et al.*, 2002]. The GRACE gravity fields are provided in the form of spherical harmonic coefficients, given at monthly intervals. Here, we use Release 1 fields from the University of Texas Center for Space Research (CSR). We use 42 monthly fields from April 2002 to April 2006. The fields have been post-processed by S. Swenson (personal communication, 2006) to reduce noise, using the method described by *Swenson and Wahr* [2006]. GRACE does not recover spherical harmonic degree-one coefficients. Instead, we use continental water storage estimates from the GLDAS/Noah land surface model [*Rodell et al.*, 2004] to compute and include those coefficients. Because the gravity fields lose accuracy at short wavelengths (i.e. high harmonic degrees), spatial smoothing is required to obtain accurate bottom pressure results. We apply a Gaussian smoothing function to the post-processed results, with a half-amplitude radius of 400 km [*Wahr et al.*, 1998].

[5] Errors in the GRACE bottom pressure results derive from a combination of measurement errors, temporal aliasing, and leakage from non-oceanographic signals. Aliasing occurs because GRACE does not monitor the entire Earth continually during a given month, but samples the gravity field only along its orbital path. At low and mid-latitudes, the interval between satellite passes at any one spot is long enough that large, short-period (<60 days) signals from the general barotropic circulation of the ocean [*Stammer et al.*, 2000; *Tierney et al.*, 2000], from ocean tides, and from variations in the distribution of atmospheric mass can all alias into the spherical harmonic descriptions of the GRACE measurements. CSR reduces the aliasing in their Release 1 fields by removing the output of a barotropic ocean model [*Ali and Zlotnicki*, 2003] with no Arctic Ocean component, a separate TOPEX-based ocean tide model (R. Eanes, The CSR 4.0 global ocean tide model, 2002, available at ftp://ftp.csr.utexas.edu/pub/tide), and atmospheric mass variations over land computed using ECMWF atmospheric fields. The monthly averages of the barotropic ocean model output can be added back to the GRACE monthly solutions if desired, though this is not necessary for our applications, since the ocean model has no Arctic Ocean signal. Contamination of the spherical harmonics by alias-

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0094-8276/07/2006GL029016

ing in the central Arctic is not as critical as at lower latitudes because the GRACE satellites pass over the North Pole region (89° orbit inclination) on each orbit, approximately every 1.5 hours. It is assumed that the inverse barometer effect applies to the Arctic Ocean so that changes in atmospheric pressure do not appear as changes in bottom pressure.

[6] Leakage from non-oceanographic signals occurs partly because there can be gravity signals caused by post-glacial rebound (PGR) in the underlying solid Earth, and partly because our smoothing functions can extend over land, particularly at near-coastal locations. We remove the PGR signal by subtracting predictions computed using *Peltier*'s [2004] ICE-5G deglaciation model and VM2 viscosity profile. Comparison of results using a range of lower mantle viscosities in the deglaciation model indicate a residual GRACE uncertainty of 0.3 cm yr^{-1} (we will refer to bottom pressure in terms of cm water layer equivalent) due to PGR.

[7] In coastal regions, there are bottom pressure errors associated with changes in the distribution of water, snow, ice and atmospheric density changes over land. Prior to filtering, we correct for the leakage from water and snow on land using the GLDAS model, to reduce this error.

[8] *Kanzow et al.* [2005] have compared GRACE time-varying ocean bottom pressure (though without the benefit of first post-processing the gravity fields) to in situ pressure measurements in the tropical northwest Atlantic Ocean. They find large differences between the bottom pressures from GRACE and those from the in situ gauges. From 2002–2003, their GRACE values show about a 4 cm peak-to-peak variation. The seasonal fluctuations measured by their in situ instruments are nearly negligible (<1 cm). They conclude that GRACE overestimates ocean bottom pressure variability, likely due to shortcomings in removal of tidal and non-tidal sub-inertial signals.

[9] For an independent measure of Arctic Ocean circulation change and ground truth observations for GRACE, we have worked with NOAA's Pacific Marine Environmental Lab (C. Meinig et al., Real-time deep-ocean tsunami measuring, monitoring, and reporting system: The NOAA DART II description and disclosure, 2005, available at http://nctr.pmel.noaa.gov/Dart/Pdf/DART_II_Description_6_4_05.pdf) to develop precision Arctic Bottom Pressure Recorders (ABPR) that are suitable for long-term deployment (up to 3 years) by aircraft landed on sea ice. The ABPRs use Paroscientific Digiquartz 410K-101, 10,000 psi (68.94 MPa) pressure sensors with resolution of 0.25 mm and sensitivity better than 1 mm of water. They sample pressure and temperature every 15 minutes and store the data. Upon command from the surface, the instruments, resting on the bottom, transmit the stored data to the surface using internal Benthos ATM-880 acoustic modems and ATM-421 transducers. A characteristic of these pressure sensors is that instrumental drift decreases with time under high pressure, so accuracy is improved the longer the instruments remain undisturbed. The acoustic modem allows us to gather the pressure data annually without disturbing the instrument and interrupting the pressure record and without the risk and logistical cost of retrieving the instrument through sea ice. Each unit is equipped with an acoustic release for instrument recovery at the end of the 3-year instrument battery life.

2. Observations

[10] In April 2005, we deployed two ABPRs in conjunction with the North Pole Environmental Observatory (NPEO) operations. ABPR1 was deployed at N89°15.260′, E60°21.58′ in 4,300 m of water near the NPEO mooring site. A second instrument, ABPR3, was deployed near the base of the Lomonosov Ridge at N89°14.85′, E148°7.54′ in 4,200 m of water. In April 2006, we recovered a full year of data from both ABPR1 and ABPR3.

[11] The data from the two gauges (Figure 1) are the first in situ bottom pressure measurements and empirical tide information in the central Arctic Ocean. Figure 1 (top) and Figure 1 (middle) show the full bottom pressure signals. The ABPR1 record is trimmed to the length of ABPR3 record, and a spurious 8 cm step-like shift in the ABPR3 pressure near the beginning of the record, perhaps due to a settling of the instrument anchor, has been removed. De-tided pressures (Figure 1, bottom) were computed using the T_TIDE Matlab analysis programs of *Pawlowicz et al.* [2002].

[12] The most significant tidal constituent for the ABPR1 record is M2 tide (frequency = 0.0805 cph) with 6.3-cm amplitude. This is in good agreement with the magnitude of Arctic Ocean Tidal Inverse Model (AOTIM) (L. Padman and S. Erofeeva, A barotropic inverse tidal model for the Arctic Ocean, 2006, available at http://www.esr.org/AOTIM/Arctic_Tides_2col.pdf), which predicts an M2 amplitude of 5.9 cm. The S2 tide (0.0833 cph) is about 2.8 cm (AOTIM = 2.7 cm). Other significant components are the K1 tide (0.0417 cph) at 3.1 cm (AOTIM = 1.6 cm) and O1 tide (0.0387 cph) at 2.2 cm (AOTIM = 1.0 cm). Aside from M2 and S2, the AOTIM produces amplitudes of about half of the observed tides. Likely owing to the small tidal amplitudes, agreement in phase between AOTIM and the observations is inconsistent. The ABPR1 tide results are representative of the ABPR3 results. Both sites show a 3.2 cm fortnightly tide, MF, though due to non-tidal energy near that frequency, the signal to noise ratio for MF is 2.3–2.7.

[13] The de-tided ABPR records show fairly well correlated (correlation coefficient equals 0.98) 10-day to seasonal fluctuations that are about 10–20 cm peak-to-peak. These are superimposed on declining trends of about 10 cm over one year subsequent to an initial transient. The RMS difference between the gauges is 1.63 cm.

[14] The comparison between GRACE-derived bottom pressure at the North Pole and the ABPR data (Figure 2) shows good agreement. Because the GRACE ocean bottom pressure at the average position of ABPRs is filtered with a 400 km radius filter, the GRACE footprint easily covers both ABPRs. In Figure 2, the ABPR records are averaged together in the same 30-day bins used for GRACE. The absolute value of bottom pressure is unknown, so the ABPR record is shifted to match its average to the GRACE average over the period of the ABPR record. The ABPR and GRACE records show differences of 3.10 cm RMS mainly at 1–2 month time scales. Agreement at longer time-scales is good. Some of the difference is likely due to comparing ABPR point measurements with the inherent spatial averages of the GRACE observations.

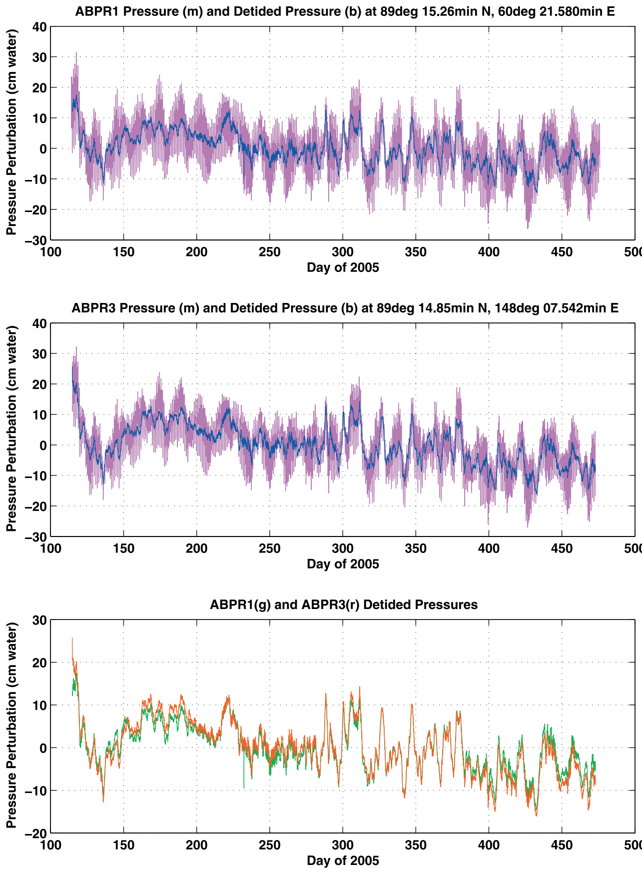

Figure 1. (top) ABPR1 and (middle) ABPR3 pressure perturbations and de-tided pressure perturbations. (bottom) De-tided perturbations from the two instruments are well correlated.

[15] A conservatively large, data-based, estimate of the GRACE uncertainty is given by simultaneously fitting a constant, a trend, and annually and semi-annually varying terms to two-year blocks of the GRACE series and computing the RMS of the residuals. Compensating for a 6% reduction in variance due to the fitting procedure, this GRACE data-based estimate of uncertainty equals 2.8 cm. The RMS difference between the records from the two ABPRs, 120 km apart, smoothed over 30 days is 1.56 cm. The 3.10 cm RMS GRACE-ABPR difference, combined with the data-based 2.8 cm GRACE uncertainty, would imply a 1.3 cm ABPR error, assuming the ABPR and GRACE errors are uncorrelated. That is only slightly smaller than the 1.56 cm RMS difference between the two ABPR's. Although the true uncertainty is not known, the consistency of the ABPR and GRACE uncertainty estimates gives us confidence that the GRACE uncertainty is on the order of 2.8 cm or less, with the qualification that some of this uncertainty is likely due to real variability at time-scales between monthly and semiannual.

[16] It is noteworthy that *Kanzow et al.* [2005] indicated that observed ocean bottom pressure variations increased with latitude, and thus might produce better signal to noise ratios at high latitudes. Our data (Figures 1 and 2) suggest this is true. The de-tided ABPR signals are about 4 times larger than those reported by *Kanzow et al.* [2005] for the tropical North Atlantic, and the tidal amplitudes are 3 or 4 times smaller, resulting in a much better signal to noise ratio for high-latitude non-tidal signals. Furthermore, because the GRACE satellite footprint passes over the Pole region about 12 times more often than the sites near the equator, aliasing should be reduced considerably in the Arctic Ocean.

[17] Both GRACE and the ABPRs show the same declining trend in 2005–2006 (Figure 2). GRACE indicates this has been going on since the start of the GRACE record in 2002 and amounts to -2.43 cm yr^{-1} or about a 10-cm decrease in bottom pressure through 2006. (Over 4 years, the uncertainty in GRACE trends associated with the 2.8 cm uncertainty in monthly values is 0.37 cm yr^{-1}.) The trend appears to be associated with a density change, or steric change of mass for fixed SSH, due to a drop in upper ocean salinity near the Pole. *Morison et al.* [2006] describe the change in hydrography near the Pole as tracked for the last 6 years by the NPEO. They have seen a reduction in upper ocean salinity associated with a change in central Arctic Ocean circulation, which they argue is related to the decline in the AO index. This represents a relaxation toward the hydrographic state prior to 1990 as described by the *Environmental Working Group* (*EWG*) [1997] climatology. The average bottom pressure change computed as the integral of in situ density over the upper 500 m of all the NPEO hydrographic casts taken each year since 2000 within 200 km of the Pole (Figure 2), shows good agreement with the GRACE and ABPR trends through 2005. The most recent NPEO hydrographic data from April 2006, taken in

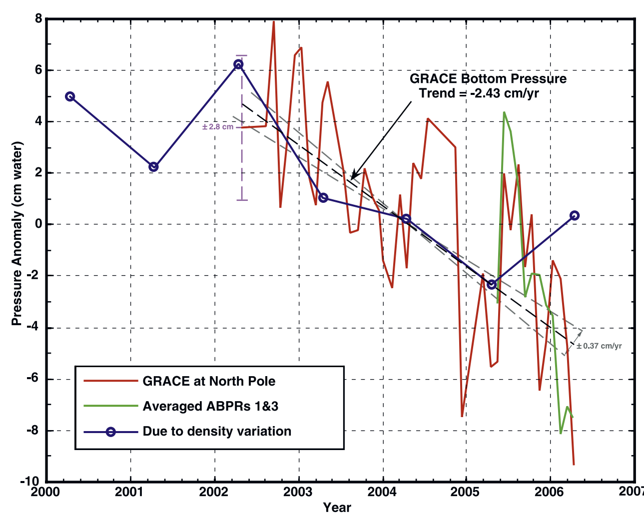

Figure 2. Bottom pressure anomaly at the North Pole from monthly averages of GRACE, 30-day combined averages of ABPR1 and ABPR3 in time bins identical to GRACE, and due to mass changes resulting from decreases in upper ocean salinity as measured by NPEO within 200 km of the Pole. The GRACE data have been subjected to a 400 km Gaussian filter, and PGR and terrestrial hydrologic signals have been removed as discussed in the text. The uncertainty in GRACE pressure (±2.8 cm) derived as described in the text is illustrated by the magenta, vertical dashed-line. The corresponding uncertainty in GRACE pressure trend (±0.37 cm yr^{-1}) is illustrated by the two gray dashed-lines.

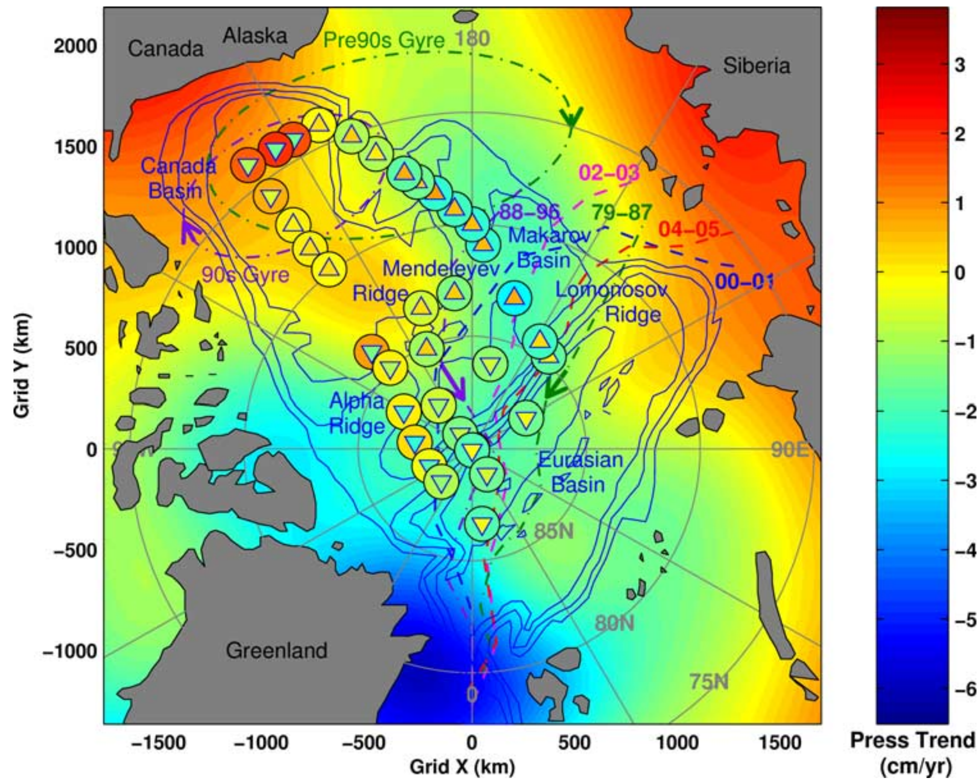

Figure 3. Contours of GRACE-derived trends in bottom pressure in the Arctic Ocean from 2002 to 2006, and circles at the Pargo '93 stations showing the trends in steric pressure associated with a hypothetical return to pre-1990 hydrography. The triangles are color-coded to indicate trends in hypothesized sea surface height changes (bottom pressure minus mass change effect). Positive SSH trends are indicated by upward pointing triangles and negative trends by downward pointing triangles. The GRACE data was treated to the same processing as in Figure 2. The uncertainty in GRACE trends is conservatively estimated to be 0.37 cm yr^{-1}. Also shown are the ice zero vorticity lines and approximate Beaufort Gyre size from *Steele and Boyd* [1998] and the zero vorticity lines for 2000–01, 2002–03, and 2004–05 from the IABP (I. Rigor, personal communication, 2006).

locations nearly identical to the 2001 and 2004 locations, do not indicate a continuation of the trend but return to roughly 2004 conditions, a trend reversal consistent with NPEO mooring time series results (K. Aagaard, personal communication, 2006). The 2006 reversal may be associated with a decrease in SSH.

[18] Figure 2 suggests sea level changes are not contributing greatly to the bottom pressure change at the Pole. There is some supporting evidence for this. *Sharoo et al.* [2006] have reported that sea surface elevation measured by satellite altimetry has decreased by 2 mm, at least for the periphery of the Arctic Ocean, which clearly is a small change compared to the observed change in bottom pressure. Furthermore, the ICESat altimeter data (2003–2006) taken at maximum latitude, selected for open water regions, and averaged over 2-month periods in winter, Feb–Mar, and 2 months in the fall, Oct–Nov, yield no significant trend in SSH.

[19] The change in the Arctic Ocean in the 1990s was characterized by an increase in upper ocean salinity in the Makarov Basin due to the counterclockwise swing of the front between more saline Atlantic-derived waters and less saline Pacific-derived waters. While *Morison et al.* [2006] are able to show that from 2000 to 2005, hydrographic conditions near the North Pole relaxed to nearly the ocean state prior to 1990, they do not have the hydrographic station coverage to reveal change over the whole Arctic Ocean. Contours of GRACE bottom pressure trends (Figure 3) indicate a 2 cm yr^{-1} decrease in bottom pressure in the Makarov Basin region between 140°E and 170°W. This is the same region that showed the largest increase in upper ocean salinity during the early 1990s [*Morison et al.*, 1998, 2000].

[20] To test whether the GRACE derived pressure trends are consistent with a relaxation to climatology, we examine the hypothesis, consistent with the findings of *Morison et al.* [2006], that conditions in the central Arctic Ocean in 2000 were similar to those found during the 1993 cruise of the *USS Pargo* (i.e., the cyclonic state of the 1990s), and that by 2006 conditions had relaxed to the anticyclonic state of the pre-1990 climatology of *EWG* [1997]. For each 1993 *Pargo* station location (Figure 3), we have plotted a circle color-coded to indicate the steric pressure trend that would apply if this hypothesis were true. The hypothetical steric pressure trends at most of the *Pargo* stations are in the same sense and about 30% greater (1.2 cm y^{-1} RMS vs. 0.9 cm y^{-1} RMS) than the bottom pressure trends from GRACE for the same locations. The Makarov Basin, between the Lomonosov Ridge and the Alpha/Mendeleyev ridges, experiences a drop in bottom and steric pressure associated with a decrease in upper ocean salinity, and in the Beaufort Sea, bottom and steric pressure trends are positive.

[21] We might be concerned that the positive trends in bottom pressure near the Alaska coast in the GRACE signal represent leakage of a terrestrial hydrologic signal. However, we used the GLDAS/Noah model to reduce that leakage and found that, with or without this correction, fundamental trends in the region are largely unchanged. The hydrographic data suggest the trend can be accounted for partly by increasing salinity. Low salinities observed in the Beaufort Sea in the late 90s have been attributed to ice melt [*McPhee et al.*, 1998] and McKenzie River runoff [*Macdonald et al.*, 2002]. Numerical model results [*Steele et al.*, 2006] suggest that reduced ice growth and consequent brine production in the fall and the anomalous northwestward advection of McKenzie River water in 1997–99 created a low salinity anomaly in the upper Beaufort Sea until summer 2002, when it dissipated. The dissipation of this anomaly could account for the increasing pressure trend observed by GRACE and suggested by the hypothetical change in hydrography since that time. The increasing bottom pressure trend on the eastern Siberian shelf would also be consistent with the shift from 1990s conditions in which runoff from the Ob and Yenisey rivers ($\sim$80°E) was carried anomalously eastward [*Steele and Boyd*, 1998] and freshened the East Siberian shelf.

[22] The three Pargo stations around 87°N, 90°–130°W show negligible hypothetical bottom pressure trends compared to the negative GRACE trends at the same locations. This is because these locations, unlike their near neighbors, showed evidence in 1993 of an intrusion of fresh Pacific-derived water eastward along the Canadian Archipelago, which was displaced by more saline water prior to the start of the GRACE mission [*Morison et al.*, 2006].

[23] Hypothetical sea surface height trends are equal to GRACE bottom pressure trends minus the hypothetical steric trends at the *Pargo* locations and are represented by color-coded triangles at the Pargo station locations (Figure 3). In most locations (e.g. the Makarov Basin and the Beaufort Sea), these SSH trends, at 0.8 cm y^{-1} RMS, are smaller than the bottom and steric pressure trends and in the opposite sense.

[24] The decreasing trend in SSH in the Beaufort Sea and the rising trend in the eastern Makarov Basin are consistent with an enlargement and westward shift of the Beaufort Gyre and clockwise rotation of the axis of the Transpolar Drift. The lines of zero-vorticity of average ice velocity for 1979–87 and for 1988–96 from *Steele and Boyd* [1998] are shown in Figure 3. These are an indication of the axis of the Transpolar Drift. We also show schematic representations of the corresponding gyre shape for those periods. The hypothesized shift back toward pre-1990 climatology would likely involve a shift in the zero-vorticity line from a pattern similar 1988–96 to a pattern more like 1979–87. Zero-vorticity lines averaged from the data of the International Arctic Buoy Program (IABP) (I. Rigor, personal communication, 2006) for 2000–01, 2002–03, and 2004–05 demonstrate just such a tendency. The corresponding enlargement and westward shift of the Beaufort Gyre would correspond to a drop in SSH near Alaska and rise in SSH farther west as shown by the hypothesized SSH trends. Thus, the hypothesized change in circulation is consistent with the GRACE data and with trends in ice drift over the last six years. We also note that the hypothetical SSH trend at the Pole is zero, in agreement with the NPEO surveys (Figure 2) and consistent with the fact that all the zero-vorticity lines pass near the Pole.

3. Conclusion and Some Speculation

[25] The agreement between the hypothetical hydrographic change and the GRACE observations tells us how the return to a pre-1990 state in the North Pole region, described by *Morison et al.* [2006], applies to the whole Arctic Ocean. The result is fundamentally important for understanding the relative roles of decadal variability and long-term climate change in the Arctic. Since the 1990s, some trends, such as decreasing ice extent, have continued in spite of a relaxation of the AO to lower levels, and they raise concerns that global warming is driving the Arctic to an ice-free state. The GRACE results (Figures 2 and 3) and *Morison et al.* [2006] suggest that at least the "wet" Arctic Ocean is gradually relaxing to a climatological circulation in response to a weakened AO.

[26] The decreasing pressure trend in Fram Strait (Figure 3) could be associated with a decrease in the net outflow from the Arctic Ocean. No correction has been made to the data of Figure 3 for possible mass signal leakage from Greenland, so we cannot rule out loss of glacier mass as a cause. However, given a lack of supporting observations for ice loss in Northeast Greenland (I. Joughin, personal communication, 2006), we should not rule out an oceanographic effects. *Steele and Ermold* [2007] indicate that Arctic Ocean steric sea level has been dropping at a rate of about 2 mm yr^{-1} in agreement with *Sharoo et al.* [2006], and that this is leading to a reduction in the net flow from the Arctic Ocean to the North Atlantic. The net outflow from the Arctic Ocean would involve a reduction in pressure on the west side of Fram Strait as observed in Figure 3.

[27] **Acknowledgments.** This work was supported by NSF grants OPP-0326109, OPP-0326109, OPP-0324721, and OPP-0326109.

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