



Relaxation of central Arctic Ocean hydrography to pre-1990s climatology

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Received 7 May 2006; revised 26 July 2006; accepted 1 August 2006; published 8 September 2006.

[1] Upper ocean hydrography in the central Arctic Ocean has relaxed since 2000 to near-climatological conditions that pertained before the dramatic changes of the 1990s. The behavior of the anomalies of temperature and salinity in the central Arctic Ocean follow a first-order linear response to the AO with time constant of 5 years and a delay of 3 years.

Citation: Morison, J., M. Steele, T. Kikuchi, K. Falkner, and W. Smethie (2006), Relaxation of central Arctic Ocean hydrography to pre-1990s climatology, *Geophys. Res. Lett.*, *33*, L17604, doi:10.1029/2006GL026826.

1. Introduction

[2] In the 1990s, changes in the marine Arctic were widespread and seemingly systematic. The influence of Atlantic water in the Arctic Ocean became more widespread [e.g., Carmack *et al.*, 1997]. The front separating more saline Atlantic-derived upper-ocean water from less saline Pacific-derived waters moved from a pre-1990 position roughly over the Lomonosov Ridge [Environmental Working Group (EWG), 1997] counterclockwise to rough alignment with the Alpha-Mendelyev ridge system. The pattern of water circulation and ice drift shifted with it [Morison *et al.*, 1998] resulting in a more cyclonic circulation and weakening of the cold halocline layer that isolates the ice cover from warm Atlantic water [Steele and Boyd, 1998]. These changes were manifest as a 2 psu increase in salinity of the upper 200 m at the North Pole and in the Makarov Basin and as a 1–2°C increase in Atlantic Water temperature along the continental slopes and Lomonosov Ridge. The changes in the 1990s roughly corresponded to a strengthening of the Arctic Oscillation (AO) [Thompson and Wallace, 1998]. The rising AO index includes a drop in surface atmospheric pressure over the Arctic and a cyclonic spin up of the polar vortex. Arguably, such a pattern brings more warm air into the Greenland Sea and increases the temperature of Atlantic water transported into the Arctic Ocean [Morison *et al.*, 2000]. The more cyclonic atmospheric circulation results in the shift in the Atlantic-Pacific upper-ocean front and more cyclonic ocean circulation. Several modeling studies support these ideas [e.g., Proshutinsky and Johnson, 1997; Zhang *et al.*, 2000].

[3] The purpose of the North Pole Environmental Observatory (NPEO) is to track and understand change in the Central Arctic Ocean. Annually since 2000, it has deployed an automated drifting station and made airborne hydrographic sections radiating from the Pole. This paper describes the recent return to near pre-1990s climatology as observed in the NPEO hydrographic sections and oceanographic buoy drifts.

[4] The NPEO hydrographic surveys utilize ski-equipped De Havilland DHC-6 aircraft that are landed on refrozen leads. A winch operated directly from the aircraft cycles a Sea-Bird SBE-19 internally recording CTD to depths of 500–1000 m. Provision is made for sampling at 4 depths with 1.5 L Niskin bottles and for drawing the water samples in a heated space. Generally we make one 555 km section every year with a station every degree of latitude on a line radiating from the Pole nominally down 90° W, 170° W, 160° E or 90° E. Sections are repeated every 2 or 3 years. Since 2004, a project named Switchyard to study circulation in the sector 70–100°W has made the CTD stations on the 90°W line south of 87°N. Every year NPEO has deployed a JAMSTEC (Japan Agency for Marine-Earth Science and Technology) Compact Arctic Drifter (J-CAD) as part of the Automated drifting station. These buoys typically include 6 Sea-Bird Microcat CTDs suspended at depths to 250 m, and over a period of about 1 year they complete a drift section to Fram Strait.

[5] Chemical analyses of water samples include salinity, phosphate, nitrate, nitrite, ammonium, siliceous acid, barium, oxygen isotopes and dissolved oxygen. Since 2003, we have used a Sea-Bird Electronics SBE-43 dissolved O₂ sensor on the CTD.

[6] Early airborne survey results, 2000 through 2003, suggested that hydrographic conditions remained similar to those in the 1990s, though some relaxation toward climatology was observed [Morison *et al.*, 2002; Steele *et al.*, 2004]. The halocline circulation pattern inferred from O₂ observations is different from a simple boundary-following cyclonic flow [Falkner *et al.*, 2005]. The J-CAD data are consistent with the airborne survey results and have revealed, among other things, changes in cold halocline formation mechanisms [Kikuchi *et al.*, 2004].

2. Comparisons to Climatology Through 2005

[7] We show recent Arctic Ocean change by comparing our observations with winter oceanographic climatology [EWG, 1997]. The values of temperature and salinity from the NPEO CTD are averaged in 4-m bins down to 500 m. The J-CAD data over 5-day periods are averaged in 4-m bins where available, and values for empty bins are interpolated from adjacent depth bins. The gridded EWG aver-

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age (1950–87) data are interpolated in space to the location of each NPEO CTD cast and 5-day average J-CAD position, and these are subtracted from the NPEO data to yield anomalies of salinity and temperature (Figure 1). In 2000–2001 (Figure 1a) the salinities in the upper 150 m near the Pole and in the northern Makarov Basin were elevated 1–2 above climatology and temperatures in the Atlantic Water core along the Lomonosov Ridge were elevated 1–2°C, conditions nearly the same as observed in 1993 [Morison *et al.*, 2000]. In the 2000 section near the coast of the Canadian Archipelago the near-surface salinity (Figure 1a) was reduced 1 below climatology. The temperature and salinity profiles (not shown) are reminiscent of the Beaufort Sea. These conditions are consistent with the 1990s advance toward North America and counterclockwise rotation of the front between saltier Atlantic-derived water on the Eurasian side and less salty Pacific-derived water on the North American side [Morison *et al.*, 1998, Figure 1; Morison *et al.*, 2000, Figures 2 and 3].

[8] Anomaly patterns for 2002–2003 (Figure 1b) are similar to those in 2000–2001. The 2002 hydrographic section angled more toward the center of the Makarov Basin than did the 2001 section. The salinity anomaly there was slightly more intense and the temperature anomaly was more pervasive. Along the 2003 section toward Ellesmere Island the temperature anomalies increased slightly relative to 2000, but the salinity anomalies were reduced slightly, and the fresh anomaly near the coast was gone. Qualitatively, conditions in 2002–2003 were still consistent with the 1990s.

[9] In 2004 and 2005, hydrographic conditions returned to near climatology. The salinity anomalies of the 2004 survey at the Pole and along the line down 90°W, and on the 2004–2005 J-CAD 8 section across the Lomonosov Ridge into the Amundsen Basin (Figure 1c) were less than half those of 2000–01 and 2002–03. Similarly, the 2004 temperature anomalies (Figure 1c) in the Atlantic Water core near the Lomonosov Ridge and Amundsen Basin were half the values of the previous year. Only the southern part of the section down 170°W shows salinity and temperature anomalies close to the 2001 levels.

[10] In 2005 near the Pole and in the west longitudes there was little evidence of the shift in frontal structure that characterized the 1990's. The upper-ocean salinity anomalies (Figure 1d) near the Pole generally decreased to near zero and are consistent with Pacific-derived salinities in the Canadian Basin. Relative to 2000, salinities at the stations closest to Canada increased to essentially climatological values. This suggests a shift in the water mass structure toward climatology in the Canadian sector. Salinity anomalies less than 1 occurred in a thin layer along 90°W and two patches on the J-CAD track through the Amundsen and Nansen basins. The maximum temperature anomalies (Figure 1d) across the Lomonosov Ridge and through the Amundsen and Nansen basins were a little less than in 2004 and nearly all less than 1°C. At the North Pole, the Atlantic Water temperature anomaly, as well as upper ocean salinity, was similar to that found by Anderson *et al.* [1994] in 1991.

[11] Based on a composite of key tracers measured in 1993–96, Jones *et al.* [1998] found that the boundary of 50% Pacific-derived surface waters was roughly along 0°–180° longitude. From this line toward Canada, the surface

waters were more than 50% Pacific-derived. This distribution reflected the 1990s counterclockwise rotation and advance toward Canada of the Atlantic-Pacific boundary [Morison *et al.*, 1998, Figures 1 and 7].

[12] In 2000 and 2001, applying the same composite of tracers used by Jones *et al.* [1998], we found the 50% Pacific-derived surface water boundary farther toward Canada at about 88°N on the 2000 section along 90°W and at 85.5°N on the 2001 section along 170°W. The 70% Pacific-derived surface water boundary (Figure 1a) was found at 87°N, 90°W in 2000 and at 85°N, 170°W in 2001. The position of the Pacific-derived boundaries differed at depth where lesser amounts of Pacific-derived water were found. At 125 m in the 2000 section, the northern boundary of Pacific-derived water (20%) was at 86°N, 70°W. Pacific-derived water below 100 m is limited to about 10% along the 170°W section except possibly at 85°N where at 75m 24% Pacific water was present.

[13] Variability is high near the surface, but overall we saw the Pacific-derived waters move north in west longitudes subsequent to 2001. In 2003, the 80% Pacific-derived surface water was found at 89°N, 90°W, and at the Pole the surface waters were 70% Pacific-derived (Figure 1b), slightly more influenced by the Pacific than in 1993–96. The 20% boundary at 125 m was between 87 and 89°N, along 90°W, north relative to 2000.

[14] For 2004 we have no chemistry data south of 87°N on the 90°W section, but the 70% Pacific-derived boundary was south of that point (Figure 1c). Deeper frontal structure continued to move north along 90°W; the 125-meter 20% Pacific-derived boundary was at 89°N, 90°W. On the 170°W line, the surface boundary was near the 2001 position.

[15] In 2005, Pacific-derived water advanced to the Pole and into east longitudes (Figure 1d). The fraction of Pacific-derived near-surface water near the Pole was substantially higher than found by Jones *et al.* [1998]. In contrast to the near-surface results from NPEO 2000 and 2003, the surface-layer water at 89.4°N, 147.4°E, (“Borneo” base camp), was nearly all Pacific-derived. Samples from 10 and 16 m at Borneo and from 20 m at 89°N 90°W and the North Pole were about 90% Pacific-derived. Despite somewhat sparse spatial coverage, the high Pacific water fraction along 90°W and at 89.4°N, 147.4°W, suggests that the orientation of the Pacific-derived surface water boundary had shifted north and rotated clockwise relative to 1993–96 [Jones *et al.*, 1998].

3. Discussion

[16] The idea that the 1990s pattern of Arctic change is related to a strengthening of the AO [e.g., Steele and Boyd, 1998; Morison *et al.*, 2000; Karcher *et al.*, 2003] has been cast in doubt by continued decreases in ice extent [e.g., Stroeve *et al.*, 2004] in spite of a decline in AO in the mid-1990s. The persistence of thin ice has been explained in terms of the need for a strongly negative AO to allow sea ice to mature [e.g., Lindsay and Zhang, 2005].

[17] With declining AO, there have been reversals in the ocean such as the partial recovery of the cold halocline layer [e.g., Boyd *et al.*, 2002]. However, the return of the central

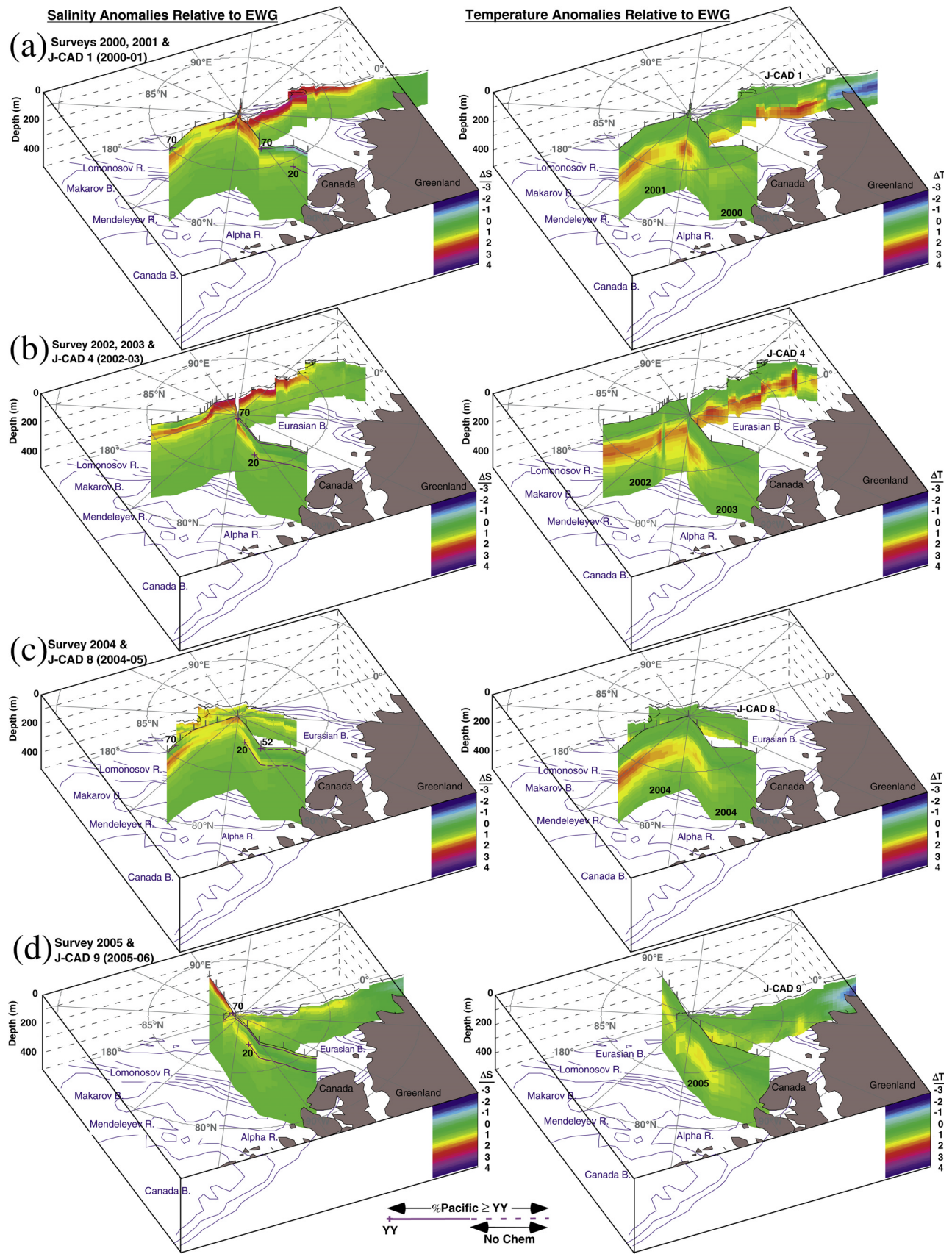


Figure 1. (left) Salinity and (right) temperature anomalies relative to EWG climatology along the NPEO surveys and J-CAD tracks for the years indicated on the temperature sections. Gray vertical lines mark survey station sites. Deep magenta lines (Figure 1, left) mark location of greater than 20% Pacific-derived water at 100–150 m. Surface lines mark greater than 70% Pacific-derived in the surface layer.

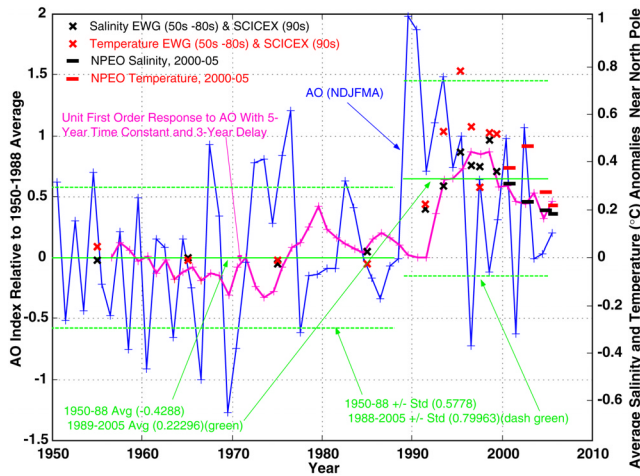


Figure 2. Winter AO Index (NDJFMA) from 1950 to 2005 in blue with a lagged, first-order linear response in magenta and average of North Pole hydrographic section temperature and salinity anomalies from Figure 1 within 100 km of the Pole and to 500m.

Arctic hydrography to near climatology is perhaps the most significant reversion we have seen. It has lagged the decline in AO considerably.

[18] The overlapping reasons for the ocean lag are likely that transport times are significant, the changes in the baroclinic circulation are slow, and the decline in AO has been gradual. Lags in water properties occur in part because, even if circulation remained constant, the transit times required to move a changed water property through the basin are measured in years [Polyakov *et al.*, 2005]. For example, a 7-year lag between Atlantic water temperature rise in the Makarov Basin and that initially seen at the North Pole was found by Kikuchi *et al.* [2005]. More importantly, the time for the ocean circulation to adjust baroclinically to a change in wind forcing is long. Ice and surface water respond almost instantly to changes in the wind field, but for those changes to penetrate to depth in a stratified fluid requires months to years.

[19] We can obtain an estimate for the adjustment time in the central Arctic Ocean by noting that the AO index, averaged November through April (Figure 2), jumped to a high value in 1989–90, yet the water mass changes at the Pole in 1991 were modest [Anderson *et al.*, 1994]. Not until 1995–1996 did the changes in water mass properties first reach extreme levels [Steele and Boyd, 1998]. Steele *et al.* [2004] found a 3-year lag between the AO and the temperature of summer Bering Sea Water in the Lincoln Sea. The time scale for adjustment for the upper ocean appears to be about 3–7 years.

[20] Complicating the picture is that, while the AO declined sharply after 1995, the 1988–2005 average remained about one standard deviation higher than the 1950–1988 average. Only in 1996 and 2001 did the index go appreciably below the 1950–88 average. Perhaps most significantly relative to the relaxation toward climatology seen in 2004 and 2005, it is only in 2003–05 that the AO

Index has remained near the pre-1989 average for three consecutive years.

[21] A simple way to account for baroclinic response, transport lags, and the unsteady nature of the AO decline is to assume the upper (e.g., 0–500 m) ocean near the North Pole generally reacts as a first-order linear response to the AO with time constant, τ , and time lag, θ . Such a response (Figure 2) to the winter (NDJFMA) AO index for $\tau = 5$ years and $\theta = 3$ years is slightly positive by 1991 and peaks in 1996–98 as observed. It also retains some signal past 2000 to at least 2005. The average of salinity and temperature anomalies relative to EWG climatology, from 0 to 500 m depth and from NPEO hydrographic sections within 100 km of the Pole (Figure 1), are well correlated with this response. The average anomalies for the EWG decadal averages and 1990s SCICEX cruises show similarly good agreement. This simple comparison suggests that the slow recovery of the central Arctic Ocean hydrography to climatology with the decline in AO is consistent with the response to the rapid rise in AO in 1989. Obviously, there remains the issue of understanding the time scales and magnitude of the response, but these findings suggest that we cannot dismiss the strength of the AO as a key driver of Arctic Ocean change.

[22] **Acknowledgment.** This work was supported by NSF grants OPP 0352754, OPP 0352984, and ARC 02230427.

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