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Pacific ventilation of the Arctic Ocean's lower halocline by upwelling and diapycnal mixing over the continental margin

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[1] Pacific winter waters, a major source of nutrients and buoyancy to the Arctic Ocean, are thought to ventilate the Arctic's lower halocline either by injection (isopycnal or penetrative) of cold saline shelf waters, or by cooling and freshening Atlantic waters upwelled onto the shelf. Although ventilation at salinity (S) > 34 psu has previously been attributed to hypersaline polynya waters, temperature, salinity, nutrient and tracer data suggest instead that much of the western Arctic's lower halocline is in fact influenced by a diapycnal mixing of Pacific winter waters (with S ~ 33.1 psu) and denser eastern Arctic halocline (Atlantic) waters, the mixing taking place possibly over the northern Chukchi shelf/slope. Estimates from observational data confirm that sufficient quantities of Atlantic water may be upwelled to mix with the inflowing Pacific waters, with volumes implying the halocline over the Chukchi Borderland region may be renewed on timescales of order a year. **Citation:** Woodgate, R. A., K. Aagaard, J. H. Swift, K. K. Falkner, and W. M. Smethie Jr. (2005), Pacific ventilation of the Arctic Ocean's lower halocline by upwelling and diapycnal mixing over the continental margin, *Geophys. Res. Lett.*, *32*, L18609, doi:10.1029/2005GL023999.

1. Introduction

[2] The major distinction between upper waters of the western/eastern Arctic Ocean is the presence/absence of Pacific waters which have entered the Arctic Ocean via the Bering Strait and the Chukchi Sea. These waters are the richest source of nutrients to the Arctic, provide almost 1/3rd of the Arctic freshwater inflow, and are a significant source of oceanic heat [*Walsh et al.*, 1989; *Woodgate and Aagaard*, 2005]. Being fresher (hence less dense) than the Atlantic inflow, they lie above the Atlantic temperature maximum (~300 m), bolstering the halocline, which provides a density barrier between the warm Atlantic water and the overlying sea-ice.

[3] Pacific waters entering the Arctic exhibit a strong seasonal cycle [e.g., *Woodgate et al.*, 2005a, hereinafter referred to as Wetal05]. Summer waters, traced as temperature maxima at salinity (S) < 33.1 psu, spread over the western Arctic, with pathways linked to atmospheric circulations [e.g., *Steele et al.*, 2004]. Pacific winter waters (PWW) have temperature-salinity (T-S) properties similar to halocline waters of eastern Arctic (here termed Atlantic) origin, and are traced by high nutrients (centered at ~33.1 psu at near-freezing temperatures (Tf)); low dissolved oxygen (relative to layers above and below); and a depression of isohalines [*Jones and Anderson*, 1986; hereinafter referred to as JA86].

[4] Mechanistically, PWW are thought to influence the Arctic halocline by two main processes [*Aagaard et al.*, 1981]: 1) injection (isopycnal or penetrative) of cold, saline shelf waters; or 2) cooling and freshening of Atlantic waters, upwelled at irregular intervals onto the shelf.

[5] Isopycnal injection can maintain the Arctic 33.1 psu, high nutrient layer, since PWW match these T-S properties [e.g., in Bering Strait, Wetal05]. Although halocline ventilation at S > 33.1 psu is often attributed to hypersaline polynya waters [*Weingartner et al.*, 1998; *Shimada et al.*, 2005, hereinafter referred to as Setal05], we suggest instead that much of the western Arctic halocline contains waters influenced by the second, upwelling mechanism, and that even without hypersaline waters, via diapycnal mixing with upwelled Atlantic waters, the Pacific waters influence the halocline to depths of 200 m, significantly below the undisturbed depth of their isopycnal in the Arctic.

2. Data

[6] In 2002, nutrient, CTD-O and CFC data were collected to WOCE standards on a 5-week hydrographic survey (CBL2002) of the Chukchi Borderland and Mendeleev Ridge (CBLMR) region of the western Arctic (Figure 1). Data are accurate to ~0.002°C; ~0.002 psu; ~1 dbar; <2 μmol/kg (CTD-oxygen, calibrated against bottle samples); <1 μmol/kg (silicate); and the larger of 0.01 pmol/kg or 1% (CFC-11).

3. Diapycnal Mixing in T-S Space

[7] Data from the CBLMR region (Figure 2) show the PWW silicate maximum centered on S ~ 33.1 psu (JA86). Note however that the Pacific influence extends to waters saltier (and deeper). For S between ~33.1 and 34 psu, whilst the Atlantic-dominated (low silicate) halocline remains near-freezing with increasing depth, the Pacific-influenced (higher silicate) halocline increases in temperature.

[8] Individual profiles from this region in 2002 suggest a diapycnal mixing between the ~33.1 psu, near-freezing

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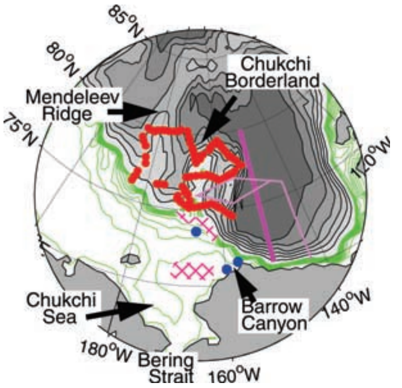

Figure 1. The Chukchi Borderland-Mendeleev Ridge (CBLMR) region, with CBL2002 stations (red); Barrow Canyon and Chukchi shelf mooring sites (blue); Chukchi Sea CTD locations (magenta hatched) from *Bourke and Paquette* [1976] ∼ 71°N, and *Münchow et al.* [2000] and SBI (http://www.joss.ucar.edu/sbi/) ∼ 74°N; and CTD lines of Setal05 (magenta line at ∼150°W) and *McLaughlin et al.* [2004] (light pink lines). Grey shaded contours indicate bottom depth, with interval 500 m (with waters shallower than 500 m contoured at 50 m intervals in green).

layer and the lower halocline near 34.3 psu and −0.6°C (Figure 3), waters usually found at depths of 120–180 m in the western Arctic. Other tracers, such as silicate, CFC-11 and dissolved oxygen (DO) support this conclusion, which was also hinted at by JA86. Note that mixing with hypersaline polynya waters (S > 34 psu and T ∼ Tf) would (in contrast) cool the 34 psu waters (Figure 3), a process not evident in our data, nor in that of Setal05. In fact, Chukchi polynya processes are generally not required to provide the S ∼ 33.1 psu, T ∼ Tf waters, since waters of these properties enter the Chukchi Sea in winter via the Bering Strait (Wetal05).

[9] The Chukchi shelf (∼50–100 m deep) is significantly shallower than the 34.3 psu isohaline further offshore (∼180 m near the Chukchi slope, ∼120 m in the deeper basin). The 33.1 psu waters are ∼1 kg/m^3 less dense than the 34.3 psu waters, ruling out penetrative convection. Thus, to mix these two waters, the 34.3 psu waters must be elevated to the depth of the 33.1 psu waters.

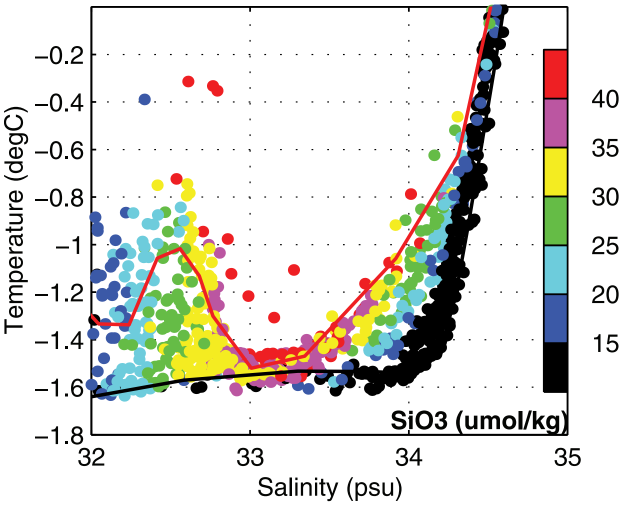

Figure 2. T-S scatter-plot of CBL2002 data, dot color indicating silicate value as per color scale. Solid lines show typical Atlantic (black) and Pacific (red) halocline profiles, as in Figure 3.

[10] The upwelling of Atlantic waters has been observed in Barrow Canyon, correlated to wind events and/or shelf waves [e.g., *Mountain et al.*, 1976; *Aagaard and Roach*, 1990]. From T-S data (Figure 1), we argue that similar upwelling processes occur on the Chukchi shelf, e.g., at 75°N in 1993 [e.g., *Münchow et al.*, 2000, their Figure 3], and in 2002 and 2003 (Shelf-Basin Interaction, http://www.joss.ucar.edu/sbi/). *Bourke and Paquette* [1976] observed modified Atlantic water at 70°N in the Chukchi Sea, in water ∼20 to 30 m deep. Furthermore, new time-series from the 110 m isobath of the northern Chukchi slope (166°W) in autumn 2002 show pulses of waters 10 m above bottom which follow the mixing lines found in the CBLMR data in 2002.

[11] Thus, up-slope advection of Atlantic water occurs frequently and extensively over the northern Chukchi shelf. Although data are insufficient to quantify the shelf extent of this upwelling or the process of mixing, we can estimate the area of influence of this upwelling/mixing within the Arctic.

4. Spatial Influence of Diapycnally Mixed Pacific Waters

[12] Elevated T (>−1.4°C) and silicate (>20 µmol/kg) on the 34 psu isohaline are indicative of waters influenced by the diapycnal mixing process (Figure 2). For the 2002 data, these parameters (Figure 4) show the Pacific influence at S ∼ 34 psu across the Chukchi Plateau, although not west of the Mendeleev Ridge. North of the Chukchi Plateau, the Pacific influence on this isohaline decreases with increasing latitude and bottom depth, being virtually absent north of the 2000 m isobath at ∼79°N. The center of the ∼50–80 m

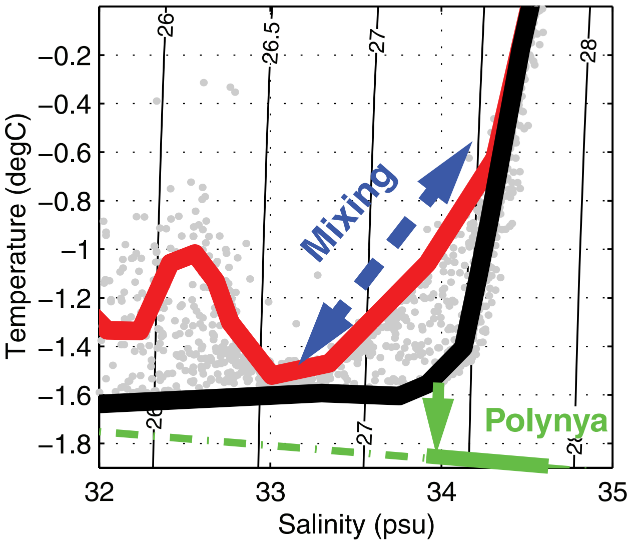

Figure 3. T-S scatter-plot of CBL2002 data (grey), showing typical Atlantic (black) and Pacific (red) halocline profiles, and hypersaline polynya waters (green). Arrows mark changes due to the diapycnal mixing process (blue) and the intrusion of polynya waters (green).

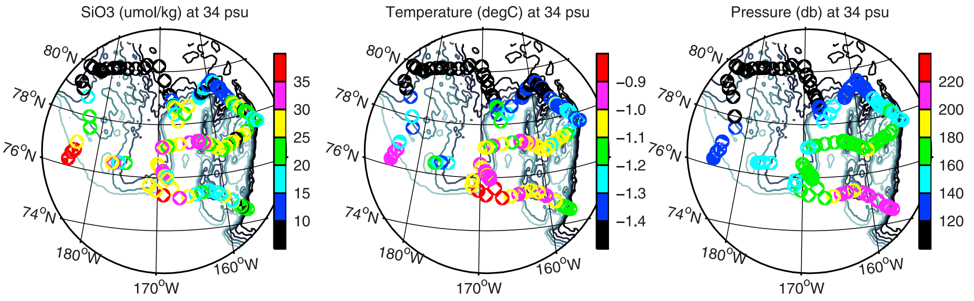

Figure 4. Distribution of silicate (left), temperature (middle) and pressure (right) on the 34 psu isohaline from CBL2002 data. Background contours are bottom depth (interval 500 m, with light colors shallower).

thick layer (taken as the 34 psu isohaline) is at nearly 200 m depth near the Chukchi slope (Figure 4).

[13] The T-S mixing line defining this layer is also evident at 150°W (Figure 1), in the data of Setal05 (their Figure 2 "Oxygen-poor LHW"), suggesting that this process has influence as far north/east as 76°N at 150°W in 2002/2003. The mixing line is also a distinctive feature of the "Type II" waters of *McLaughlin et al.* [2004], found in their 1997 and 1998 data throughout the Canada Basin and over the Northwind Ridge (Figure 1) but only over the southern portion of the Chukchi Plateau.

[14] Thus it appears that diapycnally ventilated Pacific water influences much of the western Arctic halocline, with interannual variability over the Chukchi Plateau region (cf. changes in Pacific water pathways discussed by *Steele et al.* [2004]).

5. Ventilation as Shown by CFC-11 and Oxygen (DO)

[15] The mixing line of the diapycnal process is evident in individual profiles (not shown) of other tracers (e.g., CFC-11 and DO), however, their distributions on the 34 psu isohaline (e.g., Figure 5 for CFC-11) also reflect the spatial inhomogeneity of these tracers in the end-members. For example, the lower CFC-11 values in the diapycnally influenced region are due not only to the mixing of lower CFC-11 Atlantic water up, but also reflect that the Pacific ∼33.1 psu waters are poorer in CFC-11 than the Atlantic ∼33.1 psu waters.

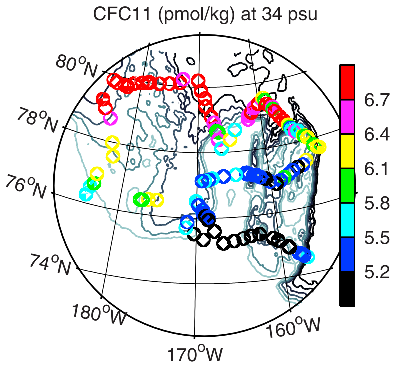

Figure 5. Distribution of CFC-11 on the 34 psu isohaline from CBL2002 data. Background contours as in Figure 4.

[16] DO values in the region are low for all Pacific waters (note the high silicate in the low DO waters in Figure 6) due to biological activity (cf. *Falkner et al.* [2005] for discussion of the multiple minima structure). Note the 33.1 and 34.3 psu end-members both have low DO (<280 μmol/kg) close to the slope and high DO (>300 μmol/kg) far from the slope (Figure 7). Within the diapycnally ventilated region, the DO-data exhibit an almost linear mixing line from S ∼ 33.1 to S ∼ 34.3 psu (left panel, Figure 7). Outside this region (right panel, Figure 7) the DO-minimum is centered on ∼33.1 to 33.5 psu (suggesting isopycnal ventilation by Pacific waters, JA86), with higher DO-values and near-freezing temperatures at S ∼ 34 psu, indicative of a dominantly Atlantic halocline at this depth.

[17] Setal05 also address these two forms of DO-profile, assigning western Chukchi origin to waters with lower oxygen (∼240 μmol/kg) for S between ∼33 and 34 psu (red/magenta lines in our right panel, their red curves) and eastern Chukchi origin to waters with higher oxygen (∼270 μmol/kg) for the same salinity range (our left panel, their blue curves), concluding primarily that the DO ∼ 270 μmol/kg values in the eastern waters are due to input of polynya waters. Although we agree that these DO ∼ 270 μmol/kg waters are probably of eastern Chukchi origin,

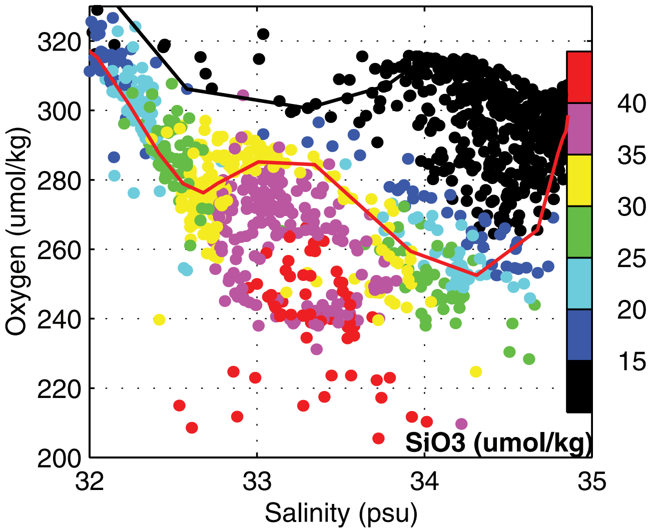

Figure 6. DO-S scatter-plot of CBL2002 data, dot color indicating silicate value as per color scale. Solid lines show typical Atlantic (black) and Pacific (red) halocline profiles.

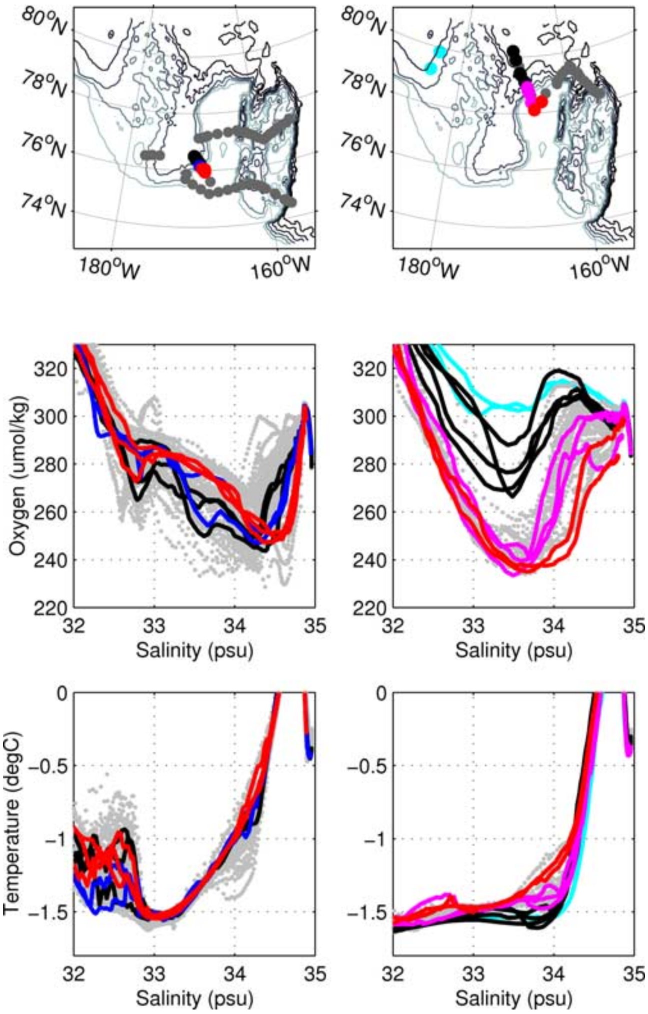

Figure 7. Location map with depth contours as in Figure 4 (top) and typical profiles for DO-S (middle) and T-S (bottom) within the diapycnally ventilated region (left panels) and outside that region (right). Within each column, color indicates location as per map. Grey dots represent stations with similar profiles (background in bottom figures).

we suggest this reflects the lower biological activity of the eastern Chukchi, not polynya formation, noting in addition that (a) the salinity range of the DO ~ 270 μmol/kg waters is within that entering the Chukchi via Bering Strait, (b) polynya waters would cool, not warm the halocline (as discussed above), and (c) estimated volumes of polynya water formation on the Chukchi shelf (~3 × $10^{11}$$m^3$/yr [*Weingartner et al.*, 1998; *Winsor and Chapman*, 2002]) are an order of magnitude too small to effect this widescale a ventilation in the Arctic (see below).

6. Estimated Budgets for Arctic Ventilation

[18] Essential to the hypothesis of our paper is a sufficient supply of upwelled Atlantic water.

[19] The Pacific inflow through the Bering Strait provides the dominant source of the shelf end-member (S ~ 33.1 psu, T ~ Tf), order 6 × 10^{12} m^3/yr of water (~0.6 Sv for 4 months, Wetal05), influencing a ~60 m layer of the Arctic halocline, of which order half is Pacific water. Spread laterally as a 30 m thick layer, the PWW would cover (in 1 year) ~2 × 10^{11} m^2, say 450 km × 450 km, i.e., comparable to the region suggested above (~4° of latitude, ~20° of longitude at 77°N). A 1-year residence time for the region (consistent with observed interannual variability) would correspond to spreading speeds of a few cm/s (450 km in 4–12 months).

[20] Our data suggest the PWW are split about equally between the 33.1 psu layer (~15 m thick) and the diapycnally ventilated layer (~50 m thick, but a mix of Pacific and Atlantic water). Thus, to mix with the PWW, we require ~3 × 10^{12} m^3/yr of upwelled Atlantic water.

[21] Data from the head of Barrow Canyon, 71°N [*Woodgate et al.*, 2005b] show that a single up-canyon flow event bringing ~34 psu, −1°C water may last for ~5 days at ~50 cm/s, yielding a volume of ~2–3 × 10^{11} m^3. Thus of order 10 events per year would suffice for our mechanism. Whilst only 2 major events occurred in the 1 year of observations at this site, *Mountain et al.* [1976] recorded 6 events over 1 year just down the Barrow Canyon axis from this site. *Aagaard and Roach* [1990] report several events of similar magnitude in 1986–1987 data. The CTD and mooring data from 200–300 km west discussed above (see Figure 1) show the process also to occur elsewhere along the Chukchi slope. It is, thus, plausible that a sufficient quantity of Atlantic water could be elevated throughout the northern Chukchi slope region.

[22] Note that the numbers cited here for ventilation are an order of magnitude greater than volume estimates of polynya water formation (see above).

7. Conclusions

[23] This paper suggests that a major part of the western Arctic lower halocline is influenced by an upslope advection/mixing process, whereby waters of the lower halocline (S > 34 psu, T ~ −1°C) are lifted up onto the Chukchi Sea slope/shelf to mix diapycnally with less dense Pacific waters. The fingerprint of this process in T-S space, in tracer distributions and DO-S space suggests pathways for Pacific waters in the Arctic. Whilst further studies are necessary to establish the forcing for this process and the dynamics of the mixing [cf. *Aagaard and Roach*, 1990], the wind/shelf wave forced nature of the upwelling suggests that to first order, changes in thermohaline properties of the Pacific throughflow (e.g., interannual variability) will not affect the efficiency of the process, but may alter Arctic halocline properties up to depths of 200 m.

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References

Aagaard, K., and A. T. Roach (1990), Arctic ocean-shelf exchange: Measurements in Barrow Canyon, *J. Geophys. Res.*, *95*(C10), 18,163–18,175.

Aagaard, K., L. K. Coachman, and E. Carmack (1981), On the halocline of the Arctic Ocean, *Deep Sea Res., Part A*, *28*, 529–545.

Bourke, R. H., and R. G. Paquette (1976), Atlantic water on the Chukchi shelf, *Geophys. Res. Lett.*, *3*(10), 629–632.

Falkner, K. K., M. Steele, R. A. Woodgate, J. Swift, K. Aagaard, and J. Morison (2005), Dissolved oxygen extrema in the Arctic ocean halocline from the North Pole to the Lincoln Sea, *Deep Sea Res., Part I*, *52*, 1138–1154.

Jones, E. P., and L. G. Anderson (1986), On the origin of the chemical properties of the Arctic Ocean halocline, *J. Geophys. Res.*, *91*, 10,759–10,767.

McLaughlin, F. A., E. C. Carmack, R. W. Macdonald, H. Melling, J. H. Swift, P. A. Wheeler, B. F. Sherr, and E. B. Sherr (2004), The joint roles of Pacific and Atlantic-origin waters in the Canada Basin, 1997–1998, *Deep Sea Res., Part I*, *51*, 107–128.

Mountain, D. G., L. K. Coachman, and K. Aagaard (1976), On the flow through Barrow Canyon, *J. Phys. Oceanogr.*, *6*(4), 461–470.

Münchow, A., E. C. Carmack, and D. A. Huntley (2000), Synoptic density and velocity observations of slope waters in the Chukchi and East-Siberian Seas, *J. Geophys. Res.*, *105*(C6), 14,103–14,119.

Shimada, K., M. Itoh, S. Nishino, F. McLaughlin, E. Carmack, and A. Proshutinsky (2005), Halocline structure in the Canada Basin of the Arctic Ocean, *Geophys. Res. Lett.*, *32*, L03605, doi:10.1029/2004GL021358.

Steele, M., J. Morison, W. Ermold, I. Rigor, M. Ortmeyer, and K. Shimada (2004), Circulation of summer Pacific halocline water in the Arctic Ocean, *J. Geophys. Res.*, *109*, C02027, doi:10.1029/2003JC002009.

Walsh, J. J., et al. (1989), Carbon and nitrogen cycling within the Bering/Chukchi seas: Source regions for organic matter effecting AOU demands of the Arctic Ocean, *Prog. Oceanogr.*, *22*, 277–359.

Weingartner, T. J., D. J. Cavalieri, K. Aagaard, and Y. Sasaki (1998), Circulation, dense water formation, and outflow on the northeast Chukchi shelf, *J. Geophys. Res.*, *103*, 7647–7661.

Winsor, P., and D. C. Chapman (2002), Distribution and interannual variability of dense water production from coastal polynyas on the Chukchi Shelf, *J. Geophys. Res.*, *107*(C7), 3079, doi:10.1029/2001JC000984.

Woodgate, R. A., and K. Aagaard (2005), Revising the Bering Strait freshwater flux into the Arctic Ocean, *Geophys. Res. Lett.*, *32*, L02602, doi:10.1029/2004GL021747.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner (2005a), Monthly temperature, salinity, and transport variability of the Bering Strait through flow, *Geophys. Res. Lett.*, *32*, L04601, doi:10.1029/2004GL021880.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner (2005b), A year in the physical oceanography of the Chukchi Sea: Moored measurements from autumn 1990–1991, *Deep Sea Res., Part II*, in press.

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