Decrease of river runoff in the upper waters of the Eurasian Basin, Arctic Ocean, between 1991 and 1996: Evidence from $\delta^{18}O$ data

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[1] Measurements of the $H_2{}^{18}O/H_2{}^{16}O$ ratio of water from two sections crossing the Eurasian Basin in 1991 and 1996 show that the observed decrease in the freshwater contained in the upper waters of the Eurasian Basin during the 1990s is due to decrease in meteoric water (mainly river runoff). The decrease in meteoric water inventories between 1991 and 1996 calculated from balances of mass, salinity, $\delta^{18}O$, and PO_4* is about 3 meters and accounts for basically the entire freshwater change inferred from salinity budgets. Climatological data are used to ensure that the two sections can be considered to belong to the same hydrographic regime. The data also suggest that in 96 the formation of sea ice from the upper waters in the Amundsen Basin was lower by about 1 meter (3 m in 1996 compared to 4 m in 1991). *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4215 Climate and interannual variability (3309); 4825 Oceanography: Biological and Chemical: Geochemistry

1. Introduction

[2] During the past decade, significant changes have been observed in the Arctic including changes in the oceanic circulation (e.g., [*Carmack et al.*, 1995; *McLaughlin et al.*, 1996; *Morison et al.*, 1998]). One notable feature among these is the retreat of the cold halocline over the Eurasian Basin [*Steele and Boyd*, 1998]. If such a retreat were to continue for an extended period of time, the heat flux from the Atlantic layer to the sea-ice cover might increase to a degree that complete melting would result [*Martinson and Steele*, 1999]. This could lead to a partially ice-free Arctic basin, significantly changing the Arctic climate. To understand the reasons for the apparently retreating halocline and its possible future evolution, the role of the individual freshwater components (river runoff and precipitation, sea-ice meltwater, and low-salinity Pacific Water) has to be known. *Steele and Boyd* [1998] hypothesize that the retreat of the halocline in the Eurasian Basin is due to a decrease in the presence of river runoff in the upper water column. Such a scenario is supported by recent modeling work. [*Maslowski et al.*, 2000; *Newton*, 2001].

[3] The $H_2{}^{18}O/H_2{}^{16}O$ tracer is an established tool for studies of transport and exchange processes in natural systems (see, for example, [*Craig*, 1961]). This method has been used successfully in the northern high latitudes over the past decades [*Redfield and Friedman*, 1969; *Ostlund and Hut*, 1984; *Schlosser et al.*, 1994; *Bauch et al.*, 1995; *Macdonald et al.*, 1989, 1995; *Khatiwala et al.*, 1999; *Ekwurzel et al.*, 2001] to identify and quantify the contribution of freshwater to specific marine water masses. We extend previous work by comparing the fractions of the individual freshwater sources to the upper waters of the Eurasian Basin along two sections occupied 5 years apart (Arctic 91 Expedition and ACSYS 96 cruise).

2. Sample Collection and Measurement

[4] Data presented in this study are from two Arctic Ocean sections (Figure 1). The first was occupied by the Swedish icebreaker ODEN during the Arctic 91 expedition between August 17 and September 4, 1991. The second one was carried out between July 31 and August 14, 1996 on the German icebreaker POLARSTERN (ACSYS 96; ARK XII). Since the southern ends of the sections are geographically separated, we use climatological data to show that the two sections fall into the same hydrographic regime (Figures 2a and 2b). Samples for measurement of the $H_2{}^{18}O/H_2{}^{16}O$ ratio of water were collected from a CTD/rosette system equipped with 24 Niskin bottles (volume of 10 liters) and stored in 100-ml glass bottles sealed with plastic caps. The depth resolution of the profiles was about 20 meters in the upper 100 meters of the water column and increased to about 50 to 100 meters at 500 meters depth. Measurements were performed in the Lamont-Doherty Earth Observatory stable isotope laboratory. After equilibrating the water sample with CO_2 at a constant temperature [*Epstein and Mayeda*, 1953; *Roether*, 1970; *Fairbanks*, 1982], the isotope

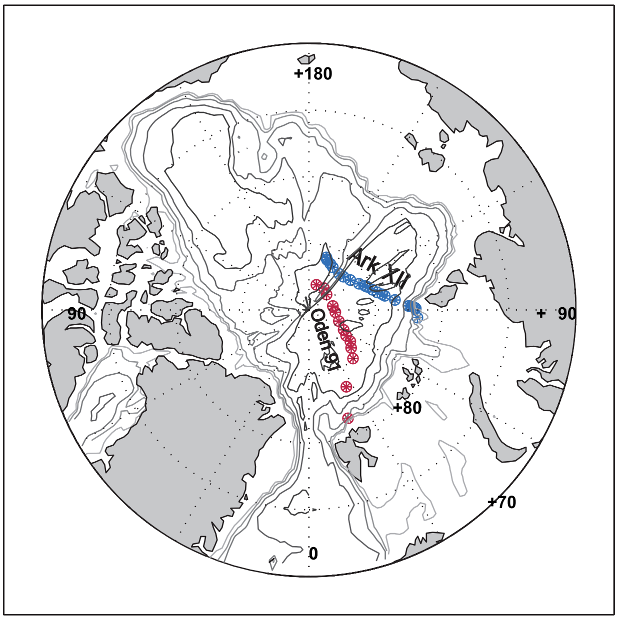

Figure 1. Geographic location of the stations occupied during the ARCTIC 91 expedition (Oden 91) and the ACSYS 96 expedition (ARK XII).

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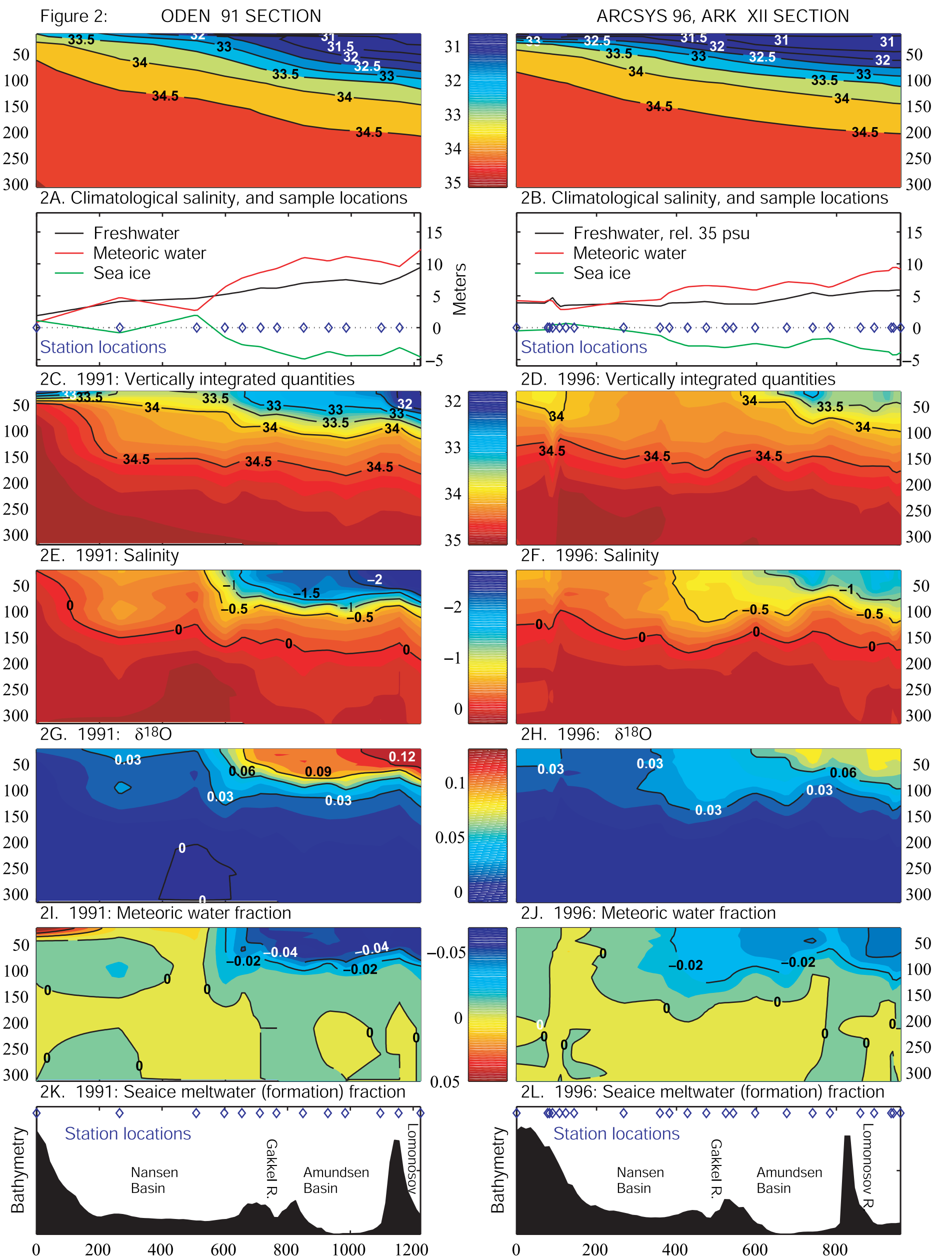

Figure 2. Sections of salinity (a, b) from the EWG climatology, freshwater component inventories (c, d), observed salinity (e, f), measured $\delta^{18}O$ (g, h), calculated meteoric water fraction (i, j), and calculated sea-ice meltwater fraction (k, l). Also shown are the topography and station locations along the two sections.

ratio of the CO_2 gas was measured using a dedicated mass spectrometer (VG Prism II). Oxygen isotope ratios are reported as $\delta^{18}O$ or the per mil deviation of the sample from that of Vienna Standard Mean Ocean Water (VSMOW) [*Craig*, 1961; *Gonfiantini*, 1981]. Measurement precision was about ±0.02 to 0.03 per mil. Temperature, salinity, oxygen and nutrient samples were analyzed on each ship using techniques reported in *Anderson et al.* [1989, 1994], and *Swift et al.* [1997].

3. Results and Discussion

3.1. Observed Salinity and $\delta^{18}O$

[5] Both the 91 and 96 salinity sections show a freshwater lens (here defined by the 34.5 isopleth) typical for the upper ca. 50 to 100 meters (Figures 2e and 2f). The salinity in the top few 10s of meters decreases from the shelf towards the Lomonosov Ridge with a particularly strong gradient over the Gakkel Ridge separating the Nansen and Amundsen Basins. North of the continental slope, there is a strong increase in salinity in the surface over the Amundsen Basin between 91 and 96 (Figures 2e and 2f) as already described by *Steele and Boyd* [1998]. The minimum salinity in the 91 section was about 31.7 over the Lomonosov Ridge. It increased to values of about 32.8 in the 96 section. A remarkable change is the significant decrease in stratification in the 96 Nansen Basin portion of the section compared to the 91 section. The $\delta^{18}O$ and salinity distribution patterns are very similar, with isopleths slanting down to the north along both sections and a strong gradient over the Gakkel Ridge (Figures 2g and 2h). Away from the continental slope, there is a significant increase in $\delta^{18}O$ related to the salinity increase. The lowest $\delta^{18}O$ values in the 91 and 96 sections are about −2.5 and −1.4, respectively, on the Canadian

side of the Lomonosov Ridge. Over the continental slope, the influx of Barents Sea water makes comparison difficult. Qualitatively, the salinity and $\delta^{18}O$ distributions indicate a decrease in freshwater of meteoric origin.

3.2. Freshwater Components

[6] Figures 2i and 2j show the calculated fractions of near-surface waters originating from meteoric sources (for details of the calculations, see *Ekwurzel et al.* [2001]). Figures 2k and 2l show the calculated sea-ice meltwater (positive values) or deficit due to sea ice formation (negative values). The meteoric water and sea-ice meltwater are concentrated in the upper 50 to 100 meters of the water column.

[7] In the 91 section, the meteoric water fractions reach from values between 2 and 4% near the shelf to more than 12.5% over the Lomonosov Ridge. The mean value over the Amundsen Basin was about 11% in the upper 50 meters. If we integrate these fractions between the surface and the core of the Atlantic Water (by definition zero freshwater), we obtain inventories that range from close to zero at the shelf to about 4 meters near the Gakkel Ridge. Between the Gakkel and Lomonosov ridges (Amundsen Basin), the inventories are about 10 to 12 meters (Figure 2c, red line). These values are about 3 to 4 meters higher than those calculated from salinity (about 6 to 8 meters; Figure 2c, black line). This difference is due mainly to sea ice formation that distills freshwater into the solid phase and leads to negative sea ice melt water fractions in the water column (Figures 2c and 2d, green lines; Figures 2k and 2l; see also [*Bauch et al.*, 1995]).

[8] In the 96 section, the meteoric water fraction was lower by several percent than in the 91 section. The maximum values in the upper 50 meters of the Amundsen Basin and over the Lomonosov Ridge were about 9%. The related meteoric water inventories were about 6 meters over the Amundsen Basin and reached a maximum of about 9 meters over the Lomonosov Ridge. These values are about 2 to 3 meters higher than those calculated from salinity data (4 to 5.5 meters; Figure 2d). The difference is accounted for by the addition of the meteoric water and the negative sea-ice melt (i.e.: ice formation, which adds salt to the water column). The 1991 sea ice meltwater fractions were about 2% in the surface waters close to the Barents shelf and dropped to about −4% over the Amundsen Basin and the Lomonosov Ridge (Figure 2k). The 96 values were close to zero at the Voronin Trough and about −3 and −4% over the Amundsen Basin and the Lomonosov Ridge (Figure 2l). For the 91 section, the sea ice inventories are about 4 to 5 meters over the Amundsen Basin and the Lomonosov Ridge. The sea-ice inventories calculated for the 96 section are lower (about 3 meters) over the Amundsen Basin (Figures 2c and 2d). The difference is small but probably significant with lower sea ice formation during 96.

[9] The average decrease in meteoric water residing in the water column between 91 and 96 was about 4 meters over the Amundsen Basin and 3 meters over the Lomonosov Ridge. This is a reduction of the average 91 inventory by about 38 to 50%, and is the main difference between the 91 and 96 sections. It accounts for basically the entire salinity increase observed between 91 and 96.

3.3. Comparability of 91 and 96 Sections

[10] In order to ensure that the 91 and 96 sections, which have different starting points in the Nansen Basin, are representing the same hydrographic regime, we extracted climatological sections from the summer EWG (Environmental Working Group) hydrographic data set along the two section tracks in the Eurasian Basin (Figures 2a and 2b). Over the continental shelf and slope the Ark-XII section is somewhat fresher. We understand this in the framework developed by *Schauer et al.* [1997]: the Ark-XII section includes input from the Barents Sea Branch of Atlantic inflow as well as Kara Sea water, which have been freshened by sea ice meltwater and meteoric waters. Away from the shelf the two transects are essentially identical. There are no significant sources or sinks of water type between them. We conclude that the large changes recorded between 91 and 96 result from temporal changes in the hydrographic regime, and not from spatial sampling variations.

4. Conclusions

[11] The $\delta^{18}O$ data from the sections across the Eurasian Basin of the Arctic Ocean occupied in 1991 and 1996 provide evidence for a decrease in the meteoric water inventory in the upper water column, especially over the Amundsen Basin. At the same time it appears as if the amount of sea ice formed from the waters observed at the two sections running across the Eurasian Basin was lower in 96 compared to 91. Fine-scale studies of the Eurasian shelf seas indicates that the source of freshwater in these areas is strongly dominated by runoff (e.g., [*Pavlov and Pavlov*, 1999]). Over the northern Arctic Basin, estimates of precipitation are very low, with most of that being ice-rafted to the south. We conclude that along these transects the meteoric water supply, and its variability, are dominated by runoff, rather than in situ precipitation. The evidence indicates that a reorganization of the horizontal distribution of runoff in the surface ocean, perhaps by a shift in the focus of shelf-basin exchange, is responsible for the dramatic changes in salinity and implied impacts on both dynamic and thermodynamic conditions. The decrease in meteoric water content of the upper waters has reduced the vertical stability of the water column, making it more susceptible to vertical flux of heat during wind events, leading to a more vulnerable Arctic sea-ice cover.

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References

Anderson, L. G., E. P. Jones, K. P. Koltermann, P. Schlosser, J. H. Swift, and D. W. Wallace, The first oceanographic section across the Nansen Basin in the Arctic Ocean, *Deep Sea Research*, *36*, 475–482, 1989.

Anderson, L. G., B. Bjrk, O. Holby, E. P. Jones, G. Kattner, K. P. Koltermann, B. Liljeblad, R. Lindegren, B. Rudels, and J. Swift, Water masses and circulation in the Eurasian Basin: Results from the Oden 91 expedition, *J. Geophys. Res.*, *99*, 3273–3283, 1994.

Bauch, D., P. Schlosser, and R. G. Fairbanks, Freshwater balance and the sources of deep and bottom waters in the Arctic Ocean inferred from the distribution of $H_2{}^{18}O$, *Progress in Oceanography*, *35*, 53–80, 1995.

Broecker, W. S., S. L. Peacock, S. Walker, R. F. Weiss, E. Fahrbach, M. Schroeder, U. Mikolajewicz, C. Heinze, R. Key, T.-H. Peng, and S. Rubin, How much deep water is formed in the Southern Ocean?, *J. Geophys. Res.*, *103*, 15,483–15,883, 1998.

Carmack, E. C., R. Macdonald, R. G. Perkin, F. A. McLaughlin, and R. J. Pearson, Evidence for warming of Atlantic Water in the Southern Canadian Basin of the Arctic Ocean, Results from the Larsen 93 Expedition, *Geophys. Res. Lett.*, *22*, 1061–1064, 1995.

Craig, H., Standard for reporting concentrations of deuterium and oxygen-18 in natural waters, *Science*, *133*, 1833, 1961.

Craig, H., and Gordon, L. I., Deuterium and oxygen 18 variations in the ocean and the marine atmosphere, in *Table Isotopes in Oceanographic Studies and Paleotemperatures. Spoleto Conf. Proc.*, edited by E. Tongiorgi, pp. 9–130, Cons. Naz. Ric., V. Lischi Figli, 1965.

Dansgaard, W., Stable isotopes in precipitation, *Tellus*, *XVI*, 436–468, 1965.

Ekwurzel, B., P. Schlosser, J. H. Swift, R. A. Mortlock, and R. G. Fairbanks, River runoff, sea ice meltwater, and Pacific water distribution and mean residence times in the Arctic Ocean, *J. Geophys. Res.*, *106*, 9075–9092, 2001.

Epstein, S., and T. Mayeda, Variation of oxygen-18 content of waters from natural sources, *Geochem. Cosmochim. Acta*, *4*, 213–224, 1953.

Fairbanks, R. G., The origin of continental shelf and slope water in the New York Bight and Gulf of Maine: Evidence from $H_2{}^{18}O/H_2{}^{16}O$ ratio measurements, *J. Geophys. Res.*, *87*, 5796–5808, 1982.

Gonfiantini, R., The d-notation and the mass-spectrometric measurement techniques, in *Stable Isotope Hydrology: Deuterium and Oxygen-18 in the Water Cycle*, edited by J. R. Gat and R. Gonfiantini, pp. 35–84, International Atomic Energy Agency, Vienna, 1981.

Jones, E. P., L. G. Anderson, and J. H. Swift, Distribution of Atlantic and Pacific waters in the upper Arctic Ocean: Implications for circulation, *Geophys. Res. Lett.*, *25*, 765–768, 1998.

Khatiwala, S., R. G. Fairbanks, and R. W. Houghton, Freshwater contributions to the coastal ocean of Northeasatern North America: Evidence from $H_2{}^{18}O/H_2{}^{16}O$, *J. Geophys. Res.*, *104*, 18,241–18,255, 1999.

Macdonald, R., E. Carmack, F. McLaughlin, K. Iseki, D. Macdonald, and M. O'Brien, Composition and modification of water masses in the Mackenzie shelf estuary, *J. Geophys. Res.*, *94*, 18,057–18,070, 1989.

Macdonald, R., D. Paton, E. Carmack, and A. Omstedt, The freshwater budget and under-ice spreading of the Mackenzie River water in the Canadian Beaufort Sea based on salinity and $^{18}O/^{16}O$ measurements in water and ice, *J. Geophys. Res.*, *100*, 895–919, 1995.

Martinson, D. G., and M. Steele, Future of the Arctic sea-ice cover: Implications of an Antarctic analog, *Geophys. Res. Lett.*, *26*, 1999.

Maslowski, W., R. Newton, P. Schlosser, B. Semtner, and Martinson, Modeling recent climate variability in the Arctic Ocean, *Geophys. Res. Lett.*, *27*, 3743–3746, 2000.

McLaughlin, F. A., E. C. Carmack, and R. W. Macdonald, Physical and geochemical properties across the Atlantic/Pacific water mass front in the southern Canadian Basin, *J. Geophys. Res.*, *101*, 1183–1197, 1996.

Morison, J. H., M. Steele, and R. Andersen, Hydrography of the upper Arctic Ocean measured from the nuclear submarine USS Pargo, *Deep Sea Res.*, *45*, 15–38, 1998.

Newton, R., Ph.D. Thesis, 315 pp., Columbia University, New York, April, 2001.

Pavlov, V. K., and P. V. Pavlov, Features of seasonal and interannual variability of the sea level and water circulation of the Laptev Sea, in *Land Ocean Systems of the Siberian Arctic*, edited by Kassens et al., pp. 3–16, Springer, Heidelberg, 1999.

Ostlund, G. H., and G. Hut, Arctic Ocean water mass balance from isotope data, *J. Geophys. Res.*, *89*, 6373–6381, 1984.

Redfield, A. C., and I. Friedman, The effect of meteoric water, melt water and brine on the composition of Polar Sea water and of the deep water of the oceans, *Deep Sea Res.*, *16*, 197–214, 1969.

Roether, W., Water-CO_2 exchange set-up for the routine ^{18}Oxygen assay of natural waters, *Int. Jour. of App. Radiation and Isotopes*, *321*, 379–387, 1970.

Schauer, U., R. D. Muench, B. Rudels, and L. Timokhov, Impact of eastern Arctic shelf waters on the Nansen Basin intermediate layers, *J. Geophys. Res.*, *102*, 3371–3382, 1997.

Schlosser, P., D. Bauch, R. Fairbanks, and G. Bonisch, Arctic river-runoff: Mean residence time on the shelves and in the halocline, *Deep Sea Res.*, *41*, 1053–1068, 1994.

Steele, M., and T. Boyd, Retreat of the cold halocline layer in the Arctic Ocean, *J. Geophys. Res.*, *103*, 10,419–10,435, 1998.

Swift, J. H., E. P. Jones, K. Aagaard, E. C. Carmack, M. Hingston, R. W. Macdonald, F. A. McLaughlin, and R. G. Perkin, Waters of the Makarov and Canada Basins, *Deep Sea Res., Part B*, *44*, 1503–1529, 1997.

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