Polarforschung 74 (1-3), 185 – 189, 2004 (erschienen 2006)

Waters of Nares Strait in 2001

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Abstract: The near surface waters north of the Canadian Arctic Archipelago consist in large part of water from the Pacific Ocean that has entered from the Bering Strait and had additional contributions from river runoff and sea ice meltwater. Underlying this is water from the North Atlantic Ocean that has entered the Arctic Ocean mostly via the Barents Sea. Near surface waters of the Arctic Ocean exit via the Canadian Arctic Archipelago, most of whose channels are less than 120 m deep. Much of the water exiting through the channels of Canadian Arctic Archipelago above depths of 100 m is of a Pacific origin. The sill depth in Nares Strait, however, is 250 m, deep enough to also allow the underlying Atlantic water to pass through. We report results from an expedition to Nares Strait in 2001. Salinity, temperature, and nutrients were measured in sections across Kennedy Channel (~ 81 °N) and Smith Sound (~78.3 °N). Water above 100 m is mostly Pacific water with some freshwater that is presumed to be mostly river runoff. Water below 100 m has an increasing fraction of Atlantic water, reaching a maximum about 80 % near the bottom.

Zusammenfassung: Das oberflächennahe Wasser nördlich des kanadischen Archipels besteht zu einem großen Teil aus Wasser des Pazifiks, das durch die Beringstraße eingedrungen ist, modifiziert durch Zuflüsse von Flusswasser und Meereis-Schmelzwasser. Unter dieser obersten Schicht liegt Nordatlantik-Wasser, das durch die Barents-See in den Arktischen Ozean gelangt ist. Das Oberflächenwasser des Arktischen Ozeans fließt hauptsächlich durch den kanadischen Archipel ab, wo die meisten Kanäle zwischen den Inseln weniger als 120 m tief sind. Das meiste durch diese Kanäle abfließende Wasser ist also von pazifischer Herkunft. In der Nares-Straße beträgt die Schwellentiefe dagegen 250 m. Dadurch kann auch das unterlagernde atlantische Wasser durch die Meeresstraße abfließen. Wir berichten hier von einer Expedition zur Nares-Straße im Jahr 2001. Salzgehalt, Temperatur und Nährstoffe wurden auf Querprofilen durch den Kennedy Channel (ca. 81°N) und den Smith Sound (ca. 78,3°N) gemessen. Wasser bis zu 100 m Tiefe ist überwiegend Pazifik Wasser mit einem Süßwasser-Anteil, der wohl von Flüssen stammt. Unter 100 m hat das Wasser einen zunehmenden Anteil von atlantischem Wasser mit einem Maximum von 80 % in Bodennähe.

INTRODUCTION

Freshwater cycles through the oceans and atmosphere shaping our climate, and changes in this cycle can have profound ef fects on the climate. Water evaporates from the oceans, is transported via the atmosphere over wide regions, falls as rain and snow, and returns to the oceans either directly or via rivers. In addition to distributing freshwater around the world, this cycle has a profound effect on ocean dynamics because the addition or removal of freshwater from seawater changes its density. Since density strongly influences ocean dynamics, ocean currents are greatly affected by how, when, and where freshwater enters and leaves the ocean through precipitation, river run-off, and evaporation. A manifestation of this is the global thermohaline circulation or "Global Conveyor Belt". Surface ocean currents transport heat from warmer regions of the earth to colder ones, where surface water is made denser and sinks. In the Northern Hemisphere outside the Arctic Ocean, this happens in winter in the Nordic seas (Norwegian, Greenland and Iceland seas) and in the Labrador Sea. The newly formed dense water flows at depth towards tropical regions, where it up-wells, becomes warm and flows to Polar regions to complete the cycle. The surface waters in the northern regions must be sufficiently dense for the thermohaline processes to be successful. The amount of freshwater entering deep-water formation regions will affect the density of the surface waters, the amount of deep water formed, and hence the strength of the global thermohaline circulation.

There is more evaporation than precipitation in the Atlantic Ocean. Much of this excess evaporation falls as rain into North Pacific Ocean, making its surface waters fresher than those of the North Atlantic Ocean. Some of the excess evaporation also falls into river drainage basins that feed into the Arctic Ocean. Pacific water enters the Arctic Ocean through the shallow (50 m deep) Bering Strait. Atlantic water flows along the northern coast of Norway, entering the Arctic Ocean through the Barents Sea and Fram Strait. Pacific and Atlantic waters partially mix within the Arctic Ocean, but the Pacific water, being less saline (less dense) than the Atlantic water, is mostly confined in the Arctic Ocean near surface layers. Sea-ice melt-water produced during the summer melt season is an additional source of freshwater in the Arctic Ocean. These three, Pacific water, river runoff, and sea-ice melt-water provide the freshwater exiting the Arctic Ocean through the Canadian Arctic Archipelago and Fram Strait into the North Atlantic Ocean. The Arctic Ocean thus provides a pathway for the return flow of freshwater from the Pacific Ocean to the North Atlantic Ocean.

Climate change scenarios from models suggest that a change in the freshwater flow to regions of deep-water formation could produce a rapid change in climate (e.g., RAHMSTORF 2003, 2002). PATERSON et al. (2002) noted an increasing river discharge to the Arctic Ocean that will undoubtedly have some impact on deep-water formation, and HÄKKINEN & RHINES (2004) suggest that there have been significant changes and a weakening in the Atlantic subpolar gyre. A part of understanding the effect of freshwater on areas of deep-water formation is to determine the sources of the freshwater reaching them. A first step in understanding the freshwater budget of the Arctic Ocean and assessing scenarios for the effect of freshwater on global thermohaline circulation is to determine freshwater sources and trace their pathways.

Pacific water in the Arctic Ocean is not identical to Pacific water in the Bering Sea before it enters the Arctic Ocean. After passing though Bering Strait, it undergoes some transformation within the Arctic Ocean, primarily in the Chukchi Sea region, where changes in salinity and in nutrient concentrations occur (Jones et al. 1998). Within the Arctic Ocean, Pacific water has salinities generally less than 33.2 and temperatures near freezing. Likewise, Atlantic water, which flows

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Manuscript received 12 January 2004, accepted 08. February 2006

into the Arctic Ocean via the Barents Sea and via Fram Strait between Greenland and Svalbard, is also modified after it enters the Arctic Ocean from the Nordic Seas, and the characteristics of water that has entered via the Barents Sea are somewhat different from that having entered through Fram Strait (RUDELS et al. 2004).

Along the North American coast the near surface layers of the Arctic Ocean consist in large part of water whose origin is the Pacific Ocean (JONES et al. 1998), with additional contributions from river runoff and sea-ice meltwater. Immediately underlying these layers along the North American coast is water of North Atlantic origin that has entered the Arctic Ocean via the Barents Sea (RUDELS et al. 2004). The near surface waters exiting via the Canadian Arctic Archipelago will influence the deep-water formation in the Labrador Sea (JONES et al. 2003). Most of the channel sills in the Canadian Arctic Archipelago are shallow, less than 120 m, thus not allowing the deeper Atlantic water to pass. Only Nares Strait, with a sill depth of about 250 m, is deep enough to allow the passage of both the Arctic Ocean near surface waters and the deeper Atlantic water.

Measurements were carried out in Nares Strait during August-September, 2001, from on board CCGS "Louis S. St-Laurent". We report results from sections across Smith Sound (~78.3 °N) and Kennedy Channel (~81 °N) (Fig. 1). The Smith Sound section with a maximum depth of about 650 m is at the northern end of Baffin Bay, the North Water region. The Kenndey Channel section with a maximum depth of about 400 m in the northern part of Kane Basin is slightly to the south of the minimum channel depth of 250 m in Nares Strait. Kennedy Channel waters are the more northern and therefore offer the best representation of waters flowing out of the Arctic Ocean through Nares Strait to Baffin Bay and the Labrador Sea. Water from the Arctic Ocean enters Nares Strait directly, and waters in Kennedy Channel will unlikely be modified to any extent and therefore will most resemble the waters flowing from the Arctic Ocean.

APPROACH

In the Arctic Ocean, nutrient relationships distinguish Pacific water from Atlantic water (Jones et al. 1998, 2003). Plots of concentrations of phosphate (PO_4) *versus* nitrate (NO_3) show two distinct linear relationships: one associated with water known to be of Pacific origin (PW) and another associated with water known to be of Atlantic origin (AW). Best linear fits to these two data sets have similar slopes but different intercepts (Fig. 2), thus distinguishing one source from the other and allowing the two sources to be identified both within the Arctic Ocean and in waters flowing out of the Arctic Ocean. Limited data from within the Arctic Ocean indicate that river runoff and sea ice melt-water have nitrate-phosphate relationships similar to those of Atlantic water. In this work we did not measure total alkalinity or oxygen isotope fraction which would have separated the river runoff and sea ice meltwater from one another; we therefore class them together simply as freshwater.

We use nutrient relationships to distinguish Pacific water from the sum of Atlantic water and freshwater, and salinity to obtain

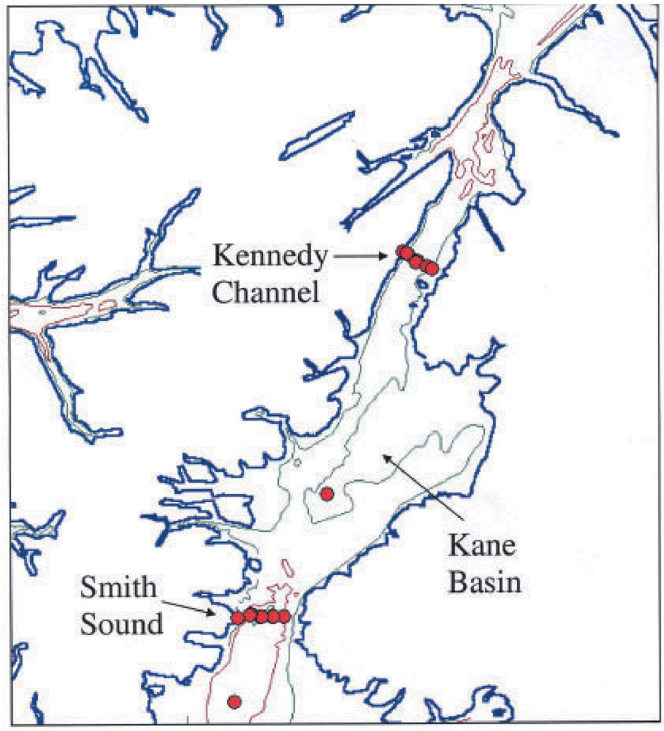

Fig. 1: Map of Stations. The stations across Smith Sound and Kennedy Channel make up the sections across each of these passages.

the sum of runoff and sea ice melt water. The first step is to determine the phosphate values for Pacific and Atlantic waters corresponding to a measured nitrate concentration:

$$PO_4^{PW} = PW_{slope} \times NO_3 + PW_{intercept}$$
$$PO_4^{AW'} = AW'_{slope} \times NO_3 + AW'_{intercept} \qquad (1)$$

NO_3 is the measured nitrate concentration in a sample at a particular position and depth in Nares Strait. AW' indicates that sea ice melt-water and river runoff are included with Atlantic water in the linear relationship. The subscripts "slope" and "intercept" refer to parameters in the linear equation giving the best fit to the Arctic Ocean data (Tab. 1).

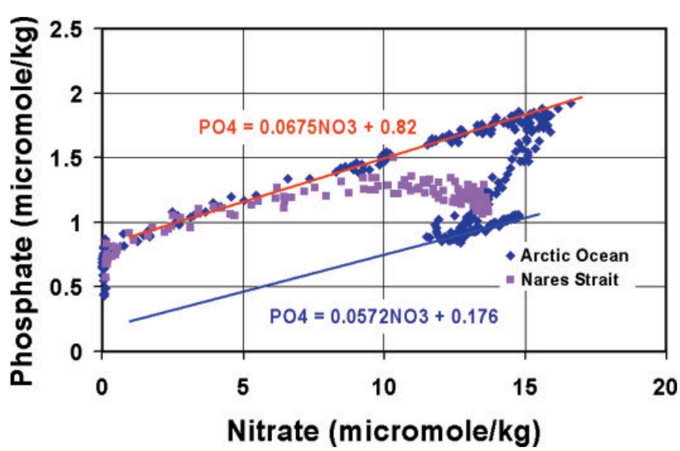

Fig. 2: Phosphate versus Nitrate: A comparison of data from the southern Canada Basin in the Arctic Ocean and from Nares Strait. The red line is a best fit (r^2 = 0.95) to data from the Canada Basin in water known to be of Pacific origin; the blue line is a best fit (r^2 = 0.95) to data from the Amundsen Basin in water known to be of Atlantic origin. A point lying halfway between the two lines, for example, would be made up of one part Pacific water and one part Atlantic water that includes freshwater from sea ice meltwater and river runoff.

	Pacific water (PW)	Atlantic water (AW)
Salinity	32.75	34.85
PO_4 *versus* NO_3 Slope	0.0675	0.0545
PO_4 *versus* NO_3 Intercept	0.82	0.1717

Tab. 1: Parameters used in Equations to Calculate Water Fractions.

Next, using the measured phosphate concentration, PO_4, we calculate the fraction of Pacific water, f^{PW}:

$$f^{PW} = \frac{PO_4 - PO_4^{AW'}}{PO_4^{PW} - PO_4^{AW'}} \qquad (2)$$

The Pacific, Atlantic, and freshwater fractions must add up to 1, and the measured salinity, S, is determined by the Atlantic and Pacific water fractions and salinities:

$$f^{AW} + f^{PW} + f^{FW} = 1$$
$$S^{AW} f^{AW} + S^{PW} f^{PW} = S \qquad (3)$$

As noted above, the freshwater component, f^{FW}, includes river and sea ice melt-water. While Pacific and Atlantic waters entering the Atlantic Ocean have a range of salinities, they are generally represented in the literature by mean values (Tab. 1).

Temperature and salinity were measured using a CTD-rosette system that also collected water samples at prescribed depths. The water samples were analyzed for nutrient concentrations as well as salinity in the laboratory several weeks after collection, the nutrient samples having been frozen at the time of collection until they were analyzed. Generally the delay in analysis has little effect on the overall quality of the data.

RESULTS AND DISCUSSION

In both Kennedy Channel and Smith Sound, Pacific water dominates the upper waters above about 100 m (Figs. 3 and 4). Atlantic water is almost absent at these depths but dominates in deeper waters, though the Pacific fraction remains always greater than about 0.3. The fairly sharp interface between Atlantic and Pacific waters in Kennedy Channel has become a little less sharp in the Smith Sound. The deeper water, with salinities greater than about 34, is fresher and colder in Smith Sound than in Kennedy Channel, probably reflecting the mixing of the colder, fresher Pacific water with the warmer, saltier Atlantic water seen in Kennedy Channel. This mixing could result from turbulence generated by the relatively complex bathymetry between the two sections.

The freshwater is confined mostly to waters with salinity less than about 31.5. In Smith Sound the freshwater fraction reaches 0.08 in the western part of section. In Kennedy Channel the maximum freshwater fraction near the surface is about 0.07, i.e., very slightly less than in Smith Sound. In both locations the freshwater is associated with salinities as low as 31.5, with the near surface salinities in Kennedy Channel being slightly higher than in Smith Sound. This might be attributable to the addition of some sea ice melt-water in Kane Basin.

Almost all of the Atlantic water entering Nares Strait is the "Barents Sea branch" halocline water, i.e., water that has

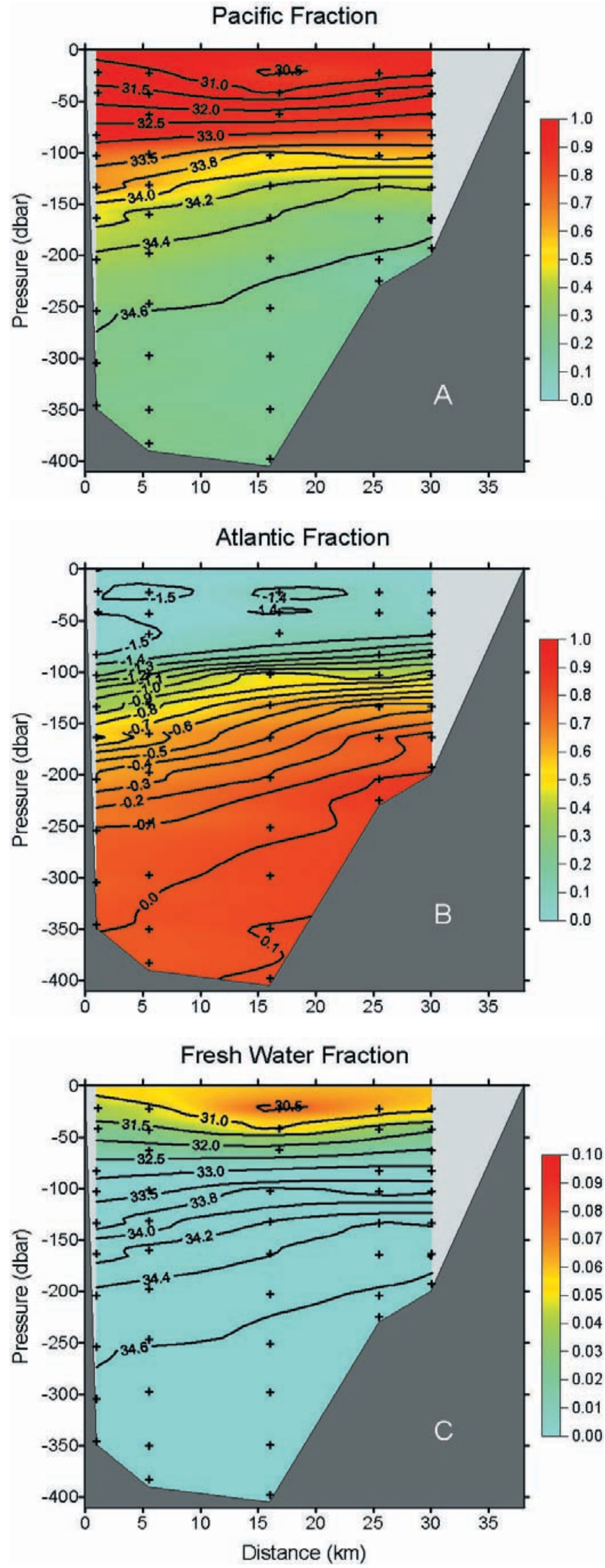

Fig. 3: Kenendy Channel Section (viewed from the north). Contour lines in (A) and (C) represent salinity. Contour lines in (B) represent potential temperature. Crosses in Figures 3A through 3C indicate the location and depth where water samples were collected.

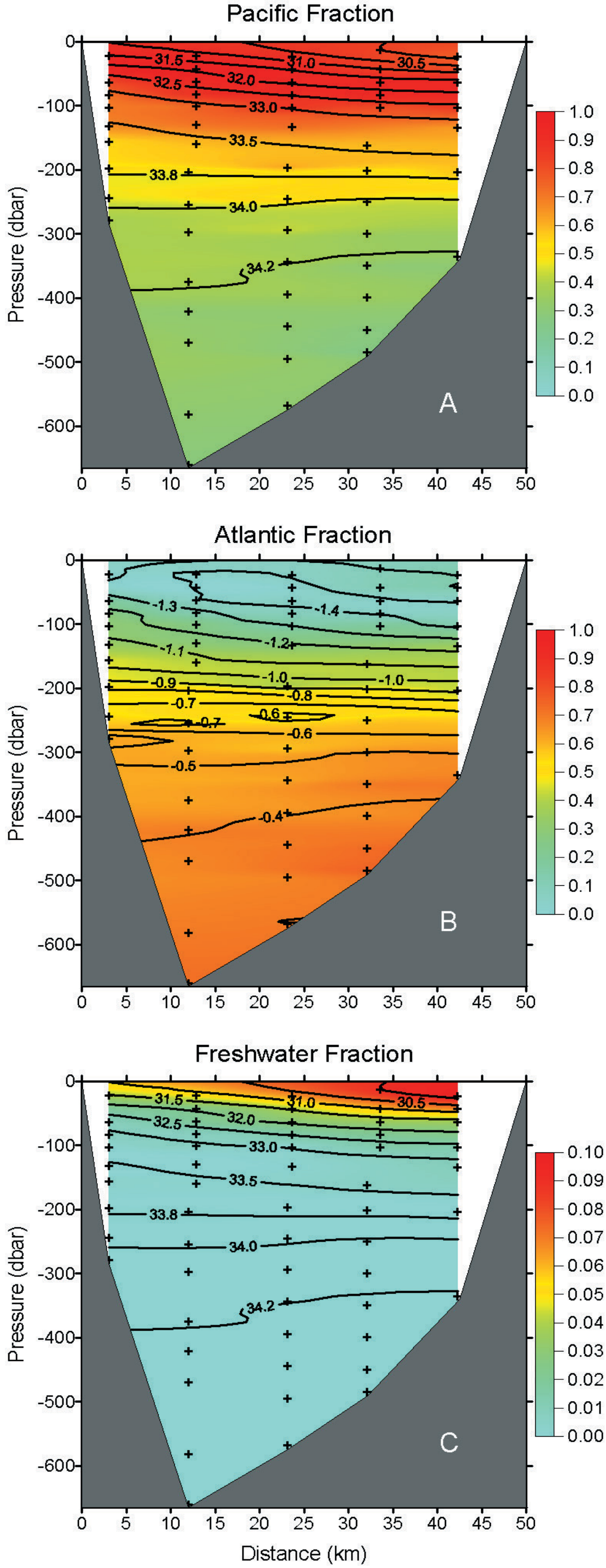

Fig. 4: Smith Sound Section (viewed from the north). Contour lines in 4A and 4C represent salinity. Contour lines in 4B represent potential temperature. Crosses in Figures 4A through 4C indicate the location and depth where water samples were collected.

entered Arctic Ocean via the Barents Sea (RUDELS et al. 2004). The Barents Sea branch halocline has temperatures from about -1.5 °C to -0.2°C and salinities from about 34.3 to 34.6. Water in Nares Strait that is warmer and saltier than that contains "Atlantic Layer" water, which has entered the Arctic Ocean via Fram Strait. Atlantic Layer water is present in Kennedy Channel but is not obviously evident in Smith Sound, probably because it has been masked by processes such as mixing and perhaps by brine produced during ice formation to the south in Kane Basin.

CONCLUSIONS

The main goal of this work was to describe the waters of Nares Strait. We have determined where the waters in Nares Strait originate and how they are partitioned.

JONES et al. (2003) concluded that essentially all of the water in Nares Strait comes from the Arctic Ocean. This study reaffirms that conclusion with the more northern results from Kennedy Channel. While there could be some influence by Baffin Bay water masses in the Smith Sound section, the salinity and temperature properties suggest that this influence is small or not existent.

In general the freshwater fraction would include river runoff and sea ice melt-water, but the measurements obtained in this study could not distinguish between them. A re-examination of data collected from Smith Sound in 1997 (JONES et al. 2003) showed that sea-ice melt-water was present and roughly equal to river runoff then. The freshwater fraction (Figs. 3 and 4) thus might be presumed to be equally partitioned between sea-ice melt-water and river runoff. We note, however, that the river runoff comes from the Arctic Ocean, whereas the sea-ice melt-water might have a local origin in Nares Strait.

The generally accepted value for the amount of Pacific water entering the Arctic Ocean is about 0.8 Sv (1 Sv = 10^6 m^3 s^{-1}) (COACHMAN & AAGAARD 1988). The "best estimate" of the river runoff is about 0.1 Sv (see review by RUDELS & FRIEDRICH 2000). In the Arctic Ocean, the freshwater content of Pacific water (salinity = 32.75) relative to Atlantic water (salinity = 34.85) is about one-tenth of the total amount of Pacific water, i.e., about the same as the freshwater provided by river runoff. The results suggest that is true also in Nares Strait, where the river runoff fraction is about one-tenth that of Pacific water.

ACKNOWLEDGMENTS

This work was partially supported by the Canada Panel on Energy Research and Development, the Canadian Climate Action Fund and by a NOAA Grant No. NA17RJ1232.

References

Coachman, L.K. & Aagaard, K. (1988): Transports through Bering Strait: Annual and interannual variability.- J. Geophys. Res. 93: 15,535-15,539.

Häkkinen, S. & Rhines, P.B. (2004): Decline of subpolar North Atlantic circulation during 1990s.- Science 304: 555-559.

Jones, E.P., Anderson, L.G. & Swift, J.H. (1998): Distribution of Atlantic and

Pacific waters in the upper Arctic Ocean: Implications for circulation.- Geophys. Res. Lett. 25: 765-768.
Jones, E.P., Swift, J.H., Anderson, L.G., Lipizer, M., Civitarese, G., Falkner, K.K., G. Kattner, G. & F. McLaughlin, F. (2003): Tracing Pacific water in the North Atlantic Ocean.- J. Geophys. Res. 108 (C4): 3116, doi: 10.1029/2001JC001141.
Paterson, B.J., Holmes, M., MacClelland, J.W., Vörösmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A. & Rahmstorf, S. (2002): Increasing river discharge to the Arctic Ocean.- Science 298: 2171-2173.
Rahmstorf, S. (2002): Ocean circulation and climate during the past 120,000 years.- Nature 419: 207-214.
Rahmstorf, S. (2003): The current climate.- Nature 421: 699.
Rudels, B. & Friedrich, H.J. (2000): The transformations of Atlantic water in the Arctic Ocean and their significance for the freshwater budget.- In: E.L. Lewis (ed), The freshwater budget of the Arctic Ocean, Kluwer Academic Press, NATO Sci. Ser. 2., Environm. Security, 70: 503-532.
Rudels, B., Jones, E.P., Schauer, U. & Eriksson, P. (2004): Atlantic sources of the Arctic Ocean surface and halocline waters.- Polar Res. 21: 181-208.