JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. C4, 3116, doi:10.1029/2001JC001141, 2003

# Tracing Pacific water in the North Atlantic Ocean

E. P. Jones,[1] J. H. Swift,[2] L. G. Anderson,[3] M. Lipizer,[4] G. Civitarese,[4] K. K. Falkner,[5] G. Kattner,[6] and F. McLaughlin[7]

Received 10 September 2001; revised 19 July 2002; accepted 10 December 2002; published 12 April 2003.

[1] In the Arctic Ocean, Pacific source water can be distinguished from Atlantic source water by nitrate-phosphate concentration relationships, with Pacific water having higher phosphate concentrations relative to those of nitrate. Furthermore, Pacific water, originally from the inflow through Bering Strait, is clearly recognizable in the outflows of low-salinity waters from the Arctic Ocean to the northern North Atlantic Ocean through the Canadian Arctic Archipelago and through Fram Strait. In the Canadian Arctic Archipelago, we observe that almost all of the waters flowing through Lancaster and Jones sounds, most of the water in the top 100 m in Smith Sound (containing the flow through Nares Strait), and possibly all waters in Hudson Bay contain no water of Atlantic origin. Significant amounts of Pacific water are also observed along the western coast of Baffin Bay, along the coast of Labrador, and above the 200-m isobath of the Grand Banks. There is a clear signal of Pacific water flowing south through Fram Strait and along the east coast of Greenland extending at least as far south as Denmark Strait. Pacific water signature can be seen near the east coast of Greenland at 66°N, but not in data at 60°N. Temporal variability in the concentrations of Pacific water has been observed at several locations where multiple-year observations are available. *INDEX TERMS:* 4283 Oceanography: General: Water masses; 4207 Oceanography: General: Arctic and Antarctic oceanography; 4804 Oceanography: Biological and Chemical: Benthic processes/benthos; *KEYWORDS:* North Atlantic Ocean, Pacific source water, Canadian Arctic Archipelago, Davis Strait, Labrador Sea, Grand Banks, Fram Strait, Denmark Strait

**Citation:** Jones, E. P., J. H. Swift, L. G. Anderson, M. Lipizer, G. Civitarese, K. K. Falkner, G. Kattner, and F. McLaughlin, Tracing Pacific water in the North Atlantic Ocean, *J. Geophys. Res.*, *108*(C4), 3116, doi:10.1029/2001JC001141, 2003.

## 1. Introduction

[2] There is more evaporation than precipitation in the Atlantic Ocean, while the reverse is the case in the North Pacific Ocean. Most of the evaporated water falls as rain in the Pacific Ocean with a lesser amount delivered by rivers flowing into it. A significant pathway for the return of fresh water from the Pacific Ocean to the North Atlantic Ocean is through the Arctic Ocean. Pacific water flows into the Arctic Ocean from the Bering Sea through the shallow (50 m deep) Bering Strait. Atlantic water flows northward along the coast of Norway and enters the Arctic Ocean through the much deeper Fram Strait and through the Barents Sea. The saline water of Atlantic origin partially mixes with water of Pacific origin within the Arctic Ocean. Pacific water being less dense (less saline) than Atlantic water tends to remain confined in specific regions of the near-surface layers in the Arctic Ocean. The two source waters, in addition to having different salinities, have constituents that do not affect their densities but that do distinguish one from the other. In particular they have different relationships between their dissolved nitrate and phosphate concentrations [*Jones et al.*, 1998].

[3] The Arctic Ocean freshwater export into the North Atlantic Ocean includes river runoff and sea ice meltwater in addition to freshwater from the Pacific Ocean. This freshwater export to the Nordic and Labrador seas can potentially affect the deep water formation rate in these regions by creating a stratified surface layer that inhibits the production of water dense enough for deep convection to occur [*Aagaard and Carmack*, 1989]. The Arctic Ocean freshwater export to the Nordic Seas (Greenland, Iceland, and Norwegian seas) leaves the Arctic Ocean via Fram Strait, follows the East Greenland Current, and leaves the Nordic Seas through Denmark Strait, while the freshwater export to the Labrador Sea occurs primarily through the Canadian Arctic Archipelago.

[4] We exploit the distinguishing nutrient relationship to trace the pathways of the Pacific water component of the Arctic Ocean water exiting into the Northern North Atlantic Ocean from Fram Strait to Denmark Strait and from the

---

[1] Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada.
[2] Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.
[3] Department of Analytical and Marine Chemistry, Göteborg University, Göteborg, Sweden.
[4] Consiglio Nazionale delle Ricerche, Istituto Talassografico, Trieste, Italy.
[5] College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA.
[6] Alfred Wegener Institute for Polar and Marine Sciences, Bremerhaven, Germany.
[7] Institute of Ocean Sciences, Sidney, British Columbia, Canada.

0148-0227/03/2001JC001141$09.0

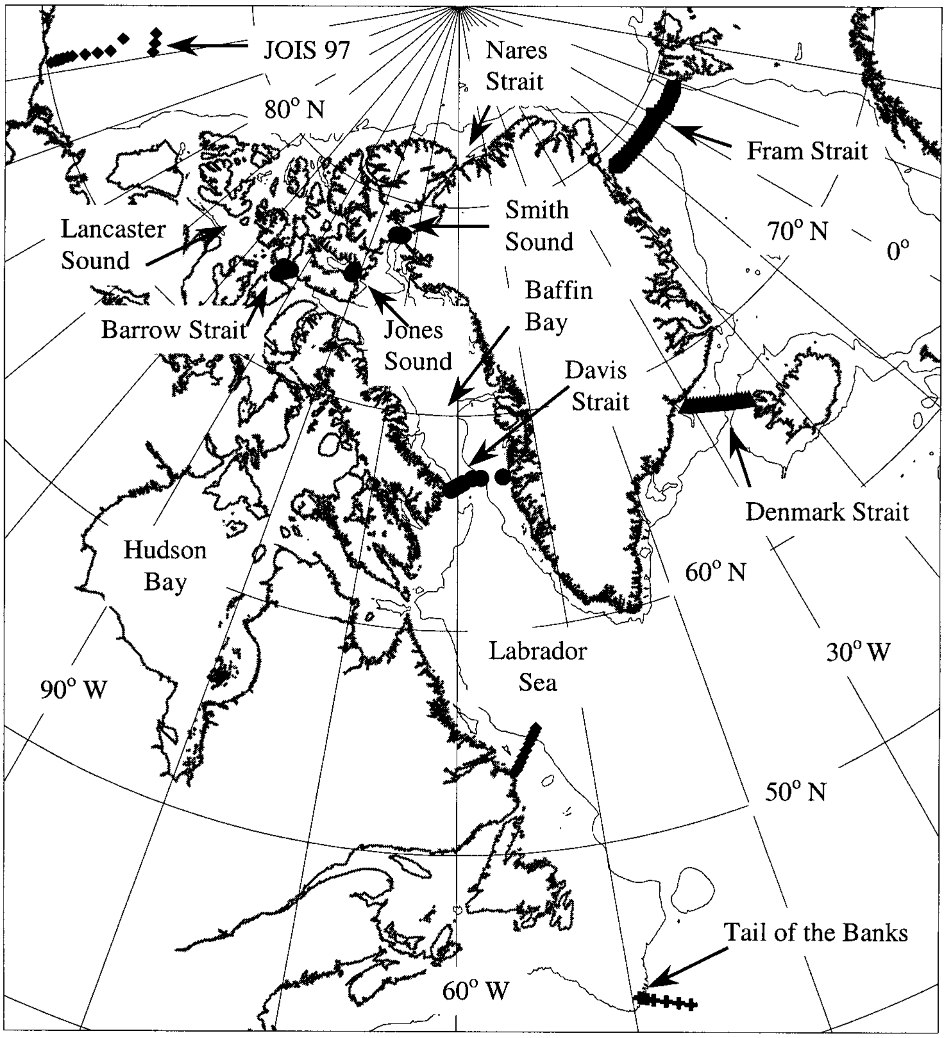

**Figure 1.** Locations of sections. Smith Sound, Jones Sound, Barrow Strait, and Davis Strait from Legs 1 and 3 of the Joint Ocean Ice Study (1997), expeditions in the Labrador Sea and Newfoundland Basin (1993, 1995, 1997, 1998), expeditions to Fram Strait (1997, 1998, 1999), and expeditions in the Denmark Strait region (1991, 1994, 1996, 1997).

Canadian Arctic Archipelago to the Labrador Sea (Figure 1), noting some variability during the past decade.

## 2. Approach

[5] Pacific water flowing into the Arctic Ocean has high concentrations of silicate, and silicate concentrations have been used to trace Pacific water within the Arctic Ocean and flowing out of the Arctic Ocean [e.g., *Codispoti and Lowman*, 1973; *Jones and Coote*, 1980; *Anderson and Dyrssen*, 1981; *Jones and Anderson*, 1986; *Anderson et al.*, 1994; *Wheeler et al.*, 1997]. In near-surface waters, silicate along with phosphate and nitrate are fixed and depleted by biological processes, with the result that nutrient concentrations lose their value as an indicator of Pacific water. *Jones et al.* [1998] took an alternative approach to trace waters of Pacific origin within the Arctic Ocean. Inside the Arctic Ocean boundaries, they noted that clearly identifiable Pacific and Atlantic source waters each had a specific nitrate versus phosphate relationship. While the slopes of nitrate versus phosphate plots (Redfield relation) for both Pacific and Atlantic waters are nearly the same, Pacific water is relatively depleted in nitrate. As a result, Pacific water exhibits an excess of phosphate of about 1 μmol/kg for a given nitrate concentration relative to what is found in Atlantic water.

[6] In this work, we use nitrate-phosphate relationships observed in the Arctic Ocean: Pacific water as found in the southern Canada Basin (Joint Ocean Ice Study JOIS 97) and Atlantic water as found in several parts of the Arctic Ocean including in the Eurasian Basin near the St. Anna Trough and below the Pacific water in the Canada Basin (Figure 2). Where a point on a nitrate versus phosphate concentrations plot lies between the Atlantic and Pacific source water lines, the relative amounts of Pacific and Atlantic waters are determined by the amount of each required to give the observed values. In all instances we take values lying to the left of the Atlantic source water line to represent only Atlantic water and values to the right of the Pacific source water line to represent only Pacific water. Additions of

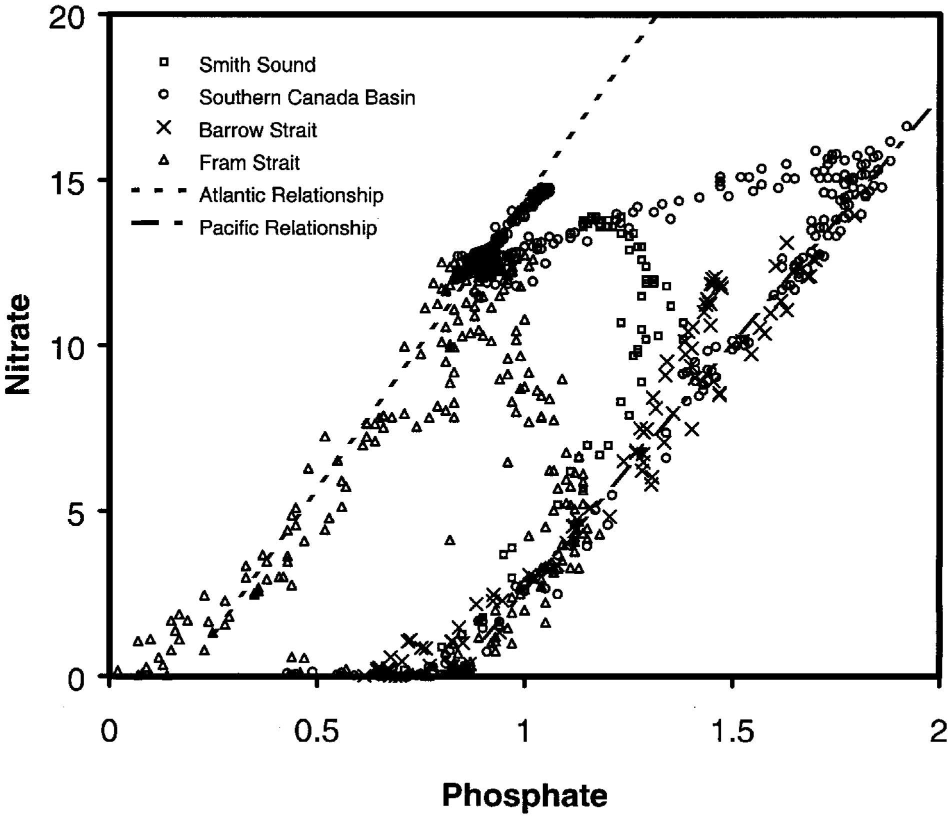

**Figure 2.** Nitrate-phosphate relationships for (a) Southern Canada Basin, (b) Smith Sound, (c) Barrow Strait, and (d) Fram Strait. Units are μmol/kg.

freshwater from rivers and sea ice meltwater will affect nutrient concentrations as well as salinity and, in principle, can reduce the apparent Pacific signal in some regions. The addition does not usually have a major effect on nitrate-phosphate relationships, however, since their total contribution to the nutrient pool is not expected to be large [*Jones et al.*, 1998]. A limitation of the method can result when local denitrification occurs, typically in shallow regions where the organic load in sediments is high and decay processes deplete oxygen. Water from such a region was observed on the upper slope bordering Chukchi Sea, where phosphate concentrations in excess of 2 μmol/kg and nitrate concentration in excess of 17 μmol/kg were observed [*Swift et al.*, 1997]. Where local denitrification occurs, it is possible to find water samples with points lying to the right of the Pacific source water line. Where such denitrified Pacific water enters a region, mostly at a few locations in the Canadian Arctic Archipelago, we have taken these waters to contain only Pacific water.

[7] Another process affecting the nitrate-phosphate relationships is nitrogen fixation that can occur in oxygenated waters where nitrate is depleted but phosphate is not. We have no direct measure of this in the Arctic Ocean, but we note that in some regions nitrate concentrations are near zero in the surface mixed layer [*Swift et al.*, 1997; *Wheeler et al.*, 1997]. Where nitrogen fixation occurs, the apparent Pacific water fraction would be reduced.

[8] A further cause of uncertainty in the calculated Pacific water fraction for regions outside those immediately bordering the Arctic Ocean arises from the choice of the Atlantic source water line. The regression line used to describe Atlantic water is one fitted to the Atlantic water entering the Arctic Ocean north of the Barents Sea near the St. Anna Trough. This water has a small excess of phosphate (about 0.2 μmol/kg) at zero nitrate concentration. A line fitted to nitrate and phosphate data of Atlantic water near Iceland does not have this small excess phosphate. The difference between these two regression lines describing Atlantic water is likely a result of a small loss of nitrogen through denitrification as Atlantic water flows north into the Barents Sea and Arctic Ocean. In determining the Pacific water fraction within the Arctic Ocean, it is clearly most relevant to use the Arctic Ocean Atlantic water regression line, and it would seem also to be the most relevant to apply to water exiting the Arctic Ocean through the Canadian Arctic Archipelago and Fram Strait. Farther south, Pacific water may be diluted by Atlantic water that has not entered the Arctic Ocean. In this work we have used the Arctic Ocean Atlantic water throughout. Using the North Atlantic nitrate-phosphate relationship for our Davis Strait, Labrador Sea, and Denmark Strait sections would increase apparent Pacific water fractions in those regions by about 0.2. Conversely, using the Arctic Ocean nitrate-phosphate relationship where the North Atlantic relationship would be more appropriate could result in apparent negative Pacific water concentrations. The precision of the nitrate and phosphate measurements is typically less than ±2%, whereas the deviation of points

from “pure” Pacific and “pure” Atlantic nutrient relationships (Figure 2) is ±5% or more. Much of the deviation likely results from the “pure” relationships not exactly representing the source waters in all regions. In most regions, we would ascribe limits in our estimations of the fraction of Pacific (or Atlantic) source water to be about 10%. Nitrogen fixing cyano-bacteria in near-surface regions, where nitrate is almost depleted, likely account for non-zero phosphate values and near zero nitrate values deviating from the “pure” Pacific nutrient relationship.

## 3. Results

### 3.1. Detecting the Presence of Pacific Water

[9] Pacific water has been traced in the Arctic Ocean along the North American coast north of channels leading into the Canadian Arctic Archipelago, and north of Greenland [*Jones et al.*, 1998]. These are the entry points of Pacific water into the northern North Atlantic Ocean. Data discussed in this paper were compiled from several expeditions in regions where water exits the Arctic Ocean and flows south into the North Atlantic Ocean (Figure 1). The existence of Pacific water outside of the Arctic Ocean is clearly evident in nitrate versus phosphate plots (Figure 2). These plots for selected regions show nutrient relationships for water flowing from the Arctic Ocean through the Canadian Arctic Archipelago and through Fram Strait. In general, Pacific water is confined to upper waters with salinity values less than about 33.5. At Barrow Strait, one of the main channels through the Canadian Arctic Archipelago (sill depth 120 m, $S < 33.2$), the water is almost entirely of Pacific origin. Essentially no water of Atlantic origin can be seen. In the Smith Sound section at the southern end of Nares Strait separating Ellesmere Island of the Canadian Arctic Archipelago and Greenland (sill depth 150 m), the upper water also contains water almost entirely of Pacific origin, with little or no Atlantic water. Atlantic water that has come via the Arctic Ocean is present below at depths of about 100 m and $S > 33.3$ (see section 3.5). In the Jones Sound section, at the eastern end of Jones Sound, the upper water is of Pacific origin and is also similar to that flowing through Nares Strait. The deeper water probably reflects processes occurring within Jones Sound that reduce nitrate concentrations relative to phosphate concentrations (see section 3.5). Atlantic water is present in this section also, and is similar to that observed in the Smith Sound section; that is, it also has entered the region via the Arctic Ocean. While we do not have measurements in Cardigan Strait at the western end of Jones Sound (sill depth 150 m, $S < 33.5$), it is likely that much of the Pacific water observed in the Jones Sound section has passed through there. On the other side of Greenland, near-surface water entering the Nordic Seas from the Arctic Ocean through western Fram Strait contains water that is almost entirely of Pacific origin.

### 3.2. Distribution of Pacific Water in Sections

[10] Vertical sections of the Pacific water fraction across principal passages and boundary regions illustrate the transit of Pacific water into the North Atlantic Ocean and its relationships to geography and bathymetry. Sections from Barrow Strait and Jones Sound are not presented. The water in Barrow Strait is essentially all of Pacific origin. The water flowing into Jones Sound passes through the shallow Cardigan Strait, precluding the likelihood of anything other than Pacific water flowing through that channel. In all sections, there is a close correlation with salinity for $S > \sim 32$. The correlation becomes lost for waters with $S < \sim 32$, though a high Pacific fraction is maintained (see section 3.6).

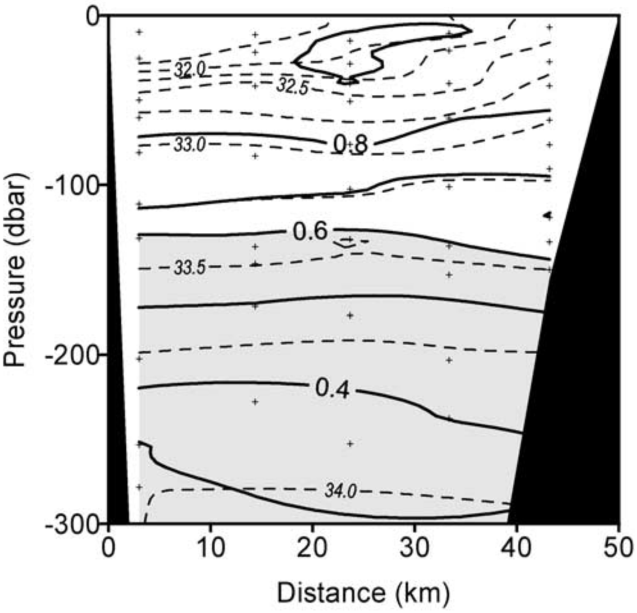

**Figure 3.** Smith Sound Section. In Figures 3–8 the Pacific fraction shaded contour intervals and solid contour lines represent the fraction of Pacific water; dashed contour lines represent salinity, and pluses indicates sampling depths. The Pacific fraction shaded contour intervals are: 0–0.3 (dark shading), 0.3–0.6 (light shading), and 0.6–1.0 (white).

### 3.2.1. Smith Sound (1997)

[11] The upper water column across all of Smith Sound to depths of more than 50 m consists almost entirely of Pacific water (Figure 3). The Pacific water fraction diminishes to about half at depths of 150 m, but still remains above 0.2 in the deepest part of the section at 570 m (not shown). The Atlantic water in this section appears to have come entirely via the Arctic Ocean (see section 3.5).

### 3.2.2. Davis Strait (1997)

[12] The Davis Strait section is located in southmost Baffin Bay, about 100 km north of the sill (depth about 600 m) that separates Baffin Bay from the Labrador Sea. Atlantic water from the Labrador Sea flows north into Baffin Bay, where it undergoes some changes in salinity and temperature as it experiences cooling, ice formation, and mixing with Pacific water. In eastern Davis Strait the nitrate-phosphate relationship is similar to that in the Labrador Sea for water with nitrate concentrations less than about 13 μmol/kg; that is, it is Atlantic in character for nearly all of the water column (Figure 4). Note that there is low-salinity near-surface water that does not coincide with Pacific source water. We can surmise that this water arises from the Atlantic water flowing from the south encountering and melting sea ice along its path (see also the discussion of Figure 10 in section 3.5).

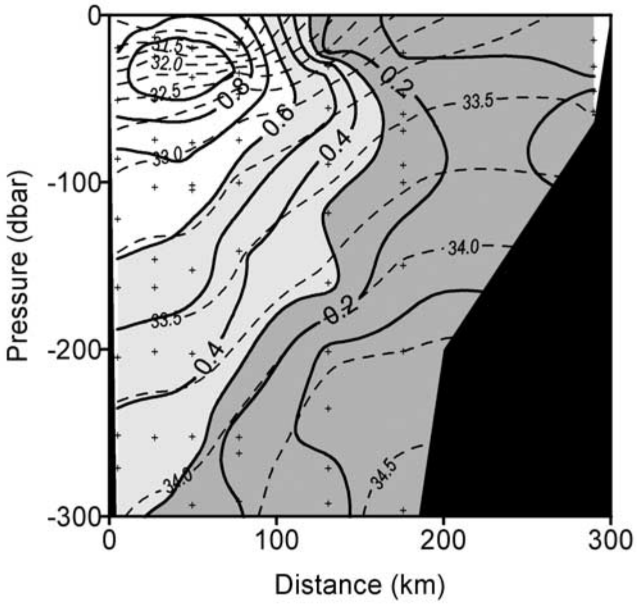

**Figure 4.** Davis Strait Section.

### 3.2.3. Southwestern Labrador Sea (1993–1998)

[13] In the southwestern Labrador Sea the Pacific water signal is found in sections that extend over the shelf and slope. Pacific water fractions of approximately 0.5 are found to depths of more than 100 m up to about 200 km offshore (Figure 5). As in Davis Strait, there is near-surface freshwater not associated with Pacific source water that likely reflects contributions from sea ice meltwater.

### 3.2.4. Tail of the Grand Banks (1995)

[14] This section shows a reduced, but still easily detectable Pacific water fraction close to the shelf west of the 1000-m isobath. Pacific water fractions up to 0.5 are found between 50 and 100 m at stations located over the seaward edge of the Tail of the Banks (Figure 6).

### 3.2.5. Fram Strait (1997–1999)

[15] The water flowing out of the Arctic Ocean in western Fram Strait above 100 m is almost entirely of Pacific origin. The Pacific water extends from the coast of Greenland to nearly halfway across Fram Strait (Figure 7). The low-salinity surface water on the eastern side of the section likely reflects contributions from sea ice meltwater as inflowing Atlantic water encounters sea ice formed there in winter as well as that exiting the Arctic Ocean.

### 3.2.6. Denmark Strait (1991)

[16] There is evidence of a significant amount of Pacific water distributed across the Denmark Strait section. A thin, mostly subsurface band nearly 150 km wide with Pacific water fractions above 0.4 extends from the western edge of the deep passage to slightly east of the deepest portion (Figure 8). Other sections between Denmark and Fram Strait show similar features (not shown).

## 3.3. Circulation of Pacific Water

[17] Various authors have described pathways of water flowing south from the Canadian Arctic Archipelago and from Fram Strait. Water flowing through the channels of the Canadian Arctic Archipelago passes through Hudson Bay and through Baffin Bay in the Baffin Island Current on its way to the Labrador Sea [*Ingram and Prinsenberg*, 1998].

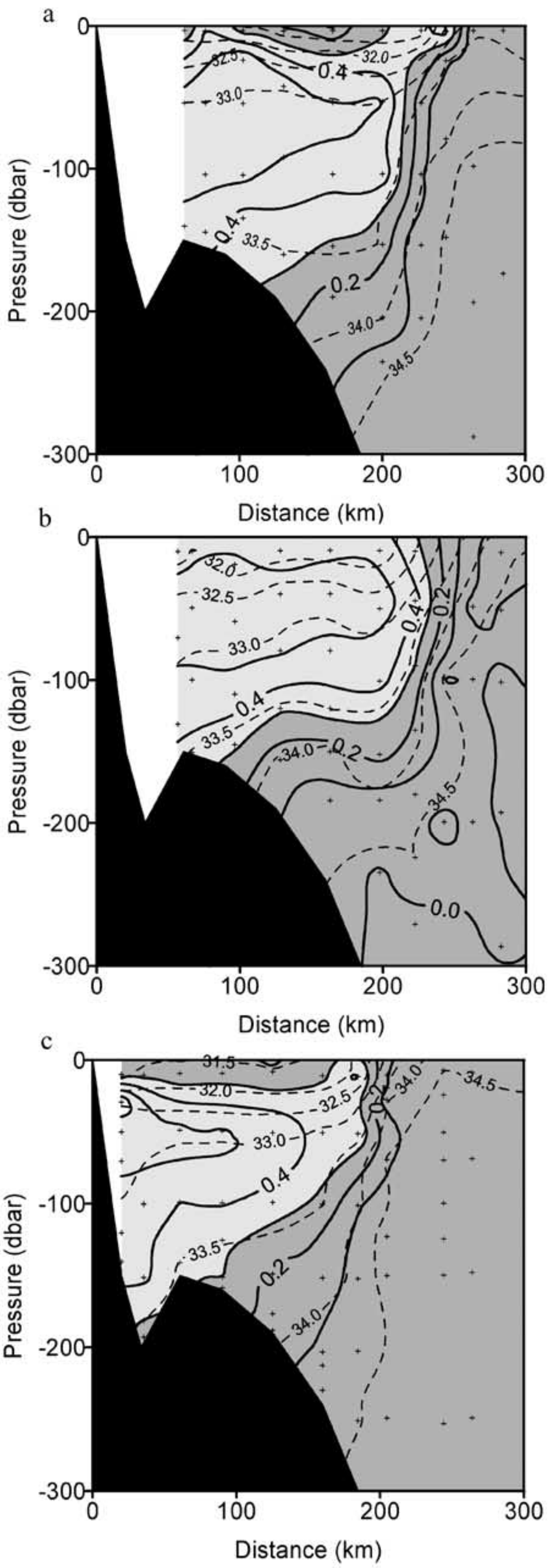

**Figure 5.** Labrador Sea AR7W Section in (a) 1993, (b) 1995, and (c) 1998. Data gaps result from ice cover preventing the ship's access to some regions.

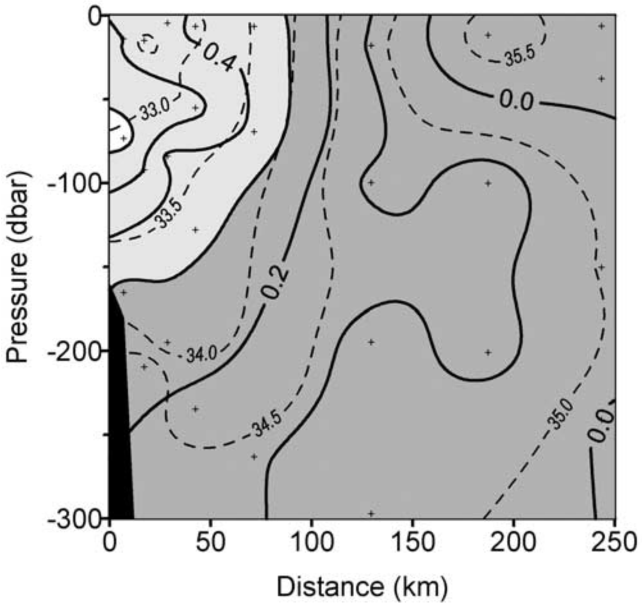

**Figure 6.** Tail of the Grand Banks Section.

These flows join in a boundary current in the Labrador Sea, following the shelf-slope bathymetry around the Grand Banks [*Petrie and Buckley*, 1996; *Loder et al.*, 1998]. This current bifurcates north of Flemish Cap. Some flow circulates around Flemish Cap and partially rejoins the flow south along the Grand Banks. Some flows to the east interacting with the North Atlantic Current. Water exiting the Arctic Ocean via Fram Strait flows south in the East Greenland Current [e.g., *Rudels*, 1995; *Dickson et al.*, 1996]. The current bifurcates north of Iceland, with the inshore branch flowing south through Denmark Strait and the offshore branch flowing east to the Norwegian Sea.

[18] Our work traces the Pacific water in these currents. Water flowing south into Hudson Bay enters via Lancaster Sound, the Gulf of Boothia, and Fury and Hecla Strait [*Ingram and Prinsenberg*, 1998]. Based on measurements in Barrow Strait, this seawater is expected to be entirely of Pacific origin. Some water flowing south along the coast of Baffin Island (also containing Pacific water) may enter Hudson Bay via Hudson Strait. Recent nutrient data in Hudson Bay are sparse; however, data from 1982 (not shown), while somewhat "noisy," indicate that the seawater in Hudson Bay is primarily of Pacific origin. This is not unexpected given the presence of Pacific water in Barrow Strait and the relatively shallow channels through which the seawater from that region must flow to reach Hudson Bay.

[19] As seen in the sections (Figures 3–8), Pacific water flows south along the east coast of Baffin Island and through Davis Strait, where it joins with water exiting Hudson Strait. Pacific water from both Hudson Bay and Baffin Bay then continues flowing south along the Labrador Coast, where it subsequently enters and can be identified in the Labrador Sea and regions farther south. The flow continues as a boundary current inside the 1000-m isobath through the Labrador Sea. The flow of Pacific water appears to follow in the main boundary current around the Grand Banks, with a Pacific water fraction up to 0.5 in sections at the Nose and Tail of the Banks. There is no strong evidence

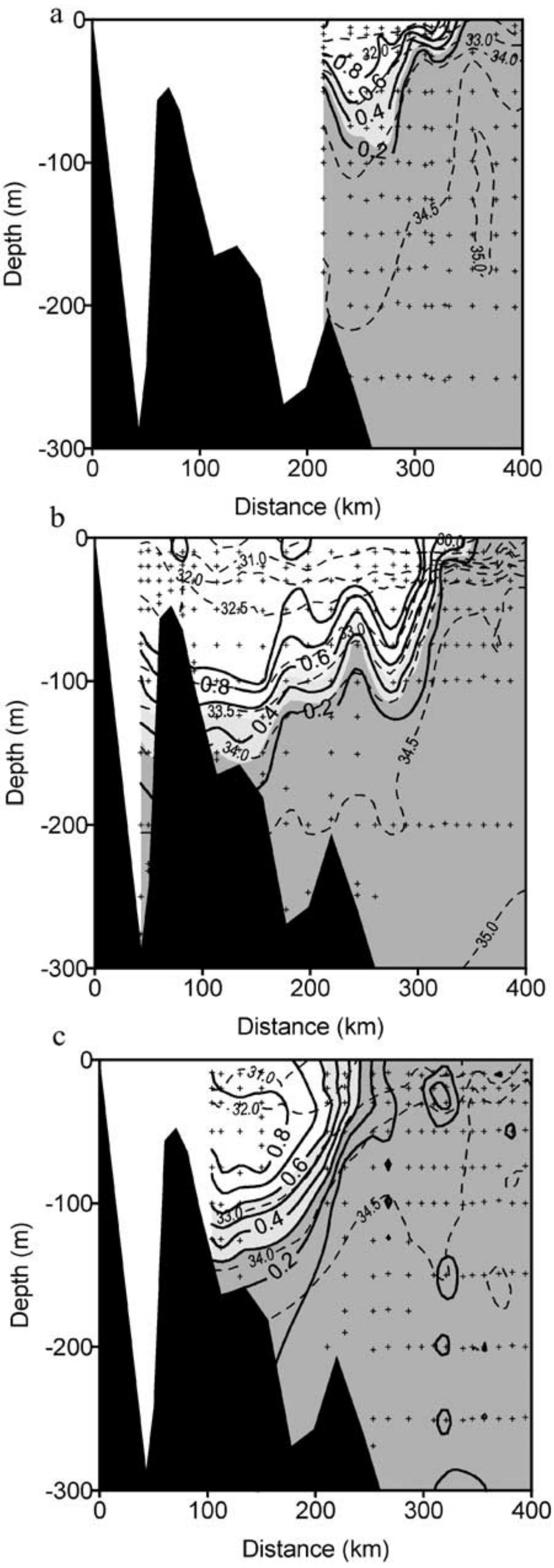

**Figure 7.** Fram Strait Sections in (a) 1997, (b) 1998, and (c) 1999. Data gaps result from ice cover preventing the ship's access to some regions.

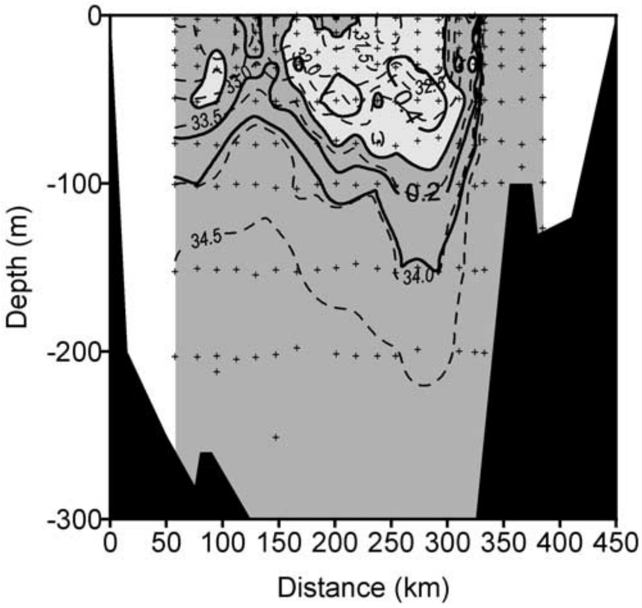

**Figure 8.** Denmark Strait Section: 1991.

from available data for the presence of Pacific water in the bifurcated flow going north of Flemish Cap.

[20] On the other side of Greenland, Pacific water flows from Fram Strait south to Denmark Strait, with some recirculation in the Northeast Polynya [*Falck*, 2001]. Somewhere between Denmark Strait and Cape Farewell (south tip of Greenland) Pacific water becomes enough modified so that its nutrient signature is not evident in data sets that we have been able to examine. Pacific water can be seen near the east coast of Greenland at 66°N, but none was observed in data at 60°N. We have found no Pacific water in observations from the West Greenland Current.

### 3.4. Temporal Variability

[21] In the past decade, various authors have documented significant and extensive changes within the Arctic Ocean that could cause variations in the amount of outflowing Pacific water. Several authors have reported warming of the Atlantic Layer in the Eurasian Basin [*Quadfasel et al.*, 1991] and Canadian Basin [*Carmack et al.*, 1997; *Swift et al.*, 1997; *Morison et al.*, 1998], the latter extending into the Canadian Basin well beyond the historical warm boundary near the Lomonosov Ridge [e.g., *Gorshkov*, 1983]. Warming in the Atlantic Layer can be related to warming in West Spitsbergen current at South Cape and is correlated with the North Atlantic Oscillation [*Swift et al.*, 1997]. Other major changes occurred in Arctic Ocean near-surface waters ($S < 34$) about the same period as this warming was taking place. There was a diminishment of the halocline suggested to result from a change in the distribution of river runoff [*Steele and Boyd*, 1998; *Guay et al.*, 2001]. In 1993, the boundary between Atlantic and Pacific waters was observed to be displaced from near the Lomonosov Ridge to near the Mendeleyev Ridge on the Siberian side of the Arctic Ocean [*McLaughlin et al.*, 1996] although the nutrient signature of Pacific water was observed across the Makarov Basin on the 1994 Arctic Ocean Section [*Carmack et al.*, 1997; *Swift et al.*, 1997; *Jones et al.*, 1998]. The SCICEX 96 cruise θ-S plots [*Smethie et al.*, 2000, Plate 3] clearly show Pacific waters in more central Canadian Basin regions near the Lomonosov Ridge. And changes in water mass characteristics of the upper layer in the Lincoln Sea over the period 1989–1994 indicate that the Pacific water has been displaced from along the Eurasian side of the Canadian Basin to more along the North American side [*Newton and Sotirin*, 1997]. A temperature maximum, north of Ellesmere Island, indicating the presence of Bering Sea Summer Water observed during 1991–1994 [*Newton and Sotirin*, 1997] was not observed at a nearby location in 1986 [*Jones and Anderson*, 1990]. The recently observed warming of the Atlantic Layer and other changes in water mass characteristics seem to have occurred sometime after about 1987 in both the Eurasian and Canadian basins.

[22] In the Canadian Basin along the coast of North America, Pacific water is a major component of the surface water [*Jones et al.*, 1998] and of the upper halocline ($S < \sim 33.5$) [e.g., *Jones and Anderson*, 1986; *McLaughlin et al.*, 1996]. Since Pacific water lies near the surface, its distribution is strongly influenced by atmospheric forcing. Changes in the near-surface flow in the Arctic Ocean can affect the amounts of Pacific water exiting to the North Atlantic Ocean through the Canadian Arctic Archipelago and Fram Strait. *Rudels and Friedrich* [2000] suggest that the forcing of the wedge of Pacific water close to the North American continental shelf by the prevailing wind fields may lead to a larger export of Pacific water through both the Canadian Arctic Archipelago and Fram Strait by the creation of a buoyancy-driven boundary current along the shelf. The strong pulses of freshwater exports, which would be associated with such a boundary current, could explain occasional high transports of freshwater in the water column that would be unlikely if only waters from the North Atlantic Ocean were involved. Since the flow of Pacific water through the Canadian Arctic Archipelago in this scenario also would increase, it means that the volume of Pacific water in the Arctic Ocean could be reduced.

[23] Some observations have been made that might track changes in Pacific water that has entered the North Atlantic Ocean. Multiyear surveys have been carried out in Fram Strait, Denmark Strait, and the Labrador Sea. The amount of Pacific water varied in Fram Strait (Figure 7), with most Pacific water being present in 1998. Significant changes in the amount of Pacific water were also observed in Denmark Strait. Understanding the changes in Denmark Strait would not be straightforward, since circulation in the region is complex, and changes in regional circulation will cause variability in concentrations of Pacific water in addition to what may result from changes within the Arctic Ocean. In the Labrador Sea, there were some differences in the amounts and distribution of Pacific water present for different years (Figure 5). The observed interannual variability in the Labrador Sea [*Newton and Sotirin*, 1997] was not related in an obvious way to variability in the Lincoln Sea. This is not surprising given the distance of the Labrador Sea from the Lincoln Sea and the potential for other processes in the Labrador Sea and neighboring regions to be masking any such relationship.

### 3.5. Nutrient Relationships in Deeper Water

[24] Denitrification removes nitrate relative to phosphate and so can increase the apparent fraction of Pacific water

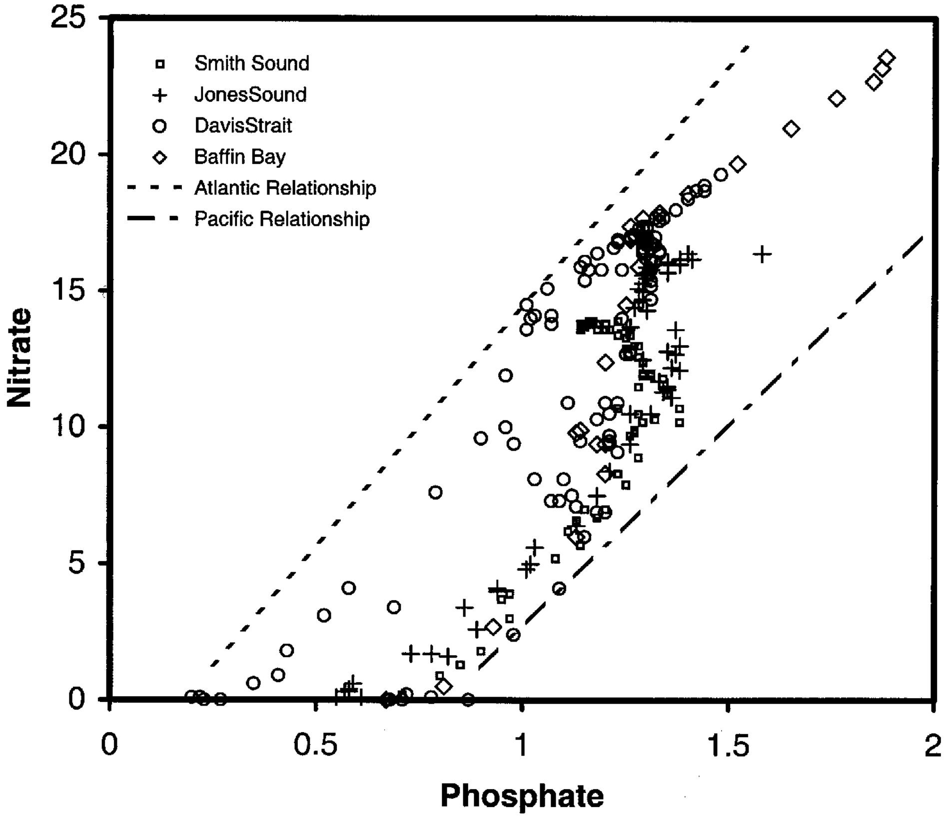

**Figure 9.** Nitrate-phosphate relationships for Smith Sound (squares), Jones Sound (pluses), Davis Strait (circles), and Baffin Bay (diamonds). Units are μmol/kg.

above the fraction actually present or when true Pacific water is not present at all. Organic decay using oxygen as an electron acceptor does not alter the calculated fraction of Pacific water because the nitrate-phosphate change would be parallel to the defining relationships of Pacific and Atlantic waters; that is, changes would follow the Redfield ratio. For nitrate concentrations lower than about 12 μmol/kg, or depths shallower than about 110–130 m, Smith Sound and Jones Sound exhibit generally similar nitrate-phosphate relationships, close to the "pure" Pacific water relationship developed from the JOIS 97 southern Canada Basin data (Figures 9 and 2). From that level to a depth of about 250 m, both regions show an increasingly Atlantic signature with lower phosphate concentrations and nearly constant nitrate concentrations toward the bottom in Smith Sound (about 600 m). The deeper Smith Sound Atlantic nitrate-phosphate relationship coincides almost exactly with that in the southern Canada Basin (Figure 9). The temperature of this Atlantic water is near −0.5°C and its salinity is approximately 34.2. These do not correspond to those of any potential sources south of Smith Sound. The water temperatures in the deeper parts of Smith Sound are only about 0.2°C warmer than water at similar densities observed at the north of Ellesmere Island to the west of the entrance to Nares Strait [*Jones and Anderson*, 1990; *Newton and Sotirin*, 1997]. They are also similar to temperatures in and north of Nares Strait (NODC file data). While the Smith Sound Atlantic water tends to be slightly warmer than Atlantic water in the Lincoln Sea north of Nares Strait, the characteristics of both are very similar in the relevant density range. We conclude that the most likely origin for all of the Pacific and the Atlantic water in the Smith Sound section is the Arctic Ocean, rather than the deeper layers being supplied with Atlantic water from the south.

[25] In the Jones Sound section, the deeper (higher nutrient) data (Figure 9) show an apparent increasing Pacific water fraction. They do not, however, resemble those in the southern Canada Basin (Figure 2). As nitrate concentrations increase above 14 μmol/kg, there is a trend to almost constant phosphate concentrations followed by nearly constant nitrate concentrations and increasingly high phosphate concentrations near the bottom (near 650 m). We interpret the first trend as arising from organic decay in waters entering the deep layer in Jones Sound from Smith Sound, with progressively greater oxidation as depth increases, more-or-less following the Redfield ratio. Here the Jones Sound and Smith Sound waters have nearly the same calculated Pacific water fraction. In the deepest layers with the highest nitrate concentrations, there is an increase in phosphate concentrations with little increase in nitrate concentrations. This does not indicate the presence of more Pacific water. Rather, it most likely reflects the result of denitrification in Jones Sound sediments. This is particularly evident in the plot of the Pacific water fraction versus salinity (Figure 10), where the deeper water apparent Pacific water fraction increases with very little change in salinity, contrary to what would have to be the case if the Pacific water fraction were indeed increasing. We note that these

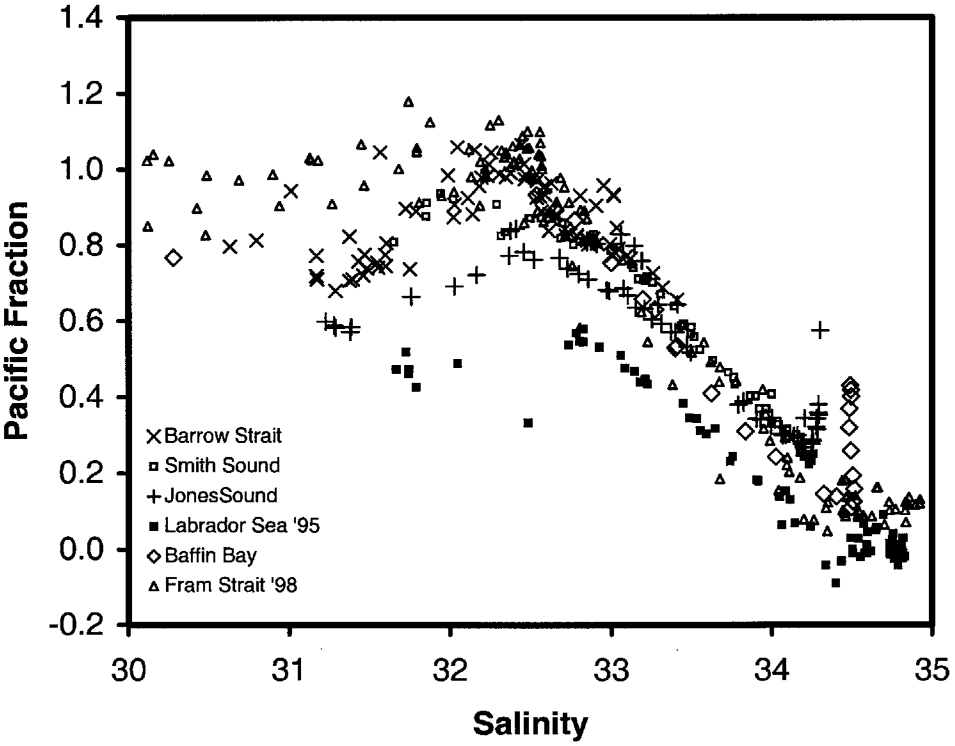

**Figure 10.** Pacific water fraction versus salinity for Smith Sound, Jones Sound, Barrow Strait, Davis Strait, and Labrador Sea.

deepest waters have low CFC and oxygen concentrations (not shown), showing that they are relatively isolated and suggesting conditions are right for denitrification. This is further indicated by the apparent increase in Pacific water with no change in salinity (Figure 10).

[26] In the Davis Strait section, the nitrate-phosphate relationships for data north of and below the sill depth down to about 960 m are the same as for Baffin Bay mid-depth water (Figures 9 and 10). In Davis Strait, points corresponding to phosphate concentrations less than about 0.9 μmol/kg and paralleling the Atlantic relationship line are data from the three most eastern stations in Davis Strait, where there is no water of Pacific origin. They also show as low Pacific fraction and relatively low salinity in Figure 10. The higher nutrient concentrations in Baffin Bay found in the deep water show evidence of organic decay, including denitrification (Figure 10), reflecting the isolation of Baffin Bay deep waters.

### 3.6. Dilution of Pacific Water by Low-Salinity Water

[27] A plot of the Pacific fraction versus salinity can reveal the presence of sources of freshwater other than that added with the Pacific water. As can be seen in the section plots (Figures 3–8), there is a not unexpected correlation between salinity and the Pacific water fraction, since the salinity of Pacific water entering the Arctic Ocean is lower than that of the Atlantic water. For salinity values from about 32.5 to 34.2, there is a nearly linear relationship between Pacific water fraction and salinity (Figure 10) consonant with dilution by Pacific water in this range. Values plotted for water in the Canadian Arctic Archipelago and Fram Strait that has just emerged from the Arctic Ocean lie on nearly the same straight line. For these waters with salinities less than about 32.5, the Pacific water fraction deviates from the straight-line fitted at higher salinities. As noted by *Jones et al.* [1998], river runoff and sea ice meltwater appear to have nutrient relationships similar to those of Atlantic water. Contributions from these sources would be evident by a constant or slightly decreasing apparent Pacific water fraction as salinity decreases.

[28] Waters in the Labrador Sea as well as in Denmark Strait (not shown) show a similar relationship, but the nearly linear relationship between the Pacific water fraction and salinity is shifted to lower salinities compared waters closer to the Arctic Ocean. Nutrient values for Atlantic water in the Labrador Sea coincide with those from the Arctic Ocean; thus the differences in Figure 10 cannot be ascribed to there being a significantly different Atlantic source water nitrate-phosphate relationship for Atlantic water in the Labrador Sea. We note a freshening of Atlantic source water with constant (zero) Pacific water fraction from about 34.8 to about 34.4. The most likely explanation is that Atlantic water was partially freshened by sea ice meltwater before mixing with Pacific water prior to there being any addition of Pacific water. Similarly, an addition of sea ice meltwater may account for the smaller shifts to lower salinities in the linear region of the plots for other the regions represented in Figure 10.

## 4. Conclusions

[29] Identifying source waters and tracing their circulation are essential in a climate context in order to understand heat, salt, and freshwater budgets and in order that ocean

currents be appropriately represented in models that describe ocean circulation. The return of fresh water to the Atlantic Ocean from the Pacific is a case in point. Nutrient relationships, nitrate versus phosphate, offer a new and powerful tool for tracing Pacific water within the Arctic Ocean and after it exits the Arctic Ocean into the North Atlantic Ocean. Pacific water can be traced through the Canadian Arctic Archipelago to the Labrador Sea and as far south as the Grand Banks near 42°N. Only Pacific water appears to have exited from the Arctic Ocean through the Canadian Arctic Archipelago except via Nares Strait, where Atlantic water of Arctic origin (rather than having arrived from the south via the West Greenland Current) is encountered at depths of 75 m and greater. Pacific water exiting Fram Strait can be identified in the East Greenland Current through Denmark Strait.

[30] Interannual variability in the concentration of Pacific water exiting the Arctic Ocean through Fram Strait is observed. Interannual variability for that exiting through the Canadian Arctic Archipelago is observed in the Labrador Sea. The variability in both regions could not be clearly associated with variability associated with the North Atlantic Oscillation, though observed changes in the Arctic Ocean circulation would certainly be expected to affect the amount of Pacific water entering the North Atlantic Ocean.

[31] **Acknowledgments.** We thank Jón Olafsson, Marine Research Institute, Iceland, and Gereon Budeus, Alfred Wegener Institute for Polar and Marine Research, Germany, for providing data from East Greenland including Denmark Strait. Data from Fram Strait were obtained through the European Union project VEINS (MAS3-CT96-0070). This work was supported by the Panel on Energy Research and Development (Canada), the Swedish Natural Research Council, and grants from the U.S. National Science Foundation (OPP9709130 to J. H. Swift and OPP9708420 to K. K. Falkner).

## References

Aagaard, K., and E. C. Carmack, The role of sea ice and other fresh water in the Arctic circulation, *J. Geophys. Res.*, *94*, 14,485–14,498, 1989.

Anderson, L. G., and D. Dyrssen, Chemical constituents of the Arctic Ocean in the Svalbard area, *Oceanol. Acta*, *4*, 305–311, 1981.

Anderson, L. G., G. Björk, 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.

Carmack, E. C., K. Aagaard, J. H. Swift, R. W. Macdonald, F. A. McLaughlin, E. P. Jones, R. G. Perkin, J. N. Smith, K. M. Ellis, and L. Kilius, Changes in temperature and tracer distributions within the Arctic Ocean: Results from the 1994 Arctic Ocean Section, *Deep Sea Res., Part 2*, *44*, 1487–1502, 1997.

Codispoti, L. A., and D. Lowman, A reactive silicate budget for the Arctic Ocean, *Limnol. Oceanogr.*, *18*, 448–456, 1973.

Dickson, R., J. Lazier, J. Meincke, P. Rhines, and J. Swift, Long-term coordinated changes in the convective activity of the North Atlantic, *Prog. Oceanogr.*, *38*, 241–294, 1996.

Falck, E., Contribution of waters of Atlantic and Pacific origin in the Northeast Water Polynya, *Polar Res.*, *20*, 193–200, 2001.

Gorshkov, S. G., *World Ocean Atlas*, vol. 3, 190 pp., Pergamon, New York, 1983.

Guay, C. K. H., K. K. Falkner, R. D. Muench, M. Mensch, M. Frank, and R. Bayer, Wind-driven transport pathways for Eurasian Arctic river discharge, *J. Geophys. Res.*, *106*, 11,469–11,480, 2001.

Ingram, R. G., and S. Prinsenberg, Coastal oceanography of Hudson Bay and surrounding eastern Canadian Arctic Waters, in *The Sea*, vol. 11, edited by A. R. Robinson and K. H. Brink, pp. 835–861, John Wiley, New York, 1998.

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

Jones, E. P., and L. G. Anderson, On the origin of the properties of the Arctic Ocean halocline north of Ellesmere Island: Results from the Canadian Ice Island, *Cont. Shelf. Res.*, *10*, 485–498, 1990.

Jones, E. P., and A. R. Coote, Nutrient distributions in the Canadian Archipelago: Indications of summer water mass and flow characteristics, *Can. J. Fish. Aquat. Sci.*, *37*, 589–599, 1980.

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.

Loder, J. W., B. Petrie, and G. Gawarkiewicz, The coastal ocean off northeastern North America: A large-scale view, in *The Sea*, vol. 11, edited by A. R. Robinson and K. H. Brink, pp. 105–133, John Wiley, New York, 1998.

McLaughlin, F., E. C. Carmack, R. W. Macdonald, and J. K. B. Bishop, 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., M. Steele, and R. Andersen, Hydrography of the upper Arctic Ocean measured from the nuclear submarine U.S.S. Pargo, *Deep Sea Res., Part I*, *45*, 15–38, 1998.

Newton, J. L., and B. J. Sotirin, Boundary undercurrent and water mass changes in the Lincoln Sea, *J. Geophys. Res.*, *102*, 3393–3403, 1997.

Petrie, B., and J. Buckley, Volume and freshwater transport of the Labrador Current in Flemish Pass, *J. Geophys. Res.*, *101*, 28,335–28,342, 1996.

Quadfasel, D., A. Sy, D. Wells, and A. Tunik, Warming in the Arctic, *Nature*, *350*, 385, 1991.

Rudels, B., The thermohaline circulation of the Arctic Ocean and the Greenland Sea, *Philos. Trans. R. Soc. London, Ser. A*, *352*, 287–299, 1995.

Rudels, B., and H. J. Friedrich, The transformations of Atlantic water in the Arctic Ocean and their significance for the freshwater budget, in *The Freshwater Budget of the Arctic Ocean*, *NATO Sci. Ser.*, vol. 2, edited by E. L. Lewis, pp. 503–532, Kluwer Acad., Norwell, Mass., 2000.

Smethie, W. M., P. Schlosser, and G. Bönisch, Renewal and circulation of intermediate waters in the Canadian Basin observed on the SCICEX 96 cruise, *J. Geophys. Res.*, *105*, 1105–1121, 2000.

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 II*, *44*, 1503–1529, 1997.

Wheeler, P. A., J. M. Watkins, and R. L. Hansing, Nutrients, organic carbon and organic nitrogen in the upper water column of the Arctic Ocean: Implications fro the sources of dissolved organic carbon, *Deep Sea Res., Part II*, *44*, 1571–1592, 1997.

---

L. G. Anderson, Department of Analytical and Marine Chemistry, Göteborg University, SE 412-96 Göteborg, Sweden. (leif@amc.chalmers.se)

G. Civitarese and M. Lipizer, Consiglio Nazionale delle Ricerche, Istituto Talassografico di Trieste, Viale R. Gessi, 2-34123 Trieste, Italy. (civitarese@itt.ts.cnr.it; marina.lipizer@itt.ts.cnr.it)

K. K. Falkner, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331-5503, USA. (kfalkner@oce.orst.edu)

E. P. Jones, Department of Fisheries and Oceans, Bedford Institute of Oceanography, P. O. Box 1006, Dartmouth, NS B2Y 4A2, Canada. (jonesp@mar.dfo-mpo.gc.ca)

G. Kattner, Alfred Wegener Institute for Polar and Marine Research, Postfach 12 01 61, Columbusstarasse, D-2850 Bremerhaven, Germany. (gkattner@awi-bremerhaven.de)

F. McLaughlin, Institute of Ocean Sciences, P.O. Box 6000, Sidney, BC V8L 4B2, Canada. (mclaughlinf@dfo-mpo.gc.ca)

J. H. Swift, Scripps Institution of Oceanography, University of California, San Diego, Mail Code 0214, 9500 Gilman Dr., La Jolla, CA 92093-0214, USA. (jswift@odf.ucsd.edu)