Water masses and their chemical constituents in the western Nansen Basin of the Arctic Ocean

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ABSTRACT

Measurements of nutrients, salinity and temperature in the western Nansen Basin and over the slope of the Yermak Plateau made from the Fram 3 Ice Station show that the near-surface water does not have the pronounced halocline and associated nutrient maximum found in many regions of the Arctic Ocean. It is argued that this near-surface water is a mixture of Atlantic layer water with surface water carried to the Nansen Basin by the trans-polar drift. The deep water in western Nansen Basin could be formed from Norwegian Sea deep water, possibly mixed with Greenland Sea deep water, with additional salt from another source such as cold Barents Sea water.

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RÉSUMÉ

Les masses d'eau et leurs constituants chimiques dans la zone ouest du bassin de Nansen de l'Océan Arctique

Des mesures de salinité, température et nutriments ont été effectuées dans la zone ouest du bassin de Nansen et sur la pente du plateau Yermak à partir de la station glaciaire Fram 3; elles révèlent que les eaux proches de la surface ne présentent pas l'halocline prononcée ni le maximum de concentration en nutriments que l'on retrouve en plusieurs zones de l'Océan Arctique. On montre que ces eaux proches de la surface résultent du mélange de l'eau atlantique et de l'eau de surface apportée au bassin de Nansen par la dérive transpolaire. L'eau de fond de la zone ouest du bassin de Nansen pourrait être composée d'eau de fond de la mer de Norvège, et probablement d'eau de fond de la mer du Groënland, avec du sel provenant d'une autre source telle que l'eau froide de la mer de Barentz.

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INTRODUCTION

Most of the exchange of water between the Arctic Ocean and the rest of the World's oceans occurs through Fram Strait, between Greenland and Svalbard, over a sill at a depth of 2 600 m. Both surface and deep water flow through Fram Strait, with inflow to the Arctic Ocean occurring on the eastern side and outflow on the western side. The major inflows are North Atlantic water, which forms the Atlantic layer, and Norwegian Sea deep water (NSDW) (*e.g.*, Aagaard et al., 1985). There is evidence that some Greenland

Sea deep water (GSDW) is also entering the Arctic Ocean through Fram Strait (Swift et al., 1983). Water flowing into the Arctic Ocean through Fram Strait first enters the Nansen Basin where modifications result in a near surface layer and the underlying Atlantic layer. The first major modifications to NSDW to form Arctic Ocean deep water (AODW) may occur there also.

We report measurements of nutrients, oxygen and salinity in samples obtained throughout the water column from the Fram 3 ice station as it drifted in the western end of the Nansen Basin and over the slope of the Yermak Plateau north of Fram Strait. The paper will

focus on nutrient data as well as salinity and temperature to suggest the origin of the components of the water in the surface region and to comment on the deep water in terms of the deep water found in Fram Strait.

METHODS

The Fram 3 ice station was established in mid-March, 1981, and abandoned two months later with the onset of summer conditions (Manley et al., 1982). The results reported here were obtained over a ten-day period during which the ice station drifted from 82°41′N, 6°33′E in the Nansen Basin, where the depth was 3 700 m, to 81°54′N, 5°28′E on the slope of the Yermak Plateau, where the depth was 800 m (Fig. 1).

Water samples were collected in 1.2L Niskin bottles mounted on a Neil Brown CTD-rosette system. Analyses were done for salinity, oxygen, nitrate, phosphate, and silicate. The oxygen samples were analyzed on site using a Carpenter-Winkler method with analytical precision of ± 1 μM. The salinity samples, which had been kept from freezing, and nutrient samples, which were frozen immediately after collection, were returned to the Bedford Institute of Oceanography for analysis. The salinity was determined from conductivity measurements made with a Guildline Autosal, model 8400, with analytical precision of ± 0.002. The nutrient samples were analyzed with an AutoAnalyzer II using standard procedures with analytical precision of ± 0.4 μM for nitrate and silicate and ± 0.02 μM for phosphate. In spite of the salinity and nutrient samples being stored for a period of weeks, the overall precision of the measurements is thought to be not much different from the analytical precision. Temperatures, precision better than $\pm 0.01°$, and depths were obtained from the Neil Brown CTD.

The deep water data, below 1 000 m, were obtained from two casts on separate days with no overlap in sampling depths (Fig. 2). The first cast sampled from 2 900 to 3 700 m and the second from 1 300 to 2 400 m. For both casts the deepest sample was taken near the bottom as the Ice Station drifted over the slope of the Yermak Plateau. The shallower water data were collected in a series of casts over several days (Fig. 2).

RESULTS AND DISCUSSION

The nutrient and temperature data are presented in section plots along the path of the ice station drift (Fig. 2). The nutrients show generally increasing values with increasing depths except for a slight maximum near 2 000 m along the slope of the Yermak Plateau. Oxygen values (not shown), except for station 1 for which they are not available, generally reflect the nutrient distributions, decreasing values with increasing nutrient concentrations. From a plot of potential temperature vs salinity for all stations (Fig. 3), one can identify a shallow (< 50 m) surface layer with temperatures near the freezing point and salinities near 34.1. Below this is the Atlantic layer, characterized at its core by temperatures near 2.5°C and salinities near 34.9. Below the Atlantic layer is the colder AODW, the boundary between the two water masses traditionally defined by the 0°C isotherm.

The relatively high salinity of the near-surface layer above the Atlantic layer is in marked contrast to that of the near surface water found in central locations of the Arctic Ocean, where the minimum surface salinity is typically near 31. In these central locations, near freezing temperatures extend well below a pronounced halocline, the temperatures gradually increasing with depth to a maximum near 0.5°C in the Atlantic Layer (e.g., Aagaard et al., 1985; Melling, Lewis, 1982). Associated with the halocline is a nutrient maximum that has been observed over a large area, including near the north pole over the Makarov and Amundsen Basins (Moore et al., 1983) and in the Canada Basin (Kinney
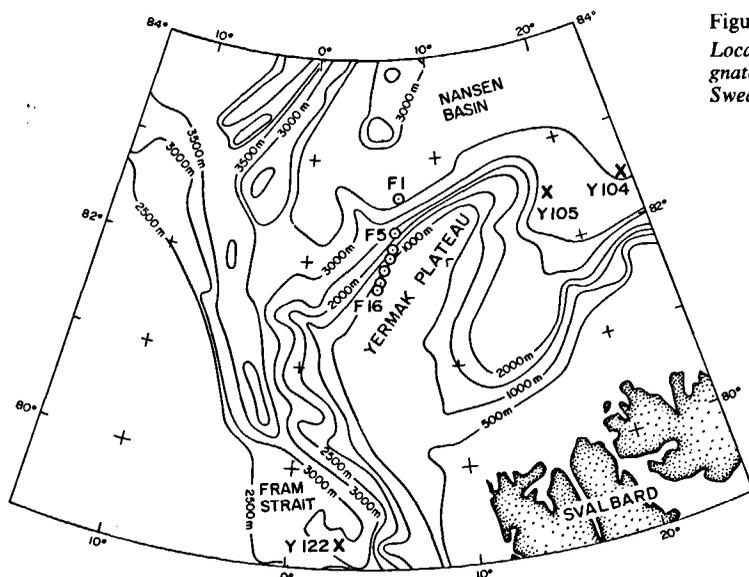
Figure 1

Locations of the Fram 3 stations and surrounding bathymetry. F designates the Fram 3 stations, Y designates stations occupied by the Swedish icebreaker "Ymer" (Anderson, Dyrssen, 1981).

Figure 2

Nutrient and potential temperature sections for the Fram 3 stations. Values not resolved near the surface decrease to 2.8 µM for silicate, 5.5 µM for nitrate, and 0.5 µM for phosphate. Surface temperatures were at the freezing point.
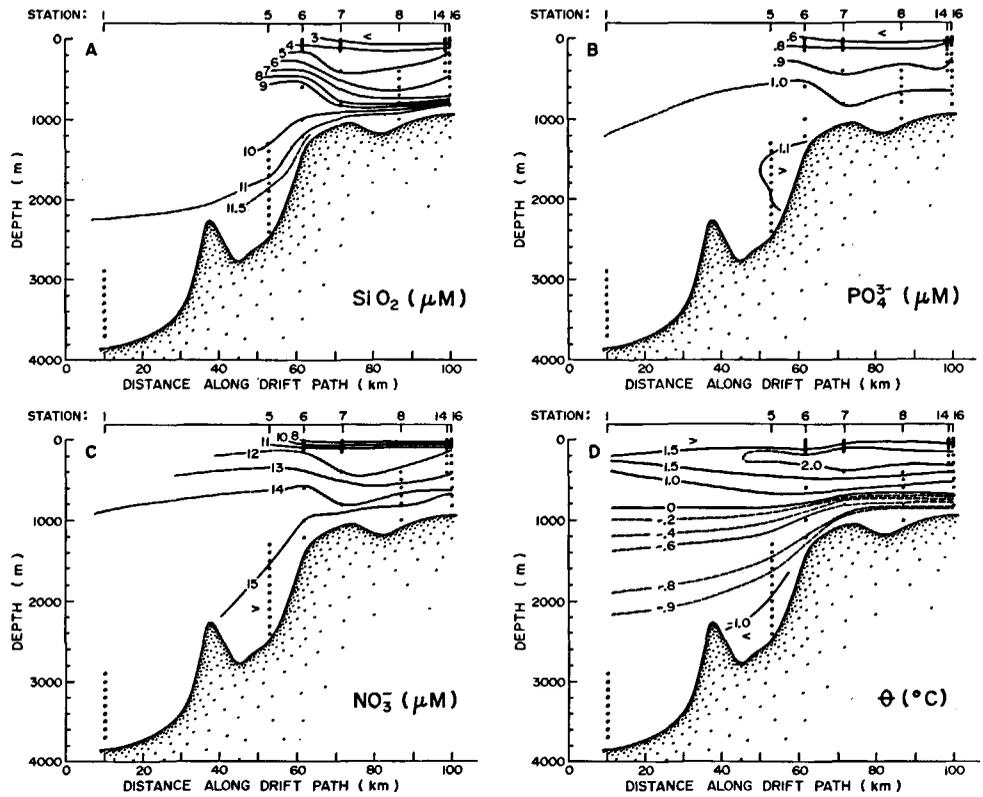
Table 1

Some characteristics of Arctic Ocean water masses below 2000 m. Where indicated, (a) represents data from 2000 to 3000 m and (b) represents data below 3000 m.

Nansen Basin

	Fram Strait NSDW	Fram 3	Ymer Stations 104 and 105 (2)	Amundsen (or Fram) Basin (3)	Makarov Basin (3)	Canada Basin (4)
θ (°C)	− 0.93 to − 1.06 (1)	− 0.99 to − 1.02 (a) − 0.95 to − 0.96 (b)	− 0.90 to − 0.96	− 0.8 to − 0.9	− 0.5	− 0.53 (4)
S	34.908 to 34.911 (1)	34.918 to 34.927 (a) 34.944 to 34.953 (b)	34.919 to 34.937	34.932 to 34. 941	34.953 to 34.954	34.95 (5)
O_2 (µM/kg)	305 to 306 (1) 308 to 316*	300 to 302 (a)	304 to 316			278 to 289 (4)
Si (µM/kg)	11.2 to 12.9 (1) 10.9 to 11.9*	11.2 to 11.5 (a) 10.6 to 10.9 (b)	10.4 to 11.2	9.7 to 10.0	12.4 to 12.8	13 to 14 (4)
NO_3 (µM/kg)		14.9 to 15.2 (a) 14.3 to 14.7 (b)				14.3 to 15.0 (4)
PO_4 (µM/kg)	0.94 to 1.00*	1.02 to 1.07 (a) 0.98 to 1.04 (b)	0.84 to 0.90			0.94 to 1.00 (4)

* Ymer Station 122.
(1) Swift *et al.*, 1983.
(2) Anderson and Dyrssen, 1980.
(3) Moore *et al.*, 1983.
(4) Kinney *et al.*, 1970.
(5) Aagaard *et al.*, 1985.

et al., 1970; Nikiforov *et al.*, 1966). None of this central Arctic Ocean surface layer water appears as such in the Nansen Basin at the Fram 3 stations. The nutrient data also provide no evidence of the high nutrient concentrations found at the halocline in the central Arctic Ocean.

The AODW below the Atlantic layer much more closely resembles that in other parts of the central Arctic Ocean, though some differences are apparent (Tab. 1). These two depth ranges will now be discussed separately.
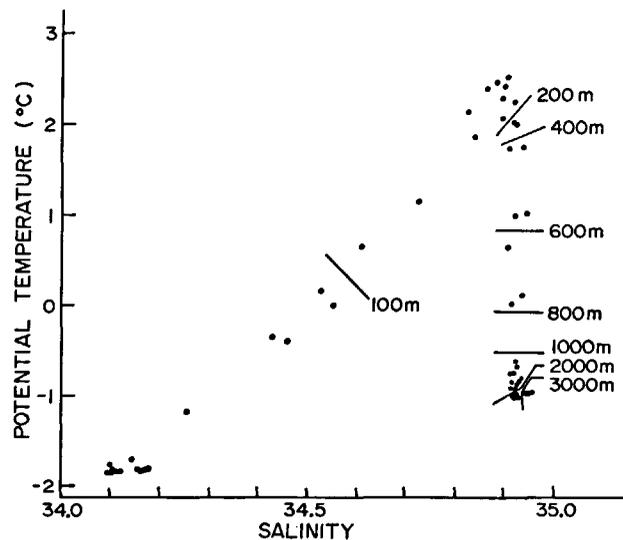
Figure 3

Composite plot of potential temperature vs salinity for all Fram 3 stations.

The near-surface layer

The θ-S plot of the 200 m deep near-surface layer (Fig. 3) is nearly linear, suggesting that this water can be represented by mixture of two components: one end-member being Atlantic layer water (ALW) at the temperature maximum of the Atlantic layer, and the other end-member being water that is colder and less saline. One plausible candidate for this latter component is sea ice meltwater. A second candidate is Arctic Ocean surface water (AOSW) transported to the Nansen Basin by the trans-polar drift. In this latter case, mixing could be occurring over a considerable region.

The sea ice meltwater end-member would result from the considerable amounts of ice that are exported from the Arctic Ocean to Fram Strait, where the ice encounters the warmer water of the West Spitzbergen current and melts. Mixing with ALW would presumably occur in the vicinity of Fram Strait. While no detailed calculations are at present available, simple estimates of heat loss and subsequent rate of ice melting in the West Spitzbergen current indicate that the freshening and cooling of the water in the region of the Fram 3 stations could be accounted for by the melting of the polar ice pack (Hunkins, 1983). The bulk salinity of melting ice, mostly multiyear ice, is 2-3, and, based on some of our measurements of nitrate and phosphate concentrations in sea ice (unpublished), the nutrient concentrations would be proportionately low. The sea ice is assumed to originate in the central Arctic Ocean. The salinity of the sea ice is taken to be 3 and, since the ice is assumed to have been formed somewhere in the central Arctic Ocean, its nutrient content is taken to be that of AOSW but reduced by the relative salinities of the sea ice and AOSW. The composition of the surface water at the Fram 3 stations turns out to be not very sensitive to these low values in sea ice and therefore not very dependent on precise values for the composition of the sea ice.

Exactly how to characterize the AOSW end-member or where the mixing of AOSW with ALW might take place is more problematical. The most recent determination of Arctic Ocean surface currents as determined from the drift of sea ice indicates that surface water at the Fram 3 stations has flowed from the Chukchi Sea through the Canada Basin to near the slope regions of the Eurasian Basin (Thorndike, Colony, 1982; Colony, Thorndike, 1984). Near-surface salinity values along this route range from approximately 31 in the Chukchi Sea to about 33 in the Eurasian Basin (Coachman, Aagaard, 1974). Surface nutrient data are very sparse throughout most of this path, making a determination of the chemical composition of an AOSW end-member uncertain; however, it would seem reasonable to adopt values for salinity and nutrients similar to the near-surface water at the low salinity beginning of the trans-polar drift current as indicated by measurements in the Chukchi Sea (Anderson, Lowings, 1981) and in the Canada Basin (Kinney et al., 1970). This water is a mixture of Bering Sea water, fresh water runoff primarily from Asia, and, undoubtedly, some sea ice meltwater.

Table 2
End-members of the near-surface layer.

Atlantic layer water		Sea ice meltwater	Arctic Ocean surface water
Salinity	34.9	3	31.0
Temperature	2.5°C	0°C	−1.7°C
PO_4^{3-}	0.87 µM	0.07 µM	1.15 µM
NO_3^-	11.9 µM	0.09 µM	1.0 µM

Sea ice meltwater and AOSW, whose chemical characteristics are summarized in Table 2, will be examined to see which end-member mixing with ALW gives the more reasonable explanation of the phosphate and nitrate concentrations in the near-surface water of the Fram 3 stations.

The major differences between sea ice meltwater and AOSW are salinity and nutrient content. While salinity is a conservative tracer, nitrate and phosphate by themselves are not. It is generally necessary to take biological processes into account before they can be used to discuss mixing of different water masses. Nitrate and phosphate are consumed during photosynthesis and remineralized during respiration. The most common way of representing this biological growth and decay process in the oceans is the Redfield-Ketchum-Richards model (Redfield et al., 1963), summarized by the equation

$$(CH_2O)_{106} (NH_3)_{16} H_3PO_4 + 138O_2 \rightleftarrows 106\ CO_2 + 122\ H_2O + 16\ HNO_3 + H_3PO_4$$
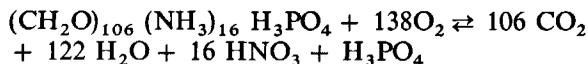
with the reaction proceeding to the left representing the fixing of nutrients and carbon to form biogenic matter, and to the right representing decay. According to this model, the ratio of the change in nitrate concentration to the change in phosphate concentration, $\Delta NO_3^-/\Delta PO_4^{3-}$, is 16. This stoichiometric model is clearly a crude representation of the complex chemistry associated with biological growth and decay, but it is consistent with measured changes in inorganic constituents in many ocean environments, with $\Delta NO_3^-/\Delta PO_4^{3-}$ varying in most instances between 14 and 17 (e.g., Alvarez-Borrego et al., 1975; Copin-Montegut, Copin-Montegut, 1983). In the region north of Svalbard not far from the Fram 3 stations, Anderson and Dyrssen (1981) found $\Delta NO_3^-/\Delta PO_4^{3-}$ to be 14.

We approach the question of mixing between ALW with either sea ice meltwater or AOSW by determining the changes in phosphate and nitrate concentrations that result from biological processes, then judging which of the two gives the more consistent agreement with the Redfield-Ketchum-Richards model. If no biological processes occurred, there would be a straight line between Atlantic layer water and each of the prospective end members on a nutrient vs salinity plot. With the values for end-members as shown in Table 2, the equations for the mixing lines are: a) for sea ice meltwater mixing with ALW:

$$PO_4^{3-} = 0.024S \qquad NO_3^- = 0.37S - 1.0;$$

and b) for AOSW mixing with ALW:

$$PO_4^{3-} = 0.0051S + 0.69 \qquad NO_3^- = 2.79S - 85.6$$

For nitrate, these mixing lines are plotted in Figure 4. The changes in nitrate or phosphate concentrations as a result of biological processes are the differences
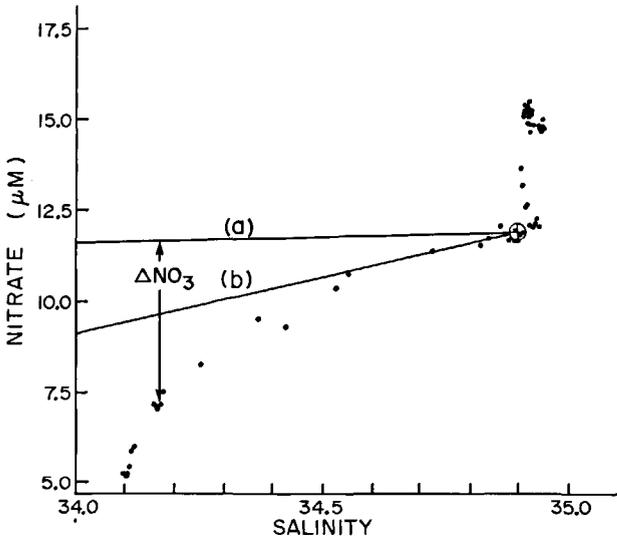
Figure 4

Composite plot of nitrate concentrations vs salinity for all Fram 3 stations. The straight lines represent Atlantic layer water mixing with: a) sea ice meltwater; and b) Arctic Ocean surface water. The amount of nitrate fixed or remineralized is the difference between each point and the line at the same salinity as shown for one point with Atlantic layer water mixing with sea ice meltwater.

between these straight lines and the observed nutrient concentrations. From plots such as Figure 4, the amount of nitrate and phosphate fixed or remineralized by biological processes for each salinity value is determined. A least squares fit to the 14 near surface points for ΔNO_3^- and ΔPO_4^{3-} obtained in this way results in

$$\Delta NO_3^-/\Delta PO_4^{3-} = 18.4 \quad (r^2 = .88)$$

for sea ice meltwater mixing with ALW, and

$$\Delta NO_3^-/\Delta PO_4^{3-} = 15.2 \quad (r^2 = .88)$$

for AOSW mixing with ALW (Fig. 5).

The AOSW end member thus gives a $\Delta NO_3^-/\Delta PO_4^{3-}$ ratio more in accord with what is expected from the Redfield-Ketchum-Richards model as well as that measured north of Svalbard by Anderson and Dyrssen (1981). The $\Delta NO_3^-/\Delta PO_4^{3-}$ values for the AODW can be included in Figure 5 by assuming that the preformed nutrient values for AODW are the same as for ALW, an assumption justified by the observed constancy of "NO" (Broecker, 1974) for these two water masses. A slope of near 15.2, corresponding to that determined with AOSW as the end member mixing with ALW, represents reasonably well all data throughout the Fram 3 section, whereas a slope of 18.4, corresponding to sea ice meltwater as the end-member, represents only the near surface data (Fig. 5). We thus conclude that sea ice meltwater is not an appropriate end-member, but that a mixture of AOSW with ALW can produce the observed near-surface characteristics in this part of the Nansen Basin.

Based on the relative salinities of AOSW and ALW, the surface water at the Fram 3 stations (S = 34.1) contains about 20% AOSW. Since this surface water is flowing south, there is a substantial flow of Arctic Ocean surface water out of the Arctic Ocean east of the front separating the out-flowing East Greenland current from the inflowing Atlantic water. We have no information that would allow a quantitative measure of this flow, but it would seem significant enough not to be ignored in Arctic Ocean budgets.

The deeper water

The AODW beneath the Atlantic Layer can be divided into two layers, the upper layer extending from the 0°C isotherm at a depth of about 800 to below 2400 m and the second from above 2800 m to the bottom (Fig. 3, 6). The upper layer has lower salinities and, at least between 2000 and 2400 m, lower temperatures than the deeper water. The nutrient concentrations in the upper layer are also slightly higher (Fig. 2). With the sill depth in Fram Strait at 2600 m, it is probably not surprising to see a distinction between water in these two depth ranges since flow between the basins on either side of the sill would be restricted.

It is generally believed that the deep water in the Arctic Ocean has its origin in the Norwegian and Greenland
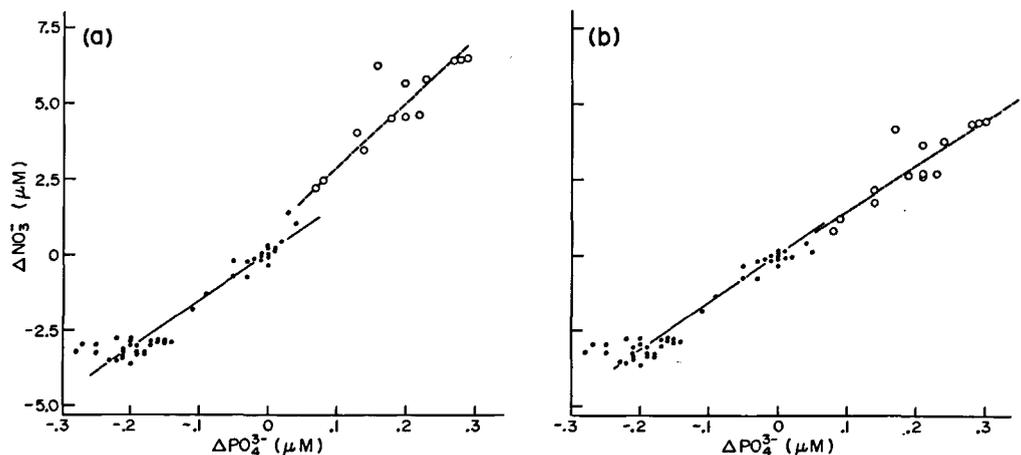
Figure 5

Composite plot of $\Delta NO_3^-/\Delta PO_4^{3-}$ for all Fram 3 stations with: a) sea ice meltwater; and b) AOSW as end members. The circled points are the near surface values fitted to the dashed straight lines with slopes of: a) 18.4; and b) 15.2. The solid line has a slope of 15.
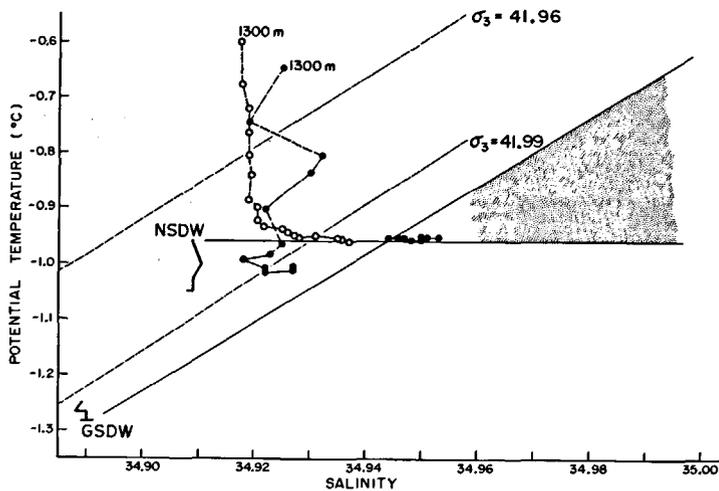
Figure 6 .

Expanded scale of composite plot of potential temperature vs salinity for the Fram 3 deep water (solid circles). The points below 2000 m are joined by solid lines and above 2000 m by dashed lines. Included are data below 2000 m from Fram Strait showing GSDW and NSDW (Swift et al., 1983) and from the Ymer station 105 (open circles) (Anderson, Dyrssen, 1980). The salinities for the Ymer station 105 have been slightly corrected from those originally reported (B. Rudels, pers. comm.). The shaded area represents the range of salinity and temperature for water that could be mixing with GSDW and NSDW to form the deep water in Nansen Basin. It covers some of the values for the cold, saline Barents Sea Water reported by Midttun (1985).

Seas (e.g., Aagaard, 1981). On the basis of measurements in Fram Strait, Swift et al. (1983) suggest that GSDW also flows into the Arctic Ocean and both NSDW and GSDW contribute to the formation of AODW. Our data show no direct evidence of the presence of GSDW at the Fram 3 stations. If the GSDW observed in Fram Strait is present as an identifiable water mass once it enters the Arctic Ocean, it may be flowing to the north and west of the Yermak Plateau.

For AODW to be formed from NSDW and GSDW, there must be another source of salt such as the Barents and Kara Seas (Swift et al., 1983). From both the θ-S relationships (Fig. 6) and silicate concentrations (Tab. 1), the water between 2000 and 2400 m in fact appears to be a mixture of NSDW with the AODW lying below 3000 m. To be formed from NSDW or NSDW and GSDW, the deeper water below 3000 m would require salt from an outside source. The shaded portion of Figure 6 indicates the ranges of salinity and temperature of water that could mix with NSDW or NSDW and GSDW to form the deeper AODW. Swift et al. (1983) have argued that water from the Barents Sea has enough salt to help form AODW, but its temperatures are too high, thus GSDW is required to reduce the temperatures to the observed AODW values. If water in the Barents Sea or elsewhere on the shelves could be found with the same salinities as summarized by Swift et al. (1983), but with lower temperatures, near −1°C, GSDW would not be required to produce the AODW. Water with salinities between 34.8 and 35.2 and temperatures between −1.8°C and −1.0°C has been reported in the Barents Sea (Midttun, 1985), and mechanisms for its transport to deeper regions have been suggested (e.g., Aagaard et al., 1985; Melling, Lewis, 1982; Aagaard et al., 1981). Thus, the deep water in the Nansen Basin at the Fram 3

stations below 2000 m could be formed from a mixture of NSDW and cold Barents Sea Water without including GSDW, though a component of GSDW cannot be ruled out. The θ-S characteristics of the water above 2000 m extend to a salinity and temperature range fairly close to those summarized by Swift et al. (1983) for the Barents Sea, suggesting that the slightly warmer Barents Sea Water could be a component of this water and thereby allowing the possibility of both the warmer and colder Barents sea water playing a role in the formation of the deep water. Exactly where such processes could take place is not known, though data from Fram Strait (Swift et al., 1983) seem to rule out their occurring in water before it enters the Arctic Ocean, the implication being that the cold, saline water required to form AODW if produced in the Barents Sea would drain northward into the Arctic Ocean and not into the Norwegian Sea between Norway and Svalbard.

Acknowledgements

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