Contribution of waters of Atlantic and Pacific origin in the Northeast Water Polynya

Eva Falck

Measurements of nitrate and phosphate taken in the Northeast Water Polynya (NEWP) during the summer of 1993 have been used to identify the contribution of waters of Atlantic and Pacific origin in the polynya. Since waters from the northern Pacific exhibit a deficit in nitrate relative to phosphate due to denitrification in low oxygen waters, the relationship between nitrate and phosphate can be used to distinguish between oceanic waters of Pacific and Atlantic origin. The Pacific Water enters the Arctic Ocean through Bering Strait and flows along the northern coasts of Alaska and Canada. Some of this water exits through Fram Strait and may therefore enter the polynya which is situated above the continental shelf off the north-eastern coast of Greenland. Compared to data from the Greenland Sea, which only show a N–P relationship of typical Atlantic Water, the data from the Northeast Water Polynya show that the upper waters of the polynya bear a clear signal of waters of Pacific origin. In the surface mixed layer an average of about 90 % is found to have Pacific N–P characteristics. Below the surface mixed layer the amount of Pacific derived water decreases through the halocline and from about 150 m to the bottom only typical Atlantic Water is found.

E. Falck, Dept. of Analytical and Marine Chemistry, Göteborg University, SE-41296 Göteborg, Sweden.

The Northeast Water Polynya is a recurrent polynya situated above the continental shelf off the north-eastern coast of Greenland north of 79° N (Fig. 1). Its formation is attributed to the combined effect of a fast ice barrier in the south, Norske Øer Ice Barrier (NØIB), and a northward flowing coastal current, the Northeast Greenland Coastal Current (Schneider & Budéus 1995). Most authors agree that the upper water of the East Greenland Shelf, between the coast and the East Greenland Polar Front, is imported from the Arctic Ocean (e.g. Bourke et al. 1987). On the other hand, Budéus et al. (1997) find that several arguments oppose this suggestion and indicate that the waters found in the upper water column of the NEWP area are locally formed.

The surface water on the East Greenland Shelf has a rather different nutrient regime than that found in the adjacent Greenland Sea. While phosphate and silicate are slightly higher, nitrate has rather low values, about 4 µM (Lara et al. 1994) before the onset of the biological season compared to about 12 µM (Smith et al. 1991) in the Greenland Sea. These differences in the relationship between nutrients are used in this work to infer the origin of the waters in the Northeast Water Polynya, and to show that the upper water mass on the shelf bears a clear signal of Pacific origin and therefore must be imported from the Arctic Ocean. The Pacific influence can be seen in the relationship between nitrate and phosphate, where Pacific-derived waters have a higher phosphate concentration relative to nitrate as compared to Atlantic Water (Wilson & Wallace 1990). This water flows into the Arctic Ocean through Bering Strait, along the northern coasts of Alaska and

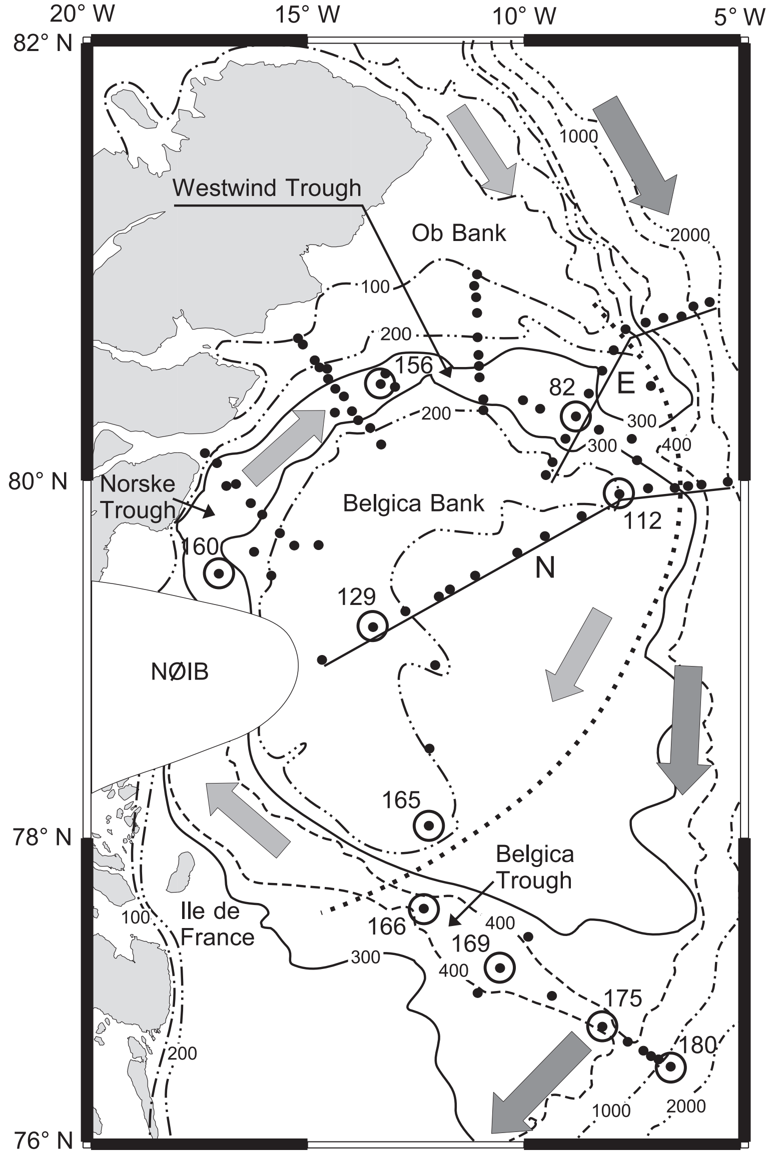

Fig. 1. Map of the Northeast Water Polynya with station positions occupied during the 1993 cruise aboard the *Polar Sea*. The dashed line separates the polynya area from the Northern Slope (stations from transect E and N that are east of the dashed line) and Belgica Trough. This line also gives the approximate limits of the distribution of the Knee Water as observed during this cruise. Circulation pattern is shown by arrows, with light arrows indicating water of high Pacific content. NØIB stands for Norske Øer Ice Barrier.

Canada and exits through the Canadian Archipelago and Fram Strait. Jones et al. (1998) found that the upper 30 m of the water close to the above-mentioned coasts had a proportion of Pacific-derived water of more than 90 %. This high percentage of Pacific Water is also found in the polynya area as seen with NEWP92 data by Wallace et al. (1995a) using the nutrient ratio NO/PO; a similar finding is shown here with the 1993 data using a N/P relation.

This work is based on hydrographic and chemical data collected between 22 July and 17 August 1993 on board the US Coast Guard cutter *Polar Sea*, taken between 76.5° N and 81° N and west of 5° W (Fig. 1). The reader is referred to Wallace et al. (1995a, 1995b) for details of the analysis procedure and the data collected.

Hydrography of the Northeast Water Polynya

The hydrography of the East Greenland Shelf has a two-layered water structure with a relatively

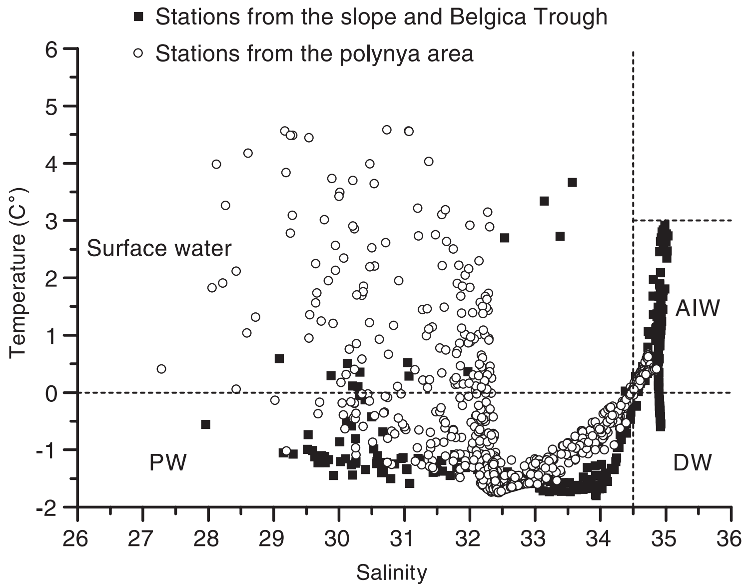

Fig. 2. Potential temperature versus salinity diagram where water types are identified as follows: Polar Water (PW), Arctic Intermediate Water (AIW), and Deep Water (DW). The surface water is the seasonally heated and diluted Polar Water.

cold and fresh water body above warmer and saltier waters (Aagaard & Coachman 1968). The water masses on the shelf have been described by Bourke et al. (1987) as Polar Water, with temperatures less than 0 °C and salinities below 34.5, and Arctic Intermediate Water (AIW), defined as 0 °C < T < 3 °C and 34.5 < S < 34.9. The 1993 data (Wallace et al. 1995b) show that in the polynya there is a layer of near-freezing point water with a salinity of about 32.4 (Fig. 2). Underneath this layer is the halocline, found at depths between about 50 and 150 m, where the salinity increases to values characteristic of the AIW. During summer the Polar Water is warmed and diluted with runoff and/or sea ice meltwater at the surface. Also illustrated in Fig. 2, Polar Water can be subdivided into two different water masses. This was done by Paquette et al. (1985), who showed the existence of a colder water type than could be obtained by linear mixing of Polar and Atlantic Water. This water mass was named Knee Water after its properties in TS space. Stations where the presence of Knee Water is evident do not show the typical near freezing point layer associated with S = 32.4 and the Knee Water type is not found inside the dashed line of Fig. 1. Therefore, in this work, the region has been divided into the polynya area west of the line, and the Northern Slope area and the Belgica Trough area east of the line. The latter subdivision is mainly done to see if there are any significant differences between the northern and southern parts of the slope.

The shelf area consists of a trough system around Belgica Bank with Belgica Trough to the south of the ice barrier and Norske Trough between the coast and Belgica Bank, with Westwind Trough north of this bank. The troughs are about 300 - 500 m deep with shallower sills separating Norske Trough from both Belgica Trough and Westwind Trough. NØIB bridges Norske Trough and is grounded on the central Belgica Bank. This bridge allows water to enter the polynya from the south except for maybe the upper 10 m (Schneider & Budéus 1997). The northward flowing coastal current follows the trough system northwards and turns east in Westwind Trough. In the northern part the eastward flow connects this current with the southward flow of the East Greenland Current (EGC). Part of the EGC crosses the shelf diagonally (Bourke et al. 1987; Budéus & Schneider 1995), and in the Belgica Trough the currents components are south-eastward except for a very narrow area close to Île de France where the northward flow is found. Topp & Johnson (1997) found from year-long current meters and ADCP sections opposites flows at each side of the Northeast Greenland Coastal Current along the slopes of the Westwind Trough.

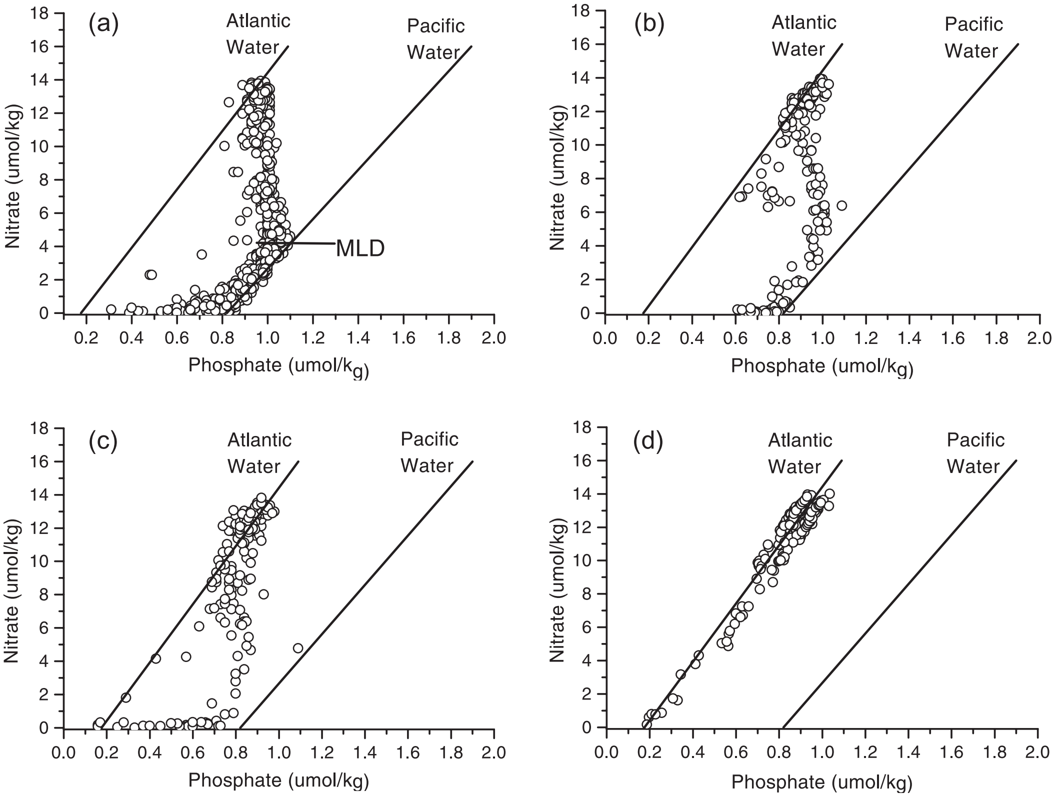

Fig. 3. Nitrate versus phosphate for (a) the polynya area, (b) the Northern Slope area, (c) the Belgica Trough, and (d) the central Greenland Sea. MLD in (a) stands for Mixed Layer Depth and data below this line are from the mixed layer.

Calculation of source waters

This work is based on the same method as used by Jones et al. (1998) to calculate the relative amounts of Atlantic and Pacific source waters. The N–P relations characterizing "pure" Atlantic Water and "pure" Pacific Water are illustrated by straight lines in Fig. 3 and given by the following equations for the Atlantic and Pacific waters respectively:

$$NO_3^{AW} = 17.499xPO_4^{AW} - 3.072 \quad (1)$$

$$NO_3^{PW} = 14.828xPO_4^{PW} - 12.16 \quad (2)$$

The second equation has been slightly modified since the paper in 1998 (Jones pers. comm.). The linear relationships define a value of phosphate of pure Atlantic Water and one for pure Pacific Water for each measured nitrate value. Together with the measured phosphate value the relative amounts of Atlantic (including freshwater) and Pacific Water are determined. River run-off and sea ice meltwater in the Arctic Ocean have a N–P relation close to the Atlantic Water. The first equation is derived from measurements in the St. Anna Trough and is characteristic of Atlantic Water in the Arctic. The second equation is based on measurements from the Chukchi Sea and characterizes water from the Bering Sea that has been modified on the Chukchi Shelf. This modified Bering Sea Water is therefore what in this work is called Pacific Water. Due to different uncertainties, Jones et al. (1998) found that the computed source water contributions should be considered somewhat approximate and likely no better than 10 %.

Results and discussion

Many stations in the NEWP area showed depletion of nitrate in the surface as a result of biological uptake during the summer. Phosphate

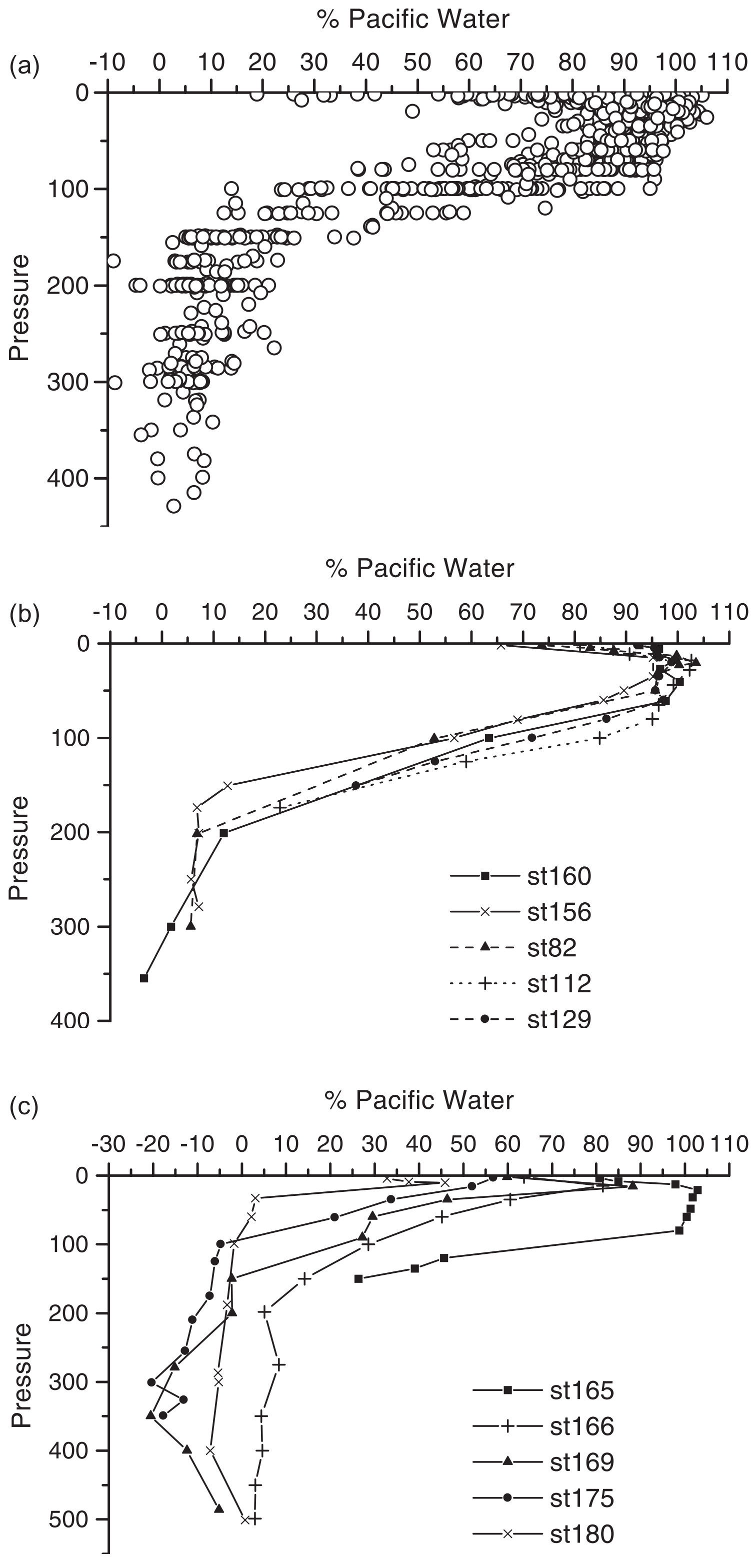

Fig. 4. Percentage of Pacific Water against depth for (a) all casts in the polynya area, (b) selected casts along the trough system and Belgica Bank, and (c) selected casts in Belgica Trough together with one cast (165) from the southern tip of Belgica Bank. See Fig. 1 for position of the selected casts.

continued to decrease after the depletion of nitrate indicating that other nitrogen sources were then used together with phosphate during photosynthesis. This gives varying values of phosphate for nitrate equal to zero in the nitrate against phosphate plots (Fig. 3). Apart from these points, one can see that data from the mixed layer of the polynya area (Fig. 3a) lie close to the Pacific Water line, while data from below about 150 m lie close to the Atlantic Water line. The data in between are from the halocline. For the Northern Slope region (Fig. 3b) the picture is more or less the same, although some of the data points have values closer to those from Belgica Trough (Fig. 3c). These measurements are from the outermost stations in transects E and N over the deeper parts of the slope. In the Belgica Trough only traces of Pacific Water is present close to the surface. For comparison Fig. 3d shows data from the upper 500 m of the central Greenland Sea (around 75° N and 0° W). Here no traces of Pacific Water signature is found; all data lie along the line of Atlantic Water.

The calculated distribution of Pacific Water with depth for all stations in the polynya area is shown in Fig. 4a. Except for the diluted upper surface water, the mixed layer content of Pacific Water has a mean value of about 90 %. Fresh water from runoff, sea ice melt, and precipitation have nearly the same N–P relationship as Atlantic Water, which, together with the above-mentioned depletion of nitrate in some areas, explains while the diluted surface water has values varying between 20 and 100 % Pacific Water. The distribution is also shown for selected casts around the deep trough system in the polynya area in Fig. 4b with the last cast (st129) being on Belgica Bank (south-western part of transect N), and for selected casts in Belgica Trough in Fig. 4c. As can be seen in Fig. 4b, a high percentage of Pacific Water is found all the way around Belgica Bank with more than 95 % in the deeper parts of the mixed layer. For the stations in Belgica Trough the upper 50 m has a variable Pacific Water content from about 90 % to 0 %. Included in this figure is also the station from the southern tip of Belgica Bank (st165) which lies just north of the most westerly station in Belgica Trough (st166). St165 shows a Pacific content of about 100 % down to 100 m while st166 has only about 80 % at 15 m depth and 60 % at 35 m depth. This shows that just inside the dashed line (Fig. 1) high values of Pacific Water are found down to the base of the mixed layer, in contrast to the small amounts only found near the surface at the stations in Belgica Trough.

It is evident that this high Pacific Water signature in the polynya and Northern Slope areas indicates an import from the Arctic Ocean. This signature could also be obtained if high denitrification took place locally on the East Greenland shelf, but this can be ruled out since oxygen concentrations are too high for local denitrification. Jones et al. (1998) found water of high Pacific content along the continental shelves north of Alaska and Canada, but also Pacific source water concentrations of greater than 90 % immediately north of Greenland, which shows that some of this water indeed has to exit through Fram Strait. Newton & Sotirin (1997) show that an eastward flowing boundary current is positioned over the continental slope of the Lincoln Sea between the shelf break and the base of the slope. They also showed that during 1991–94 the presence of Pacific Water (Bering Sea Water) in the upper halocline of the Lincoln Sea increased significantly. This water can be seen in the Arctic Ocean as a relative T_{max} associated with salinities of about 31.9 - 32.7 overlying a relative T_{min} associated with salinities in the range of 32.7 - 33.5.

For both the polynya and the Northern Slope areas there is a maximum in both silicate and phosphate in the middle of the halocline at a salinity of about 33 to 33.5. This coincides with the core salinity of the nutrient rich water of the Upper Halocline Water of the Arctic Ocean (Jones & Anderson 1986). The fractions of Pacific and Atlantic Water at this salinity is about 50/50 ± 10 and is found at about 100 m in all the casts from the polynya area, but higher up in the water column, at about 50 m, over the Northern Slope. At the stations from the Belgica Trough this maximum is not seen. There is a good correlation between silicate and phosphate, but a clear difference is seen in the slope between the different areas. In the polynya and the Northern Slope areas the slope is about 24, while in Belgica Trough the slope is about 12.5, the two lines intersect at the silicate value of about 12 µM.

Silicate and phosphate concentrations at the bottom of the mixed layer water and at the top of the Atlantic layer are more or less equal—about 11.5 µM and 1 µM, respectively. From the increase in these constituents down to the middle of the halocline it is evident that this halocline water cannot be produced on the shelf through mixing between the surface and the Atlantic water, but has to be advected into the region. The same conclusion was put forth by Topp & Johnson (1997) from current meter measurements of temperature and salinity, and they suggested that this distinct water mass possibly was a mixture of Polar Water, Knee Water and Atlantic Water. The low silicate concentrations of the Knee Water (about 6 µM; Budéus et al. 1997), however, oppose this idea. To achieve a 50/50 mixture of Pacific and Atlantic waters with the higher silicate and phosphate concentrations found in the polynya halocline the only candidate is the nutrient rich Upper Halocline Water of the Arctic Ocean. For instance, a 50/50 mixture between the surface mixed layer water and the Upper Halocline Water, which is also of Pacific origin, with the Atlantic water below, would indeed result in silicate values similar to those found in the polynya halocline at salinities of 33.0 - 33.5.

During 1991 to 1993 the increase in T_{max} of the Pacific Water over the Lincoln Sea slope was accompanied by a reduction in the thickness of the surface mixed layer from about 80 to 20 m (Newton & Sotirin 1997). Taking into account the distance from the Lincoln Sea area and the approximate time it takes for this water to flow into the polynya area one can compare the measurements from the polynya with those from the Lincoln Sea. Surface currents are weak in the Lincoln Sea, about 1-2 cm s^{-1} over the shelf. This indicates a passage time of about two years. The 1991 profiles in the Lincoln Sea show a well-mixed surface layer (Polar Mixed Layer) down to about 75 m with T at the freezing point and salinity close to 32.4. In the following years the mixed layer decreased and freshened, giving lower freezing temperatures. The increasing T_{max} just below the MLD also got shallower, with the highest (and shallowest) T_{max} in 1993. The boundary current over the slope was faster (about 4 cm s^{-1}) and with this speed the water would reach the the northeastern shelf of Greenland in a little less then one year. This can explain the shallow signal of the Upper Halocline Water seen at stations from the Northern slope compared to the deeper position of the halocline inside the polynya area.

The water of Atlantic origin can be seen in Fig. 4 as water of about 0 % and is found below the halocline. Negative values, as those seen in Fig. 4c, are typical of Return Atlantic Water, i.e. water that flows north with the West Spitsbergen Current but does not enter the Arctic Ocean. Instead it recirculates just south of Fram Strait, emerging under the Polar Water and following the EGC southwards. This water can be seen at depths between 100 and 500 m with a core at about 300 - 350 m in the Belgica Trough. At the depth of the Knee Water temperature minimum, e.g. eastern part of transect E, where the temperature minimum is -1.8 at 100 m depth, the amount of Pacific Water is close to 0 %, indicating an Atlantic origin of the Knee Water. In accordance with Budéus & Schneider (1995) and Budéus et al (1997), it is shown here that the part of the East Greenland Current that contains Knee Water does not enter the NEWP.

Conclusions

These results show that waters of both Pacific and Atlantic origin are present above the East Greenland Shelf. Since the distribution of source waters must reflect the circulation pattern of the region, the following sheme is visualized: Pacific-derived surface water from the Chukchi Sea follows the northern coasts of Alaska, Canada and Greenland and enters the NEWP area through Fram Strait as an inner branch of the East Greenland Current. Due to the northward flowing coastal current along the trough system, which seems to be a persistent feature of the circulation pattern in the polynya, the imported surface water probably passes over Ob Bank and flows south close to the coast of Greenland and/or circulates south of the Belgica Bank before it turns northward following the current in the polynya. The outer part of the EGC containing the Knee Water must be drawn from a more easterly part of the Arctic Ocean, and when the EGC crosses the shelf diagonally south of Belgica Bank, the inner branch is caught up in the northward flowing coastal current while the outer part continues southward. Several indices support this sheme, as discussed above.

The water mass structure in the Northeast Water Polynya is two-layered, with a surface layer consisting of Pacific-derived water, as found on the Chukchi shelf down to the mixed layer depth, and Atlantic Water below the halocline. In the middle of the halocline, where the mixture of the two water masses is about 50/50, the signal of the Upper Halocline Water from the Arctic Ocean is seen as a maximum in silicate and phosphate at a salinity of about 33.1. The slope region of the northern NEWP area shows the same trend as the polynya data, although the Upper Halocline Water is present at shallower depths. The measurements from the Belgica Trough, south of the polynya, only show small fractions of Pacific Water as this water derives from a more easterly part of the EGC. The Knee Water, which is present only outside the polynya area, has a clear Atlantic origin.

Acknowledgements.—The author is very much indebted to Douglas Wallace for many fruitful discussions on the Northeast Water Polynya and for the opportunity to use the 1993 data in this work. Also special thanks to Leif Anderson who gave me the idea for this work and has been of great help in the writing of the manuscript. The paper was written with financial support from the Swedish Natural Science Research Council.

References

Aagaard, K. & Coachman, L. K. 1968: The East Greenland Current north of Denmark Strait: Part II. *Arctic 21*, 267–290.

Bourke, R. H., Newton, J. L., Paquette, R. G. & Tunnicliffe, M. D. 1987: Circulation and water masses of the East Greenland Shelf. *J. Geophys. Res. 92(C7)*, 6729–6740.

Budéus, G. & Schneider, W. 1995: On the hydrography of the Northeast Water Polynya. *J. Geophys. Res. 100(C3)*, 4287–4299.

Budéus, G., Schneider, W. & Kattner, G. 1997: Distribution and exchange of water masses in the Northeast Water Polynya (Greenland Sea). *J. Mar. Syst. 10*, 123–138.

Jones, E. P. & Anderson, L. G. 1986: On the origin of the chemical properties of the Arctic Ocean Halocline. *J. Geophys. Res. 91(C9)*, 10759–10767.

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.

Lara, R. J., Kattner, G., Tillmann, U. & Hirche, H.-J. 1994: The Northeast Water Polynya (Greenland Sea) II. Mechanisms of nutrient supply and influence on phytoplankton distribution. *Polar Biol. 14*, 483–490.

Newton, J. L. & Sotirin, B. J. 1997: Boundary undercurrent and water mass changes in the Lincoln Sea. *J. Geophys. Res. 102(C2)*, 3393–3403.

Paquette, R. G., Bourke, R. H., Newton, J. F. & Perdue, W. F. 1985: The East Greenland Polar Front in autumn. *J. Geophys. Res. 90(C3)*, 4866–4882.

Schneider, W. & Budéus G. 1995: On the generation of the Northeast Water Polynya. *J. Geophys. Res. 100(C3)*, 4269–4286.

Schneider, W. & Budéus G. 1997: A note on Norske Ø Ice Barrier (Northeast Greenland), viewed by Landsat 5 TM. *J. Mar. Syst. 10*, 99–106.

Smith, W. O., Jr., Codispoti, L. A., Nelson, D. M., Manley, T., Buskey, E. J., Niebauer, H. J. & Cota, G. F. 1991: Importance of Phaeocystis blooms in the high-latitude ocean carbon cycle. *Nature 352*, 514–516.

Topp, R. & Johnson, M. 1997: Winter intensification and water mass evolution from year long current meters in the Northeast Water Polynya. *J. Mar. Syst. 10*, 157–173.

Wallace, D. W. R., Minnett, P. J. & Hopkins, T. S. 1995a: Nutrients, oxygen, and inferred new production in the Northeast Water Polynya, 1992. *J. Geophys. Res. 100(C3)*, 4323–4340.

Wallace, D. W. R., Hopkins, T. S., Behrens, W. J., Bignami, F., Deming, J., Kinder, C., Shi, Y., Smith, W. O., Top, Z. & Walsh, I. D. 1995b: *Collaborative research on the Northeast Water Polynya: NEWP93. Hydrographic Data Report, USCGC Polar Sea Cruise, July 18–August 20, 1993.* Upton, NY: Brookhaven National Laboratory.

Wilson, C. & Wallace, D. W. R. 1990: Using the nutrient ratio NO/PO as a tracer of continental shelf waters in the Central Arctic Ocean. *J. Geophys. Res. 95(C12)*, 22193–22208.