Hydrographic conditions in the Fram Strait, summer 1982

B. FARRELLY, T. GAMMELSRØD, L. G. GOLMEN AND B. SJØBERG

Farrelly, B., Gammelsrød, T., Golmen, L. G. & Sjøberg, B. 1985: Hydrographic conditions in the Fram Strait, summer 1982. *Polar Research 3 n.s.*, 227–238.

Hydrographic (CTD) observations obtained with R/V 'Lance' in July–August 1982 across the Fram Strait are presented. The extent and the presence of traditional water masses such as Atlantic Water, Polar Water and Greenland Sea Deep Water are discussed. The complicated hydrographical structure in the upper water masses due to eddies and fronts near the ice edge is noted. An intermediate water mass characterized by a salinity minimum is found all across the Strait, and is suggested to originate in the Greenland Sea. The deep water in the south-west part of the Strait shows strong horizontal salinity and temperature gradients, and the structure of the corresponding station profiles indicates large hydrographical activity. This is in contrast to the east-north-east part, where the horizontal gradients are much weaker and the profiles much smoother. Thus most of the deep- and bottom-water communication between the Greenland/Norwegian Seas and the Arctic Ocean seems to take place west of the 0° meridian.

B. Farrelly, T. Gammelsrød, L. G. Golmen and B. Sjøberg, Geophysical Institute, Department of Oceanography, University of Bergen, Bergen, Norway; December 1984 (revised May 1985).

In July/August 1982 a multidisciplinary expedition to the Fram Strait with the icebreaker 'Lance' was organized by the Norwegian Polar Research Institute.

Although ice conditions were quite severe, the ship was able to penetrate westwards to the East Greenland shelf, so that near synoptic sections across the whole Fram Strait were obtained. Since this Strait is the only deep connection between the Arctic and the world oceans, such sections are essential for the determination of the heat, salt and mass budgets of the Arctic Ocean. The CTD stations constitute two deep sections across the Strait, and were to our knowledge the most complete hydrographical data set obtained until then in the region.

In total, 103 CTD stations were obtained (Fig. 1). The cruise track follows the edge of heavy ice from stations 11 to 55, 63 to 68, and 77 to 90. Attempts made to penetrate the ice at stations 31 and 42 on the basis of indications from satellite images were unsuccessful. Thus most of the stations were taken in the vicinity of the ice edge, and the influence of the ice on the surface layer is readily seen in our data (see under 'Surface and shelf water'). The Atlantic Water is observed to flow northwards in the eastern part of the Strait (see under 'The Atlantic Water'), but is also observed in the central and western parts. Processes which concern modification and recirculation of the Atlantic Water in the Strait are briefly discussed.

Our observations revealed a salinity minimum at 500–1000 metres depth across the whole Fram Strait. This is discussed under 'Salinity minimum layer'.

Finally, we discuss the deep water. To save time on this multidisciplinary expedition, about two thirds of the stations were taken only to 1000 m depth even in the deepest part of the Fram Strait. Although the grid of deep stations is relatively sparse, it is still a valuable contribution to our understanding of the deep water circulation in the Strait. The influence of Greenland Sea Deep Water and Arctic Ocean Deep Water is noted.

Methods and water masses

A Neil Brown CTD with on-line computer facilities was used. The CTD was checked and calibrated prior to the cruise, in accordance with standard laboratory routines.

In order to have a check on drift in the conductivity sensor of the CTD, water samples were collected at several stations throughout the cruise. The samples were collected using Nansen bottles attached to the CTD wire, just above the sonde, and triggered while the sonde was held at maximum observation depth. Two or three samples were obtained from each cast and later analysed for salinity at the Geophysical Institute. The CTD was found to give salinities on the average 0.004

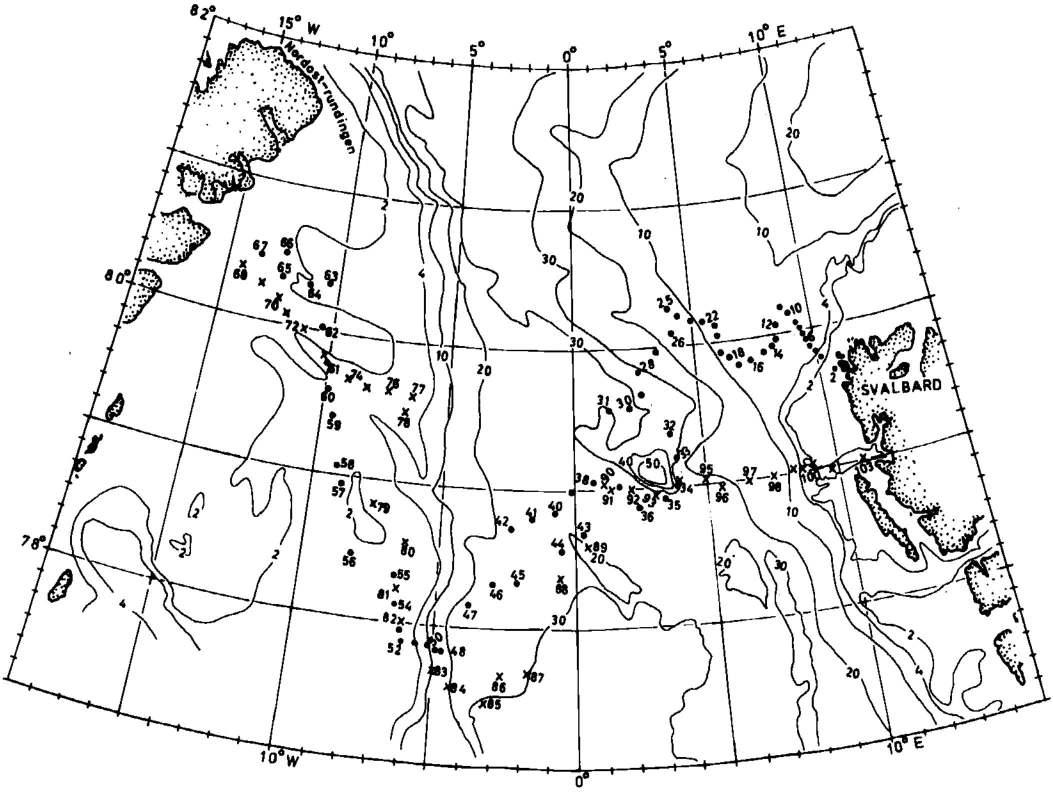


Fig. 1. Fram Strait. Station map and bottom topography. ● stations taken on the way west; × stations taken while going east.

higher than the salinometer (standard deviation 0.004 for 23 stations), with no drift. This offset was compensated for by a corresponding change of the conductivity cell constant when computing the final salinities.

The temperature and pressure sensors were subject to pre- and after cruise checks, and no irregularities were found. These sensors are therefore assumed to have maintained their manufacturer specifications on accuracies of ±0.005°C and ±0.1% of full pressure scale (6500 decibars), respectively. Absolute accuracy of salinities is estimated to be within ±0.01, and relative accuracy to be less than ±0.003 in the data set.

The original CTD data have been reduced to two decibar averages of the measured parameters, after going through despiking routines based on certain difference tests. The salinities (PSS-78) are calculated from the average values.

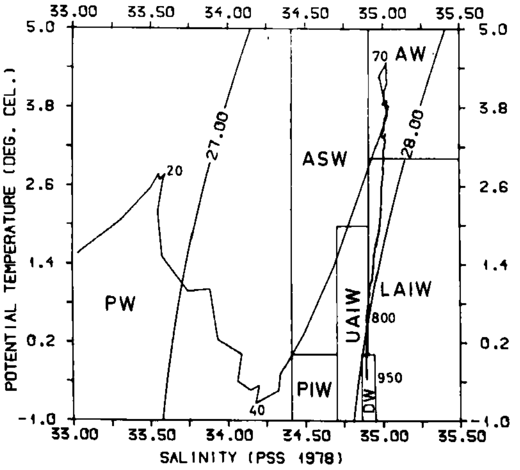


Fig. 2. Potential temperature v. salinity plot for station 92. Some typical water-masses are indicated (see Table 1). DW includes GSDW, NSDW and AODW.

Table 1. Definition of water masses. (Definitions are from Swift et al. 1981, except for AODW, which is taken from Swift et al. 1983, their YMER 1980 stations 105, 162, 168.) Temperatures in parentheses are typical values.

Name	Abbreviation	Salinity	Temperature (°C)
Polar water	PW	$S < 34.4$	$T_f < T$
Arctic Surface Water	ASW	$34.4 < S < 34.7$	$0 < T$
		$34.7 < S < 34.9$	$2 < T$
Atlantic Water	AW	$34.9 < S$	$3 < T$
Polar Intermediate Water	PIW	$34.4 < S < 34.7$	$T_f < T < 0$
Upper Arctic Intermediate Water	UAIW	$34.7 < S < 34.9$	$T < 2$
Lower Arctic Intermediate Water	LAIW	$34.9 < S$	$0 < T < 3$
Greenland Sea Deep Water	GSDW	$34.88 < S < 34.9$	$T < 0 (-1)$
Norwegian Sea Deep Water	NSDW	$34.9 < S < 34.94$	$T < 0 (-0.4)$
Arctic Ocean Deep Water	AODW	$34.919 < S < 34.936$	$-.96 < T < -0.70$

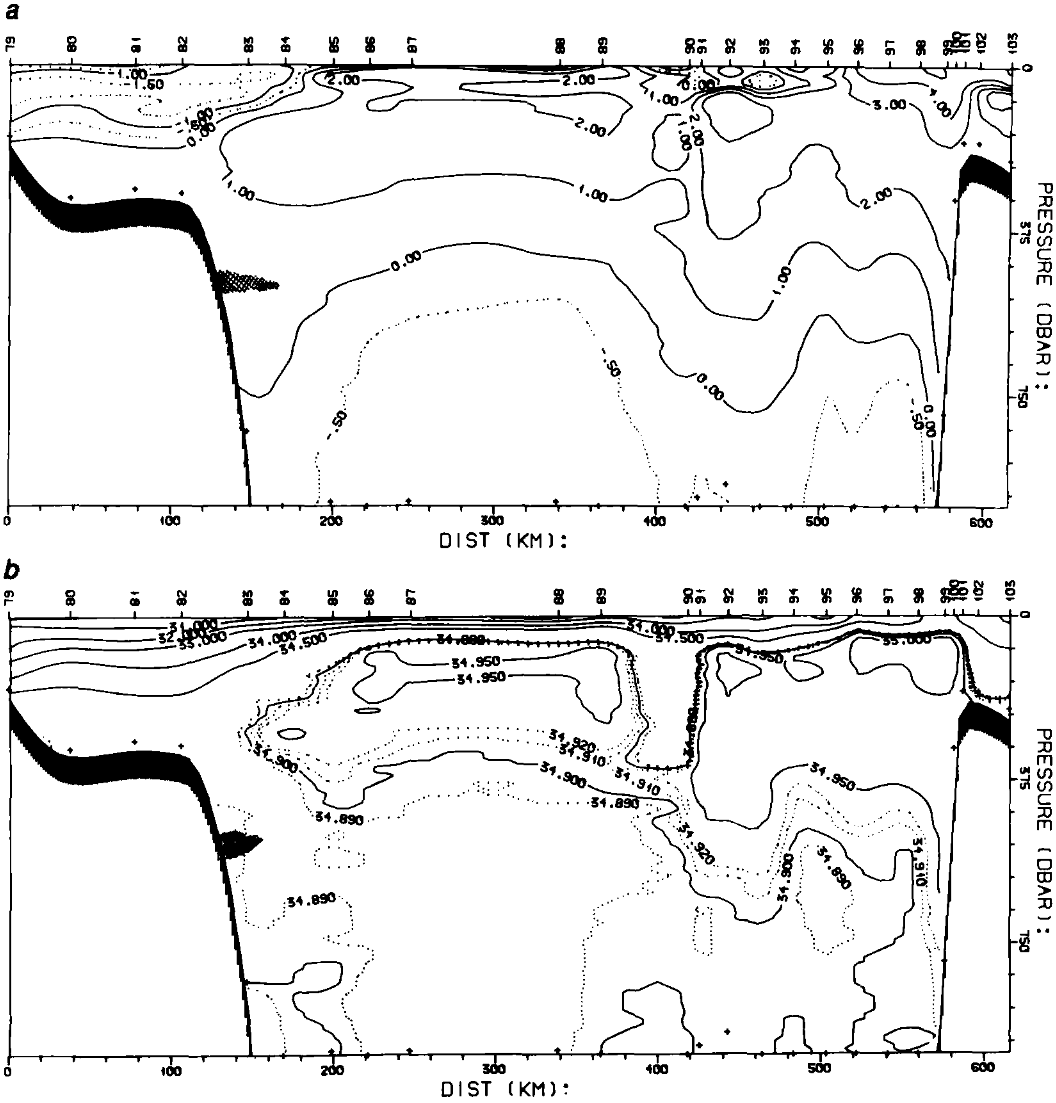


Fig. 3. Sections of: a. potential temperature, and b. salinity for stations 79–103. Shaded region indicates local temperature and salinity maximum.

All data plots are based on the averaged data. The vertical sections presented are computer drawn; these were afterwards inspected and corrected where over-interpretations of data occurred. The documentation by Røyset & Bjerke (1982) gives more details on the various computer routines involved in the data preparation and presentation. An example of a θ-S plot is shown in Fig. 2 (Station 92), where water masses according to the definitions of Swift & Aagaard (1981) are indicated (see Table 1). These definitions must be used with caution since they are based on studies of the deep basins of the Greenland and Iceland Seas rather than the northernmost part of the Fram Strait.

Surface and shelf waters

The surface layer shows great variability (Fig. 3). As most of the stations were obtained in the vicinity of the ice edge, much of this variability may be related to the large horizontal gradients which are typical for the marginal ice zone during summer. The surface layer is dominated by Polar Water, but at stations 98–100, near the Svalbard

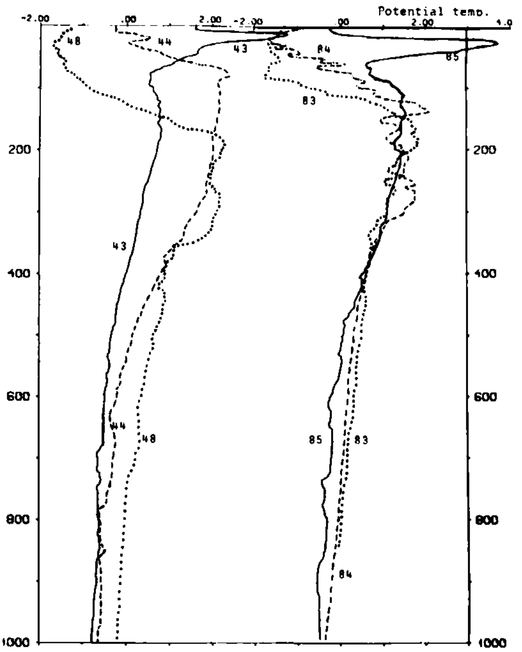


Fig. 5. Two groups of depth profiles of potential temperature from the central part of the Strait.

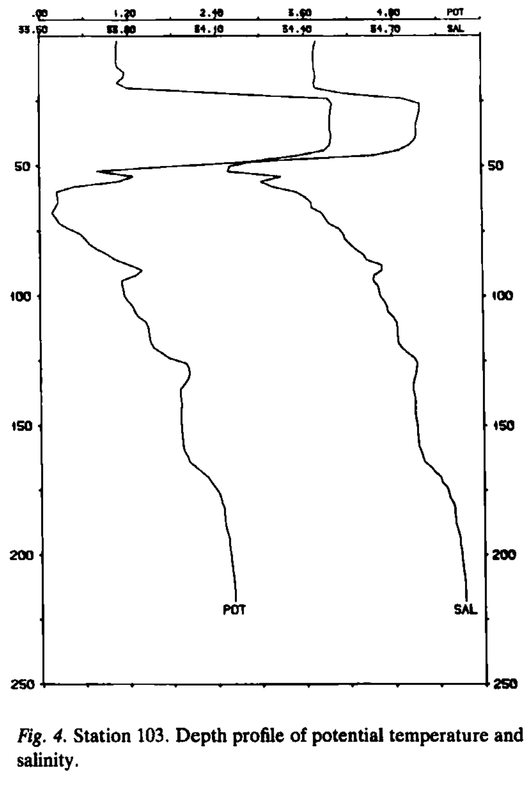


Fig. 4. Station 103. Depth profile of potential temperature and salinity.

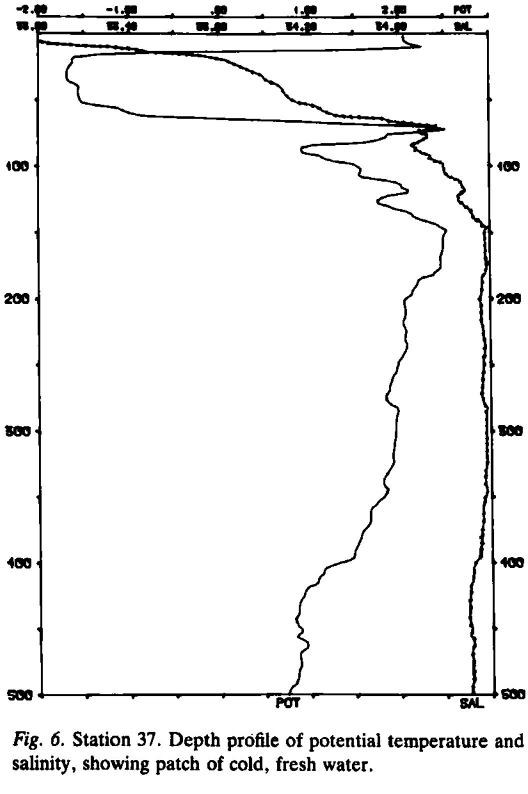


Fig. 6. Station 37. Depth profile of potential temperature and salinity, showing patch of cold, fresh water.

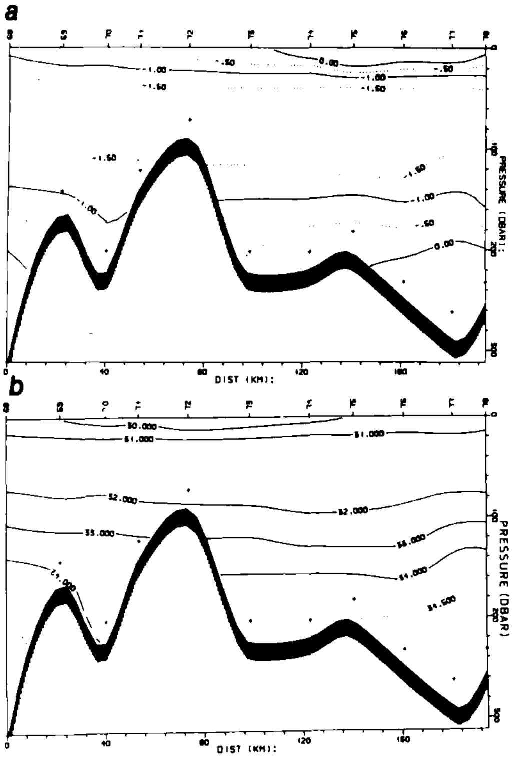


Fig. 7. Sections of: a. potential temperature, and b. salinity for stations 68–78.

shelf-break, the Polar Water is swept away by water of Atlantic origin in the West Spitsbergen Current and surface salinities above 34.4 are observed.

At the two easternmost stations (102, 103) there are significant temperature and salinity minima near 60 m depth (Fig. 4). It was suggested by Helland-Hansen & Nansen (1912) that these minima are due to cold and relatively fresh water originating in the Barents Sea, there forming a coastal current which turns around the South Cape and flows northwards close to the West Spitsbergen coast.

Farther west, patches of cold, low salinity water centred at a depth of around 40 m are found at stations 37, 91 and 93 (see Figs. 3 and 6). Such low temperatures (T < −1.5°C) for this depth are only found near the East Greenland shelf, which indicates that the patches are due to cold-core eddies formed by instabilities in the East Greenland Current.

The abrupt change in the temperature profiles between stations 43 and 44, and between stations 84 and 85 (Fig. 5) denotes the eastern border of the East Greenland Current which carries Polar Water southwards. The lack of Polar Water at stations 40–42 indicates that the East Greenland Current abruptly meanders eastwards in the area towards station 44, as does the ice edge.

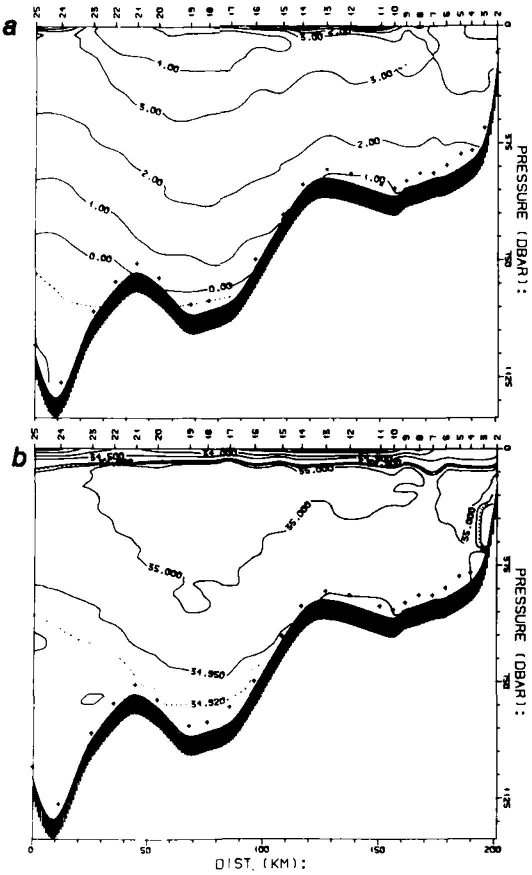


Fig. 8. Sections of: a. potential temperature and b. salinity for stations 2–25.

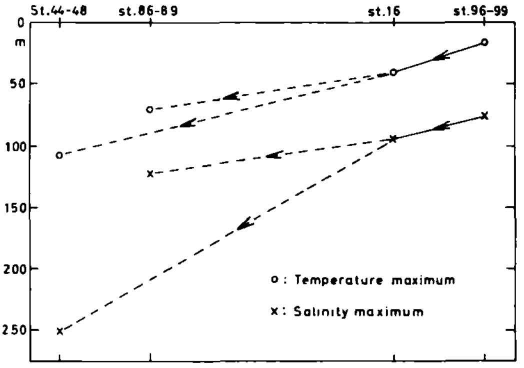
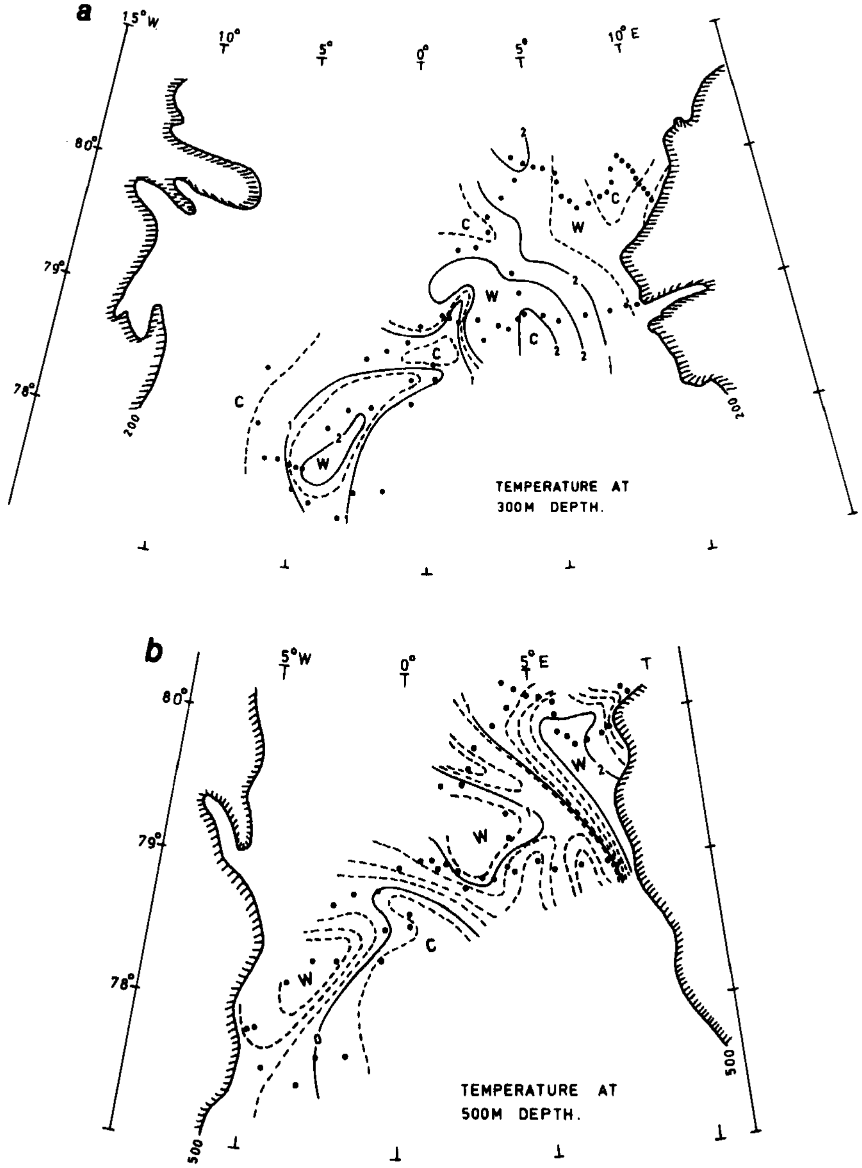


Fig. 9. Depths of temperature and salinity maxima of the Atlantic Water for some selected stations.

Approaching the East Greenland Shelf the thickness of the Polar Water layer increases (Fig. 3), and on the shelf the horizontal distributions of temperature and salinity are remarkably uniform (Fig. 7). The vertical structure is similar to that found in the surface water of the Eurasian Basin of the Arctic (SCOR-58, 1979). The fresh and relatively warm surface layer (upper 20 m) is a summer phenomenon. The bulk of the water mass on the shelf is Polar Water with temperatures near −1.5°C and with a characteristic minimum at around 75 m depth.

The CTD sections on the East Greenland shelf were easily obtained because of the large ice-free area south of Nordøstrundingen (Fig. 1). Ice charts (compiled by the Norwegian Meteorological Institute) from the period reveal an approximately 300 n.m. long and 50 n.m. wide tongue of open or nearly open water south-southeast of the Nordøstrundingen. This polynia has been discussed by Wadhams (1981), who suggested that upwelling is a possible mechanism for its formation. An alternative to Wadhams' explanation could be that the polynia is caused



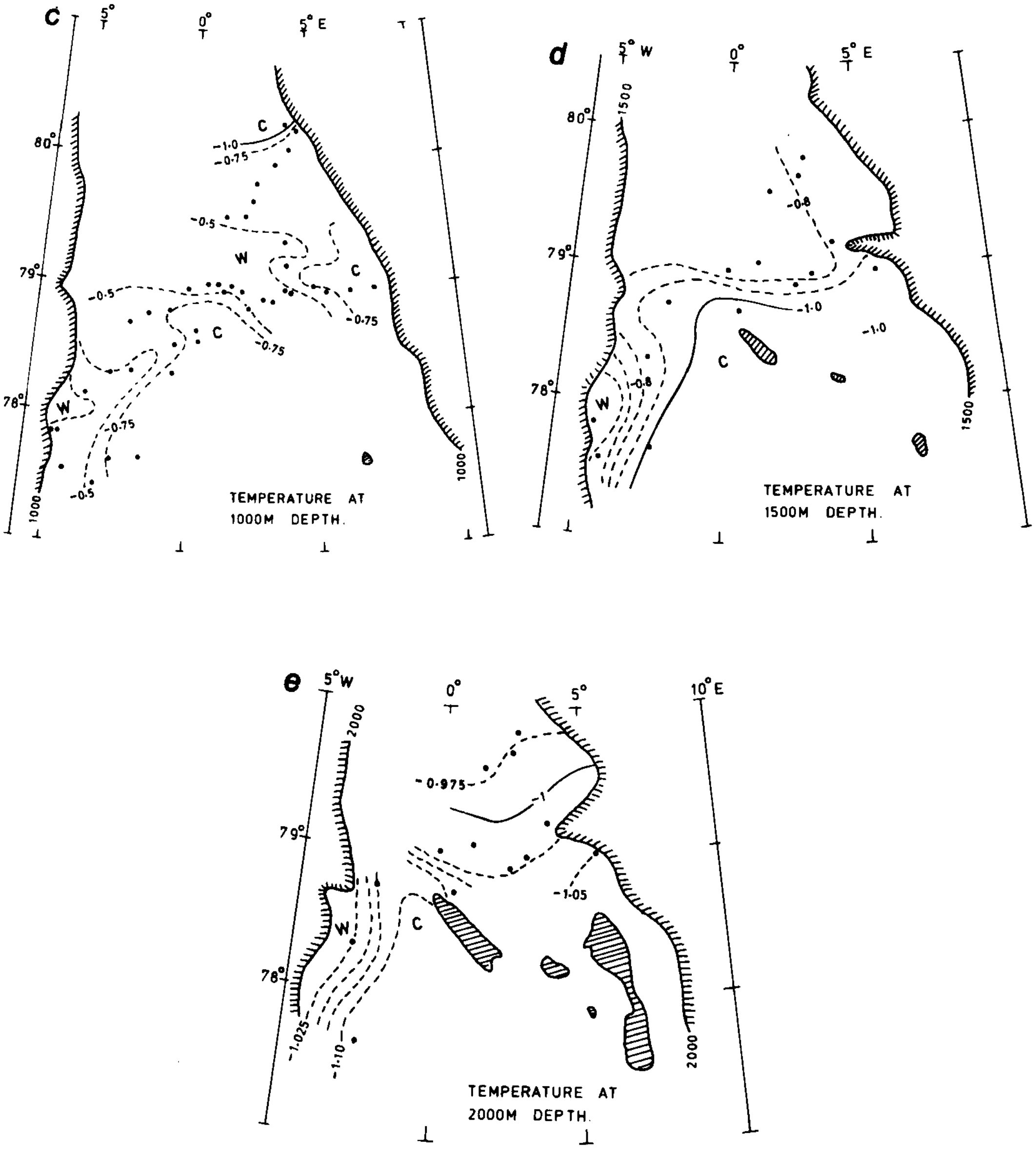


Fig. 10. Horizontal distribution of temperature at: a. 300, b. 500, c. 1000, d. 1500, and e. 2000 metres depth. Shaded regions show interception of the bottom by the depth surfaces.

by a lee-effect due to the prevailing current system. In fact the latter suggestion seems to be more realistic taking into consideration the low temperatures (no available heat) and the uniform conditions (no divergence) observed on the shelf (Fig. 7).

The Atlantic Water

To determine the heat, salt and mass budgets for the Arctic Ocean it is crucial to determine how much of the Atlantic Water flowing northwards in the West Spitsbergen Current enters into the Arctic Ocean proper and how much is recirculated in the Fram Strait.

Fig. 3 shows that the Atlantic Water in the West Spitsbergen Current has a temperature of 3–5°C. The salinity section (Fig. 3b) indicates two separate cores of Atlantic Water with salinities above 35. The easternmost of these (stations 96–100) shows a tendency to split. From our data we cannot decide whether these separate cores represent more or less permanent branching of the West Spitsbergen Current or eddies, which are known from studies of infrared satellite imagery to be frequent in the West Spitsbergen Current.

Following the current further north, two distinct cores of Atlantic Water are found (Fig. 8). These cores seem to be related to the topography and therefore represent a splitting of the West Spitsbergen Current with one branch turning eastwards along the shelf break north of Svalbard, and the other branch flowing north along the western slope of the Yermak Plateau (see Fig. 10a). Observations by Gammelsrød & Rudels (1983) and Johannessen et al. (1983) also indicate a similar branching.

Fig. 8 displays projected E–W distances between stations and indicates a larger volume of Atlantic Water flowing northwards than eastwards (though the difference is exaggerated by the projection). However, without an indication of the current speeds involved it is not certain whether the transports are well represented by the volumes.

In the western part of the Fram Strait a layer of warm, saline water (T>2°C, S>34.9) between 100 and 500 m depth is observed (see Figs. 3 and 12). This is slightly modified Atlantic Water probably on its way south. We believe that this water is recirculated in the Fram Strait.

A detailed study of the individual station profiles shows a weak salinity and temperature maximum of about 450 m on the Greenland Shelf slope, indicating a deep current there (Fig. 3, shaded region). Rudels & Anderson (1982) suggested that this is the return flow of Atlantic Water which has been modified within the Arctic Ocean proper.

It is generally accepted that the Atlantic Water descends beneath the Polar Water as it flows northwards. Fig. 9 demonstrates how the depths of the maximum temperature and salinity vary in the Strait. The maximum values are found at larger depths in the west, which indicates that the core depths increase with the time the Atlantic Water has spent in the Strait.

Another interesting feature of the Atlantic Water shown in Fig. 9 is that its temperature

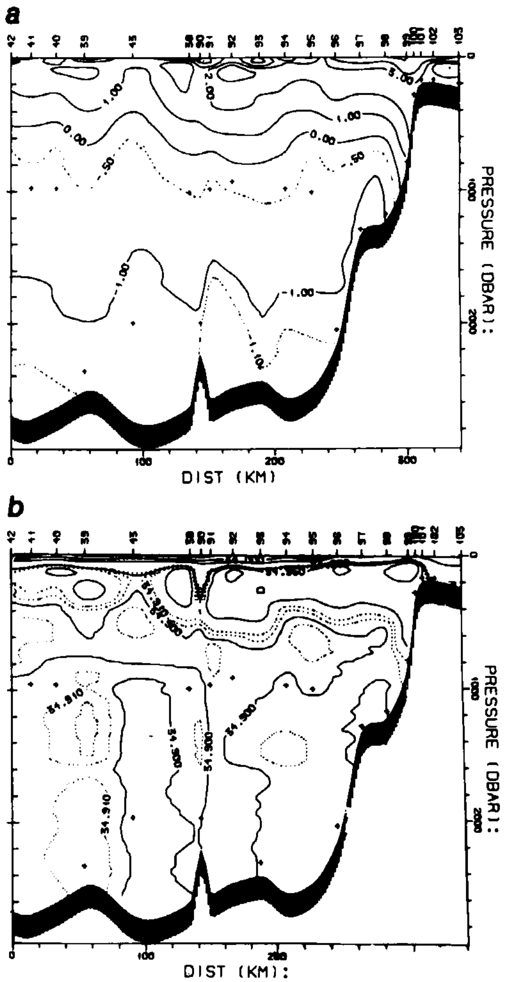


Fig. 11. Sections of a. potential temperature, and b. salinity for stations 42–103 to bottom.

and salinity maxima do not coincide; the salinity maxima are always found below the temperature maxima. The mixing of Atlantic Water with the warm, fresh water above in the eastern part of the Strait may cause this asymmetry. However, the tendency towards an increased difference in the maximum levels in the western part of the strait (stations 44–48, Fig. 9) supports the idea of Carmack (1972) that this 'core splitting' is the result of a double diffusive process which he denoted as core convection.

Salinity minimum layer

Below the Atlantic Water a salinity minimum layer (S<34.9) is observed between 600 and 1000 m depth (see Figs. 3, 11, 12 and 13). Salinities as low as 34.87 were found at stations 87 and 88 (Fig. 3). The minimum layer is found at greater depths in the north-eastern part of the Strait than in the south-west. On the section at 80°N (Fig. 8) this salinity minimum layer seems to penetrate some distance up on the shelf in a 50 m thick, well mixed bottom layer which is modified by the warmer and more saline water above (see Fig. 14 for the vertical profiles at station 16).

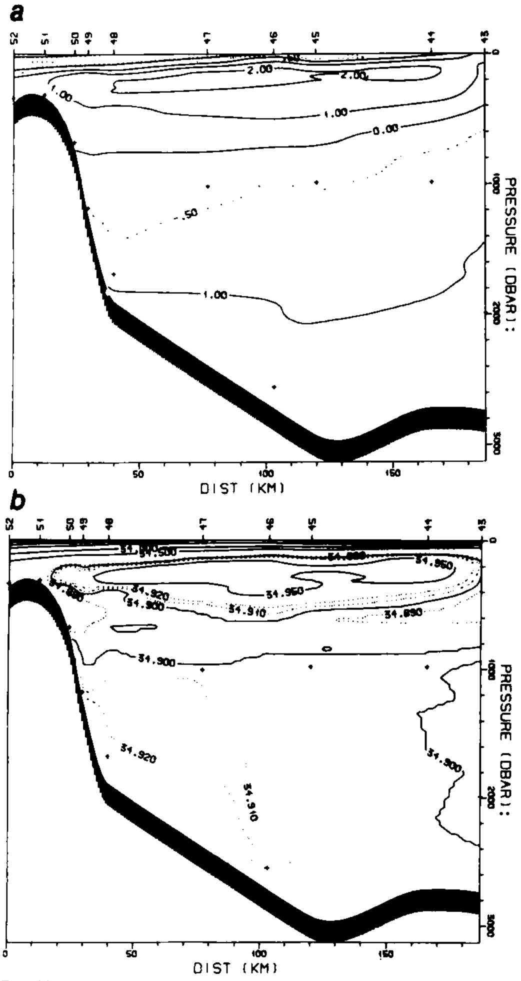


Fig. 12. Sections of a. potential temperature, and b. salinity for stations 43–52 to bottom.

This layer was of similar extent in 1980 and 1981, but was less distinct in 1983 (Rudels & Anderson 1982; Gammelsrød & Rudels 1983; Rudels, pers. comm.).

Data from April 1980 taken in the periphery of the Greenland Gyre show a similar salinity minimum at around 500 metres (Golmen 1983). This may indicate that winter cooling and sinking of surface water to intermediate depths in the central Greenland Sea, followed by lateral spreading, is the origin of the salinity minimum layer in the Fram Strait.

Deep water

Below 1000 m the water is near isohaline (see Figs. 11, 12 and 13). The potential temperature typically varies between −.50°C at 1000 m down to −1.15°C near the bottom.

There are essentially three water masses which may contribute to the deep water in the Fram Strait. These are Norwegian Sea Deep Water, Greenland Sea Deep Water and Arctic Ocean Deep Water (see Table 1). Station 86 (Fig. 15) is dominated by relatively fresh and cold Greenland Sea Deep Water, while a gradual change towards Arctic Ocean Deep Water values is observed going north-east via station 42 to station 29 (Fig. 15, see Fig. 1 for locations). The contribution from the Norwegian Sea Deep Water is difficult to estimate without observations from the south-eastern part of the Strait.

Figure 10c, d, e shows that there are marked horizontal temperature gradients in the deep water in the Strait with temperatures generally increasing towards north and west. The strong east–west gradients in the western part of the Strait indicate the presence of a deep, south-ward flowing current there. The weaker north–south gradients in the eastern part of the Strait indicate that the direct communication between deep water masses north and south of the Strait is here dominated by diffusion, in contrast to a more effective advection in the west.

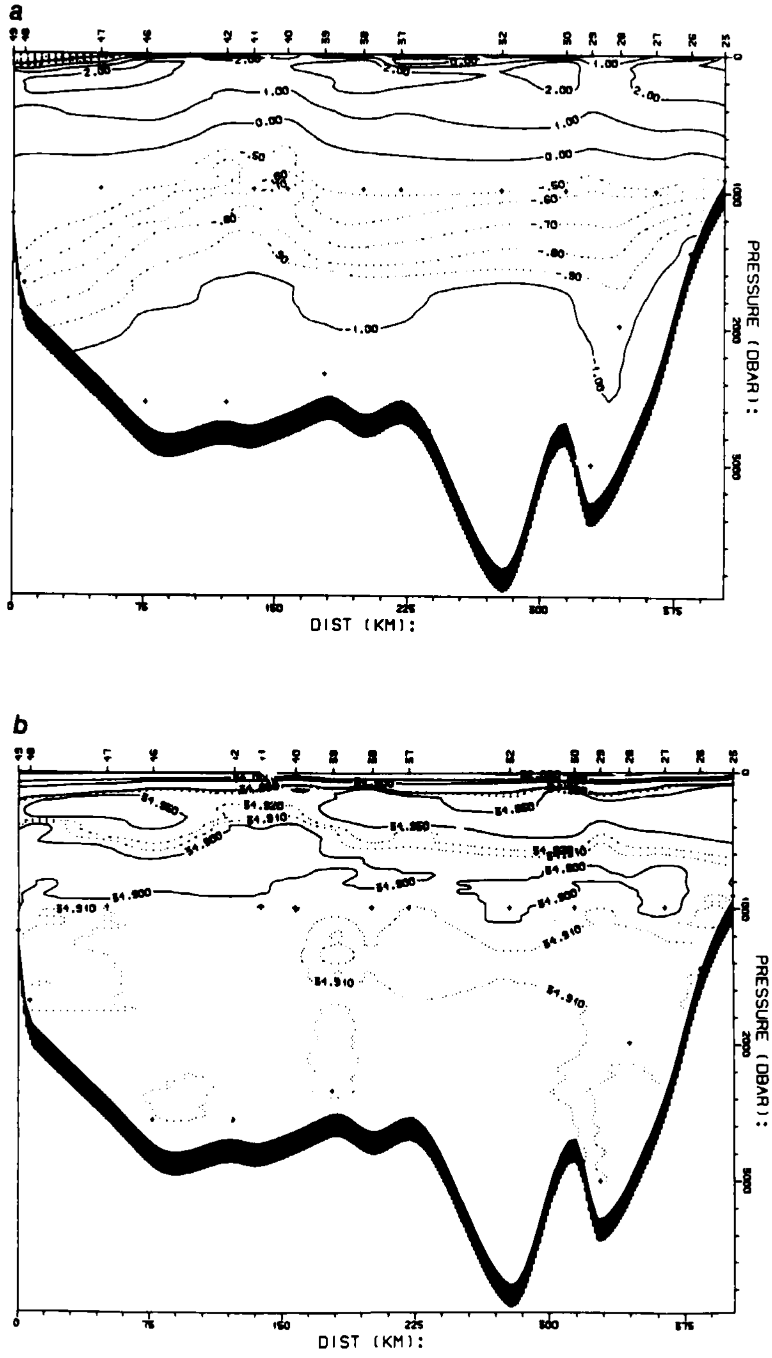


Fig. 13. Sections of a. potential temperature, and b. salinity for stations 23–49 to bottom.

Swift et al. (1983) suggested that Greenland Sea Deep Water flows northwards near the bottom through a topographic depression at 78° 15'N and 4°E (see Fig. 1). Our data (Fig. 10e) indicate that Greenland Sea Deep Water also intrudes farther west in the Strait. For instance the converging of temperature and salinity towards Greenland Sea Deep Water values near the bottom at station 42 (Fig. 15) and the greater small scale variability here in contrast to station 29 further east, indicate

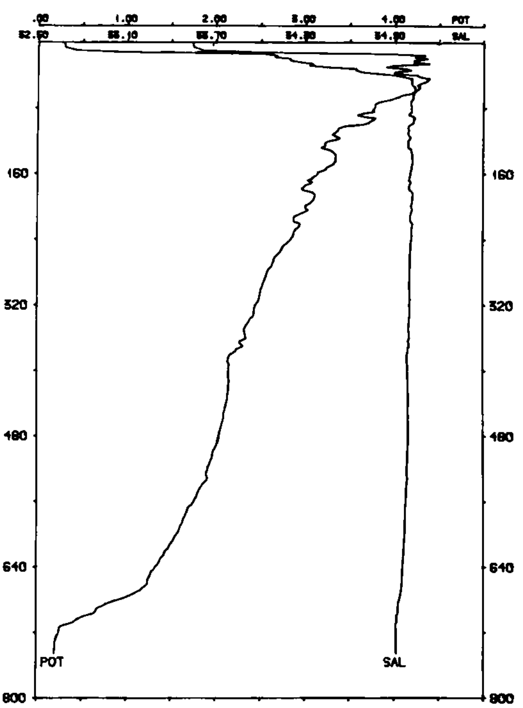


Fig. 14. Stations 16. Depth profile of potential temperature and salinity.

an active intrusion west of the 0° meridian. Fig. 13 shows that around stations 40–42 there is a minimum in both temperature and salinity, which indicates that the intrusion influences the whole water column (see also Fig. 10a-e).

Summary

The surface layers shows great small-scale variability, which partly can be ascribed to the fact that most of the CTD stations were taken near the ice edge. But patches of cold and fresh Polar Water distant from the ice edge also suggest eddy activity in the area.

The West Spitsbergen Current, which carries warm and saline Atlantic Water northwards, shows a tendency to splitting into different branches. One main branch seems to turn northeast along the shelf break north of Svalbard, while another branch continues northwards along the

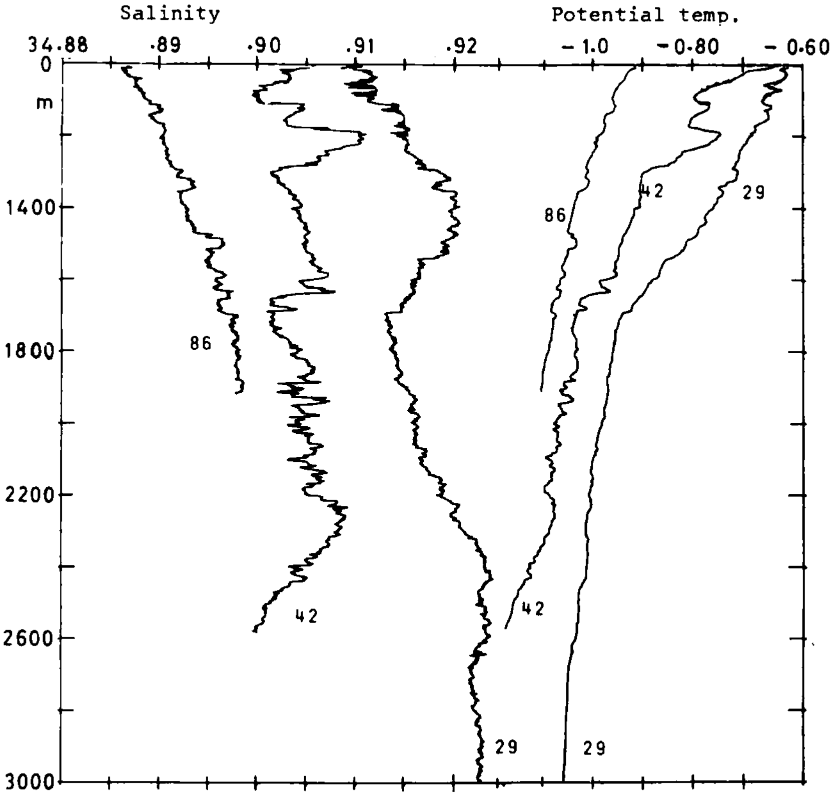


Fig. 15. Depth profile of potential temperature and salinity for stations 29, 42, and 86, showing how the whole water column becomes colder and fresher when going from station 29 southwest to station 86 via station 42.

Yermak plateau. Slightly modified Atlantic Water is found in the central and western parts of the Strait, suggesting that some recirculation is going on within the strait. The difference in depths of temperature and salinity maxima in each core of Atlantic Water is consistent with the idea that double diffusion is an important modification process.

A characteristic feature of the Fram Strait hydrography seems to be a salinity minimum layer at 500–1000 m depth. It is suggested that this water originates in the Greenland Sea. A detailed study of this salinity minimum layer, its distribution and year to year variability, may turn out to be helpful in our understanding of the deep and bottom water formation in the area.

In the deep water the influence of both Greenland Sea Deep Water (GSDW) and Arctic Ocean Deep Water (AODW) has been clearly identified. Horizontal temperature charts (Fig. 10) show an intrusion of cold GSDW (below 1000 m) west of the 0° meridian resulting in relatively sharp east–west temperature gradients. This is in contrast to what is found in the central and eastern parts of the Strait, where the gradients are much weaker and directed more north–south. Mixing, too, seems to be most vigorous in the western parts of the Strait (Fig. 15), suggesting that this area might be of considerable interest for further research aimed at surveying the deep water exchange between the Arctic and the Greenland Seas.

References

Carmack, E. 1972: *On the Hydrography of the Greenland Sea.* Ph.D. thesis, University of Washington, Seattle, USA.

Gammelsrød, T. & Rudels, B. 1983: Hydrographic and current measurements in the Fram Strait, August 1981. *Polar Research 1 n.s.*, 115–126.

Golmen, L. G. 1983: *En hydrografisk undersøkelse i Grønlandshavet i april 1980.* Thesis, Geophysical Institute, Div. of Oceanography, Univ. of Bergen, Norway.

Helland-Hansen, B. & Nansen F. 1912: The sea west of Spitsbergen. The oceanographic observations of the Isachsen Spitsbergen Expedition in 1910. *Videnskapsselskabets skrifter, I. Mat. Nat. Klasse 1912, No. 12.*

Johannessen, O. M., Johannessen, J. A., Morison, J., Farrelly, B. A. & Svendsen, E. A. S. 1983: Oceanographic conditions in the marginal ice zone north of Svalbard in early fall 1979, with an emphasis on mesoscale processes. *J. Geophys. Res. 88C5*, 2755.

Rudels, B. & Anderson, L. 1982: Observations on the mass, heat and salt exchange through the Fram Strait. *Gøteborg Universitet, Oceanografiska Institutionen, Report 42.*

Røyset, H. & Bjerke, P. E. 1982: CTD data processing program package — users reference manual. *Techn. Rep. Geophys. Inst. Div. A, Univ. of Bergen, Norway.*

SCAR Working Group 58, 1979: The Arctic Ocean Heat Budget. *Rep. No. 52, Geophysical Institute, Div. A, University of Bergen, Norway.*

Swift, J. H. & Aagaard, K. 1981: Seasonal transitions and water mass formation in the Iceland and Greenland Seas. *Deep Sea Res. 28A*, 1107–1129.

Swift, J. H., Takahashi, T. & Livingston, H. D. 1983: The contribution of the Greenland and Barents Seas to the Deep Water of the Arctic Ocean. *J. Geophys. Res. 88 (C10)*, 5981–5986.

Wadhams, P. 1981: The ice cover in the Greenland and Norwegian Seas. *Rev. of Geophysics and Space Physics. 19(3)*, 345–393.