 https://doi.org/10.17895/ices.pub.19271849

ICES Marine Science Symposia, 219: 319–325. 2003

Temporal switching between sources of the Denmark Strait overflow water

Bert Rudels, Patrick Eriksson, Erik Buch, Gereon Budéus, Eberhard Fahrbach, Svend-Aage Malmberg, Jens Meincke, and Pentti Mälkki

Rudels, B., Eriksson, P., Buch, E., Budéus, G., Fahrbach, E., Malmberg, S.-A., Meincke, J., and Mälkki, P. 2003. Temporal switching between sources of the Denmark Strait overflow water. – ICES Marine Science Symposia, 219: 319–325.

The Denmark Strait overflow water derives from several distinct sources. Arctic Intermediate Water from the Iceland Sea, Atlantic Water of the West Spitsbergen Current recirculating in the Fram Strait, and Arctic Atlantic Water returning from the different circulation loops in the Arctic Ocean all take part in the overflow. Denser water masses, such as the upper Polar Deep Water and the Canadian Basin Deep Water from the Arctic Ocean and Arctic Intermediate Water from the Greenland Sea, are occasionally present at the sill and could contribute the deepest part of the overflow plume. A comparison between hydrographic observations made during the Greenland Sea Project in the late 1980s and early 1990s and during the European Sub Polar Ocean Programme (ESOP) and Variability of Exchanges in the Northern Seas (VEINS) programmes in the late 1990s shows that the Greenland Sea Arctic Intermediate Water has largely replaced the Arctic Ocean deep waters. In the less dense fraction of the overflow the Recirculating Atlantic Water and Arctic Atlantic Water carried by the East Greenland Current have become more prominent than the Iceland Sea Arctic Intermediate Water. If the Denmark Strait overflow were to switch between different sources, it would lead to changes in the characteristics of the overflow water that add to the variations caused by the variability of the source waters.

Keywords: Denmark Strait, East Greenland Current, overflow water, water masses.

Bert Rudels, Patrick Eriksson and Pentti Mälkki: Finnish Institute of Marine Research, Helsinki, Finland; Erik Buch, Danish Meteorological Institute, Copenhagen, Denmark; Gereon Budéus and Eberhard Fahrbach: Alfred-Wegener-Institut für Polar und Meeresforschung, Bremerhaven, Germany; Svend-Aage Malmberg: Marine Research Institute, Reykjavik, Iceland; Jens Meincke: Institut für Meereskunde der Universität Hamburg, Hamburg, Germany.

Introduction

The northernmost part of the North Atlantic – the Arctic Mediterranean Sea – is the end and the beginning of the global thermohaline circulation. The strong heat loss, the excess precipitation, and the large run-off all contribute to the water mass transformations in the Arctic Mediterranean. Northward flowing Atlantic Water that crosses the Greenland–Scotland Ridge becomes transformed, partly into low salinity surface water, but mainly into cold, dense intermediate and deep waters that return as "overflow waters" to the deep North Atlantic (Worthington, 1970). The most important sites and processes for dense water formation are the seasonal cooling of the Atlantic Water in the Norwegian Sea, the cooling and brine rejection occurring in the Barents Sea and on the shelves of the Arctic Ocean, and the winter convection in the Greenland and Iceland Seas.

Cooled Atlantic Water flows in the West Spitsbergen Current to Fram Strait, where one part recirculates and forms the Recirculating Atlantic Water, the rest entering the Arctic Ocean and becoming the Arctic Atlantic Water. Dense waters from the Barents Sea and from the Arctic shelves drain into the deep Arctic Ocean forming the Arctic Ocean intermediate and deep water masses that eventually exit through the Fram Strait and, along with the Arctic Atlantic Water returning from its loops in the different basins, forms the East Greenland Current. In Fram Strait these waters are joined by the Recirculating Atlantic Water and continue southward along the Greenland slope. On its route, the East Greenland Current interacts with the waters of the Greenland Sea. Some deep waters, the Eurasian Basin Deep Water and part of the Canadian Basin Deep Water enter the Greenland Sea (Aagaard *et al.*, 1985) and Arctic Intermediate Water is incorporated into the East Greenland Current, which continues across the Jan Mayen Fracture Zone into the Iceland Sea. The dense water formed in the Iceland Sea, the Iceland Sea Arctic Intermediate Water, does not join the East Greenland Current but instead flows directly towards the Denmark Strait, constituting a separate source of overflow water (Swift *et al.*, 1980).

Waters too dense to cross the Jan Mayen Fracture Zone and the sill in Denmark Strait eventually reach the Norwegian Sea and pass through the Faeroe–Shetland Channel to the North Atlantic. The Denmark Strait Overflow Water and the Faeroe–Shetland Overflow Water supply the North Atlantic Deep Water and feed the Deep Western Boundary Current and thus the lower limb of the global thermohaline circulation. The Denmark Strait overflow has a closer connection with the different sources than the Faeroe–Shetland overflow, which mainly drains the pool of dense water in the Norwegian Sea, and reflects more strongly the interplay between and the variability of the different sources.

Observations

The present discussion is based on hydrographic observations gathered by several institutions over the past 15 years: AWI, Bremerhaven; Finnish Institute of Marine Research, Helsinki; Institut für Meereskunde, Hamburg; Marine Research Institute, Reykjavik; Norwegian Polar Research Institute, Tromsø; Royal Danish Administration of Navigation and Hydrography, Copenhagen as part of different international projects: European Sub Polar Ocean Programme (ESOP); Greenland Sea Project (GSP); Marginal Ice Zone Experiment (MIZEX); World Ocean Circulation Experiment (Nordic WOCE); Variability of Exchanges in the Northern Seas (VEINS). Only a few representative stations are shown and their positions are indicated in Figure 1.

Fram Strait

During the past 10–15 years the water mass characteristics in Fram Strait have changed considerably. Rudels *et al.* (2000) compared sections from 1984 and 1997 and found that the deeper layers had become warmer and more saline, indicating a stronger presence of Arctic Ocean deep waters. In 1984 the warm, saline Atlantic layer located between 100 and 600 m, comprising the northward flowing and the recirculating part of the West Spitsbergen Current, reached across the entire strait from Svalbard to the Greenland continental slope. In 1997 the recirculation was less extensive, leaving a corridor, about 1/5th of the total width of the Strait, east of the Greenland slope and allowing an almost free passage for the Arctic Atlantic Water exiting the Arctic Ocean. This suggests that the recirculation in the Fram Strait has weakened and that a larger part of the West Spitsbergen Current enters the Arctic Ocean.

Central Greenland Sea

Figure 2 shows θ-S curves and potential temperature and salinity profiles from the centre (75°N, 2°W) and the western part (75°N, 7°W) of the Greenland Sea gyre taken in 1988, 1993, and 1998. After convection deeper than 2500 m in 1988 the convection depth diminished, and the penetration of the Arctic Ocean deep waters, no longer stirred into the Greenland Sea Deep Water by the local convection, from the rim towards the centre of the gyre became visible. First the deep salinity maximum deriving from the Eurasian Basin Deep Water grew in prominence and then the intermediate temperature maximum of the Canadian Basin Deep Water appeared. The latter has more or less become the deep boundary for the local convection, and the convection in the Greenland Sea presently produces Arctic Intermediate Water spreading out above the temperature maximum rather than deep water. The salinity and temperature of the deeper layers have gradually increased, while the temperature maximum is displaced downwards (Budéus *et al.*, 1998). The confinement of the convection to above the temperature maximum could be instrumental in pushing the maximum downwards.

The Iceland Sea

The Jan Mayen Fracture Zone prevents the densest water of the East Greenland Current from entering the Iceland Sea. The characteristics of the waters that cross the ridge do not display large along-slope variations between the Greenland Sea and the Iceland Sea as compared to the annual variability. The warm Recirculating Atlantic Water–Arctic Atlantic Water core as well as the thermocline above the core retained their properties since Fram Strait. The characteristics of the thermocline correspond to

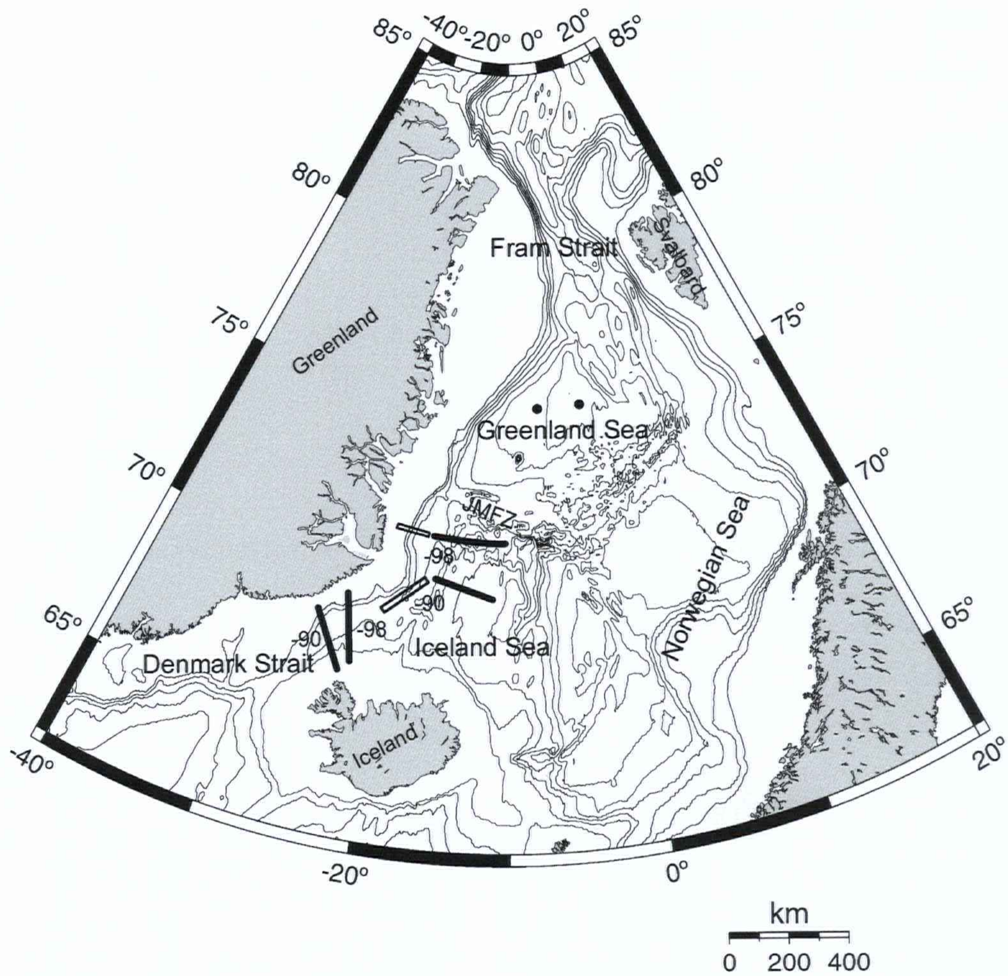
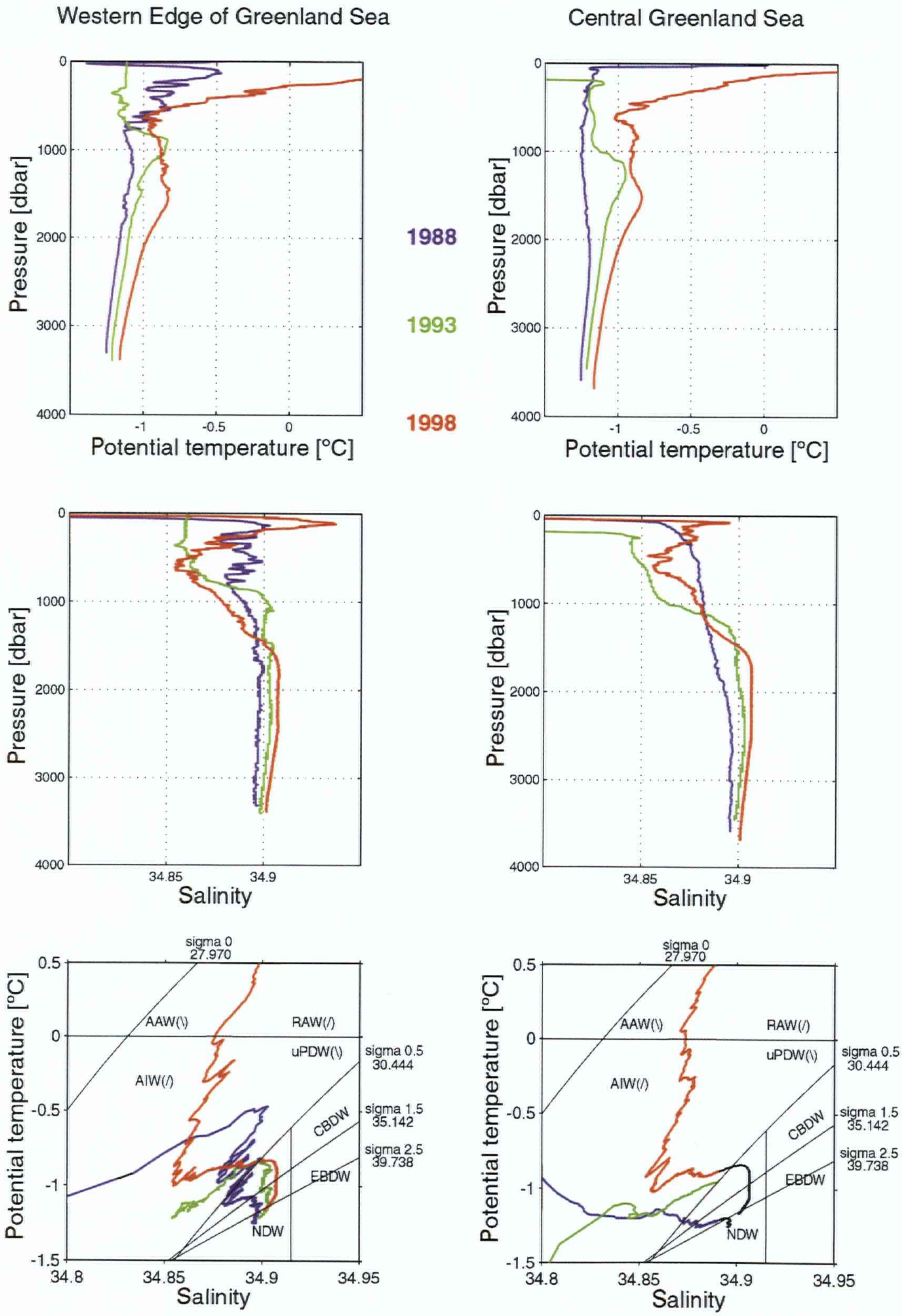


Figure 1. Map of the Nordic Seas. The positions of the Greenland Sea stations are shown as dots, and the bars indicate the positions of the sections from 1990 and 1998 in the Iceland Sea and northern Denmark Strait. The filled bars correspond to the blue stations, the open bars to the red stations in Figure 3. JMFZ (Jan Mayen Fracture Zone).

those of the Polar Intermediate Water (Malmberg, 1972), and the Arctic Ocean is therefore a probable source for the Polar Intermediate Water.

The central Iceland Sea appeared disconnected from the western area dominated by the East Greenland Current and the year to year variations of the Iceland Sea Arctic Intermediate Water, comprising an upper temperature minimum and a lower temperature maximum (Swift and Aagaard, 1981; Carmack, 1990), did not follow the advected changes in the East Greenland Current. Figure 3 compares the waters of the East Greenland Current and in the central Iceland Sea just south of the Jan Mayen Ridge in 1990 and 1998. The upper Iceland Sea Arctic Intermediate Water temperature minimum was almost removed by summer heating in 1990 but in 1998 its temperature was close to freezing. The salinity was around 34.6, which is considerably more saline than the 34.2–34.4 that characterize the knee between the halocline and the thermocline in the East Greenland Current and supports the notion that the temperature minimum is formed locally in the Iceland Sea. The temperature maximum also varied from year to year but it was always cooler and less saline than the warm, saline Arctic Atlantic Water–Recirculating Atlantic Water core in the East Greenland Current.

The salinity in the deeper layer has decreased between early and late 1990s (Figure 3). This is caused by a change in the water masses crossing the Jan Mayen Fracture Zone. During the stronger convection in the 1980s the convecting waters were denser and the less dense Canadian Basin Deep Water was forced across the ridge into the Iceland Sea. In the late 1990s the less saline, and now the less dense, Arctic Intermediate Water rather than the Canadian Basin Deep Water crossed the Jan Mayen Ridge into the Iceland Sea.


Western Edge of Greenland Sea
Central Greenland Sea
Pressure [dbar]
Potential temperature [°C]
1988
1993
1998
Salinity
Potential temperature [°C]
sigma 0
27.970
AAW(\)
RAW(/)
uPDW(\)
AIW(/)
sigma 0.5
30.444
sigma 1.5
35.142
sigma 2.5
39.738
CBDW
EBDW
NDW

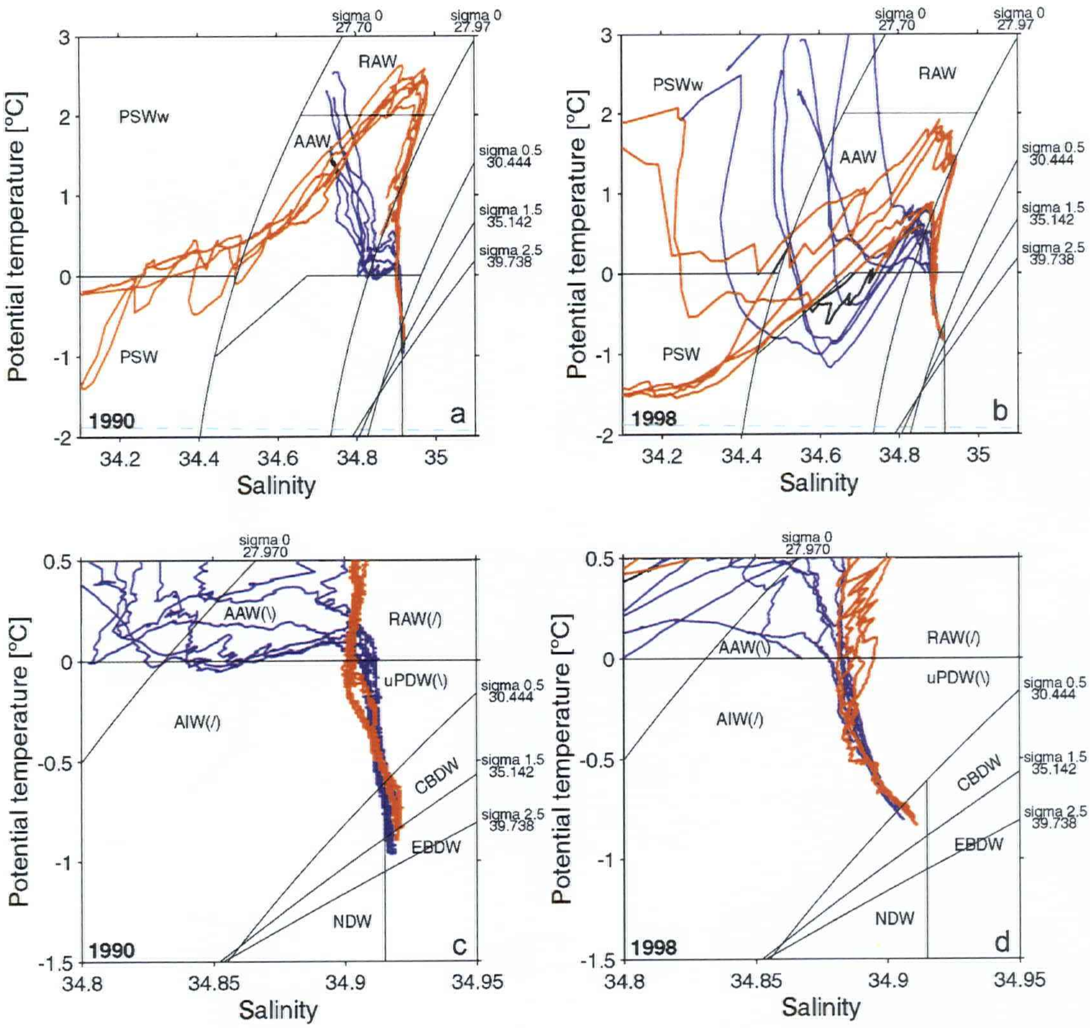


Figure 3. θ-S diagrams (full scale and blow-up) from stations in the East Greenland Current (red lines) and in the central Iceland Sea (blue lines) just south of the Jan Mayen Fracture Zone taken in 1990 and in 1998.

Denmark Strait

On sections between Greenland and Iceland just north of Denmark Strait (Figure 4) the upper layer was dominated by low salinity polar water and no temperature minimum that could have originated in the Iceland Sea was observed. The temperature of the temperature maximum was generally between that of the East Greenland Current and the Iceland Sea temperature maxima, which suggests mixing between the two sources. The temperature was higher in 1998 than in 1990, implying an increased fraction of Recirculating Atlantic Water–Arctic Atlantic Water in the Denmark Strait overflow. The trend of decreasing salinity in the deeper layers noticed further north in the Iceland Sea was also seen in Denmark Strait.

Figure 2. Profiles of potential temperature, salinity, and Q-S diagrams (blow-up) from stations in the centre (75°N, 2°W) and at the western rim (75°N, 7°W) of the Greenland Sea gyre taken in 1988 (blue lines), 1993 (green lines), and 1998 (red lines). The water mass classification indicated on this (and on other Q-S diagrams below) is aimed for Fram Strait (see Rudels *et al.*, 1999b). PSW (Polar Surface Water), PSWw (Polar Surface Water warm) (ice melt on top of Atlantic Water from the south), RAW (Recirculating Atlantic Water), AAW (Arctic Atlantic Water), uPDW (upper Polar Deep Water), CBDW (Canadian Basin Deep Water), EBDW (Eurasian Basin Deep Water), NDW (Nordic Deep Water, comprising both Greenland Sea Deep Water (GSDW) and Norwegian Sea Deep Water (NSDW)). (/) and (\) indicate the most prominent slope of the water mass in regions where the characteristics of two water masses overlap. The water mass boundaries are shown as orientation, although the classification does not apply outside Fram Strait.

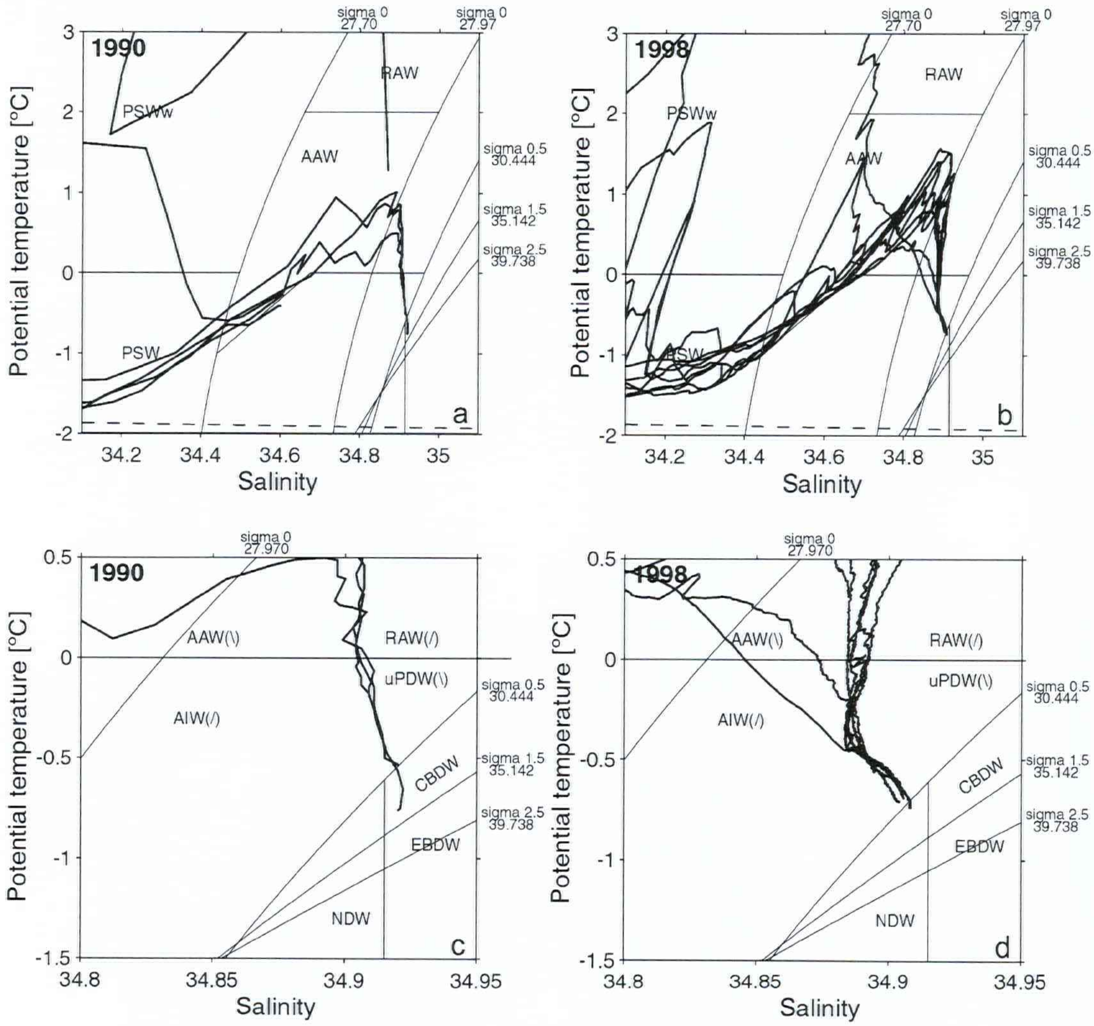


Figure 4. θ-S diagrams (full scale and blow-up) from stations in northern Denmark Strait taken in 1990 and in 1998.

Sections taken at the sill displayed yearly changes but even stronger variability over a week are present (Ross, 1984; Rudels *et al.*, 1999a). A possible cause of these rapid changes could be the encounter between the East Greenland Current and the Irminger Current from the south. The two currents contend for space in the central part of the Denmark Strait and a strong presence of Irminger Current water will obstruct the passage of the East Greenland Current. The overflow shifts westward onto the Greenland shelf, and the southward passage of denser overflow waters could temporarily become obstructed.

Summary

The variability of the Denmark Strait overflow is manifested on several time scales from a few days to more than 10 years. The contest between the Irminger Current and the East Greenland Current will affect the overflow in periods of a week and this variability is likely caused by local weather conditions. The characteristics of the intermediate water of the Iceland Sea change from year to year due to variations in the wintertime heat loss. Changes in the wind fields over periods of months to years are likely to create conditions favouring either a flow of Iceland Sea waters or East Greenland Current waters to the Denmark Strait. Variability on still longer time scales is seen in the Greenland Sea, where a change from convective deep water renewal to a period of mainly Arctic Intermediate Water production occurred in less than 10 years. During this period the deep Greenland Sea has become transformed into a passive "bay" more or less dominated by the Arctic Ocean deep waters. The shallower convection, on the other hand, creates an almost direct communication between the

Greenland Sea, the East Greenland Current and Denmark Strait. In 1998 the Greenland Sea produced water for the Denmark Strait overflow rather than for the Faeroe–Shetland overflow, which was the case in the deep convecting situation. The prominence of the Recirculating Atlantic Water in Fram Strait has decreased during the same period as the weakening of the Greenland Sea convection, indicating less recirculation and larger exchanges between the Nordic Seas and the Arctic Ocean in this density range. Changes with still longer periods are expected for the intermediate and deep waters of the Arctic Ocean, where variations in the water mass characteristics occur over 10–100 years.

The state of the convection in the Greenland Sea could be one key to the 5–10 years variability. A strong Greenland Sea convection creates a denser central dome in the Greenland Sea that intensifies the cyclonic circulation. This could, in addition to keeping the Arctic Ocean deep waters above the convecting water and closer to the rim, also force the Atlantic Water of the West Spitsbergen Current to recirculate in Fram Strait rather than enter the Arctic Ocean (Rudels *et al.*, 2000). The inflow to the Arctic Ocean would then comprise denser, deeper lying water masses formed by convection in the Greenland Sea. The stronger recirculation restricts the outflow of Arctic Atlantic Water and the Recirculating Atlantic Water would dominate in the East Greenland Current and in the Denmark Strait overflow. Weaker convection slackens the doming (Meincke *et al.*, 1997) and the recirculation in Fram Strait would diminish, causing more Arctic Atlantic Water and less Recirculating Atlantic Water to enter the East Greenland Current. Such a shift in the flow pattern would change the overflow characteristics from the fairly saline flow reported by Dickson and Brown (1994) for the 1980s, to the less saline overflow observed in the 1990s (Dickson *et al.*, 1998). The climatic conditions behind these changes in convection activity in the Greenland Sea are, of course, not answered by speculation like this, but must be found by a complete study of the different components of the climate system.

References

Aagaard, K., Swift, J. H., and Carmack, E. C. 1985. Thermohaline circulation in the Arctic Mediterranean Seas. Journal of Geophysical Research, 90: 4833–4846.

Budéus, G., Schneider, W., and Krause, G. 1998. Winter convective events and bottom water warming in the Greenland Sea. Journal of Geophysical Research, 103: 18513–18527.

Carmack, E. C. 1990. Large-scale physical oceanography of Polar Oceans. *In* Polar Oceanography, Part A, pp. 171–212. Ed. by W. O. Smith Jr. Academic Press, San Diego, California. 406 pp.

Dickson, R. R., and Brown, J. 1994. The production of North Atlantic Deep Water: sources, rates and pathways. Journal of Geophysical Research, 99: 12319–12341.

Dickson, R. R., Osborn, T. J., Hurrell, J. W., Meincke, J., Blindheim, J., Ådlandsvik, B., Vinje, T., Alekseev, G., and Maslowski, W. 1998. The Arctic Ocean response to the North Atlantic Oscillation. Journal of Climate, 13: 2671–2696.

Malmberg, S.-A. 1972. Intermediate Polar Water in the Denmark Strait: "overflow" August 1971. ICES CM 1972/C: 6. 6 pp.

Meincke, J., Rudels, B., and Friedrich, H. 1997. The Arctic Ocean–Nordic Seas Thermohaline System. ICES Journal of Marine Sciences, 54: 283–299.

Ross, G. K. 1984. Temperature—salinity characteristics of the "overflow" water in Denmark Strait during "Overflow 1973". Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer, 185: 111–119.

Rudels, B., Eriksson, P., Grönvall, H., Hietala, R., and Launiainen, J. 1999a. Hydrographic observations in Denmark Strait in Fall 1997, and their implications for the entrainment into the overflow plume. Geophysical Research Letters, 26: 1325–1328.

Rudels, B., Friedrich, H. J., and Quadfasel, D. 1999b. The Arctic Circumpolar Boundary Current. Deep-Sea Research Part II, 46: 1023–1062.

Rudels, B., Meyer, R., Fahrbach, E., Ivanov, V. V., Østerhus, S., Quadfasel, D., Schauer, U., Tverberg, V., and Woodgate, R. A. 2000. Water mass distribution in Fram Strait and over the Yermak Plateau in summer 1997. Annales Geophysicae, 18: 687–705.

Swift, J. H., and Aagaard, K. 1981. Seasonal transitions and water mass formation in the Icelandic and Greenland Seas. Deep-Sea Research, 28: 1107–1129.

Swift, J. H., Aagaard, K., and Malmberg, S.-Aa. 1980. The contribution of the Denmark Strait overflow to the deep North Atlantic. Deep-Sea Research, 27: 29–42.

Worthington, L. V. 1970. The Norwegian Sea as a Mediterranean basin. Deep-Sea Research, 17: 77–84.