

## The West Spitsbergen Current: Disposition and Water Mass Transformation

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Recent work suggests that the West Spitsbergen Current, which provides the principal contribution to the Arctic Ocean of salt and sensible heat, as well as of a variety of anthropogenic tracers, is a rather complex circulation feature. North of 79°N, where the isobaths diverge markedly, the current contains two separate warm cores that follow different isobaths. The western core, carried by the offshore branch of the current, follows the western flank of the Yermak Plateau, and north of 80°N at least part of this flow detaches from the plateau, probably to contribute to the recirculation in Fram Strait. In contrast, the inshore branch follows the shelf break into the Arctic Ocean. It is this inshore branch that provides the primary focus in this paper. During the transit of the inshore waters past northwestern Spitsbergen, the core properties change primarily through vertical heat flux, which during ice-free conditions in winter is estimated to be of the order of  $200 \text{ W m}^{-2}$  from the core layer alone. Together with some freshening within the Arctic Ocean, this process is responsible for fully transforming the original Atlantic water into arctic intermediate water within about 600 km of Fram Strait.

### INTRODUCTION

The principal contribution to the Arctic Ocean of salt and sensible heat, as well as of a variety of anthropogenic tracers, comes via the West Spitsbergen Current, hereafter referred to as the WSC [Mosby, 1962; Aagaard and Greisman, 1975; Livingston *et al.*, 1984]. This poleward flow through eastern Fram Strait, between Greenland and Spitsbergen, is the northernmost extension of the Norwegian Atlantic Current. It maintains essentially ice-free conditions west and north of Spitsbergen to 80°–82°N before its waters sink and spread at intermediate depths, in part within the Arctic Ocean and in part east of Greenland in a southward recirculation.

The early work of Nansen [1915] suggested the WSC to be a rather broad flow, perhaps as much as 300 km wide. This appears to have been consistent with the perception of subsequent investigators until quite recently [e.g., Timofeyev, 1963]. Within the past few years, however, observations of both the hydrographic and velocity fields have shown a current with considerable cross-stream structure on much smaller spatial scales. In particular, Hanzlick [1983] has found banded flow with cross-isobath scales of 10–20 km, based on long-term current measurements at 79°N (sites A–D in Figure 2). Slightly farther north, conductivity, temperature, and depth (CTD) sections suggest that the WSC diverges together with the isobaths, with one branch following the western flank of the Yermak Plateau and the other following the shelf break north-

west of Spitsbergen. Convincing evidence for such a bifurcation has been presented by Farrelly *et al.* [1985, Figure 8], following earlier work by Gammelsrød and Rudels [1983], Johannessen *et al.* [1983], Lewis and Perkin [1983], and Perkin and Lewis [1984].

The observations we shall present here provide confirmation of the bifurcation of the WSC, but more important, they document the course of the inshore branch and the changes in its core properties during winter in the open water north of Spitsbergen. Furthermore, supplementary measurements north of Franz Josef Land suggest that the transformation into arctic intermediate water of the core of Atlantic water carried northward by the WSC has been completed within 500–600 km of the entry of WSC waters into the Arctic Ocean. Finally, our data suggest that the offshore branch of the WSC, which initially follows the western flank of the Yermak Plateau, does not in recognizable form rejoin the inner branch where the isobaths again converge east of the Yermak Plateau.

### THE DATA

Our principal data base consists of 97 CTD stations taken west and north of Spitsbergen during late November 1977 from the *Polarsirkel*. The study area is shown in Figure 1 and the station locations in Figure 2. The station locations also define the open-water area, since each section was run out to the ice edge. The instrument used was a Neil Brown Instrument Systems microprofiler for which field calibration was provided by a Nansen bottle attached to the wire immediately above the profiler. The salinity samples were stored in aged glass bottles and run in Bergen on an Autolab bench salinometer. The absolute accuracy of the observations is somewhat uncertain because of the single-point calibrations, but the precision appears to be within 0.01°C and 0.01 for temper-

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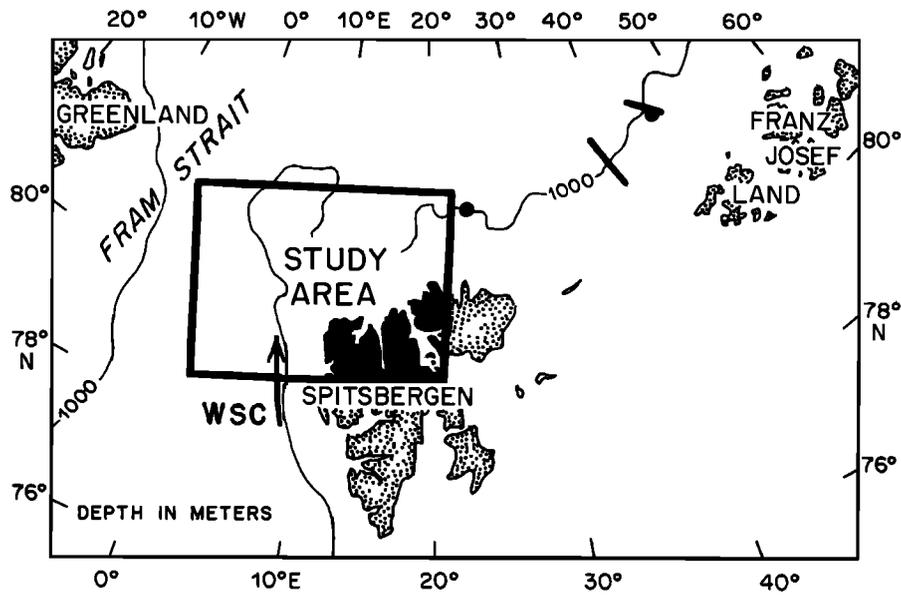


Fig. 1. Location of study area. The two heavy lines near 40° and 45°E denote the locations of the sections in Figure 8. The dots near 23° and 45°E show mooring sites.

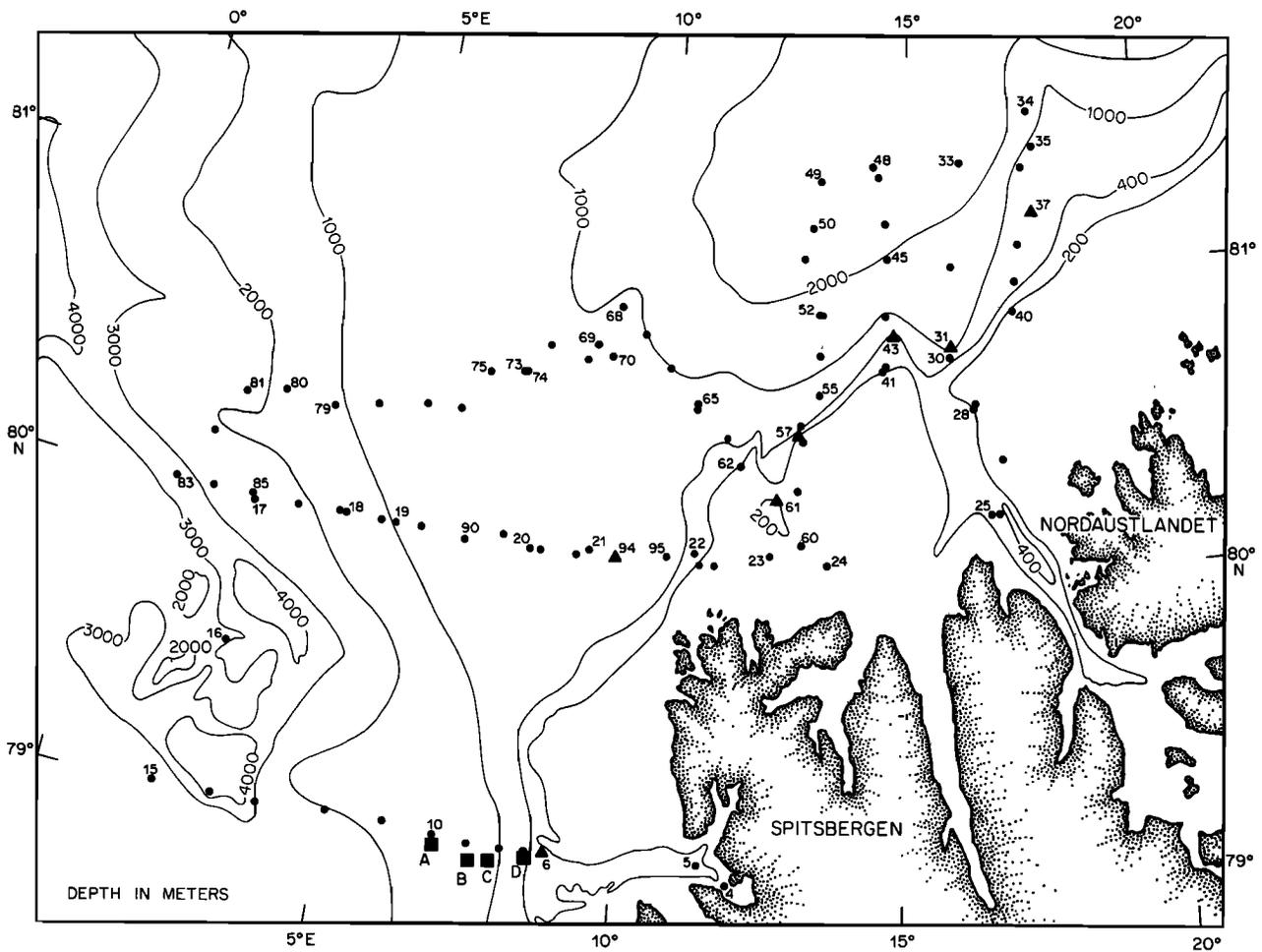


Fig. 2. CTD stations occupied by the *Polarsirkel* during November 20–27, 1977. Triangles represent the positions of CTD stations with mean TS correlations indicated by triangles in Figure 7. Boxes A–D show long-term mooring locations.

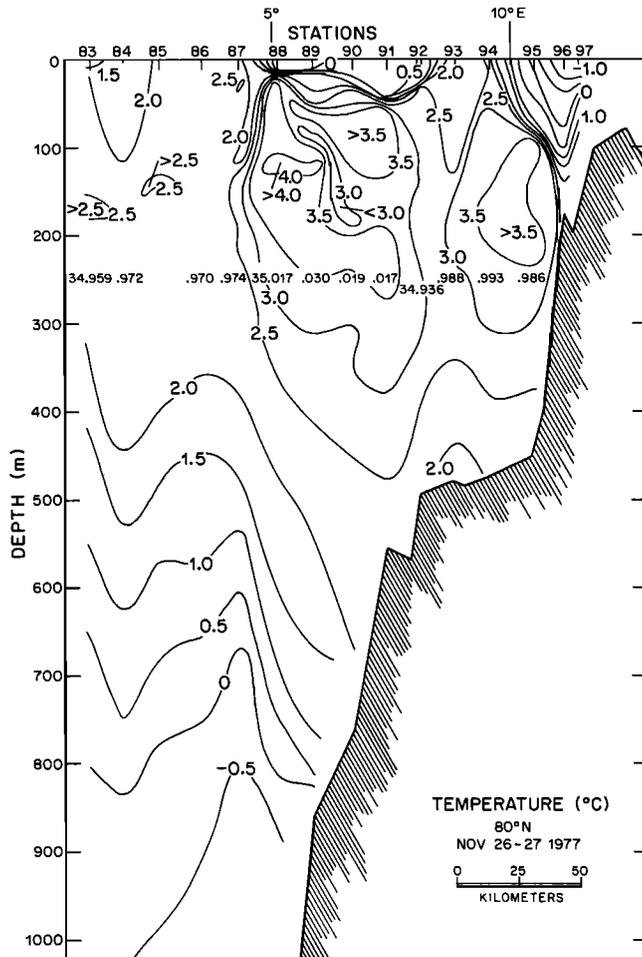


Fig. 3. Temperature along 80°N during November 26–27, 1977. The mean salinity between 200 and 300 m at stations with a vertical salinity maximum is shown near 250 m.

ature and salinity, respectively. This is amply adequate for purposes of the present discussion.

A particularly important geographical feature is the divergence of the isobaths that occurs near 79°30'N. This is illustrated in Figure 2 by the 400-m and 1000-m contours, which crowd closely south of this latitude but diverge to the north. The 400-m isobath follows the shelf break toward the northeast around Spitsbergen, while the 1000-m line heads north-northwest along the west flank of the Yermak Plateau. Eventually this isobath rounds the plateau and returns south to approach the 400-m contour near 11°–12°E.

Figure 3 shows the temperature along 80°N. A striking aspect is the presence of two distinct warm cores, with the intervening water about 1°C cooler. The western core is the larger one, extending perhaps 60 km laterally, versus about 40 km for the eastern, inshore core. The salinity range in the section is very small, nominally a few tenths, but even within this weak gradient a horizontally similar salinity core struc-

ture can be discerned. Figure 3 gives the mean salinity between 200 and 300 m at the stations where a salinity maximum occurred in this depth range. (The surface waters are generally slightly diluted, so that there is usually a weak salinity maximum between 200 and 250 m, before the salinity decreases with depth to about 34.92.) Note that moving eastward along the section, elevated mean salinities were found at stations 88–91, corresponding to the offshore warm core, then decreased at station 92, before increasing to a secondary maximum at station 94, coincident with the inshore warm core.

One can also discern a two-core structure in the upstream section, at 79°N, but only in the salinity field. This difference between the two sections is probably related to the bathymetry in the following way. Since recent direct current measurements in the West Spitsbergen Current show relatively strong flow extending to the bottom [Hanzlick, 1983], we should expect a tendency for trajectories to follow isobaths. The clear separation of the flow into two distinct cores at 80°N, where the bathymetry is divergent, can then be contrasted with the structure at 79°N, where the isobaths are parallel and lie close together, and where the cores are nearly indistinguishable. Our starting hypothesis is therefore that if neither temporal variability nor mixing is too large, we should be able to track the individual cores along preferred isobaths determined by their initial upstream potential vorticity. This would be in accord with the suggestion of Perkin and Lewis [1984].

The horizontal distributions of water characteristics support this expectation for the inner core but suggest it is not fulfilled in the case of the outer core, although the data coverage is too sparse to allow firm conclusions. Figure 4 shows the mean temperature between 100 and 200 m, which layer contains the temperature maximum, and Figure 5 shows the mean salinity between 200 and 300 m, which contains the salinity maximum. The vertical averaging over 100 m has been done to smooth the fields, which are quite noisy for small vertical scales. The distribution of the temperature maximum (Figure 4) suggests that the inner warm core follows the shelf edge toward the northeast rather closely, even to some fine detail near 15°–16°E. There is little indication of offshore excursions or strong mixing. In contrast, the offshore core appears broader and more diffuse, with considerably less laterally constraining influence. The salinity distribution (Figure 5) gives much the same impression. Particularly noteworthy in these two figures is the absence on the eastern flank of the Yermak Plateau (stations 66–68) of any suggestion of southward flow of a remnant outer warm and saline core that might have followed the 1000-m isobath around the plateau. Rather, the TS structure of the water at these stations closely resembles that found west of the outer core at 79°N. For example, the mean TS properties of the 100 to 200-m layer at stations 66–68 bracket those at stations 14–15 (cf. Figure 7). This suggests that the outer core either detaches from the plateau downstream of 80°N or is so thoroughly mixed in its course as to be unrecognizable by the time it reaches the southeastern flank of the plateau.

It is of course possible that the absence of recognizable warm core water in the vicinity of stations 66–68 simply reflects a variable upstream source. For example, in Figure 5 the higher salinity north of 79°N points to such a temporal variability. However, a temperature record is available from 100 m

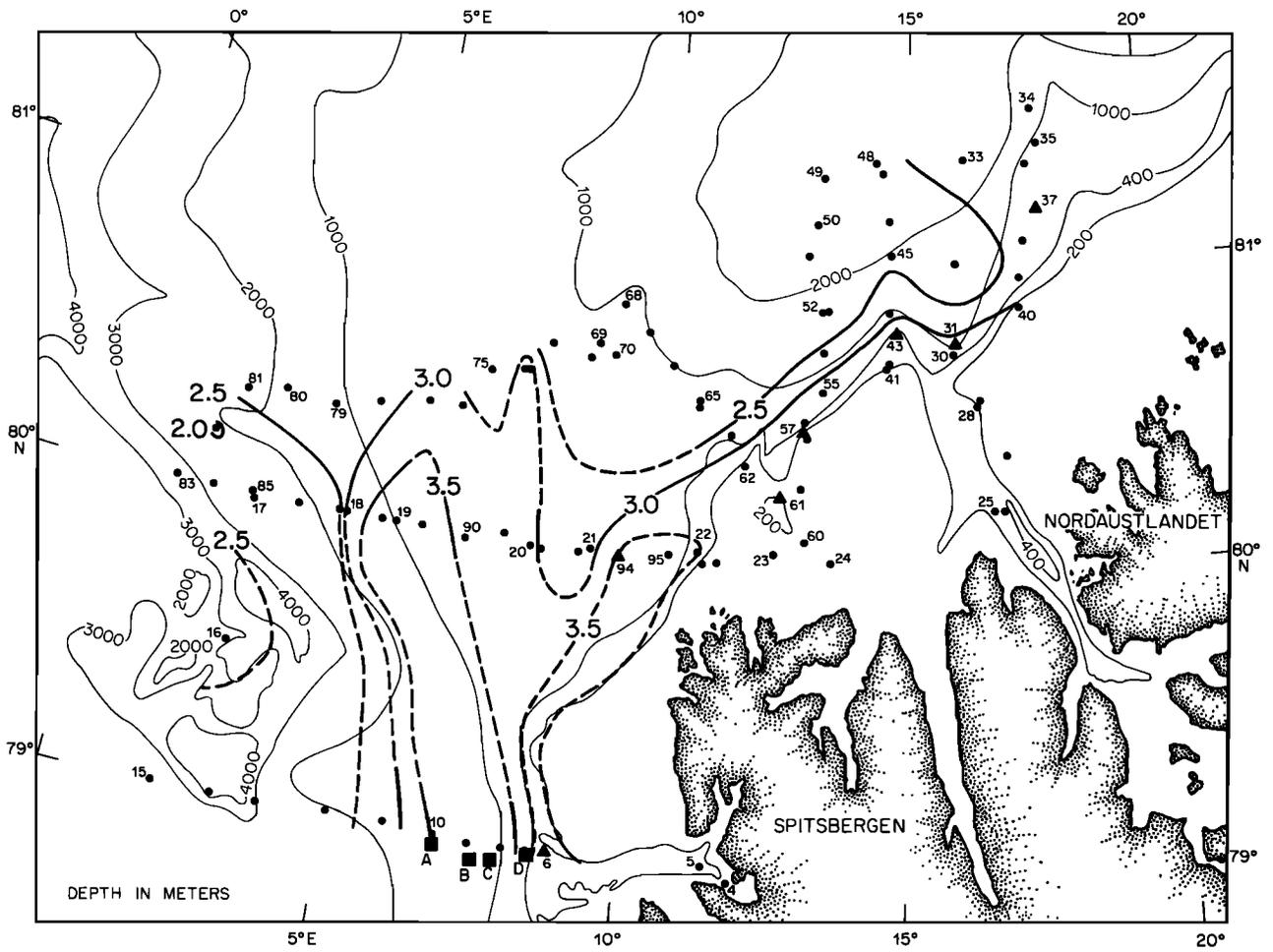


Fig. 4. Mean temperature between 100 and 200 m, which layer contains the temperature maximum.

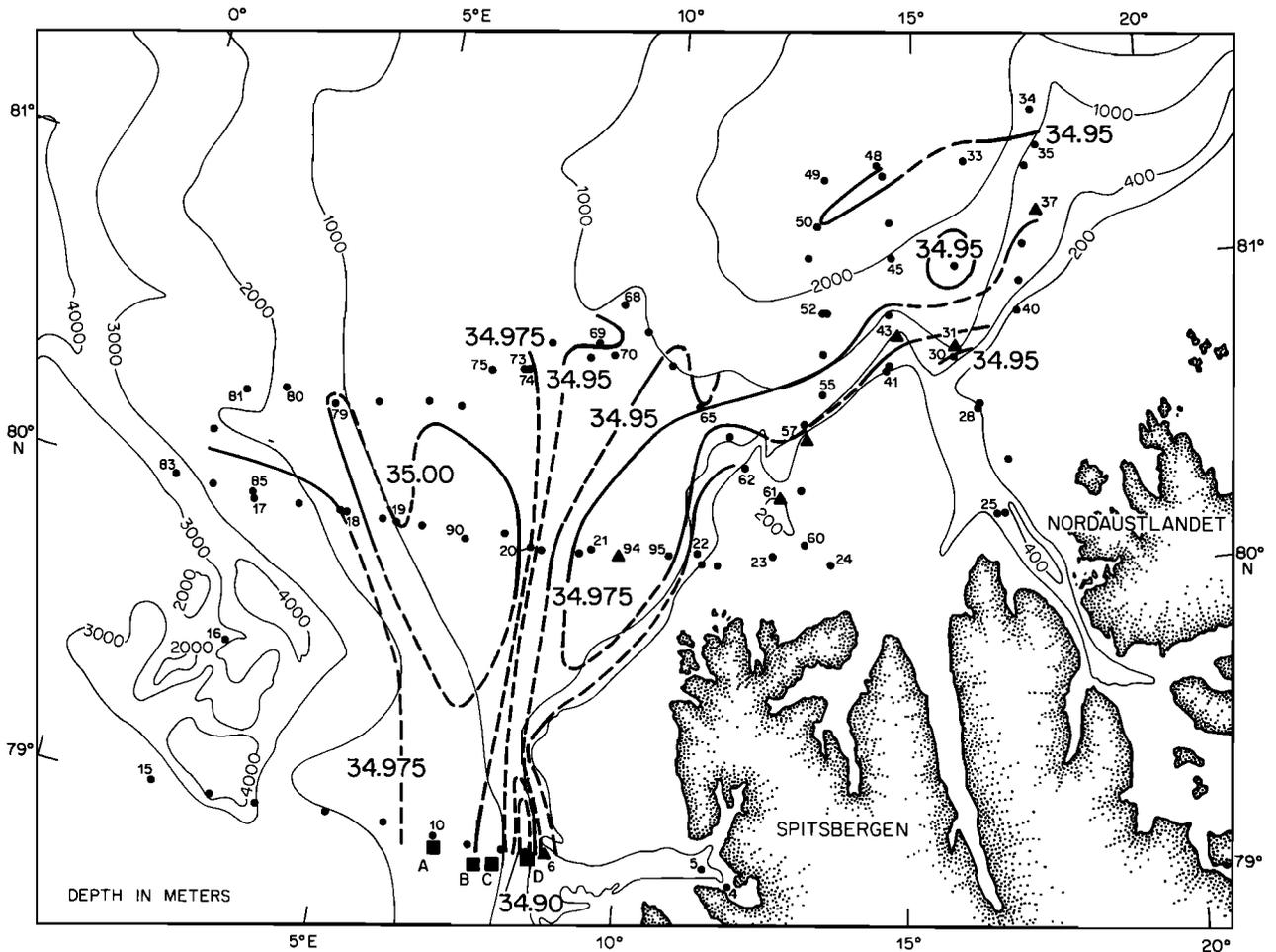


Fig. 5. Mean salinity between 200 and 300 m, which layer contains the salinity maximum.

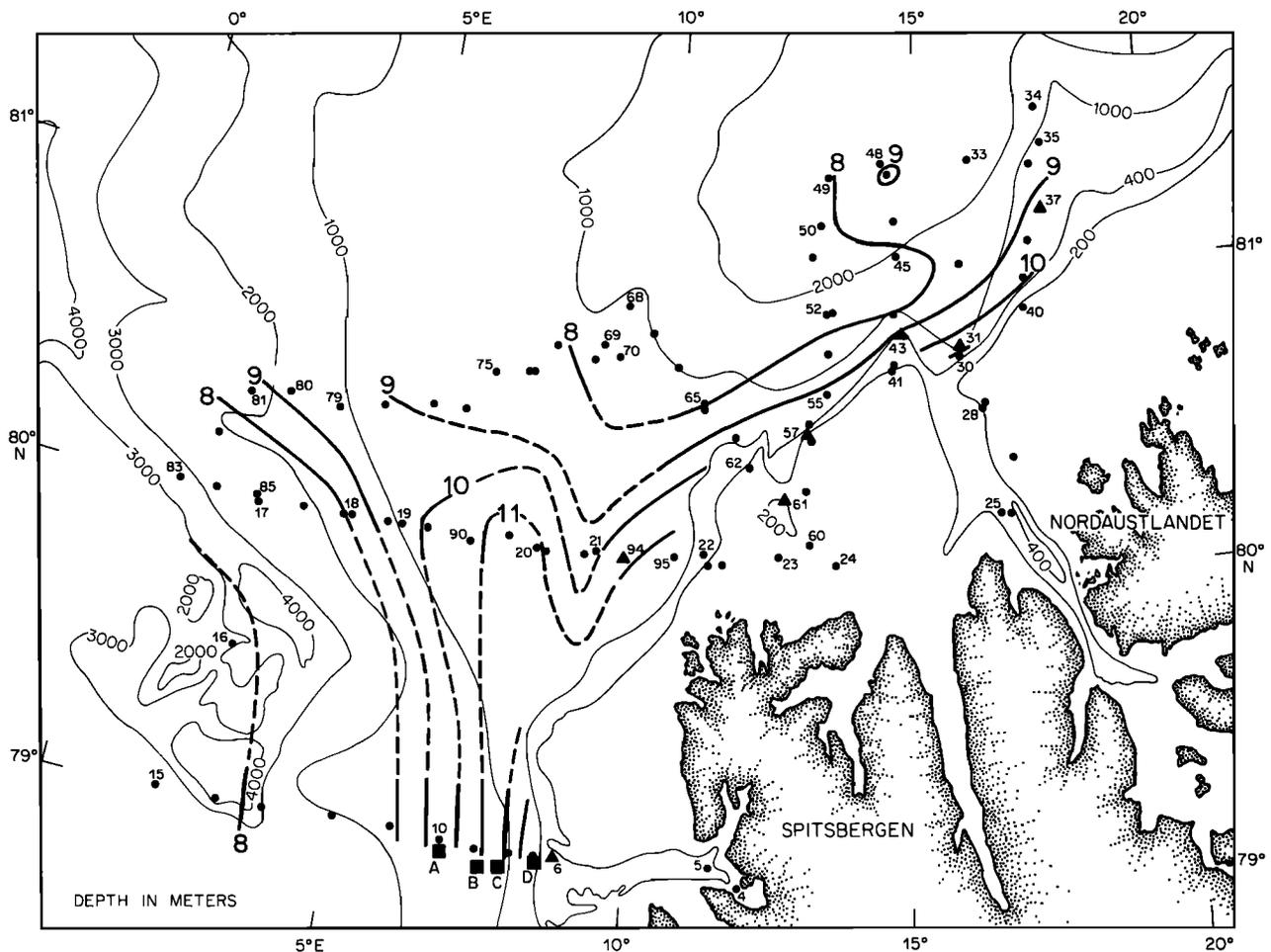


Fig. 6. Dynamic topography, 20/400 dbar, dynamic centimeters.

at a mooring at site C, essentially coincident with the upstream outer core location at  $79^{\circ}\text{N}$ , and a comparison can be made as follows. The distance around the Yermak Plateau along the 1000-m contour from site C to station 67 is about 700 km, while the mean current recorded at site C during both October and November 1977 was  $20\text{ cm s}^{-1}$  northward. This corresponds to a travel time of 41 days. Stations 66–68 were occupied on November 25, so that at  $20\text{ cm s}^{-1}$ , water traveling along the 1000-m contour should have passed site C on October 15. The record at site C actually starts on September 6, and at no time during the recording period did the daily mean temperature drop much below  $3^{\circ}\text{C}$ , i.e., at least  $1^{\circ}\text{C}$  warmer than observed at stations 66–68 (cf. Figure 7).

The dynamic topography (20/400 dbar, Figure 6) is also consonant with the divergence of the WSC north of  $79^{\circ}\text{N}$ , showing the inshore branch directed northeastward just seaward of the shelf break, while the offshore branch follows the western flank of the Yermak Plateau. Figure 6 also suggests that north of  $80^{\circ}\text{N}$  at least part of this offshore branch detaches from the plateau, probably to contribute to the recirculation in Fram Strait, which feeds warm and saline water into the southward flow on the eastern side of the strait, adjacent to the Greenland margin. The dynamic topography over the plateau itself appears to be rather flat, corresponding to weak geostrophic currents. This is in fact in agreement with the

SOFAR float trajectories observed by Gascard [1984] during the 1984 MIZEX, as is also the suggested detachment of flow from the western flank of the plateau north of  $80^{\circ}\text{N}$ .

#### DISCUSSION

While there is no coverage of the Yermak Plateau north of about  $80^{\circ}30'\text{N}$ , and the data set is limited to a single quasi-synoptic snapshot of the hydrography, the observations give a consistent picture of the WSC as separating into two streams north of  $79^{\circ}\text{N}$ . The disposition of the outer branch is uncertain, for example, with respect to the degree it contributes to recirculation in Fram Strait. The failure of this branch to reappear in recognizable form along the southeastern flank of the Yermak Plateau, however, suggests that to the extent the branch does not recirculate in Fram Strait, its contribution of salt and heat to the Arctic Ocean is delivered north or west of the plateau.

On the other hand, the inshore branch of the WSC appears trapped close to the shelf break as it enters the Arctic Ocean, and the TS correlations suggest that changes in core properties are primarily caused by vertical heat flux, rather than through lateral mixing. Figure 7 shows the mean TS characteristics in the 100- to 200-m layer for each station. The triangles in the upper right-hand part of the figure represent the

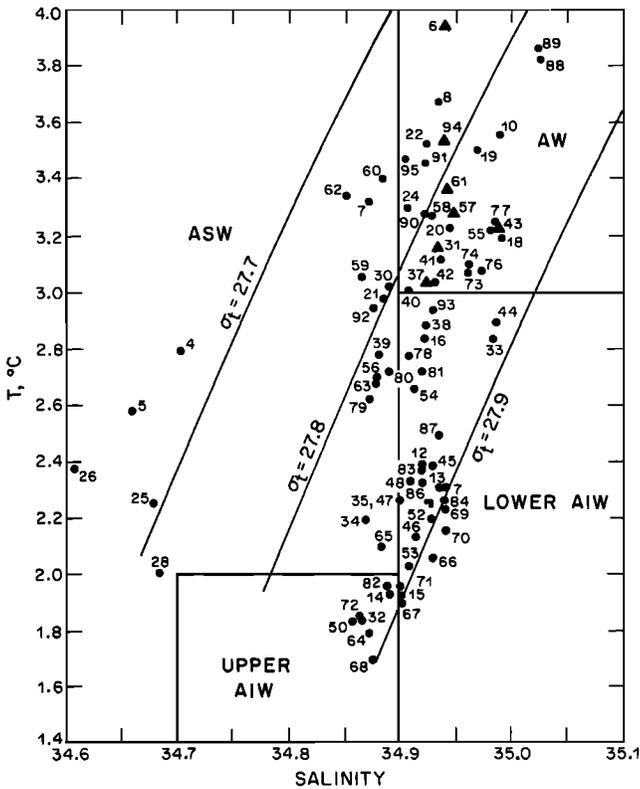


Fig. 7. Mean TS correlations in the 100- to 200-m layer. Triangles denote stations containing the temperature and salinity maximum in each section (cf. Figures 2, 4, 5, or 6 for locations).

stations containing the inshore temperature and salinity maximum in each section. There is in fact an orderly downstream progression of decreasing maximum temperature from station 6 at 79°N, through stations 94, 61, 57, 43, and 31 to station 37 in the northeast corner of the surveyed area, while the salinity does not show a statistically distinguishable trend. This con-

trasts with the expected trend if lateral mixing predominated, for in that case the core should both freshen and cool downstream as it mixed with the cold, low-salinity water offshore. While the monotonic nature of the temperature decrease may well be fortuitous, the overall cooling trend corresponds convincingly to a warm core whose primary interaction with its surroundings is a heat loss to the surface layer. We can estimate this heat loss in the following way. A time series of moored current measurements at 100-m depth over the upper slope at 79°N (site C) shows a mean northward velocity of 20 cm s<sup>-1</sup> during both October and November of that year, and if this is assumed to be the velocity of the warm core, the observed downstream temperature decrease corresponds to a heat loss of about 230 W m<sup>-2</sup> from the 100- to 200-m layer. This is an extremely large heat loss, since the heat flux at the sea surface would include both this loss and that from the upper 100 m. As a point of comparison, the mean surface heat flux from a polynya at 76°N in the Canadian Archipelago during the last 3 weeks of March was calculated by *den Hartog et al.* [1983] as 330 W m<sup>-2</sup>. There are obviously large uncertainties in our flux estimate, but the point is that it is of roughly the right magnitude, so that we can reasonably account for the observed temperature progression by vertical heat loss from a core that experiences little lateral mixing.

Our heat flux calculations can be contrasted with those of *Perkin and Lewis* [1984] for the same general area, but for the spring under iced-over conditions. They observed extensive interleaving, with large temperature contrast between adjacent layers. For this situation they calculated a double-diffusive vertical heat flux (across a single step) that was an order of magnitude smaller than our result. In contrast, our observations were for ice-free conditions, with an upper ocean stratification substantially less than that of *Perkin and Lewis* and without extensive and strong interleaving over the slope. The contrast thus appears to be between an ice-covered double-diffusive regime, with relatively small vertical fluxes, and an open-ocean one in which intensive cooling at the sea surface

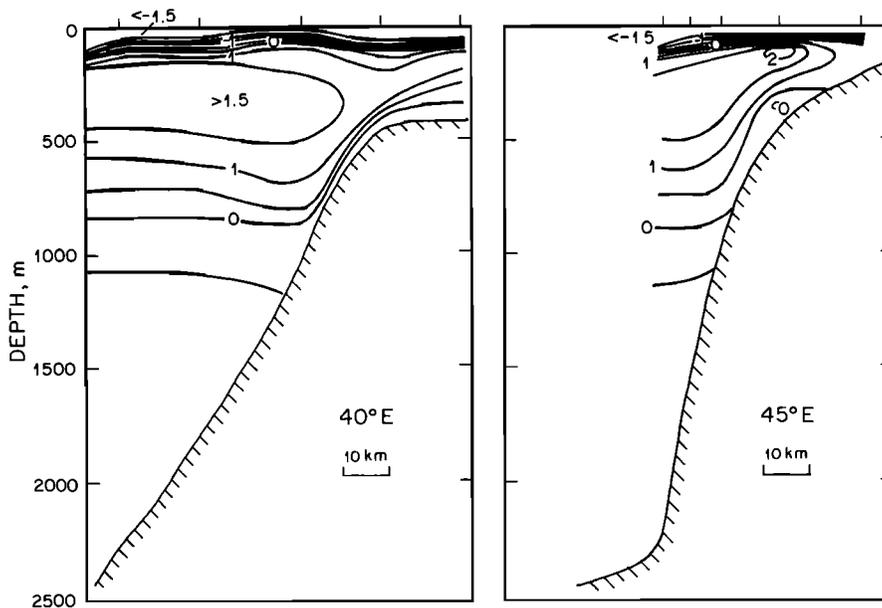


Fig. 8. Temperature during July 23–26, 1980, in sections near 40° and 45°E shown in Figure 1 [adapted from *Aagaard et al.*, 1981].

and subsequent convection result in a large vertical heat flux. It follows that the variability of ice conditions near Spitsbergen likely lead to a corresponding variability in downstream heat content in the Atlantic layer of the Arctic Ocean. This may, for example, contribute to the variability in this layer observed by *Timofeyev* [1958].

The further fate of the inshore branch of the WSC is suggested by two sections done from the *Ymer* in the summer of 1980. The section locations are indicated by the two heavy lines near 40° and 45°E in Figure 1. Figure 8 [adapted from *Aagaard et al.*, 1981] shows the temperature in these sections. At 40°E the maximum observed temperature was less than 2°C, and at 45°E it was just above 2°C. The corresponding salinities were less than 34.9, so that at this distance into the Arctic Ocean the core properties have essentially disappeared and the water is similar to that offshore from the warm core near Spitsbergen. Using the water mass nomenclature of *Swift and Aagaard* [1981], the warm core carried northward with the WSC has been fully transformed from Atlantic water into upper arctic intermediate water. Since the salinity has also been reduced somewhat, this requires mixing with a lower salinity source, in addition to the surface heat loss, but just how this mixing occurs is unknown. In 1980 we also deployed two moorings on the upper continental slope within the Arctic Ocean (positions shown by the two heavy dots in Figure 1). The maximum mean temperature over the 2-month deployment period was 2.1°C at the western site and occurred at 200 m, while at the eastern site it was 1.3°C and occurred at 130 m. These observations are thus consistent with the transformation scenario we have proposed.

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