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Variability of Water Masses, Currents and Ice in Denmark Strait

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Abstract

Environmentally-related work in Denmark Strait during more than 100 years elaborates the fascinating variability of air-sea-bottom interaction in this part of the North Atlantic Ocean. From the available literature and recent observations in the Dohrn Bank region, the order of magnitude of this variability is demonstrated.

Introduction

During the January 1985 Meeting of the NAFO Scientific Council, it was noted that the northern shrimp (*Pandalus borealis*) stock in Denmark Strait may be living under extreme and unstable environmental conditions, and it was recommended that a study of environmental conditions, including ice and currents, be undertaken in the area (NAFO, 1985). At the January 1986 Meeting, concern was again expressed that few data were available on environmental conditions, and the previous recommendation was reiterated (NAFO, 1986). As a first approach toward meeting the requirements of the Scientific Council regarding assessment of the shrimp stock in Denmark Strait, the intent of this paper is to present an overview of environmentally-related work in Denmark Strait and to display some recent results of surveys in Denmark Strait by research vessels of the Federal Republic of Germany. Special emphasis is given to the variability of water masses on Dohrn Bank.

Historical Synopsis

The scientific literature contains numerous papers on the hydrographic conditions in the Denmark Strait area. The first results were published in the middle of the 19th century by a Danish navigator (Irminger, 1854, 1861). His investigations dealt with the surface currents between Iceland and Greenland. He concluded that warm Atlantic water flows westward off Iceland, and this current was later called the Irminger Current. He also revealed that cold polar water flows southward off the east coast of Greenland.

The influence of the Greenland-Iceland sill on the exchange between the cold Arctic Deep Water of the European Polar Sea and the warm Atlantic Water was examined during the *Ingolf* expedition in 1879 by Mourier (1880). During the Swedish *Sofia* expedition shortly afterwards, Hamberg (1884) found that the cold East Greenland Current between Denmark Strait and Cape Farewell is very shallow, and that there is warm Atlantic Water below the cold layer. Knudsen (1899) reported that the overflow of Arctic Water across the sill sinks to greater depths in the region south of the Greenland-Iceland Ridge. The existence of different water masses in Denmark Strait was shown during the *Øst* expedition in the summer of 1929. According to Braarud and Ruud (1932), three water masses of different origins meet and mix in this area: East Greenland water, North Atlantic water and Arctic deep water. A thorough investigation of the East Greenland Current, during the *Dana* summer expeditions of 1931, 1932 and 1933, revealed the borderline of the East Greenland Current as well as an intense indentation of Polar and Atlantic water in Denmark Strait. It was shown that the geographic location of the current is rather constant. Thomsen (1934) concluded that a topographic steering is present. He also stated that the overflow of Arctic deep water across the ridge is irregular. Defant (1931) pointed out that there is turbulent mixing at the oceanic Polar Front, leading to mesoscale and smallscale meandering and eddies. Dietrich (1957), during the first cruise of *Anton Dohrn* in June 1955, revealed that the Subarctic bottom water of the northern North Atlantic is renewed in batches. He also calculated volume transports of the northern North Atlantic water.

The Icelandic-Norwegian expedition between Iceland and Greenland in 1963 yielded detailed information on the distribution of water masses, temperature and salinity, as well as the distribution of currents which were measured by moored devices at four sites (Gade *et al.*, 1965). Worthington (1969), after recovering 10 current meters from 30 which has been moored, obtained data only from one instrument in the middle of Denmark Strait at a depth of 760 m, where the maximum current velocity was 143 cm/sec. Mann (1969) found large variability in the composition of the overflowing bottom water, both in the horizontal and vertical directions. Malmberg (MS 1972) and Stein (MS 1972) indicated considerable change in distribution of

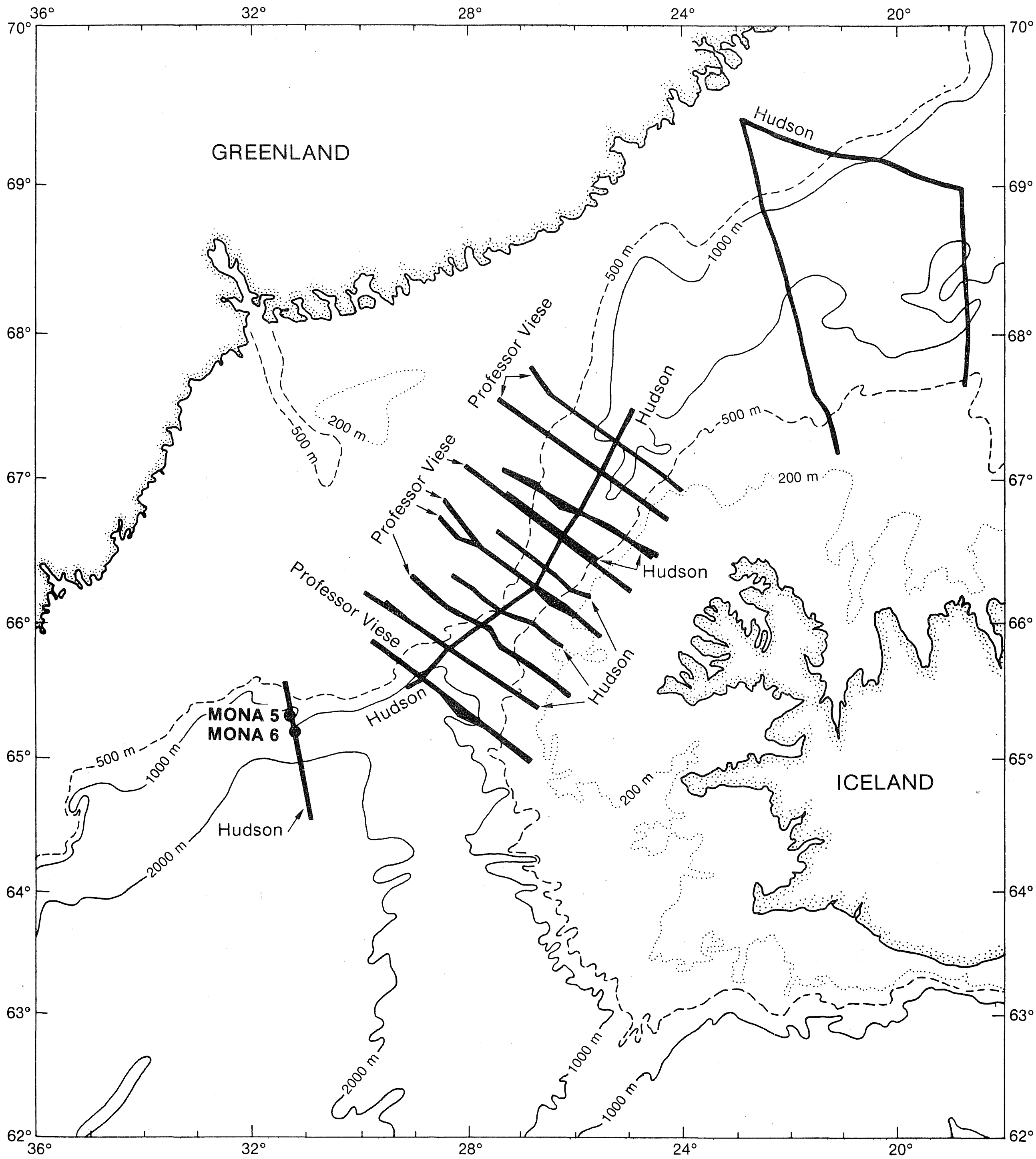

Fig. 1. Locations of "Overflow '73" hydrographic sections in Denmark Strait (from Müller *et al*., 1979), and the two long-term monitoring stations (MONA 5 and MONA 6).

different water masses over a period of 8–9 days. There was a concentration of "overflow" water on the western side of Denmark Strait. On the basis of observations by the Icelandic research vessel *Bjarni Saemundsson* during August 1971, Stein (1974) indicated that there is intense mixing of Northeast Atlantic, Polar and Arctic water masses, which varies in space and time. The current measurements indicated peak values of about 120 cm/sec in the 225° direction, representing the outflow of Greenland Sea water through Denmark Strait. In the near-bottom layer, the recorded flow was parallel to the isobaths at speeds of 50–60 cm/sec. The current measurements revealed large variation in mean flow and a 2-day periodicity. These fluctuations are coupled to atmospheric pressure changes.

The international "Overflow '73 Expedition" to the Greenland-Scotland Ridge in August-September 1973 stimulated the publication of many papers in succeeding years, some of which will be noted later. In the light of large variations in the current and density fields during this expedition, the International Council for Exploration of the Sea (ICES) launched a project called Monitoring the Overflow into the North Atlantic (MONA). Eleven long-term recording instruments were moored in the Greenland-Scotland Ridge area, two of them (MONA 5 and MONA 6) on the East Greenland slope. These near-bottom moorings provided annual data over the 1975–78 period.

Research vessels of the Federal Republic of Germany have conducted groundfish surveys off East Greenland annually since 1981. During the course of these surveys, oceanographic data were obtained at stations on standard sections from Dohrn Bank to Discord Bank (Stein, MS 1982). During the 1984 oceanographic cruise of *Walther Herwig* to East Greenland and West Greenland, the variability of water masses on Dohrn Bank was mapped by using a 10-nautical-mile station grid (see below).

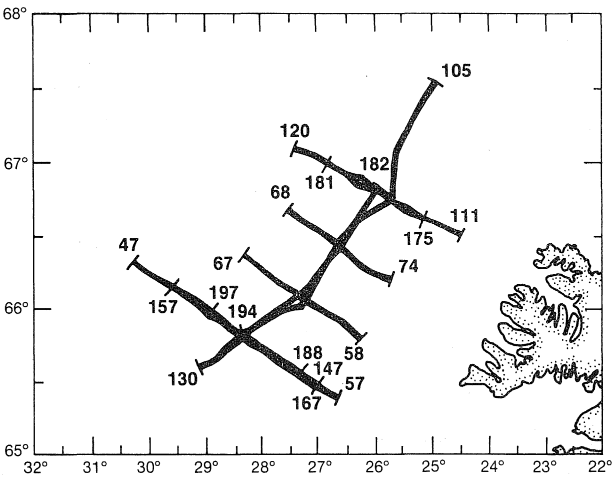

Fig. 2. Locations of hydrographic sections in Denmark Strait occupied by the research vessel *Hudson* on 24–25 August 1973 (stations 46–52 and 54–57) and on 8–9 September 1973 (stations 157–167) (extracted from Müller *et al.*, 1979), including other sections occupied during the survey.

This overview of historical activities with regard to hydrographic conditions in the Greenland-Iceland area is by no means a complete one. However, it indicates that intensive research has been conducted in the area for more than 100 years.

Water Masses on Greenland-Iceland Ridge

Müller *et al.* (1979) have provided a rather comprehensive report on the distribution of water masses in Denmark Strait, based on data from the ICES "Overflow '73 Expedition" (Fig. 1). They arrived at the following conclusions:

"Looking first at the Atlantic components, one finds two deep waters. Irminger Sea water (IS) (~4° C, ~34.97 ‰) is observed in a thick layer below Labrador Sea water (LS) (~3.8° C, ~34.88 ‰) and North Atlantic water (NA) (≥7° C, ≥35.10 ‰). IS, LS and NA

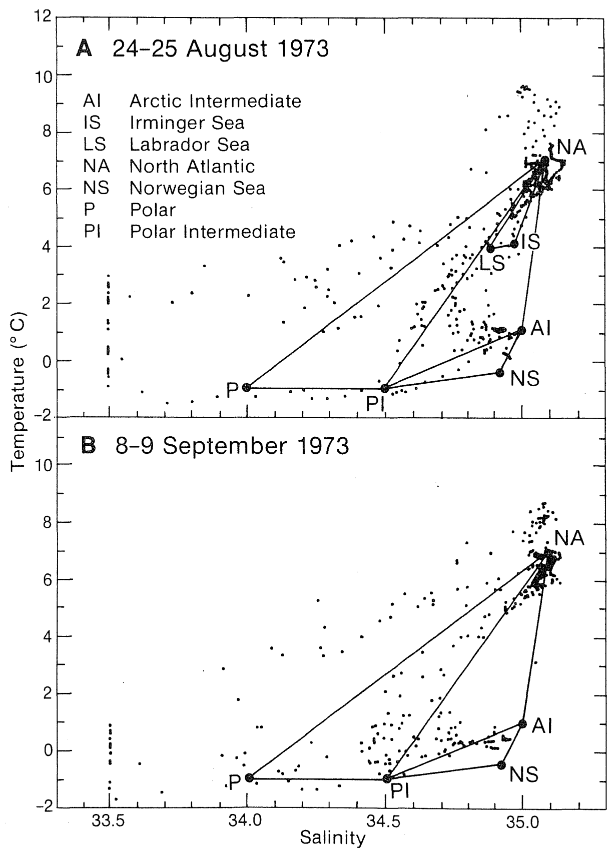

Fig. 3. Temperature-salinity diagrams of observations in Denmark Strait, (**A**) at stations 46–52 and 54–57 on 24–25 August, and (**B**) at stations 157–167 on 8–9 September 1973 (from Müller *et al.*, 1979).

proceed towards the sill of the ridge northwards on the Icelandic side, but IS and LS seem not to cross the sill whereas NA contributes nearly completely to the northerly flow. Note that NA in this region is less warm and saline than further southeast.

"There are four water masses flowing southwards across the ridge. At the surface on the Greenland side, it is the East Greenland Current with very low saline Polar water with admixtures of low saline Greenland Shelf waters. In the uppermost meters, this water is summer heated. Since the analysis is mainly concerned with the deep overflow, a definition close to one of Stefansson (1962) for Polar water (P) has been used (≤1.0° C, ≤34.00 ‰).

"The most dense water is the Norwegian Sea deep water (NS) (≤0.5° C, ~34.92 ‰) which fills the basin north of the sill and is also observed at most stations south of the sill.

"Two intermediate water masses contribute also to the overflow. Arctic Intermediate water (AI) (~1° C, ~35.00 ‰) is formed by cooling of Atlantic water and

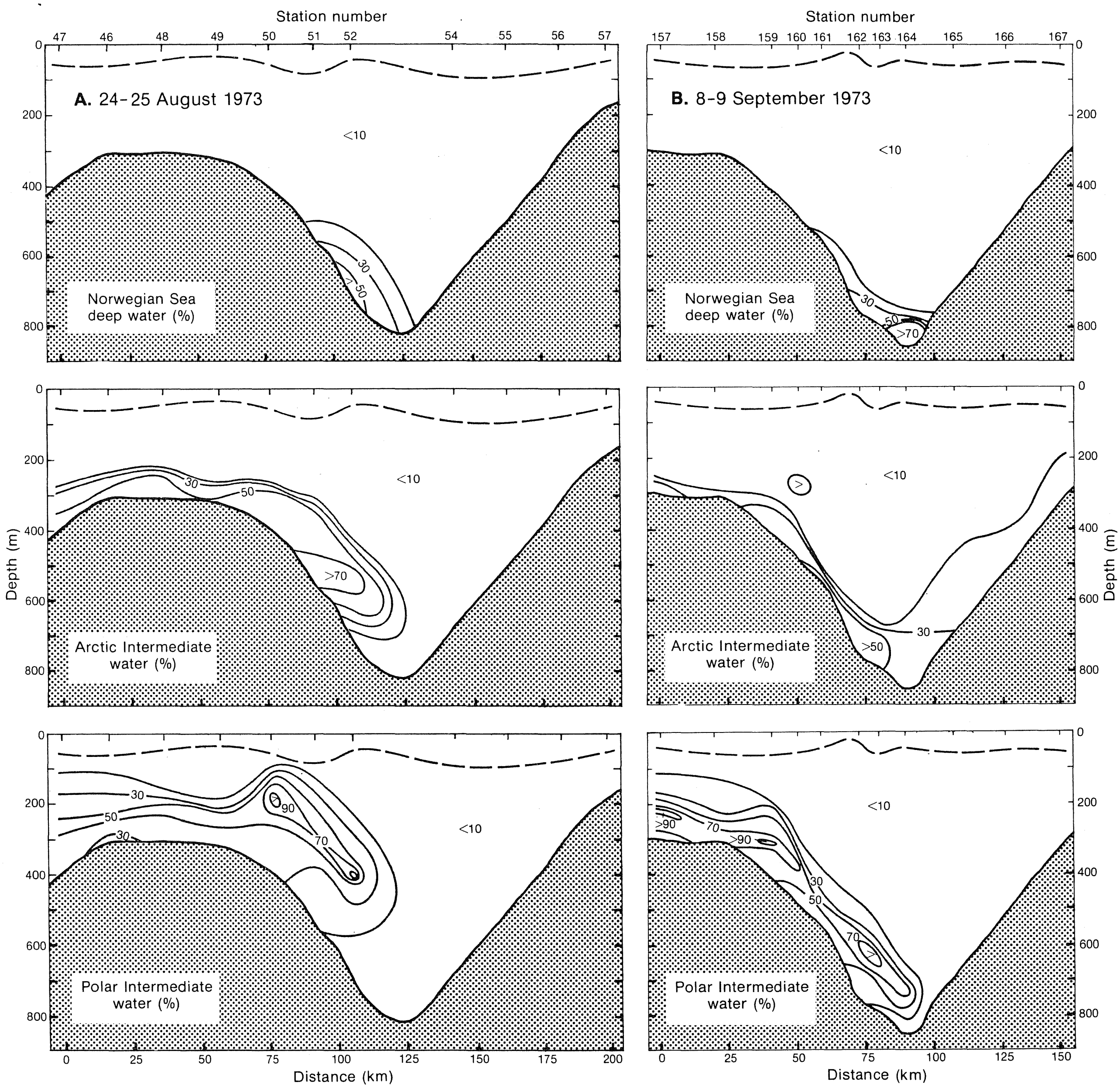

Fig. 4. Water mass distributions in Denmark Strait, (**A**) at stations 46-52 and 54-57 on 24-25 August, and (**B**) at stations 157-167 on 8-9 September 1973 (adapted from Müller *et al.*, 1979).

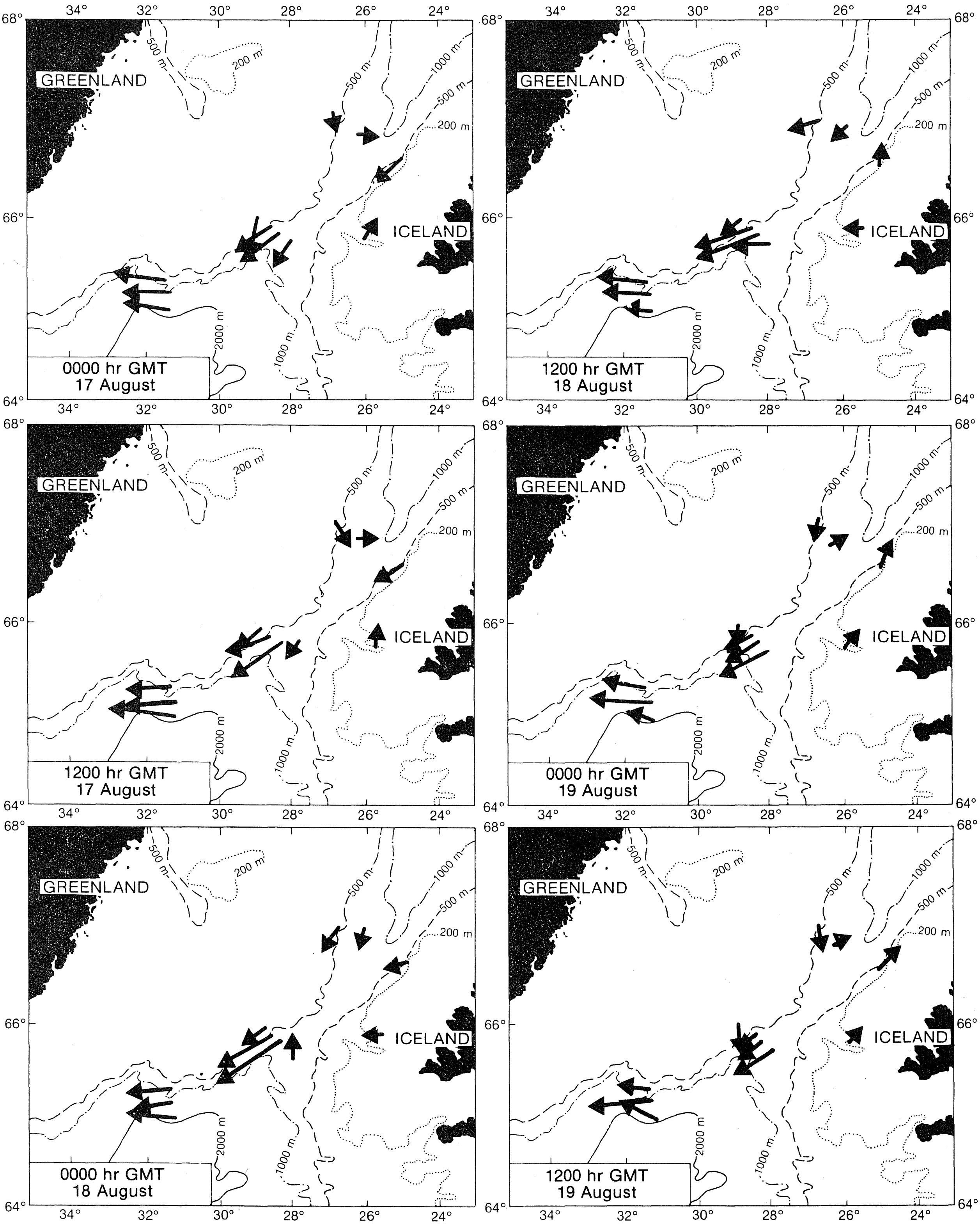

Fig. 5. Mean near-bottom current vectors from observations at 0000 hr and 1200 hr GMT on 17–19 August 1973 in Denmark Strait (from Ross and Meincke, 1979).

mixing with Polar water and bottom water far north of Iceland (Stefansson, 1962) and probably originates from the Spitzbergen Atlantic Current (Helland-Hansen and Nansen, 1909). Its high salinity supports this idea, since it cannot be formed by mixing of NA from the western part (7° C, 35.10 ‰) with NS, and the waters of the Spitzbergen Atlantic Current originally comes from the more saline inflow from the Northeast Atlantic. When reaching the sill region, AI density is very close to that of NS. Thus due to probable mixing, AI and NS cannot be distinguished far south of the sill, and NS has been taken as the only reference at these stations.

"The second intermediate water mass shows not so clear a signal in the T–S diagram but seems to be present at all stations on the Greenland side north of the ridge in about 100–200 m depth. According to Gade *et al*. (1965), this water with low temperature and salinity ($\leqslant$–1.0° C, ~34.5 ‰) is formed further north. Because of its polar constituents, Malmberg (MS 1972) called it Polar Intermediate water (PI) (<–1° C, 34.50±0.1 ‰). Far south of the ridge, it is formed on the Greenland side of the continental break in a thin and deep intermediate layer above NS, probably mixed with P."

Denmark Strait was quite well covered by hydrographic sections in August–September 1973 when the "Overflow '73 Expedition" was carried out (Fig. 1). In the map showing the sections which were occupied by the Canadian research vessel *Hudson* (Fig. 2), the two most southwesterly lines contain sections in the vicinity of Dohrn Bank (stations 31-37, 138–145, 200–203, and 47–57, 157–167, 188–197). An example of variability of water masses can be seen in the T-S diagrams of observations at stations 46–52 and 54–57 on 24–25 August and at stations 157–167 on the same line about 2 weeks later on 8–9 September 1973 (Fig. 3). A more illustrative indication of variation in Norwegian Sea deepwater, Arctic Intermediate water and Polar Intermediate water during the two periods is given in Fig. 4A and 4B. The percentage distributions clearly demonstrate the changes in individual water masses over a 2-week period both in magnitude and in horizontal and vertical extensions.

Currents in Denmark Strait

The near-bottom current vectors, which were observed in Denmark Strait during the "Overflow '73 Expedition", were published by Ross and Meincke (1979). Centered at 0000 hr and 1200 hr GMT, the mean near-bottom current vectors were illustrated for the period from 11 August to 19 September 1973. Those for 17–19 August 1973 are shown in Fig. 5. A common feature of all records is the swift flow (at times exceeding 100 cm/sec) parallel to the isobaths on the western side of the Strait and the slow motion, which varies considerably in direction, on the Icelandic shelf and north of the sill.

Vertical current and temperature profiles were measured on Dohrn Bank in August 1971. An example of vertical current shear is given in Fig. 6 (Stein, 1974). It indicates a flow to the west in the upper 100 m, whereas, in the deeper parts of the water column, the current direction gradually turns toward the southwest, which reflects steering of the bottom topography. Time series of a moored current-meter array on Dohrn Bank (Fig. 7) revealed a periodicity in the range of 30–40 hr (Stein, 1974).

Hourly means of current vectors at depths of 156, 338 and 389 m on Dohrn Bank were combined to form progressive vector diagrams (Fig. 8). The same technique was applied to 3-hourly means of wind vectors at two locations in Iceland. Both parameters (wind and current) show similar phenomena during the period of observation. The dominating mean current flows to the west (156 m), west-southwest (389 m) and southwest (338 m) are superimposed at their respective depths by a rotating motion with a period of 1–2 days. During 24–26 August, the influence of the rotary motion had diminished and the trajectories followed the mean current. At the end of the observation period, the rotary motion became dominant again, as seen clearly at the

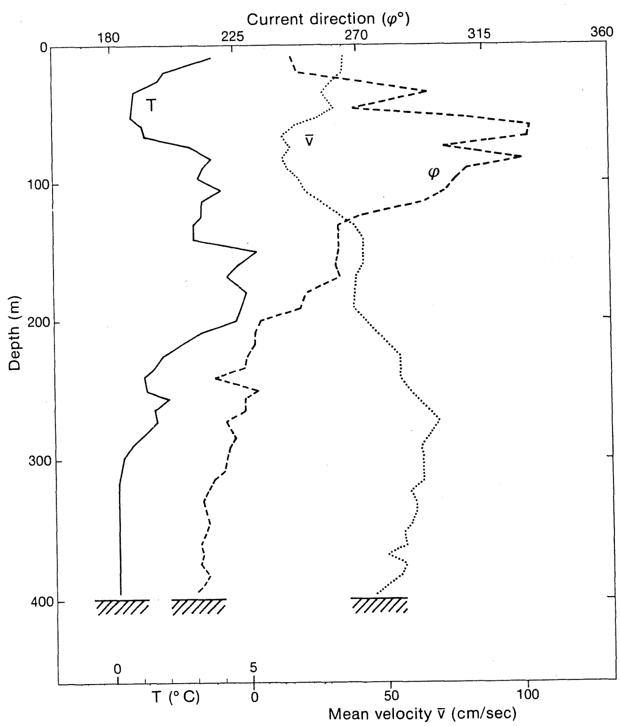

Fig. 6. Vertical current shear on Dohrn Bank during August 1971 (from Stein, 1974).

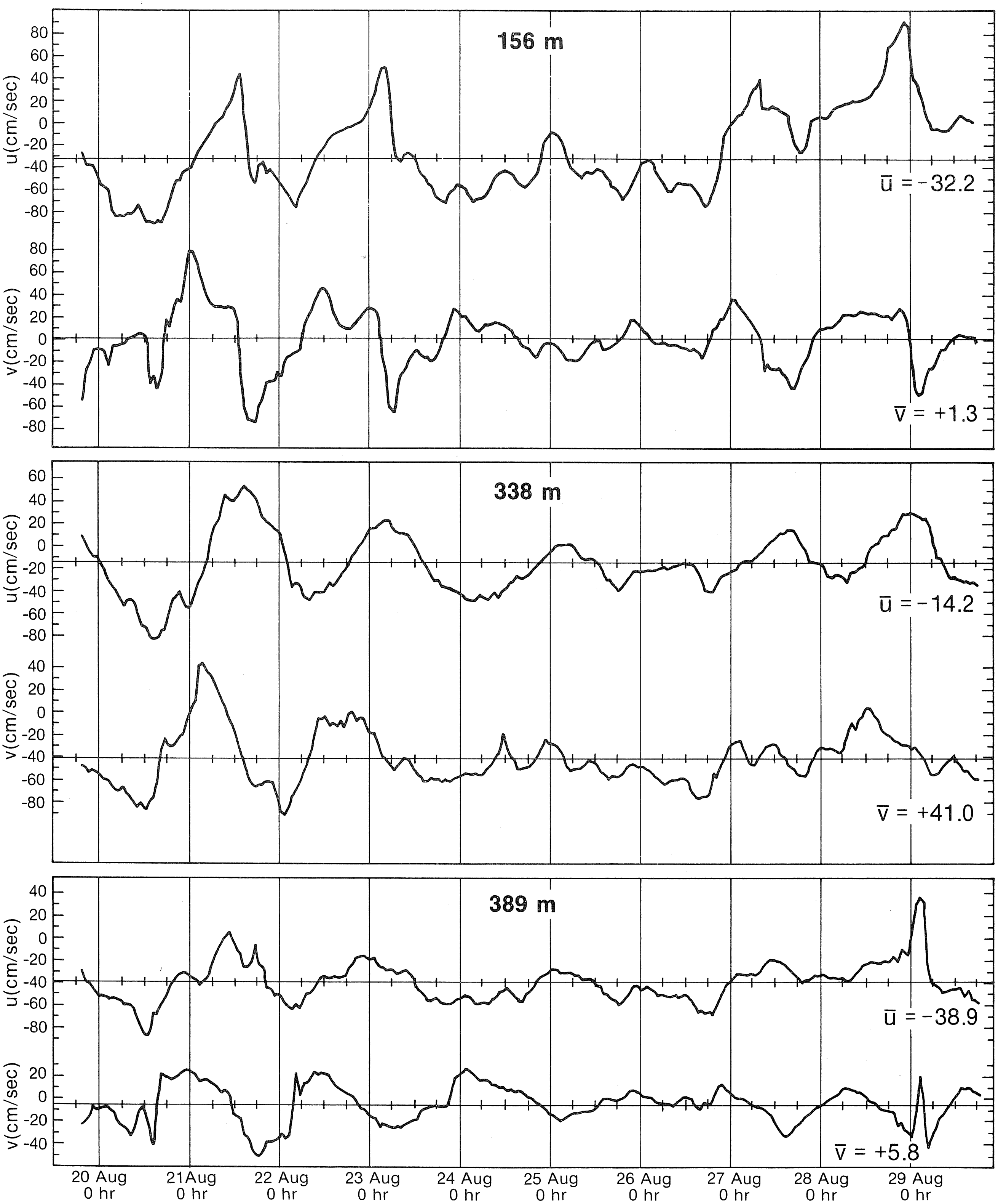

Fig. 7. Variation in current speeds at three depths from moored meters on Dohrn Bank during 19-29 August 1971 (from Stein, 1974).

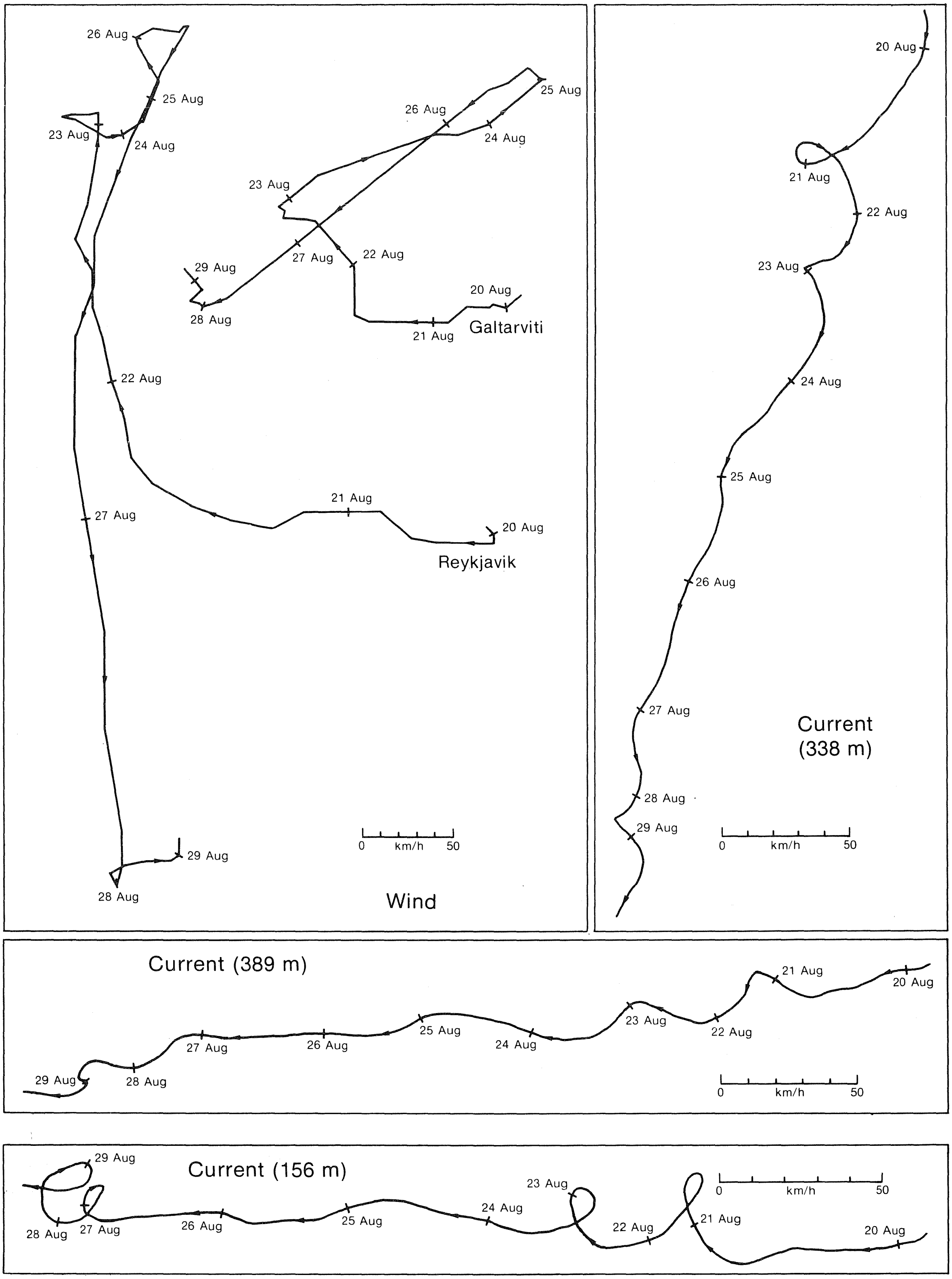

Fig. 8. Progressive vector diagrams of current measurements at three depths on Dohrn Bank and of wind observations at two sites in Iceland, August 1971 (from Stein, 1974).

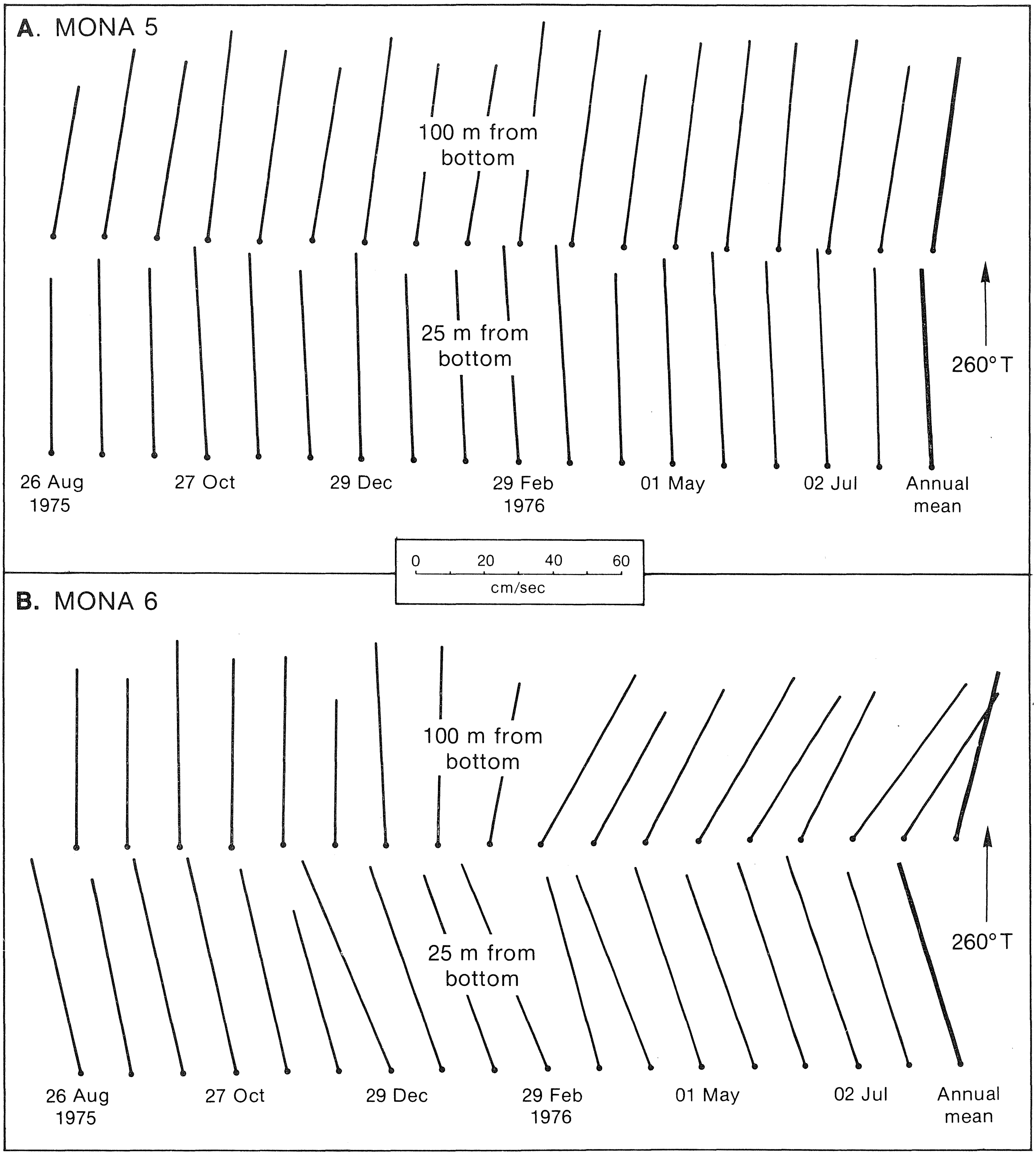

Fig. 9. Mean current vectors for 3-week periods from August 1975 to July 1976 and annual means, at (**A**) MONA 5 and (**B**) MONA 6 (adapted from Aagaard and Malmberg, 1978).

156 m depth. The wind trajectories behaved in the same manner (Fig. 8), the periodicity of the changes being also 1-2 days. Thus, the analysed current motion may be explained as follows: "The barotropic motion represents an oscillation due to external forces, i.e. air pressure gradient or the resulting wind. The excitation occurs at the beginning as well as at the end of the observation period, with a fading over 3 days (24-26 August). The agreement in the significant period range from the present limited material implies the existence of a coupling of periodic air pressure variations with those of the currents."

Results from MONA 5 and 6 (Fig. 1, Fig. 9) were reported by Aagaard and Malmberg (MS 1978). Downstream from the sill, the Denmark Strait overflow is composed of a strong mean flow of about 1 knot (0.5 m/sec), upon which are superimposed various low-frequency variations. The mean flow is directed nearly along the isobaths. Mean current vectors by 3-week periods at 100 and 25 m above the bottom are shown in Fig. 9A and 9B for MONA 5 and MONA 6 respectively. Whereas the current flow at MONA 5 was rather stable throughout the year, the two meters at MONA 6 revealed pronounced differences in current directions.

Thermohaline Variability on Dohrn Bank

During the oceanographic survey in October-November 1984 by the *Walther Herwig*, an attempt was made to map the variability of the temperature and salinity fields on a small grid of stations which were spaced 10 nautical miles apart on Dohrn Bank (Fig. 10), termed the "Dohrn-Bank Box". Due to severe weather conditions, only 24 of 35 stations on the grid could be sampled during 17-19 October 1984 (Fig. 11A). Nearly a month later during 13-15 November 1984, sampling was repeated at the same stations (Fig. 11B). The results indicate that mixing processes play an important role in this area of Denmark Strait. Cold bands of the East Greenland Current alternate with warm bands of the Irminger Current. These bands have horizontal extensions of less than 20 nautical miles (Fig. 11). Due to bottom topography south of Dohrn Bank, the warm water of the Irminger Current flows along the Greenlandic continental slope and into the deep Kangerdlugsuak Fjord (Fig. 10). The repetition of measurements in November indicates that a considerable shift of water masses has taken place. Areas which were covered in October by water of the East Greenland Current were now under the regime of the Irminger Current.

The vertical distributions of temperature, contoured at 0.5° C intervals, within the "Dohrn-Bank Box" (Fig. 12) indicate rather complex pictures of the thermal field in October-November 1984. Temperatures above 6° C indicate the domain of North Atlantic water of the Irminger Current, near-surface temperatures

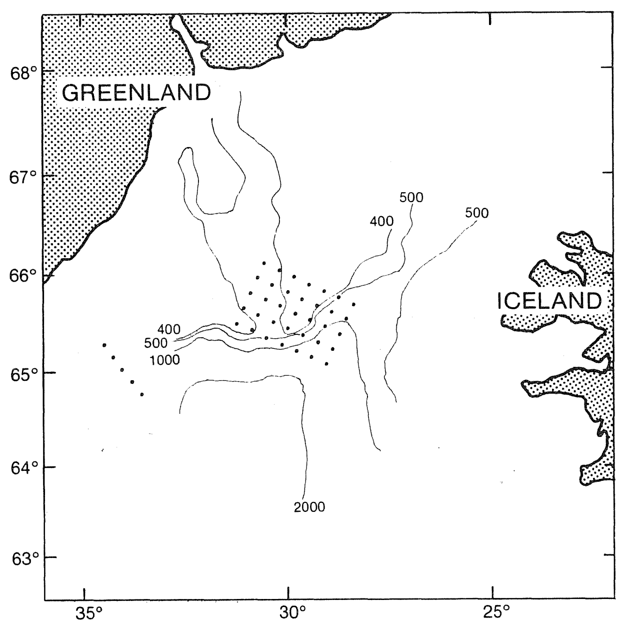

Fig. 10. Location of the "Dohrn-Bank Box" of hydrographic stations, October-November 1984.

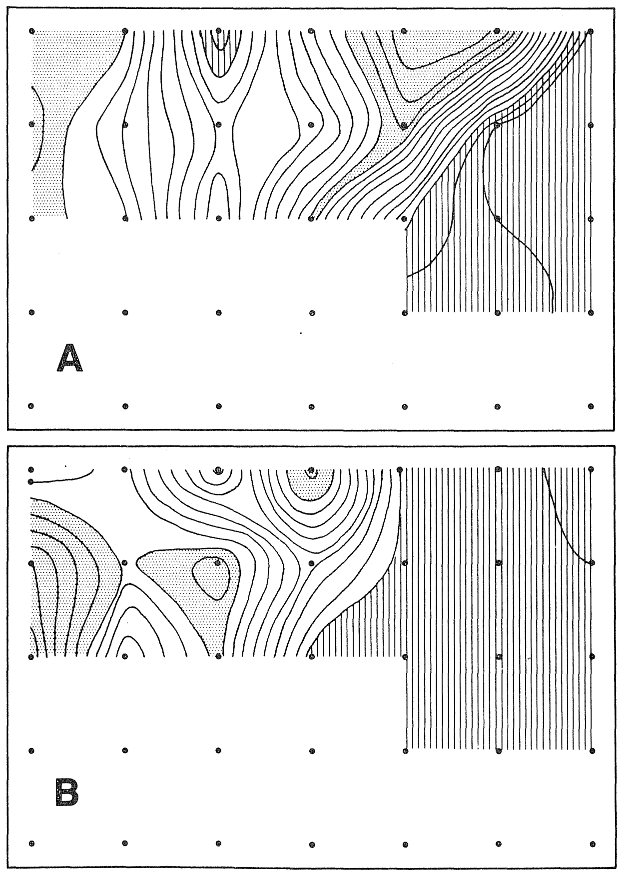

Fig. 11. Sea-surface temperatures in the "Dohrn-Bank Box" during (**A**) 17-19 October and (**B**) 13-15 November 1984.

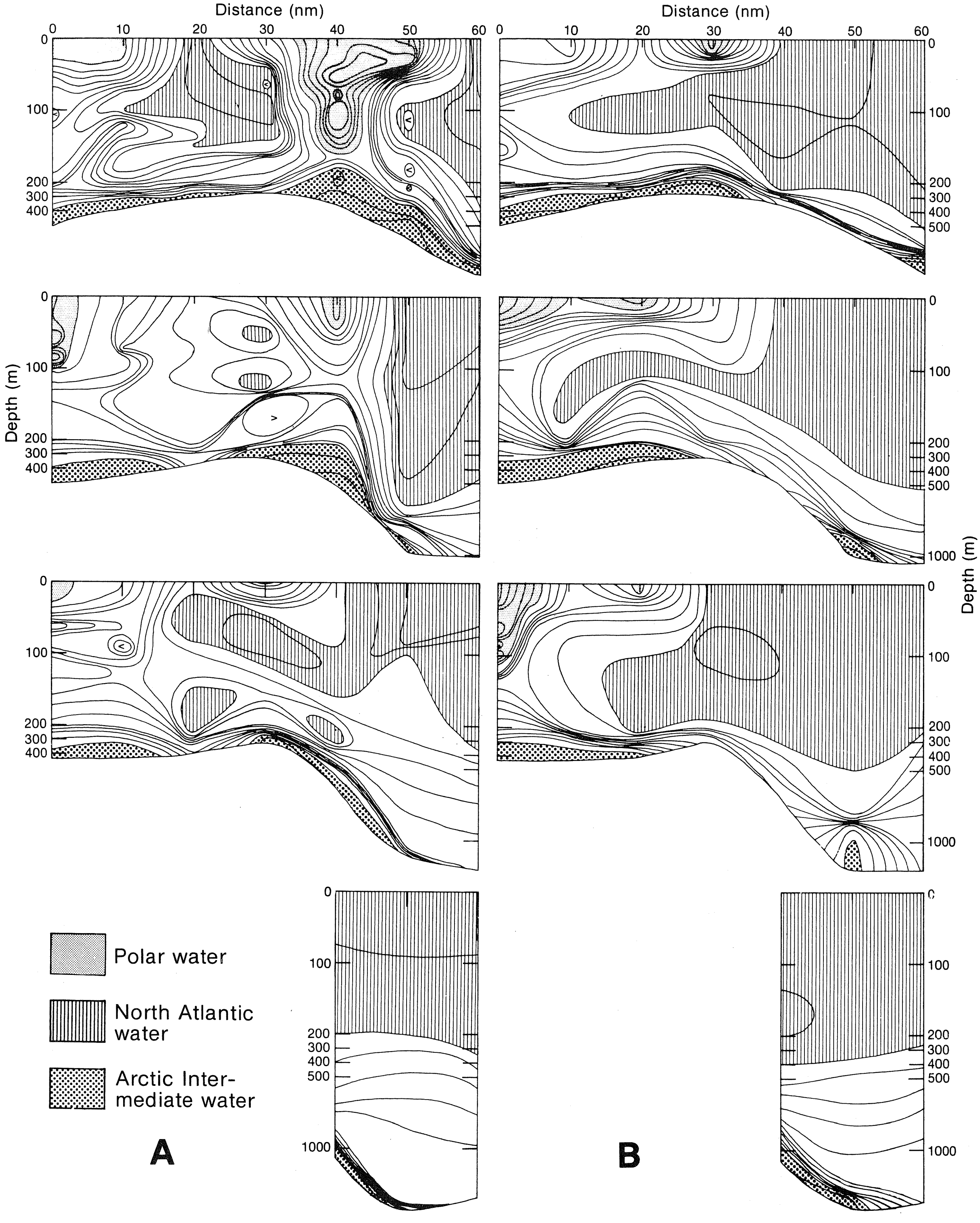

Fig. 12. Vertical distribution of temperature on west-to-east sections of the "Dohrn-Bank Box" during (**A**) 17–19 October and (**B**) 13–15 November 1984.

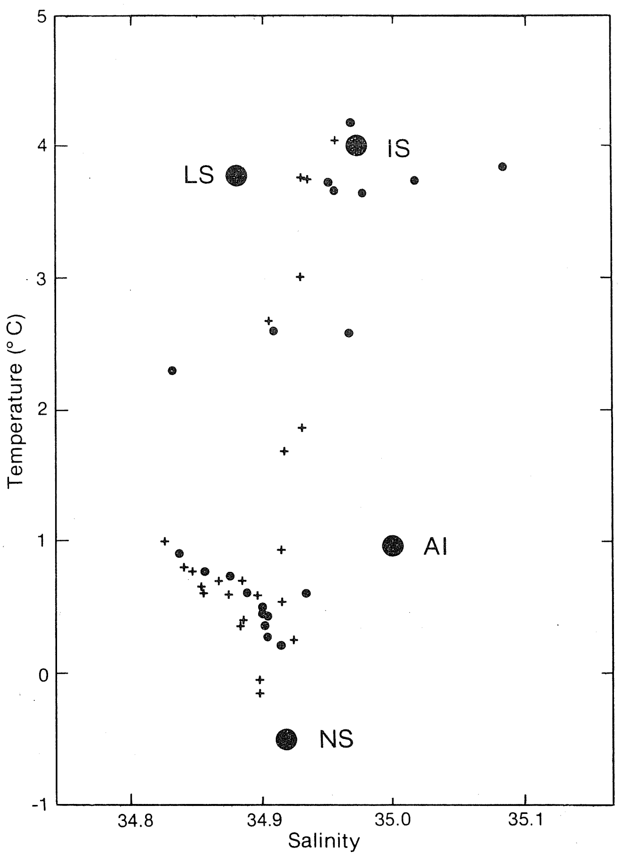

Fig. 13. Temperature-salinity diagram of bottom water in the "Dohrn-Bank Box" during October (+) and November 1984 (•). (Labrador Sea water, LS, T~3.8° C, S~34.88; Irminger Sea water, IS, T~4° C, S~34.97; Arctic Intermediate water, AI, T~1° C, S~35.00; Norwegian Sea deep water, NS, T~ −0.5° C, S~34.92.)

less than 2° C represent polar water of the East Greenland Current, and the cold bottom layer is composed of Arctic Intermediate water (T~1° C, S~35.00) and Norwegian Sea deep water (T⩽−0.5° C, S~34.92).

Comparison of the vertical distributions for mid-October and mid-November indicated a cooling of about 0.5° C within the core of the Irminger Current. Whereas the October observations indicated characteristics of North Atlantic water (T⩾7° C, S⩾35.10), temperatures in November did not exceed 7° C. Also, there was some variation in the vertical extension of this water mass, but it was not as large as in the horizontal field. During October, parcels of North Atlantic water were found in the central part of the sections (Fig. 12A), whereas the November measurements indicated tongues of North Atlantic water stretching below the near-surface extension of mixed polar water of the East Greenland Current (Fig. 12B). Variability in the near-bottom water is apparent in all sections. In one case, northeast corner of the grid in October, subzero temperatures were found but salinity ranged from 34.83 to 35.09 psu. This indicates the mixing of different water masses in the near bottom layers.

In the temperature-salinity diagram of bottom water in the "Dohrn-Bank Box" (Fig. 13), most of the points are grouped in the vicinity of Arctic Intermediate water and Norwegian Sea deep water, whereas the waters underlying the warm Irminger Current are characteristized by T-S values in the vicinity of Labrador Sea water and Irminger Sea water. Twice as many T-S values were located near the warm water region (LS, IS) in November than in October. This reflects the great variability of bottom water masses in the Dohrn Bank area. However, at stations where bottom water temperatures were low (T⩽1° C), there was less variability than in the warmer water. The observations in November were less variable than those in October.

Distribution of Ice

Weekly ice charts, based on satellite observations, are prepared and distributed by the Joint Ice Center of the US Navy and National Oceanic and Atmospheric Administration (NOAA). Observations for the Greenland and eastern Canada region from 2 October 1984 to 26 March 1985 are shown in Fig. 14. During the entire autumn-winter period, Dohrn Bank was ice free. Only the northern parts of Denmark Strait were covered by ice in December and January.

In a study on the interrelationships between ice drift, atmospheric circulation and fishing activity off southeastern Greenland, Meyer (1964) concluded that ice movement is affected greatly by wind. Westerly winds drive the ice seaward, often beyond the edge of the continental shelf, whereas winds from the north to east squeeze the ice against the coast, making the offshore banks free of ice. About 24 hr after the wind changes to westerly, ice reappears on the banks and fishing is disrupted. Westerly winds are caused mostly by "lows" moving toward Denmark Strait. Ice conditions are severe in years with a northward shift of the Atlantic Low but are quite light in years with a strongly developed Greenland High and a southward shift of the Low.

Some information on ice drift through Denmark Strait has been obtained from tracking the movement of pack ice, which was monitored with a radio beacon (Fig. 15). The ice-float passed southward through the middle of Denmark Strait and along the southeast coast of Greenland. After passing Cape Farewell, it began to move northwestward, but it subsequently made an anticlockwise loop south of Cape Farewell and then vanished.

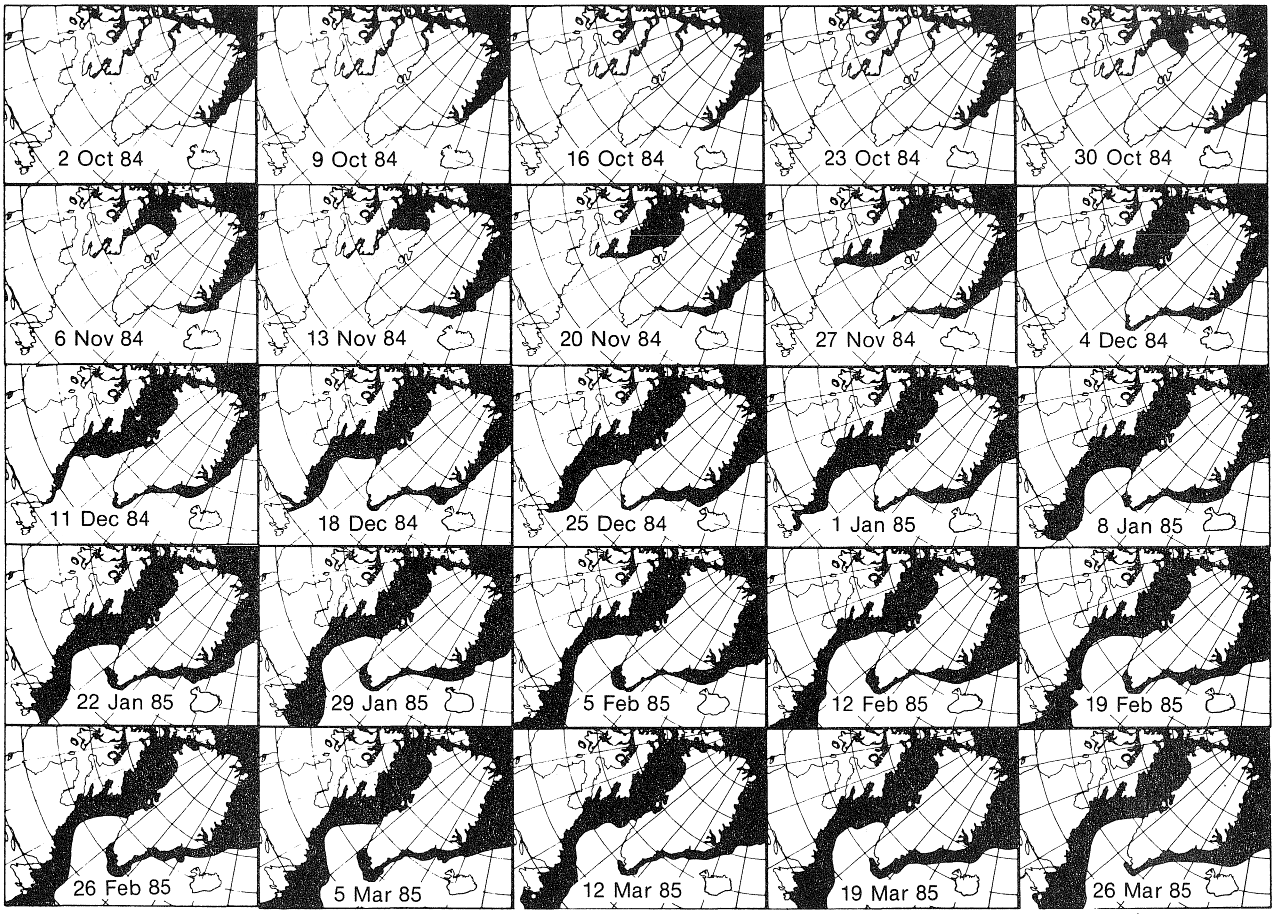

Fig. 14. Ice cover (black) in Canadian and Greenland waters, October 1984 to March 1985.

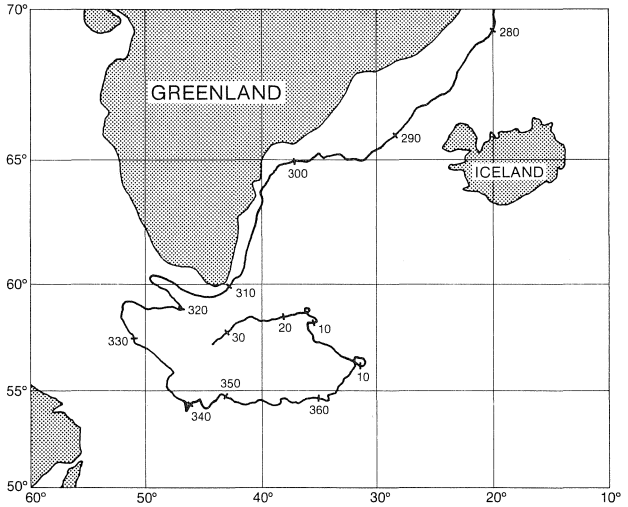

Fig. 15. Monitored track of an ice float from October 1984 (day 280) to February 1985 (day 35). (Courtesy of A. Clarke, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada.)

Conclusions

Historical data and recent observations in Denmark Strait reveal a picture of an ocean region that is governed by processes which extend from the atmosphere to the cryosphere. Large-scale observations (i.e. Overflow '73 Expedition) indicate the nature of overflow events which lead to injections of cold polar bottom water from north of Denmark Strait into the North Atlantic Ocean. Current meter records from the Dohrn Bank area show the time-scale of atmosphere-induced variations in the ocean, as well as the order of magnitude of current shear in the water column. From current meter moorings near bottom for a year (MONA Project), mean conditions and overflow events are shown. Variability on the small-scale elucidates the width of polar and subtropical current bands which meet and mix in the area of Dohrn Bank. The sum of all dynamic and thermohaline processes in the area forms the highly variable environment of the northern shrimp (*Pandalus borealis*) stock in Denmark Strait.

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