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On the Variability of Water Masses, Currents and Ice in Denmark Strait

by

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Narrative

During the January 1985 Scientific Council Meeting of NAFO it was noted that the shrimp (Pandalus borealis) stock in Denmark Strait may be living under extreme and unstable environmental conditions. It was recommended that a study on environmental conditions be undertaken, including ice and currents in the area (NAFO, 1985). On the occasion of next years meeting STACFIS expressed its concern, that still few data were available on the environmental conditions and therefore reiterated the recommendation that a study on environmental conditions be undertaken (NAFO, 1986). To meet the demands of the assessment group of shrimp in Denmark Strait, the present paper, as a first approach intends to compile an overview of environmentally - related work in Denmark Strait, as well as to display some recent results of cruises performed by the Federal Republic of Germany in Denmark Strait. Special emphasis is given to the variability of water masses on Dohrn Bank.

Historic Data

From the area of Denmark Strait numerous publications are available which deal with the hydrographic conditions of the area. First published results originate from the Danish admiral Irminger (1854, 1861). His investigations delt with the surface currents between Iceland and Greenland. He concluded that warm Atlantic Water flows west off Iceland to the north, later-on called the Irminger Current. Irminger 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 1879 by Mourier (1880). During the Swedish "Sofia" expedition of E. v. Nordenskiöld, Hamberg (1884) found that the cold East Greenland Current between Denmark Strait and Cape Farewell is very shallow. Below the cold water he revealed warm Atlantic Water. Knudsen (1899) reported the overflow of Arctic Water across the sill sinking south of the Greenland - Iceland Ridge to greater depths. The existence of different water masses in

Denmark Strait was shown during the "Øst" expedition in summer 1929. According to Braarud and Ruud (1932) three water masses of different origion meet and mix in this area: East Greenland Water, Atlantic Water and Arctic Deep Water. A thorough investigation of the East Greenland Current during the "Dana" summer expeditions 1931, 1932 and 1933 revealed the boarder line 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) points at turbulent mixing at the oceanic Polar Front leading to meso- and small-scale 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 Ocean. The IcelandicNorwegian expedition to the area between Iceland and Greenland during 1963 yielded detailed results on the distribution of water masses, temperature and salinity, as well as the distribution of currents, measured by moored devices at four mooring sites (Gade et al. 1965). Worthington (1969), after having recovered 10 current meters out of 30 moored instruments, got results from only one current meter in the mid of Denmark Strait at a depth of 760 m. He measured maximum current speeds of 143 cm/sec. Mann (1969) found a large variability in the composition of the overflowing Bottom Water, both in the horizontal and vertical magnitude. Malmberg (1972) and Stein (1972) indicated considerable change in distribution of different water masses in a period of only 8 to 9 days. A concentration of the "Overflow" water on the western side of Denmark Strait was found. Based on observations carried out by the Icelandic "Bjarni Saemundsson" during August 1971 Stein (1974) revealed intense mixing of Northeastatlantic, Polar and Arctic water masses, which varies in space and time. The current measurements indicated peak values of 120 cm/sec into the direction of 225°representing the outflow of the Greenland Sea through Denmark Strait. In the near-bottom layer a flow was recorded being parallel to the isobaths at speeds between 50 and 60 cm/sec. The current measurements show large variations of the mean flow and in addition they reveal a two 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 a large amount of publications in the succeeding years. Some of these results will be delt with later. Based on large variations in the current - and density field during this expedition the ICES Working Group Overflow '73 launched a project called MONA (Monitoring the Overflow into the North Atlantic). Eleven long-term moorings were anchored in the Greenland-Scotland Ridge area, two of them, MONA 5 and MONA 6 on the East Greenland Slope. The near - bottom moorings recorded one entire year, covering the period 1975 to 1978.

Since 1981 the Federal Republic of Germany, during the annual groundfish survey off East Greenland, completes a set of oceanographic standard sections from Dohrn Bank to Discord Bank (Stein, 1982). During the 1984 oceanographic cruise of FRV "Walther Herwig" to East Greenland and West Greenland the variability of water masses on Dohrn Bank was mapped using a 10 nautical mile station grid (see below).

This overwiev on historic activities with regard to the hydrographic situation is, of course, no a complete one. It indicates, however, the intensive research in this area for more than 100 years.

Water Masses on Greenland - Iceland Ridge

A rather comprehensive publication on the distribution of water masses in Denmark Strait is given by Müller et al. (1979). Based on Overflow '73 data this data report displays a detailed analysis of water masses which meet and mix in the Greenland - Iceland Ridge area. Citing from this report the authors conclude as follows: "Looking first at the Atlantic components one finds two deep waters. Irminger Sea water (IS, $\sim$ 4° C, $\sim$ 34.97 ^{o}/oo) is observed in a thick layer below Labrador Sea water (LS, $\sim$ 3.8 ° C, $\sim$ 34.88 ^{o}/oo) and North Atlantic water (NA, $\gtrsim$7° C, $\gtrsim$ 35.10 ^{o}/oo). IS, LS and NA procede 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 inflow. Note that NA in this region is less warm and saline as 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 upper most meters this water is summer heated. Since the analysis is mainly concerned with the deep overflow, a definition close to the one of Stefánsson (1962) for Polar water has been used (P, $\leq$ 1.o° C, $\leq$ 34.00 ^{o}/oo).

The most dense water is the Norwegian Sea Deep water (NS, $\leq$ 0.5° C, $\sim$ 34.92 ^{o}/oo) 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, $\sim$ 1° C., $\sim$ 35.00 ^{o}/oo) is formed by cooling of Atlantic water and 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). It's high salinity supports this idea, since it cannot be formed by mixing of NA from the western part (7° C, 35.10 ^{o}/oo) with NS and the waters of the Spitzbergen Atlantic currents originally come from the more saline inflow from the North East Atlantic.

When reaching the sill region it's 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 shows not so clear a signal in the TS-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 ($\leq$ -1.0° C., $\sim$ 34.50 ^{o}/oo) is formed further north. Because of it's polar constitutents, Malmberg (1972) called it Polar Intermediate water (PI, $\leq$-1° C, 34.50 $\pm$ 0.1 ^{o}/oo). Far south of the ridge it is found on the Greenland side of the continental break in a thin and deep intermediate layer above NS, probably mixed with P."

As may be seen from fig. 1 the Denmark Strait was quite well covered by hydrographic sections during August / September 1973. Fig. 2 indicates the location of sections in the vicinity of Dohrn Bank (stations no. 31 - 37, 138 - 145, 200 - 203, and 47 - 57, 157 - 167, 188 - 197) as performed by the Canadion RV "Hudson". As an example on the variability of water masses T, S-diagrams of stations no. 46 - 52, 54 - 57, and 157 - 167 are given in fig. 3. Another, more illustrative presentation on variation of water masses NS, AI, PI is given in fig. 4 and 5. The percentage distribution clearly demonstrates the change of the individual water masses in magnitude and in their horizontal and vertical extension.

Currents in Denmark Strait

Near - bottom current vectors observed during the Overflow '73 experiment were published by Ross and Meincke (1979). Centred at 0000 GMT and 1200 GMT the mean current vectors are given from August 11, 1973 to September 19, 1973. For three successive days fig. 6 displays the near - bottom currents in Denmark Strait. A common feature of all records is the swift flow parallel to the isobaths on the western side, exceeding at times 1 m/sec, and the slow motion on the Icelandic shelf and north of the sill which varies considerably in direction.

An example of the vertical current shear is given in fig. 7 which is derived from Stein (1974). The vertical current and temperature profile was measured on Dohrn Bank. 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 to southwest which reflects steering of the bottom topography. Time series of a moored current meter array on Dohrn Bank (fig. 8) reveal a periodicity in the range of 30 hours to 40 hours (Stein, 1974). These variations are consistent with high- energetic fluctuations of the atmospheric spectrum as could be shown in the same paper by comparing the progressive vector diagrams of current measurements and wind observations on Iceland (fig. 9).
Results from MONA 5 and 6 (figs. 10 - 12) are given by Aagaard and Malmberg (1978):

"Downstream from the sill, the Denmark Strait overflow is composed of a strong mean flow of about 1 knot, upon which are superimposed various low-frequency variations. The mean flow is driven from an reservoir of nearly constant density and pressure head. This flow is baroclinic and increases with depth; it is directed nearly along the isobaths. A frictional boundary layer extends at least 25 m from the bottom. Modulations of the mean flow on time scales of weeks to months are random and do not exceed about 20 %; there is, for example, no seasonal modulation. By far the largest of the low-frequency variations is a persistent signal with a time scale of 1.5 - 2.5 days and amplitude comparable to the mean flow. It probably represents a baroclinic instability. The statistics of this instability band are highly non-stationary, however. Other fluctuations include those of synoptic meteorological time scales and of tides; there is apparently no inertial signal."

Recent Observation on the Thermo-haline Variability on Dohrn Bank

It was planned to map the variability of the temperature and salinity fields on Dohrn Bank on the basis of a narrow station grid with 10 nautical miles interstation distance (fig. 13). Due to severe weather conditions only 24 of 35 stations of the small-scale grid could be sampled between October 17, 1984 and October 19, 1984 (fig. 14a). A month later, from November 13, 1984 to November 15, 1984 the same grid was repeated (fig. 14b). The results indicate that mixing processes play an important role in this area of Denmark Strait. Cold current bands of the East Greenland Current alternate with warm current bands of the Irminger Current. These bands have a horizontal extension of less than 20 nautical miles (fig. 14a,b). Due to the bottom topography the warm water of the Irminger Current flows south of the Dohrn Bank along the Greenlandic continental rise and flows into the deep Kangerdlugsuak fjord (fig. 13). The repetition of measurements elucidates that a considerable shift of water masses has taken place. Areas which were covered a month ago by the waters of the East Greenland Current were now under the regime of the Irminger Current and vice versa (fig. 14b). Figs. 15 and 16 display the vertical distribution of temperature within the "Dohrn-Bank-Box". Contoured at 0.5°C intervals the isothermes indicate a rather complex picture of the thermal field in October/November 1984 in the Dohrn Bank area. To elucidate the distribution of water masses different shadings were used. Temperatures above 6°C (vertical lines) indicate the domain of the North Atlantic Water of the Irminger Current, small dots ($t < 2$°C) represent the near surface polar water of the Eastgreenland Current, and large dots ($t < 1$°C) mark the cold bottom water layer which is composed of Arctic Intermediate water ($t \sim 1$°C, $S \sim 35.00*10^{-3}$) and of Norwegian Sea Deep water ($t \leq -0.5$°C, $S \sim 34.92*10^{-3}$).

Comparing the mid-October and mid-November survey the vertical temperature distribution yields a cooling within the core of the Irminger Current which may be estimated as 0.5°C. Whereas the October observations indicate the characteristics of the NA-water (see above), the November data do not exceed 7°C. Also the vertical extension of this water mass shows some variability which is, however, not as large as the considerable horizontal variation. During October parcels of NA-water were found in the central part of the sections, whereas the November measurements yield tongues of NA-water stretching below the mixed polar water of the near surface temperature expression of the Eastgreenland Current bands. Variability in the bottom near layer is apparent in all sections. In one case, northeast corner of the box during October, sub-zero temperatures were found. Salinity in this layer, as determined from Rosette water samples for calibration of the conductivity sensor of the CTD, ranges from $34.830*10^{-3}$ to $35.083*10^{-3}$. This indicates the presence of different water masses mixing in the near bottom layer.

T,S-Diagram of Bottom Water in "Dohrn-Bank-Box"

Fig. 17 displays the temperature/salinity data of the bottom water in "Dohrn-Bank-Box". Most of the T,S values are grouped in the vicinity of Arctic Intermediate water and Norwegian Sea Deep water, whereas those waters, underlaying the warm Irminger Current are characterized by T,S-values in the vicinity of Labrador Sea water and Irminger Sea water. As shown in fig. 17 during November, 1984 twice as much T,S-dots were found in the warm water region of the diagram (LS,IS) than during the previous month. This reflects the high variability of bottom water masses in the Dohrn Bank area. The water layer marked by large dots ($t < 1°C$) shows less variability. Here, 11 of 16 stations indicated cold, mixed bottom water conditions in November compared to October.

Distribution of Ice in Denmark Strait

Ice observations from space are shown in fig. 18. This figure is based on weekly ice charts as distributed from U.S. Navy NOAA Joint Ice Center. It shows small ice cover with regard to East Greenland waters. During the entire autumn 1984 and winter 1984/1985 season the Dohrn Bank area was ice free. Only the northern parts of Denmark Strait were covered by ice in December and January. An example of ice drift is given in fig. 19. From October 1, 1984 to March 21, 1985 a pack-ice float with ice beacon was monitored to pass Denmark Strait, the near coastal waters of East Greenland to vanish south of Cape Farewell after having tried to flow northward along the West Greenland coast.

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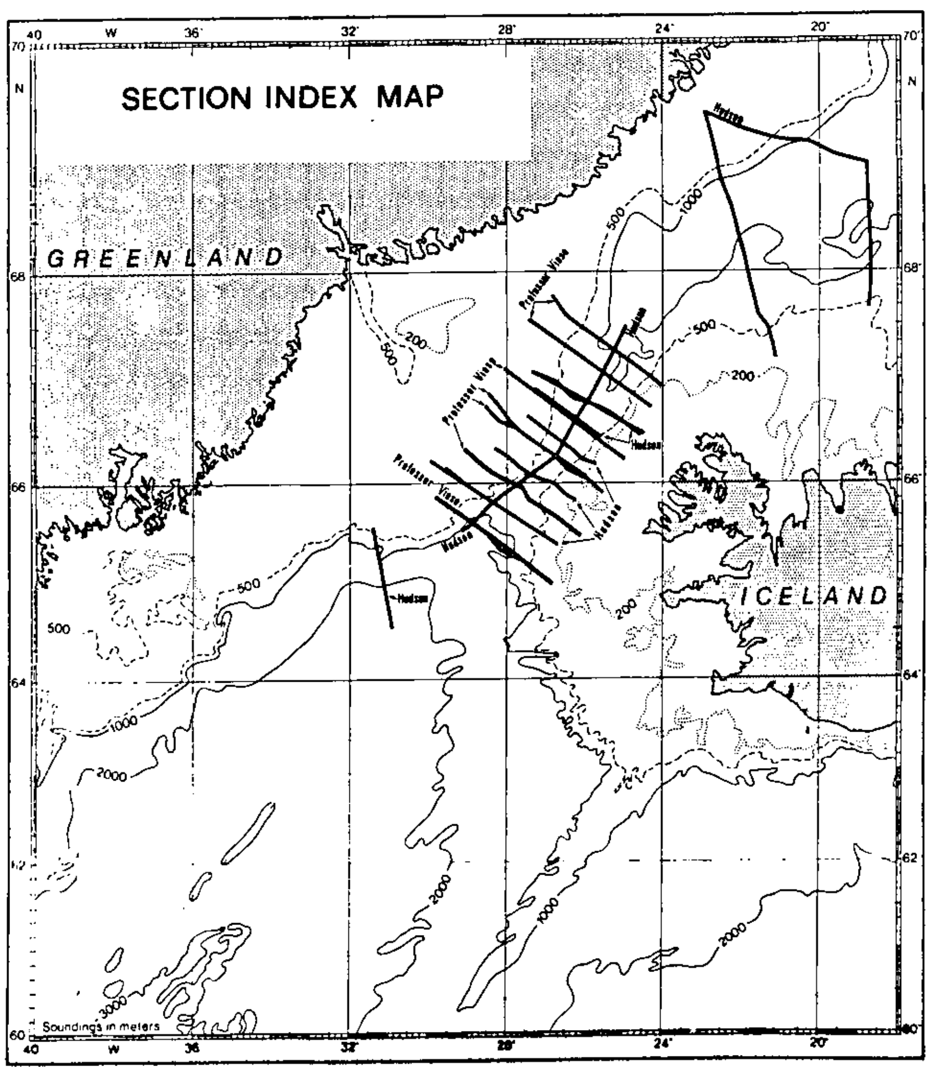


Fig. 1 Location of Overflow '73 Sections in Denmark Strait (from Müller et al., 1979)

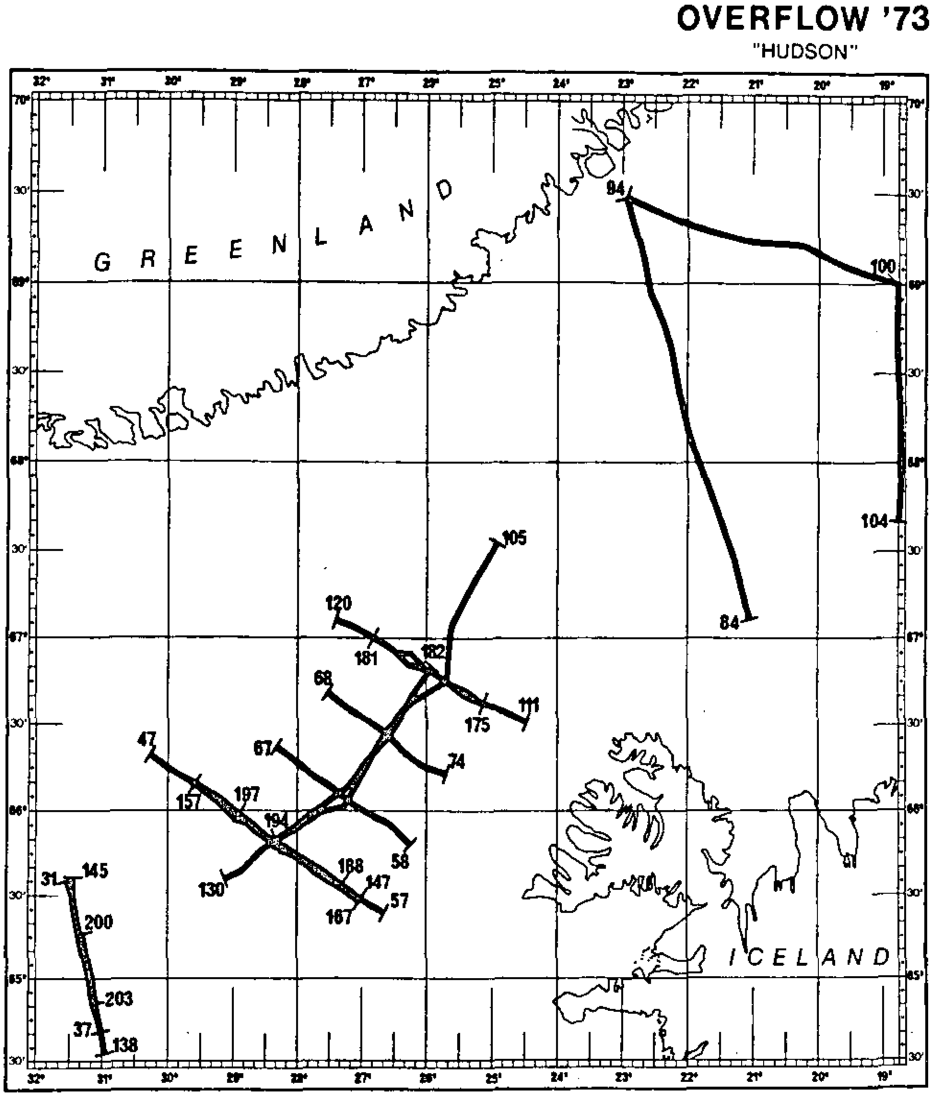
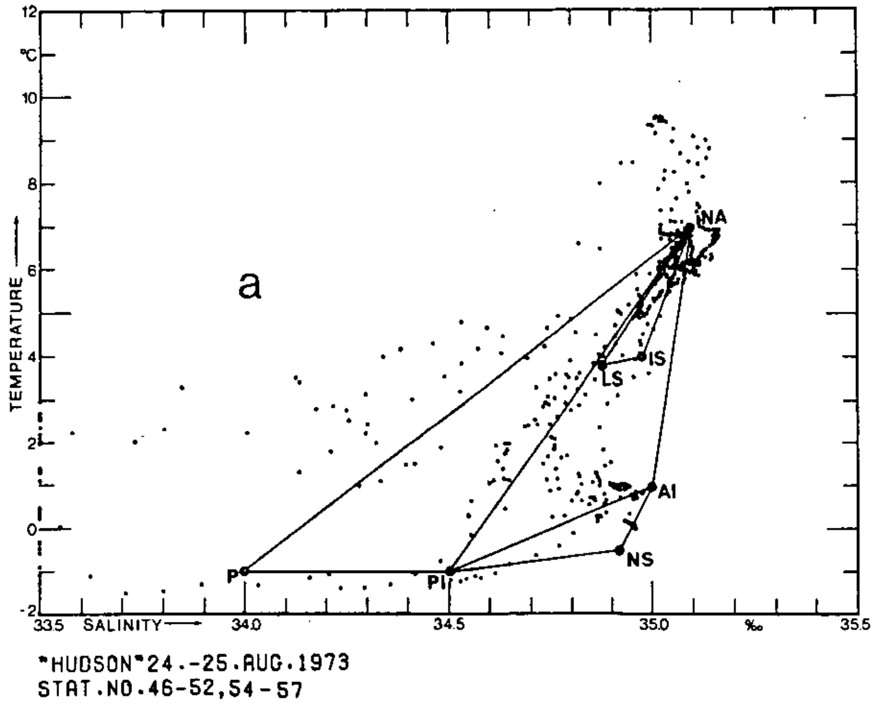


Fig. 2 Location of Overflow '73 Sections performed by RV "Hudson" in Denmark Strait (from Müller et al., 1979)



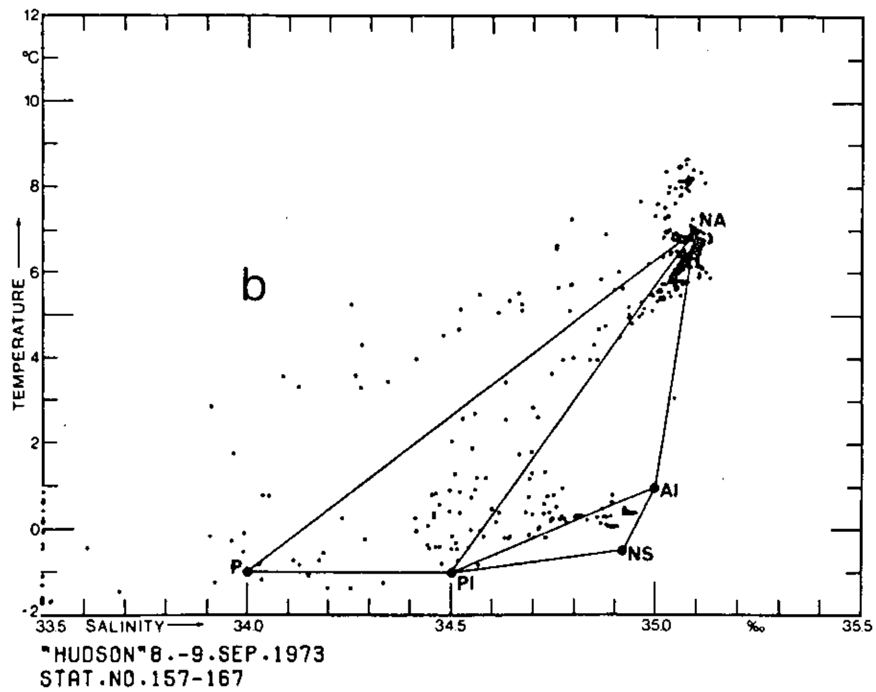


Fig. 3 Temperature/salinity diagram of stations 46-52, 54-57 (a) and 157-167 (b) (from Müller et al., 1979)

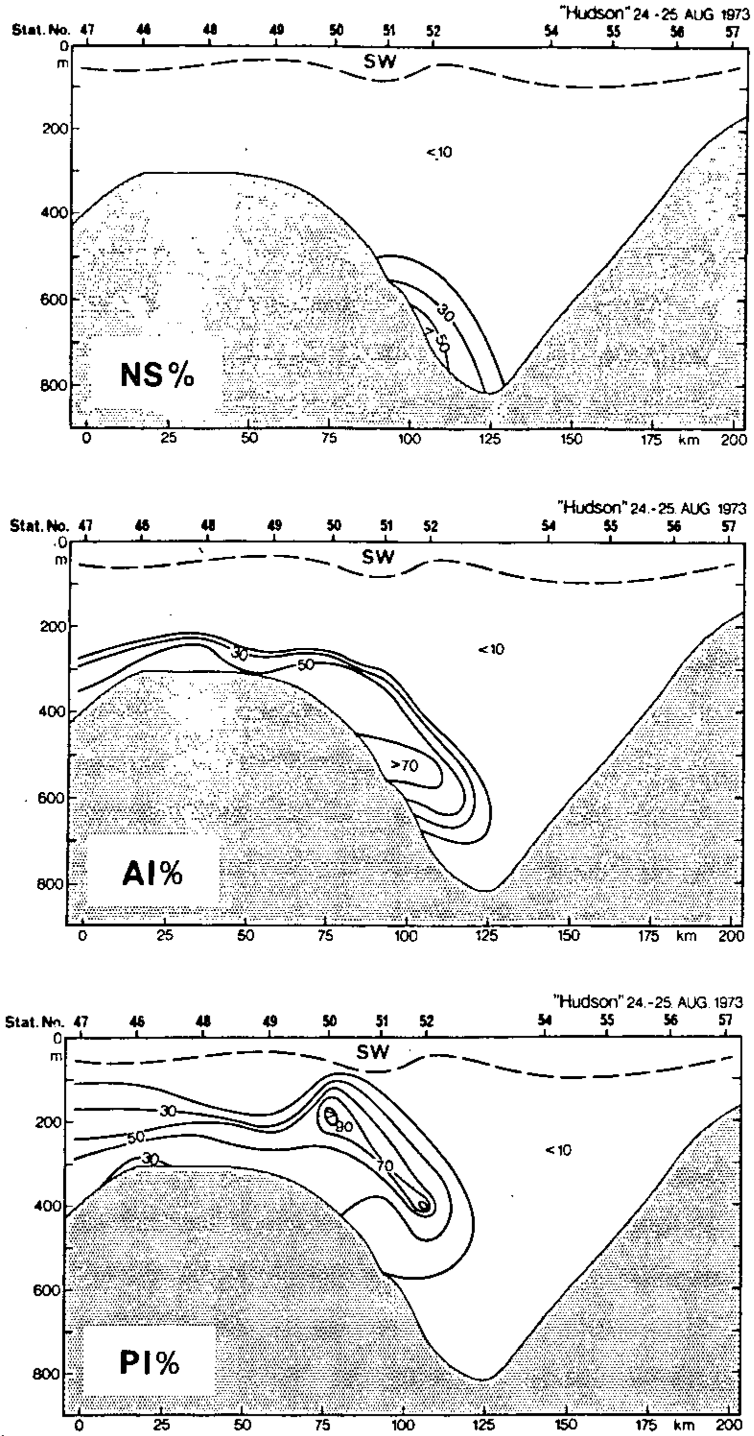


Fig. 4 Water mass distribution along section (a); for water mass definitions see text (from Müller et al., 1979)

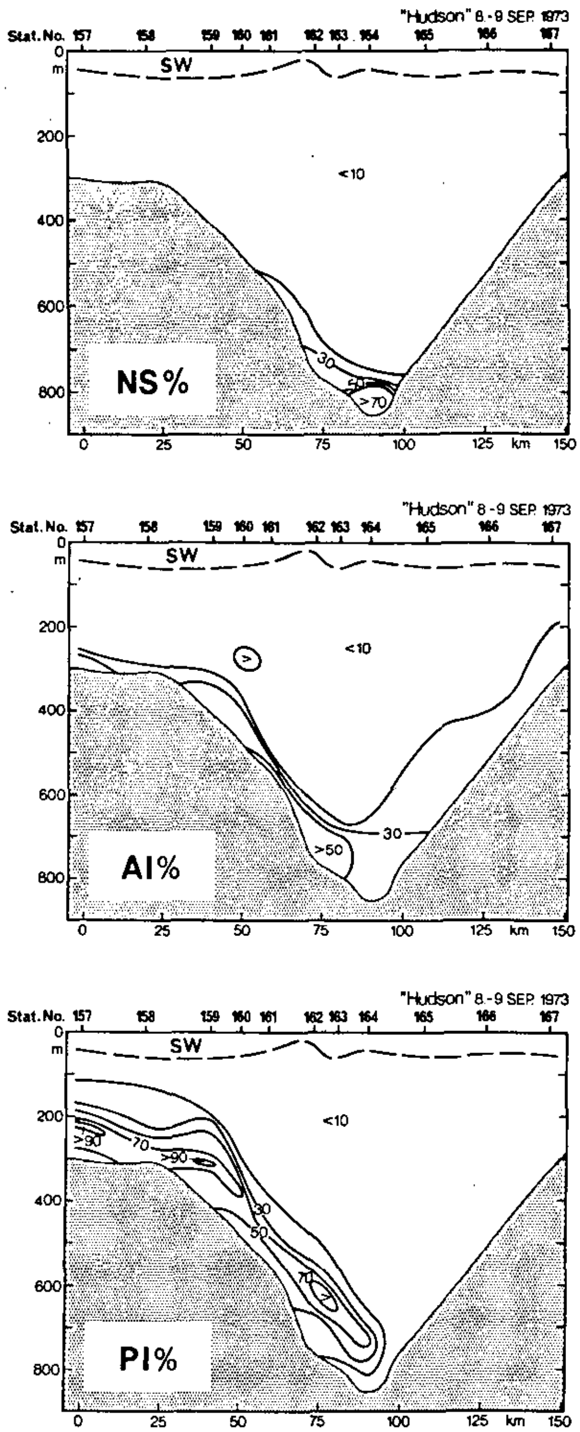


Fig. 5 Water mass distribution along section (b); for water mass definitions see text (from Müller et al., 1979)

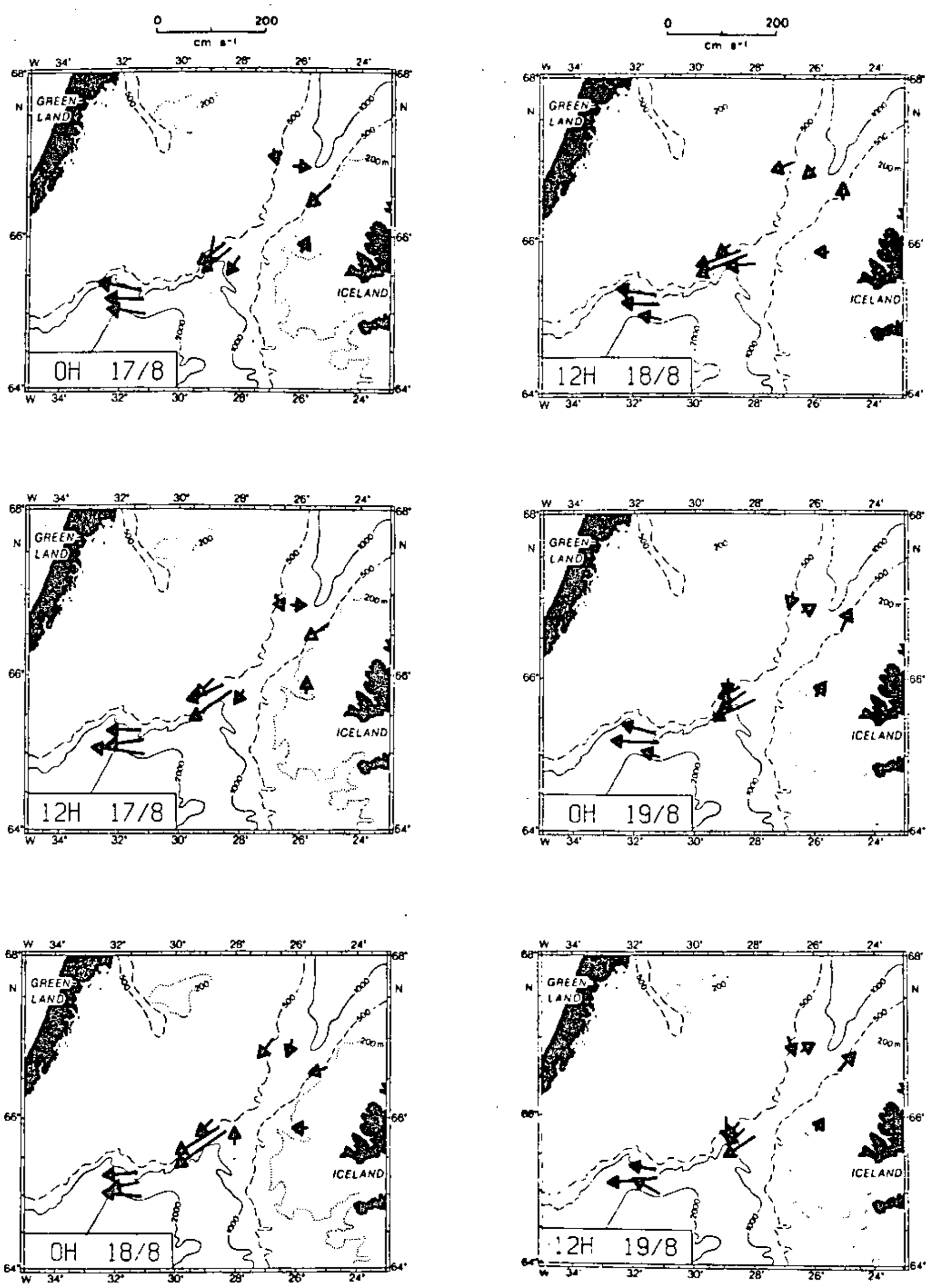


Fig. 6 Mean Bottom Current vectors during Overflow '73 in Denmark Strait (from Ross and Meincke, 1979)

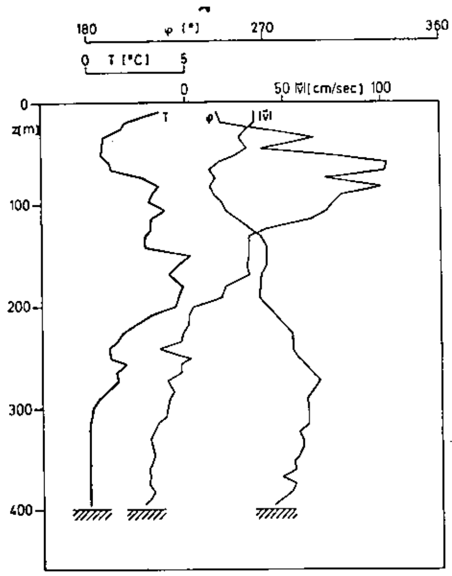


Fig. 7 Vertical current shear on Dohrn Bank during August 1971 (from Stein, 1974)

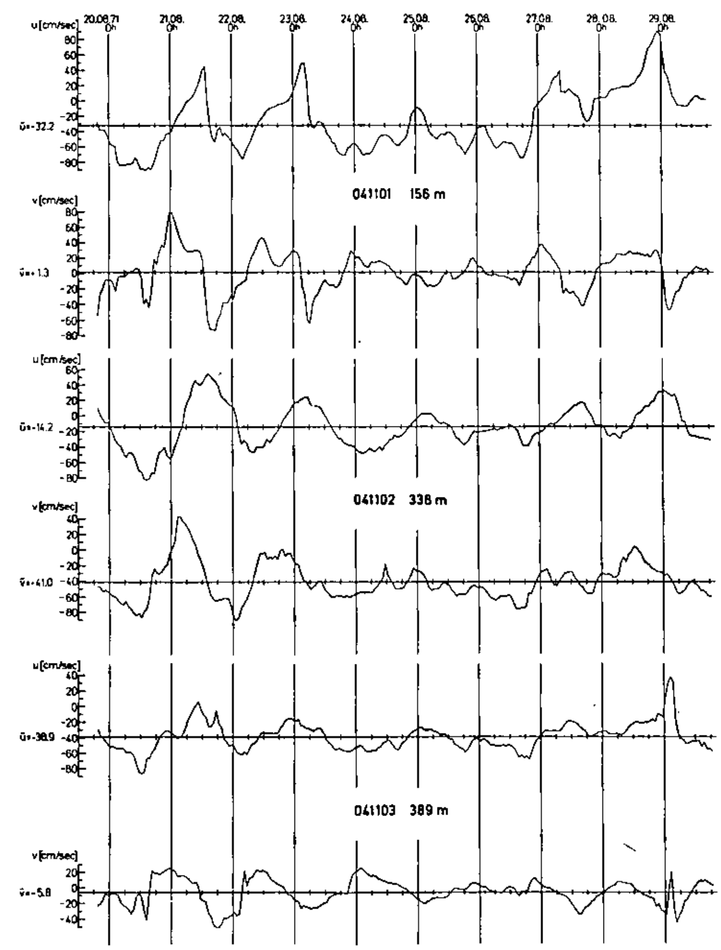


Fig. 8 Time series of moored current meters on Dohrn Bank during August 1971 (from Stein, 1974)

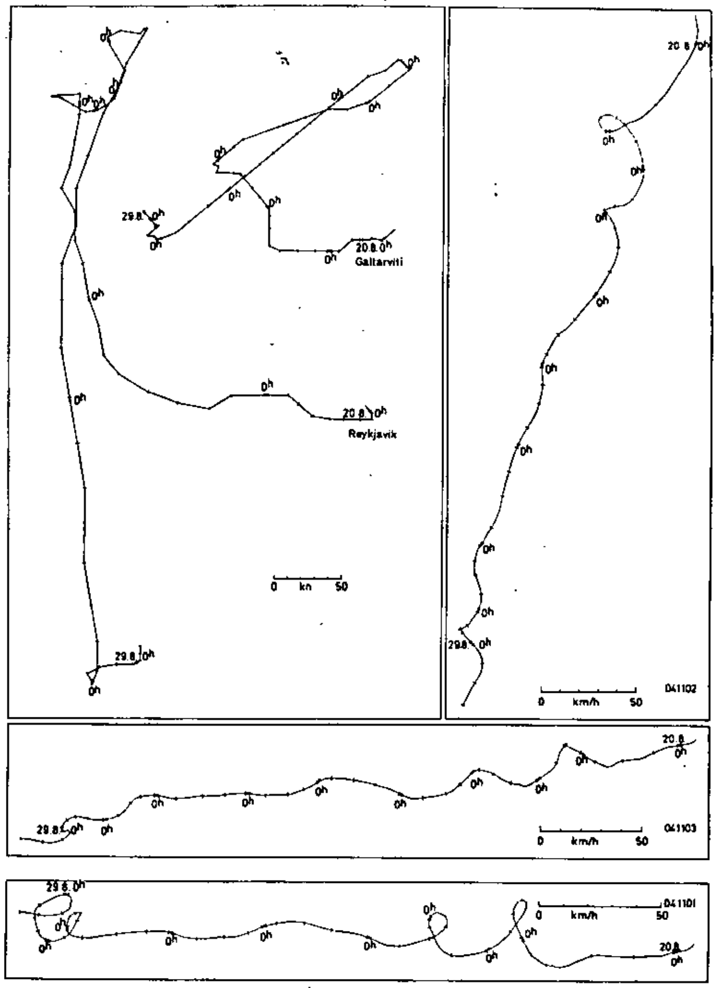


Fig. 9 Progressive vector diagrams of current measurements on Dohrn Bank and of wind observations on Iceland, August 1971 (from Stein, 1974)

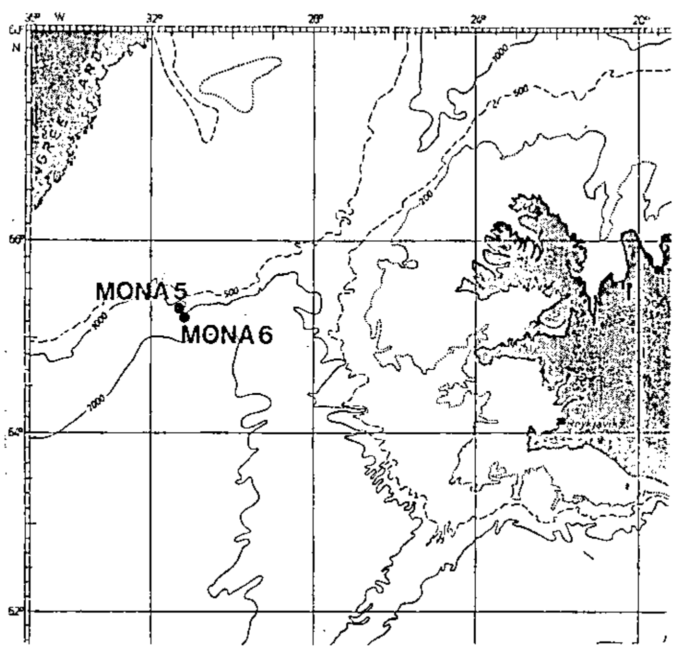


Fig.10 Location of MONA 5 and 6 current meter moorings (MONA = Monitoring the Overflow into the North Atlantic)

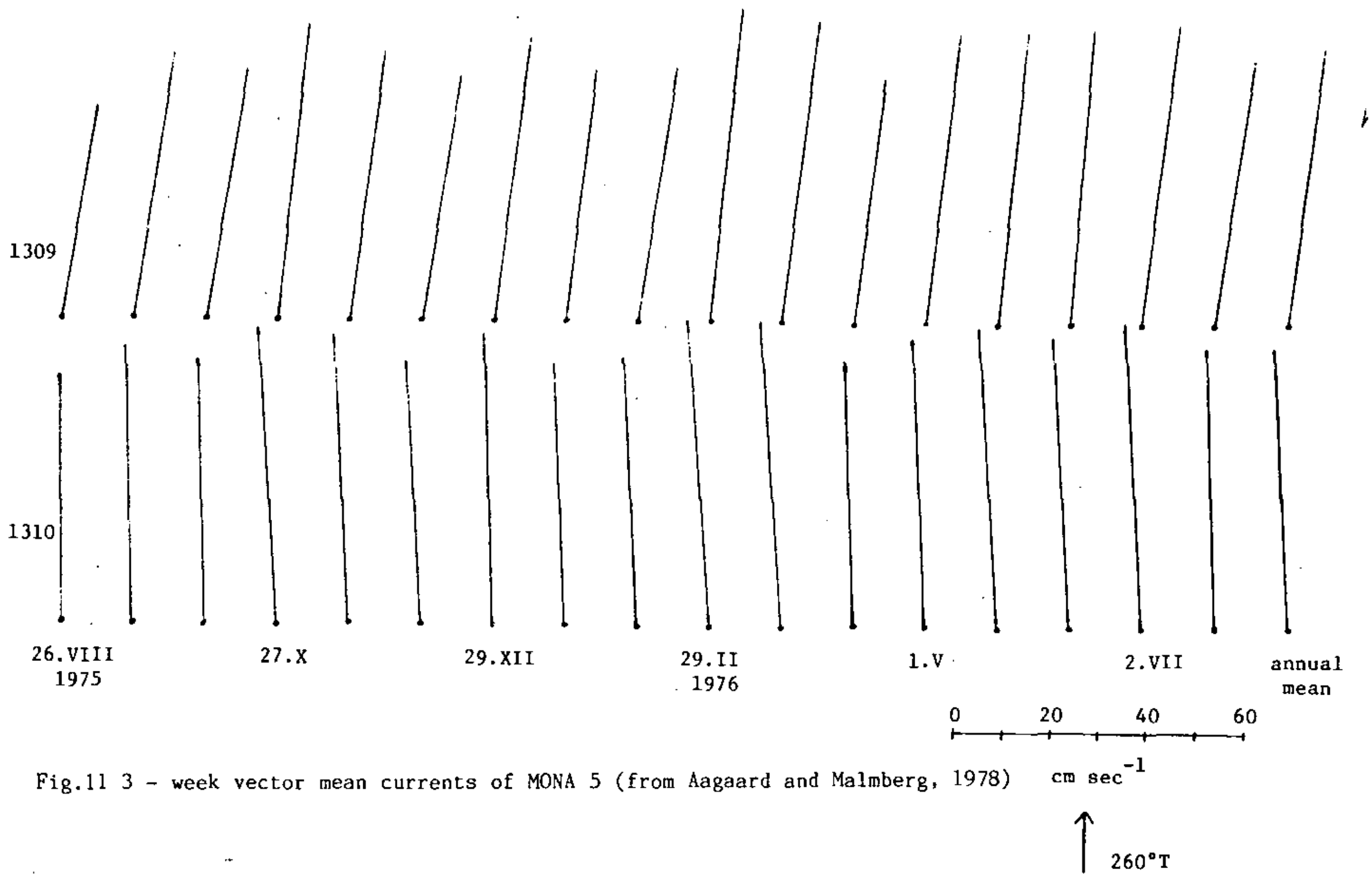


Fig.11 3 - week vector mean currents of MONA 5 (from Aagaard and Malmberg, 1978)

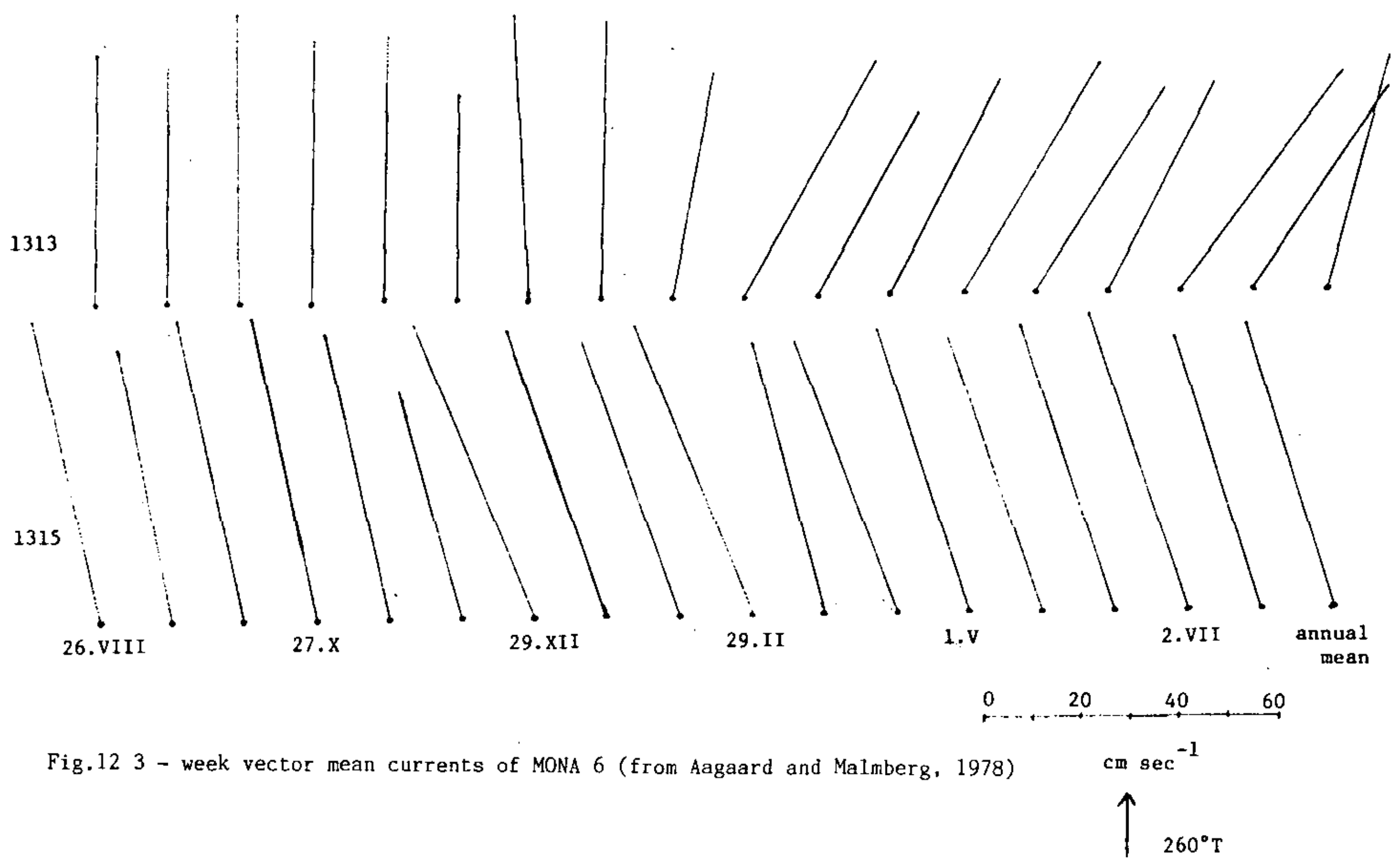


Fig.12 3 - week vector mean currents of MONA 6 (from Aagaard and Malmberg, 1978)

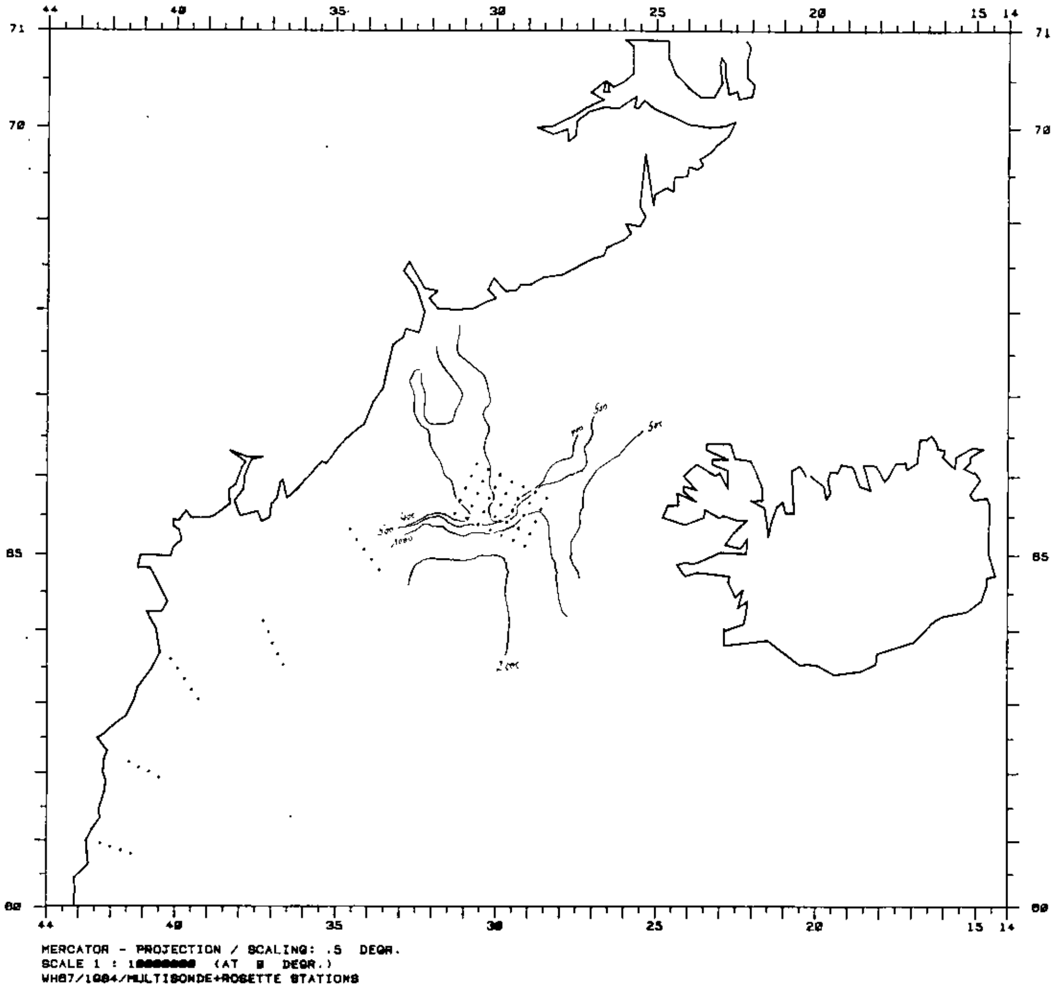


Fig.13 Location of "Dohrn-Bank-Box" during October/November 1984

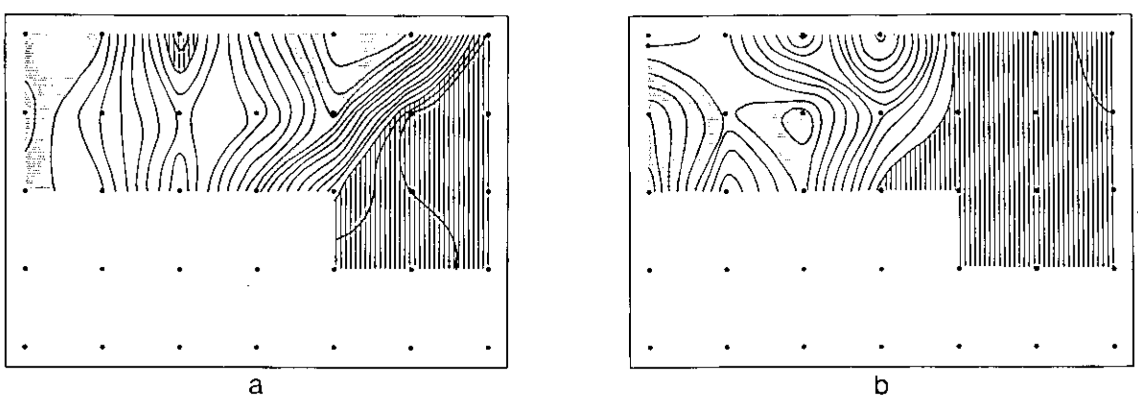


Fig.14a Sea surface temperature in "Dohrn-Bank-Box" during 17 October - 19 October, 1984

Fig.14b Sea surface temperature in "Dohrn-Bank-Box" during 13 November - 15 November 1984

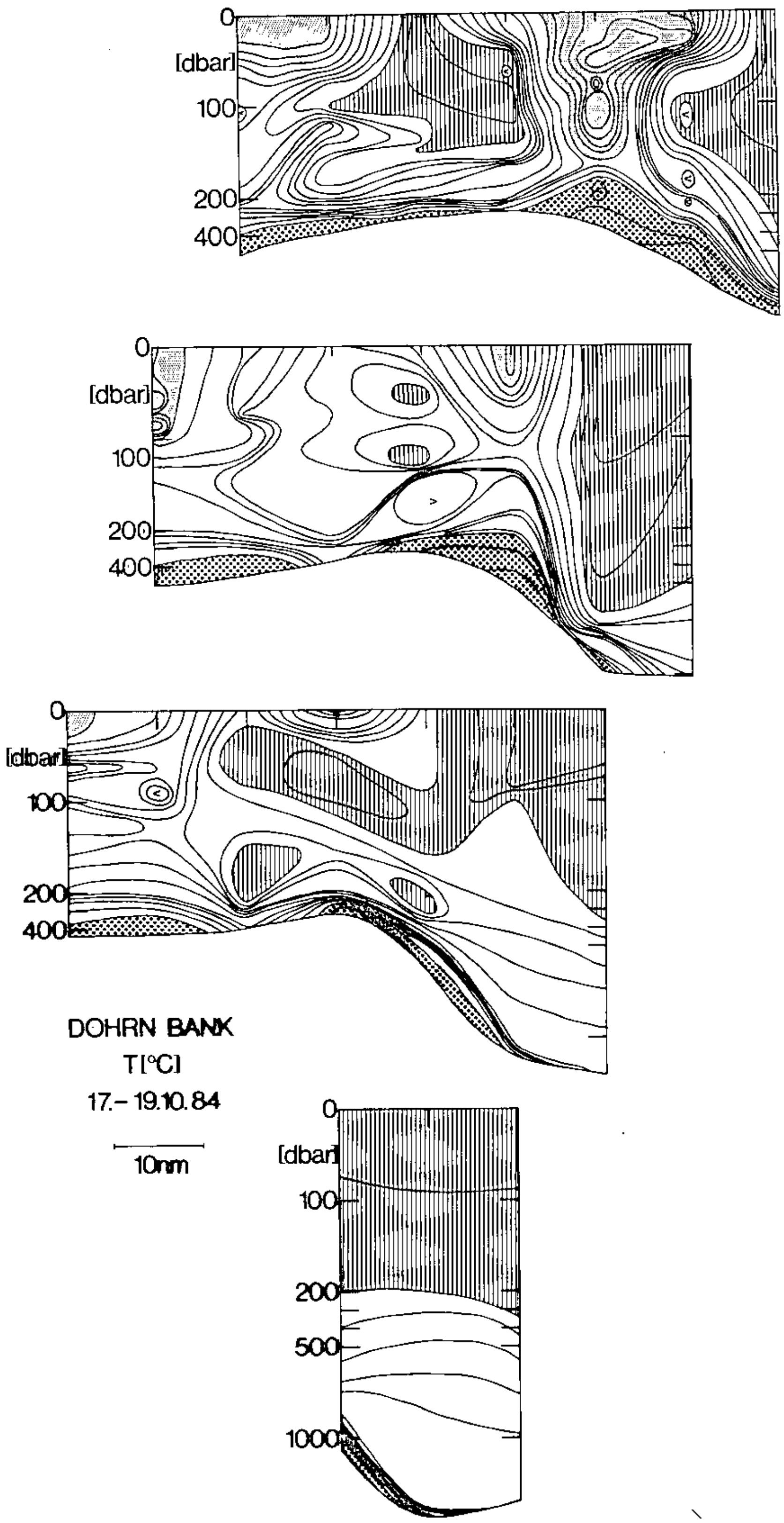


Fig.15 Vertical distribution of temperature in "Dohrn-Bank-Box" during 17 October - 19 October, 1984 (shaded: North Atlantic water t > 6°C; small dots: surface water of polar origin t < 2°C; large dots Arctic Intermediate Water t ~ 1°C)

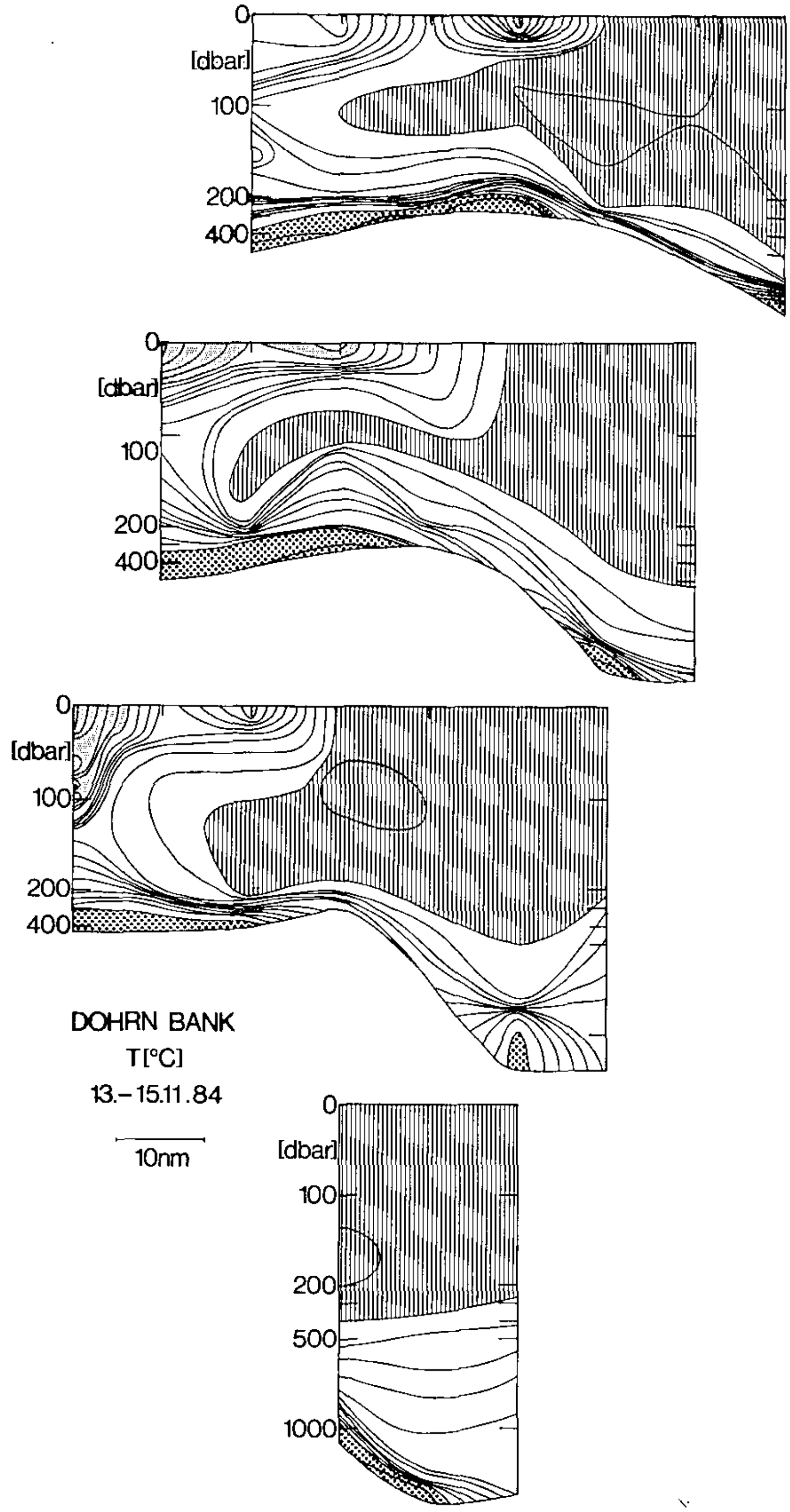


Fig.16 Vertical distribution of temperature in "Dohrn-Bank-Box" during 13 November - 15 November, 1984 (shaded: North Atlantic Water t > 6°C; small dots: surface water of polar origin t < 2°C; large dots Arctic Intermediate Water t ~ 1°C)

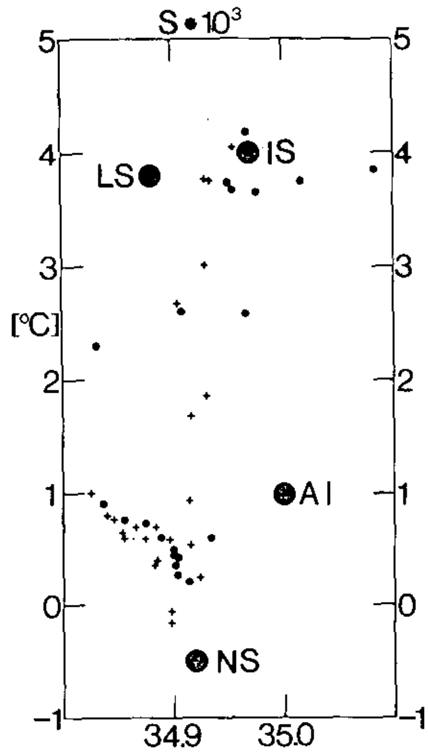


Fig.17 Temperature/salinity diagram of bottom water in "Dohrn-Bank-Box" during October (+) and November (•); Labrador Sea water (LS, ~ 3.8°C, ~ 34,88* 10^{-3}), Irminger Sea water (IS, ~ 4°C, ~ 34.97*10^{-3}), Arctic Intermediate water (AI, ~ 1°C, ~ 35.00*10^{-3}), Norwegian Sea Deep water (NS, ≤ -0.5°C, ~ 34.92*10^{-3})

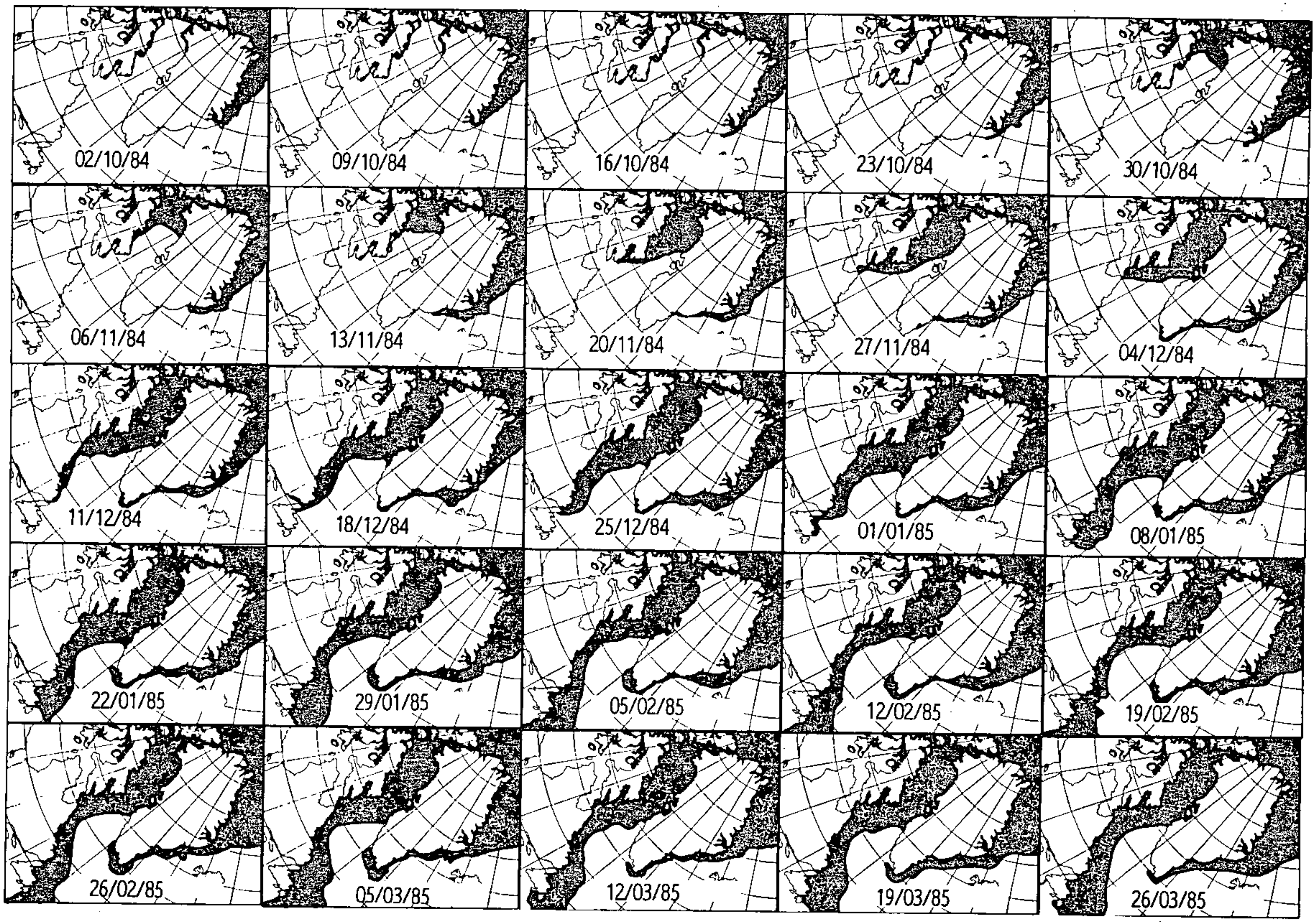


Fig.18 Ice cover in Greenland and Canadian waters (October, 1984 to March, 1985)

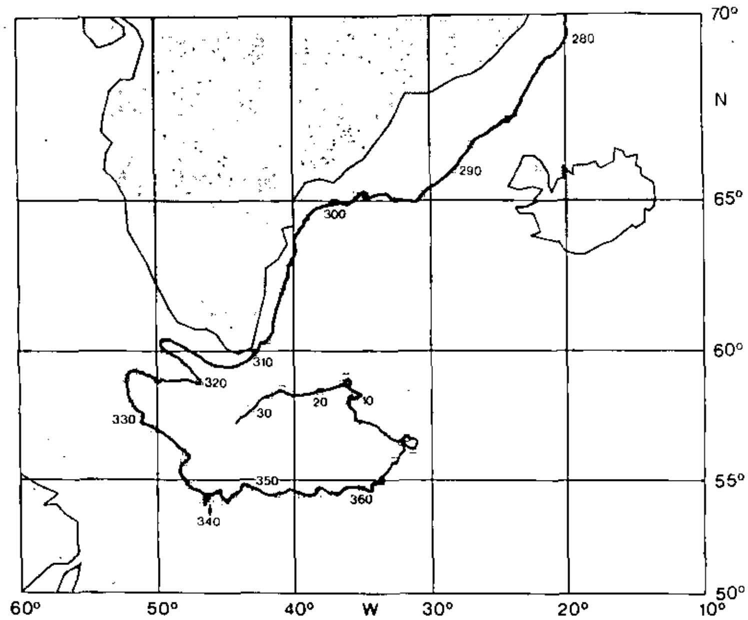


Fig.19 Track of ice-float between October 1, 1984 and March 21, 1985 (by courtesy of A. Clarke, Bedford Institute of Oceanography, Canada)