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SEASONAL VARIATIONS IN THE ATLANTIC INFLOW TO THE NORDIC SEAS

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ABSTRACT

A repeat section between 64°40' N on the prime meridian and 62° 30' N off the Norwegian coast was operated monthly during 1990 and 1991. The sections were worked by the Weather Ship "Polarfront" on return voyages from Ocean Weather Station "M". Estimates of volume and heat transport have been worked out, based on computations of geostrophic current, referred to 1000 m depth. The obtained volume transports range from 2.4 Sv to 7.9 Sv while heat transports fluctuate between $49 \cdot 10^{12}$ W and $251 \cdot 10^{12}$ W. There are clear indications of higher transports during winter than during summer, although large variations occur between consequtive sections.

INTRODUCTION

Although the submarine ridge between Scotland and Greenland constrains the deeper circulation between the North Atlantic, the Nordic Seas (the Greenland, Iceland and Norwegian Seas), the Arctic Ocean and its surrounding shelf seas, it is still the main flow passage between these seas and the rest of the world ocean. The Atlantic inflow to this region has three components; one through the Faroe-Shetland Channel, a second, between the Faroe Islands and Iceland flows eastward north of the Faroes to merge with the Faroe-Shetland Component further to the northeast. Finally, a branch of the Irminger Current forms a third component which flows inn through eastern Denmark Strait and turns east along the Norh Icelandic coast.

In the literature, the flow through the Faroe-Shetland Channel is often considered to be the major component (Tait, 1957; Worthington, 1970; Dooley and Meincke, 1981; McCartney and Talley, 1984). In his analysis of 69 sections across the Faroe-Shetland Channel, Tait (1957) arrived at transport values ranging from 1.4 to 23.4 $km^3/hr.$, the mean value being 8.2 km^3/hr, which is equal to 2.3 Sverdrup (Sv). In general he obtained higher transport estimates for winter observations compared to preceding summer magnitudes. While Tait's estimates were based on geostrophic estimates, Gould et al. (1985) presented estimates based on year-long current measurements and arrived at an average transport of 7.5 Sv northwest of Shetland, also these seasonally varying with maxima in winter. This compares well with Worthington's mean estimate of 8 Sv.

Estimates of the transport north of the Faroe Islands range between wider limits. Worthington (1970) do not include this component in his balance figures at all. Hermann (1948) arrived at an estimate of 4.5 Sv, while Tait (1957) considered it to be in general considerably smaller than the flow through the Faroe-Shetland Channel, although he mentioned one oposite case. Russian researchers, on the other hand, have presented transports of up to 12 Sv in this component (Rossov, 1972). Based on data from an array of 7 current meter riggs during two weeks in June 1986, Hansen et al. (1986) arrived at a transport of 3.8 Sv.

Recent transport estimates for the the Icelandic component are presented by Kristmannsson (1991). During the 5-year period from 1985 to 1990 the transport varied between 0 and 2.8 Sv, generally with seasonal maxima in May through August and November through January.

The present work aims at assessing the volume and heat transport in the Norwegian Atlantic current in a repeat section somewhat further to the northeast which was worked monthly through 1990 and 1991.

It is now well known that inter annual fluctuations in the heat transport, or the ocean climate, are of great ecological importance and affects both distribution, growth and recruitment in commercially important fish stocks. Furthermore, temperature variations which are due to advective variability may be observed 1 to 2 years earlier in the southern Norwegian Sea than in the Barents Sea and the Svalbard area. To monitor such ocean climate variability the Institute of Marine Research, Bergen, operates a net of standard sections. The present repeat section is worked in the same positions as one of these standard sections which has been occupied two times annually since 1978. One goal is to see whether this observational frequency is sufficient for monitoring the more large scale fluctuations in the current system.

MATERIAL

On monthly return voyages from Ocean Weather Station "M" in the Norwegian Sea the weather ship "Polarfront" worked repeat hydrographic sections across the Norwegian Atlantic Current. The section was laid between 64° 40' N, 00°00' E/W and 62° 29' N, 04° 56' E where it transects the Norwegian Atlantic Current (Fig. 1). This figure is a composite depiction of the temperature distribution at 200 m depth and the position of the Arctic front. South of 71° N it is based on data from August 1984 while the northern part is from August 1981 (Monstad and Blindheim, 1986). The figure shows that the section is situated in an area where the Atlantic flow is relatively narrow as its width is constrained by the waters from the East Icelandic Current. Further, the section is situated north of the offshoots from the Norwegian Atlantic current into the North sea. Therefore it covers the flow which continues northward into the Nordic Seas.

Observations and samples were collected the classical way by reversing water bottles and thermometers to 1000 m depth. Deeper casts were not worked due to restrictions on ship time. In February both in 1990 and 1991 and in April 1991, the section could no be worked due to severe weather conditions. Similarly, in December of both years, the most northwestern station was omitted. In the other months during the two-year period the section was repeated with stations in fixed positions. In September 1990 the section was repeated both in the beginning and at the end of the month.

During the period from 8 January to 11 February 1991 a mooring with current meters at 186, 286, 586 and 836 m depth (bottom depth was 886 m), was deployed at 63° 00' N, 03°49' E on the section to compare direct measurements with the computed currents. The position of the current meter mooring is indicated in the section from January 1991 which is shown as an example in Fig. 2.

METHODS

The volume transports are worked out by geostrophic computations with the 1000 m depth considered as the 1000 decibar level and used as reference level of no motion. Here it may be argued that a depth to pressure conversion should be applied, but in relation to the accuracy of waterbottle data, such a conversion would probably not improve the results significantly. Transport estimates were worked out only between stations from the shelf break and beyond as the transport on the shelf mainly belongs to the coastal current. Dynamic depths in the slope area were obtained by integrating specific volume anomalies along the bottom as described by Helland-Hansen (1934). As this method involves rather uncertain extrapolations and interpolations, it affects the resulting transport values accordingly.

The heat transport is estimated from values of specific heat which are computed from the station data by the formula given by Millero et al (1973) as presented by Fofonoff and Millard (1983). As the specific heat capacity obtained by this method is in units of Joules/kg°C, the assessments of volume transport were converted to mass transport by multiplying with a mean *in situ* density of 1030 kg/m^3. In computations of the heat transport, heat capacities are integrated over the temperature range from 0°C to the observed temperature and only the water column from the surface to the depth of 0°C was integrated both for heat content and mass transport. This lower temperature limit is chosen since it largely defines the border between the upper, inflowing water and the deeper intermediate and deep watermasses which ultimately flows over the sills of the Greenland-Scotland Ridge and sinks into the North Atlantic. Under similar assumptions, the same temperature limit was chosen by Samuel et al (in press) in a study on the Atlantic inflow to the Nordic Seas, using GEOSAT altimeter data.

RESULTS

The computed volume and heat transports are compiled in Table 1 and shown in Fig. 3 and Fig. 4 respectively. As may be expected with geostrophic estimates, there are cases with large differences between consequtive sections. In spite of this, however, there is a clear indication of lower transports during summer months than during winter. Both years had their maxima in January and, in general, low transports from May through August. The annual mean was 5.5 Sv in 1990 and 4.7 Sv in 1991. Interpolated values for February of both years and April 1991 are included in these averages.

The heat transports were also highest in winter (Fig. 4) but here the seasonality was less prominent than in the volume transport as higher temperatures in the upper part of the water column during summer to some extent compensate for the lower transport. In both years maxima occurred in January and amounted to $212.2 \cdot 10^{12}$ W and $251.3 \cdot 10^{12}$ W in 1990 and 1991 respectively. The annual mean was $122.6 \cdot 10^{12}$ W in 1990 and $118.8 \cdot 10^{12}$ W in 1991.

Table 1. Volume and heat transport by month.

Volume transport, Sv.

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1990	7.9	–	6.5	4.7	4.0	3.2	5.2	4.6	5.4	5.6	6.4	5.4
1991	7.6	–	4.1	–	3.3	5.3	3.9	4.6	2.4	4.9	5.4	5.4
Heat transport, $W \cdot 10^{-12}$.												
1990	212	–	138	90	76	49	115	118	116	105	169	109
1991	251	–	105	–	89	102	88	107	64	136	84	126

Table 2. Data from direct current measurements, 08 Jan. - 11 Feb. 1991.

Depth of instrument	186 m	286 m	586 m
Mean NS - component, cm/s	2.65	2.68	- o.11
Mean EW - component, cm/s	13.03	12.79	0.68
Mean velocity, cm/s	13.30	13.06	0.69
in direction	78°	78°	99°
Maximum velocity, cm/s	71.43	65.32	38.59
in direction	95°	88°	66°
Mean speed, cm/s	122.03	19.35	15.37

The current meters at 186 and 286 m depth yielded almost identical results as indicated by the progerssive vector diagrams in Fig. 5. The mean current velocity during the 34-day period was between 13 and 14 cm/sec. toward 78° at both depths. At 586 m depth the current had more character of an east/west oscillation as shown by the progressive vector-diagram in Fig. 6, and the mean velocity for the period was only 0.7 cm/sec toward 99°. Single observations had hovever considerably higher values as indicated in the compilation of means and maxima in Table 2. The ninimum values were practically zero at all depths. The instrument at 836 m depth did not function due to battery failure.

DISCUSSION

The computed volume and heat transports in the series of sections as a whole indicate a seasonality in the transport. This is in agreement with the findings of Tait (1957) and a clear seasonal trend was also obtained by Pistek and Johnson (1992) as well as Samuel et al. (in press) who present transport estimates as determined from satellite altimetry. Also in the northeastern Barents Sea Loeng et al. (1993) observed a seasonal variability in the volume transport with maximum in early winter. A likely reason to think of for this seasonality is the similar phase of the seasonality in wind stress.

In several cases there are large differences in transport between consequtive sections. Mesoscale vortices passing through the section and varying velocities at the reference layer. are the most plausible reasons for such fluctuations. A similar conclusion was drawn by Sælen (1959) who observed quite different current structures in sections taken only a few days appart.

Also the direct current measurements on the section indicate that there are fairly large short term fluctuations in the current, typically with a frequency of a few days. During such periods the current velocity may vary considerably and even be reversed (Figs 5 and 6). Although the mean velocity at 586 m depth was below 1 cm/sec., the observations at this depth showed current speeds up to almost 40 cm/sec. It is therefore not unlikely that considerable current speeds occur also at 1000 m depth and affect the geostrophic assessments accordingly. On the other hand, the results might not be much different if a shallower depth was chosen as reference layer. This was also indicated by the geostrophic computations.

The relevant segment of the section from January 1991 can not easily be compared with the direct current measurements as the curent meters showed unstable current during the relevant period with a shift in direction from NE to E. The NE component (normal to the section) decreased from 15 cm/sec. to values below 10 cm/sec. Largely, however, the direct current measurements in this case may indicate an underestimate in the geostrophic computations as the computed components at 200 and 300 m depth were 4.5 and 4.7 cm/sec, respectively.

The number of estimates and the noice in the results do not allow any detailed analysis of the seasonal sycle. Furthermore, data from February which could support the high estimates obtained in January, are lacking in both years. The December sections are both one station short at the northwestern end and give therefore also somewhat incomplete results. In the sections of the other monts, however, 15 of the 20 sections had transport toward northeast in this segment. Therefore, the estimates for December would probably be higher if these sections were complete. It is therefore concluded that there was a transport maximum around January and a minimum from May through August. This is in fairly good agreement with the estimates from the Faroe-Shetland Channel as presented by Hopkins (1991) based on the Scottish data set (Tait, 1957, Tait and Martin, 1961). These estimates also indicate a secondary peak in June. The present estimates from 1991 have a similar trend, but in consideration of the noice in the results and the small number of estimates, it seems unrealistic to draw any firm conclusion here. On the other hand the the peak around January differs from the results obtained from satellite altimetry as both Pistek and Johnson (1992) and Samuel et al. (in press) find the winter peak in February/March. The explanation of this remains still unclear, as also mentioned by Samuel et al. (in press).

Although the present section is situated north of the area where the Atlantic Current exports some water to the North Sea, the obtained transport values are in general somewhat higher than those obtained by satellite altimetry and considerably higher than those presented by Tait (1957) in the Faroe-Shetland Channel. One reason for the difference compared with Tait's results is that his geostrophic calculations in sections across the Faroe-Shetland Channel reflected little of the water from the component north of the Faroes (Dooley and Meincke, 1981) while the present section includes the total flow. Hence, the summer estimates are less different from the transport of 3.3 Sv which was obtained by Dooley and Meincke (1981) who also included water from the current component north of the Faroes which recirculates into the Faroe-Shetland Channel before it flows into the Norwegian Sea. Further more, some Atlantic water from this source may take a more direct route into the Norwegian Sea and add to the volume transport compared with Dooley and Meinke's results. In addition there will be some entrainment over the distance from the Faroe-Shetland area to the section which is dealt with here. It should also be noted that the total transport above the reference layer is included in the present estimates.

In considering the present results, it may be questioned whether the observational frequency , twice yearly, in the long-term standard section in this area is sufficient. The fairly often occurring large differences between consequtive sections in the present data set, suggest that only two repetitions per year in some cases may give misleading results. Year-long direct transport measurements compared with frequently repeated sections would improve the value of such dynamic estimates.

The heat transport is directly depentent on the volume transport and will be affected by the same uncertainties. The error which is introduced by applying a mean density of 1030 kg/m^3 is considered to be small as it was chosen from computed means on a selection of stations. The differences from 1030 kg/m3 on these stations were between 1 and 3 in the fourth decimal place of the density anomaly.

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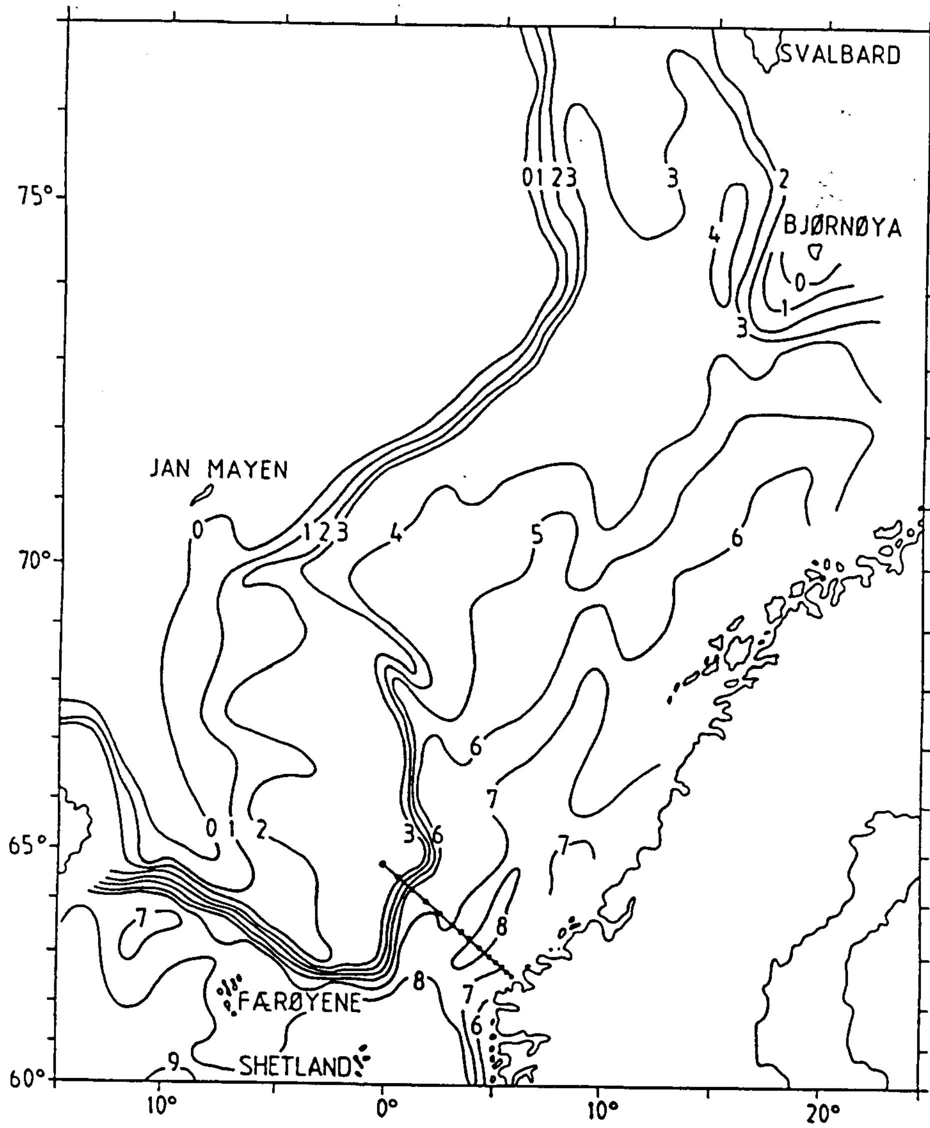

Figure 1. Temperature distribution at 200 m depth showing the position of the repeat section in relation to the Arctic front. The figure is based on data from August 1984 south of 71°N while the northern part is from August 1981.

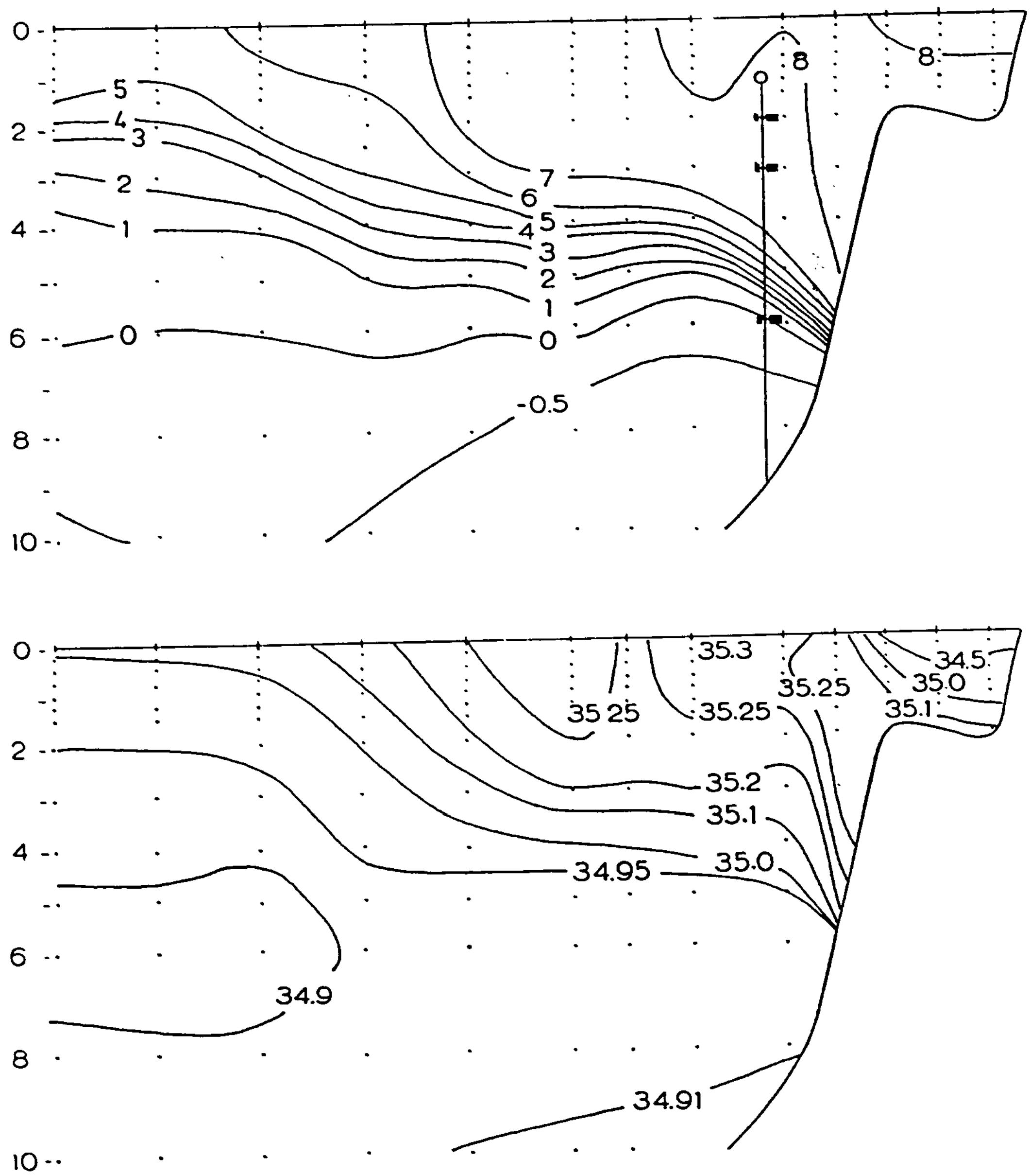

Figure 2. Temperature and salinity distribution in the repeat section , January 1991. Position of the current meter mooring on the section is indicated.

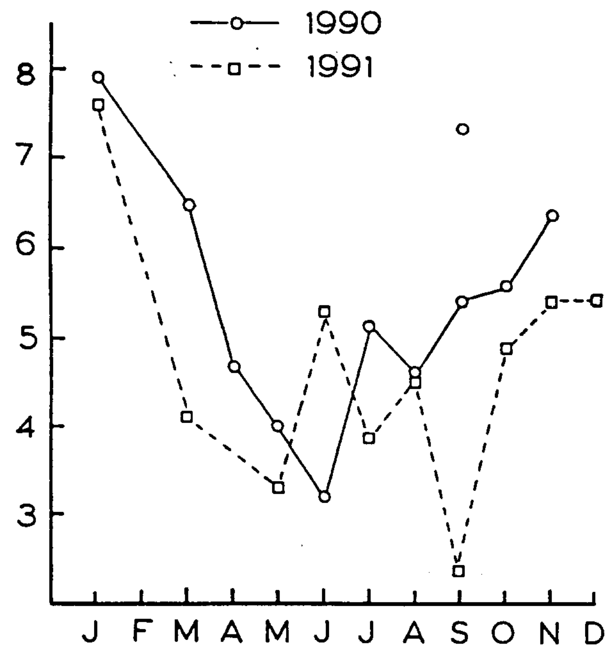

Figure 3. Volume transport through the repeat section. Units in Sverdrup, 10^6 m^3/sec.

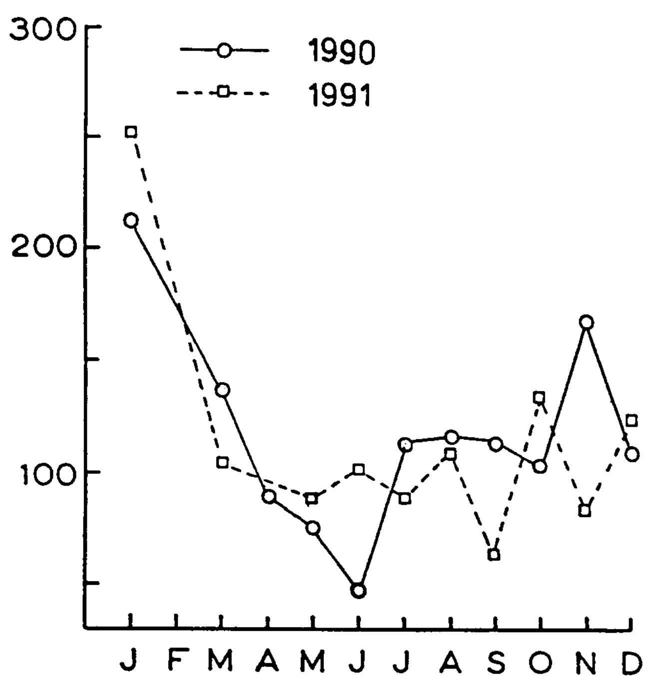

Figure 4. Heat transport through the repeat section. $W \cdot 10^{-12}$.

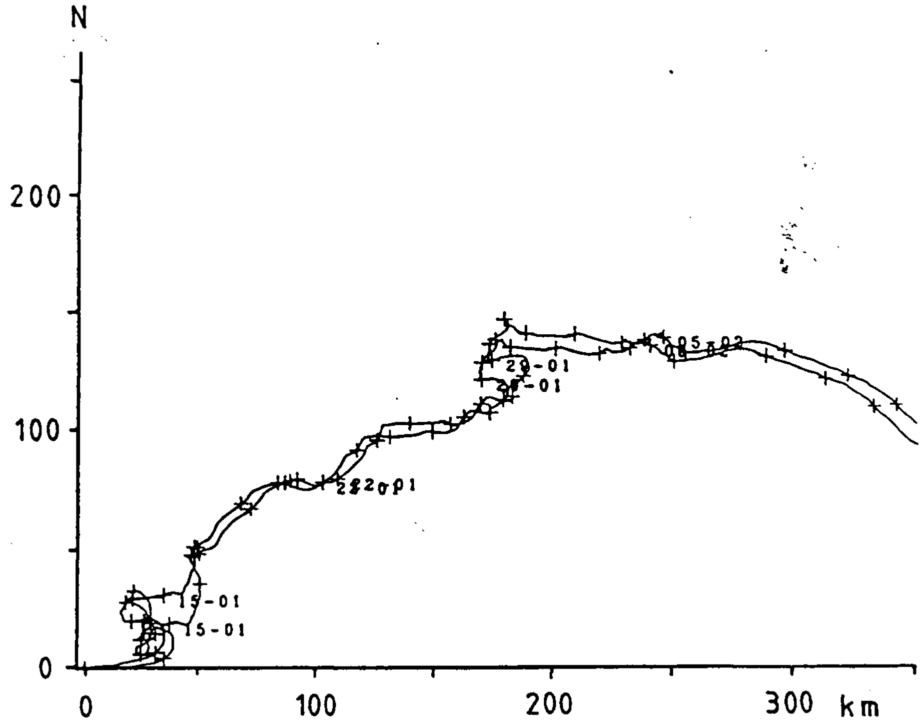

Figure 5. Progressive vector diagram of the current at 186 and 286 m depth at 63° 00' N, 03° 49' E during the period 8 January - 11 February 1991.

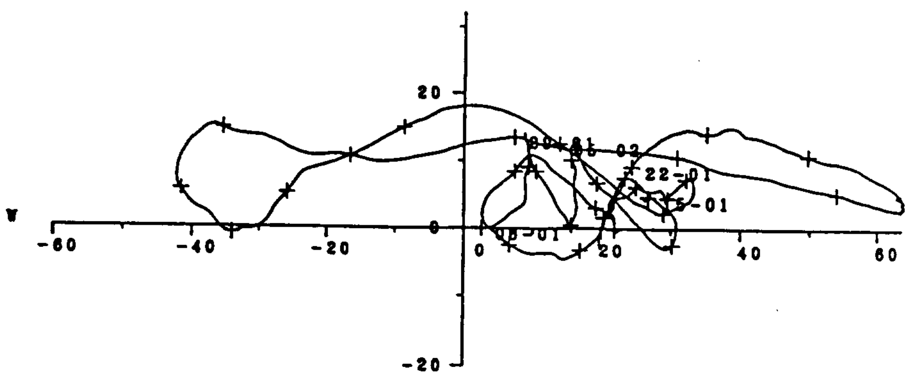

Figure 6. Progressive vector diagram of the current at 586 m depth. Positionand time as for Fig. 5.