International Council for
the Exploration of the Sea

C.M. 1988/C:32
Hydrography Com.

NORTHERN NORTH SEA CIRCULATION DURING EARLY FALL

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Abstract

During the fall of 1987 the Autumn Circulation Experiment (ACE) was carried out in the northern North Sea. The transversal flow of mixed Scottish coastal and Atlantic water from northeast of Scotland towards Norway was clearly observed through the thermohaline, nutrient and current distribution. A significant core of high salinity Atlantic water were found to the north of this, demonstrating a pronounced flux of Atlantic water onto the northern North Sea plateau. A topographically steered cyclonic eddy with a scale of 100 km was clearly documented. A major barotropic southeastward flow towards Skagerrak of cold, heavy bottom water from the northern plateau was revealed, in addition to the more well known circulation in the vicinity of the Norwegian Trench.

Introduction

The historical background for studies of the circulation of the northern North Sea has been reviewed by Dooley (1974). The major inflow of Atlantic Water (AW) comes from the north along the western slope of the Norwegian Trench. However, several observations, numerical model results and the general thermohaline structure indicate that some water of Atlantic origin (AW(W)) flows south in the western part of the basin (e.g. Ljøen 1980, Backhaus and Heinbucher 1987). Part of it is topographically steered eastward from the Scottish coast towards the southwestern Norwegian Trench. In addition an inflow of mixed Scottish and Atlantic water through the Orkney-Shetland channel known as the Fair Isle current (FI) is taking place. The FI seemes to be confined to a zone less than 30nm wide adjacent to the Orkney Islands. At about 58°N the flow turns eastward and follows approximately the 100m isobath toward the Norwegian Trench (Dooley,1974). These major inflows to the North Sea are indicated in Fig.1 together with the 100 and 200m isobaths and a frame around the experimental area and ship tracks of the Norwegian contribution to the Autumn Circulation Experiment (ACE) in September 1987. This frame is the basis for later horisontal distribution maps.

The transversal flow associated with the topography in the vicinity of the 100m isobath (also referred to as the Dooley Current (DC)) is the major target for this study. Dietrich et.al. (1959) demonstrated that this current during summer penetrates and splits the cold bottom water of the northern North Sea into two parts. This feature is further supported by Ljøen (1971, 1980). The current also seems to influence biological distributions as shown by Iversen et.al. (1974). The Norway pout mainly spawns in the northwestern North Sea, and the O-group seems to be confined to the northern cold area. The current is one of the major transport routes toward the eastern North Sea and Skagerrak of herring larvae spawned off the Scottish coast.

Current measurements have been carried out along the approximate current path between Scotland and Norway. In May-June 1962 the Deutches Hydrographishe Institute had several moored current meters for 16 days (Anon, 1969), and four of these stations were re-occupied in September 1972 (Ramster et.al, 1973). In April-May 1973 the British established 13 moored current meter stations in the northern North Sea (Ramster et.al., 1975). Five of these were along 1°E between 57 and 58°N. During the INOUT part of JONSDAP'76 in March-April 1976 a large number of current meters were deployed covering the northern North Sea (Riepma, 1980). The JONSDAP data have also been dealt with by Dooley and Furnes (1981). Some of these results are delt with in the discussion.

The inflow by the Fair Isle Current seems to be subject to seasonal variations (Dooley, 1983). The current speed increases during summer while during winter the current is predominantly wind driven. There also seems to be a shift of the location of the inflow according to season. About the previous statement of an Atlantic inflow (AW(W)) to the east of Shetland (see Fig.1), Dooley (1974) argues that there is no direct measurements of this. According to Steele (1957) the persistence of cold, dense bottom water over the northern North Sea plateau will prevent Atlantic inflow to the area during summer.

However, indications of a significant flux of warm Atlantic water onto the northern North Sea plateau at least during winter, is revealed in the sea surface temperature distribution in February 1986 derived from a NOAA infrared satellite image (Fig.2). The temperature front around 58°N where the 6°C isotherm approximately follows the 100m isobath (see Fig.1), is assosiated with the DC, with relatively warm water to the north (6-6.5°C). This indicates a direct influence of AW in this area. The 6°C isotherm also indicates the presence of a cyclonic eddy which will be discussed later. In addition the cold Norwegian Coastal Current (NCC, 3-5°C) is seen to the east and also the warm AW (>7°C) penetrating from the north just to the west of the NCC.

Although the existence of the transversal flow across the North Sea has been known for several years, no detailed study of its lateral extent, typical water transport and signature and current structure has been published. Therefore we believe that the below description and discussion of the observed thermohaline, nutrient and current structures may contribute to a better understanding of the northern North Sea circulation.

Experiment

The 10 days field investigation was carried out from 17 to 27 September 1987 with R/V Håkon Mosby. It is equipped with an Acoustic Doppler Current Profiler (ADCP) and a towed profiling CTD (SEASOAR) in addition to standard CTD and hydrographical equipment. The ADCP was set to give a time-average vertical absolute current profile every 5 minutes (every 0.5-1.0 nmile with typical ship speed 6-12 knots) with 4m vertical resolution from 10m depth to 10-15m above the bottom. The ADCP was running all the time. Samples for nutrients analysis were taken at ICES standard depths on most of the CTD stations with typical station spacing of 5nm. The samples were conserved with chloroform and stored cool and dark until analysis ashore. Storing samples with the use of chloroform do not alter the nitrate and silicate values, while the phosphate values tend to be slightly elevated (Hagebø and Rey, 1984). On the Seasoar sections the station spacing is roughly 0.5 nm with typical vertical coverage from the surface to 70m. Seasoar sections 7-10 were run continuously back and forth along CTD section 6 at 0° longitude (Fig.1) to study short time variability.

In the North Sea there are large spatial variability in the tidal currents, typical ranging from 0.5 m/s near the Scottish coast to near zero at an amphidronic point southwest of Norway (Davies and Furnes 1980). This creates a problem for the interpretation of the ADCP data being sampled as a function of time and space. This was planned overcome by redeployment of two currentmeter rigs sampling only for a few tidal periods at different locations in the experimental area. Unfortunately the rigs were lost at the first location. This means we have to consider previous measurements and/or model results of the tidal components while interpreting the ADCP data.

During the experiment nine Argos drifters were deployed. These consisted of a sphere-shaped 80cm diameter surface buoy and a $12m^2$ window blind drogue at 30 or 60m depth.

Measurements

Thermohaline and Nutrient distribution

The vertical and horisontal thermohaline structure varies in the experimental area according to season (Tomczac and Goedecke, 1962). During summer, a stable stratification with a relatively thin upper layer develops due to solar heating and lateral spreading of less saline water from the NCC (Sætre et.al. 1988). Close to the Scottish coast however, the strong tides keeps the water fairly well vertically mixed throughout the year. In the fall, increased mixing mainly due to stronger winds causes a deepening of the upper layer being fairly homogeneous. The lower layer still keeps its signatures from the previous winter. In November/December, except for the region associated with the NCC, the whole area is fairly vertically homogeneous.

A comparison of the development of the temperature and salinity structures from north-south sections taken between 1 and 2°E in July, September (this experiment) and November 1987 are shown in Fig.3a,b,c. In July a strong thermocline was present at about 30m depth, and the salinity distribution shows clear indications of relatively fresh NCC water at the northern part of the upper layer. The DC is revealed by the deepening of the 7 and 8 degree isotherms and the surfacing of the 13°C isotherm.

In September (Fig.3b), the thermocline has deepened to about 50m, and now even clearer the location of the DC is assosiated by the deepening of the 8 and 9°C isotherms. A significant change in the salinity structure has tacen place with a core of high salinity (>35.2) water in the lower layer just to the north of the DC. This is the core of the previously mentioned AW(W) which most likely has passed around (north of) Shetland and is flowing south in the western part of the North Sea (see Fig.1) and turning eastward along with and to the north of the DC. As seen, it was not present in this area two months earlier.

In November (Fig.3c) most of the thermohaline structure was broken down. Since this section was taken further to the east than in September, it is only crossing a branch of the AW(W) (to be discussed later), and the reduction of the area covered by high salinity AW(W) is not an indication of this current dissappearing. The temperature structures in Fig.3a,b,c, clearly shows that the cold lower layer water is split approximately around the 100m depth, confirming the presence of the DC in the period July to November. Fig.3 demonstrates the importance of the earlier mentioned mixing process taking place during fall, with a gradual deepening og the upper mixed layer. The speed of this process depends on the severity of storms during fall, and to our knowledge this is an important effect which is not considered in present numerical circulation models.

The 10 days (September 1987) quasi-synoptic horizontal distribution of salinity and temperature at 70m depth is shown in Fig.4. Here the warm tongue (above 10°C) of mixed Scottish coastal water and AW is turning eastward and passing the 0° longitude at about 57°30'N, in close correspondance with the 100m isobath (Fig.1). Between 0 and 1°E there is a tendency of splitting of the tongue, one part turning southward and one part topographically steered in a northeastward direction (the Dooley Current).

Comparing Fig.4a and b shows clearly that in this area, the salinity maximum (>35.2°/oo) is located to the north of the Dooley current. To the east of 1°E these two current systems becomes less clearly separable probably due to mixing processes.

At about 2°E the 100m isobath makes a sharp turn toward southeast. Fig.4 also indicates that so does the current to a certain degree. However the major feature is the cyclonic structure in both temperature and salinity, indicating a cyclonic eddy with a scale of the order of 100km. A detailed study of the topography shows a depression (>150m) centered at 58°15'N, 0°50'E and a shoaling to the northeast of this. Both theory for conservation of potential vorticity and direct topographic steering is in favour of producing a stationary cyclonic eddy in this region, and to our knowledge this is the first time such an eddy is clearly documented in this area. However, while knowing this, evidence of this eddy is clearly seen in several earlier observations (Dietrich et.al., 1957, Riepma 1980, Kautsky, 1985). Clearly the eddy is also seen in the surface temperature distribution from February 1986 (Fig.2), confirming the presence of a (semi)-stationary eddy. A topographically steered cyclonic eddy will due to bottom friction cause convergence and upwelling in the center of the bottom layer. This might be an important process for bringing nutrients up into the euphotic zone and thus for primary production.

Fig.4 also indicates a third and relatively cold watermass in the center of the eddy. This water is colder (<7^{o}C) than the two previous watermasses (assosiated with the DC and AW(W)), with a salinity in between. It is not clear where this water comes from, although Steel (1957) and Ljøen and Sætre (1987) suggest that such a water type is fairly stagnant water from last winter. It is clear that this water lies as a band from the eddy center towards east and southeast, west of the major inflow of AW in the Norwegian Trench. Also there is a connection to the north observed through section 1 (Fig.1). This water mass has a clear minimum in temperature, however, within this minimum there is in the eastern area a horizontal salinity gradient indicating a mixing of different watermasses taking place. This high density water is most clearly seen in the north-south section 15 along 3^{o}E (Fig.5), where also the DC is seen to the south (deepening of the 7 degree isotherm) and a branch of high salinity AW from the Norwegian Trench in the northern part. This heavy water can be traced toward southeast (section 16 and 17, Fig.1), and we conclude that it is the lower layer water from the northern North Sea plateu (north of the DC) which has been cooled the previous winter and is flowing along with the AW into the Skagerrak. Actually this water might be preconditioned for deep and/or bottom water formation in Skagerrak (Ljøen and Swansson, 1972, Ljøen, 1981, Magnusson 1985).

All the CTD data are shown in a T-S diagram (Fig.6a) where a broken curve is roughly drawn around the data. In general all the data above 10^{o}C represent upper layer water above 30-50m (not to be discussed any further), except for the Dooley Current (DC) entering the area at 0^{o} longitude. Clearly seen is the AW assosiated with the western slope of the Norwegian Trench, and what we call Norwegian Trench Water (NTW), being heavy and cold water flowing out from Skagerrak below the NCC. We have also marked the North Sea Water (NSW(S)) found to the south and southeast in the area of study (south of DC), and at last a water type called CAW (Cooled Atlantic Water), which to our understanding only can be prodused on the plateau through an extensive cooling of high salinity water during the previous winter.

For a more detailed discussion of the different lower layer watermasses and mixing prosesses, we have expanded the salinity scale for the water saltier than 34.8 (Fig.6b). Following downstream the subsurface cores of maximum salinity of the two Atlantic watermasses, it is seen that the major influx of AW gradually is mixed with colder and fresher water and leaves the area towards southeast at a similar signature as the Atlantic Water (AW(W)) entering the area from west as it crosses the 0° longitude. The AW(W) which only can be traced to about 2°E, is mainly being cooled due to mixing with the more stagnant CAW to the north, however a certain mixing with the DC is especially taking place between 1 and 1°30'E.

Also following downstream the DC with the signature taken as the vertical average from 60m to the bottom in the area of maximum temperature, it is seen that between 0 and 1°E an extensive mixing with AW(W) has taken place, and also Fig.4 idicates that much of the light DC water is forced southward in this area. The mixing with AW(W) is continuing towards northeast, however at 2°E the DC has lost contact with the AW(W) which mainly turns into the topographically steered eddy. How much of the DC which also flows into the cyclonic eddy is not known, however the part of the DC which continues toward southeast is now strongly mixed with NSW(S).

The earlier mentioned water having a minimum in temperature with a gradient in the salinity is marked in Fig.6b with an elongated shape connected to the CAW. In general the minimum temperature (varying from year to year roughly between 5 ang 7°C) on the northern North Sea plateau is found in March-April. In April-May 1987 the Institute of Marine Research, Bergen made some observations in this region, which indicated a watermass marked in Fig.6b as NNSWW (Northern North Sea Winter Water). This corresponds well with earlier observations (Ljøen, 1971), and explains our "elongated shaped watermass" (Fig.6b) being NNSWW laterally mixed with AW (or CAW) and DC. Ljøen (1971) found a positive correlation between temperature and salinity in the NNSWW, and he concludes that the heat content very much depends on admixture of AW and not on the winter cooling only.

In general very small amounts of nitrate and silicate were present above the pycnocline at about 40m (+/-10m) due to the summer primary production. Below the pycnocline quite variable amounts were found, and we choose to present the horizontal distribution of nitrate at 70m depth (Fig.7a). The Dooley current is here clearly represented by the very minimum in nitrate concentration stretching from 57°30´N, 0° longitude towards the east, turning northeastward at 1°E and crossing 2°E at about 58°30´N where it splits with one tongue turning northwest towards the eddy and two tongues, one following the 100m isobath towards southeast and one just to the south of this. The vertical section 14 along 2°E (Fig,7b) clearly shows these two tongues as dips in the isolines.

Currents

The vertical current profiles from the ADCP obtained contineously during the whole experiment, showed as expected that in the homogeneous watermasses to the southwest, also the currents were homogeneous with respect to depth. In most of the area a two layer thermohaline system persist (most clearly defined in the northern and eastern areas), and Fig.8 shows the horizontal distribution of the absolute currents at 25m and 60m taken to be representative for each layer.

The strong tidal component along the Scottish coast is most clearly seen in sections 4 and 5 (see Fig.1), and each section is seen to cover approximately half a M_2 tidal period at opposite phase. Davies and Furnes (1980) show that for the experimental area, the major tidal axis is oriented north-south, such that tidal components in the east-west direction in general will be negligible (<5cm/s). This means that the east-west components of the ADCP data is representative for the instantaneous east-west residual current, while the north-south components must be treated with great care.

In the northern part of section 1 and in sections 12,13 and14 (Fig.1 and 8), clear indications of the two layer current system is seen, while most of the other sections reveale smaller vertical current shear. Some of the strongest currents are seen in the northeastern part and frontal region of the eddy (section 22), where the velocity reached near 100cm/s in a northwesterly direction. Due to its complexity, Fig.8 is hard to describe in detail, but the information has been important for the interpretation of the information presented in Figs. 4 and 7a.

The sentral parts of CTD section 6 (Fig.1) were run back and forth as sections 7,8,9 and 10 during 20 hours with Seasoar and ADCP data being sampled. While the termohaline structure displayed only minor changes, the currents showed large variability. In Fig.9 the currents are shown at 25m and 60m depth with the tides (taken from tide tables) subtracted at selected points. Also the residual currents (open arrows) display significant variability as a function of time, probably due to mesoscale prosesses and uncertainties in the tidal estimates. The mid open arrow of each section should be representative for the Dooley current, and in agreement with the termohaline and nutrient horizontal structure, it is seen to be directed mainly eastward with speeds ranging from 10 to 30 cm/s. The current here is mainly barotropic (due to minor vertical velocity shear), and with a width of 10-15km, we estimate the transport going east to be about $0.25*10^6 m^3/s$ (+/- 50%). This is near the same magnitude as estimated totally to enter the North Sea between Scotland and Shetland, (Dooley,1974, Otto,1983), indicating that a major part is flowing east in this area. This is to a certain degree confirmed by one of the drifting Argos buoys (1558, Fig.12) with a drogue at 30m depth, which drifted just south of 57°N and around 0° longitude where it became fairly stationary for about two months before it continued further southwards.

However, Fig.4 indicates that a significant southward current is set up between 0 and 1°E due to the light DC water meeting with the much heavier water to the east. This would mean that the eastward transports should be reduced especially from 0 to 1°E. The measured east velocity component distributions along 0, 1 and 2°E are shown in Fig.10. Clearly seen is the drastically change in the DC current pattern from being fairly vertical homogenious at 0° longitude, while at 1°E the major currents are found in the upper layer. This does not show the fully true situation since the major current direction is northeast at 1°E, however it is clear that a significant decrease in transport has taken place between the two sections. Much of the DC has been lifted to flow east in the upper layer. Such a behaveour leads to a decrease in relative vorticity, and might be the cause for the meander towards southeast between 1 and 2°E (Fig.4 and 7a). These figures also indicate a cyclonic eddy crossed by the section along 0° longitude which is confirmed by the core of westward velocity down to about 60m (Fig.10a). At 2°E the DC can not clearly be seen in the velocity distribution (Fig.10c), but it should be noted that there is a relatively large overall transport towards east.

Discussion

As seen from both Fig.4 and 7 the Dooley current was well defined especially in the nitrate and temperature distribution, and the width was only 10-15 km. East of about 2°30´E it was not so well defined neither in the termohaline nor the nutrient distribution although it can be traced to about 3°30´E. This is probably due to the fact that a major part of it turns cyclonically towards and into the topographically steered eddy, and that the minor branches moving southeastward is subject to extensive horizontal mixing.

Based on all the previous presented information, a tentative quasi-synoptic horizontal circulation pattern (Fig.11) of the lower layer has been suggested. Fairly well documented is the Dooley Current (solid line) and the AW(W) (open line) to the north of this. Also clearly observed is the NTW (solid line) flowing northwest and northwards below the Norwegian coastal water and the south flowing AW (open line) on the western slope of the Norwegian Trench. These currents are also confirmed by three moored currentmeter rigs where the 10 days average currents during the experiment at different depths are plotted in Fig.11. It is interesting to note that a maximum average current of 27cm/s were found at 100m depth on the front between the NCC and NTW.

More uncertain is the exact transport route (from the eddy center and northern areas) of the dense, winter cooled, lower layer water from the

northern North Sea plateau seen to flow southeast toward Skagerrak along with the AW and indicated by a dashed line in Fig.11. The ADCP current measurements reviels a major barotropic current component (20-40cm/s), and we speculate if this is a response caused by a larger scale pressure gradient set up against the AW flow along the western slope of the Norwegian Trench. In other words, when AW(W) and FI flows onto the northern plateau (Fig.1), due to volume conservation some water has to leave the area. Kautsky (1985) found from measurements of artificial radio nuclides in February 1978, transport northwards from about 58^{O}N between 2 and 3^{O}E. Our buoy 1584 (Fig.12) indicates a similar transport, however this might be more related to a direct wind drift rather than the general current structure.

Studies of JONSDAP current meter data (Riepma, 1980) showed that a similar circulation pattern as in Fig.11 was obtained during calm wind conditions, after some days of north westerly and northerly winds and to a certain degree at the onset of westerly winds. At other wind conditions the circulation pattern was quite different, however under all conditions a major southeasterly flow towards Skagerrak were observed (dashed line in Fig.11). Most of the data including our experiment and other Argos drift data indicate that this flow tends to be directed at a slight angle to the topography, towards shallower water. This can be explained by the sharpening in this area of the western slope of the Norwegian Trench, which may lead to convergence and thus increased currents turning slightly to the right.12.

The indicated branches from the currents in Fig.11 were also to a certain degree observed. Unfortunately only two of the Argos drifters (1580 and 1572) with drogues in the lower layer (60m) survived. These are plotted in Fig.4, and 1580 seems to partly follow the Dooley current with a 5 days average southeastward velocity of 17 cm/s. Due to a period of strong southeasterly wind it was forced northwards and into the the AW, and then followed this current southeastwards.

The other Argos buoy (1572) were deployed just to the north of the core of the Dooley current at 0^{O} (Fig.4). It clearly followed the current eastward with a 10 days average east velocity component of 10 cm/s. At about $1^{O}30'$E it turned into an anticyclonic eddy branch, and from there on it unfortunately seemed to have lost its drogue

Several authors (eg. Dooley and Furnes, 1981, Riepma, 1980) have suggested that much of the circulation in the North Sea is driven by the windstress, and especially the upper layer while a pycnocline persist in the summer and fall. Therefore we have compared daily averaged Argos buoy drifts (with drogues at 30m), with daily vector averaged wind velocities measured from a platform at 58°12'N, 2°12'E. The buoy data is averaged with a delay of about 6 hours compared to the wind, which is an estimated time for a 10m/s wind to increase the average speed of a 40m thick ocean layer by 10cm/s. Fig.12 shows the progressive wind vectors from 24 September to 29 October with starting point at the observation site, together with the drift tracks of the buoys for the same period. Clearly little or no correlation is seen, which was confirmed by scatter diagrams (not shown) of the Argos drift speed versus wind speed, and the directional difference between the buoy drift directions and wind direction versus wind speed. We can conclude that the circulation below 30m in the experimental area can not be represented by the simplest wind drift models such as e.g. 1-2% of the wind speed and a certain turning angle, typically being used for oil and ice drift simulation and prediction. The ADCP data also displayed fairly uniform currents up to the minimum measurement level at 10m, (or maybe15m during the strongest wind events), which means that the above statement is valid from below approximately 10m.

Conclusions

Interpretation of the Autumn Circulation Experiment observations in September 1987, leads to the following conclusions:

The Dooley Current (DC) with water from the Fair Isle Current was clearly detected especially in the temperature and nitrate distribution and found closely to follow the 100m isobath (Fig.11) in agreement with earlier observations.

To the north of the DC a clear core of Atlantic Water (AW(W)) was found flowing parallel with the DC. Most probably this water has entered the North Sea just east of Shetland (Fig.1). This conclusion contradicts statements in some earlier publications. This Atlantic water flow in the western part of the North Sea is varying with time since no trace of this water was found two months earlier.

Parts of the DC and AW(W) enters into a semipermanent topographically steered cyclonic eddy with a scale of 100 km, here for the first time clearly stated and documented.

Several branches of the DC were found to separate especially to the right of the main flow, which can be explained as a result of conservation of potential vorticity giving that anticyclonic vorticity is produced by shallowing of the current column.

East of approximately 2^{o}E a major transport of heavy and cold water was found flowing southeast toward Skagerrak along with the AW on the western slope of the Norwegian Trench. This water is most probably water from the northern North Sea plateau which have been cooled and fairly stagnant from the previous winter. This outflow might be seen upon as a result of continuity due to the inflow of the AW(W) and the Fair Isle current onto the plateu.

At last, even with a fairly strong pycnocline, there is no direct correlation between wind velocity and upper layer current velocity, except maybe for the upper 10m.

Acknowledgment

We like to thank Walter Løtvedt for extensive work on the figures, the very good crew and captain on R/V Håkon Mosby and Kjell Orrvik for computer plots.

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Figure captions

Fig.1: Major current systems with experimental area, numbered ship transects and rough bathymetry in meter.

Fig.2: Sea surface temperature distribution derived from NOAA satellite infrared image from 17.Feb.1986.

Fig.3: Vertical temperature and salinity distribution in 1987 from
a) July along $1^{0}20'$E,
b) September (this experiment) along 1^{0}E (section 12, Fig.1)
c) November along 2^{0}E.

Fig.4: Horizontal distribution of a) temperature and b) salinity at 70m depth together with drift tracks of two Argos buoys with drogues at 60m depth.

Fig.5: Vertical distribution along 3^{0}E (section 15, Fig.1) of temperature, salinity and density.

Fig.6: a) T-S diagram of CTD measurements with markings of typical watermass signatures (see text).
b) Same as a) with expanded salinity scale, also showing the downstream signature development of the major currents.

Fig.7: a) Horizontal Nitrate (mmoh) distribution at 70m depth.
b) Vertical Nitrate distribution along 2^{0}E (section 14, Fig.1).

Fig.8: Horizontal distribution of absolute currents at a) 25m depth and b) 60m depth.

Fig.9: Repeated ADCP current measurements at 25m and 60m depth along 0^{0} longitude with subtracted tidal currents at selected points.

Fig. 10: Vertical distribution of the eastward (positive) velocity component (cm/s) along 0, 1 and 2°E (sections 6, 12 and 14 respectively, Fig. 1)

Fig. 11: Horizontal circulation pattern representative for the lower layer together with 10 days average current vectors from moored current meters.

Fig. 12: Progressive wind vectors and 4 Argos drift tracks with drogues at 30m depth for the period 24 Sep. to 29 Oct.

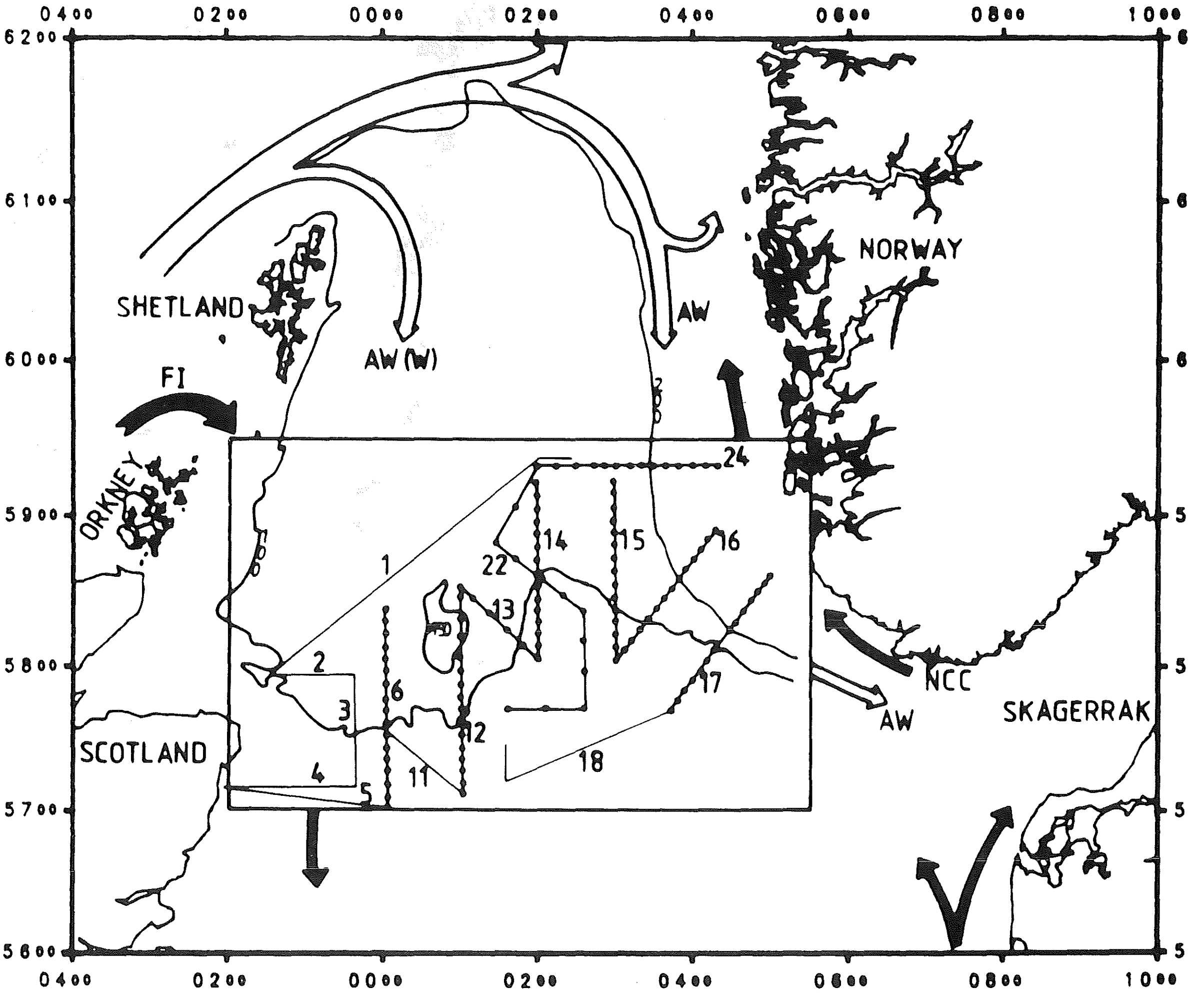

0400
0200
0000
0200
0400
0600
0800
1000
6200
6100
6000
5900
5800
5700
5600
SHETLAND
AW(W)
AW
NORWAY
FI
ORKNEY
SCOTLAND
SKAGERRAK
NCC
AW
1
2
3
4
5
6
11
12
13
14
15
16
17
18
22
24

FIG.1

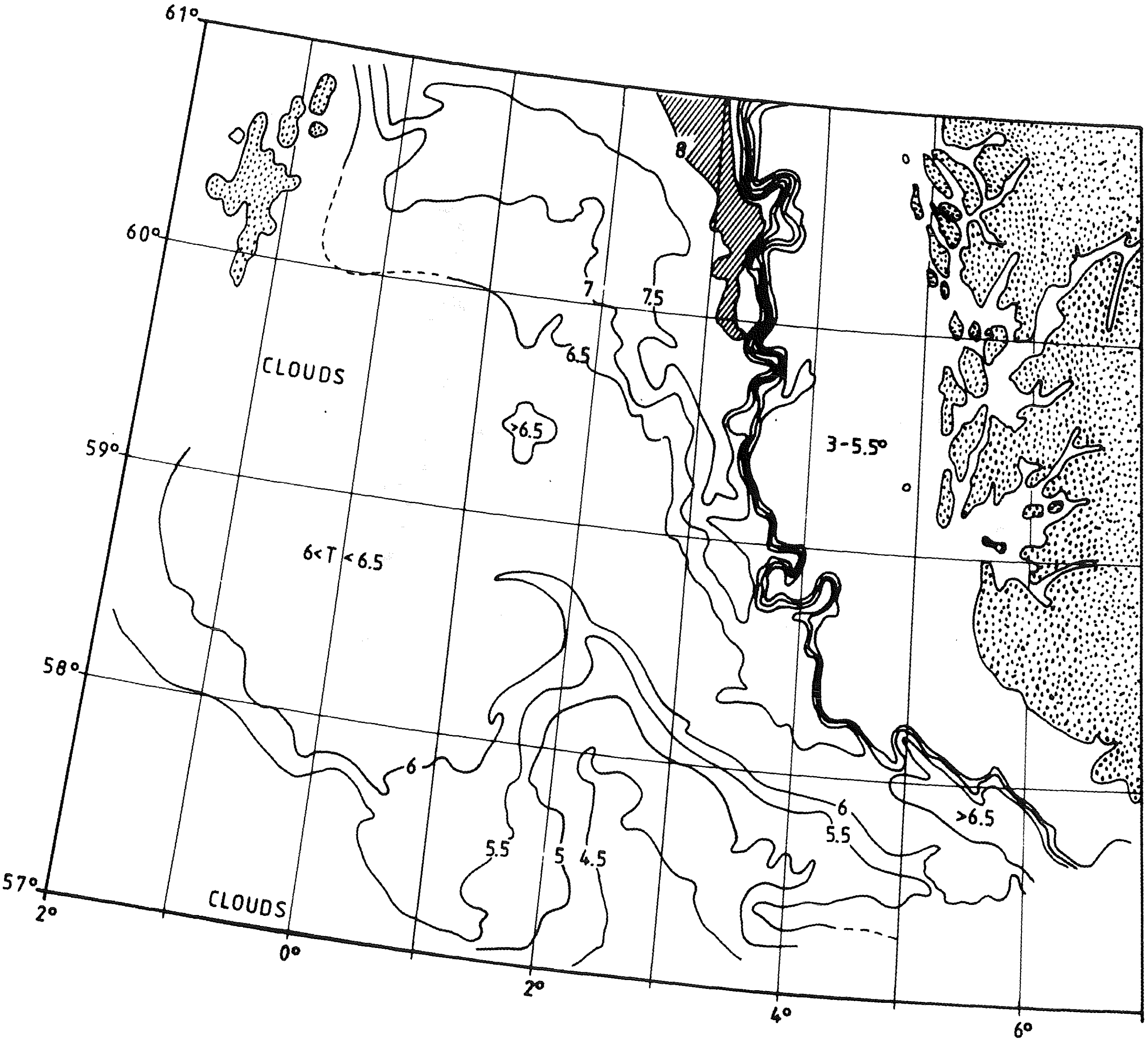
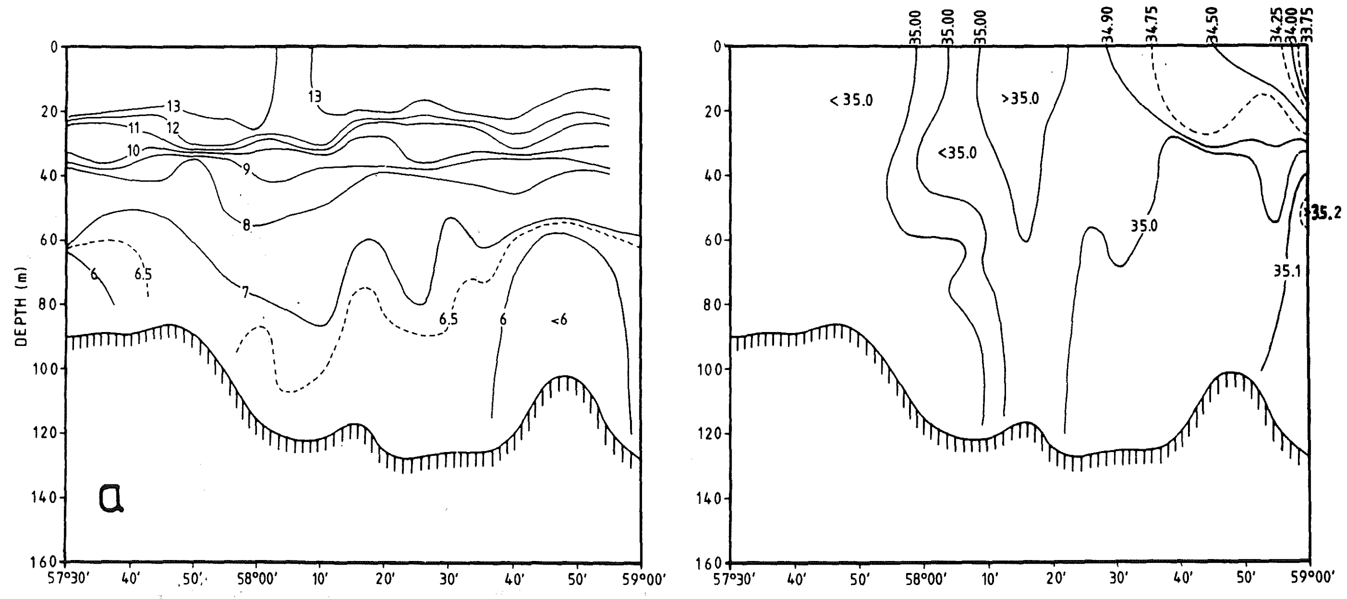
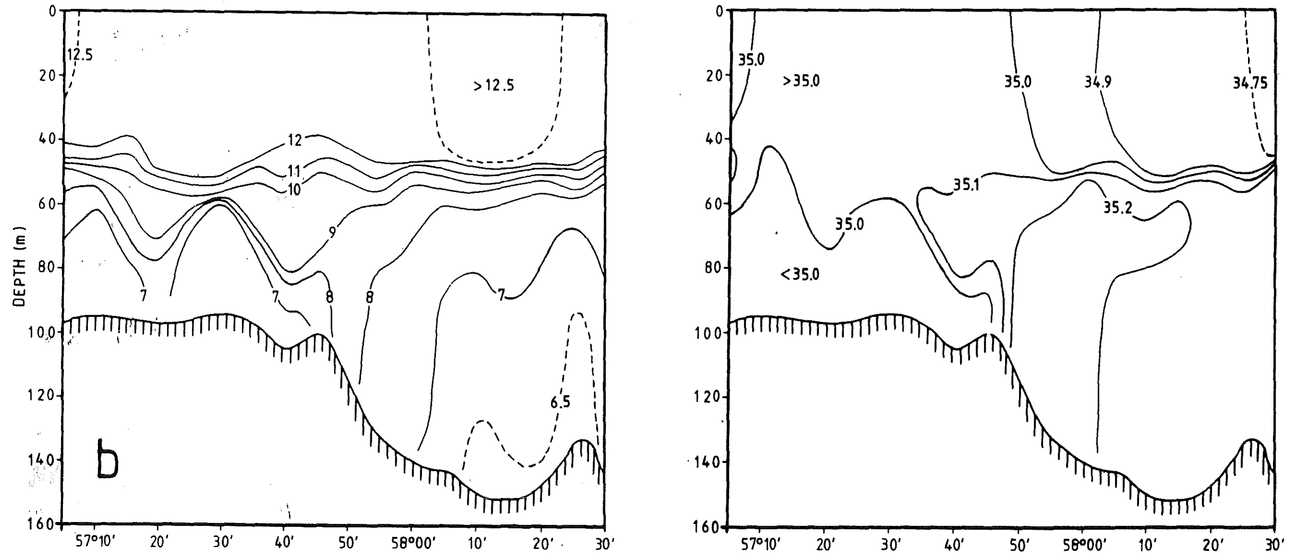

61°
60°
59°
58°
57°
2°
0°
2°
4°
6°
8
7
7.5
6.5
CLOUDS
>6.5
3-5.5°
6<T<6.5
6
5.5
5
4.5
6
5.5
>6.5
CLOUDS

FIG. 2



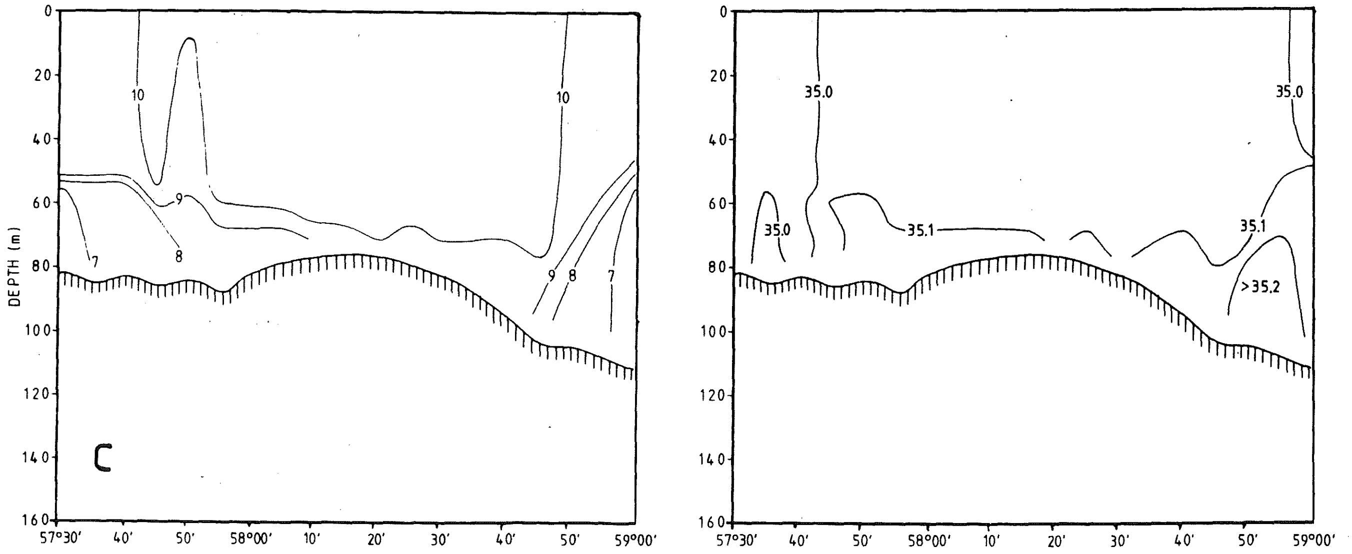
TEMPERATURE ALONG 1°20', JULY 1987

SALINITY ALONG 1°20', JULY 1987



TEMPERATURE ALONG 1°E, SEPTEMBER 1987

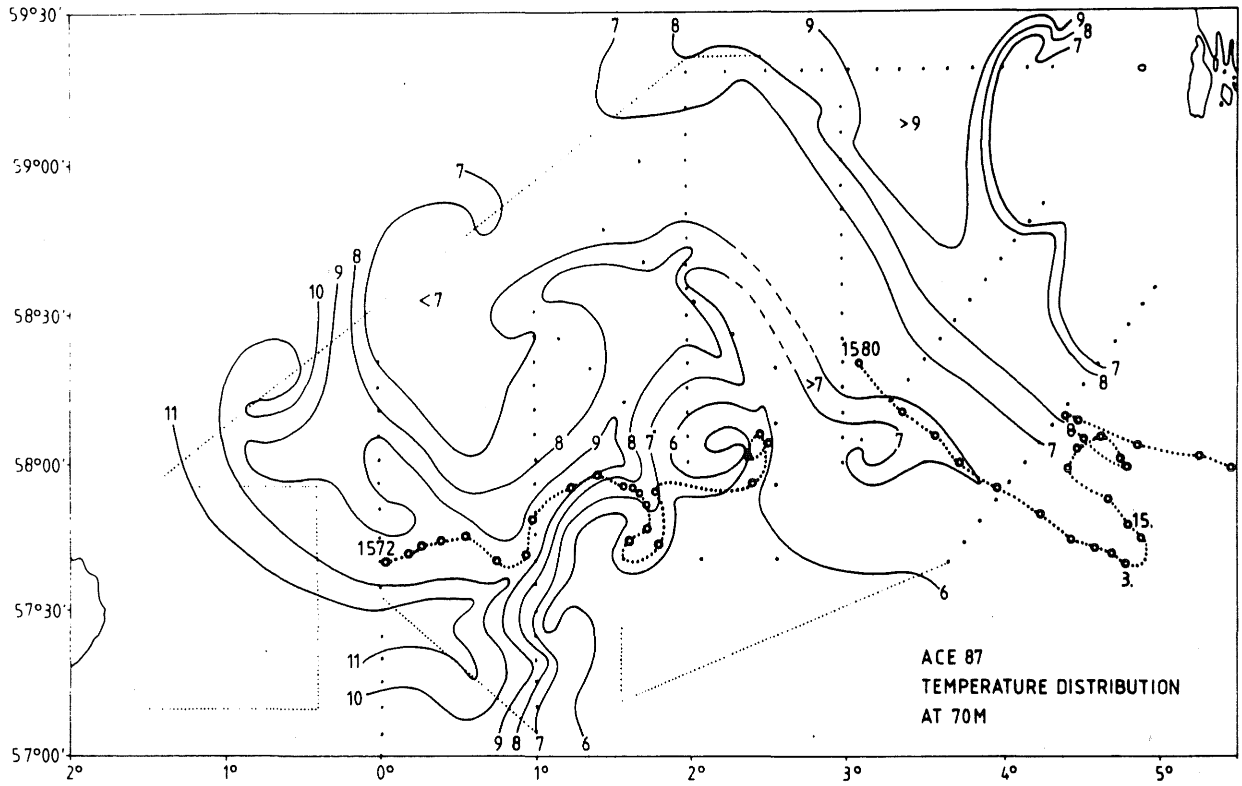
SALINITY ALONG 1°E, SEPTEMBER 1987



TEMPERATURE ALONG 2° E, NOVEMBER 1987

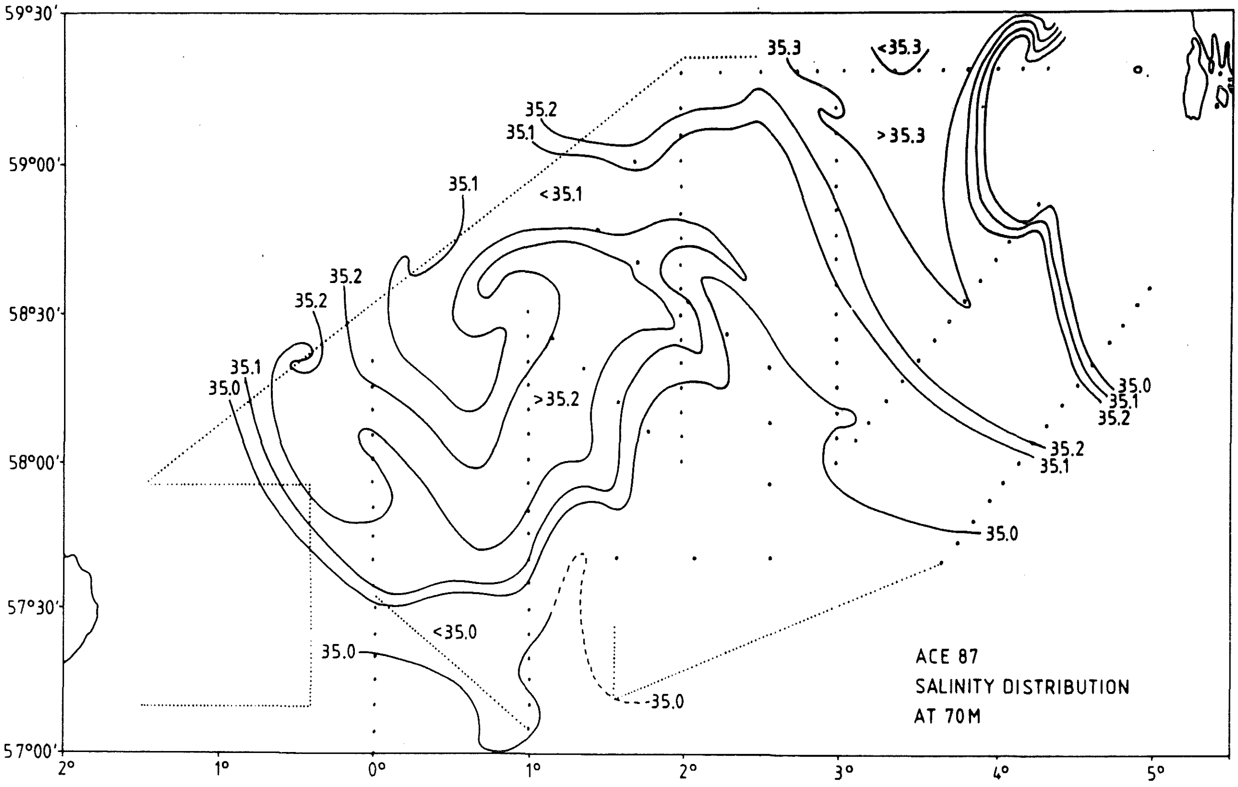
SALINITY ALONG 2° E, NOVEMBER 1987

FIG. 3



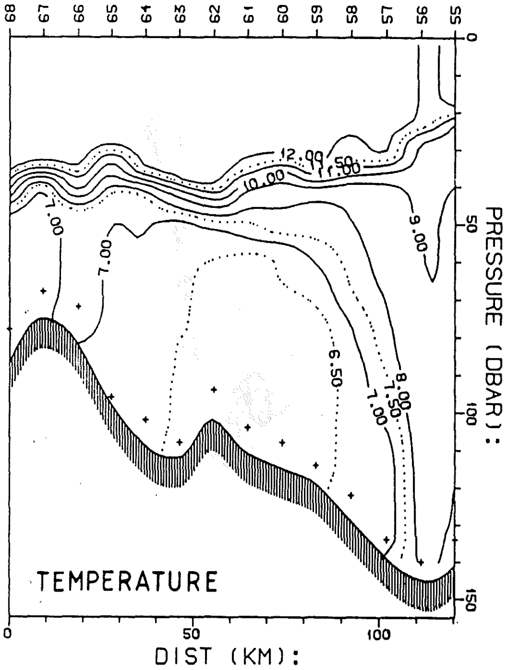
ACE 87
TEMPERATURE DISTRIBUTION
AT 70M

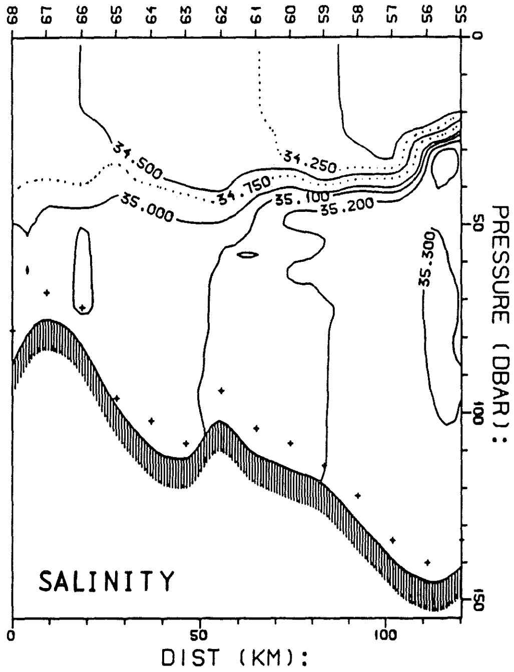
FIG. 4a



ACE 87
SALINITY DISTRIBUTION
AT 70M

FIG. 4b


TEMPERATURE
PRESSURE (DBAR):
DIST (KM):
0
50
100
150
68
67
66
65
64
63
62
61
60
59
58
57
56
55
12.00
11.00
10.00
9.00
8.00
7.50
7.00
6.50


SALINITY
PRESSURE (DBAR):
DIST (KM):
0
50
100
150
68
67
66
65
64
63
62
61
60
59
58
57
56
55
34.250
34.500
34.750
35.000
35.100
35.200
35.300

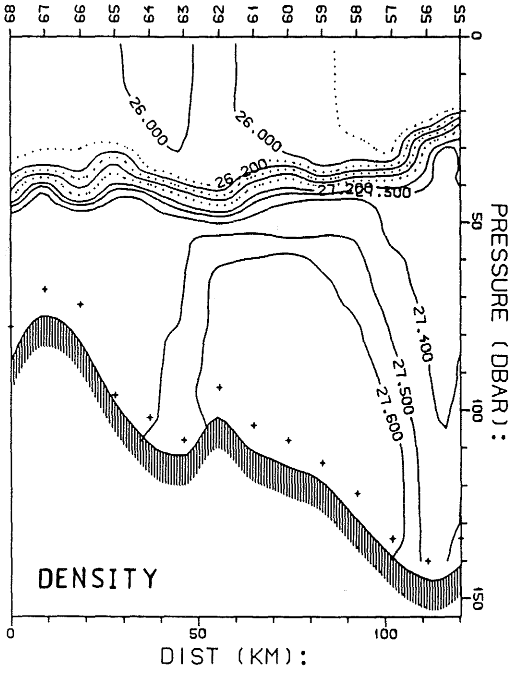

DENSITY
PRESSURE (DBAR):
DIST (KM):
0
50
100
150
68
67
66
65
64
63
62
61
60
59
58
57
56
55
26.000
26.200
27.200
27.300
27.400
27.500
27.600

FIG. 5

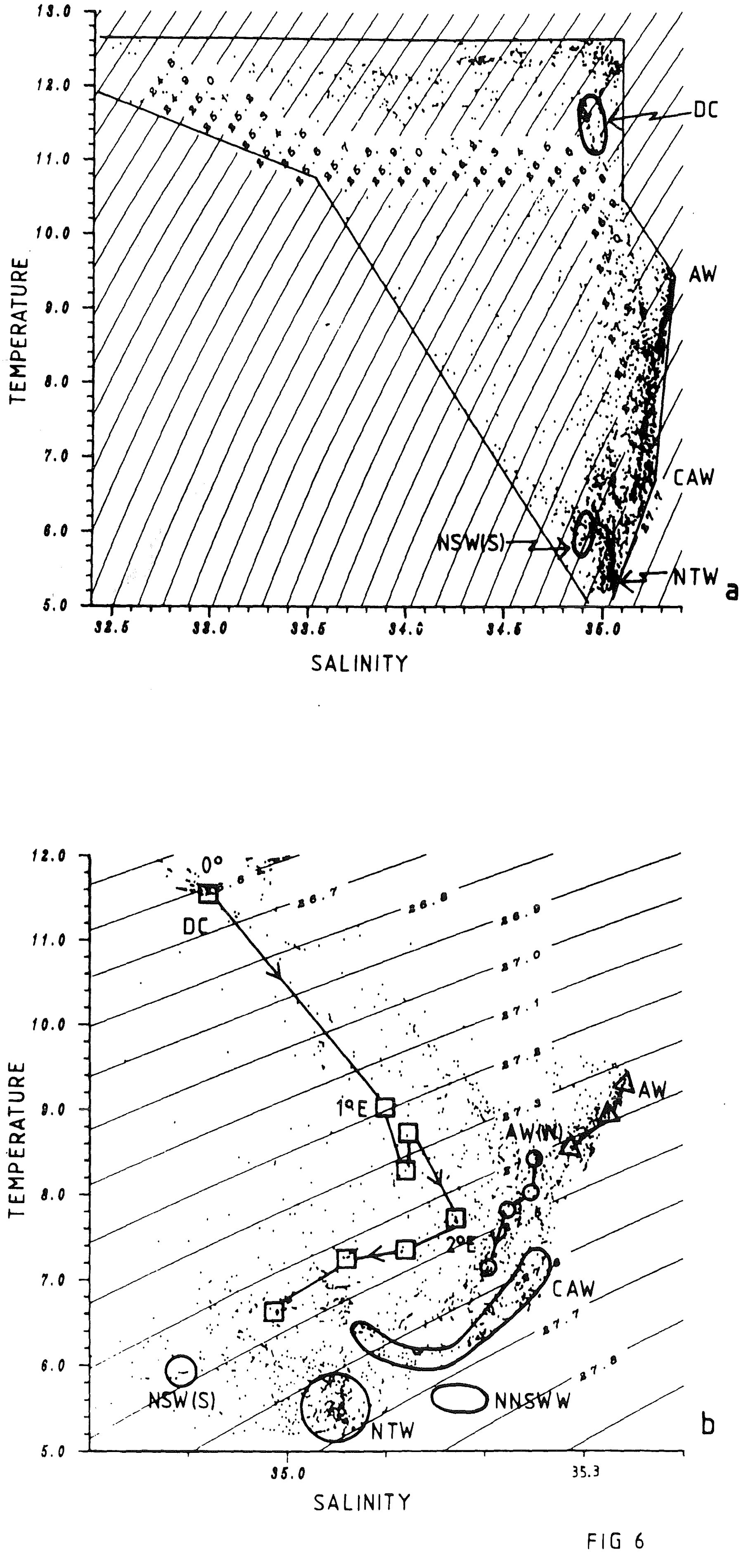
TEMPERATURE
SALINITY
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
32.5
33.0
33.5
34.0
34.5
35.0
DC
AW
CAW
NSW(S)
NTW
a
0°
26.7
26.8
26.9
27.0
27.1
27.2
27.3
27.7
27.8
1ºE
2ºE
AW(N)
NNSWW
35.3
b

FIG 6

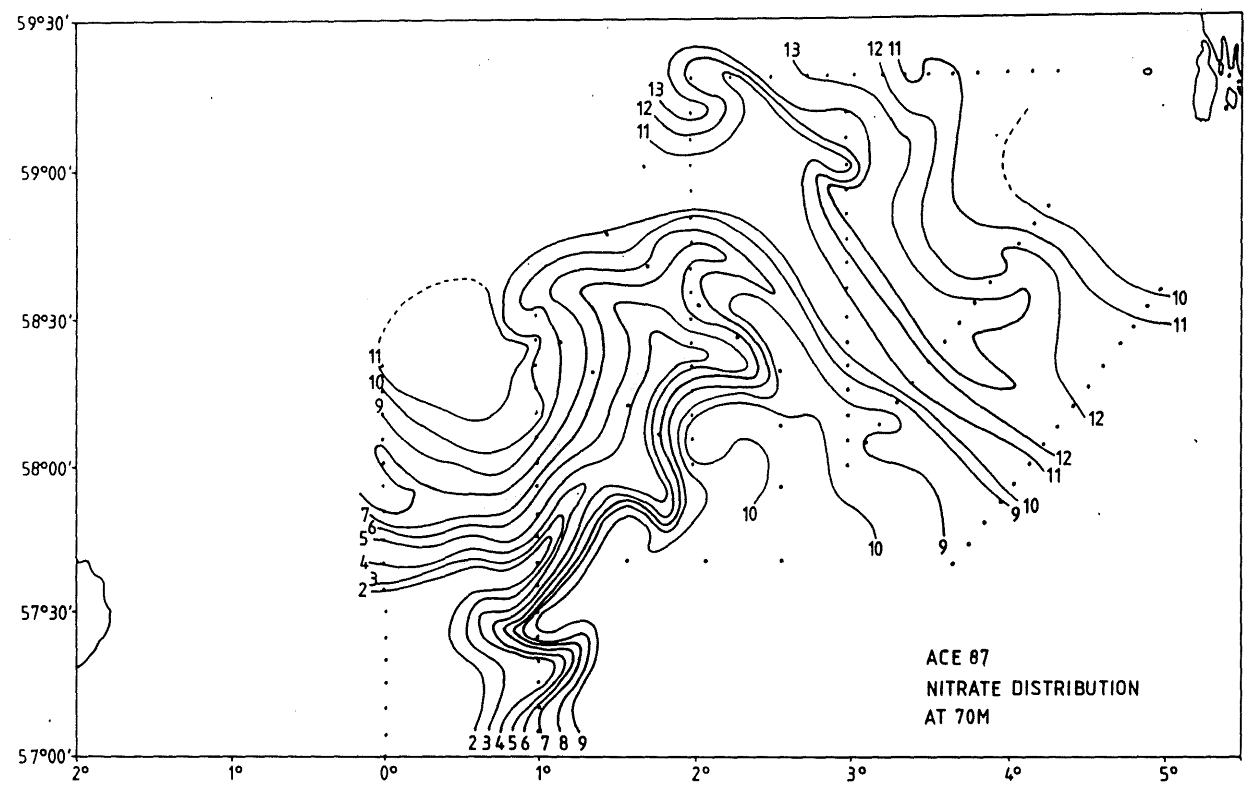

59°30'
59°00'
58°30'
58°00'
57°30'
57°00'
2°
1°
0°
1°
2°
3°
4°
5°
13
12 11
13
12
11
10
11
11
10
9
12
12
11
9 10
7
6
5
4
3
2
10
10
9
2 3 4 5 6 7 8 9
ACE 87
NITRATE DISTRIBUTION
AT 70M

FIG 7a

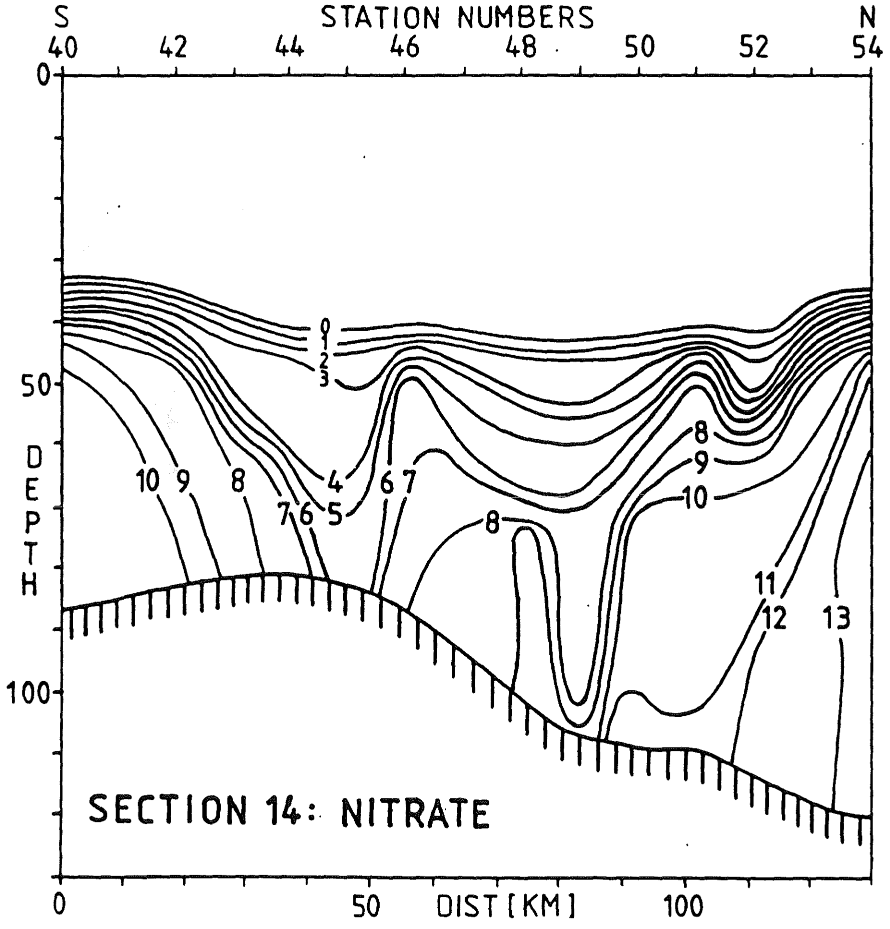

S
STATION NUMBERS
N
40
42
44
46
48
50
52
54
0
50
100
DEPTH
0
1
2
3
8
9
10
10 9 8
4
7 6 5
6 7
8
11
12
13
SECTION 14: NITRATE
0
50
DIST [KM]
100

FIG 7b

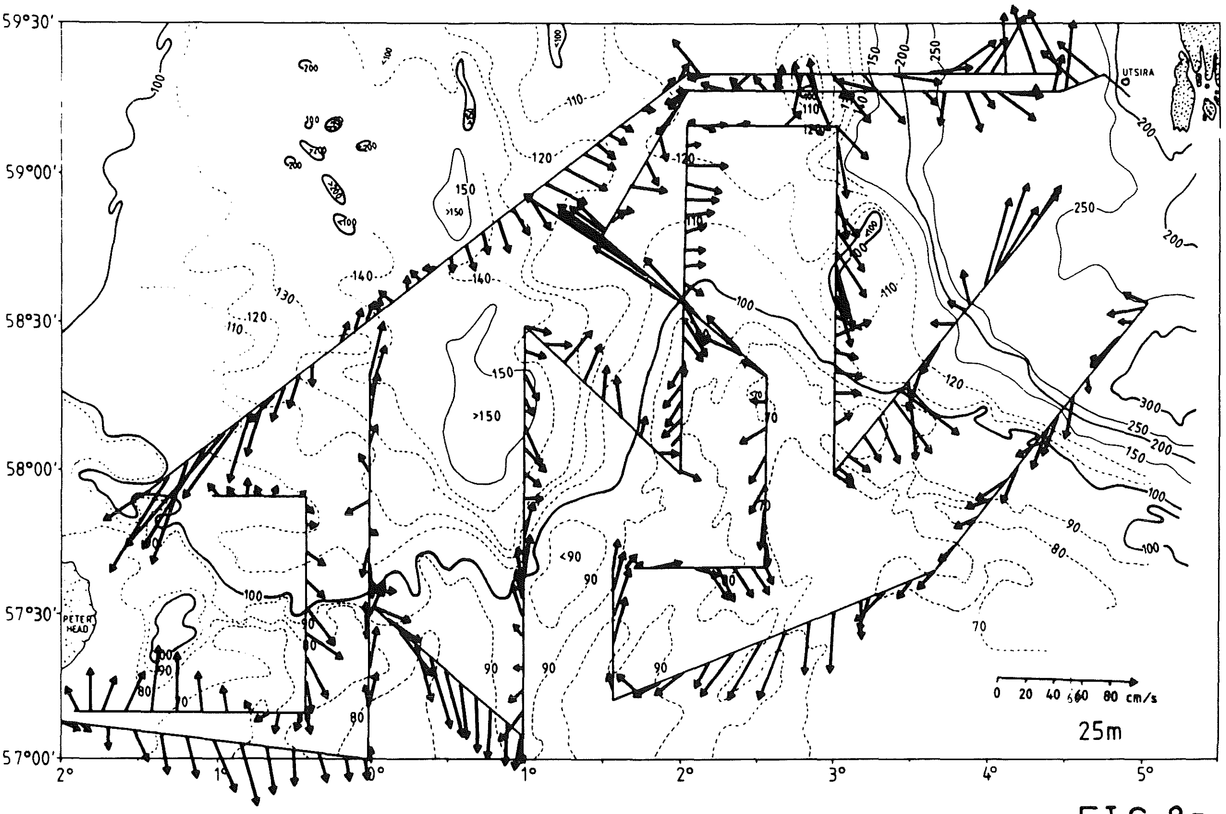

59°30'
59°00'
58°30'
58°00'
57°30'
57°00'
2°
1°
0°
1°
2°
3°
4°
5°
PETER HEAD
UTSIRA
0 20 40 60 80 cm/s
25m

FIG. 8a

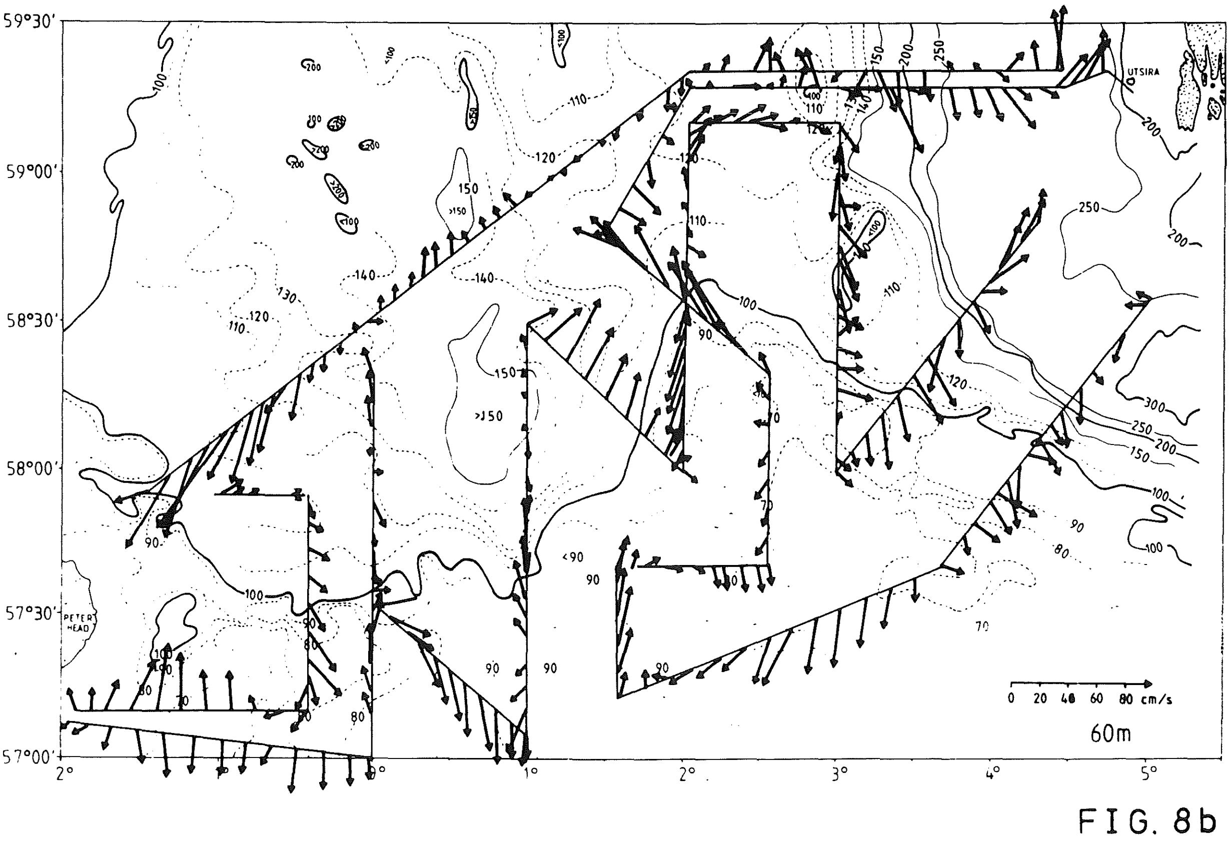

59°30'
59°00'
58°30'
58°00'
57°30'
57°00'
2°
1°
0°
1°
2°
3°
4°
5°
PETER HEAD
UTSIRA
0 20 40 60 80 cm/s
60m

FIG. 8b

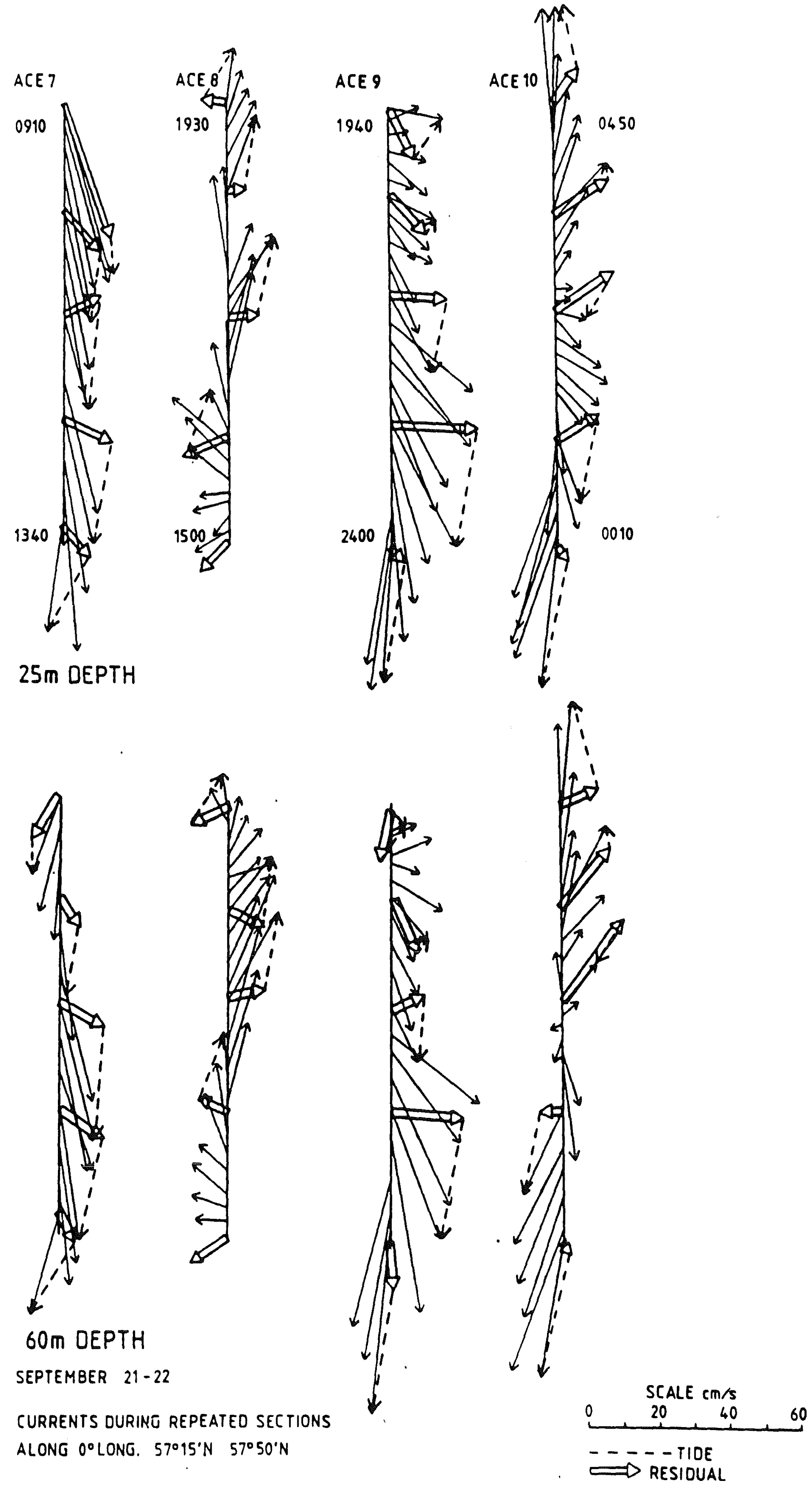
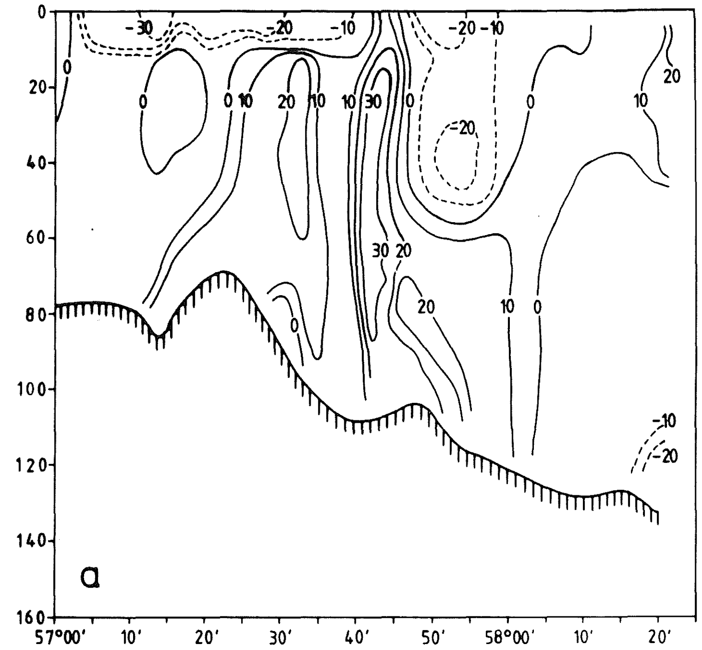
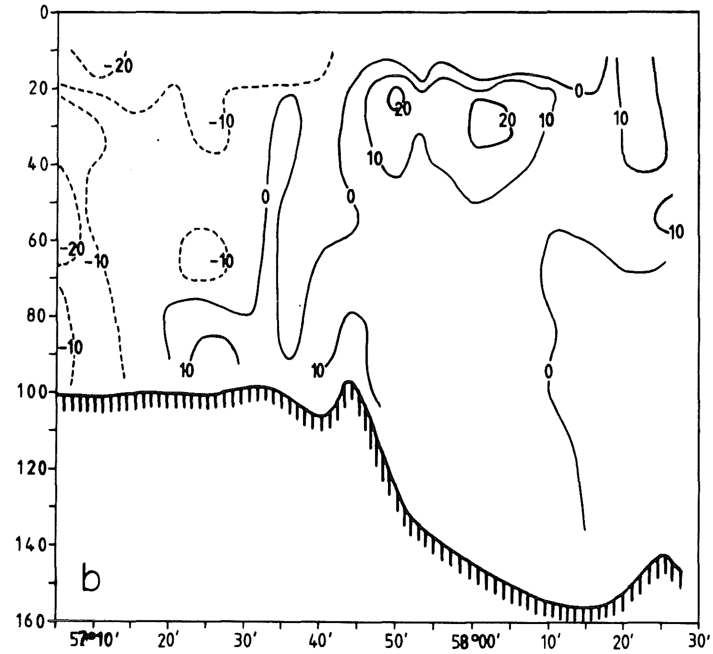

ACE 7
ACE 8
ACE 9
ACE 10
0910
1930
1940
0450
1340
1500
2400
0010
25m DEPTH
60m DEPTH
SEPTEMBER 21-22
CURRENTS DURING REPEATED SECTIONS
ALONG 0°LONG. 57°15'N 57°50'N
SCALE cm/s
0
20
40
60
TIDE
RESIDUAL

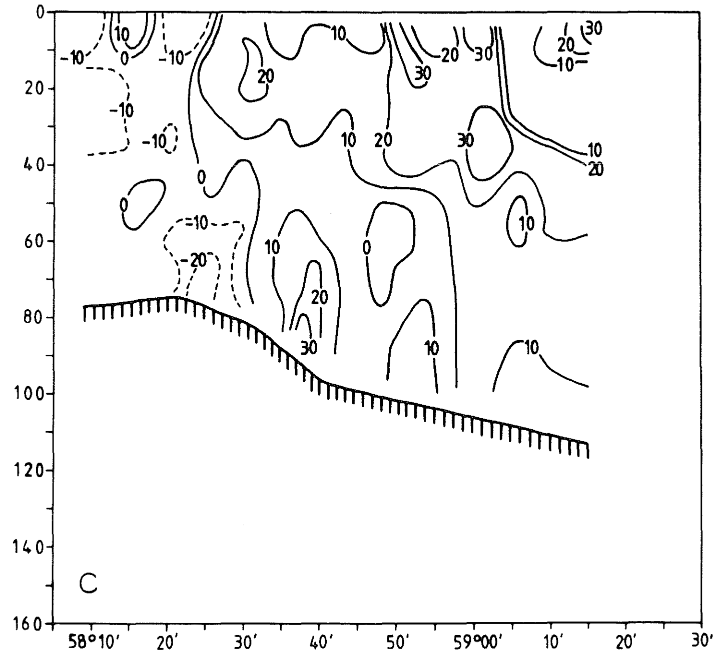
FIG 9



ADCP, EAST VELOCITY COMPONENT ALONG 0°



ADCP, EAST VELOCITY COMPONENT ALONG 1°E



ADCP, EAST VELOCITY COMPONENT ALONG 2°E

FIG. 10

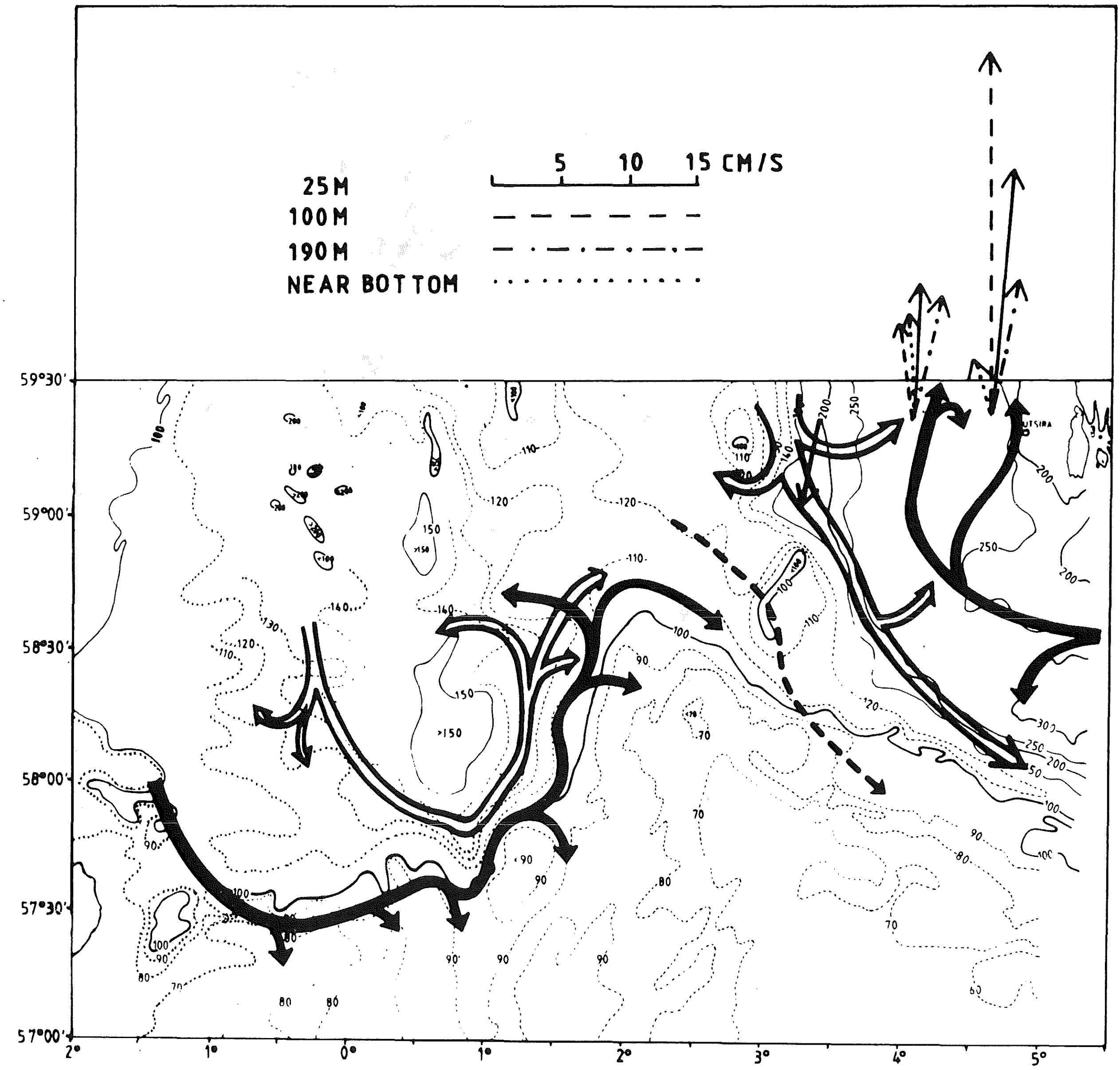

5 10 15 CM/S
25M
100M
190M
NEAR BOTTOM
59°30'
59°00'
58°30'
58°00'
57°30'
57°00'
2°
1°
0°
1°
2°
3°
4°
5°
UTSIRA
100
110
120
130
140
150
>150
200
250
300
90
80
70
60

FIG 11

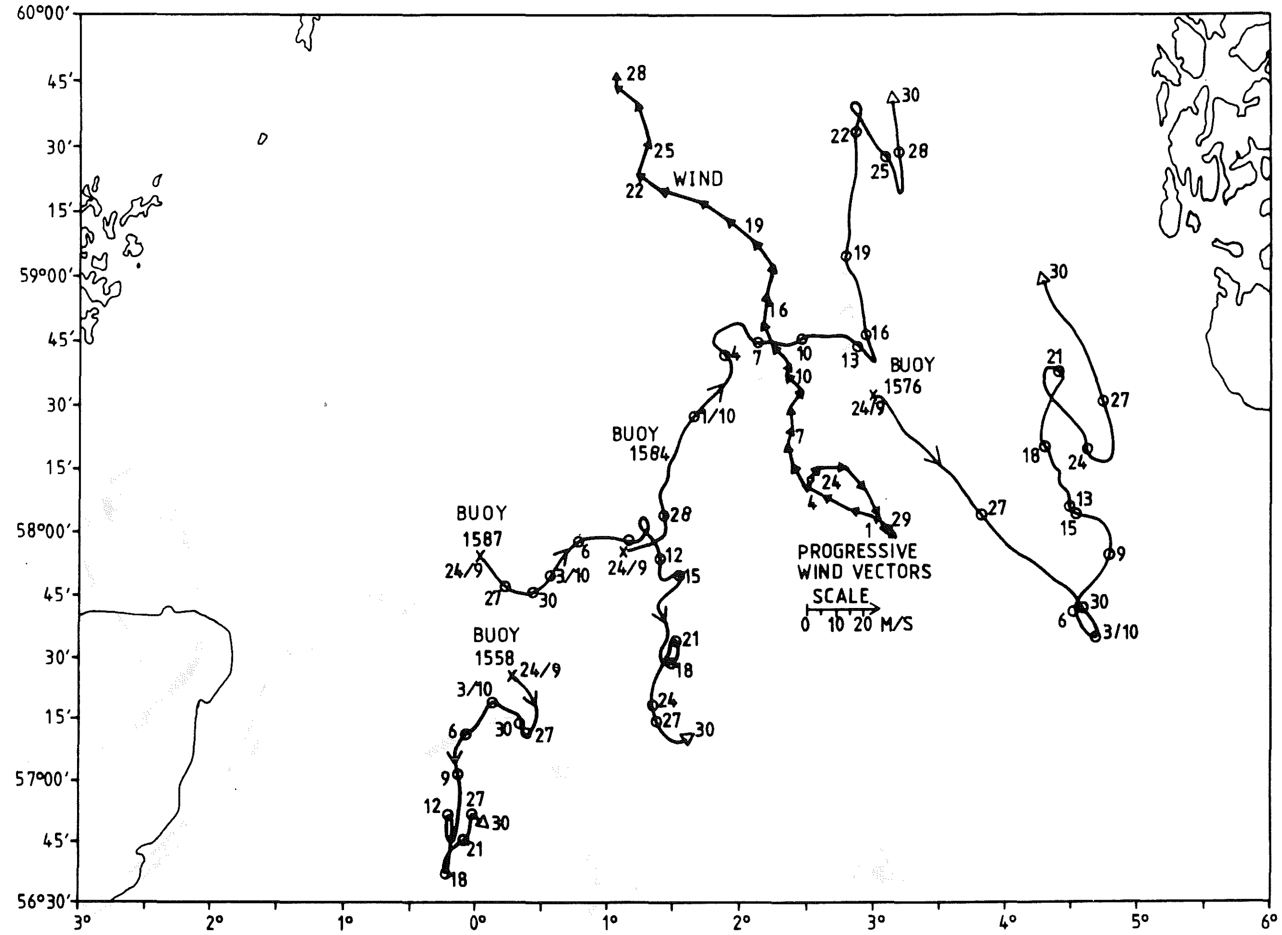

60°00'
45'
30'
15'
59°00'
45'
30'
15'
58°00'
45'
30'
15'
57°00'
45'
56°30'
3°
2°
1°
0°
1°
2°
3°
4°
5°
6°
WIND
28
25
22
19
16
10
7
4
24
1
29
BUOY 1576
24/9
16
19
22
25
28
30
13
10
7
27
30
3/10
6
9
15
13
18
24
21
27
30
BUOY 1584
1/10
4
28
24/9
12
15
21
18
24
27
30
BUOY 1587
24/9
27
30
3/10
6
BUOY 1558
24/9
3/10
30
27
6
9
12
27
30
21
18
PROGRESSIVE WIND VECTORS
SCALE
0 10 20 M/S

FIG. 12