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Larval Drift and Retention: Baltic Cod, a Modeling Approach

by

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Abstract

In order to clarify mechanisms influencing the long term trends in the reproductive success and recruitment of Baltic cod a modeling exercise was performed to examine the effects of circulation patterns in the Bornholm Basin on the advection of cod larvae. A three-dimensional eddy-resolving baroclinic model of the Baltic Sea was used to investigate the evolution of hydrographic fields in the Bornholm Basin during July 1994 with special emphasize on the transport of larval cod. Larvae drift was simulated by the addition of a passive tracer centered at the site of highest larval abundance. Simulation of the evolution of the hydrographic fields for the July 1994 period was verified by ADCP measurements and hydrographic observations taken during a survey which took place at the beginning of August 1994. Initial fields of temperature and salinity are constructed by objective analysis using hydrographic observations obtained during a hydrographic survey in the Bornholm Basin in early July, 1994. Model simulations were forced with a) realistic wind data for the period taken from meteorological observations and b) a number of different constant wind stresses (in order to examine variations in larval drift due to specific wind scenarios). Most of the observed hydrographic features found during the August survey were correctly simulated by the model. It was the intent of this experiment to estimate larval drift trajectories utilizing model simulations in order to design a sampling grid to a) test the ability of the model to estimate larval distribution patterns and b) examine the seasonal variation in transport and settling site. Comparisons of the modeled output and the physical field data suggest that an estimate of larval distribution based on the model can be made with a high degree of confidence. Estimates of larval drift as well as modeled and observed physical oceanographic features in the Bornholm Basin will be presented and discussed.

1. Introduction

In recent years hydrographic parameters, especially their influence on transport of fish early life stages, have become recognized as important parameters influencing recruiment success of fisheries stocks (e.g. Fortier and Leggett, 1985; Iles and Sinclair, 1982; Smith and Stoner, 1993 Lough et al., 1994). In order to investigate the influence of the circulation patterns on larval and juvenile distributions and variations in recruitment success, advective and diffusive fluxes have to be estimated from either empirical relationships (Sinclair et al., 1985) or from numerical simulations with physical circulation models (e.g. Bartsch 1988; Bartsch and Knust, 1994; Berntsen et al.,1994; Lough et al., 1994).

In the Baltic two cod stocks exist whose eggs and larvae are subject to be transported by circulation patterns. These stocks are the western Baltic stock, historically a minor component (Mean of 33,000 +- 12,400 tonnes; Anon, 1994), considered to be located west of the island of Bornholm, and the eastern Baltic stock, east of Bornholm (Bagge and Thurow, 1993). During recent years successful spawning of the eastern stock has been limited to the Bornholm Basin due to anoxic conditions in the other primary spawning sites (Gdansk and the Gotland Basins, e.g. Bagge et al., 1995). Fluxes of eggs and larvae in the Bornholm Basin as well as transport to larval nursery sites are presently poorly described (Mackenzie et al., 1995).

The Bornholm Basin is characterized by a distinct summer thermocline occuring at approximately 20 to 30 meters of depth and a halocline at a depth between 50 and 75 meters (Kullenburg and Jacobsen 1981; Møller and Hansen, 1994). Neutral bouyancy of cod eggs in the Bornholm Basin occurs in the region of the halocline (50-75 m) where peak egg abundances are found, with small quantities occurring in the higher saline deep layer (Kändler,1944; Müller and Pommeranz, 1984; Wieland, 1989). The larvae hatch within 15 days (Wieland et al., 1995) and begin to migrate vertically through the halocline into the shallower, low saline surface layers. At these depths larvae are transported by both the baroclinic and wind driven circulation. In order to describe potential larval drift trajectories, a baroclinic three-dimensional eddy-resolving Baltic Sea model (Lehmann, 1994 & 1995) was utilized during this study to simulate the circulation as well as the temporal development of the mesoscale distribution of cod larvae and hydrographic parameters. The experiment and simulations were based on two hydrographic and ichthyoplankton surveys, 3 weeks apart occurring during July and August, 1994. The main purpose of the experiment was to give an estimate of larvae drift on the basis of physical model calculations thereby deriving information for the design of a second survey to describe larval distributions inside and outside of the Bornholm Basin, as well as identifying potential larval and juvenile nursery areas.

2. Current system of the Baltic

The current systems in the Baltic are mainly developed due to the response to different forces:

a) windstress acting at the sea surface

b) horizontal density differences due to the impact of fresh water at the sea surface (river runoff, ice melting) and inflow of saline water masses through the Danish Straits

c) sea level inclination from the Danish Straits (low) towards the interior of the Baltic (high)

The principle response of a stratified elongated basin to wind forcing in length direction of the basin (Fig. 1) is described by Krauß and Brügge (1991):

a) For the near surface layers results an Ekman transport in cross direction, depending on the magnitude of wind stress, the eddy viscosity coefficient, and the geographical latitude.

b) The resulting Ekman transport produces a sea level rise on the right-hand coast (viewing in wind direction) and a lower sea level on the left-hand side. Downwelling occurs on the right-hand and upwelling on the left-hand side resulting in baroclinicity of the same sign at both coasts.

c) As a consequence coastal jets are produced along both coasts in wind direction, compensated by a week return flow in the central interior of the basin.

The flow field in the Baltic due to a sudden wind event is mainly determined by Ekman dynamics in the surface layer and associated inclinations of the deep density layers due to Ekman pumping or suction. The development of the mesoscale baroclinic structures in the Baltic are mainly influenced by horizontal advection, diffusive processes and the heat flux through the surface which shows a high annual variability.

The water mass exchange between the North Sea and the Baltic through the Belt Sea is controlled by the sea surface inclination mainly influenced by wind stress and bottom friction. The sea level difference between the Kattegat and the western Baltic forces a barotropic current.

3. The Baltic Sea model and initial conditions

The model is based on the free surface Bryan-Cox-Semtner model (Killworth et al., 1989) which is a special version of the Cox numerical general ocean circulation model (Bryan, 1969; Semtner, 1974; Cox, 1984). The basic equations are the Navier-Stokes equations. The horizontal resolution of the model is 5 km, with 21 vertical levels specified. Model initial conditions are the results of hydrographic surveys designed to examine the three-dimensional distributions of temperature, salinity and additional tracers. The model is forced at the surface by highly resolved two-dimensional wind fields with seasonal fluctuations of temperature and salinity included. The model domain comprises the entire Baltic Sea including the Gulf of Bothnia, Gulf of Finland, Gulf of Riga as well as the Belt Seas, Kattegat and Skagerrak. The model has proved to be suitable to simulate the major features of the Baltic Sea, these include the general circulation, mixed layer dynamics, water mass exchange between the North Sea and the Baltic, exchange between the deep basins, as well as major Baltic inflows and drift studies. A detailed description of the equations and some applications are presented in Lehmann (1995).

Within the Bornholm Basin the model was initialized with the three-dimensional temperature and salinity fields from the RV "ALKOR" (07/94) survey. For each depth level the data were interpolated onto the model grid utilizing objective analysis (Hiller and Käse, 1983). Unfortunately, no T/S-profiles were taken outside the Bornholm Basin, in the Gotland Basin to the east and the Arkona Basin to the west. In order to overcome the lack of these data to describe the initial conditions outside the basin, the general features of the Baltic were utilized. To simulate the mean spatial horizontal density gradient across the Bornholm Basin, the water column structure was taken from the most western profile (Bornholm Gat) and the position of the halocline was extended to the east to the most eastern profile (Stolpe Trench). Wind stress estimates were obtained from observations onboard ALKOR during the 07/94 survey as well as from atmospheric weather charts for the model period. Initialy during the modeled period, low to moderate northerly winds were observed. No significant wind inputs were observed after day 6 therefore wind forcing was switched off after this time. The model was then run for 21 days under these conditions in order to estimate transport and evolution of hydrographic conditions between the surveys.

4. Particle tracking model

In order to establish a Lagrangian view of the circulation in the Baltic a particle tracking model was formulated. Prognosticated Eulerian velocity fields, specified at spaced grid points, were obtained from the simulations with the Baltic Sea model serving as a data base for Lagrangian particle tracking. The calculation of drift routes from the Eulerian model velocity field was performed by application of an iterative Lagrangian particle tracking technique (Hinrichsen et al., 1995).

In order to evaluate the model's ability to reproduce the drift trajectories of passive tracers, cod larvae can be released as Lagrangian drifters into the modeled flow field. Drifters can be launched either in historical regions of peak egg and larval abundance or at locations representing successfully larvae sampling during ichtyoplankton surveys.

The model is able to take into account vertical distribution of the larvae in the water column. Furthermore, the model can be applied to simulate the vertical larval migratory behaviour. A preliminary study on the vertical distribution of cod larvae (Grønkjær, 1994) indicates the importance of vertical migration for the final distribution of the tracer fields.

5. Results

a) Comparison of survey results and drift model output

A numerical simulation of hydrographic fields using the Baltic Sea model was performed with data from RV "ALKOR" July 1994 and compared with observations on hydrographic variables, cod larvae distributions, and directly measured currents (ADCP) observed by RV "DANA" in August 1994. A detailed description of the experiment may be found by Hinrichsen et al. (1995).

During the ALKOR and other previous cruises, larval cod were found to be distributed vertically over the entire water column with the maximum abundance occuring between 30 and 40 m (Groenkjaer, 1994). Horizontally, in August 1994 the largest abundance of cod larvae was found to be located in the central region ($55^0 20' N, 15^0 45' E$; Fig. 2) of the Bornholm Basin. Additional intermediate maxima were observed in the west and southwest of the central basin. Generally, larvae were located within a uniform low saline water mass, approximately correlated to the area enclosed by the 60 m isobath. The highest abundances of larvae were found in anticyclonic retentive eddies in the Basin while in regions of upwelling cod larvae were absent.

For a detailed comparison of directly measured ADCP velocities with the modeled flow field the 33m level was chosen. The integration includes 3 days to allow the model dynamically to adjust to the prescribed mass field. For the beginning of the model integration period (day 3), the flow pattern was in close agreement with the observations obtained during the July survey (Fig.3 a,b). East of Bornholm a strong westward orientated outflow through the Stolpe Trench and an anticyclonic meander in the center region of the Bornholm Basin were the most prominent features of both flow fields. To the south of this anticyclonic eddy, a strong cyclonic circulation cell was generated being responsible for strong upwelling. Further agreement between the different current fields can be recognized in the area north of Bornholm, yielding another weaker cyclonic circulation cell. Generally, the flow fields indicate the absence of inflowing higher saline water from the Arkona into the Bornholm Basin.

The simulation of the evolution of the hydrographic fields was verified by direct current measurements and hydrographic observations taken during the DANA survey in the beginning of August, 1994. Generally, the simulated flow field at day 21 of the integration is in close agreement with the observations of the survey. Fig.4 a,b show the directly measured and simulated velocity fields of August, 1994. Typically, the currents reflect the response to the meteorological situation of the second half of July for which no significant wind stresses acting at the sea surface were observed; the circulation pattern breaks down generating an eddy field. The flow fields confirm the picture of the anticyclonic eddy in the centre of the basin as well as the cyclonic circulation east of the Bornholm Gat, although enlarged in horizontal scale.

In contrast to the July current fields (see Fig. 3 a,b), a flow component from the southern Gotland Basin into the Bornholm Basin occured at the northern edge of the Stolpe Channel. This water mass leaving the Stolpe Trench was transported to the north, mainly controlled topographically by the 60m isobath. South of $55^0 N$ the horizontal vector fields reveal a structure of larger scale, indicating a cyclonic circulation.

A comparison of modeled and measured vertical salinity distributions is represented by a north-south orientated transect through the Bornholm Basin along $16^0 E$ (Fig. 5). Note, that hydrographic observations in August extend farther to the north as for the July survey. The strong depression of the halocline near the centre of the section which corresponds to the anticyclonic circulation cell (see Fig. 3 and Fig. 4) vanishes during the temporal evolution. The doming character of the upper halocline in the south indicating an upwelling area has strongly decreased during the same time period. The overall agreement between observed and modeled salinity distributions (Fig. 5 b,c) is high. Although, not initially observed in July the inclination of the isohalines in the north is also present in the numerical simulation.

In addition to the introduction of cod larvae as passive tracer fields into the model, Lagrangian drifters were launched at locations representing successfully larvae sampling sites during the July survey (Fig. 6a). Larvae sampled in the centre region of the anticyclonic circulation structure remained within this low kinetic energy regime, whereas at the northern edge the particle trajectories show a significant tendency to leave this feature and drift towards the north. In contrast, larvae sampled at the southern edge were strongly advected towards the south, entering the southern cyclonic circulation cell. An additional anticlockwise rotating current feature was obtained for larvae sampled north of Bornholm.

During the August survey only low abundances of cod larvae were found (Fig. 6b). Successfully sampling was mainly restricted to the northwestern cyclonic circulation regime, although, the simulated larvae drift also prognosticated higher abundances in the south of the observation area (Fig. 6c). The particle tracking technique also allows a backward calculation of drift trajectories. Fig. 6d represents backward calculated drift routes as well as the larvae sampling sites of the August survey. The drift pattern supports the implication that larvae found at locations 2-6 might have their origin within the intermediate cod larvae distribution north of Bornholm (see Fig. 2). Only two sampling positions (7,8) correspond to the maximum larvae abundance initially observed within the anticyclonic circulation cell in the centre region of the Bornholm Basin. The larvae found at 9 were hatched within the second intermediate maximum distribution southeast of Bornholm.

b) Wind scenarios

Besides the work on actual data, model simulations were forced with a number of different constant wind stresses, in order to examine variations of larval drift due to specific wind scenarios.

In order to study the influence of stratification on the results, within the Bornholm Basin the model was initialized with realistic three-dimensional temperature and salinity fields of the Alkor survey in July 1994 (Hinrichsen et al., 1995). As atmospheric forcing idealized wind fields have been used. They are constant in space and time over a period of 10 days. In all cases the wind speed applied is 8 m/s which is approximately equivalent to a wind stress of $0.1 N/m^2$. The cod larvae drift was simulated by application of the particle tracking model. Larvae were released as Lagrangian drifters into the modeled Eulerian flow fields closely related to locations of maximum larval abundance observed in July 1994 (see Fig. 2). These positions are correlated to the area approximately enclosed by the 80 m isobath.

As known from a previous study (Grønkjær, 1994) the number of cod larvae showed peaks above and below the halocline. The most appropriate level of the model representing the maximum larval abundance was chosen to be 33 m. The larval drift behaviour at this level due to the response to winds coming from different directions (west, south, east, and north) is displayed in Fig. 7. Larval drift towards the west and north is mainly correlated to winds of westerly and southerly directions. At the end of the simulations (10 days) the larvae were highly concentrated in the areas north and east of Bornholm. In this intermediate layer easterly and northerly winds produce currents which are opposite to those induced by wind coming from the south and west. Drifters released north of $55^0 N$ were mainly transported towards the east representing high larval abundances in the center region of the Bornholm Basin. The prevailing drift direction for the southern part of the basin is towards the south. As can be seen from Fig. 7d, northerly winds are most efficient to transport larvae initially observed within the eastern most area of the basin from the Bornholm Basin into the Stolpe Channel.

Similar drift patterns were produced for the 57 m level (Fig. 8). Due to the response of southerly and westerly winds the compensating current in the deep layers is only weak. Drifters released within the Bornholm basin yield no tendency to leave this area. Contrary to the flow fields described above easterly and northerly winds produce strong eastward orientated compensating currents, channeled by bottom topography.

Generally, this experiment shows no significant tendency of wind induced currents, transporting larvae from the Bornholm Basin into areas west of Bornholm. Winds acting from both northerly and easterly directions, are most favourable to transport water masses and its associated tracers from the Bornholm Basin into the Gotland Basin.

6. Discussion

The utility of circulation models for elucidating transport and feeding success of larval fish has been clearly demonstrated in systems such as Georges Bank where extensive field programs have been coupled to physical modeling programs (e.g.Lough et al., 1994; Werner et al., 1995). In other regions, such as the North Sea and the Baltic, drift models have primarily been utilized for examining the potential transport of larvae without corresponding field surveys (e.g. Aro et al., 1990; Berntsen et al., 1994).

In this study, the transport of Baltic cod larvae from the Bornholm Basin was investigated during two detailed ichtyoplankton-hydrographic surveys coupled with drift model simulations. During the initial cruise survey of the Bornholm Basin the distribution of larval cod was found to be strongly influenced by circulation patterns observed by both the ADCP data from the cruise and model simulations. The highest abundances of larvae were found in anticyclonic retentive eddies in the Basin while in regions of upwelling cod larvae were absent (Figs. 2, and 3). These observations suggest that transport of larvae to nursery areas and demersal habitat is highly dependent on the spatial and temporal variablity of these eddies. In this study, in addition of introducing cod larvae as a passive tracer into the model, direct calculations of particle trajectories from Eulerian velocity fields were performed. Furthermore, the Lagrangian particle tracking technique allowed both projection of future distributions as well an estimate of drift trajectories offering the possibilty to trace larvae back to their hatching site.

The lack of success in verifying the modeled distribution of larvae with field observations during the second cruise 3 weeks later could be the result of a number of mechanisms causing the distribution of larvae to become decoupled from the modeled flow as well as the result of sampling problems. First, the modeled current velocities were on the order of half of those observed with the ADCP. This suggests that even though predicted and observed water column structure and eddy fields were similar the larvae may have been advected out of the system much faster than predicted by the model. The prognostic model dynamics strongly depend on quasi-realistic initial conditions. In order to determine a more improved baroclinic flow field as well as to obtain a realistic water mass exchange between the deep basins, additional hydrographic observations have to be carried out in the Arkona Basin, the Bornholm Gat area, and in the Stolpe Trench. Secondly, larvae may have been advected into shallow water regions or depths which were not sampled. The sampling grid did not include regions with depths less than 20 meters nor was larvae sampling performed within 5 meters of the bottom. Juvenile herring and sprat have previously been observed in high abundances in regions where the thermocline and halocline approach the bottom (Ojaveer and Kaleis, 1974; Raid, 1989). In this study, due to the sampling techniques and grid survey employed inadquate sampling of this region occurred thus larvae could have been retained in this region. Thirdly, the vertical distribution of larvae employed in the model was based on the observed peak abundance of larvae. This distribution does not neccessarily describe the distribution of those larvae surviving to later stages. The larval distribution utilized in the model should in future be based on the distribution of larvae of enhanced condition (as determined morphometrically or biochemically) as presumably these larvae have the highest probability of survival (Miller et al., 1988) although this hypothesis is open to debate (Litvak and Leggett, 1992).

The suitability of our 3-D eddy resolving baroclinic model of the Baltic Sea for examining the circulation and transport of larval cod is clearly identified in this coupled field and modeling exercise. Future simulations of larval transport are required to increase the coherence of field observations of larval transport with simulated estimates. Upon further refinement of the biological and physical inputs, model simulations will examine the variation of larval drift patterns between years of high and low recruitment success. The simulations will allow an examination of potential recruitment variability due to variations in demersal habitat and due to the effect of vertical migration on larval transport and the subsequent transport to larval and juvenile nursery areas.

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Figure Captions

Fig. 1. Schematic of wind produced currents in an elongated basin (Krauß and Brügge, 1991)

Fig. 2. Initial cod larvae abundance 30-40m ALKOR July, 1994, estimated from objective analysis, dots indicate locations of successful larvae sampling, contour interval $0.1n/m^3$

Fig. 3. a) July 1994 current field at the 33 m level obtained from vessel mounted ADCP measurements during the ALKOR survey. The velocity vectors were derived from a stream function field constructed by objective analysis b) Simulated velocity field at the 33 m level after 3 days of integration.

Fig. 4. a) same as in Fig.3 obtained from vessel mounted ADCP measurements during the DANA survey during August 1994. b) Simulated velocity field at the 33 m level after 21 days of integration.

Fig. 5. Salinity transect along 16^0E in the Bornholm Basin (a) ALKOR July 1994, (b) DANA August 1994, and (c) simulated model salinity after 21 days of integration.

Fig. 6. Cod larvae drift at 33 m for 21 days of integration (a) forward integration, dots indicate larvae sampling locations during ALKOR July 1994, (b) numbers of cod larvae observed during DANA August 1994, (c) prognosticated larvae abundance after 21 days of integration, and (d) backward integration, numbers indicate larvae sampling locations during DANA August 1994, dots indicate predicted starting points of larvae drift at the beginning of the integration.

Fig. 7. Drift trajectories at the 33 m level simulated due to the response to winds coming from (a) west, (b) south, (c) east, and (d) north. Wind speeds are constant in space and time over a period of 10 days. The wind speed applied is 8 m/s which is approximately equivalent to a wind stress of $0.1N/m^2$.

Fig. 8. Same as in Fig. 7 estimated for the 57 m level.

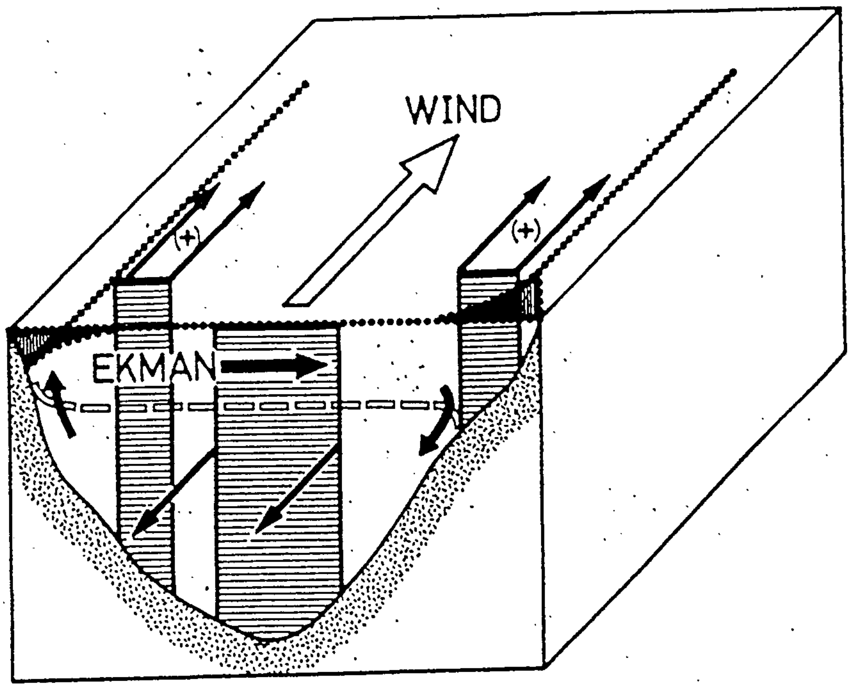


FIG. 1

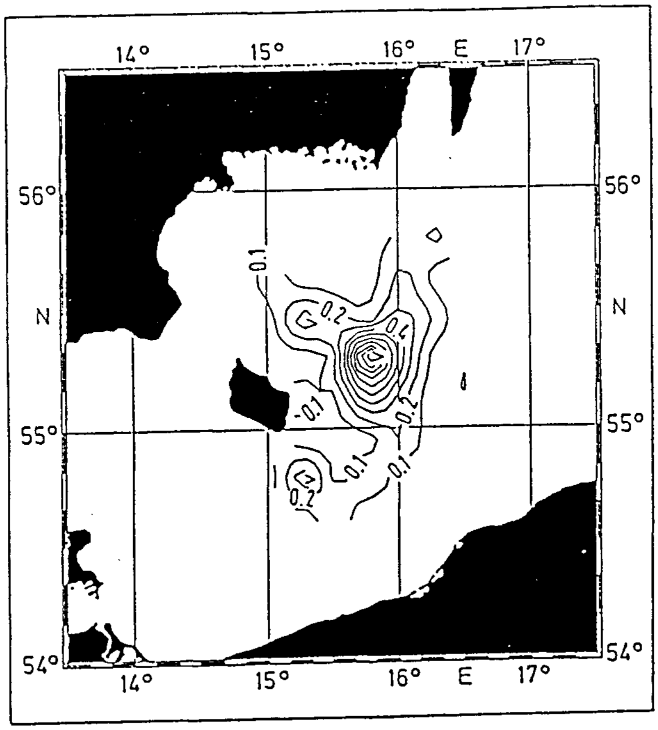


FIG. 2

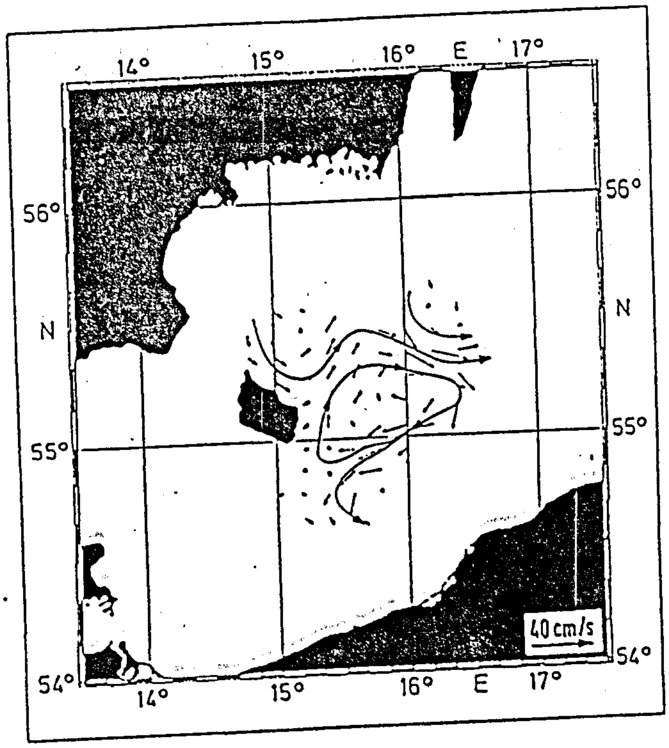


FIG. 3a

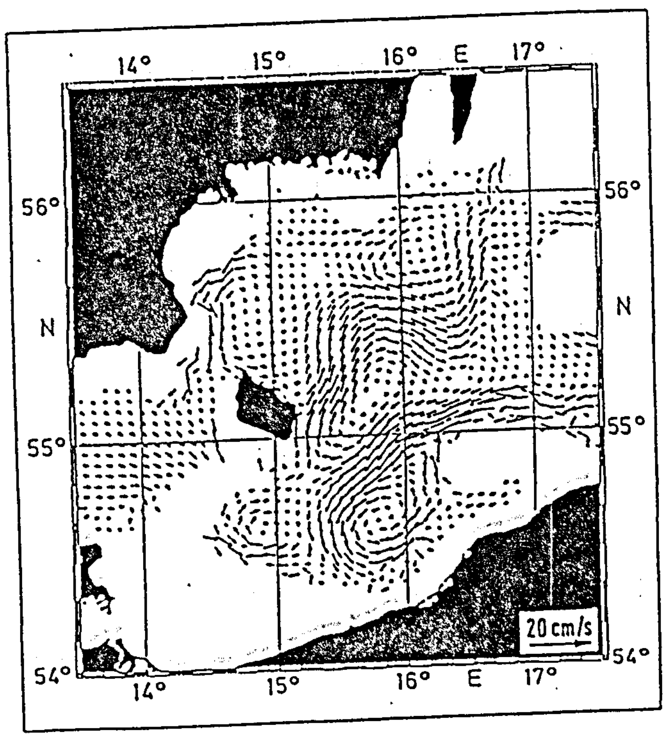


FIG. 3b

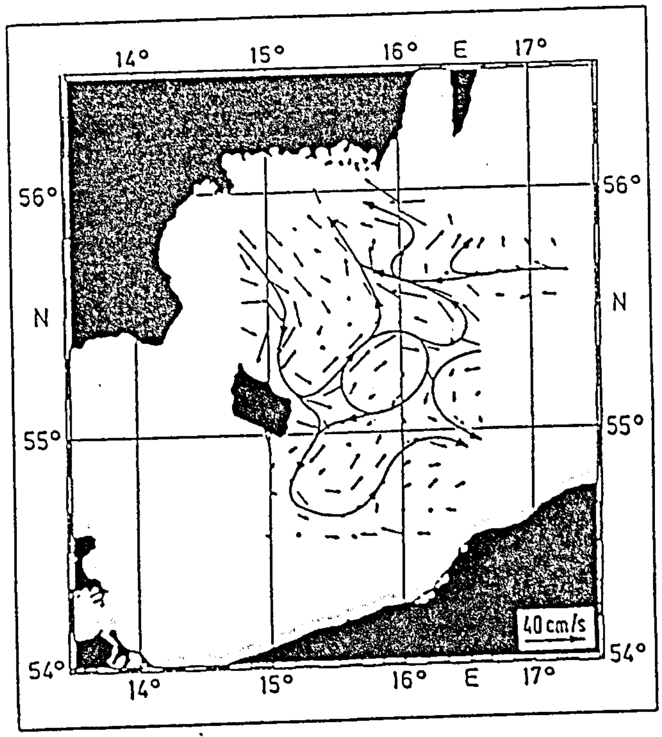


FIG. 4a

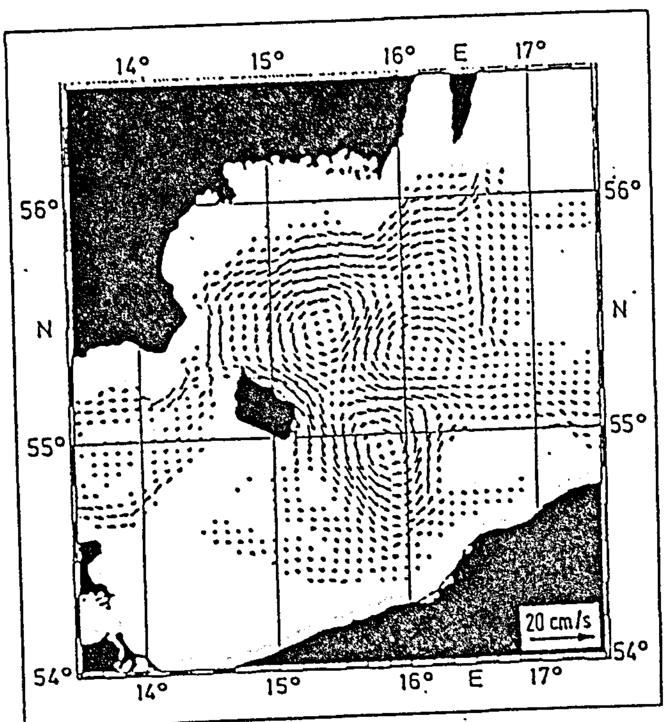
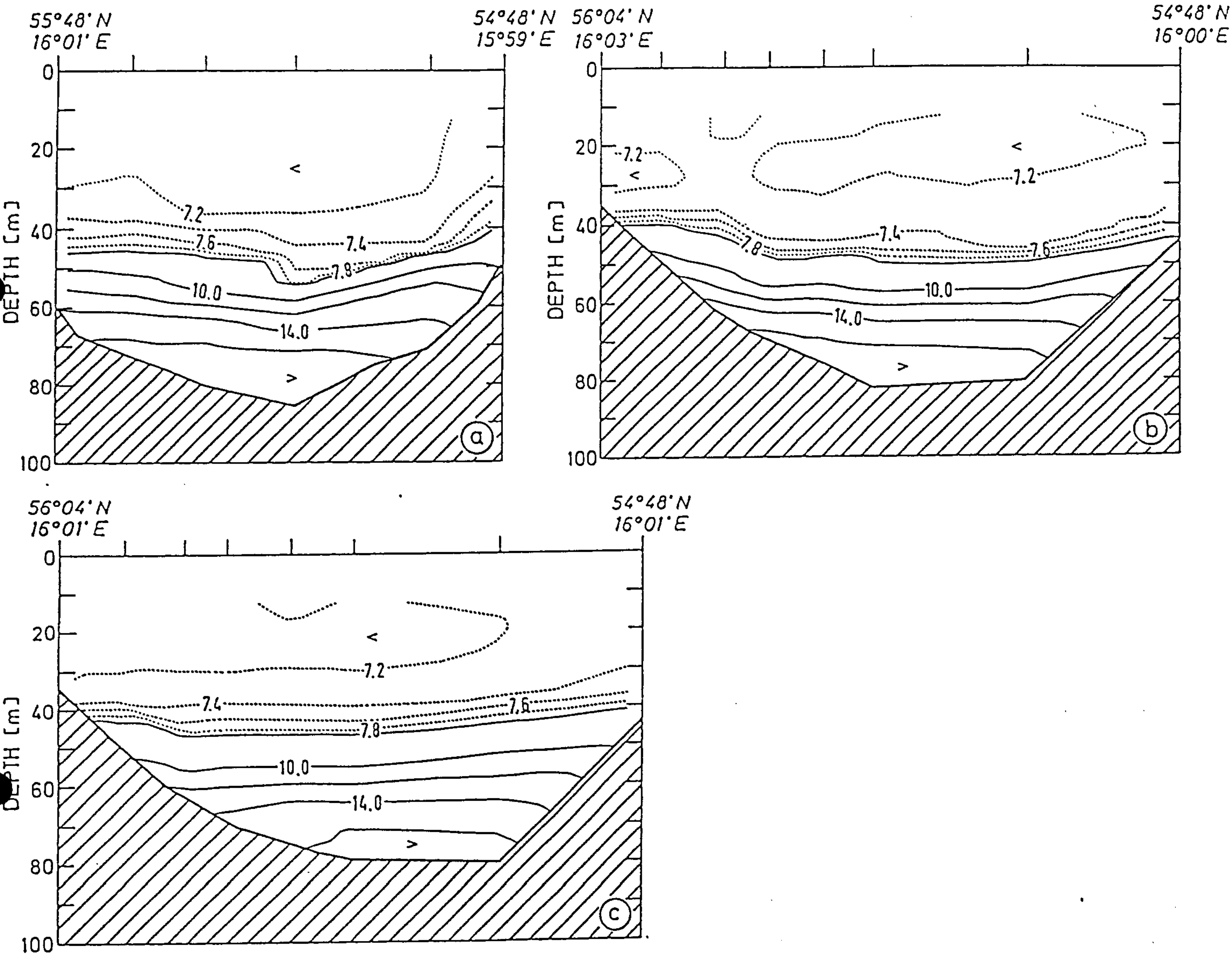


FIG. 4b



55°48' N
16°01' E
54°48' N
15°59' E
DEPTH [m]
0
20
40
60
80
100
7.2
7.4
7.6
7.8
10.0
14.0
a
56°04' N
16°03' E
54°48' N
16°00' E
7.2
7.4
7.6
7.8
10.0
14.0
b
56°04' N
16°01' E
54°48' N
16°01' E
7.2
7.4
7.6
7.8
10.0
14.0
c

FIG. 5

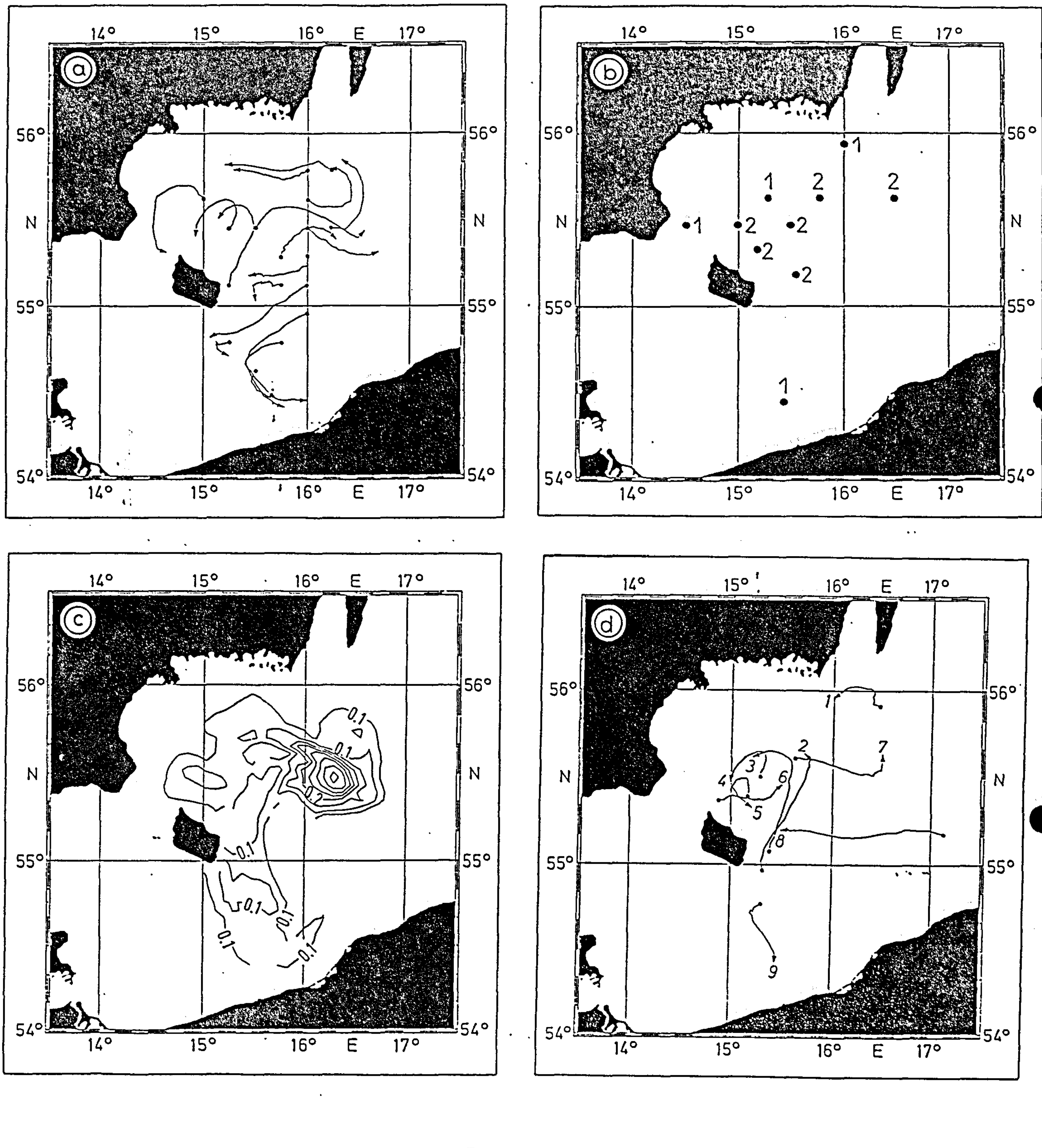

a
14° 15° 16° E 17°
56° N 55° 54°
b
14° 15° 16° E 17°
56° N 55° 54°
1 1 2 2 1 2 2 2 2 1
c
14° 15° 16° E 17°
56° N 55° 54°
0.1 0.1 0.2 0.1 0.1 0.1 0.1 0.1
d
14° 15° 16° E 17°
56° N 55° 54°
1 2 3 4 5 6 7 8 9

FIG. 6

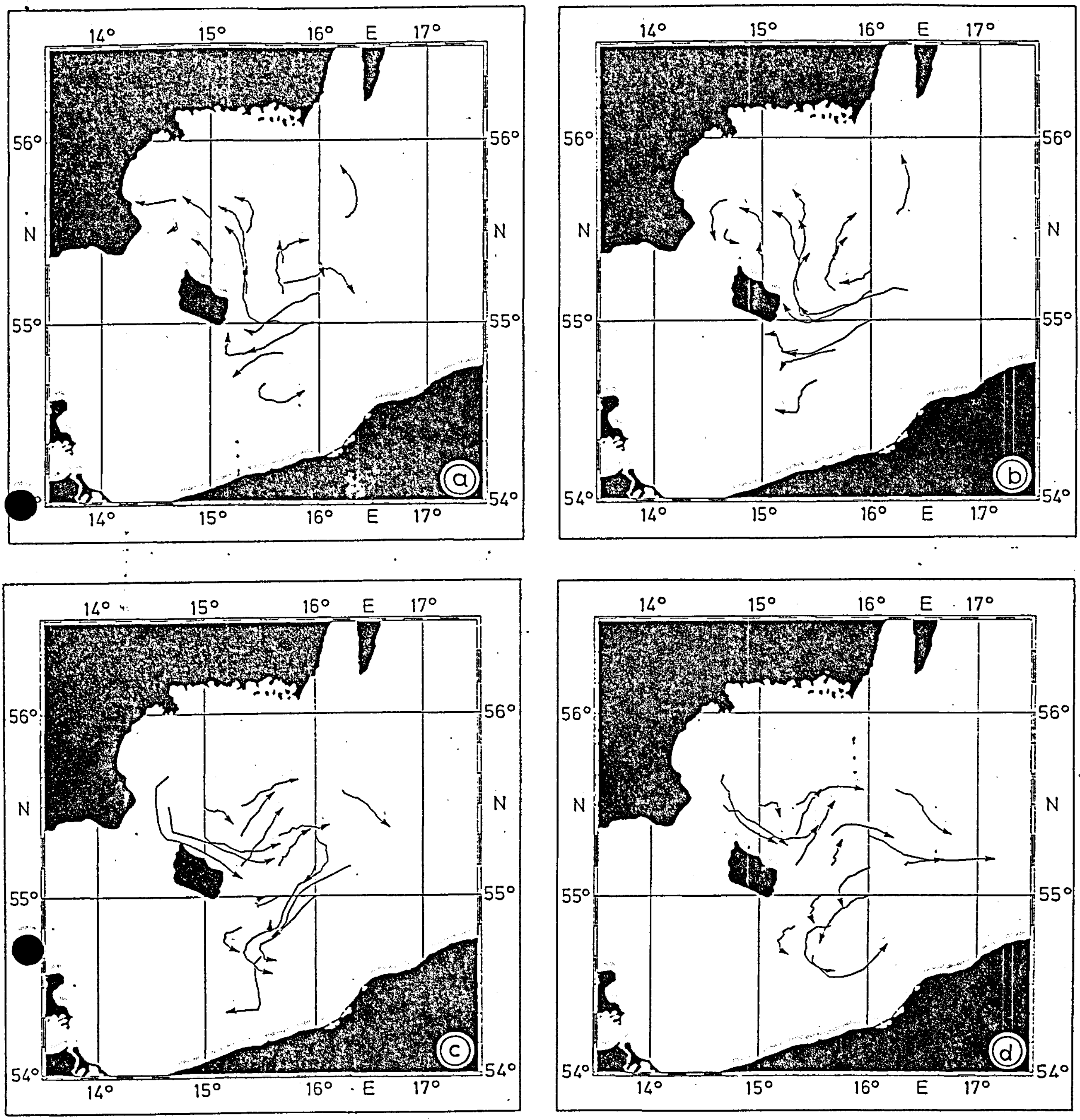


FIG. 7

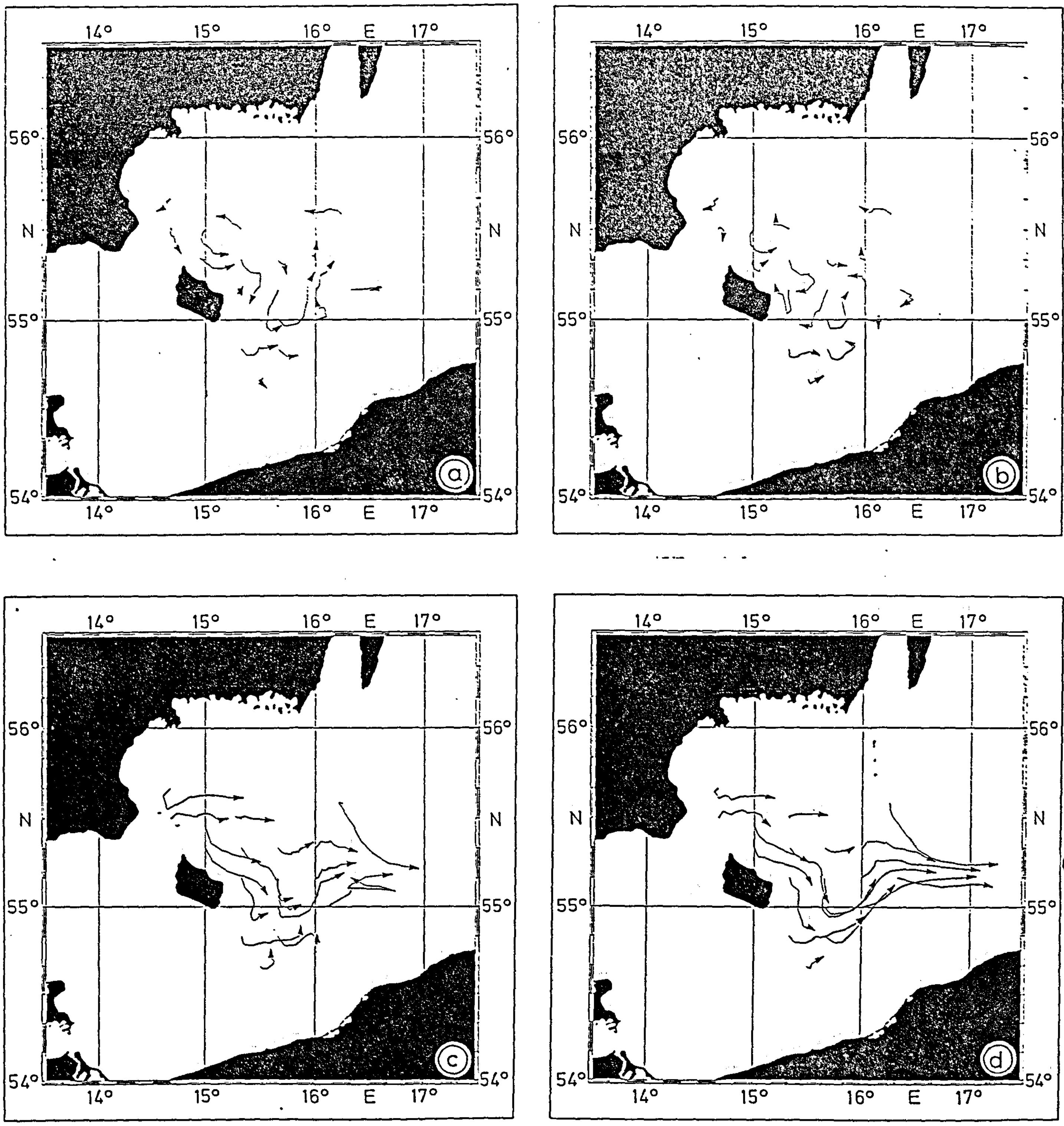


FIG. 8