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SKAGEX: SOME PRELIMINARY RESULTS

by

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1. Abstract

A series of synoptic hydrographic and biological investigations were carried out in the Skagerrak area in May-June and September 1990 and in January and May 1991 (Skagerrak Experiment or SKAGEX).

The hydrographic conditions in the area have been demonstrated to be very complicated and dynamic. Six different water masses of importance have been identified. These water masses constitute or merge into different current systems. Nitrate rich water outside the west coast of Jutland (Jutland Coastal Water, JCW) seems only sporadically to reach the Skagen and northern Kattegat area.

Typical transports of water into or out from the western Skagerrak have been estimated to be 0.5-1.5 Sverdrup in the upper 100 m with significant fluxes also below this level. The main transport of water from the Kattegat to the Skagerrak seems to take place to the west of the island of Läsö.

Blocking of surface water in the Skagerrak seems to be a frequent phenomenon. During SKAGEX I strong NW winds forced a significant upwelling of nutrient rich water at the Norwegian coast and almost 90 km offshore. Also surface water from the central and southern Skagerrak was found far south and west of Hanstholm at the southern border to the North Sea. These surface transports blocked the Norwegian coastal water to leave the Skagerrak and the Jutland coastal water to enter it.

Several eddy-like features were observed during SKAGEX I both at hydrographic measurements and with drifting buoys. Persistent eddies were found with drifting buoys in the northern Kattegatt performing for several days an anti-cyclonic and a cyclonic circulation, respectively.

Nitrite maxima were found at all larger Skagerrak sections in the core of the inflowing Atlantic water. At section G, where ammonia was also measured, a separate ammonia maximum was found. These nitrite and ammonia maxima indicate a diversified nitrification process in the water.

Over large areas of the Skagerrak and in the northern Kattegat, the maximum chlorophyll-a concentrations were recorded in subsurface layers. **In situ** primary production measurements in the northern Kattegat showed high rates of production in subsurface phytoplankton populations.

Secondary production, measured as copepod egg production, reached its highest values in the shallow areas north of Skagen. Occasionally, high rates were also found at nearshore stations west of Jutland and in the eastern Skagerrak close to the Swedish coast.

2. Introduction

2.1. Background

The Skagerrak may be regarded as a part of the transitional area between the Baltic and the North Sea. It is a very productive sea area with a production of fish of 70 kg/hectare/year, almost double that of the North Sea. The Skagerrak is thus of great economical importance to the surrounding countries. It has been stated that the major part of the continental, coastal water of the southern North Sea makes a turn into the Skagerrak before being exported from the North Sea. The Skagerrak is also a nursery and feeding area for about two thirds of the North Sea herring (Böhle, 1989). Today, the Skagerrak area is threatened by pollution from different sources, and since the hydrobiological conditions of the area are very complex and dynamic, many features are poorly known.

At the SKAGEX meeting in Moscow (C.M. 1991/C:1) it was decided that a preliminary report on the scientific results of SKAGEX should be presented at the coming ICES statutory meeting. The report should merely give a hint of what was achieved during SKAGEX (the Skagerrak Experiment). The presentation should also be of some guidance for further contributions.

The main topography, the obligatory transects investigated (A-H) and main entering water masses of the Skagerrak are indicated in Fig. 1a and b.

This paper was mainly produced at an informal meeting in August 1991 at the Institute of Marine Research, Flödevigen Marine Station, Norway, where pleasant and comfortable meeting facilities were provided.

2.2. Synoptic investigations

The planning of the ICES project SKAGEX commenced in 1988 under the leadership of Dr Bernt I Dybern, Sweden, and continued in 1989 and early 1990. During this period several meetings took place between scientists from the interested countries. The field work commenced with SKAGEX-I in May-June 1990 with a participation of 17 research vessels from 7 states around the Baltic Sea and the Skagerrak-Kattegatt area. The primary aim was to cover the sea area with synoptic measurements of key parameters at a number of transects in order to obtain data for the mapping of the hydrographical and biological conditions and to compile information on the transport mechanisms (mainly currents) and general dynamics.

The participating vessels mainly worked every third day at obligatory stations along the obligatory transects. The following obligatory parameters have been investigated: salinity, temperature, density, nutrients, oxygen, fluorescence, chlorophyll, phytoplankton, primary productivity and zooplankton. Currents have been measured by use of registrating current meters at the A- and G-sections and by use of ADCP on various sections. Satellite images have been used for the interpretation of hydrographical and biological data, and meteorological observations have been carried out.

For further details of objectives, parameters, methods used etc. the reader is referred to the "Report of the Study Group on Skagex" (C.M. 1990/C:31).

During SKAGEX-I an intercalibration exercise was carried out in Arendal, Norway, the preliminary results of which were presented at the 78th ICES Statutory Meeting (Föyn, 1990).

At an early planning stage it had been decided that three minor additional expeditions, SKAGEX-II-IV, should be carried out during 1990 and 1991 in order to cover different seasons. Five ships took part in SKAGEX-II between September 10-15, 1990 and three ships in SKAGEX III between January 12-18, 1991. During these two expeditions the most important transects were covered. The final expedition, SKAGEX-IV, took place between May 13-17, 1991, with participation of 6 vessels. On the basis of different results obtained during this final expedition was carried out in a somewhat different manner in order to get a more complete picture of the water areas between the main transects (cf ICES C.M. 1991/C:1).

The information presented in this paper is based on uncorrected data. IT should be regarded as preliminary. A very large number of SKAGEX data are still to be analyzed, especially from SKAGEX II - IV, and eventually corrected

3. Water masses

A differentiation/distinction between water masses entering the Skagerrak from the North sea and low salinity water entering Kattegat from the Baltic will be of help in understanding the circulation and the biological processes in the Skagerrak and the Kattegat. An approximate division between entering water masses is shown in Fig. 1b. In Fig. 2 a and b, the Temperature - Salinity (T - S) and Nitrate - Salinity (N - S) relations of these waters are presented.

During SKAGEX I six water masses were distinguished in the Skagerrak, and they are presented in Table 1.

Table 1. Main water masses during SKAGEX I

Water mass	**Salinity**	**Temperature**	**Comments**
SW, surface water	15 - 32	10 -15	Low nutrients, outgrown; thickness 5 - 20 m
JCW, Jutland Coastal	32 - 34	10 - 15	High nitrate, low phosphate; thickness 35 m
SNSW, Southern North Sea Water	34.8-34.9	8 - 9	Low nitrate, (0 - 1 μmol/l)
CNSW, Central North Sea Water	34.8-35.0	8 - 9	Subsurface nitrate (2 - 5 μmol/l)
AW^h, Atlantic Water high	35.0-35.15	8 - 10	Nitrate (0 - 7 μmol/l), nutrients increasing with depth
AW^l, Atlantic Water low	35.18-35.32	7.2- 8	Nitrate (10 -15 μmol/l)

Baltic Water (BW), salinity about 8, enters Kattegat at about 56° N, is mixed fairly rapidly to an approximately 10 m thick surface layer, with salinities between 15 and 20 north of 57° N. This water can enter Skagerrak both east and west of Läsö (Rydberg and and Andersson, 1989), and continues generally along the Swedish coast to the border of Norway where it turns westward as the Norwegian Coastal Water (NCW). On this route it gradually mixes (both horizontally and vertically) with water of higher salinity, and leaves the Skagerrak with salinities between 25 and 32 in the upper 10 - 20 metres.

Due to northerly to westerly winds, meandering and eddies, the BW often spreads out over large areas of the Skagerrak surface. Since the above water masses are all roughly restricted to the upper 20 m and connected to the inflow of Baltic water (BW), we define it all just as Surface Water, SW. The common features of the waters composing the SW are the gradual increase in temperature from about 10 - 15 C during the time of the experiment (SKAGEX I), and the very low content of nutrients during the whole period, due to primary production.

The picture of the water masses entering Skagerrak from the North Sea is much more complex (Fig 1b). The most dominating inflow during SKAGEX consisted of Atlantic Water (AW), with a core salinity of around 35.3, and high nitrate, phosphate and silicate concentrations closely corresponding to the Redfield ratio of deep ocean water. This water follows the Norwegian Trench from the north, and when entering Skagerrak it is found mainly between the 100 and 300 m bottom contours on the Danish side of the trench. Svendsen and Magnusson (1991) have demonstrated large year to year fluctuations in this flow, whereas the SKAGEX focus was on the short time variability.

Atlantic water is generally defined as water with a salinity above 35.0. It has been found convenient to separate the Atlantic water in a "high" (shallow), AW^h, and a "low" (deep), AW^l, part, Fig. 1b. The AW^h is especially interesting with respect to biology, because it may contain high amounts of nutrients available for primary production. Typically it was found that parts of the AW^h was directed somewhat south of the Norwegian trench while entering Skagerrak.

The AW^l was typically found at variable depths from 200 to 500 m. The distribution of nitrite and ammonia in the upper part of this water mass indicates age differences as their maxima are separated.

South of the in flowing AW^h it was also observed inflow of water from the central North Sea, Central North Sea Water (CNSW), and from the southern North Sea, Southern North Sea Water (SNSW). These water masses are separable in the nitrate - salinity diagram, Fig. 2b,in which the SNSW below the photic zone is characterized by its lack of nitrate. The reason for this, as suggested by Föyn (pers. comm.), is the difference in origin (i.e. English Channel water), with the transport route from the English Channel flowing north eastwards mainly <u>south</u> of the Dogger bank where these relatively shallow areas have a high production even during winter, consuming nutrients originally transported into the area from the Channel. During SKAGEX it was, however, found that some phosphate was left in the water mass concerned.

The CNSW (Central North Sea Water) is water of north Atlantic origin mixed with Scottish coastal water transported eastwards over a wide area north of the Dogger Bank. This water has an increasing nutrient content with depth, similar to the AW^h.

An additional water mass entering Skagerrak from the North Sea is the Jutland Coastal Water (JCW), (Fig 1b and 2). This water originates in the German Bight and is a mixture of continental river water and SNSW. The river water has a high nutrient load and depending on seasons and rainfall the discharge of nitrate is in large excess over phosphate, giving JCW a characteristic feature of extremely high nitrate and low phosphate values (in relation to the Redfield ratio).

The JCW flows northwards close to the western Danish coast, parallel with the the SNSW, gradually increasing its salinity due to horizontal mixing. As the JCW enters Skagerrak close to Hanstholmen it typically has salinities between 32 and 34 probably also due to an additional mixing with CNSW and AW^h. Due to tidal mixing and bottom friction JCW is vertically homogeneous and generally spreading over the shallow area at depths less than 35 meter.

From Fig. 2b it is clear that in principle it should be relatively easy to locate the JCW in Skagerrak and Kattegat. However, at the beginning of the experiment, due to strong north westerly winds, large amounts of Surface Water (SW) were transported south to the western coast of Denmark, and it was strongly interacting with and changing the typical signature of the JCW.

As seen in Fig.1b, all the different water masses from the North Sea are entering the Skagerrak in a narrow area of about 50 km, and clearly, a mixing between all of them (in addition to the surface water) can occur in this region.

The bottom water, below 500 m, of the Skagerrak (SBW) is partly formed by AW^l and other Atlantic winter water cooled in the northern central part of the North Sea and sank into the deepest parts of Skagerrak (Ljöen 1981 , Magnusson 1985, and Svendsen et al. 1991). As this water is only occasionnally renewed it acts like a sink for organic matter. Elevated nutrient concentrations are found demonstrated by high silicate values (10 - 14 μmol/l).

4. Some results on the water circulation

A moored current meter section located between Hanstholm and Kristiansand in the western area of the Skagerrak (Fig. 1b, Section G), and some Argos drifting buoys as well as shipborne ADCP (Acoustic Doppler Current Meter) were used to study the inflow and the circulation in the Skagerrak. The results from the current meter section clearly show a large-scale cyclonic circulation taking place at the entrance of the Skagerrak. Inflow (of which the surface part is referred to as the Jutland Current in the literature) takes place along the southern side of the Skagerrak from the surface layer to the bottom, and outflow along the northern part also extending from the surface layer to the bottom. The flow at transect G is changing direction along a vertical section above down to vicinity of the 400 m isobath. In Fig. 3 the velocity distribution is shown as the mean from three consecutive days. The total time series covers a period of 30 days (May 21 to June 20) and demonstrates that the above given circulation is indeed persistent. During the same period of time ADCP measurements along the transect from Tyborön and 70 nm northwest (Section H), exhibits similar current characteristics as those found at transect G.

Preliminary estimates from the ADCP measurements indicate a total volume transport in the upper 100 m of about 1 SV (1 SV = 10^6 m^3/s) varying with +/- 0.5 SV during the first part of the SKAGEX I. However, while studying the individual inflowing water masses in relation to the observed currents, clearly a variability of more than 100 % occurred. Significant variability in the currents appears at a typical-time scale of 1 to 2 days. For example, the JCW pulsated into Skagerrak on May 23 to 25, June 4 to 6, 11 and 20, to some extent correlated with winds from S to W. However, this water was never observed east of section F (Fig 1b) during SKAGEX I. Similar pulsating behaviour of the JCW was found during the other SKAGEX missions.

As seen in Fig. 3, there often seems to be a clear core of maximum velocities into the Skagerrak located along the area approximately between and above the 35-80 bottom depth on the Danish side. This bottom depth range represents most of the southern and central North Sea, and the drastic focussing on especially this topographic range at the entrance to the Skagerrak can easily explain the maximum velocities. However, the most interesting findings are the shifts in water masses which this flow represents. By combining the currents with the salinity and the nitrate observations (below the surface layer) from May 20 until June 1 mainly the AW^h (partly mixed with CNSW at the beginning) was represented in this core. From June 1 to June 3 the inflow of AW^h was reduced and replaced by SNSW. For the rest of the experiment it seems that it is mainly this SNSW with nearly no nitrate, which is entering the Skagerrak in this area with the exception of the end of the experiment on June 20, when the SNSW is again replaced by the AW^h.

As stated above the deeper and the main parts of the Atlantic Water was in general flowing into the Skagerrak on the southern side. This flow, however, seems to have turned into a week outflow during the period June 6-13, although the current meter observations are sparse (Fig. 3, June 8 and 11).

The surface layer in the Skagerrak (SW) extended to the halocline, which in general was found at 20 m depth. It covered the whole inner part of the Skagerrak area with low salinity water (<31). Below the halocline the nutrient distribution (nitrate) shows weak vertical but strong transversal gradients with maximum values around the zero velocity zone (cf Fig. 14). This feature dominated all the transversal transects in the Skagerrak during SKAGEX I. An example of the nitrate distribution at 50 m depth is shown in Fig. 4. The largest nitrate concentrations are found in the central parts of the Skagerrak, extending from transect H towards the inner parts. A similar nitrate and chlorophyll distribution in the Skagerrak has been found, among others, by Pingre **et al** (1982). In a review paper by Richardsson (1989) it was suggested that these characteristic distributions involved both biological, chemical and physical processes. Regarding the SKAGEX I study, and at the present stage, it is assumed that this nutrient distribution may be intensified by an upward transport of deep water, which is driven by an Ekman pumping forced by the large-scale transversal geostrophic velocity shear (cf Fig. 3). This more or less continuous pumping of nutrients towards the euphotic zone may be the feeding mechanism for the high biological productivity generally observed here (cf. Fig. 12,15,17).

Fig. 4 also indicates an enhanced lifting of the nutrients in the eastern Skagerrak. This might be caused by a similar process, but probably intensified in this area due to topographically steered recirculation around the deepest parts in the Skagerrak. This feature is often referred to in the literature as the "dome", but the SKAGEX data indicate that this "dome" is highly variable and at times not present. Fig. 4 also indicates some mesoscale upwelling features in the salinity distribution, which will be discussed later on.

Several drifting Argos buoys were deployed with draughs at 10 m depth in order to study the drift currents in the surface layer of the Skagerrak. Some drift tracks are shown in Fig. 5. In general the surface drift is in accordance with what is expected from earlier investigations and thus conforms to the cyclonic circulation in Skagerrak. Several of the Argos drifters coming from north of Skagen go straight east towards the Swedish coast and either turn northward along with the coastal water, or south into the Kattegatt following the bottom topography (trench). Just to the north of Skagen the eastward transport is converging along the coast, resulting in a high velocity jet stream strongly interacting with the northward outflow of the lighter KSW (Kattegatt Surface Water). This interaction between currents of more or less different directions and of varying strengths, implies that this might be an area for the initiation of meanders and eddies (discussed below). There are also indications that this jet stream is so strong that it totally may block the outflow from the Kattegatt.

5. Some specific features

5.1 The blocking event on May 24 to 29

Blocking events of the Skagerrak surface water during strong westerly winds are well known. It causes piled up water in the inner Skagerrak, which after the wind has ceased penetrates along the Norwegian coast as a coastal rotating gravity current (Mork and Saetre, 1980, Mork, 1981, Johannesen **et al**, 1989 and Håkansson **et al**, 1990). However, less attention has been focused on the blocking event itself and its implications on other currents and water masses in the area (i.e. Saetre **et al**, 1988 and Håkansson, 1990), like the winddriven upwelling, occurring along the Norwegian coast as well as the spread of the surface water in Skagerrak .

During May 24 to 27 a strong upwelling driven by winds from NW was observed both with **in situ** and remote sensing data. The wind event lasted for 4 days with speeds from 5 to 15 m/s. An example of the wind distribution, calculated by using an objective analysis technique is shown in Fig. 6. The wind driven Ekman transport forces surface water offshore along the southwestern part of the Norwegian coast, which for continuity reasons are replaced by cold upwelling water. The upper satellite image in Fig. 7, showing the sea surface brightness temperature, is indicating the time evolution of the upwelling as well as the size of the area. The horizontal distribution of the surface water salinity and nitrate are shown in Fig. 8. These maps have been elaborated on the basis of data from ship measurements on May 27, demonstrating that the upwelling area is also characterized by high surface water salinity (>33) and nitrate (>5 umol/l). The upwelling continues for three days, whereafter the warm surface water in the Skagerrak is spreading above the upwelled water along the coast (cf. Fig. 8 and the lower image from May 28, 1990). The upwelled area is probably limited in the alongshore direction by the curvature of the coast, since the upwelling is most effective when the wind direction is parallell with the coastline. The offshore extent should depend on the strength of the wind impulse as well as the thickness of the surface layer.

During the same event the northwesterly winds also transported SW, generally found along the Norwegian coast of the inner Skagerrak, as far south as to the Danish coast at Hanstholm. This is most clearly indicated in the satellite image from May 25 and in the maps of surface salinity and nitrate distribution shown in Fig. 7 and 8, respectively. Note also, that the currents close to the shoreline is heading south on May 27 (Fig. 3), indicating that the JCW is blocked during this event. According to the satellite images from May 25 and 28 warm SW can also be found far west of Hanstholm in the North Sea. This water mass is also of low salinity and nitrate according to Fig. 8. It thus appears that northwesterly winds can spread the surface water of Skagerrak to a large extent and in manner which is not previously well documented.
It should also be noted that upwelling was observed along the Swedish coast in the northern Kattegatt during May 28 and 29, and during May 3 and 4 along the Norwegian coast in the inner part of Skagerrak.

5.2 Mesoscale features

The well known topographically steered subsurface transport southward in the Kattegatt is during SKAGEX also clearly seen (by several Argos drifters) to affect the near surface current. At 10 m depth, the southward flow seems to stop close to 57°20'N. Clearly much of the outflow of the KSW/BW to Skagerrak is to be found on the Danish side and this might be caused by a barotropic effect caused by the southward flow along the trench on the Swedish side. This tendency for an anticyclonic velocity shear can produce an anticyclonic eddy as indicated in Fig. 9, showing an Argos drifter rotating for more than two weeks (June 2-18) on a scale of about 20 kilometer.

As mentioned earlier it is assumed that the eastward jet stream from Skagen interacting at varying strength with the KSW might produce meanders or eddies. Johannessen **et al.** (1989) described a similar process on the west coast of Norway where the AW interacting with the NWC produced a strong eddy downstream in the NCW. Fig. 10 showing the horisontal salinity distribution obtained May 23-25,demonstrates such a cyclonic eddy at about 58°10' (downstream relative to the outflowing KSW) with a scale of about 50 km, and a cyclonic eddy was observed in this region several times during SKAGEX I. The typical upwelling in the center of the eddy in this region is clearly shown in the salinity distribution in Fig. 4 (June 15-17), and historical data from the Inst. of Mar. Res., Norway, indicate that such an upwelling is present here most af the time (Danielssen, pers. com.). In addition to what can be recognized in several of the horizontal distribution maps, this eddy was also tracked by a buoy from 10-17 June. In the western part of the eddy the southward movement of the water was rather slow, while in the eastern part the northward velocities were about 50-60 cm.

From the biological measurements it is evident that this area to the north of Skagen exhibited the highest values of secondary production (of the areas studied), and it is assumed that this fact is related to the convergence of the water and that the eddy is bringing out (westwards) a stable thin surface layer with high nutrient contents etc. favouring a high biological production.

A similar upwelling phenomenon can be seen in the north eastern area of the Skagerrak (cf. lower image in Fig. 7), indicating the presence of a strong eddy feature bringing NCW far south from the coast. Due to the bottom topography, this eddy can be caused by a similar process as described above, this time by the AW flowing northwards towards the Norwegian coast, punching into and initiating a meandering process here.

Another mesoscale feature west of Hanstholmen at about 57° N (earlier discussed by Aure **et al.**, 1990) is as an example seen in the salinity distribution of May 23-25 (Fig. 10). Here a fraction of the watermasses from the North Sea (either CNSW and/or AW^{h}) flowing towards the Skagerrak, turns southwards due to topographical steering. Such a tendency of a southward flux will tend to block a possible inflow of JCW. This blocking mechanism is clearly different from the above described directly winddriven SW meeting the JCW, and the SKAGEX data confirm that the pulsation of the AW^{h}/CNSW might be important for the steering of the inflow of the JCW.

5.3 Nitrification processes

In the SKAGEX I experiment, elevated concentrations of nitrite (and ammonia, which was measured in the G section only) were observed in the water below the halocline outside the Danish as well as the Norwegian coast lines, generally at depths of 30 m to the bottom at 100-400 m throughout the whole period in the sections C, E, F, G and H.

In the following, these features will be described by choosing a representative transect from the SKAGEX I experiment (May-June 1990), when current measurements were carried out. It should be pointed out, that all through SKAGEX II (September 1990) and IV (May 1991) similar results were obtained. In the winter experiment, SKAGEX III (January 1991), such maxima were not observed.

In a section close to section G, a series of recording current meters were anchored, and the results (averaged over three days, 26-28 May) are presented in Fig. 3 (May 27). For comparison, the distribution of salinity, nitrate, ammonia and nitrite in section G on May 27 are shown in Figures 11 a-d.

The nitrate distribution (Fig. 11 c) shows that the highest concentrations were found close to the centre of the section between stations 4 and 6, which coincides with the zero velocity zone in the current section (Fig. 3). South of the zero-line, in the inflowing Atlantic Water (salinity > 35.0, Fig. 11 a), the ammonia distribution shows a maximum (station 8-9 in Fig. 11 c), extending down to the bottom.Nitrite also shows a maximum, but somewhat closer to the centre of the section (at station 7 in Fig. 11 d). Both ammonia and nitrite maxima coincide with an increasing nitrate gradient towards the centre of the transect.

North of the zero velocity zone (Fig. 3), at the Norwegian coast, there is a similar situation. Both ammonia and nitrite show elevated concentrations down to the bottom at about 300 m, and, again, the nitrate shows an increasing gradient towards the centre or the current zero-line.

A study of the current section shows that the ammonia maximum was located in the core of the inflowing Atlantic Water, where the current velocity was higher than 30 cm/s. The nitrite maximum appeared north of the core and at lower velocities, 15-20 cm/s. At the Norwegian coast, both ammonia and nitrite maxima were found in the outflowing water with the highest velocities.

It is known, that when organic material is degrading, the amines from proteins form ammonia. Eventually, ammonia may be oxidized to nitrate in a process called nitrification. This process is carried out in two steps, first to nitrite and then further to nitrate, by two different kinds of nitrifying bacteria. Based on the experiences from SKAGEX I and II, it was decided that the nitrification potential should be measured during SKAGEX IV (May 1991) by means of incubation of water samples with nitrogen-15. Samples were collected all over the SKAGEX area at various depths and prepared for this purpose. They are still to be analyzed.

One hypothesis is, that the ammonia in the inflowing water emanates from algal production and subsequent algal degradation in surface water before it enters the Skagerrak as a subsurface current. The Atlantic Water (AW in Fig. 1b) originates in an area west of Norway with a very high productivity (Föyn, pers. comm.). The formation of ammonia, appears to be under way in the core of the Atlantic Water with the highest velocity. This is the youngest water in the sense that it most recently was at the surface, in the photic layer of the Northern North Sea.

In the Skagerrak, the current velocity decreases on the northern side of the core and at the same time it is forced to the left (see Chapter 4). Meanwhile, the ammonia is oxidized to nitrite, and the nitrite maximum appears in water with higher age. The final step is the formation of nitrate, and consequently, an increasing nitrate gradient towards the centre of Skagerrak.

The deep water in the Skagerrak is turning to the north outside the Swedish coast and is flowing back westward along the Norwegian coast (see Chapter 4). Similar nitrite maxima could be observed in the C transect (Fig. 1b) (ammonia was not measured) and along the Norwegian coast. Separation of the nitrification substrate (ammonia) and products (nitrite and nitrate) into different water masses was also found there, even if the frequency (in space) of sampling points does not make it obvious in all sections.

Another explanation to the separated ammonia and nitrite maxima may be that water with ammonia and nitrite maxima have different origins in the North Sea (cf. Chapter 3) and, therefore, do not coincide. Because, on some occasions, (not shown in Fig. 11) high ammonia concentrations were found in SNSW, which was low in nitrate. In those cases, the ammonia could be the degradation product from an earlier algal production in the Southern North Sea.

The winter experiment, SKAGEX III, did not show any ammonia and nitrite maxima in the Atlantic Water, which could be explained by low productivity during the winter season.

5.4 Subsurface chlorophyll-a and primary productivity maxima

A pronounced feature during the cruises in May and September 1990 and in May 1991 was the large concentrations of phytoplankton found at subsurface levels over large areas in the Skagerrak and northern Kattegatt (Fig. 12). The vertical profiles of fluorescence and chlorophyll-a exhibited single or multiple peaks at levels from approximately 10 m down to more than 30 m depth. Such high subsurface concentrations of chlorophyll-a has earlier been reported from this area by Dahl and Danielssen (1981), Pingree **et al.** (1982) and Dahl **et al.** (1987).

In September, during SKAGEX II, maxima were at times found as deep as 40-50 m depth (Fig. 13) in the border between the upper nutrient-poor water (SW) and the nutrient-rich Atlantic water (AWh) (Fig. 14). During this period, more than 4 ug/l chlorophyll-a was recorded (Fig. 14) and up to 370 000 cells/l of **Gyrodinium aureolum** were found at transect F. In a previous study carried out during the same time of the year, Dahl **et al.** (1987) also found that the subsurface maximum consisted mainly of **G. aureolum**. The authors stated that **Gyrodinium** may have utilized nitrogen down to at least 50 m depth. This statement is supported by the findings of Paasche **et al.** (1984) and Richardson and Kullenberg (1987), which indicate that **G. aureolum** is able to assimilate nitrogen at low light intensities.

When multiple peaks appeared, they were often separated by only one or a few metres. The species composition usually differed in the different peaks. At the transect in northern Kattegat (B) in May-June 1990 for instance, the upper peaks of fluorescence were generally dominated by diatoms and the lower peaks by dinoflagellates.

The subsurface chlorophyll maxima were generally found in stratified water bodies, below the pycnocline. The phenomenon in May, June and September can, however, be considered to general, occurring over wide areas, in water bodies of qiute different charateristics. It was thus found in the northwestern Kattegatt, in the central Skagerrak and along parts of the western coast of Jutland. It was conspicuous, however, that the Southern North Sea Water (SNSW) entering the Skagerrak, contained very low chlorohyll-a concentrations throughout the May-June cruises (Fig. 12).

The high concentrations in the central Skagerrak seem to be sustained over long periods of time due to a more or less continuous supply of nutrients found in the border area between the surface water and the nutrient-rich Atlantic water. This border area appears as a "ridge" in the central Skagerrak and the nutrients are through upwelling spread along the sides of this "ridge" (Fig. 14).

High concentrations of phytoplankton in the surface layers also occur (Fig. 15). They may be found along the coasts during situations of upwelling, and in the nitrate-rich Jutland Coastal Water (JCW), which originates from the German Bight. The resulting high lightsaturated primary productivity in this water mass was clearly recognized at transect H.

Although the subsurface chlorophyll maxima were observed on many occasions and over substantial periods during SKAGEX I, no **in situ** primary production measurements were made to quantify the activity of these phytoplankton populations and their contribution to the total water column productivity. During SKAGEX IV, however, in situ primary production measurements were introduced at a station in north west Kattegat where a pronounced chlorophyll maximum was found in a high salinity (33.6) water body close to the bottom (Fig. 16). These measurements, which were run over a period of three days, showed that the primary production maxima throughout the period coincided with the chlorophyll maxima (which was located in the nutricline). The nutricline was initially at a depth of 13 metres, the next day at 15 metres and day three at 18 metres. The primary productivity remained high as the depth of the nutricline increased and the productivity rates were very high, even when compared with rates generally found in surface layers.

Secondary production

During SKAGEX I in May-June 1990, a group of planktologists were engaged in measurements of copepod egg production (Tiselius **et al.** 1991). This was performed on six transects ranging from northern Kattegat to western Skagerrak. These studies showed that the shallow areas north of Skagen were the most productive overall. However, large variations in egg production over short distances were observed in this area (Fig. 17). This is also clearly illustrated in measurements of lightsaturated primary production in the area.

Relatively high and stable values were recorded in northern Kattegat during the period 8-20 June. This corresponds to the relatively stable hydrographical conditions in the area where only minor water exchange with Skagerrak could be observed.

In the coastal water along western Jutland, high levels of secondary production were recorded during the period June 14-17. During the same period, high rates of primary production were also recorded in that area.

6. Concluding remark

The significant and variable inflows from the North Sea of different water masses found during SKAGEX, clearly indicate that many of the physical, chemical and biological processes in the Skagerrak are strongly affected by processes outside, especially processes in the North Sea. In relation to nutrient budget and biological productivity speculations it must be important to recognize the mechanisms of the rapid shifts between the different inflowing water masses and their individual variability with time. It is assumed that ongoing efforts in running full 3-dimensional, baroclinic, numerical models for the North Sea and the Skagerrak/Kattegatt will be of great help to study these mechanisms, and the SKAGEX data-sets are probably one of the best, ever obtained to evaluate such regional models.

7. Acknowledgements

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8. References

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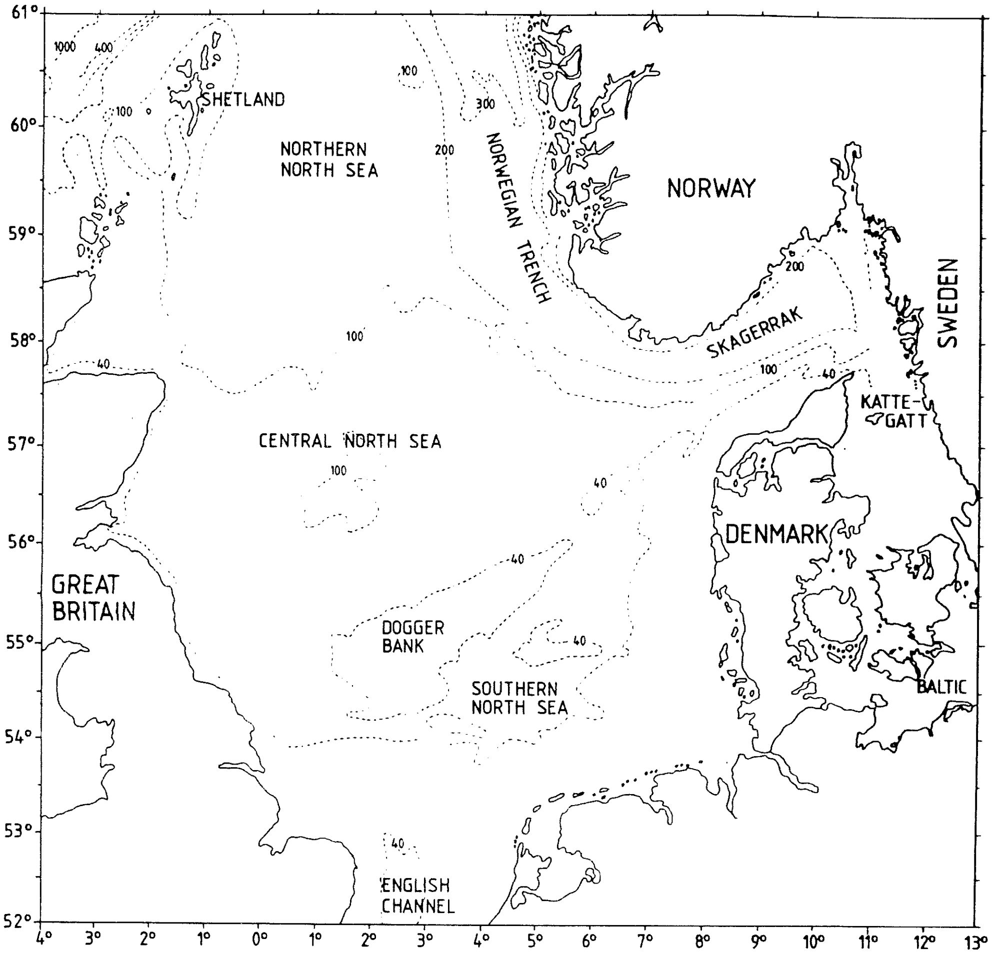


Fig. 1a. Skagerrak, topography and adjacent water areas.

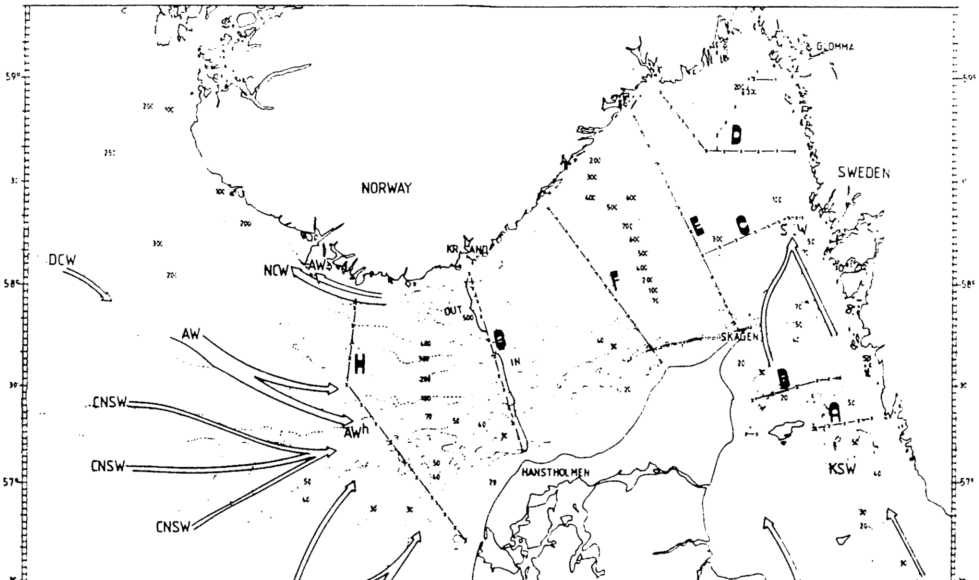


Fig. 1b. Skagerrak, main transects (A-H) and relevant water masses. (AW= Atlantic water, AW^h= Atlantic water high (shallow), AW^l= Atlantic water low (deep), BW= Baltic water, CNSW= Central North Sea water, DCW= Dooley Current water, ECW= English Channel water, GBW= German Bight water, JCW= Jutland coastal water, KSW= Kattegatt surface water, NCW= Norwegian coastal water, SNSW= Southern North Sea water, SW= Surface water).

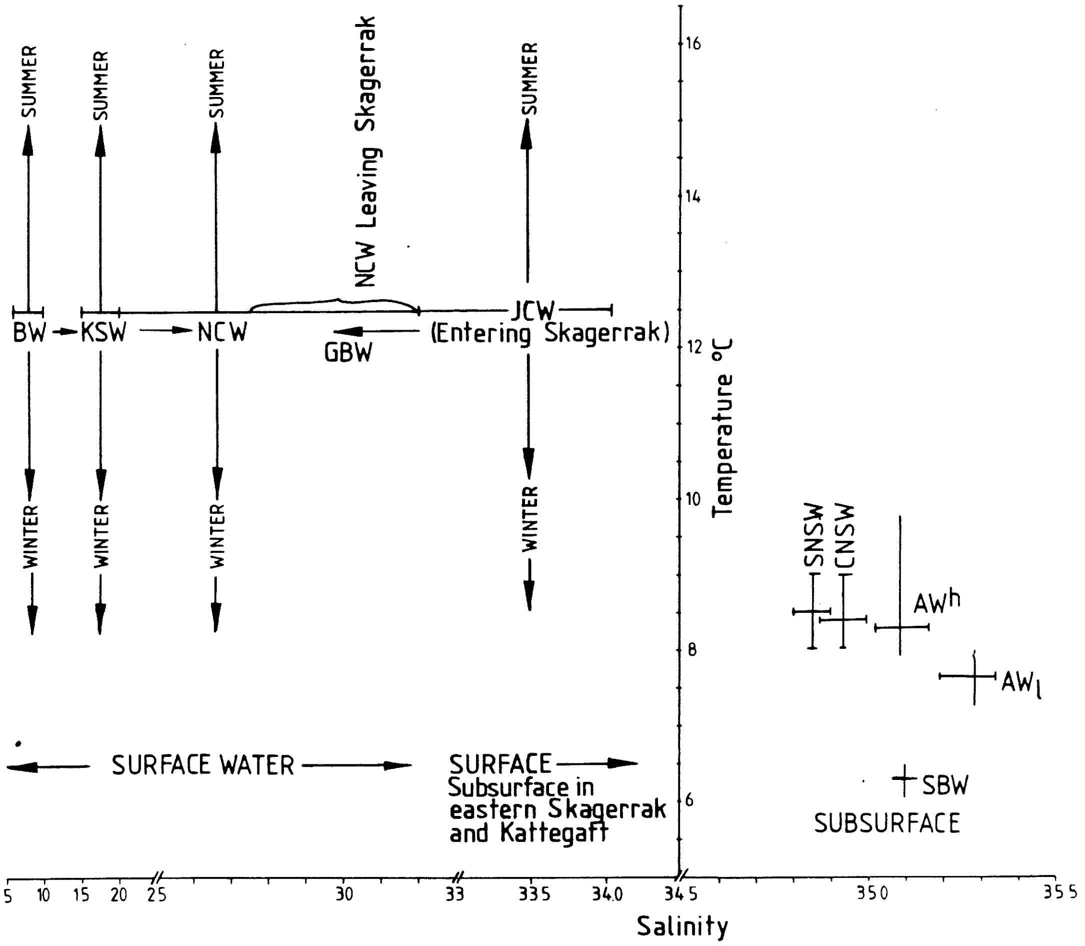


Fig. 2a. Temperature-salinity (T-S) relations between different water masses (SBW= Skagerrak bottom water, other abbreviations, see text and Fig. 1b).

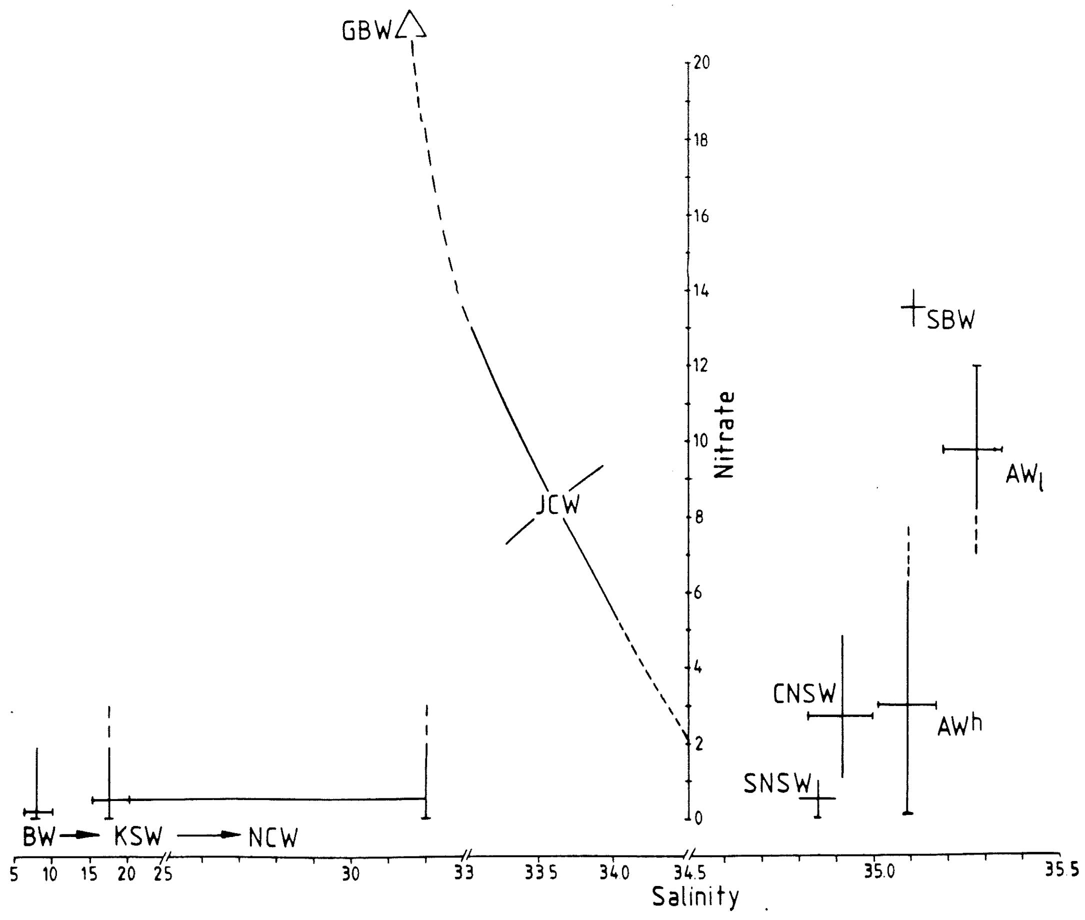


Fig. 2b. Nitrate-salinity (N-S) relations between different water masses (abbreviations, see text and Fig. 1b).

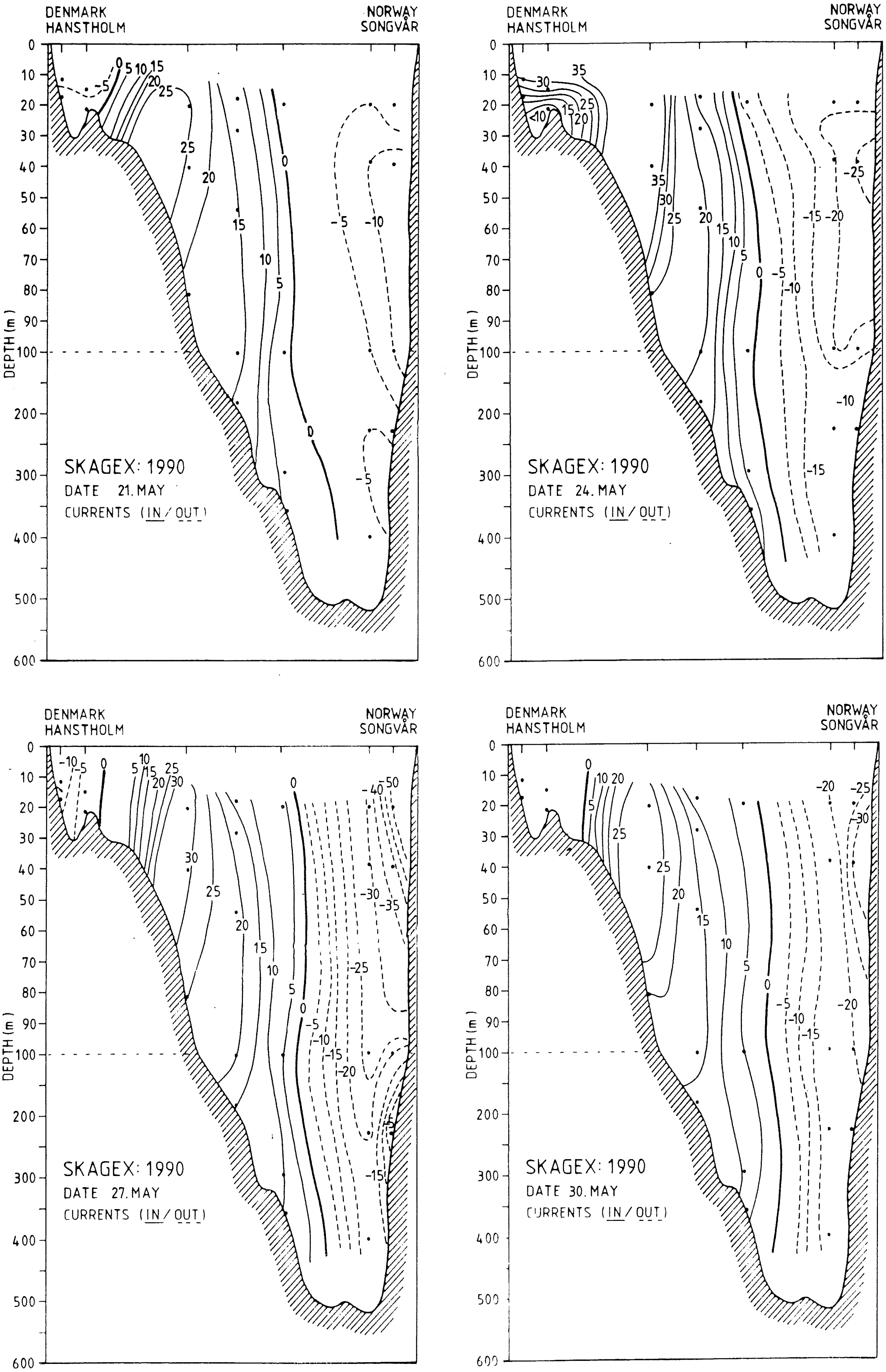
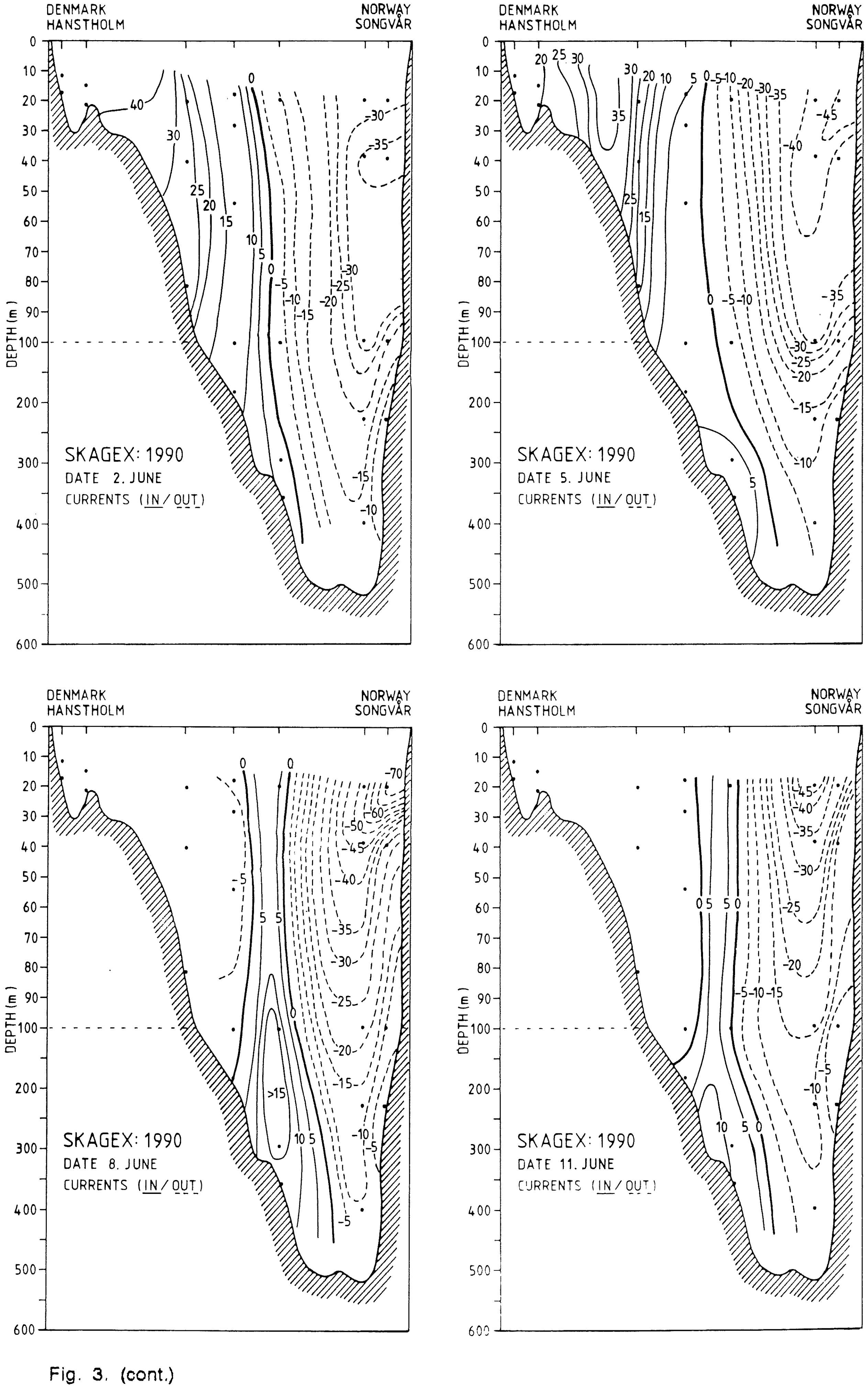


Fig.3 Three day mean in/out flow velocities along the transect G between Hanstholm and Kristiansand from May 21 to June 20, 1990 (21 May, mean flow velocity for May 20-22, May 24, mean flow velocity for May 23-25 etc).

DENMARK
HANSTHOLM
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DEPTH (m)
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SKAGEX: 1990
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CURRENTS (IN / OUT)
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10
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SKAGEX: 1990
DATE 5. JUNE
CURRENTS (IN / OUT)
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SKAGEX: 1990
DATE 8. JUNE
CURRENTS (IN / OUT)
-70
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SKAGEX: 1990
DATE 11. JUNE
CURRENTS (IN / OUT)
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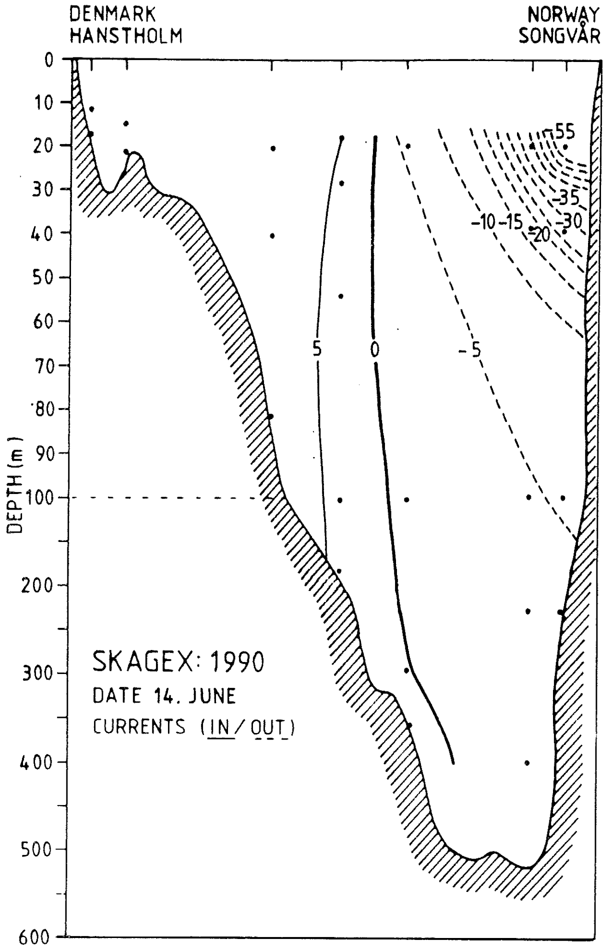
Fig. 3. (cont.)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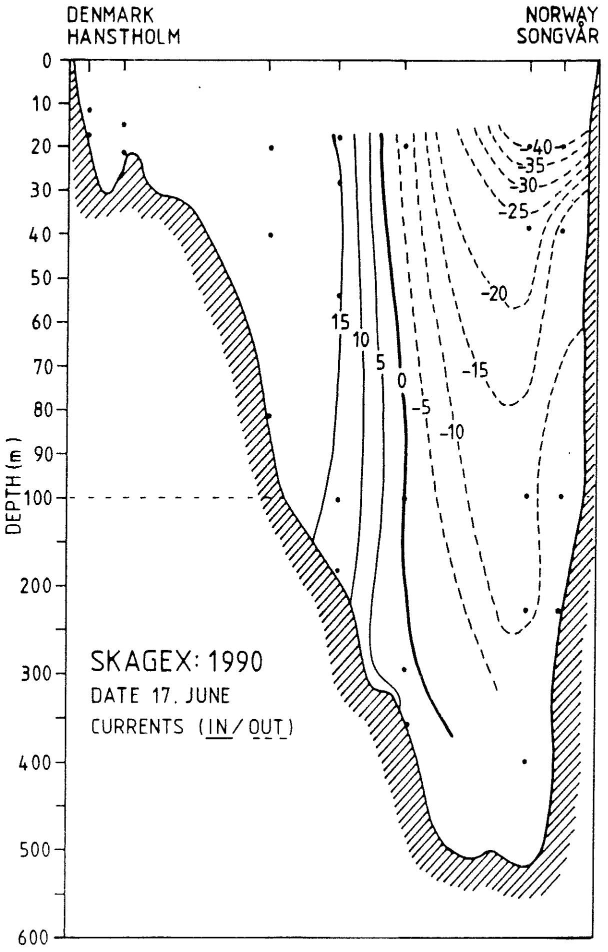
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SKAGEX: 1990
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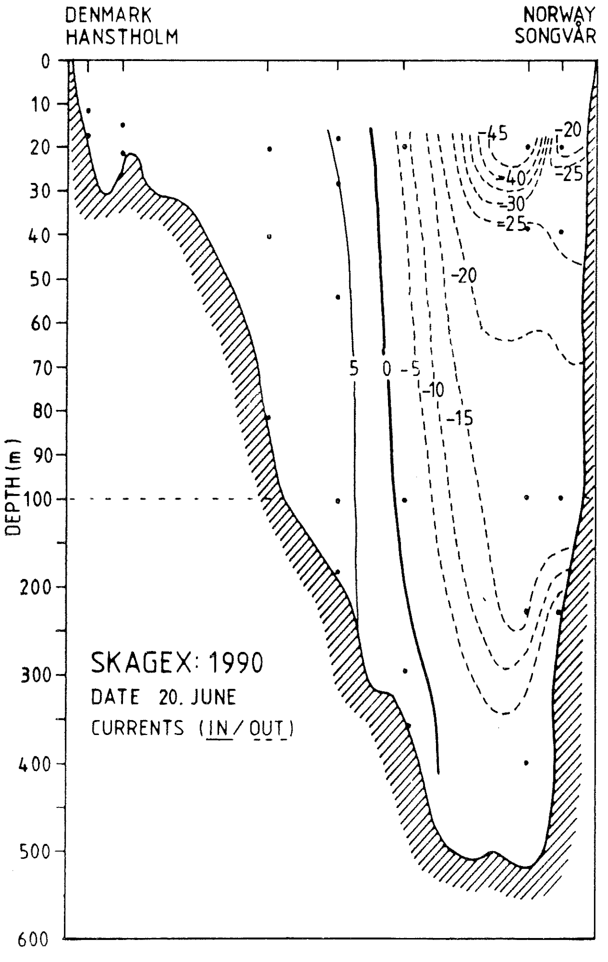
CURRENTS (IN / OUT)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SKAGEX: 1990
DATE 20. JUNE
CURRENTS (IN / OUT)

Fig. 3. (cont.)

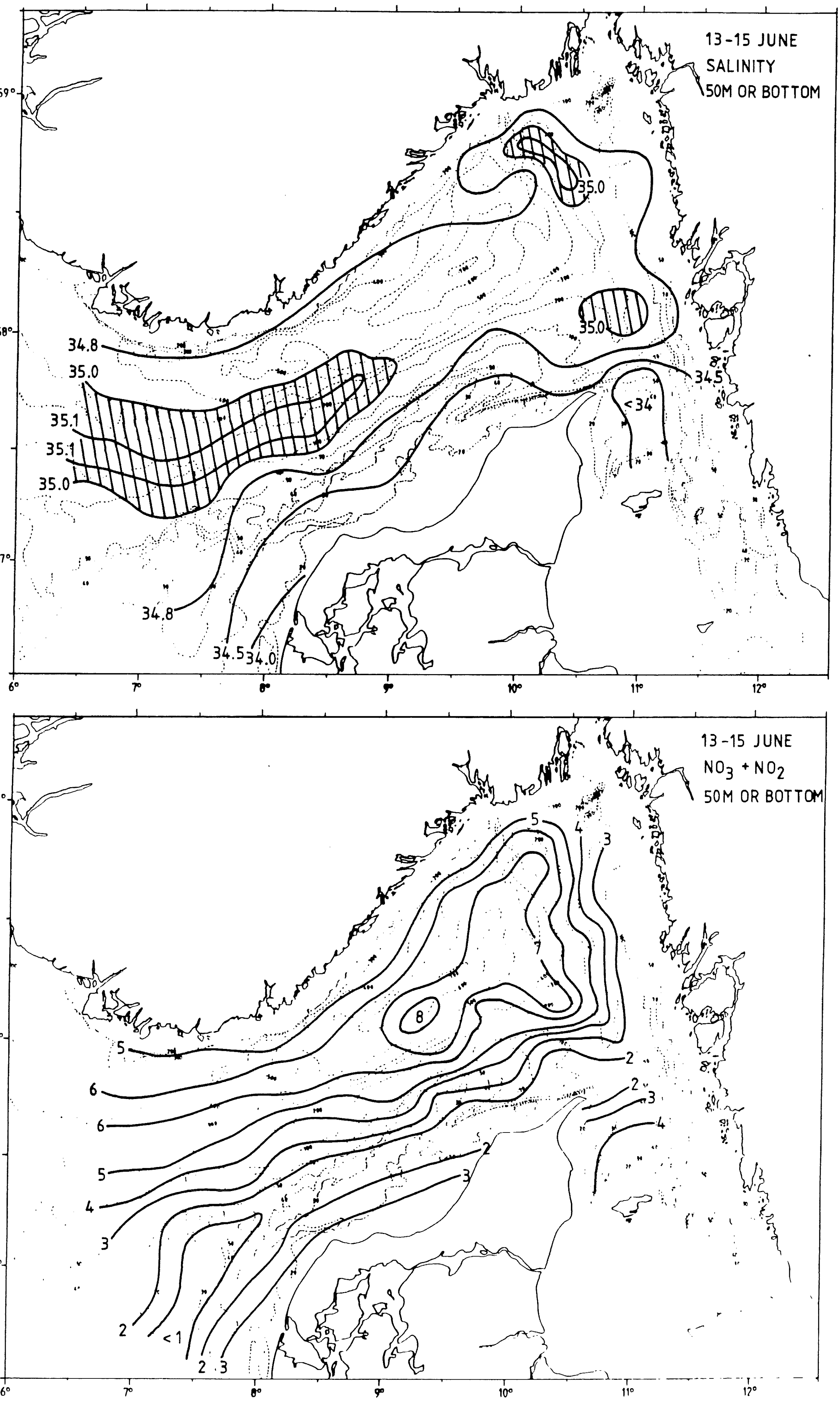


Fig. 4. Horizontal distribution of nitrate and salinity at 50 m depth or at the bottom during June 13 to 15, 1990.

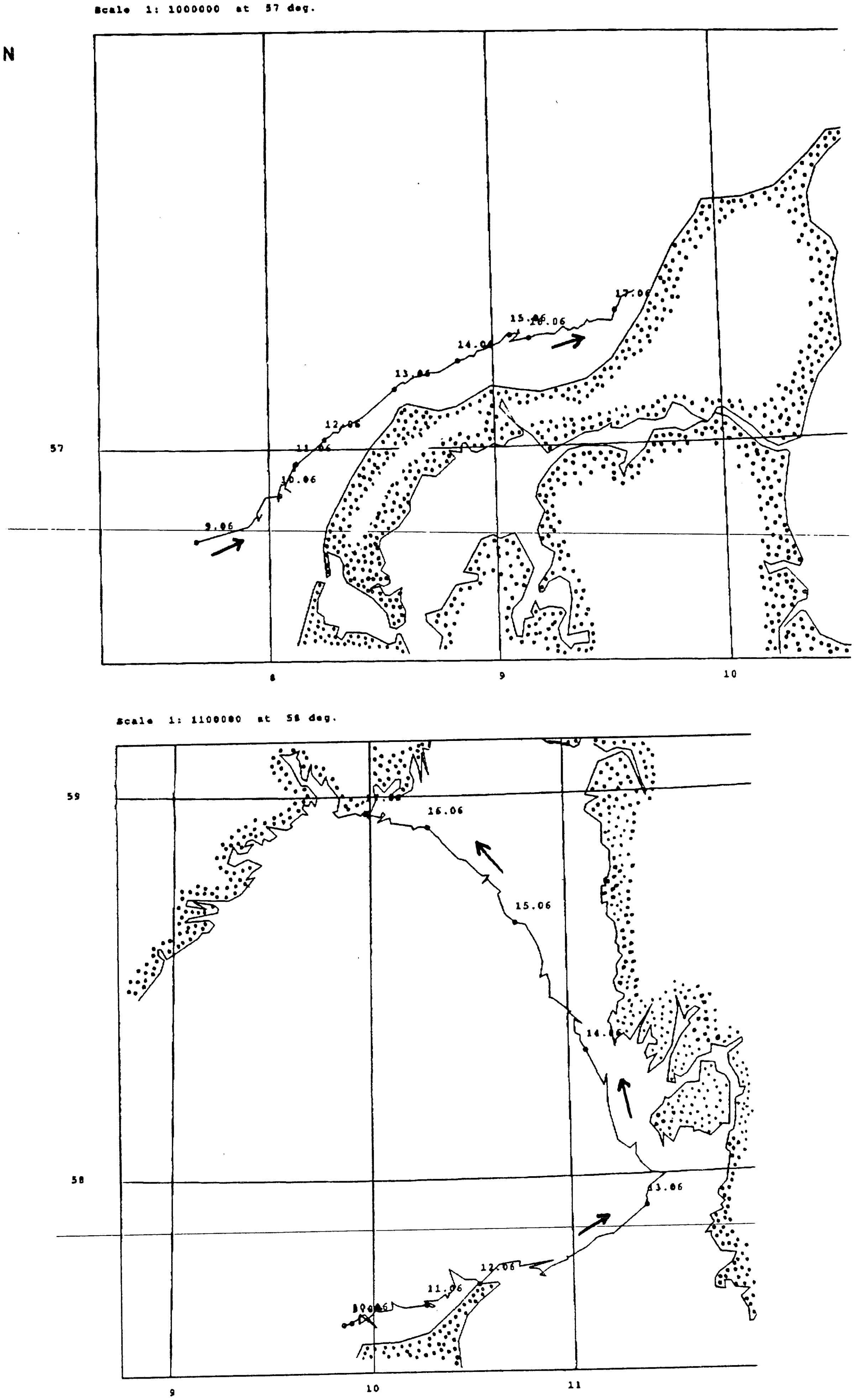


Fig. 5. Some drifter tracks during SKAGEX I.

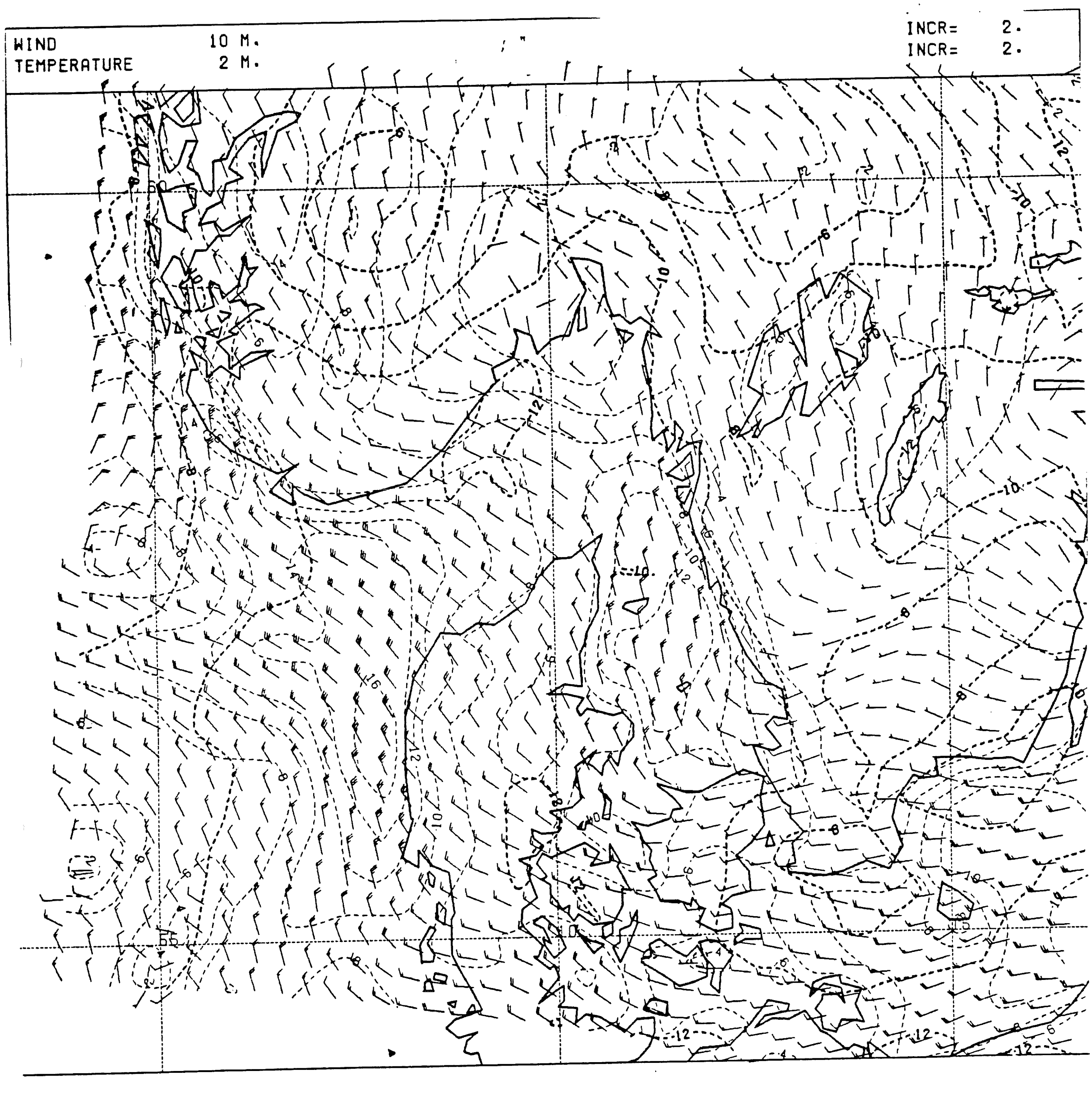


Fig. 6. Winds at 10 m height and air temperature at 2 m height from May 27, 1990, 12^{00} utc.

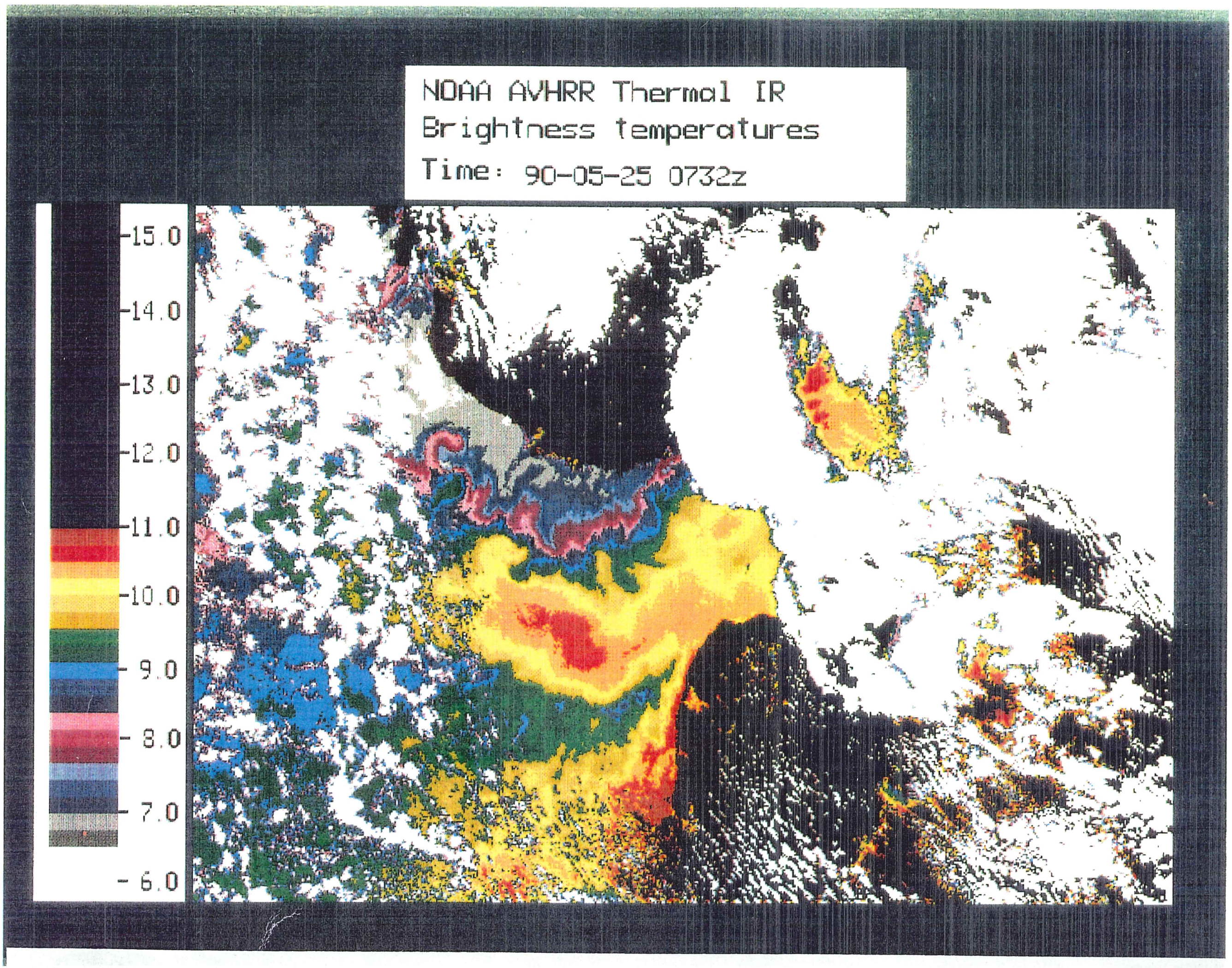
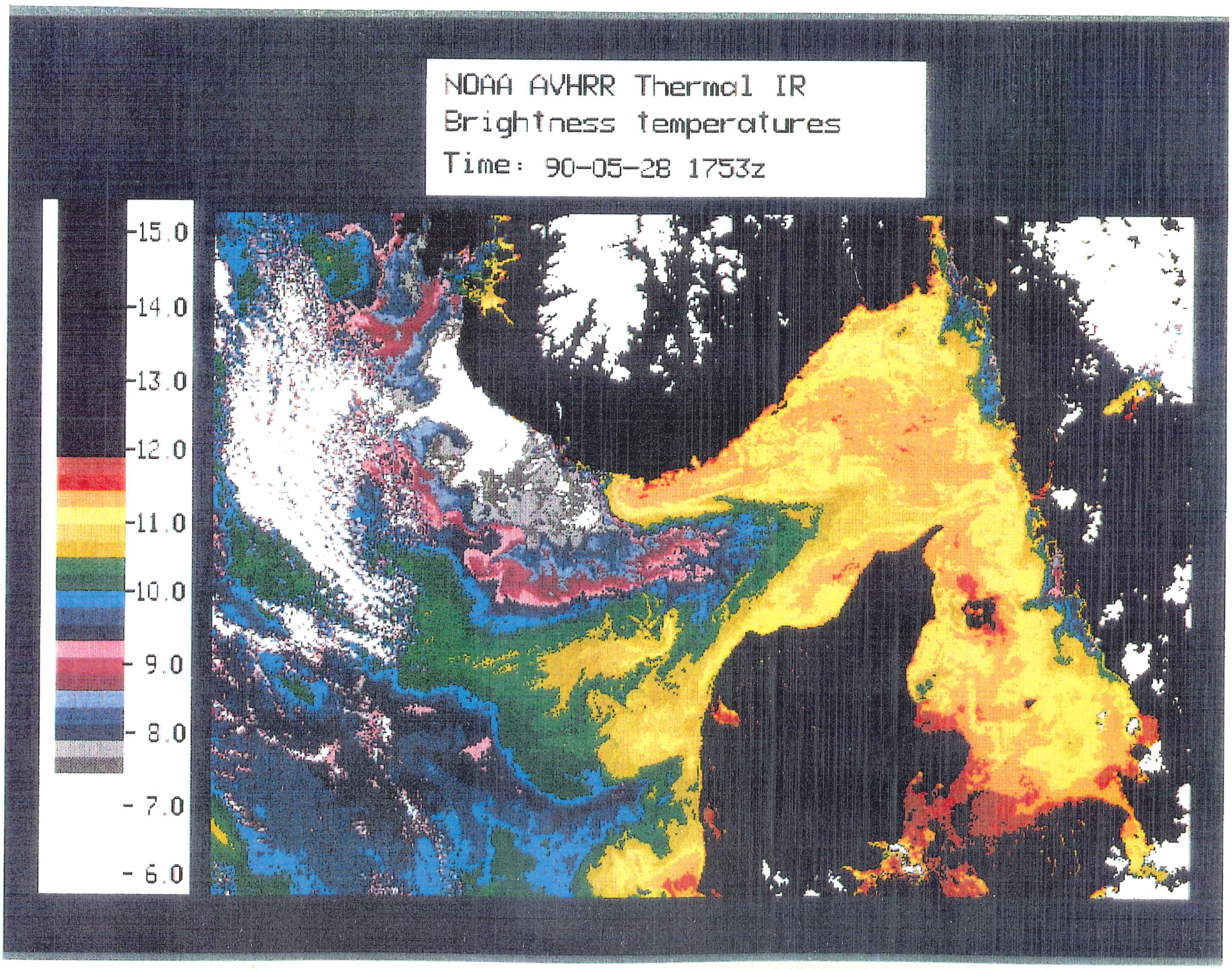


Fig. 7 Sea surface brightness temperature from NOAA-AVHRR images on May 25 and 28, 1990.



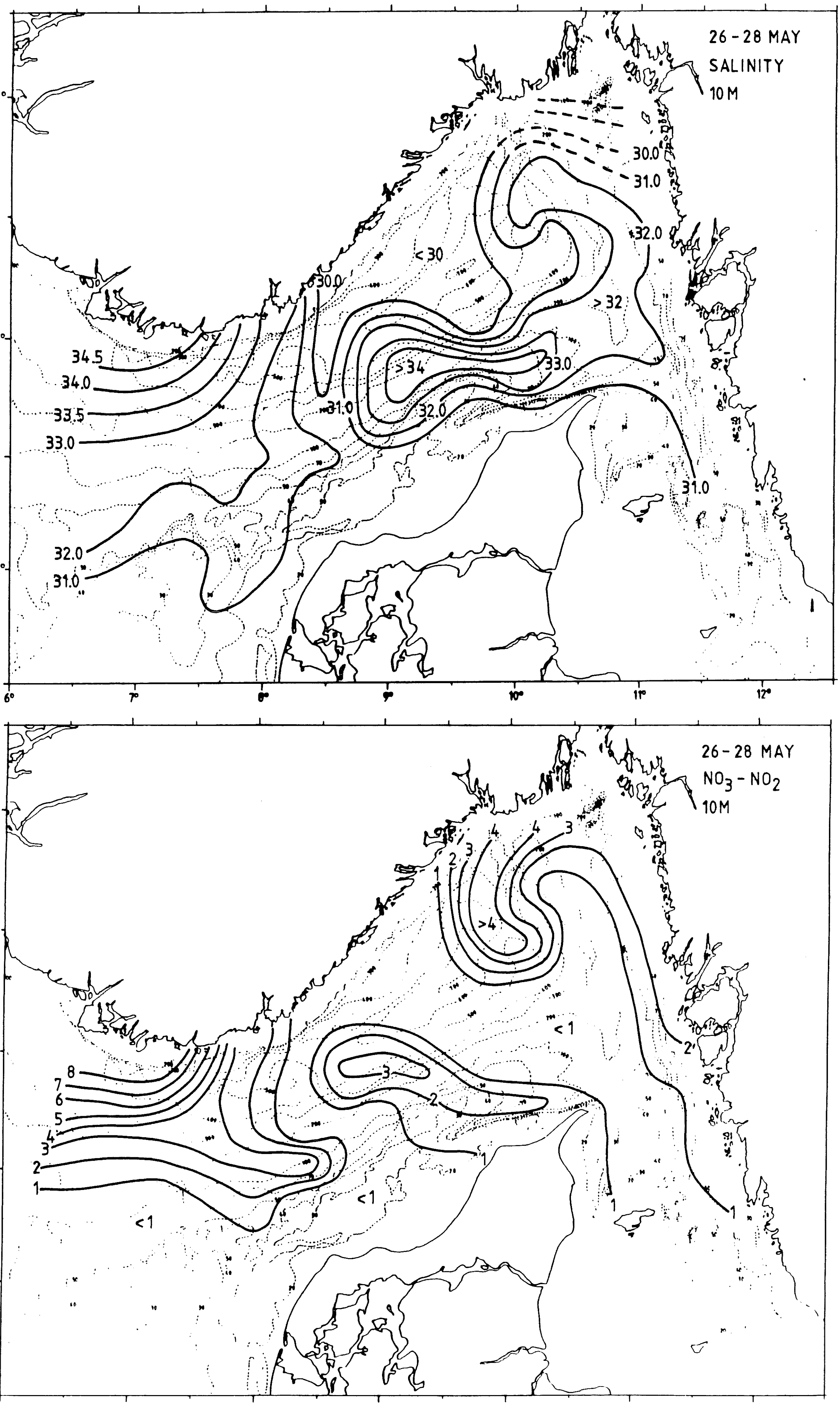


Fig. 8. Horizontal plot of salinity and nitrate from 10 m depth , May 27, 1990.

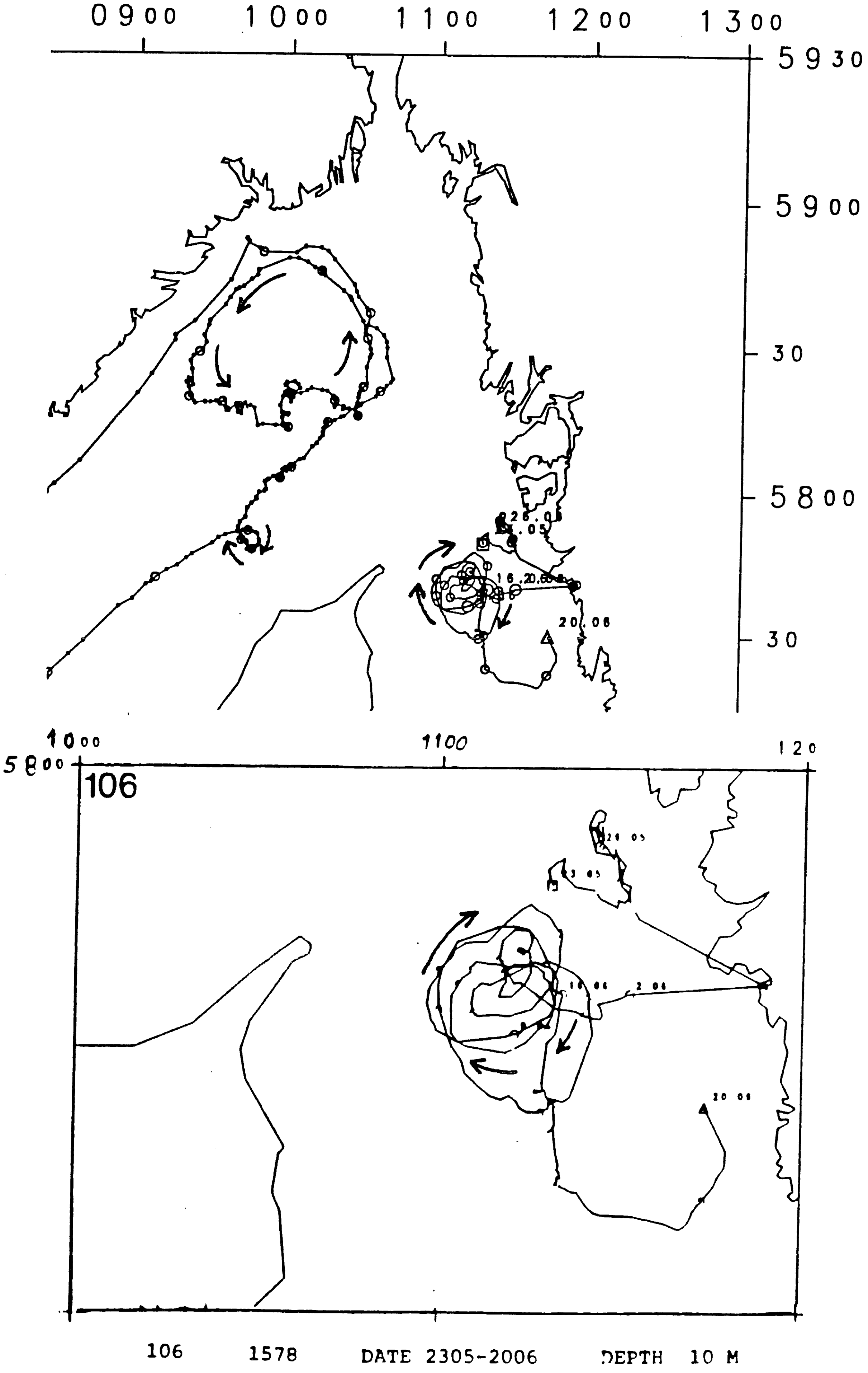


Fig. 9. Argos drifter tracks in the northern Kattegatt during SKAGEX I.

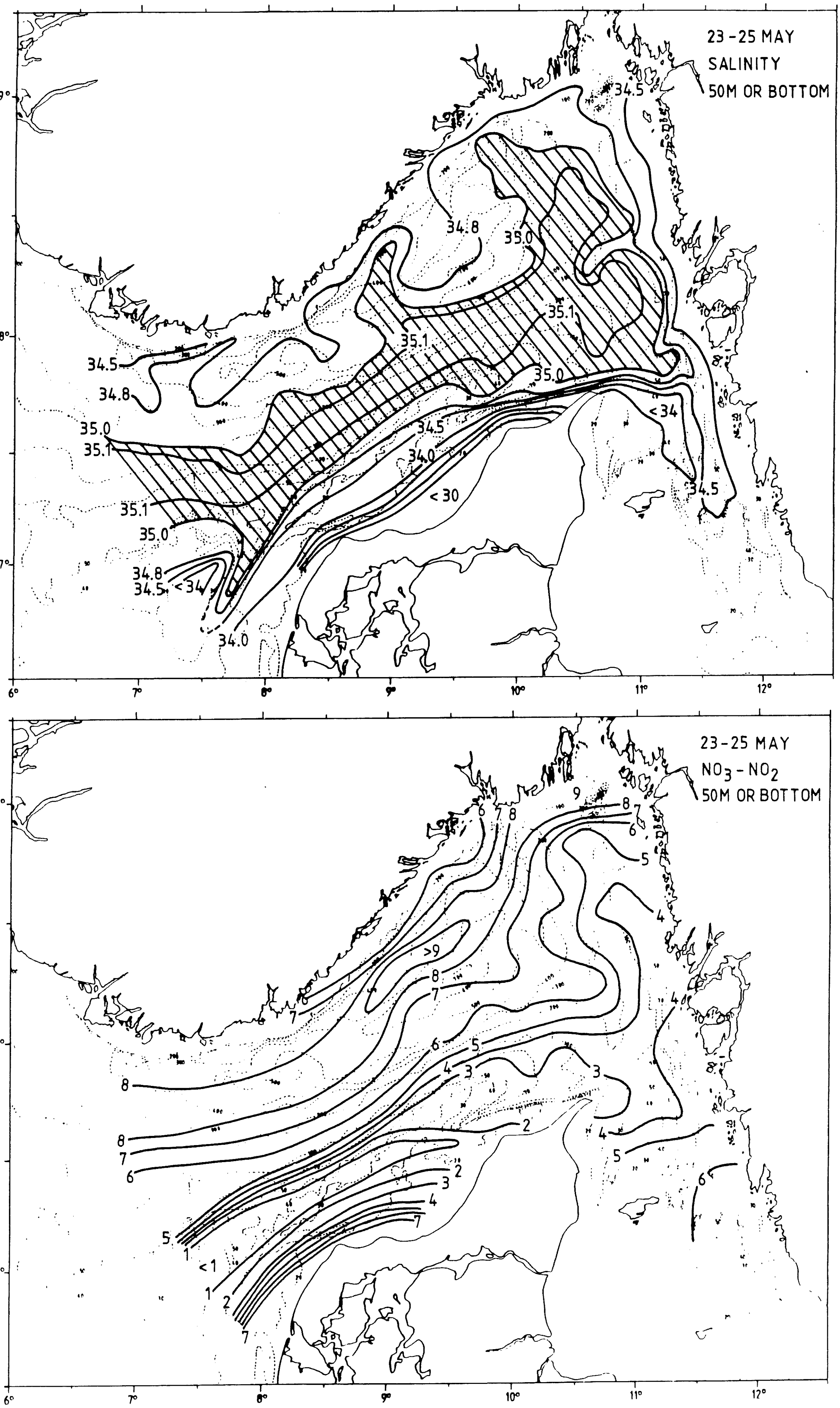


Fig. 10. Horizontal surface salinity distributions in the Skagerrak, May 23-25, 1990.

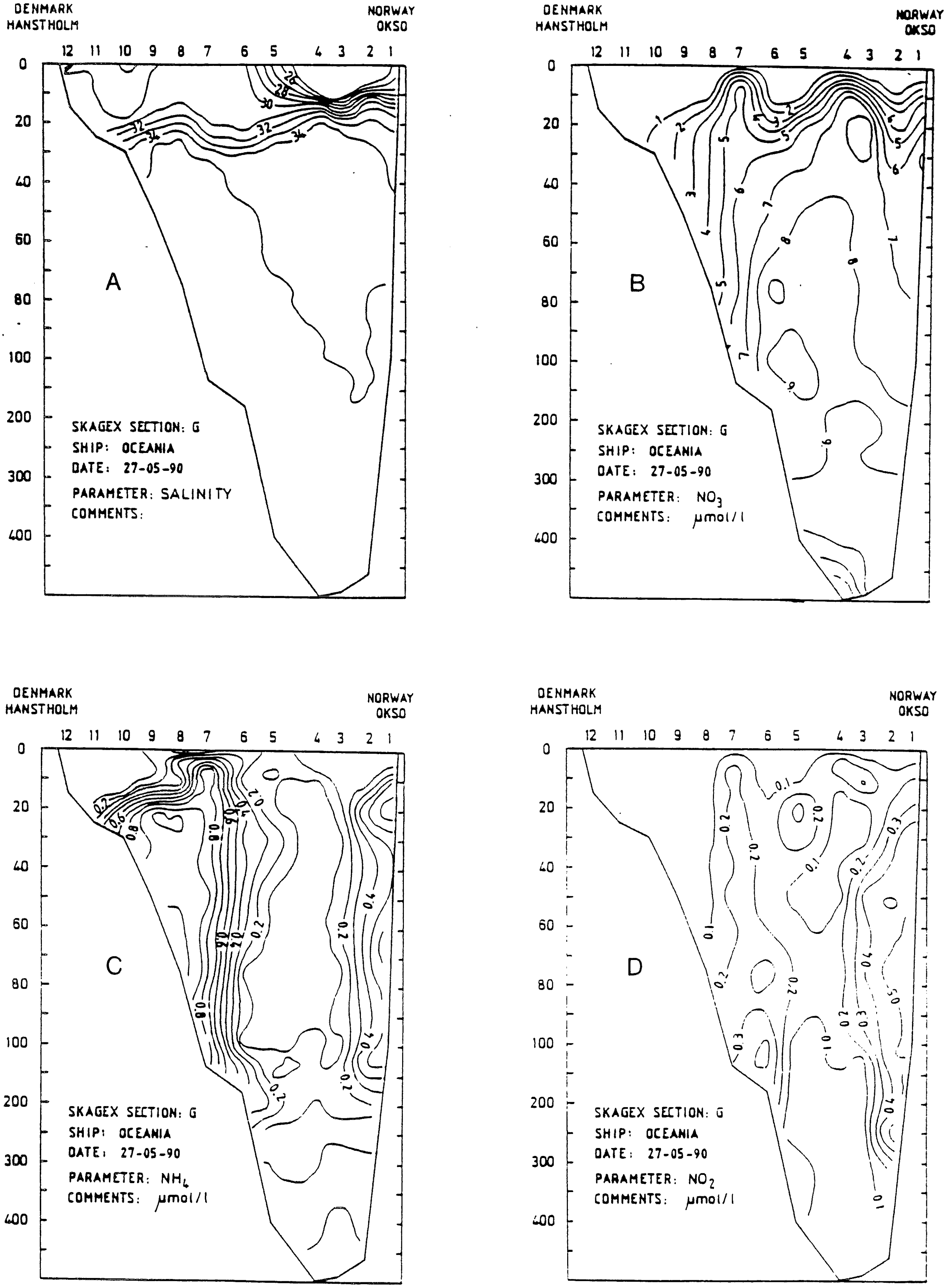
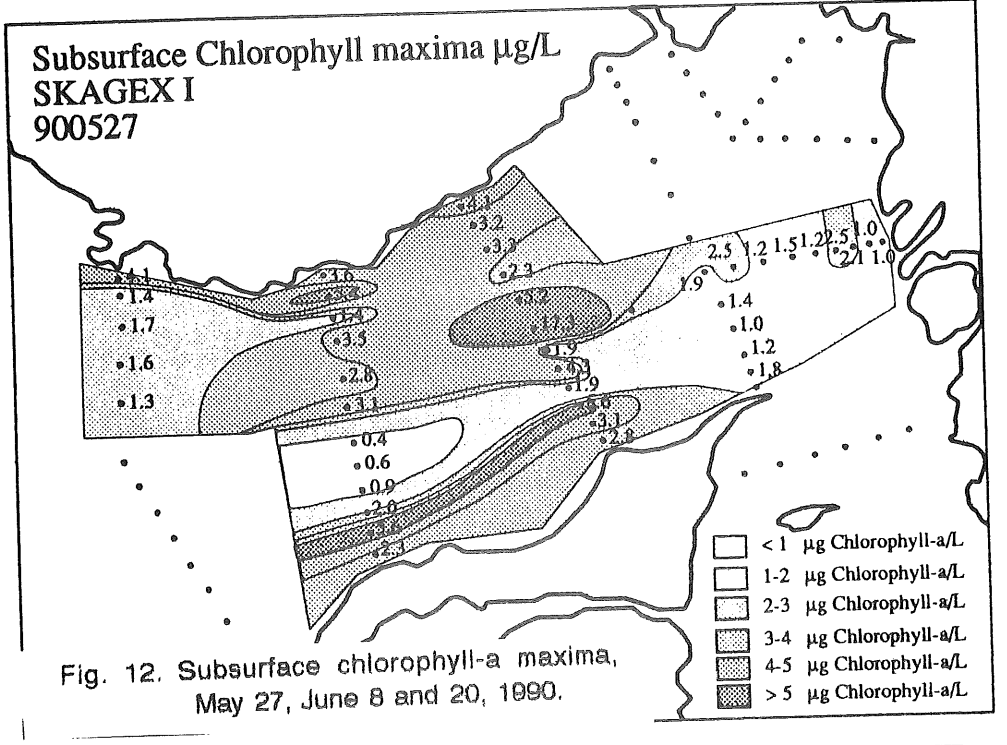
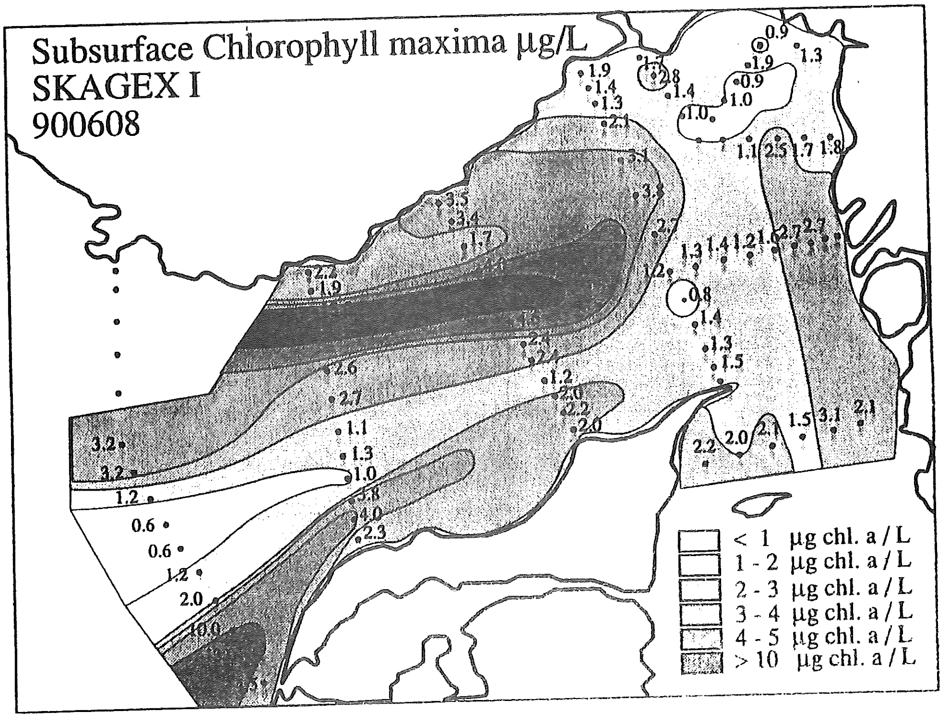


Fig. 11 Distribution of salinity (A), nitrate (B), ammonia (C) and nitrite (D) in section G on May 27, 1990.





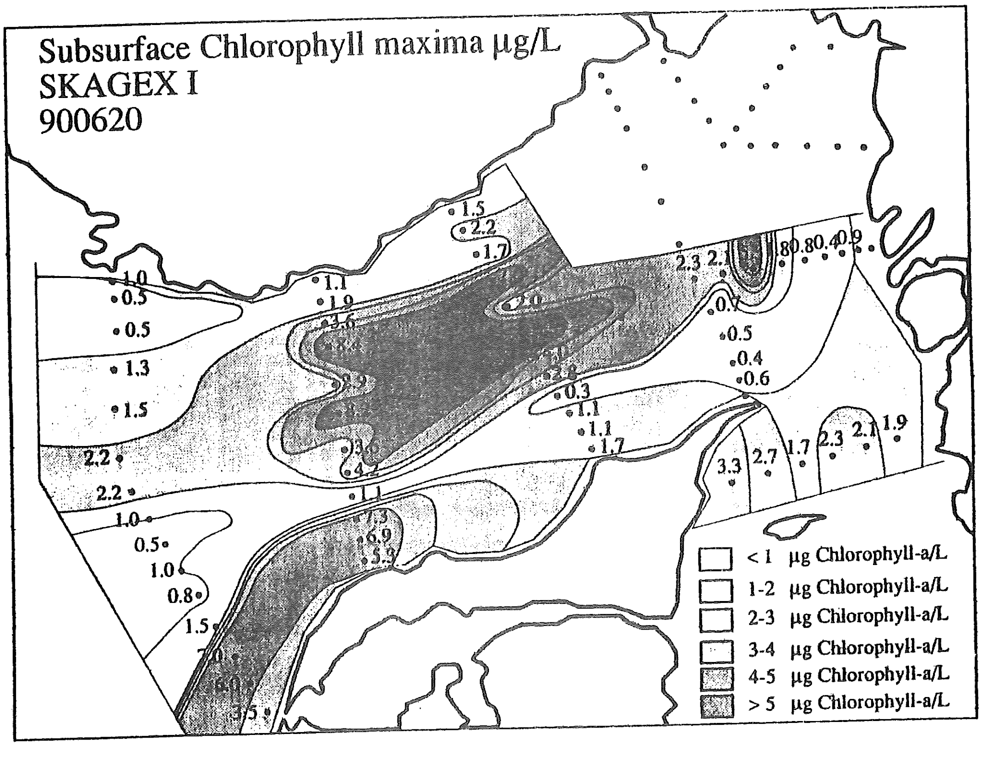


Fig. 12. Subsurface chlorophyll-a maxima, May 27, June 8 and 20, 1990.

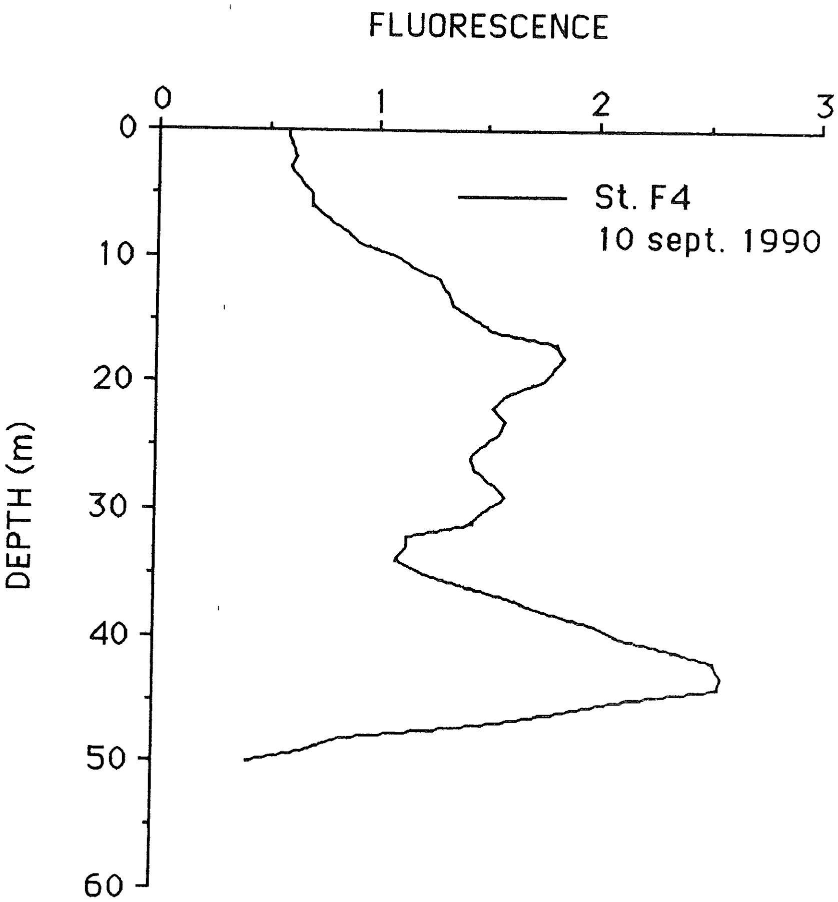


Fig. 13. Fluorescence (arb. units) at station F4, September 10, 1990.

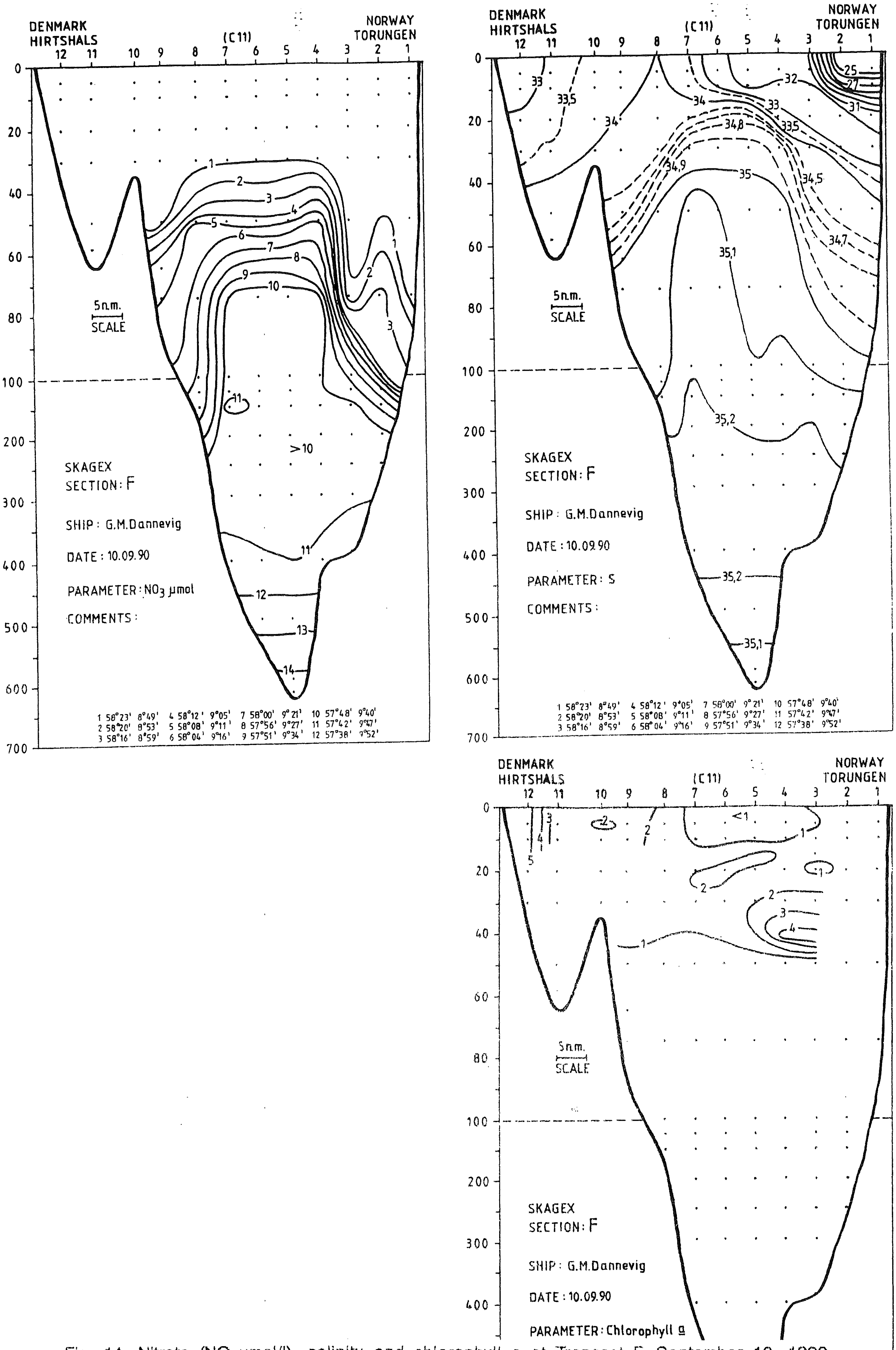


Fig. 14. Nitrate (NO$_3$umol/l), salinity and chlorophyll a at Transect F, September 10, 1990.

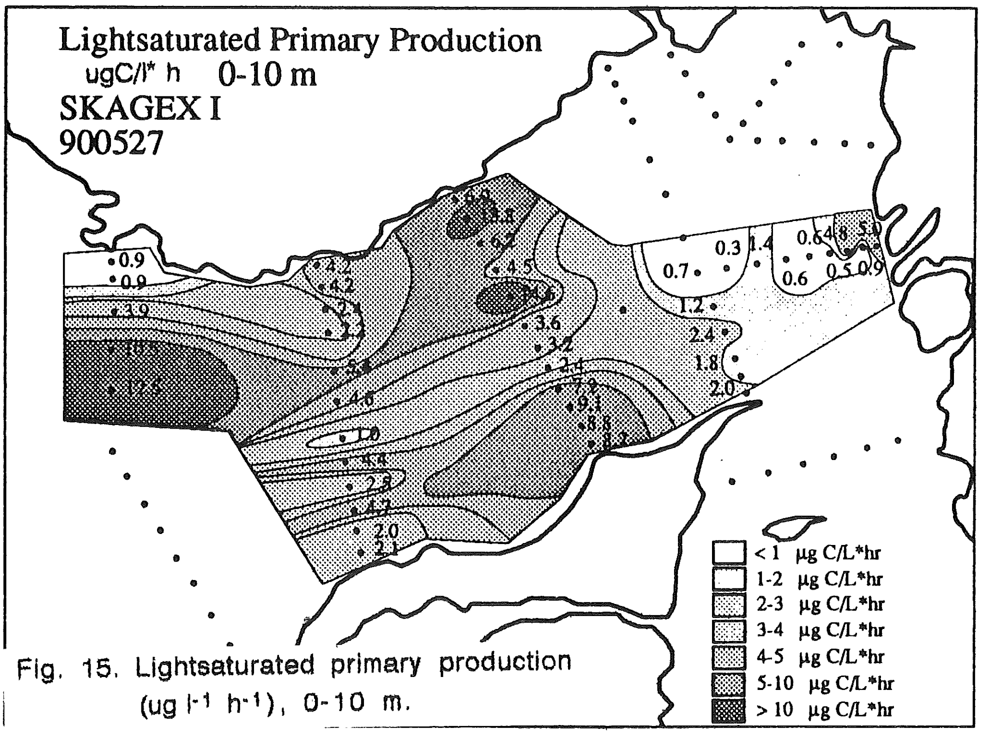
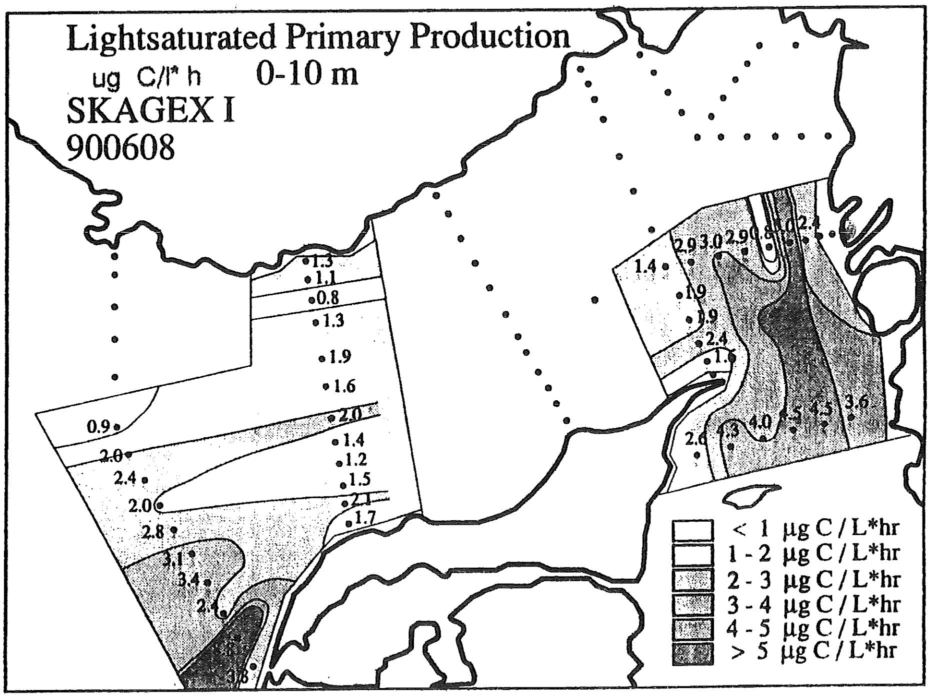
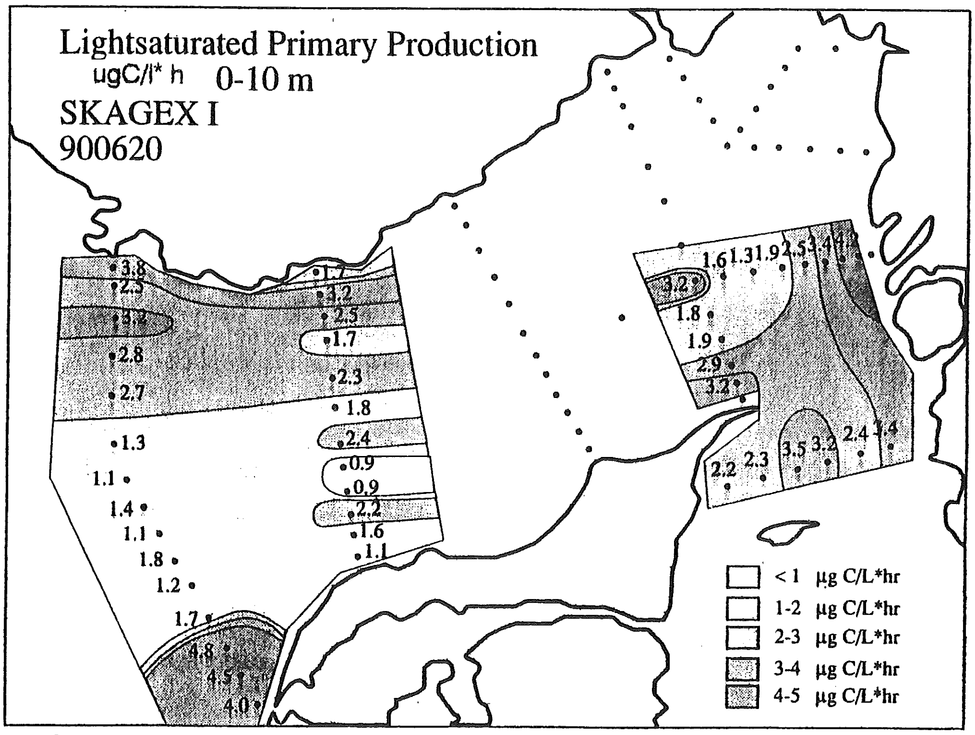


Fig. 15. Lightsaturated primary production (ug l-1 h-1), 0-10 m.





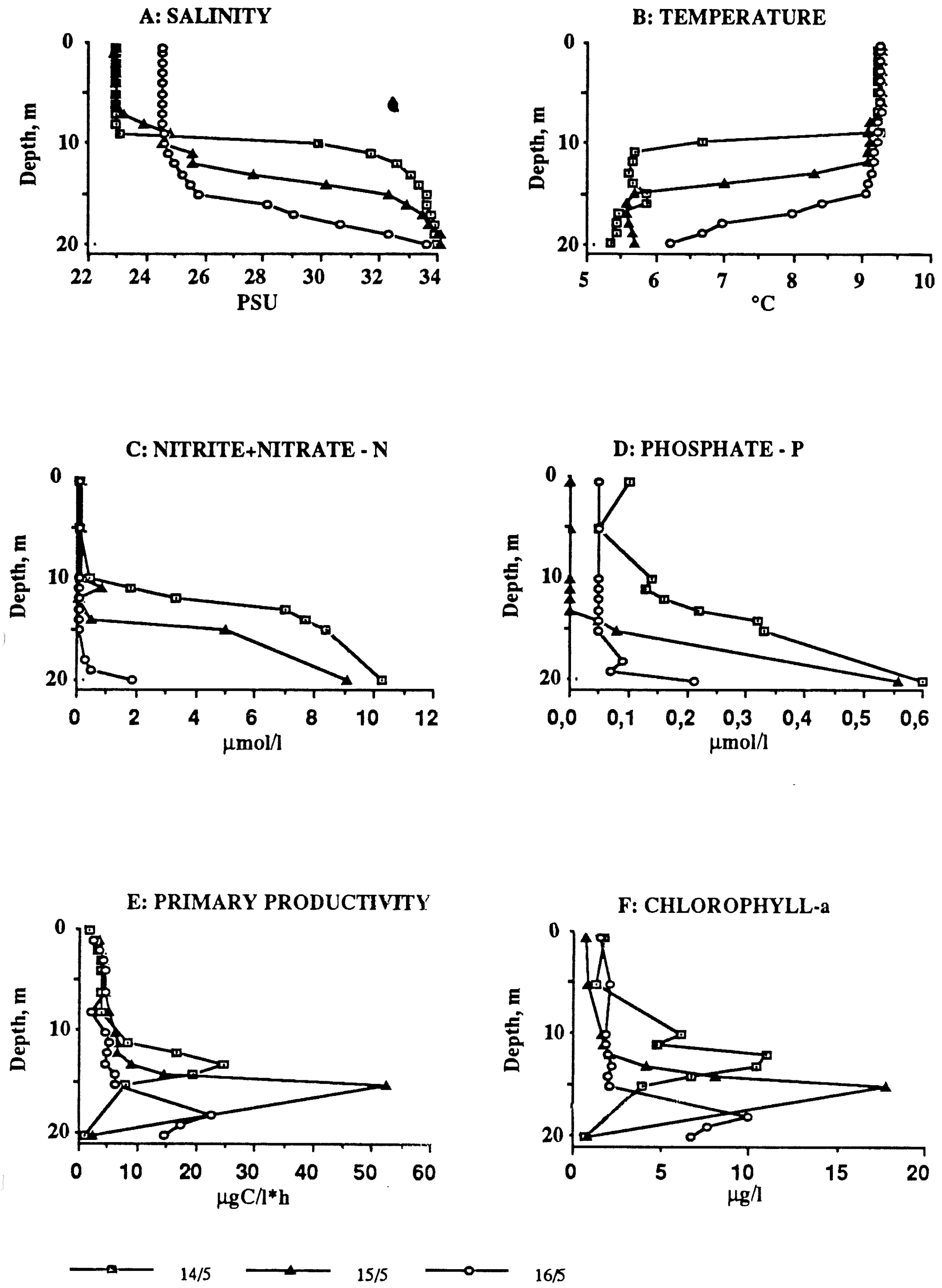


Fig. 16. Hydrography, chlorophyll-a and in **in situ** primary production at station Y1 (57°38,0' N, 10°45,0' E), May 14-16, 1991.

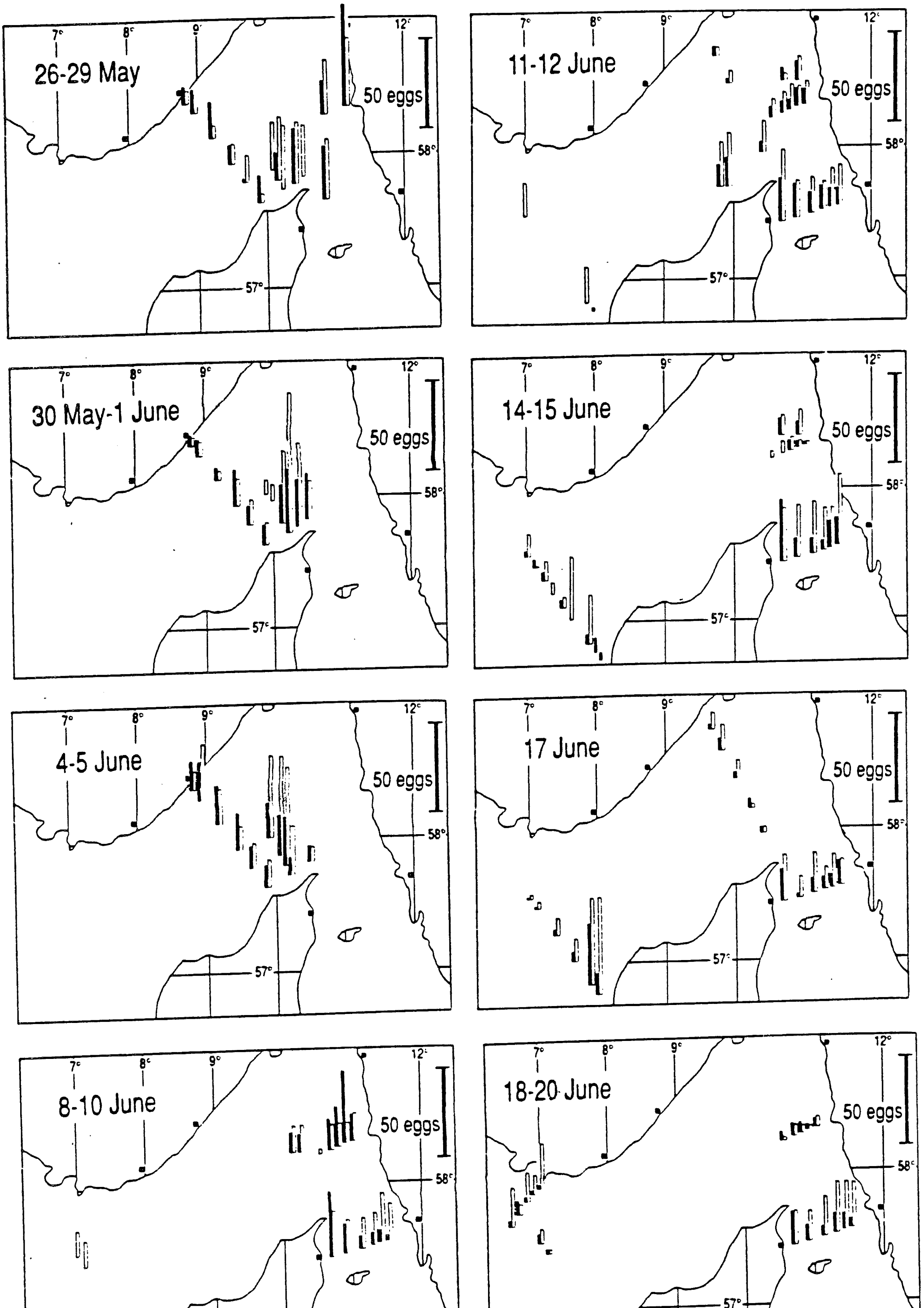


Fig. 17. Average egg production (eggs female $^{-1}$ day^{-1}) for *Acartia clausi* (solid columns) and *Centropages hamatus* (open columns) May 26 - June 20, 1990.