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Oceanographic variability in the Skagerrak and Northern Kattegat, May–June, 1990

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The Skagerrak Experiment (SKAGEX), was a large, international, ICES-supported joint venture, carried out in the Skagerrak–Kattegat area on four different surveys in the period 1990–1991. It involved some 20 institutes and, at times, up to 17 research vessels. The main aim of the Experiment was to identify and quantify the different water masses entering and leaving the Skagerrak area and their variation over time. It also aimed to investigate the mechanisms that drive the circulation and to study their effects on biological processes. The aim was to be attained mostly through extensive synoptic observations. This paper focuses on the variability in physical, chemical and biological parameters during the first part of SKAGEX, 24 May–20 June 1990. During the first half of the period of investigation, the main outflow from the Skagerrak, represented by the Norwegian Coastal Current, was barotropic with daily mean velocities varying from 10–40 cm s^{-1}. During the second half a clear baroclinic current component developed, giving rise to near surface velocities of up to 100 cm s^{-1}. A pronounced feature in the Skagerrak during the study was the counter-clockwise circulation of the Norwegian Coastal Current at times of strong northwesterly winds. During such conditions this surface water reached as far as the Danish coast south of 57°N and upwelling along the Norwegian coast was also found. During northerly winds upwelling also occurred along the Swedish coast. The nutrient-rich Jutland Coastal Water, originating from the German Bight, was never found to reach the inner part of the Skagerrak during this first part of SKAGEX. It was partly blocked or diluted by other water-masses. A large ''ridge'' of nutrient-rich Atlantic water was found in the central Skagerrak throughout the investigation. It is shown that this elongated ''ridge'' was associated with the deepest (>500 m) area of the Skagerrak. Within this area, high subsurface chlorophyll concentrations were always found and, due to the persistence of the supply of nutrients, it is concluded that this phenomenon could be one of the main reasons for the high productivity of the Skagerrak.

Key words: Skagerrak, Kattegat, circulation, upwelling, nutrients, chlorophyll, primary production.

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Introduction

The Skagerrak may be regarded as a part of the transitional area between the Baltic and the North Sea and is heavily influenced by both seas. It is a very productive sea area with a yearly fish production of 7 g m^{-2} (I. Olsson, pers. comm.). This is almost double that of the North Sea. The Skagerrak is thus of great economic importance to the surrounding countries and is also a nursery and feeding area for about two-thirds of the North Sea herring stocks (Böhle, 1989). However, due to the topography most of the watermasses in the North

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Sea flow through the Skagerrak and it acts as a sink for pollutants. This led the North Sea Task Force to proclaim the condition of the area as an issue of concern (North Sea Task Force, 1993). Since the hydrobiological conditions of the area are very complex and dynamic many features are still poorly known. This is partly due to the fact that most earlier studies of the Skagerrak have been single ship observations. Great variability on a time scale of the order of one day called for a multi-ship, multi-disciplinary approach which led to the initiation of SKAGEX.

During the period May 1990 to May 1991, marine scientists and up to 17 research vessels at a time from nine ICES nations joined forces in the largest joint venture in marine research ever performed in the Kattegat–Skagerrak area. Additional information was obtained from moored current meters, drifting buoys and satellite images. By these means, it was possible to produce a synoptic picture of the dynamics of the area. The objectives of SKAGEX were:

(1) to identify and quantify the various water masses entering and leaving the Skagerrak area and their variation over time;
(2) to investigate the mechanisms that drive the circulation in the area and its links with biological processes; and,
(3) to investigate the pathways of contaminants through the Skagerrak.

SKAGEX was divided into four distinct observing periods; in 1990 May–June, and September and in 1991 January and May respectively. This paper focuses mainly on the variability in physical, chemical and biological parameters during the first part of the experiment (SKAGEX I), 24 May–20 June 1990.

Materials and methods

The general cyclonic circulation and distribution of water masses in the Skagerrak are mainly regulated by the in- and outflowing water to and from the North Sea and the steep local bottom topography (Fig. 1) which is of special importance for the behaviour of the water masses. The short-term variability of the inflow from the Baltic to the Kattegat is regulated mainly by the water level in the Kattegat (Stigebrandt, 1980). The distribution of the relatively fresh surface waters in the Skagerrak and the Kattegat is strongly influenced by varying weather conditions, but during weak local wind situations the surface waters mainly follow the general circulation (Fig. 1). Unpublished modelling results indicate, however, a clear tendency for the anticyclonic circulation of the surface water in the eastern Skagerrak in contrast to the deeper cyclonic circulation.

The area of investigation during SKAGEX I extended from the northern Kattegat to the border between the Skagerrak and the North Sea (Fig. 2). Within this area, eight sections were sampled synoptically every third day, following a strict pattern that optimized the possibilities of producing a synoptic picture of the whole area. During the two days between the obligatory sampling days, each ship carried out its own studies and these added valuable additional data.

The programme that was followed on each station along the transects (Fig. 2) included vertical profiling of the following obligatory parameters: salinity, temperature, nitrate, nitrite, phosphate, silicate, fluorescence, chlorophyll and phytoplankton. In addition, oxygen, ammonia, light, bacteria, potential primary production, nitrogen and phosphorous uptake, zooplankton, species composition and secondary production were measured by some of the ships but are not included in this paper. Currents were measured using recording current meters moored at transects A and G (Fig. 2), continuous shipmounted Acoustic Doppler Current Profiler (ADCP) every 4 m depth, averaged over 5 min intervals and satellite-tracked Argos drifting buoys. Twenty-two partly cloud-free NOAA satellite images of the sea surface temperature distributions of the area have been used as well as standard meteorological recordings in the interpretation of the field data.

During the compilation of the results a data handling programme developed by M. Ostrowski at The Oceanology Institute in Sopot, Poland was used (Ostrowski, 1994). This includes a database holding most of the SKAGEX data and an interactive software package as a tool for a variety of graphic applications as illustrated in this paper (e.g. XY charts, vertical sections, time plots and horizontal distribution maps). The complete hydrographic database including nutrients, chlorophyll and potential primary production is stored at the ICES headquarters.

Results

Major exchanges with the North Sea

As seen in Figure 1, there are several water masses entering the Skagerrak from the North Sea and in the literature this total inflow is often referred to as the Jutland Current (Svansson, 1975). The open arrows indicate the sub-surface transports which sometimes also reach the surface, while the filled arrows indicate surface transports with less saline water. While the general cyclonic circulation around the deepest region was present, with varying strength, throughout the experiment, some of the mesoscale features were only occasionally observed. Due to mixing within the Skagerrak and the supply of Baltic Water (BW) via the Kattegat and fresh riverine water, the outflowing water can be identified as either low salinity Norwegian Coastal Water (NCW) or subsurface Atlantic Water

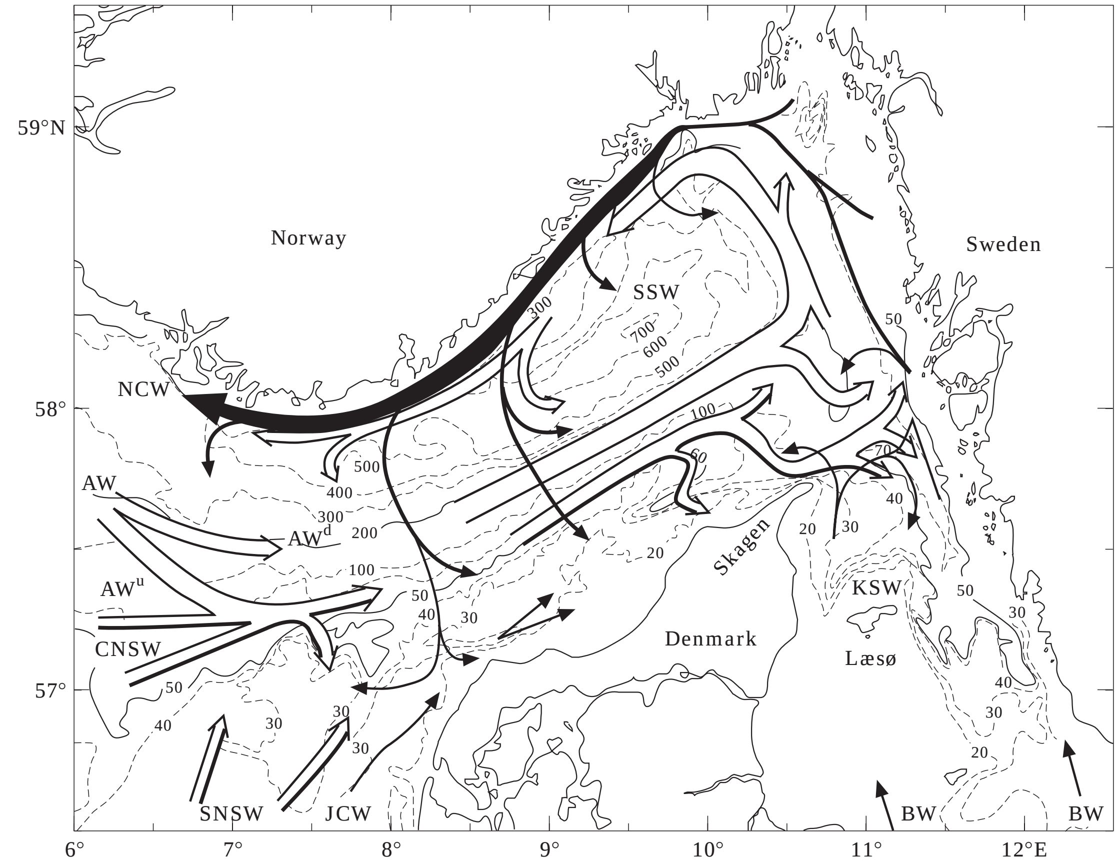

Figure 1. Schematics of the general circulation of the relevant water masses in the Skagerrak and adjacent areas. Open and filled arrows indicate subsurface and surface water, respectively. AW = Atlantic water, AW^u = Atlantic water upper (shallow), AW^d = Atlantic water deep (deep), BW = Baltic water, CNSW = Central North Sea water, JCW = Jutland coastal water, KSW = Kattegat surface water, NCW = Norwegian coastal water, SNSW = Southern North Sea water, SSW = Skagerrak surface water.

(AW), also referrred to as Norwegian Trench Water (NTW) in this area, or mixtures of all. Together this outflow is referred to as the Norwegian Coastal Current (NCC).

Somewhat modified from Danielssen *et al.* (1991) the characteristics of the water masses present during SKAGEX I are shown in Table 1 and Figure 3. The typical and relatively strong cyclonic circulation pattern was confirmed by the ADCP data (Fig. 4) which also show some of the complexity and variability in the area. The drifting buoys, showing speeds up to 1 knot on the Danish side and sometimes up to 2 knots on the Norwegian side, confirmed the general pattern as well. In the area north of 57°N the tidal currents are negligible and therefore the ADCP data have not been adjusted for tidal effects.

At the beginning of the experiment 10 recording current meter rigs were moored along transect G (Fig. 2) to monitor the water movements in and out of the region. Three rigs were totally lost and, on the Danish side, several rigs were soon dragged up by fishing gear. As a consequence there is no good time series of the inflows along the Danish side of the transect. However, results from the extensive ADCP data mainly along section H, indicate a total volume transport into and out of the Skagerrak in the upper 100 m of about 1 (± 0.5) Sverdrup (1 SV = 10^6 m^3 s^{-1}) during the first half of SKAGEX I. Figure 5 is an example of the ADCP measured velocity structure on 27 May, showing the clear separation between the in- and out-flowing water-masses. The transports were calculated by planimetry, extending the isolines subjectively to the surface in the upper 10–15 m where the ADCP does not measure.

The inflows to the Skagerrak and Kattegat areas from rivers and from the Baltic are much smaller than the exchanges from the North Sea. Therefore there must, on average, be a close balance between the in- and outflowing water exchanges with it. The transport variability of ± 0.5 SV cited earlier suggest a possible imbalance between in- and outflows of the order of

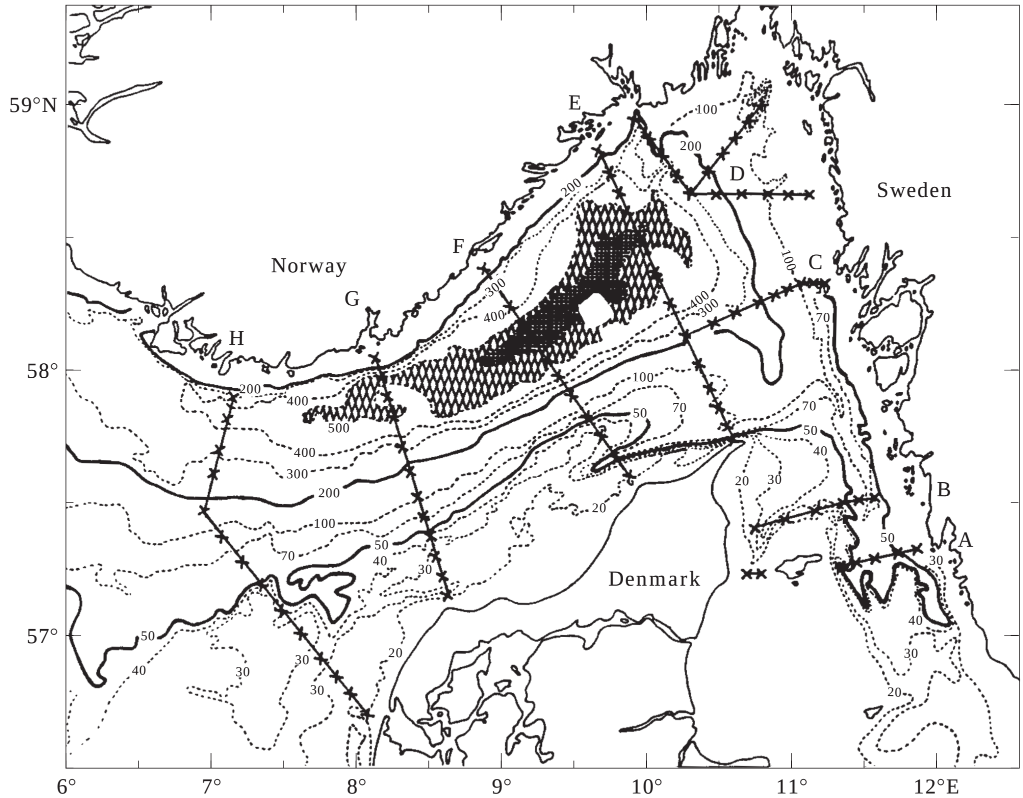

Figure 2. Topography of the Skagerrak and adjacent areas. A, B, C, D, E, F, G, and H show the different sections with the positions of the hydrographic stations. Areas deeper than 500 m are hatched and the 50 and 200 m bottom contour are shown emboldened.

Table 1. Main water masses during SKAGEX 1 (somewhat modified from Danielssen *et al.*, 1991).

	Salinity	Temp.	Comments
In the Kattegat			
Baltic Water (BW)	8.5–10	8–15	Low N, P, some Si
Kattegat Surface Water (KSW)	15–25	8–15	Low N, P, some Si ca. 10 m thick
Kattegat Deep Water (KDW)	30–35	5–10	High nutrients
In the Skagerrak			
Skagerrak Surface Water (SSW)	20–32	10–15	Low nutrients 10–20 m thick
Norwegian Coastal Water (NCW)	25–32	10–15	Low nutrients (part of SSW)
Mixed Skagerrak Water (MSW)	32–35	8–12	
To the Skagerrak from the North Sea			
Jutland Coastal Water (JCW)	32–34	10–15	High N, low P
Southern North Sea Water (SNSW)	34.5–34.8	8–10	Low N
Central North Sea Water (CNSW)	34.8–35.0	8–10	Varying N, P with depth
Atlantic Water (upper)	35.00–35.15	8–10	Varying nutrients (0–7 μmol N/l)
Atlantic Water (deep)	35.15–35.32	7.2–8	7–12 μmol N/l

0.5 SV. However, with the given surface area of the Skagerrak/Kattegat, such an imbalance can last for about a day at maximum before an unrealistic sea-surface height will occur. This means that the total volume transport variability in one direction must rapidly be compensated by a counterflow. Figure 6 shows the daily averaged time series of outflowing currents at different depths at about 10 nautical miles (nmi) from the Norwegian coast. This station is located in the NCC. It is assumed that the variable currents shown in these

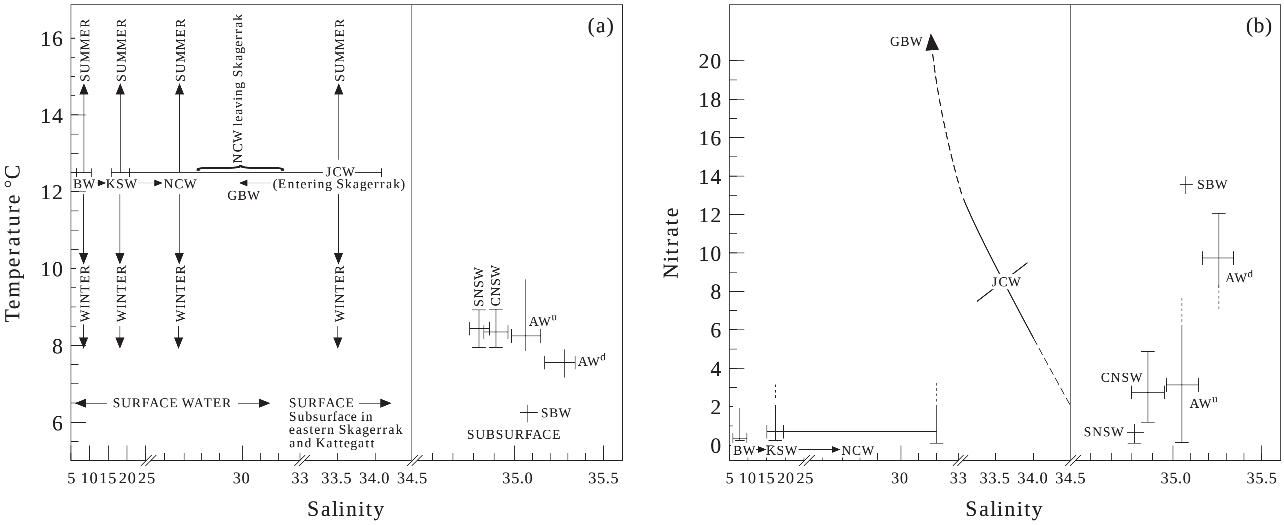

Figure 3. Temperature–salinity (T–S) relations (a) and nitrate–salinity (N–S) relations (b) between different water masses. SBW = Skagerrak bottom water, other abbreviations, see Table 1 and Figure 2.

results also indicate the variability of the transport to the North Sea and thus also of the variability of the inflow on the Danish side. In this respect the water exchange with the Baltic is negligible.

It is interesting to note that during the first period, i.e. until about 5 June, the currents, shown by both the moored instruments and the ADCP data (Fig. 5) are roughly equal at all depths. This means that there is no significant forcing from the density field. The variability seems to be regulated from the outside through the inflowing subsurface AW, and/or CNSW (Figs 1, 5, Table 1) with the overlaying NCW flowing relatively passively out on top of this.

After 5 June a gradual decrease (Fig. 6) is seen in the flow of the deeper water (Atlantic Water), which on the Norwegian side was found up to about 50 m depth (Fig. 5). Then a typical baroclinic situation, with larger velocities towards the surface, was established which lasted throughout the experiment. The transport of AW seemed to drop close to zero around mid June, followed by a significant increase at the end of the experiment. The decreased velocity of the AW also seemed to influence the upper water masses but with a time lag of several days. During the period of increasing flow towards the end of the experiment, however, there was an immediate response in the velocity of the water body above the AW.

The Jutland Coastal Water (JCW)

The nitrate-rich JCW originates in the German Bight and is formed by fresh water from the continental rivers being gradually mixed with nutrient-poor Southern North Sea Water (SNSW) on its way north along the western coast of Jutland (Danielssen *et al.*, 1991). At the entrance to the Skagerrak the JCW water must ''compete'' with the other water masses possibly present in the area, and the result is often that there is no inflow of this water. When there is an inflow it follows the shallow coastal areas along the coastline.

Figure 7 shows the development of the vertical distribution of salinity and nitrate from the innermost station on section H, G, F and E over one month. The nitrate distribution indicates that the JCW was present, through section H and G, at the beginning, but that it had totally disappeared by 27 May. The moored current meter data shows an inflow in the period 23–24 May but by the 27th there was an outward flow in the area (Danielssen *et al.*, 1991). The cause of this was a period of strong northwesterly wind (Beaufort 7) (Fig. 8), forcing the NCW to flow across to Denmark (Fig. 1), and causing the salinity to drop to less than 30 (Fig. 7). Both the direct wind stress and the NCW acted to block the JCW from flowing into Skagerrak. In addition, strong mixing between the NCW and the relatively small volume of JCW rapidly diluted the high nitrate values to near zero. After a period of weak winds, picking up to strong southerly wind on 3–4 June (Fig. 8), the JCW again appears at transect H (5 June, Fig. 7), progressing to section G by 8 June and seeming to be at maximum strength by 11 June. The JCW never reached section F. After 11 June a clear dilution of the upper 15 m is again observed (Fig. 7, nitrate at sections G and H). From 17–20 June there is again a rapid progress of the JCW through section H and G, as is also seen in the horizontal distribution map of nitrate from 19–20 June (Fig. 9). Modelling experiments (Skogen *et al.*, 1997), however,

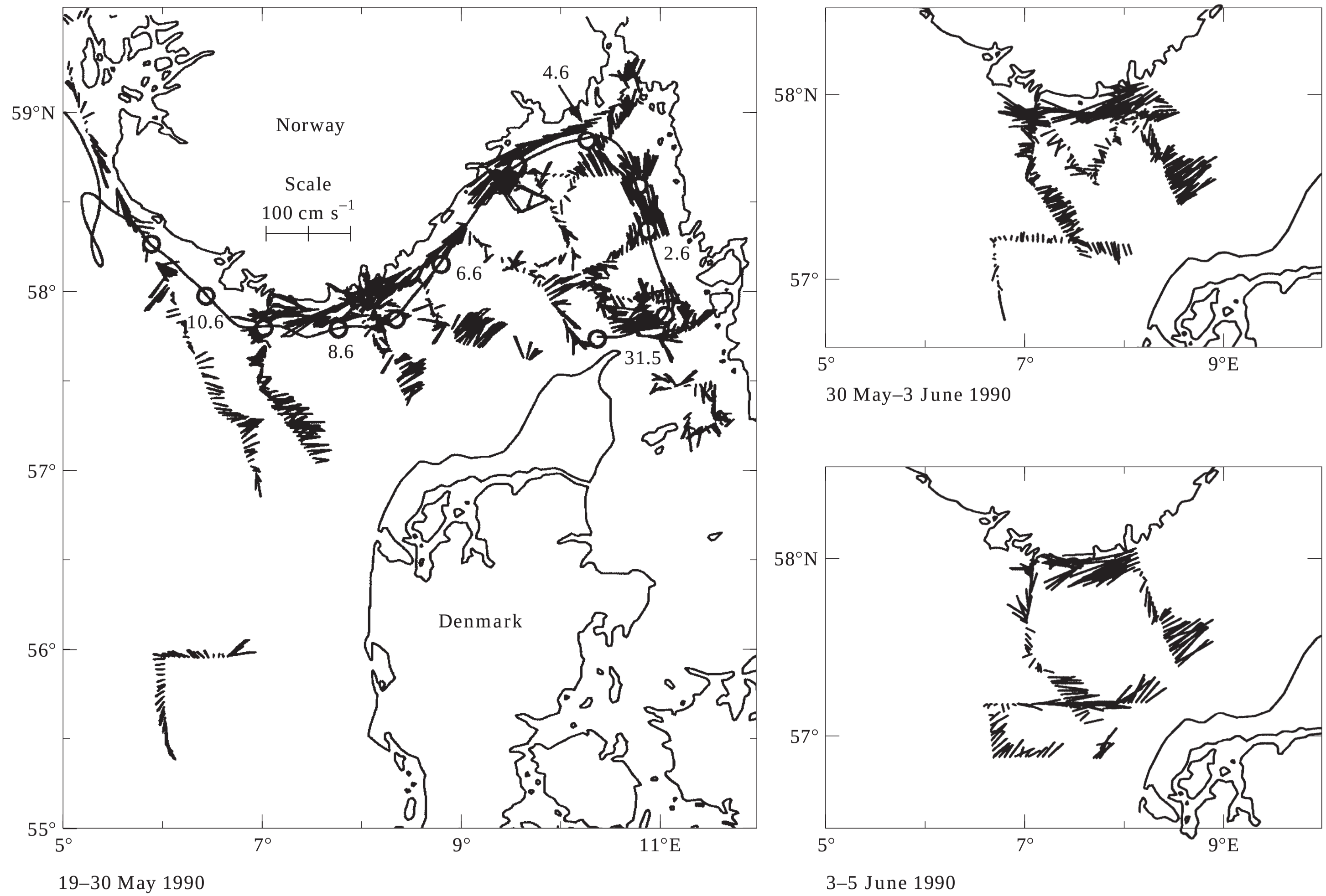

Figure 4. Acoustic Doppler Current Profiler (ADCP) data from 29 m depth obtained by ''G. O. Sars'' in the three periods: 19–30 May 1990, 30 May–3 June 1990 and 3–5 June 1990. Drift track with daily positions of one Argos buoy with drough at 10 m depth deployed 31 May north of Skagen (one day between each filled circle).

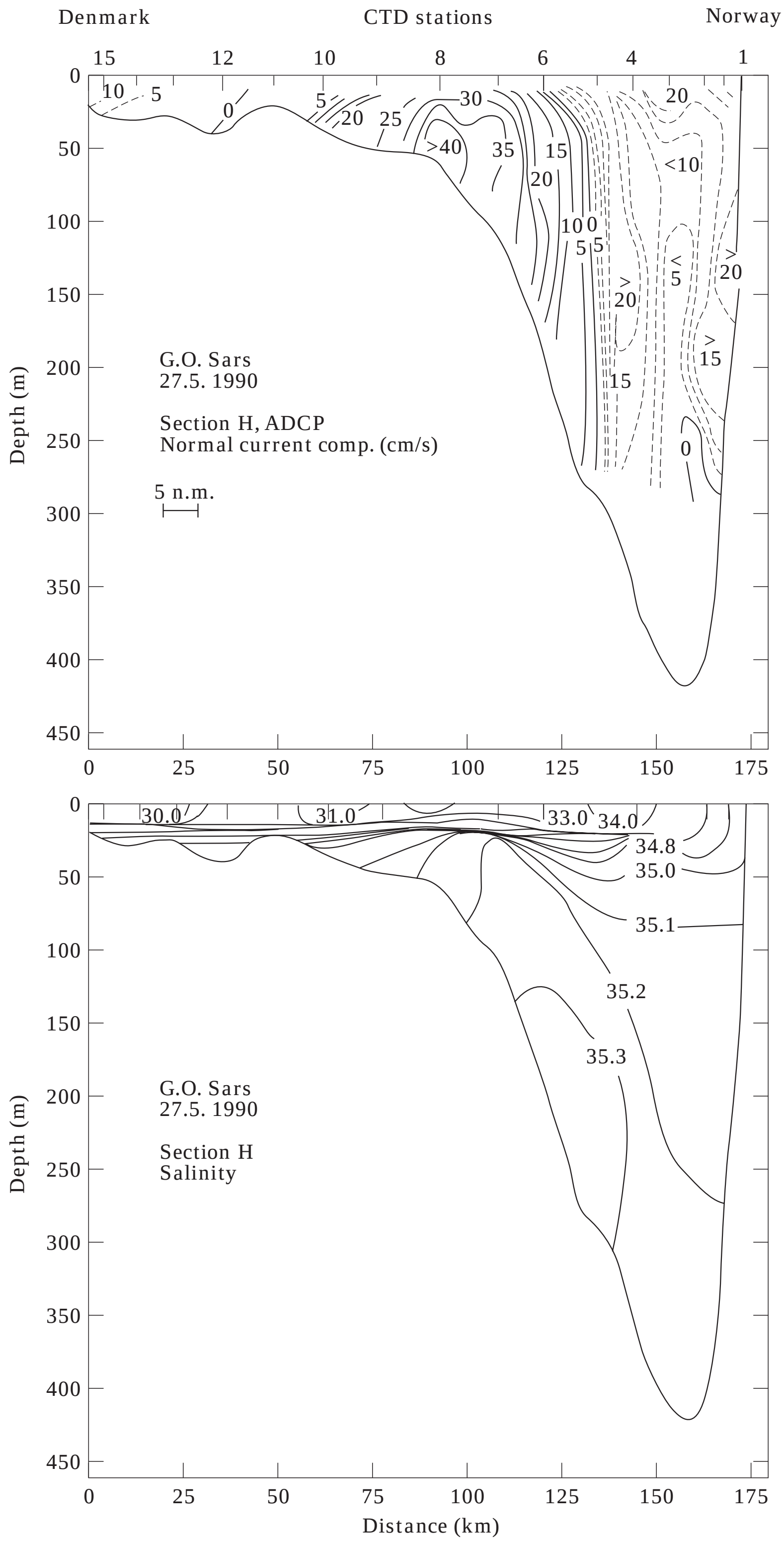

Figure 5. Vertical structure of velocity (normal to the section) from section H on 27 May measured by shipmounted ADCP (upper figure). Solid/dashed lines represent velocities into/out of Skagerrak, respectively. Salinity distribution from the same section and date is shown on the lower figure.

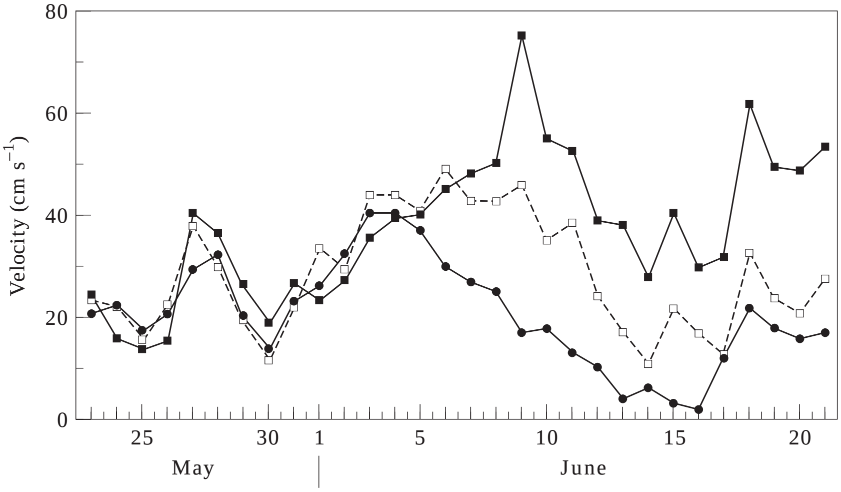

Figure 6. Variations in velocity at 20 (–■–), 40 (– –□– –) and 100 (—●—) m depth measured during SKAGEX I by current meters 10 nmi from the Norwegian coast on section G.

indicate that the presence of nitrate at the beginning of the SKAGEX I originates from AW and not from JCW. With respect to the other two nitrate ''pulses'', there is an agreement with the model that this is the progressing JCW.

The surface water (SW)

The salinity of the surface water in Skagerrak (SSW) varied during SKAGEX I between 20 and 32 and the temperature range was 10 to 15°C. The SSW formed a layer approximately 20 m deep which was separated from the sub-surface water by a halocline. The silicate content in the SSW was low, generally less than 1 μmol l^{-1}. This may be attributed partly to mixing with water originating from the North Sea.

The Kattegat surface water (KSW) was identified as a layer extending from the surface to approximately 10 m depth with a salinity between 15 and 25. Due to the supply of silicate from river water, the silicate content was comparatively high. During SKAGEX I, the concentrations sometimes reached more than 6 μmol l^{-1}. The KSW can enter the Skagerrak both east and west of Læsø (Poulsen, 1991). A small part of it may occasionally turn west around Skagen but the main part generally continues along the west coast of Sweden to Norway where it turns westward. It is then called the Norwegian Coastal Water (NCW) and continues along the Norwegian coast out into the North Sea. As the water flows along the Swedish and Norwegian coasts fresh water from many rivers is mixed into the water mass.

Sætre *et al.* (1988) have demonstrated that because of the influence of northerly winds, the core of the NCW typically follows an offshore route in the western Skagerrak. During SKAGEX I it was shown that occasionally the NCW may cover most of the Skagerrak down to the Danish coast. The detailed salinity time series show that this water reached the Danish coast near section G prior to or around 24 May (Fig. 7). Around 27 May, this water, with relatively low salinity water, seems to have spread both eastward to section F (and E) and southwestward to section H (see also Fig. 2). During SKAGEX I it was almost completely stripped of nutrients due to primary production.

In connection with the very strong northwesterly winds during the last week of May (Fig. 8), there was a pronounced penetration of Skagerrak Surface Water into the Kattegat. This increased the surface salinities in the Kattegat considerably (Fig. 10) and it effectively blocked the outflow of Kattegat Surface Water.

Figure 10 illustrates the development with time of the salinity and silicate concentrations at 5 m depth across sections B and C. The outflow of Kattegat water seems to have been more or less blocked during most of SKAGEX I. An outflow of KSW into the Skagerrak was only detected during the first day of SKAGEX I (24 May), somewhat stronger around 11 June and at the very end of the experiment on 20 June. On each occasion it was found close to the Swedish coast (section C, Figs 2, 10), although within the Kattegat the surface water was present across all of section B. This is in accordance with Andrulewicz *et al.* (1997) who finds that only small volumes were transported through the Læsø Channel. The weak outflow of KSW was also indicated by an Argos drifter that was rotating for more than two weeks (2–18 June) in the northern Kattegat (Danielssen *et al.*, 1991).

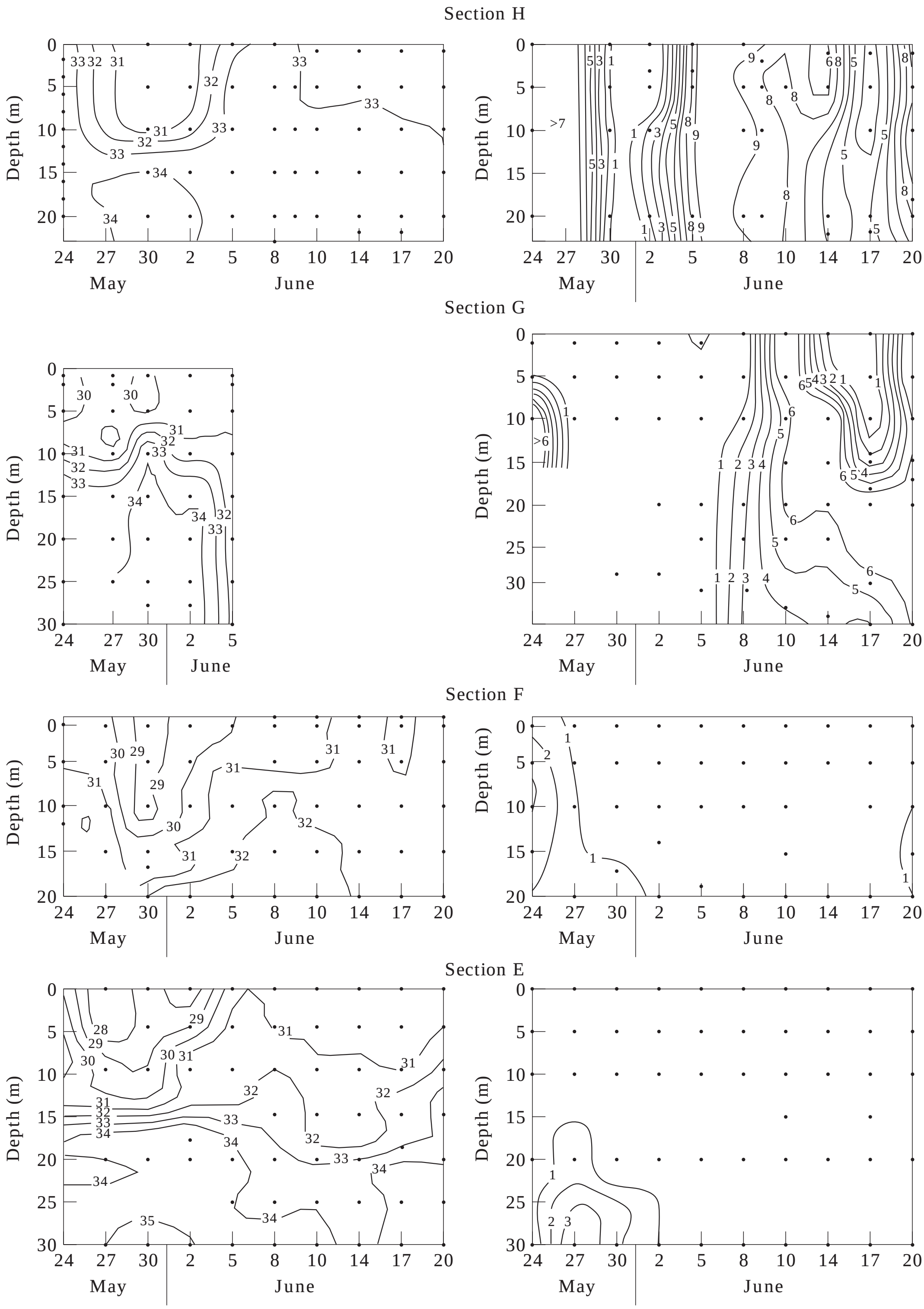

Figure 7. Time evolution of the vertical distribution of salintiy (*left*) and nitrate (*right*) at the innermost station to the Danish coast from section H, G, F, and E during SKAGEX I.

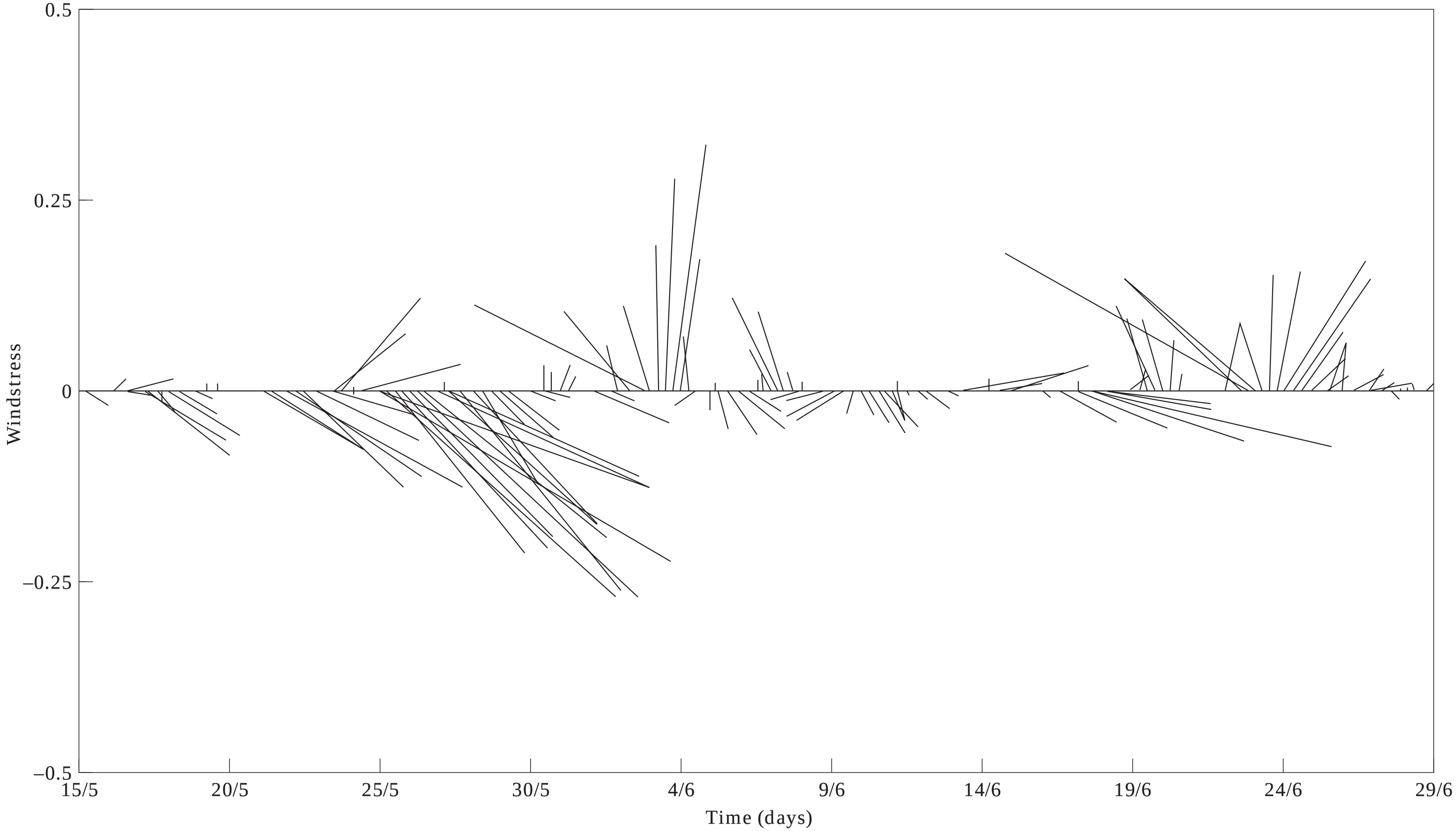

Figure 8. Vector-diagram of the windstress in the outer Skagerrak during the SKAGEX I; windstress of 0.05 N m^{-2} = windvelocity of 5 m s^{-1}; windstress of 0.19 N m^{-2} = windvelocity of 10 m s^{-1}; windstress of 0.43 N m^{-2} = windvelocity of 15 m s^{-1}.

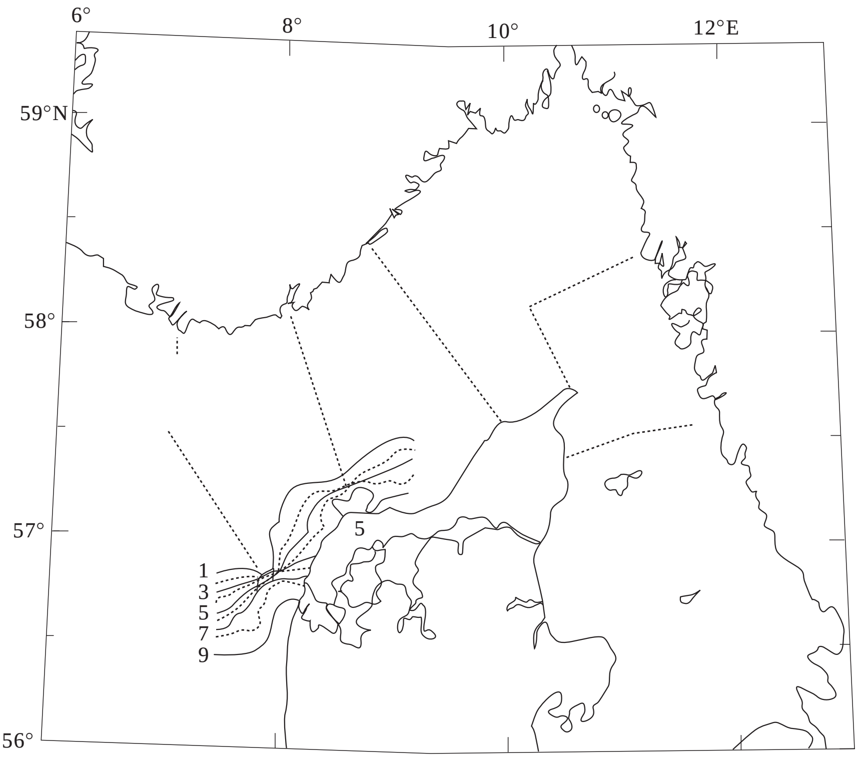

Figure 9. Horizontal distribution of nitrate at 5 m depth in the period 19–20 June 1990 in the whole area.

The ridge

The phenomenon referred to as the ''dome'' by Pingree *et al.* (1982) and Richardson (1989) was seen over a large area during most of SKAGEX I. As can be seen from the distributions of nutrients (Fig. 11), its contour coincided remarkably well with the 500 m depth isoline (Fig. 2). Due to its elongated form we prefer to call it the ''ridge''. In Danielssen *et al.* (1991) it was suggested that the ridge is formed by upward Ekman pumping driven by the gross circulation of the water. During this month-long study the ridge seemed to be partly steered by the topography and showed great variability in form and areal distribution. By calculating the areas of the 4 and 6 µmol l^{-1} isolines for nitrate at 30 m depth, we have measured the coverage of the ridge at that depth in relation to the whole Skagerrak. As seen in Figure 12, the 4 µmol l^{-1} isoline shows a coverage of almost 60% at the beginning. In early June the ridge area at 30 m depth decreases quite drastically and during the last part of the study only 30 to 45% of the Skagerrak area is covered. The isoline for 6 µmol l^{-1} shows the same development, with a decrease from about 40% in the beginning to 15–25% towards the end of the observing period. In early June the ''ridge'' decreased in size by descending to somewhat greater depths in the central-eastern part of Skagerrak. A few days later it was back but had now descended in the western part. The main decrease from 2 to 5 June was coupled to a physical descent of the ''ridge'' found from the change in the horizontal density distributions at 30 m depth.

The areal distribution of the subsurface chlorophyll maximum was clearly connected to the ridge (Fig. 11), which suggests that the phytoplankton utilize the nutrients continuously pumped to depths relatively close to the surface in the ridge to form large populations. Time series of integrated chlorophyll at the transects F and G clearly indicate the continuity of the large phytoplankton populations along the ridge (Fig. 13). The maximum chlorophyll concentrations were generally found around 20 m depth but in some instances they were located near 10 m and at others down to 30 m depth. In Figure 12 we have depicted areas of more than 4 µg chlorophyll l^{-1}. In many places and instances, however, the chorophyll concentrations were much higher. Values of more than 20 µg l^{-1} were found on several occasions. Contrary to the development of the ridge the percentage coverage of the sub-surface chlorophyll maximum slowly increased during the study from about 20 to 30% of the total area.

Upwelling

During SKAGEX I there were several examples of upwelling along both the Swedish and the Norwegian

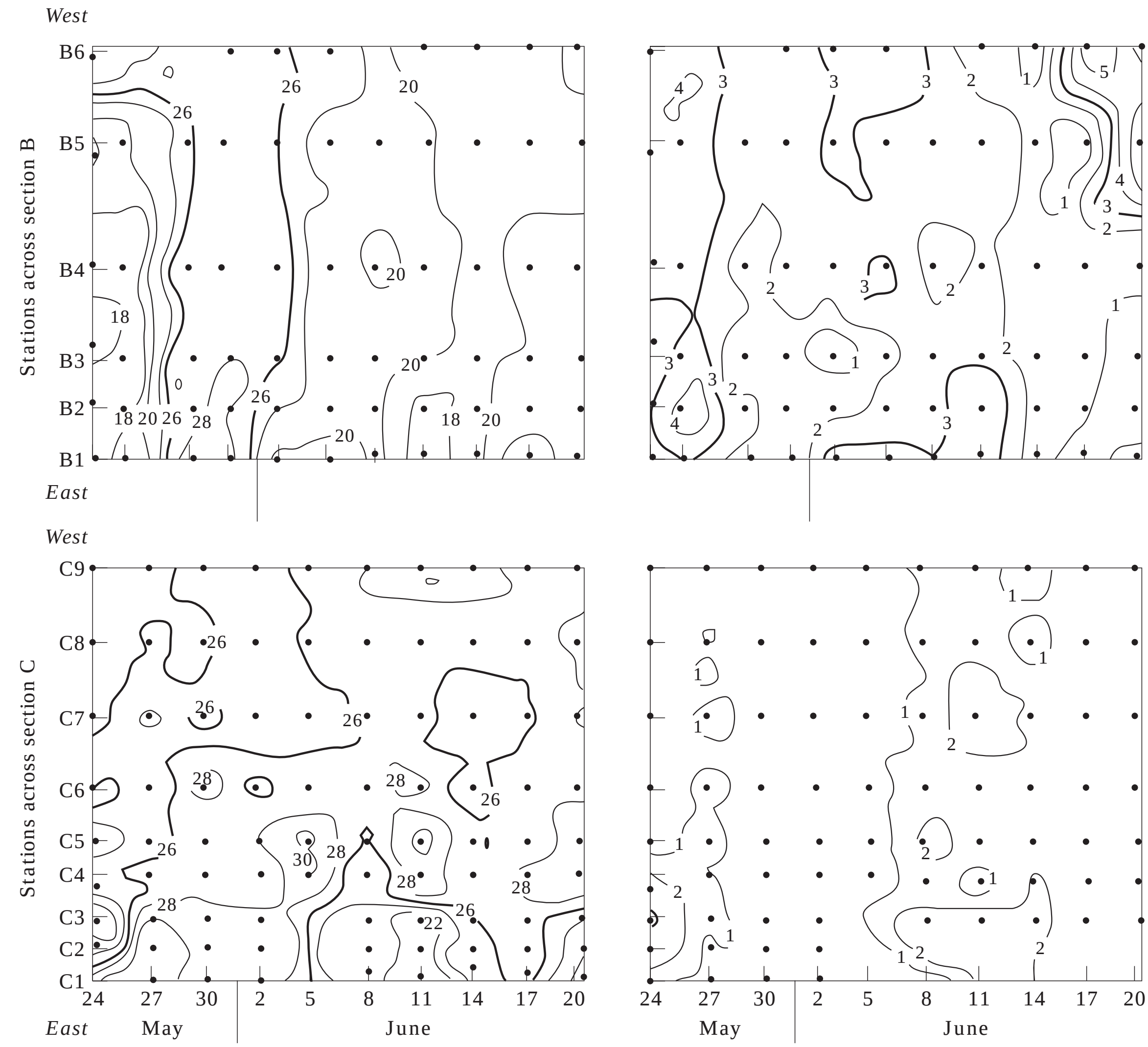

Figure 10. Time evolution of the vertical distribution of salinity (*left*) and silicate (*right*) at 5 m depth along section B and C during SKAGEX I.

coasts. One that occurred along the south-west coast of Norway, at the entrance to the Skagerrak was very obvious and resulted in increased primary productivity. The upwelling was underway already on 24 May and seemed to culminate around the 27th (Fig. 14). Together with high saline water (>34.5), high concentrations of nutrients were also introduced from about 30 m depth to the surface layer close to the coast. Nitrate concentrations rose to 8–9 μmol l^{-1} during that period (Fig. 15). Further out, about 25 nmi from the coast, there was a sharp front where the concentrations dropped to levels lower than 1 μmol l^{-1} in the upper 10 m. In the upwelled water near the Norwegian coast, the chlorophyll concentration was very low. Integrated over a 20 m water column the values ranged between 11 and 14 mg m^{-2} (Fig. 16). Off the coast, where the salinity decreased, the chlorophyll concentration increased successively to a maximum 10 times higher (168 mg m^{-2}). Phytoplankton primary production showed the same pattern (Fig. 16), with very low production in the upwelled water and a successive increase to levels 10 times higher further offshore. In the upwelled water phytoplankton were scarce and the bulk of nutrients had not yet been utilized. The increase in nutrients in the front between the two water masses, however, obviously stimulated phytoplankton production considerably.

On 30 May, the upwelled water was replaced by NCW with much lower salinity (Fig. 17). This water contained considerably more phytoplankton and an increased production during the following week was also seen, although nitrate concentrations were as low as 1–2 μmol l^{-1} in the surface layer. Outside the upwelling area, the

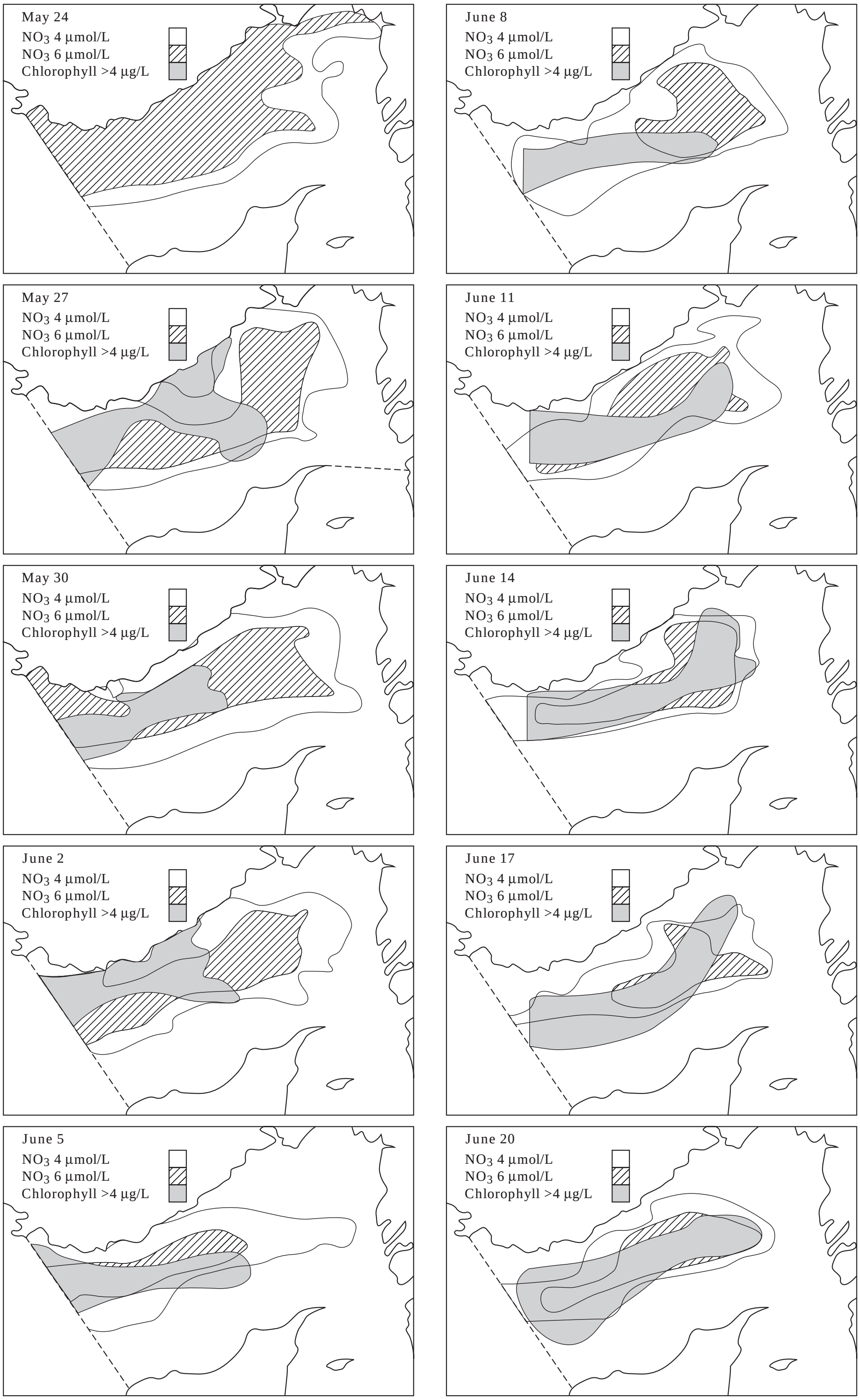

Figure 11. The variation in areal distribution of the 4 μmol l^{-1} and 6 μmol l^{-1} of nitrate and subsurface chlorophyll maximum of more than 4 μg l^{-1} during SKAGEX I.

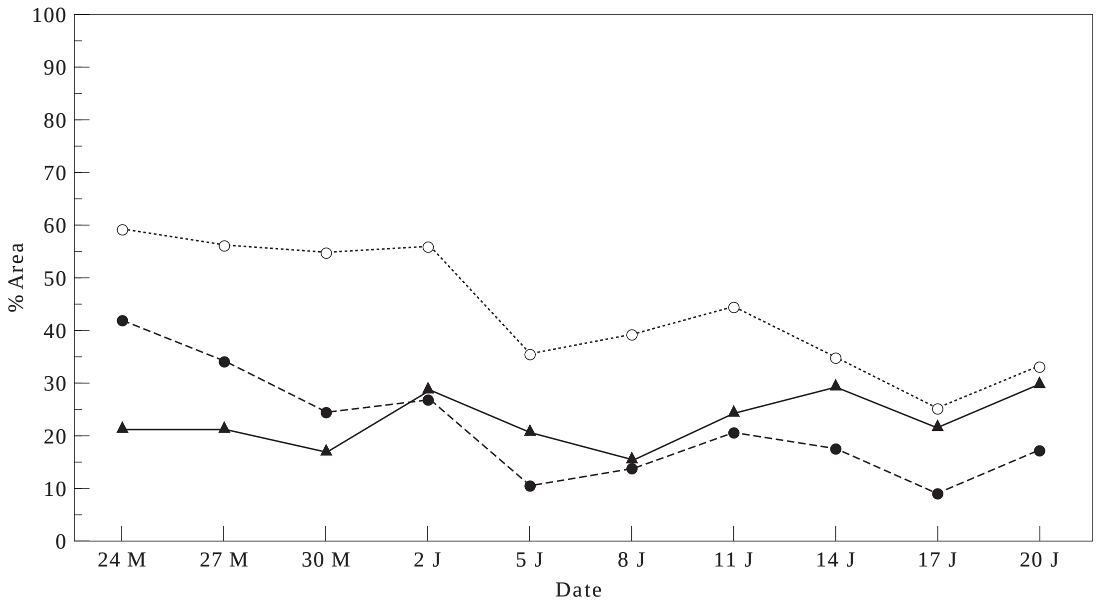

Figure 12. Areal distribution in percent of the ridge at 30 m depth for nitrate concentrations of 4 (·····○·····) and 6 μmol l^{-1} (– – ● – –) and of subsurface chlorophyll maximum of more than 4 μg l^{-1} (— ▲ —).

very high biomass continued to be present until the beginning of June. At this time biomass and productivity decreased, which may be attributed to either lack of nutrients or dilution of the watermass.

The addition of nutrients to the surface through the upwelling made high primary productivity possible along a rather narrow front between the water masses. We suggest that the short-term upwellings along the coasts result in only a limited addition to produced carbon as the upwelled water lacks initial phytoplankton populations. The ridge, however, spread over a larger area and able to ''seed'' populations developing as subsurface maxima, is probably the main reason for the high productivity of the Skagerrak.

During the period 26–28 May upwelling occurred at the Swedish coast and is shown both in the surface salinity and nitrate distributions (Figs 14, 15). At section F, near the Norwegian coast, upwelling occurred on 30 May and between 8 and 14 June. The upwelling on 30 May was strong (Fig. 17) and high concentrations of nitrate, more than 3 μmol l^{-1}, were brought to the surface layer.

''Twin peaks''

A relatively permanent phenomenon throughout the experiment was the dual peaked nature of the upper salinity distribution on several of the sections across the Skagerrak. This ''twin peaks'' phenomenon is not seen in any of the nutrient distributions, as Figure 18 shows in the case of nitrate on section F, and it conflicts with the general idea of the upward Ekman transport associated with the ridge. A possible explanation could be that the salinity peaks relate to the shallow Atlantic Water which has lost its nutrients, due to primary production probably on the northern North Sea plateau at this time of the year, and which is rapidly circulating around the relatively stationary water in the centre (Fig. 19). However, the depression of the isohalines in the centre below about 20 m depth, approximately the euphotic zone, is probably caused by a dynamic balance due to maximum subsurface velocities in the shallow Atlantic Water masses, or a near-surface anticyclonic circulation inside the large scale general cyclonic circulation. Another explanation for the ''twin peaks'' feature may be that there is an anticyclonic surface circulation on top of the general cyclonic circulation. This has been found recently in unpublished modelling experiments and needs further investigation.

Conclusions

The main outflow from the Skagerrak, represented by the Norwegian Coastal Current, was mainly barotropic during the first half of the experiment with daily mean velocities varying typically from 10–40 cm s^{-1}. After 5–6 June, a clear baroclinic current component developed giving rise to near-surface velocities of up to 100 cm s^{-1}. However, from the available moored current-meter data, it has not been possible to estimate reliable time series of absolute volume transports in and out of the Skagerrak and consequently it has not been

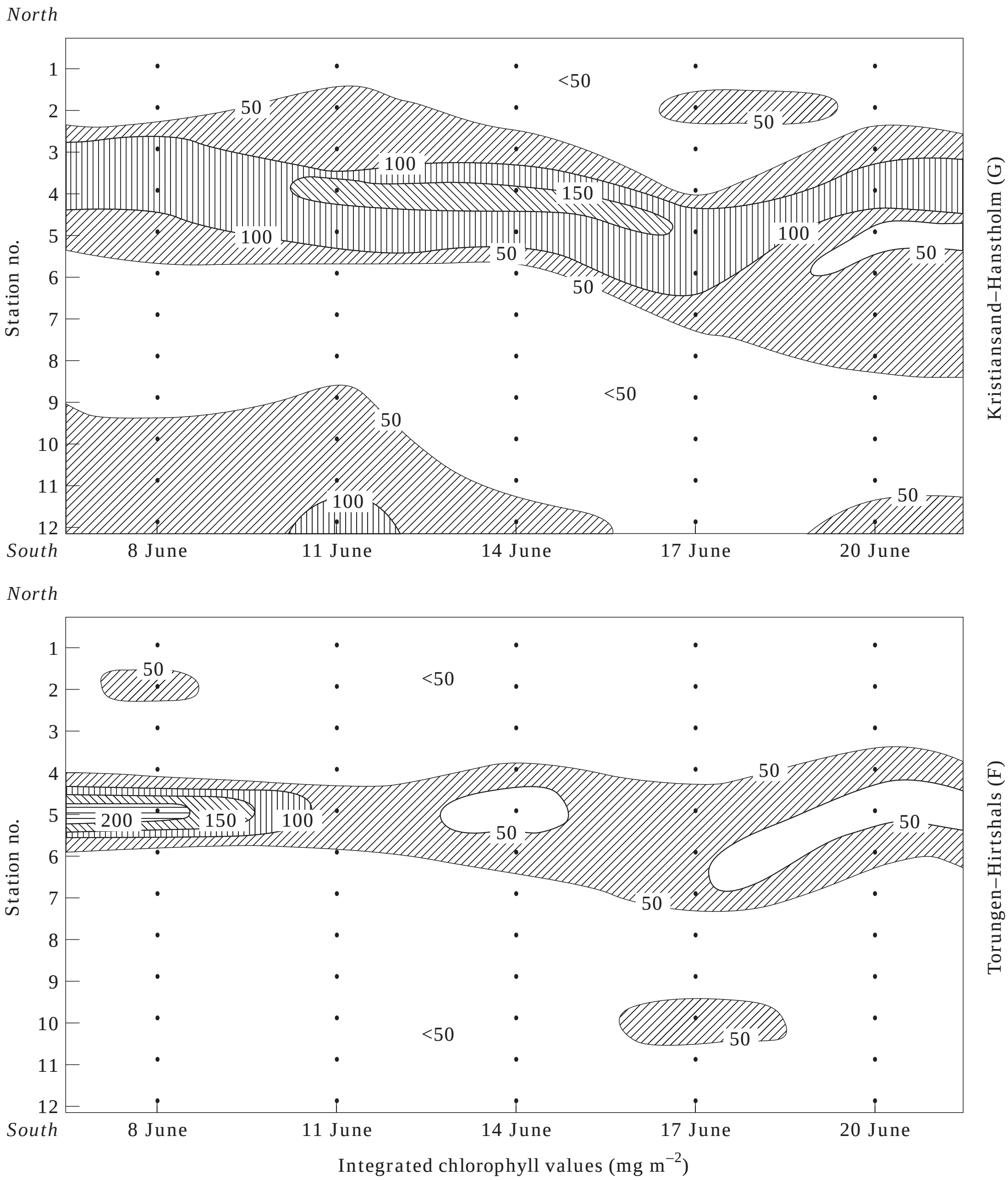

Figure 13. Time evolution of the vertical distribution of integrated chlorophyll values in the upper 50 m at transect F and G during the last two weeks of SKAGEX I.

possible to quantify the exchange of, for example, nutrients with the North Sea.

Due to the sharp pycnocline that occurs the surface water has a tendency to disperse over large areas of the Skagerrak and, during strong north-westerly winds, it can be seen reaching also the Danish coast south of 57°N. During such wind conditions pronounced upwelling occurs along the Norwegian coast. It is also found along the Swedish coast during northerly wind conditions.

The reasons for the variable presence of Jutland Coastal Water are well documented and this water did not reach the inner part of the Skagerrak durng the whole period of observation. It was partly blocked or diluted by other water masses and therefore the effect of an increase in nutrients to the surface layer was not seen

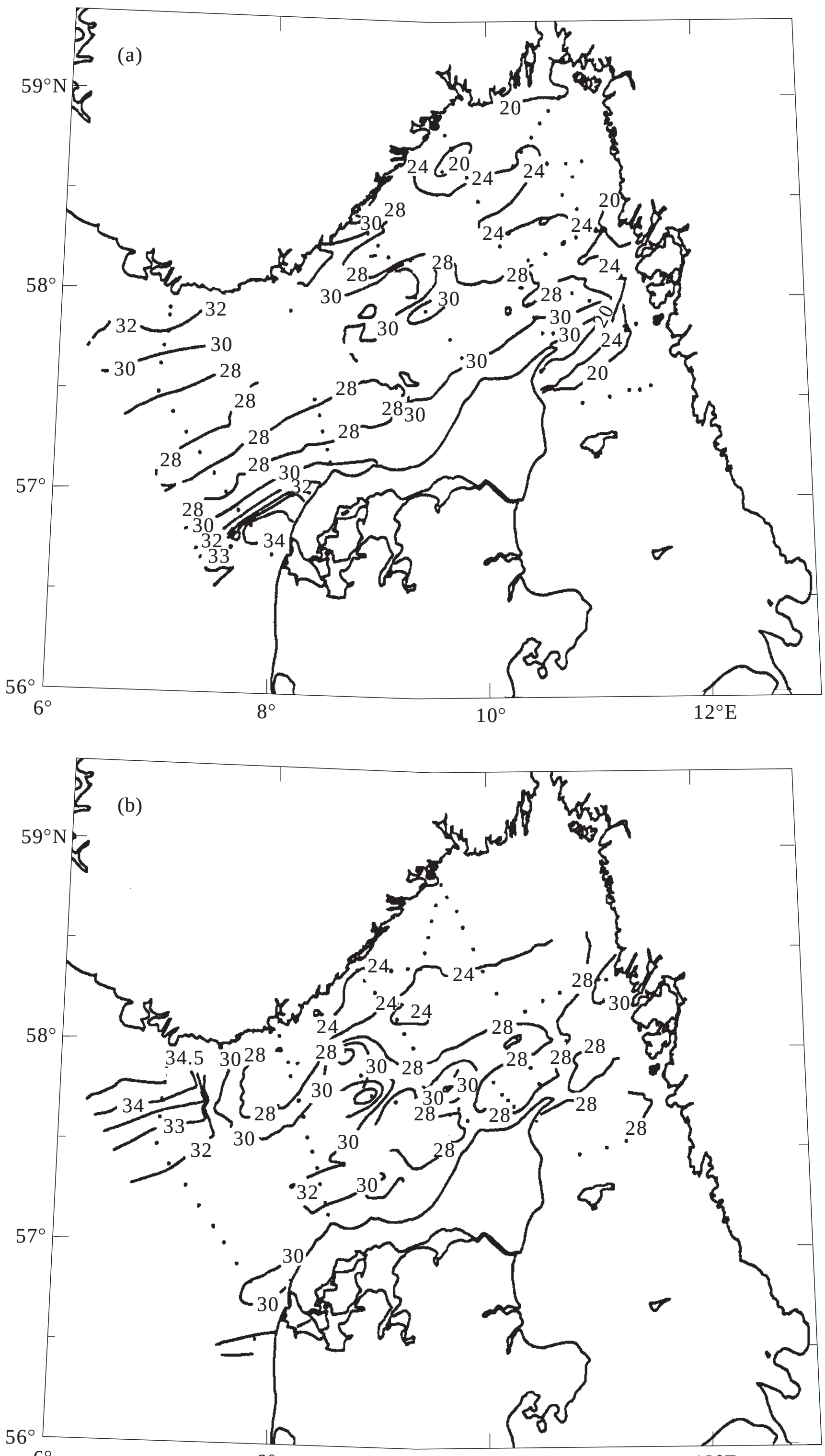

Figure 14. Horizontal distribution of salinity at 5 m depth over the whole area in (a) the period 24–25 May 1990, and in (b) the period 26–28 May 1990.

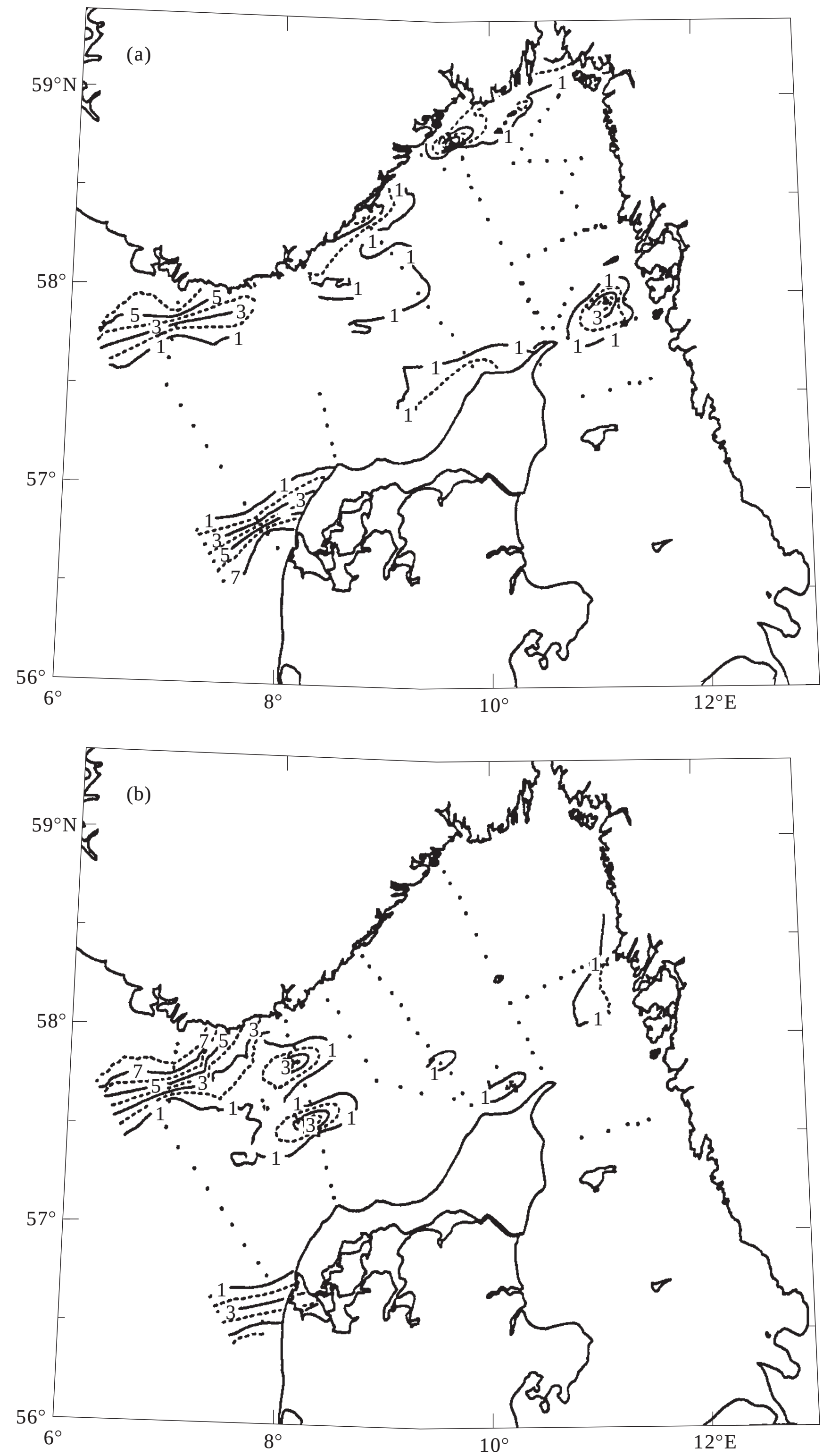

Figure 15. Horizontal distribution of nitrate at 5 m depth over the whole area in (a) the period 24–25 May 1990, and in (b) the period 26–28 May 1990.

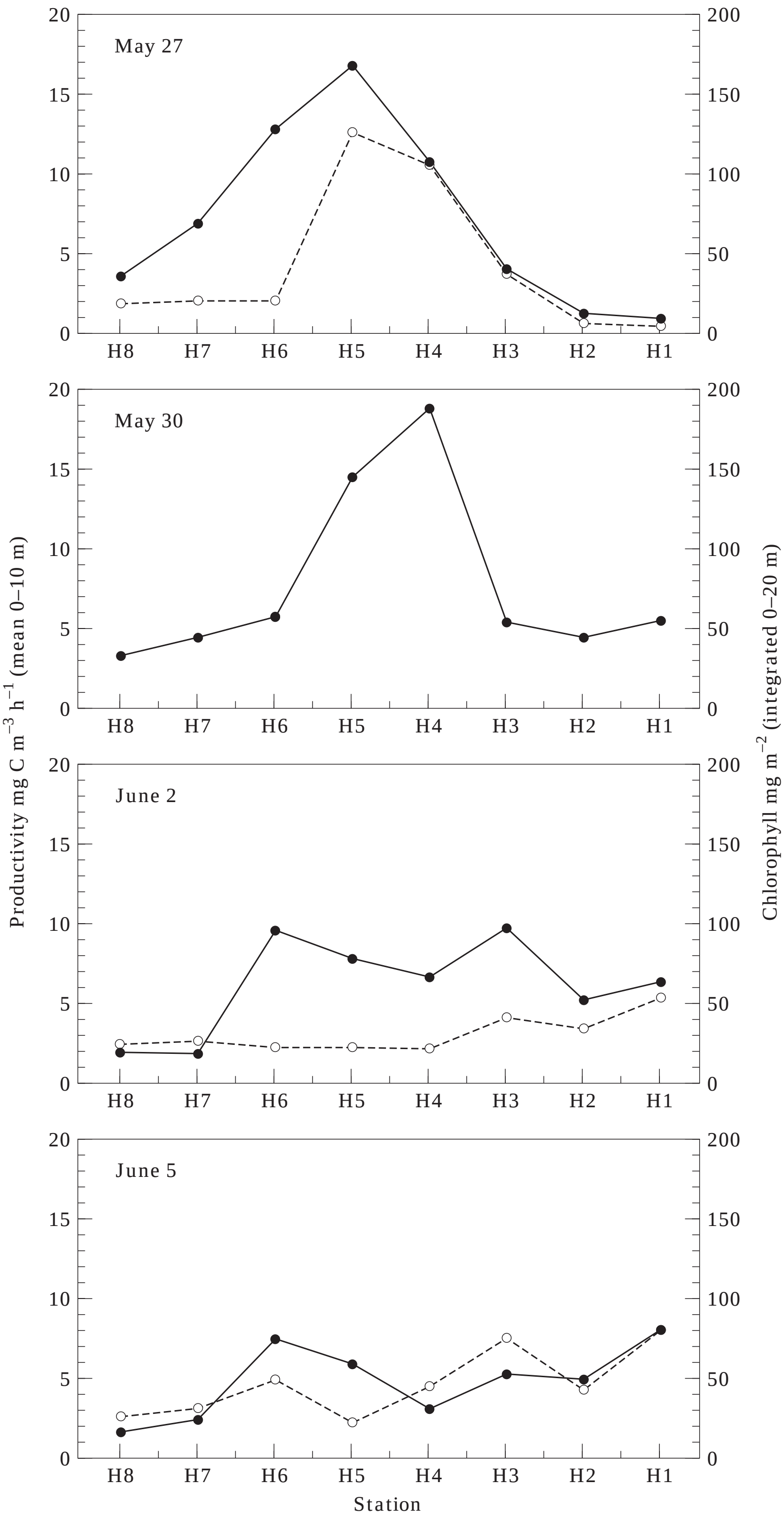

Figure 16. Integrated values of chlorophyll between 0 and 20 m depth (—●—) and mean values of productivity between 0 and 10 m depth (- - -○- - -) along the section H in the period 27 May–5 June 1990.

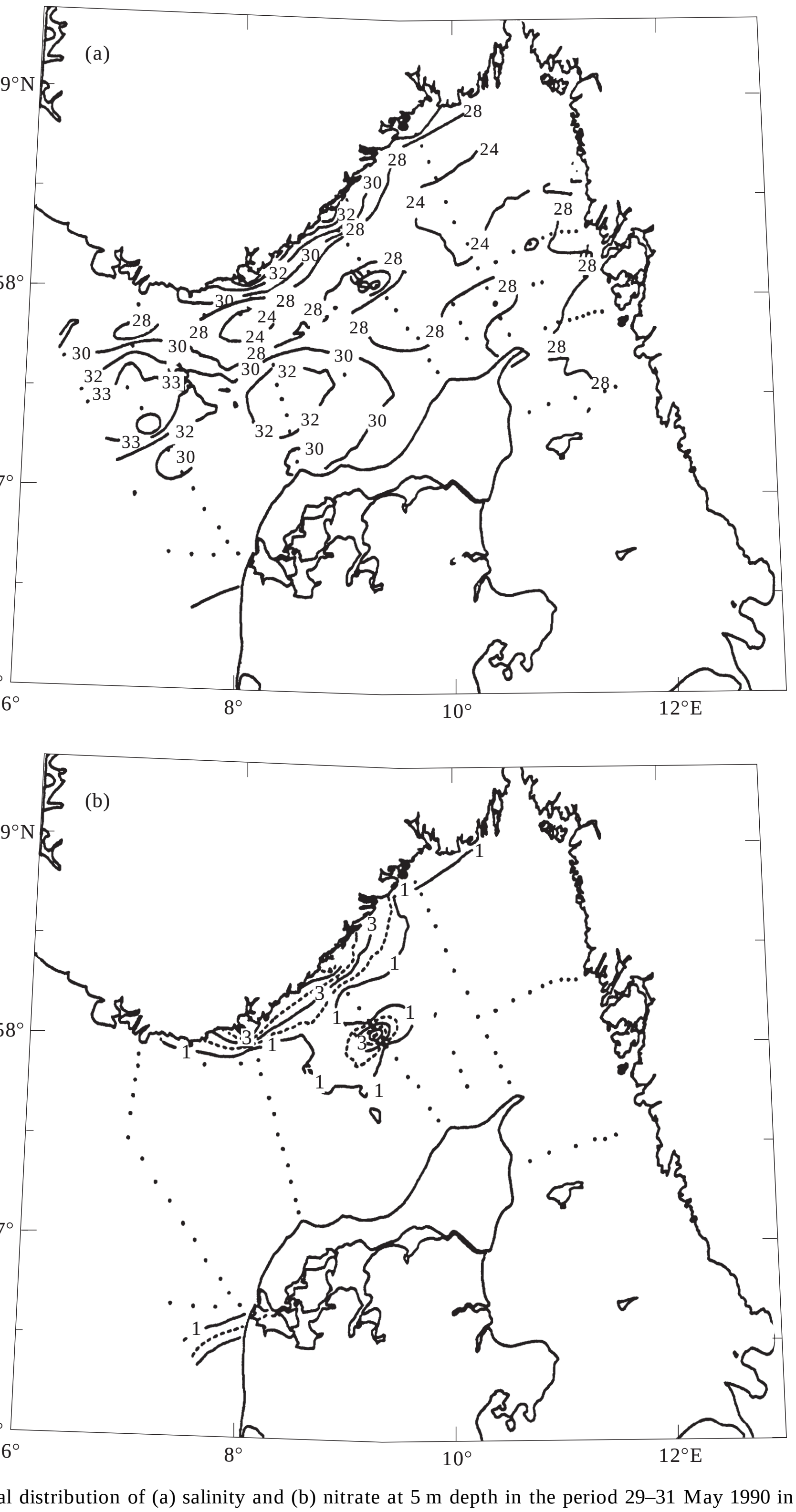

Figure 17. Horizontal distribution of (a) salinity and (b) nitrate at 5 m depth in the period 29–31 May 1990 in the whole area.

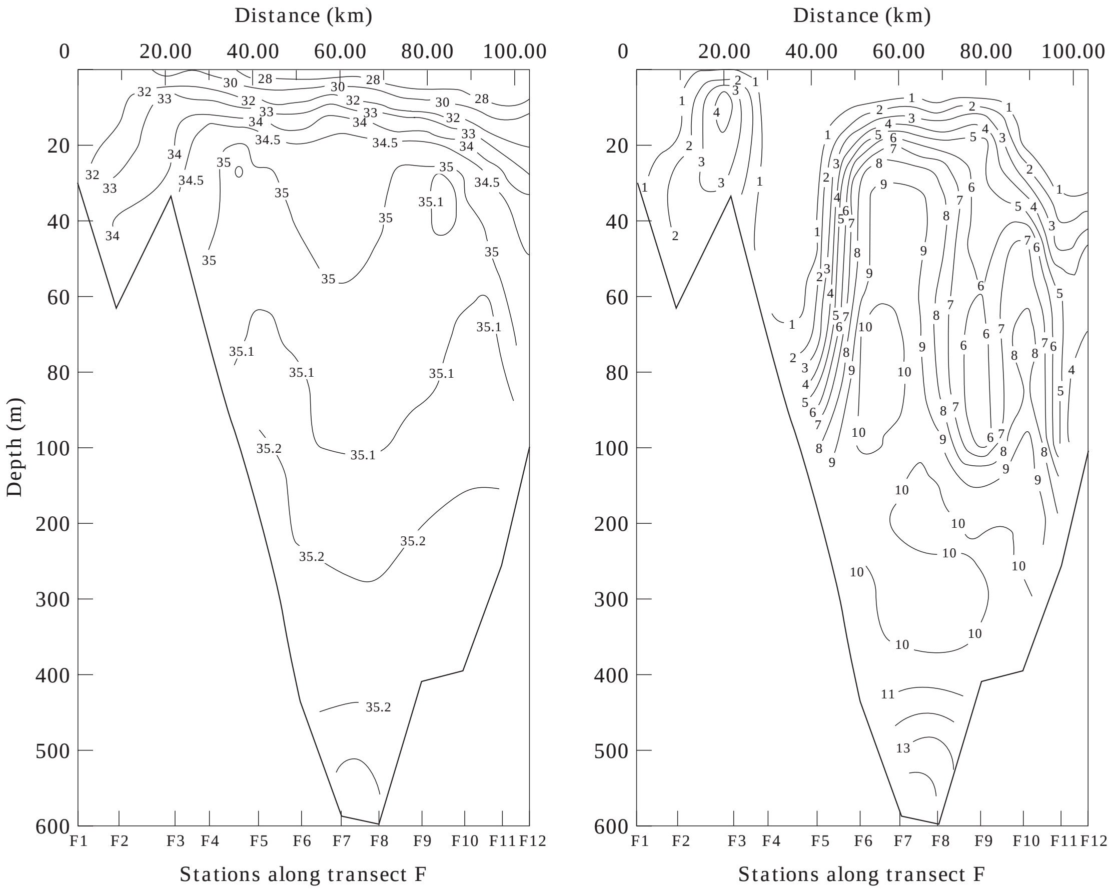

Figure 18. Vertical distribution of salinity and nitrate at section F on 17 June 1990.

in that area. The elongated ‘‘ridge’’ of nutrients is associated with the deepest area of the Skagerrak (>500 m). This upwelling of Atlantic Water is probably caused by Ekman pumping due to the general cyclonic velocity shear in this region.

The importance of the variable inflow and spatial distribution of nutrient-rich Atlantic Water on the biological processes has already been stressed in Danielssen *et al.* (1991). Our analyses of the spatial and temporal variability of the processes during SKAGEX I show that such variability certainly does exist. It is found in the areal distribution of high chlorophyll concentrations along the ‘‘ridge’’ and in upwelling events creating high primary productivity in specific areas. It is illustrated by large variations in zooplankton egg-production over short distances (Tiselius *et al.*, 1991). However, the general conclusion made in Danielssen *et al.* (1991), that the ‘‘ridge’’ constitutes a more or less continuous supply of nutrients that sustains high sub-surface phytoplankton production over long periods of time in central Skagerrak, still holds. Local upwellings will certainly contribute to the high productivity found in Skagerrak but they are probably of minor importance compared to these subsurface processes.

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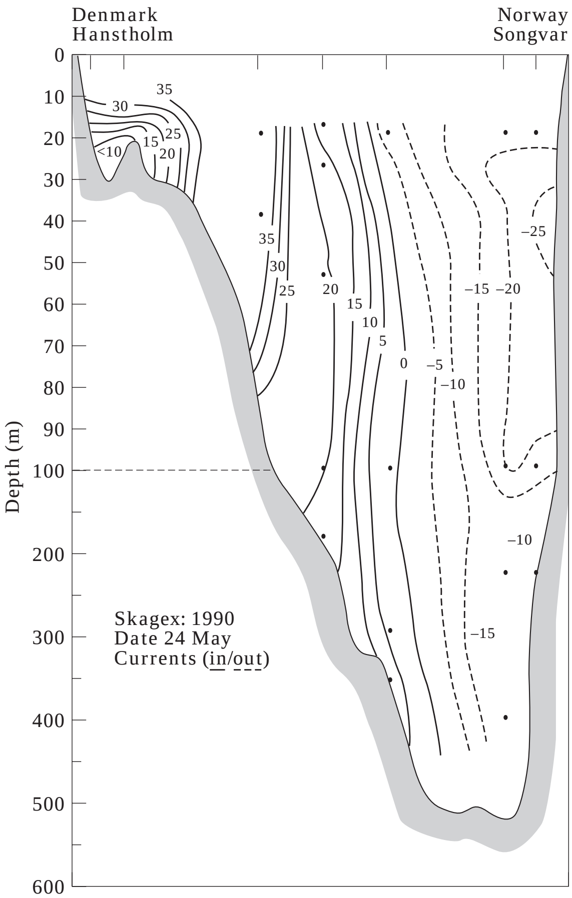

Figure 19. Three day mean in/outflow velocities from moored current meters along the transect G between Hanstholm and Kristiansand, 23–25 May 1990. Dots indicate the positions of individual current meters (Fig. taken from Danielssen *et al.*, 1991).

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