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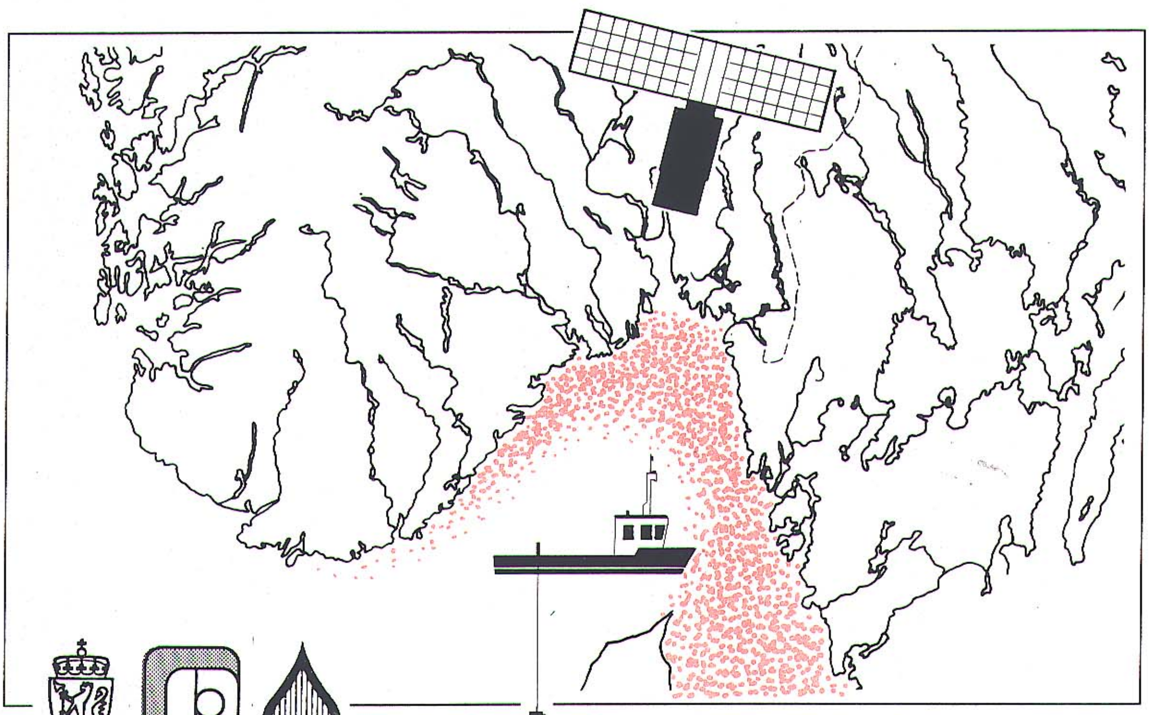
Remote Sensing and the Vertical Distribution of the *Chrysochromulina polylepis* Bloom in the Skagerrak in 1988



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Abstract: The present study contributes to explain the development of the *C. polylepis* bloom and to evaluate the importance of combined use of in situ monitoring and remote sensing techniques. The results show the difficulties to map the surface distribution of *C. polylepis* via satellite data and to judge the primary sources of water to the area. However, the satellite data indicate the temperature to be a possible prime factor in the acceleration of the bloom. In the later phase of the bloom, the *C. polylepis* was associated with the warm surface water, but for large areas the algae was situated at a depth of 15-20 m, thus preventing direct mapping by remote sensing. *C. polylepis* has probably not been present in concentrations above 0,5 mill. cells/ litre further north than Horten-Moss in the Outer Oslofjord. Subsurface layers of *C. polylepis* reached concentrations of 16 mill. cells / litre at the entrance of the Outer Oslofjord, and chemical analyses indicated that among the plant nutrients phosphorous was limited.

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Remote Sensing and the Vertical Distribution of the *Chrysochromulina polylepis* Bloom in the Skagerrak in 1988

Oslo, 17.12.1991

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Summary

The objective of this report is to describe the physical and chemical conditions in the Outer Oslofjord and the Skagerrak in connection with the *Chrysochromulina polylepis*-bloom in May 1988. The study contributes to explain the development of the bloom and evaluate the importance of <u>in-situ</u> and remote sensing techniques for the detection and monitoring of similar future phytoplankton blooms.

The experiences from this study are that it is not possible to judge the primary sources of water to the Skagerrak during the spring of 1988 from satellite imagery. The images indicate that temperature could possibly be the prime factor in accelerating the bloom, assuming the supply of nutrients and light being sufficient. Neigther the satellite images nor any <u>in-situ</u> data provide evidence that a certain water-mass, rich in algae, was moving along the Swedish-Norwegian coast during the early phases of the bloom. In the later phases upwellings and flow separation seem to split up the volumes of water along the Norwegian coast. The *C. polylepis* was then connected to the warm water. The frontal zones as seen from Landsat were located to quite different areas than near the coast-line as indicated by other authors based on just NOAA data.

For algal monitoring the NOAA satellites give frequent passages but poor resolution, while earth resources satellites allow a 10 to 80 m resolution but less frequency. Therefore the combination of several satellite sensors to get the best possible coverage of a bloom should be recommendable. Often the best approach is to use temperature as a tracer and sometimes the near-IR bands for direct determination. Today only a couple of turbidity and optical parameters in addition to temperature can be recorded. Even if there are several complications in handling water data these variables may often be used as tracers.

The **difficulties** when mapping algae arise when different algae show different spectral responses, as well as changing responses in the developing stages of the algae. The algae could be allocated anywhere within the upper layers of the water mass, which creates various spectral responses. E.g. at the end of the bloom, the *C. polylepis* was located at about 18 m depth, which completely prevented mapping from remote sensing sensors. A mixture of different algae as well as a mixture of algae and inorganic matter may further complicate the mapping efforts.

Important **advantages** with satellite sensors are that they provide unique information on current patterns, water mass structure and temperature distribution, and large areal coverage. The fact that many algal blooms are initiated during good weather conditions favours the use of remote sensing techniques and low cost per unit area of information.

In the Outer Oslofjord the*C. polylepis* does not seem to have been present in concentrations above 0.5 mill./l further north than Horten-Moss in the late stage of the bloom (May 29 to June 2). Most likely *C. polylepis* concentrations of approximately 5 mill./l have reached the Fulehuk area on the west side of the Outer Oslofjord, as well as the outer shallow areas of the Hvaler archipelago and the Koster area. This is also documented by the severe effects on the rocky bottom animals and attached algae. The highest concentrations of *C. polylepis* (up to 16 mill./l) were found between 15-20 m at

the entrance of the Oslofjord. In the plankton layers, dominated by the *C. polylepis,* chemical analysis indicated that among the plant nutrients the phosphorus was limited. Laboratory experiments by others have also shown that limiting concentrations of phosphorus belong to conditions triggering toxin production of the *C. polylepis.*

1. INTRODUCTION

Public concern about the conditions of the marine waters around the Nordic countries has been increasing in view of several environmental alerts. During 1988 a large number of seals were killed and a serious bloom of a poisonous alga occurred in the seas of Skagerrak and Kattegat. The heavy load of toxicants and nutrients is commonly blamed for the serious conditions in our marine environment. Previously the interest has been focused on local environments such as the Bay of Laholm, Sweden and the outlets of rivers such as Glomma, Norway and Wisla, Poland, but it is obvious that all of our surrounding seas are threatened by our wastes and call for the rapid elaboration of a plan for management of our sea resources.

The present investigation was part of a program initiated by the Norwegian Institute for Water Research (NIVA) in Oslo, Norway and the Environmental Quality Laboratory in Uppsala, Sweden (later by the Centre for Image Analysis). The main interest of the Swedish participants was to investigate the possibilities of monitoring water quality using satellite imagery while that of the Norwegians was to monitor the outlet of the River Glomma and the conditions in Skagerrak. Both parties also emphasized the calibration of different satellite sensors for water quality variables. The field work was done in collaboration with the project "Eutrophication in the Outer Oslofjord" (Sørensen et al.,1990 a-c) and the intensive monitoring program that was carried out in connection with the bloom of *Chrysochromulina polylepis* during the spring of 1988. The Østfold County Environmental Administration also participated in the field work and in the analysis of phytoplankton samples.

The objective of this report is to describe the physical and chemical conditions in the Outer Oslofjord and the Skagerrak in connection with the *Chrysochromulina polylepis*-bloom in May 1988. It should contribute to explain the development of the bloom and evaluate the importance of in-situ and remote sensing techniques for the detection and monitoring of similar future phytoplankton blooms.

Several papers have been published on this *C. polylepis*-bloom and the ecological effects on the biota. The present contribution focuses on the remote sensing information and the vertical distribution of the algae in the later parts of the bloom in the northern Skagerrak.

2. MATERIALS AND METHODS

2.1 Area of investigation

During the months of May and June 1988 several field cruises were per-formed in the Outer Oslofjord and the Northern Skagerrak as part of the on-going project by the Norwegian Institute for Water Research and Centre for Image Analysis, as well as increased monitoring due to the plankton bloom. The positions of the reference stations for measurement and water sampling are shown in Figure 1.

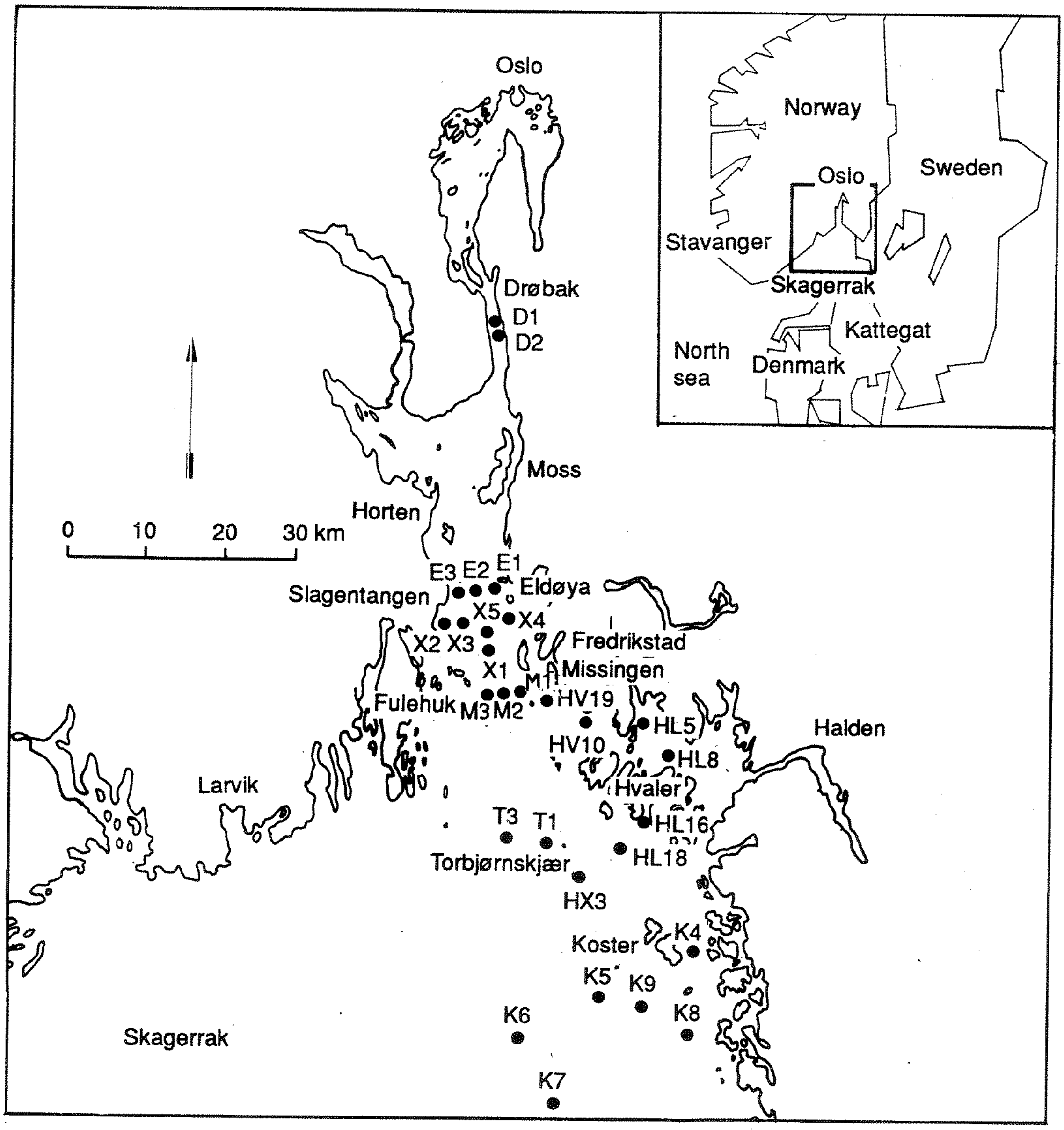


Figure 1. The area of investigation with sampling stations in the Oslofjord and the Skagerrak Sea in May and June 1988.

2.2 In-situ measurements and analysis

Unfortunately almost no recordings of the *C. polylepis* was made by anyone until late in the bloom. Therefore very few ground truth recordings for the remote sensing study was available. Our vertical sampling started in late May including temperature and salinity profiles made with a Salinoterm, and the distribution of phytoplankton was determined by a Variosens underwater fluorometer or a transmissometer (c-meter). Two types of c-meters with different wavelengths were used: a Martec transmissometer with a 520 nm filter and an in-house constructed transmissometer (Environmental Quality Lab) with a pulsating monochromatic (635 nm) diode (Lindell,1979).

Water samples were collected from the surface layer and in the chlorophyll-a maxima of the chlorophyll fluorescence profiles. The samples were analysed for chlorophyll-a (Holm-Hansen et al., 1965), and nutrients: ammonium, nitrate/ nitrite, phosphate and particulate phosphorus according to standard methods used by NIVA (Norwegian Standard). Some samples were analysed for particulate carbon and nitrogen by a Carlo-Erba HCN analyzer.

2.3 Satellite data

The remote sensing activity by our groups in the Skagerrak was initiated several years ago and thus independent of the bloom that occurred during the months of May and June, 1988.

Mapping of the distribution and movement of a larger scale phytoplankton bloom like the one in Skagerrak in the spring of 1988 requires some type of remote sensing technique. It was thus important to purchase remote sensing data available for the area and time of interest. All relatively clear satellite scenes over Skagerrak for the period March through June 1988 were bought. Satellite data for May are presented here.

Both regional weather satellite data AVHRR (Advanced Very High Resolution Radiometer) and earth resources satellite data in digital form were bought. Data from all existing earth resources satellites were purchased: Landsat (Thematic Mapper=TM, Multispectral Scanner=MSS), SPOT (multispectral) and Japanese MOS-1 (multispectral=MESSR). All AVHRR data were bought from the University of Dundee and a special program for reading and calibration of those data thus had to be constructed. The images used in this study are listed in Table 1.

Table 1. Satellite data used in the study, May 1988.

Date	Satellite	Sensor	Scene	Coverage	Figure
880507	NOAA-9	AVHRR	afternoon	Scandinavia	Fig 4
880511	NOAA-9	AVHRR	afternoon	Scandinavia	Fig 4
880513	NOAA-10	AVHRR	morning	Scandinavia	Fig 6
880513	NOAA-9	AVHRR	afternoon	Scandinavia	Fig 4+6
880513	Landsat	MSS	197/19	Skagerrak	Fig 3
880513	Landsat	TM	197/19	Skagerrak	Fig 3
880514	NOAA-9	AVHRR	afternoon	Scandinavia	Fig 4
880515	NOAA-9	AVHRR	afternoon	Scandinavia	Fig 4
880518	NOAA-9	AVHRR	afternoon	Scandinavia	Fig 4
880521	NOAA-9	AVHRR	afternoon	Scandinavia	Fig 5
880528	NOAA-9	AVHRR	afternoon	Scandinavia	Fig 4

The evaluation of earth resources satellite data has been performed by using statistical techniques applying different combinations of sensors and ratios of sensors including chromaticity transformations (Lindell et al., 1986). One of the problems of using Landsat data has been the uncertainty about the absolute calibrations of the sensors

(Lindell et al., 1986 and 1991 and Sørensen et al., 1990). Therefore most of our earlier mapping has been based upon simultaneous field calibrations.

The evaluation of AVHRR data has been performed using an in-house designed program based on the pre-launch and in-flight calibrations given by NOAA and on the internal calibration facility of the satellite using a technique developed by Singh (1984). Our program reads the original data to the EBBA-GIS image processing system and converts the data into spectral radiances for the reflecting wavelengths and into temperature for the two thermal wavelengths.

One of the main tasks of the overall project has been to optimize the use of different sensors and a separate paper has been published on this subject (Sørensen et al., 1989). As no single satellite sensor today is particularly designed for or has been very suitable for water applications, it is important to evaluate possibilities of combining different sensors.

2.4 Other observations

German weather maps were used for the analysis of the weather situation during the spring and the climatological statistics were based on mean values supplied by the Swedish Meteorological and Hydrological Institute (SMHI).

3. RESULTS

3.1 Meteorological and hydrological conditions

The amount of precipitation during the winter season 1987/88 was about 50% higher than normal in the areas around the Skagerrak, which led to high discharges of the rivers entering the seas. The same applied to the rivers entering the German Bight, which carried about 3 times the normal amount of water (SNV, 1989). The runoff and surface erosion, especially from agricultural areas, during the winter months and early spring had been unusually large due to the snow-free winter with a number of winter rains. This caused the total amounts of nutrients to be much higher than normal.

The weather in April 1988 started with a high pressure situation centred over the British Isles. Then the high pressure moved slowly south-east until the middle of the month, when it was located over the continental parts of Europe. A belt of warm and moist air then approached the area from the south-west. At the end of this period the first so-called Scandinavian spring cyclone of the year reached the area, leading to a strong high pressure cell becoming established in the centre of Skagerrak and the temperature reaching very high levels for this time of the year. The high pressure remained in that position until the end of the month. May started with weak and variable winds, and continuously high temperatures. High pressure was then established over the northern part of Scandinavia starting on May 7. The circulation around the high pressure cell caused a long period of easterly winds and a transport of water out of the Baltic and an up-welling of nutrient-rich bottom water, particularly in the southern Baltic (German weather maps). Warm surface water from the Kattegat and the southern Baltic was thereby transported northwards along the Swedish coastline towards the Skagerrak.

Then the wind decreased gradually and became variable but, as a mean, maintained an easterly component. On the Skagerrak side the wind direction changed to westerly during this period (Aksnes et al., 1989 a) and the first toxic effects of the *C. polylepis* were observed on May 9 in Bohuslän, Sweden in the warm water (SNV, 1989) and along the Norwegian coast on May 14 (Lindahl & Dahl, 1990). During the rest of the month the weather was sunny and warm. On May 20 a new high pressure system entered the area from the west and at the end of the month the weather was more variable but warm, dry and with weak winds. A number of thunder-storms interrupted the drought, which supplied additional nitrogen to the area. The solar radiation flux was well above normal for most of May. No less than 12 days during this period were more or less clear and thus it was very easy to follow the situation in detail from the satellite images.

June continued with weak systems and quasi-stationary fronts, which gave little or no precipitation. The temperature had been exceptionally high during the major part of the spring.

3.2 The hydro-chemical conditions and vertical distribution of *C. polylepis.*

In the beginning of the bloom (May 11) it is likely that the algae were located in the surface layers of the water-mass on the Norwegian coast near Arendal (Dahl, 1988). Our observations from a calibration cruise in the Torbjørnskjær area and north of Koster on May 13 gave no indication of high levels of phytoplankton in the surface water. Secchi disk depths of > 8 m and chlorophyll-a of < 0.5 µg/l were recorded (Aas et al., 1990, Sørensen et al., 1990). This cruise took place before we became alarmed about the plankton bloom and therefore no chlorophyll fluorescence profiles were measured. The *C. polylepis* might, however, have been present in the deeper layers.

The*C. polylepis*developed and progressed in the surface water (Dahl et al, 1989) and it was found in the surface layer on May 21 and 22 in concentrations of about 6 million cells/l along part of the Norwegian coast and in the central Skagerrak. At the same time,*C. polylepis* was found at about 8 m depth along the Swedish coastline (SNV, 1989).

During the investigation in the Outer Oslofjord the chlorophyll fluorescence or light beam attenuation profiles were used to detect and determine the distribution of phytoplankton during the cruises May 29, 31, and June, 1, 2 and 6. Appendix A shows all the fluorescence profiles and hydrographic data. Direct counting of *C. polylepis* was performed on samples from May 29 and June 2 (Appendix B). The distinct fluorescence peaks below 10 meters were more or less entirely dominated by *C. polylepis*. Therefore the chlorophyll fluorescence could be used to extrapolate the *C. polylepis* concentrations at stations where microscopic counting was not performed.

In the outer Oslofjord and Skagerrak, *C. polylepis* was found in high concentrations at 18 m on May 29 at station T1 (Torbjørnskjær) as seen from Figure 2 and Appendix A1.

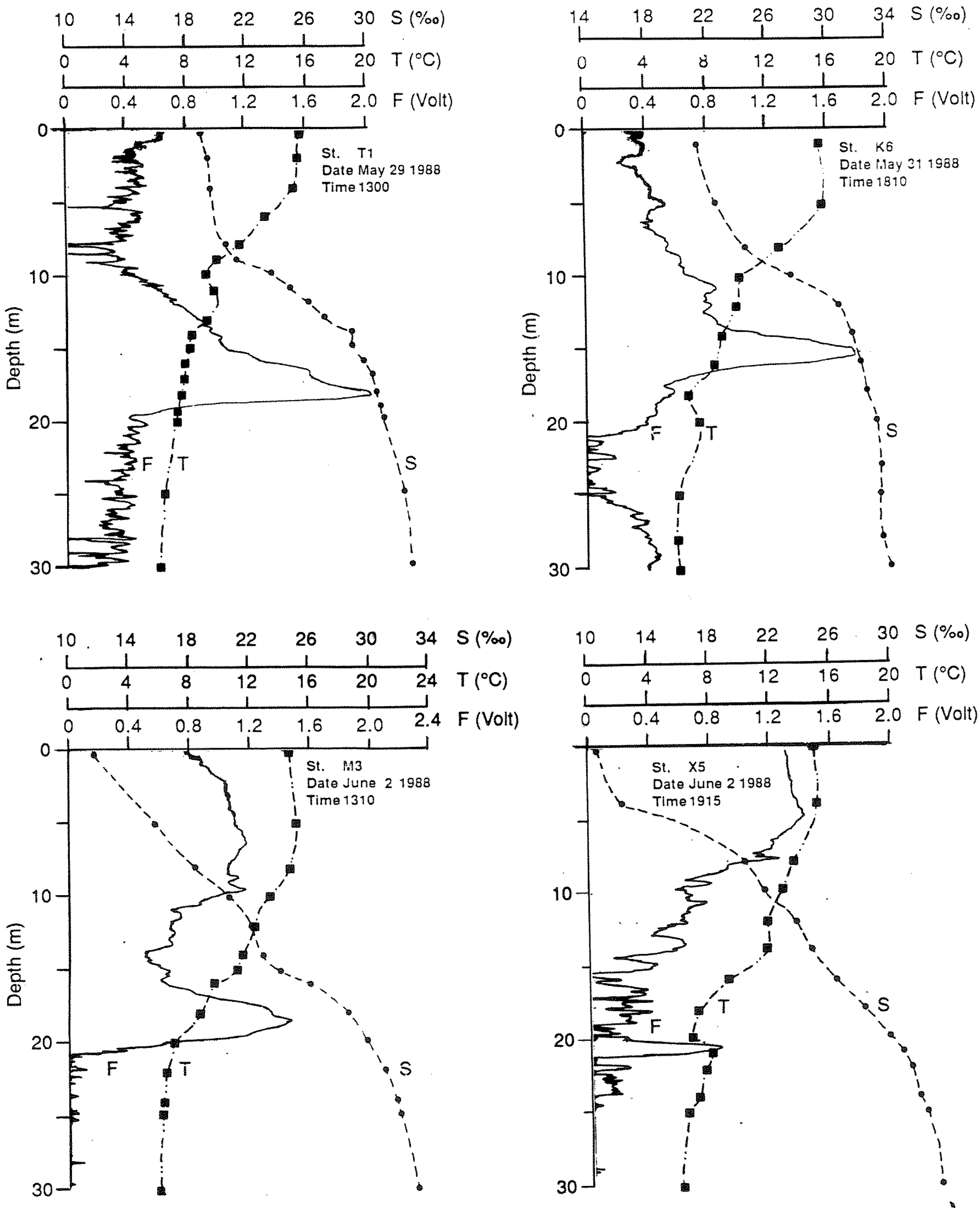


Figure 2. Vertical distribution of relative (logarithmic) chlorophyll-a fluorescence (F), temperature (T) and salinity (S) in the Torbjørnskjær (T1), Koster (K6) and Outer Oslofjord area (M3 and X5) in May and June 1988.

Close to the Hvaler area and inside the archipelago, the concentrations of *C. polylepis* decreased rapidly and the vertical distribution changed from the distinct peak (18 m) at Torbjørnskjær to a more widespread distribution between 8 and 15 m most likely due to large scale movements of the pycnocline. Approximately the same distribution and the same *C. polylepis* concentrations were found in the shallow areas closer to the coast.

The *C. polylepis* concentration was 15.7 mill. cells/litre at 18 meters (Table 2) at Torbjørnskjær (T1) and decreased to about 3-4 mill/l closer to the coast (HX3 and HL18). In the western outlet of the Glomma River (station HV10 and M1) the diatom *Skeletonema costatum* was dominating the surface water (App. A2 and B). It was dominating the surface water of the whole area. No distinct *C. polylepis* peak was present and inside the Hvaler archipelago *C. polylepis* decreased rapidly to < 0.5 mill/l.

Table 2. The number of *C. polylepis* (mill./l), chlorophyll-a (μg/l), and particulate carbon, nitrogen, and phosphorus ratios (atom/atom) at selected stations and depths for maximum chlorophyll fluorescence, May-June, 1988.

Date	Station	Depth	*C. polylepis*	Chl-a	C/N	N/P	C/P
880529	T1	18	15.7	21.3	10.2	72.84	740.9
	HX3	17	2.7	2.5	4.2	41.36	174.8
	HL18	13	3.8	1.8	4.1	32.76	134.5
880531	K6	15	-	21.4	6.1	52.84	324.9
	K4	14	-	7.6	-	-	-
880602	M3	18.5	2.3	9.8	13.6	36.76	498
	X3	13.5	0.86	0.83	4.0	23.55	93.6
	X4	15	0.41	0.73	2.7	19.85	54.0

The highest concentrations of *C. polylepis* were located in the water with a temperature of 7.5-9 °C and a salinity of 28-31 ‰ (Table 3). The temperature and salinity associated with the *C. polylepis* were the same as found by Lindahl (SNV, 1989) earlier during the bloom.

C. polylepis was associated with water of low phosphate (<0.1 μM) and nitrate/nitrite (0.2-1.1 μM) content, but high in ammonium, >0.9 μM (Table 3). Brockmann & Dahl (1989) found similar conditions in the Skagerrak on the May 30 and it was likely that the *C. polylepis* was present (at this depth) all over the Northern Skagerrak (cf. Discussion).

Table 3. Temperature (°C), salinity (‰) and nutrients (µM) at selected depths (m) and stations in Outer Oslofjord and Skagerrak during the *C.polylepis* bloom in May and June, 1988.

Date	Station	Depth	Temp	Salinity	PO4	NO_3	NH_4
880529	T1	18	7.8	30.8	0.08	0.20	2.0
	HX3	17	-	-	<0.05	1.1	0.93
	HL18	13	11.3	26.1	0.05	0.64	1.2
880531	K6	15	7.6	31.0	0.06	0.70	1.1
	K4	14	-	23.9	<0.05	0.21	0.93
880602	M3	18.5	8.8	28.7	0.06	1.9	1.6
	X3	13.5	-	23.5	<0.05	0.64	1.7
	X4	15	-	25.2	<0.05	1.1	0.90

On May 31 the sampling was performed in the Koster area along the Swedish coastline. A similar vertical distribution (as at station T1) with a distinct maximum at 15 meters was found for station K6 (Figure 2). No direct counting of *C. polylepis* was performed, but approximately the same concentrations could be assumed from the chlorophyll fluorescence profiles and the chlorophyll-a concentrations as at station T1. The *C. polylepis* was associated with the same water as was found further north at Torbjørnskjær (Table 3). South and east of Koster C. *polylepis* was found between 10-17 meters (App. A3). *S. costatum* and other dinoflagellates (B. Rex pers. comm.) were dominating above the *C. polylepis* layer. Here *S. costatum* was located deeper in the water column than in the Hvaler area on May 29.

On June 2, another sampling was performed in the Outer Oslofjord between Slagentangen and Missingen. At the Missingen-Fulehuk transect *C. polylepis* was found at 18-19 m depth with higher concentrations (2.3 million cells/l) at station M3 (Fig. 2 and App. A4) on the west side of the fjord. At this depth the salinity was between 26-30‰ and the phosphate was still low (<0.1µM), but the nitrate slightly higher than further out. In the central part and on the east side of the fjord the high peak concentration decreased and disappeared further north (Appendix, A5). The *C. polylepis* concentrations in the 13-15 m layer at stations X3 and X4 were 0.86 and 0.41 million cells/l, respectively (Table 2). At station X3 and some of the southernmost near-coastal stations *C. polylepis* was mixed with *S. costatum* which dominated the surface water (0-2 m) with concentrations of 25.3 million cells/l.

Light measurements were performed at station E1 which gave a 1% light depth at 6 m and 0.1% light depth at 12 m (App., A6). Light therefore could be a limiting factor for growth of *C. polylepis* in the deeper layers. Further north in the Outer Oslofjord (Horten-Moss), the concentration of *C. polylepis* was <0.2 mill. cells (Larsen, 1988 and 1989) and in the Drøbak area no distinct peak of the *C. polylepis* was detected (App., A7).

On the June 6 the high concentrations of *C. polylepis* earlier found in the Koster area had completely disappeared . Only at station K5 and possibly also at station T3 could some *C. polylepis* still be detected (App., A8). In the Outer Oslofjord (Stations T3 and M2) the S. *costatum* was dominating the surface waters.

Table 2 shows ratios between different values of particulate organic materials at the end of the *C. polylepis* bloom in Outer Oslofjord and Skagerrak. C/N ratios were mainly between 4-14 and the highest values were found in the areas with high concentrations of *C. polylepis*. Brockmann & Dahl (1989), found values between 10-14 in the layer of *C. polylepis* further south in the Skagerrak, between Skagen, Denmark and the Gullmar fjord on the west coast of Sweden.

N/P ratios were in the range of 19-73, with the highest values in the water samples collected in high concentrations of *C. polylepis*. These were higher ratios of N/P than found by Brockmann & Dahl. The C/P ratios were in the range of 54-740. At stations with high *C. polylepis* concentrations the C/P ratio was above 300, which was about the same as recorded by Brockmann & Dahl (1989).

3.3 The characteristics of *Chrysochromulina polylepis* and earlier occurrences

C. polylepis was first described by Manton & Parke (1962). The *C. polylepis* cells are approximately 8-12 µm long and covered with inorganic scales. Manton & Parke have shown that *C. polylepis* could receive nutrients by incapsulating organic particles and this characteristics may have had importance in the bloom of *C. polylepis*.

Chrysochromulina spp. have occurred on several occasions during the last few years, as recorded by the Swedish Environmental Agency (SNV, pers. comm.,Torbjörn Willén), and in fairly large concentrations (sometimes up to 8 million cells per litre). However 1988 was the first time toxic effects of *C. polylepis*. had been noticed. Observations from Åland (Finland) had indicated blooms of other species of Chrysochromulina. Toxicity of algae from a general point of view is not uncommon in these waters or elsewhere. In most cases in Scandinavia, poisonous effects of different dinoflagellates have been observed and which, in some cases, have had lethal effects also on fish. The problem with toxins in the Skagerrak has been most frequently noticed as a result of effects on shellfish e.g. along the Swedish coastline. That toxicity may also affect human consumers (Tangen, 1983).

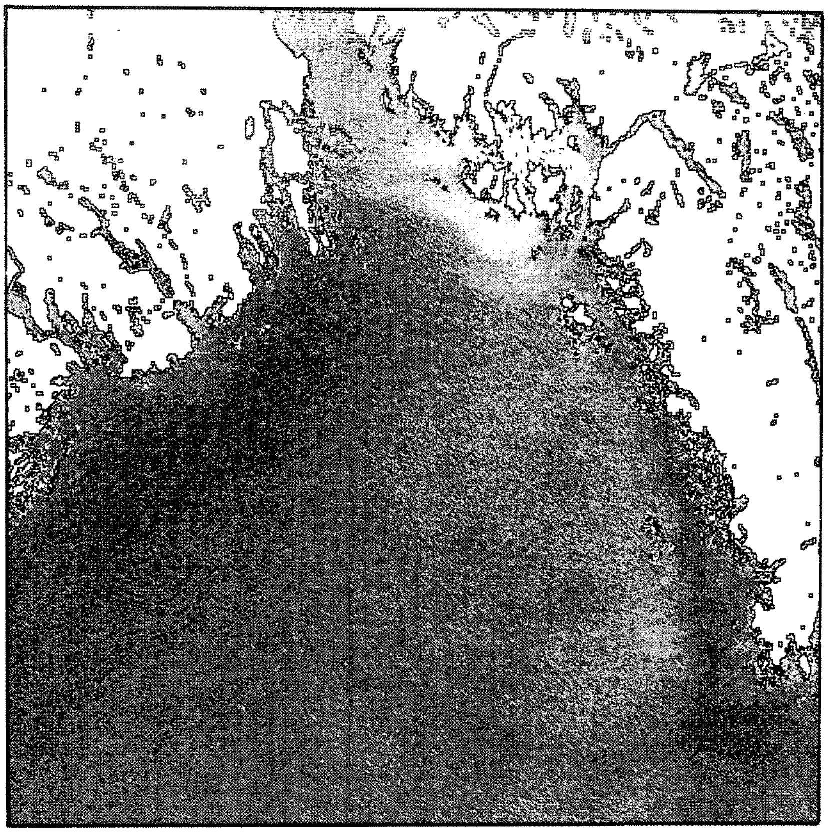
Samples of *C. polylepis* from our cruises in the outer Oslofjord and the Koster area were used by different research groups for the positive identification of the species by scanning microscopy and for testing of the toxicity. *C. polylepis* samples collected from 18 m depth at Torbjørnskjær (T1) May 29 was tested for hemolytic activity when grown in different concentrations of selenite and phosphate (Edvardsen et al., 1990) The results indicated that *C. polylepis* produces toxin when limiting the phosphate. Paasche et al. (1990) have shown that cultures isolated from the same sample produced a mixture of two cell types of *C. polylepis*. The *C. polylepis* from 15 m depth in the Koster Area (K6) was used by Underdahl et al. (1989) to demonstrate toxic effects in the standard mussel test. The samples from 18-19 m in the Missingen area (M3 and M2) on June 2 also showed hemolytic activity and are thus likely to be involved in the fish death (Yasumoto et al., 1990). Testing of water from 16 and 23 m depth in the Koster area (K5) on June 6, after the disastrous bloom of *C. polylepis* had disappeared, showed that toxins were still present in the water-mass (Skulberg, pers. comm.)

3.4 Surface mapping and remote sensing data

The *C. polylepis* bloom was extremely complicated to identify from remote sensing sensors. The absorbance of *C. polylepis* seemed to be better defined than reflectance properties. It was likely that the algae caused radiance minima along the Swedish and Norwegian coastlines (Figure 3). The signature from the satellite data might also be interpreted as gradually clearing water, but in this case the most likely explanation is absorbance in algae.

The maximum surface occurrences of *C. polylepis* were found along the Danish Kattegat coastline (SNV, 1989). The AVHRR images from the earliest part of the spring (March-early April) indicate that the surface water of Skagerrak could have been supplied either from the Elbe, from the Danish or/and Swedish rivers entering Skagerrak and Kattegat as well as from the Baltic. If the *C. polylepis* bloom developed in the same way as the earlier blooms of Chrysochromulina spp., it is likely that the Baltic water and the rivers discharging into Kattegat play an important role. It is, however, difficult to judge the respective volumes of water that might have been reaching the Kattegat and the Skagerrak. Therefore it is not possible to identify which sources mainly influenced the situation during the spring of 1988. The surface waters of the central Skagerrak mainly emanate from the North Sea, a water mass that usually has a density lower than the Atlantic but higher than that in the Skagerrak (Aksnes et al., 1989a). This water could be introduced to the surface water through the frequent up-wellings. The up-wellings are mainly an effect of the normal anti-cyclonic circulation of the Skagerrak (Svansson, 1975).

The very rapid heating of the water-masses started in early May and was located to the Kattegat and the southernmost parts of the Skagerrak and there is no doubt that the heavy bloom accelerated along the Swedish west coast. Already on May 6 and 7 unusually high temperatures were observed close to the Swedish coast and this could be clearly identified on May 7 (Figure 4). Two days later the first observations of toxic effects were observed in Bohuslän, Sweden (SNV, 1989). On May 11 almost all surface water of the Skagerrak and Kattegat had a homogeneous temperature of about 9-11 ^{o}C. According to Dahl (1988), the *C. polylepis* was already present along the Norwegian coastline before the toxic effects were observed. High chlorophyll-a concentrations (37 µg/l) were recorded in the surface waters (0-5 m) around Arendal on May 11 (Dahl, pers. comm).



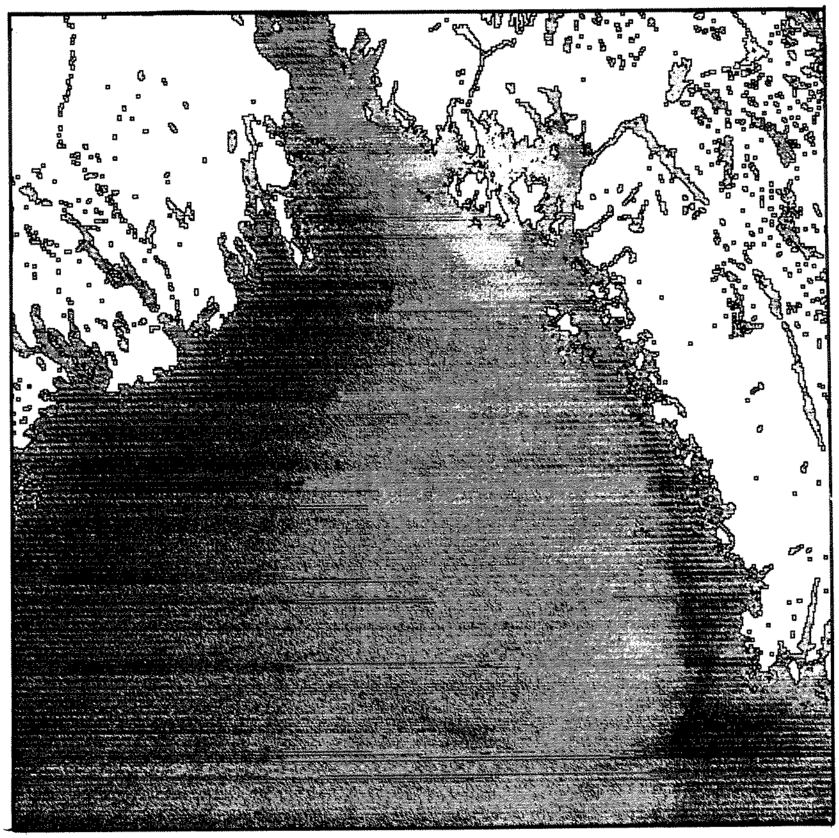


Figure 3. Maps showing the radiance minima (dark) probably caused by the *C. polylepis* algae along the Swedish and Norwegian coasts based on Landsat, May 13, 1988. Relative radiances from MSS (upper) and TM (lower).

A salt content of 20-30‰ gave good conditions for the growth of *C. polylepis* (SNV, 1989). From this and local observations we could assume that the *C. polylepis* avoided the plume of fresh water from the Glomma River. However from the vertical distribution of *C. polylepis* in this area, and from local observations of mass deaths of different marine organisms, *C. polylepis* had had severe effects even below the fresh water layer. On May 14 the first observations of fish death occurred in Norway in the area of Arendal. This area is located close to the front between water of about 11 °C (yellow) and the warm water of about 13 °C (red) (Figure 4).

When comparing the AVHRR data with the high resolution TM data (not shown in the figure here) the water current structures became rather obvious. A front located in roughly NW-SE direction across the Skagerrak was separating the waters of the central sea from the water in progress to the north and west (Sørensen et al., 1989). If the algae followed the warm "water-mass" it might have stayed in a narrow zone outside the coast and away from the Glomma River estuary. Another alternative is that the algae crossed the Skagerrak and then a return current brought it back toward the Swedish coast. This pattern of the currents in northernmost part of the Skagerrak is further demonstrated in hydro-dynamical models (L.P. Røed, pers. comm.). The situation could be seen from the May 13 (Figure 4). We may also assume that the *C. polylepis* located at the pycnocline was transported under the freshwater due to the esturine circulation process around the Glomma River outlet. We emphasized the identification of the different water-masses and the reflectance properties from the reflective bands of the different sensors. It is likely that the *C. polylepis* could be "identified" in both the TM and MSS (Figure 3), and possibly also in the AVHRR. The problems with the latter could, at least to some extent, be caused by sun-glint that disturbed the images. Several different ratioing and difference imaging techniques were tested for AVHRR but with little success for this purpose. For the TM and MSS different ratioing techniques were used to enhance the images and most of them gave significant discrepancies of the areas supposed to contain the *C. polylepis* as compared to the typical Skagerrak water.

From Figure 3 it could be observed that the low radiance values of the areas on opposite sides of the Skagerrak most likely are caused by the absorbance of *C. polylepis*. There are, however, very few direct observations of the algae during the initial days of the heavy bloom. We may assume that the algae followed the water at a speed of about 40 km per day calculated from the images (Fig. 4) until May 15. During the following week a decrease in speed to about 30 km per day was observed (Dundas et al., 1989). The movement of the front was monitored by the Nansen Environmental and Remote Sensing Center in Bergen based on data from Tromsø Satellite Station. This monitoring enabled damage to the fish farms along the Norwegian West coast to be limited.

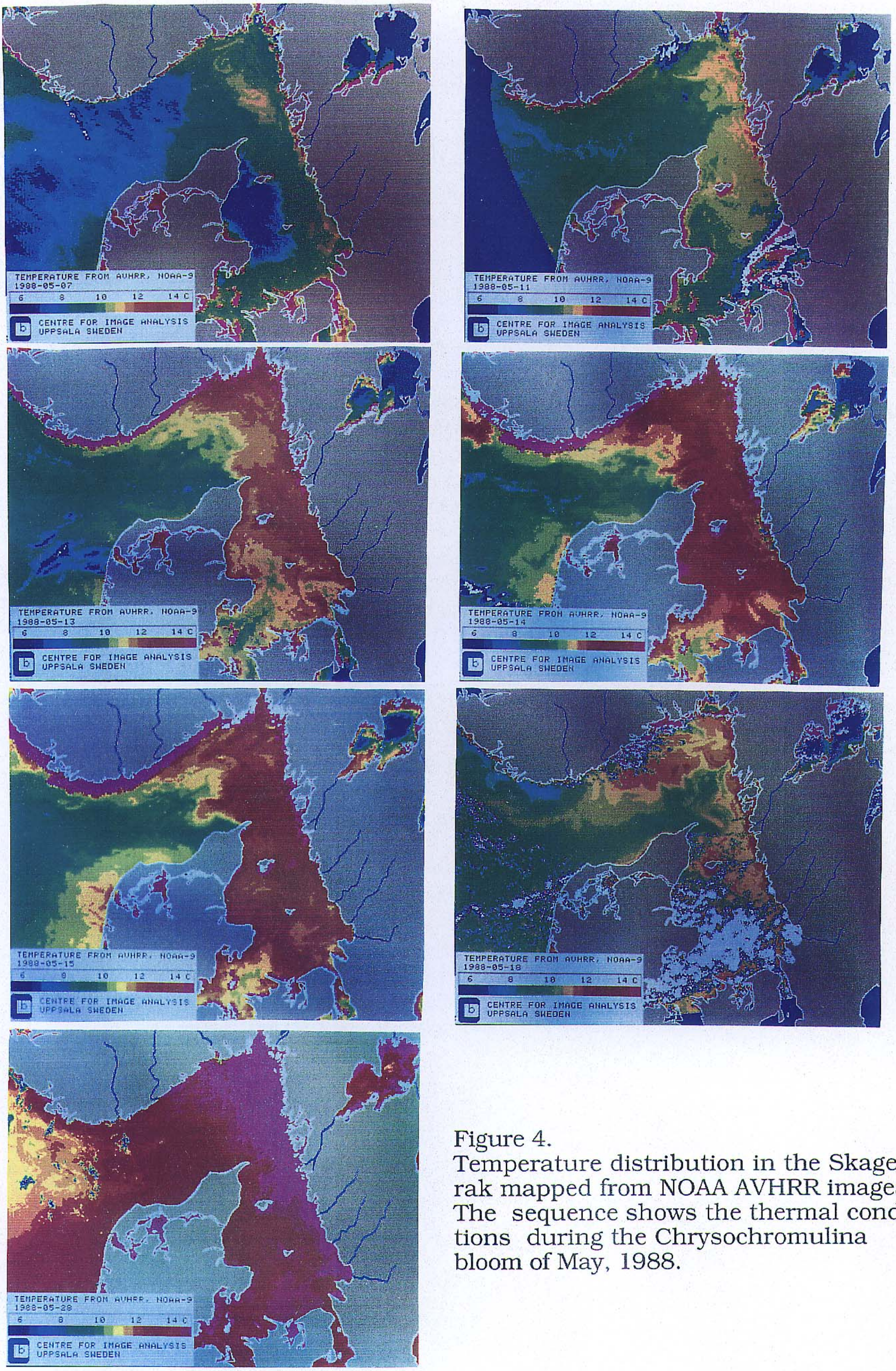
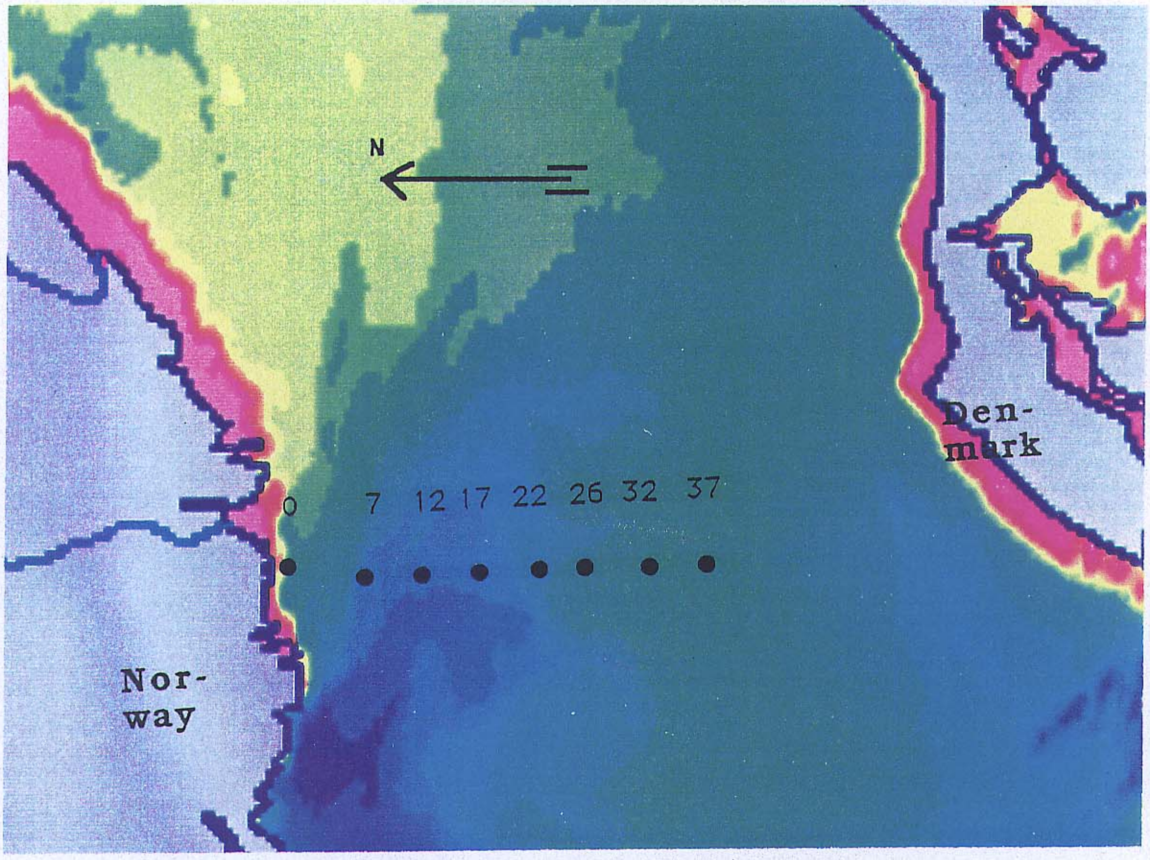


Figure 4.
Temperature distribution in the Skagerrak mapped from NOAA AVHRR images. The sequence shows the thermal conditions during the Chrysochromulina bloom of May, 1988.

From May 18 it is interesting to observe the flow separation of the watermass from the Norwegian coast. During this period we could expect an extensive outflow of water from the Skagerrak following the decline of a strong westerly wind. On May 21 Dahl (1988) had observed a flow separation from the observations of temperature, salinity, and *C. polylepis*. concentrations. This could be verified by the satellite image of May 21 (Fig 5). The



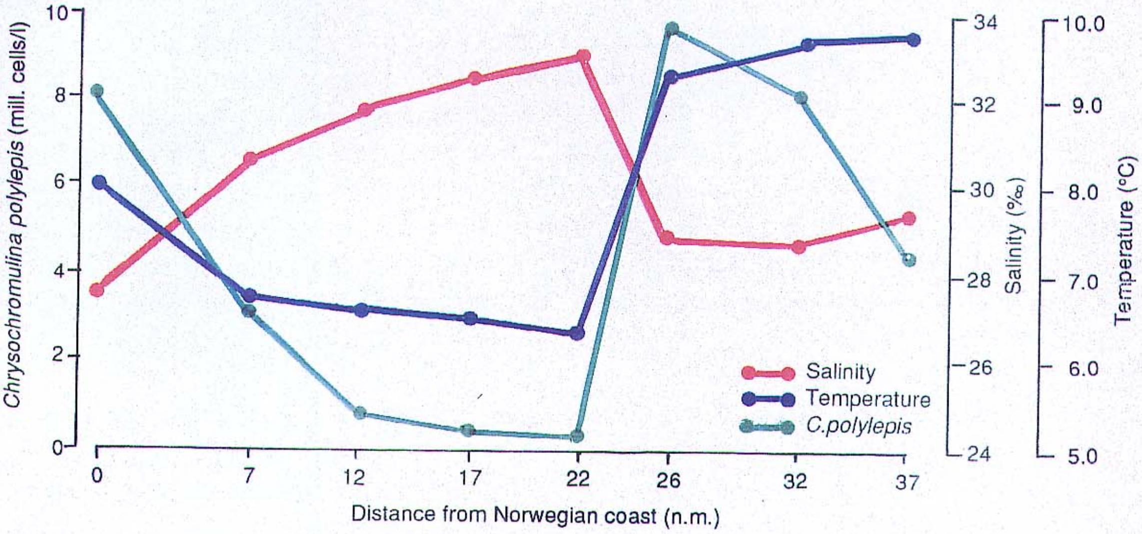


Figure 5. Temperature distribution in the Skagerrak between Norway and Denmark NOAA AVHRR (top) and field samples of temperature (T), salinity (S),, and concentrations of *C. polylepis* (mill. cells/litre). Field data from Dahl, 1988.

figure also shows a close connection to the field data collected by Dahl. In this area upwellings and flow separation seem to split up the volumes of water along the Norwegian coast, with a distinct separation also of the distribution of the *C. polylepis.* Here the *C. polylepis* was associated with the warm water.

During the following week the outflow continued and the warming up of Skagerrak and Kattegat progressed until the end of the month. On May 28 the temperature was almost homogeneous(15 °C) throughout both the Skagerrak and the Kattegat (Figure 4). Between the 17th and 28th of May the cloudy weather (Figure 4) made it difficult to interpret most of the satellite imagery.

4. DISCUSSION AND CONCLUSIONS

A mild winter with abundant precipitation supplied large amounts of nutrients, especially nitrogen, to the North Sea, Skagerrak and the Kattegat. In the southern parts of the North Sea (The German Bight), very high concentrations of nitrates (25 μM) were recorded. In the Kattegat, values of nitrates and phosphates were within the normal range. Water-masses with high concentrations of nitrates were transported from the southern parts of the North Sea to the Kattegat during the months of February and March and were mixed with the Baltic water-masses covering the upper 10-15 m. At that time water from the Baltic had considerably lower concentrations of nutrients than the North Sea water (Aksnes et al., 1989).

The distribution of *C. polylepis* in the Skagerrak and Kattegat varied both in time, location and vertically within the water-mass. The first positive identification of *C. polylepis* was from a mixed sample off Arendal along the Norwegian coast already in April (Trondsen and Eikrem, 1989). In Kattegat the first observations of *C. polylepis* were made on May 4, but death of marine organisms had already been reported on April 30 (Aksnes et al.,1989 a). Dahl (1988) also reported surface findings of C. *polylepis* off Arendal already before any toxic effects were noted. Nielsen and Richardson (1989) had observed that *C. polylepis* was blooming in a one meter thick layer in the lower part of the pycnocline in the Kattegat in late May. The same was found by Hortman and Jochem (1989) in the beginning of June. This means that *C. polylepis* was present and blooming in the pycnocline most likely in the whole area between the southern Kattegat and the Outer Oslofjord during late May and early June. During this time the algae was developing in the surface water along the Norwegian west coast. Due to the fact that the algae was blooming in a very narrow layers at the pycnocline it was easy to miss its existence when sampling. Nielsen and Richardson (1989) suggest that *C. polylepis* could have bloomed in intermediate layers of the Kattegat for a long period of time. Trondsen and Eikrem (1989) found other species of *C. polylepis* in the Kattegat in April, which coincides with the earlier findings of *Chrysochromulina spp.* in rather high concentrations on earlier occasions (Willén, pers. comm.)

The first reports of the toxic effects along the Swedish coastline was from May 9. Judging from the different observations the algae was probably present in much of the Skagerrak and Kattegat in early May and possibly the rising temperature due to local heating and large scale advection was one of the effects that triggered the bloom. The earlier findings of the *Chrysochromulina spp.* which had previously appeared in this area in rather high concentrations (Willén, pers. comm.), support the theory of initiation in this area.

It should be clearly stated that it is difficult to detect and quantify directly most types of phytoplankton from any operational satellite available today. This is obvious from our long-term calibration work and can be seen from the broad spectral bands of satellites and from the complex reflectance properties of the algae. Therefore it has been necessary to apply indirect methods for detecting and tracing the algae. For detection of the movements of the water masses we have had to depend on temperature recording of the water. The fact that the algae seemed to prefer certain thermal conditions made this approach more meaningful. Good conditions for *C. polylepis* growth seems to be 8-14 °C according to laboratory tests (SNV, 1989). Thus the situation in early May and later, might have been very positive for the growth of *C. polylepis* in certain areas of the Skagerrak and Kattegat. However, this is only one of several factors affecting the growth of the algae in the sea.

The high concentration of algae could have followed the common currents of the area and progressed northwards and then to the west following the Norwegian coast. However, it is equally possible that the warming-up of the coastal waters by advection or local heating could have created very favourable conditions for a massive bloom of the algae and thus the transport mechanism could be of less importance. In some papers (J.A. Johannessen et al., 1989 and others) it has been proposed that the progress of the water-mass containing *C. polylepis* could be easily followed by using satellite imagery in defining and identifying the frontal zone of the warm water-mass. This warm front was particularly used when forecasting the movement of the algae. Horstmann and Jochem (1989) also describe the *C. polylepis* mass occurrence as coinciding with the warm surface water. However, we can not be sure that we have a well-defined warm front here and thus not a movement of a certain water-mass with well-defined physio-chemical properties. This water-mass is considered to constitute the environmental boundaries for the bloom of the algae. We have little evidence that the water quality before and after "the front" during the first part of May is different, and similarly its thermal properties and the gradual change of temperature should not be defined as a front (cf. below). Note also the local heating of the near-coastal waters along the Norwegian coast from May 11 until May 15 (Fig. 4) which should not be confused with the "frontal" movement.

The problem of identifying the warm water-mass becomes very obvious when studying one morning and one afternoon image from the very same day. On May 13 in the morning (Figure 6) it is very difficult to outline the boundaries of the water-masses after the nightly cooling of the whole water surface. The only obvious fact about that image is that the water temperature is rather homogeneous over most of the Skagerrak and that most likely there is an outflow of water from the Skagerrak with the same temperature as most of the water of the centrally located Skagerrak water-mass. It is interesting to note that the coldest areas along the coastline in the morning image are

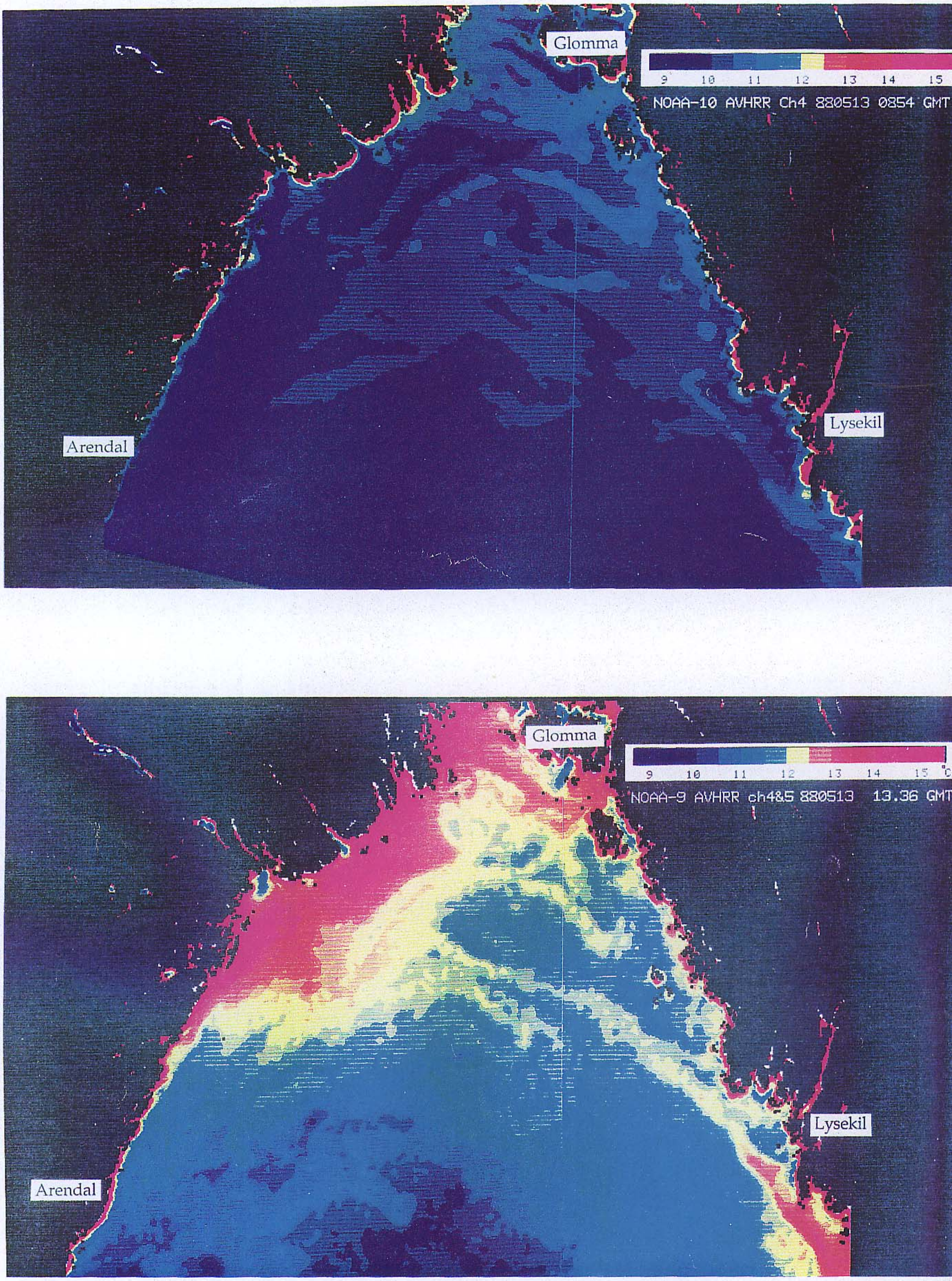


Figure 6. Surface temperature from NOAA-9-10, AVHRR from the morning (0854) and afternoon (1336) passages.

rapidly warming up and become the warmest ones in the afternoon. The very small change of colour scale in this figure compared to Fig. 4 gives a completely new impression of currents and "water-masses". Thus, it is easy to incorrectly interpret an artificially adapted colour scale with a solid redcolour identifying the "warm" water. When comparing the two figures it is clear that the change in temperature is rather gradual *without* sharp fronts. The real fronts, however, show up much better in the TM images (Sørensen et al.,1989). The TM scene of May 13 clearly identifies a number of frontal zones but none was located along the border between the red and yellow colours in Figure 4. Nevertheless, we still have to explain the rapid heating of the water-mass from the morning image until the afternoon, which might have been caused by coastal warming. Another component might be that the water filled with algae or other constituents heat more rapidly than clear water. Examples of this effect have been described by Sathyendranath el al. (1991) in the Indian Ocean. A thermal bar-like situation with a more developed thermocline in the near-coastal areas will also most likely trap the absorbed energy. Similar effects of heating were noticed by Gower and Borstad (1991), who were able to identify a phytoplankton bloom quite clearly in bands 1-2 of the AVHRR, but the chlorophyll concentrations were far higher in their study.

During the initiation of the bloom of *C. polylepis* in early May the concen-trations of nitrate and phosphates in the upper layers of the Kattegat and Skagerrak were relatively low, being 0.5-1.5 μM for NO3 and 0.05 μM for PO4 (Lindahl & Dahl, 1990). The N/P ratio was relatively high during this period. Around the end of May (the end of the bloom) *C. polylepis* was found in the deeper layers of the waters (13-19 m, at the pycnocline) in the Outer Oslofjord. The concentrations of the nutrient at that time were low, being 0.6-1.9 μM for NO3, 0.9-2.0 μM for NH4 and <0.05-0.08 μM for PO4. Records during the same time in the south-eastern Skagerrak gave similar values (Brockmann and Dahl, 1989). It is clear that in areas with high concentrations of *C. polylepis* the particulate N/P and C/P-ratio was high (cf. ch. 3.2), which indicates that phosphate could be limiting. Paasche et al.(1987) give atomic ratios of N/P >20 and C/P >200 as possible limitations for phosphorus. Also the low concentrations of phosphate (<0.1 μM) indicate the same. It was also evident that *C. polylepis* was toxic in those areas, and one may assume that the low phosphate concentrations could be one of the triggering factors for the toxin production of *C. polylepis* (Edvardsen et al., 1990).

On the basis of the vertical distribution of chlorophyll fluorescence, the direct counting and other observations, the distribution of *C. polylepis* in the Outer Oslofjord and northern Skagerrak between May 29 and June 2 has been summarized in Figure 7. The *C. polylepis* does not seem to have been present in concentrations >0.5 millions/l in the late stages of the bloom further north than Horten-Moss. Most likely *C. polylepis* concentrations of approximately 5 millions/l have reached the Fulehuk area on the west side of the Outer Oslofjord, as well as the outer shallow areas of the Hvaler archipelago and the Koster area. This is also documented by the severe effect on the rocky bottom animals and attached algae (Berge et al., 1988).

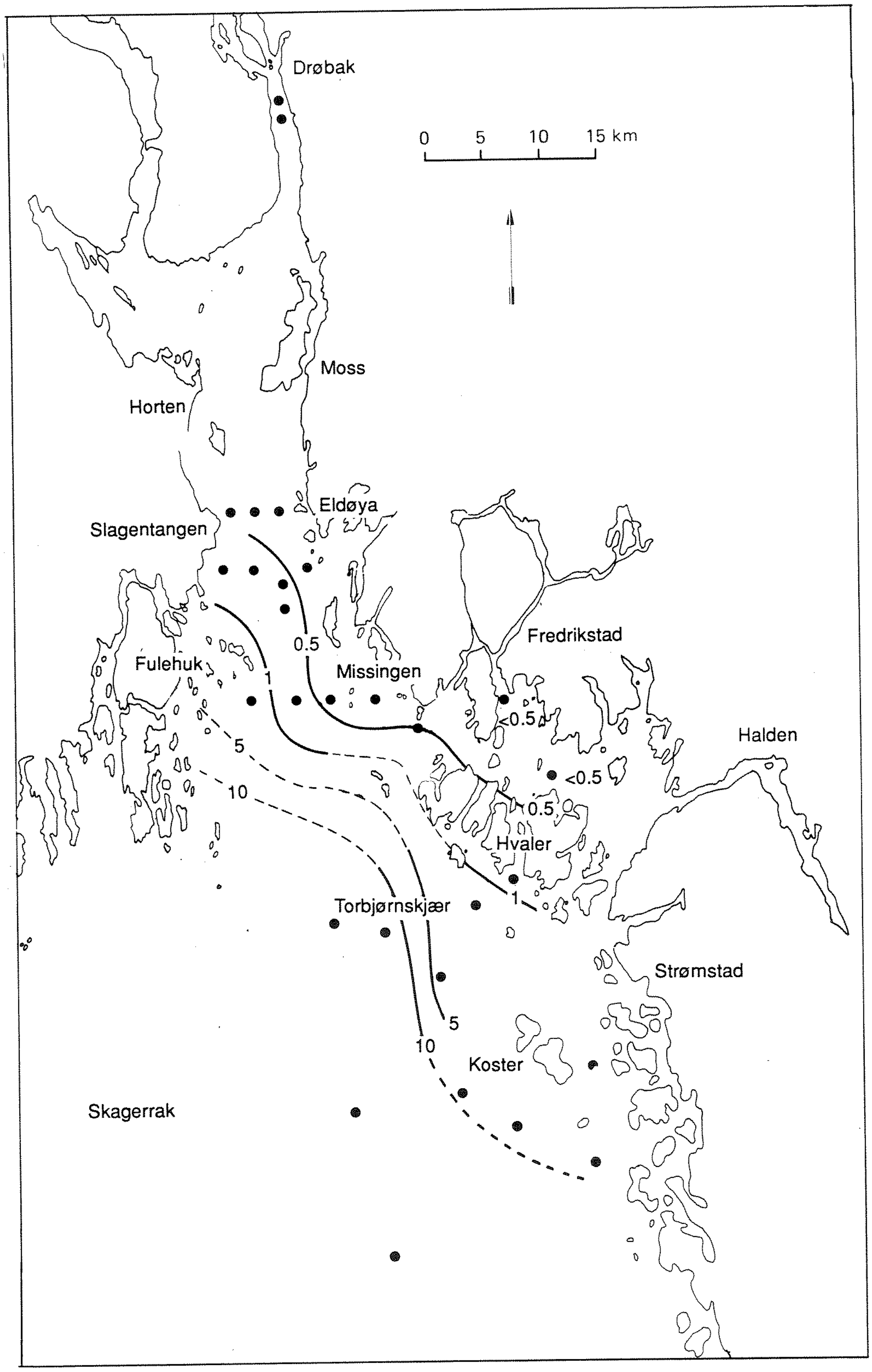


Figure 7. The horizontal distribution of *C. polylepis* (in mill. cells/l) in the 10-20 m depth at the Outer Oslofjord and northern Skagerrak between May 29 and June 2, 1988.

In summarizing we must conclude that presently it is difficult to use any of the operative satellites for direct algal monitoring. Limitations are the inadequate spatial, temporal or radiometric sampling. The limitations make it necessary always to use satellite data in combination with field data to limit mis-interpretations. It is well-known that it is not possible to combine high frequency of satellite sampling with a high spatial resolution of the satellite. The NOAA satellites give frequent passages (many every day) but poor resolution (about 1 km). On the other hand earth resources satellites allows a 10 to 80 m resolution but a frequency of 16 to 26 days with possible repeat coverage (SPOT) or path overlap 7/9 days (Landsat). It is therefore likely that earth resources satellites may only capture an ocean bloom once or possibly twice whereas the NOAA satellites may capture it several times. It is recommendable to combine several satellite sensors to get the best possible coverage of a bloom. By this combination a higher frequency of scenes from high resolution satellites can be achieved (cf. Sørensen et al., 1991). The best alternative is often to use temperature as a tracer (AVHRR or TM). Sometimes the near-IR bands of the TM, MSS, SPOT or MOS-1 could be used for direct determination of algae but seldom the near-IR bands of the NOAA satellites.

There are also several limitations as to the number of water parameters that could be directly recorded by the satellites. Presently we can only record a couple of turbidity and optical parameters and temperature and there are several complications in handling water data (Lindell & Sørensen, 1990). However, those parameters can often be used as tracer for other constituents.

Air-borne sensors sometimes have the advantage of fewer limitations because of cloud cover, but air-borne sensors are more complicated when it comes to evaluation of data (calibration, geometry, atmospheric corrections etc.) Sørensen et al. (1991).

Difficulties arising when mapping are that different algae show different spectral responses, as well as changing responses in the developing stages of the algae. The algae could be allocated anywhere within the upper layers of the water mass, which creates various spectral responses. E.g. at the end of the bloom, the *C. polylepis* was located at about 18 m depth, which completely prevented mapping from remote sensing sensors. A mixture of different algae as well as a mixture of algae and inorganic matter may further complicate the mapping efforts.

However there are some very important advantages with satellite information. It provides unique information on current patterns, water mass structure and temperature distribution. The areal coverage is an extra-ordinary good property and the fact that the data comes in digital form offers excellent possibilities for quantifications. The fact that many algal blooms are initiated during good weather conditions are favouring the use of remote sensing techniques. A further advantage is the relatively low cost per unit area of the satellite information.

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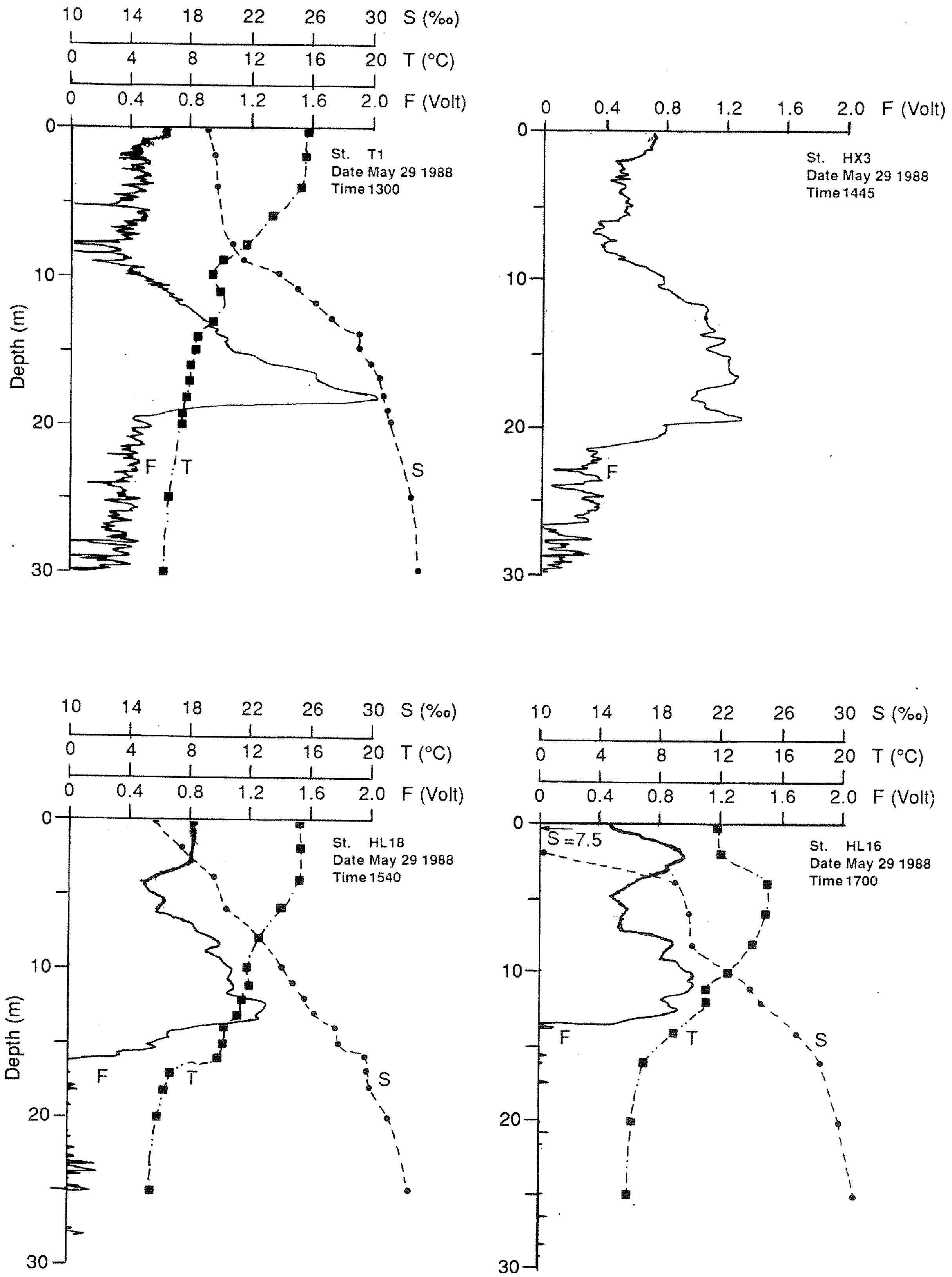
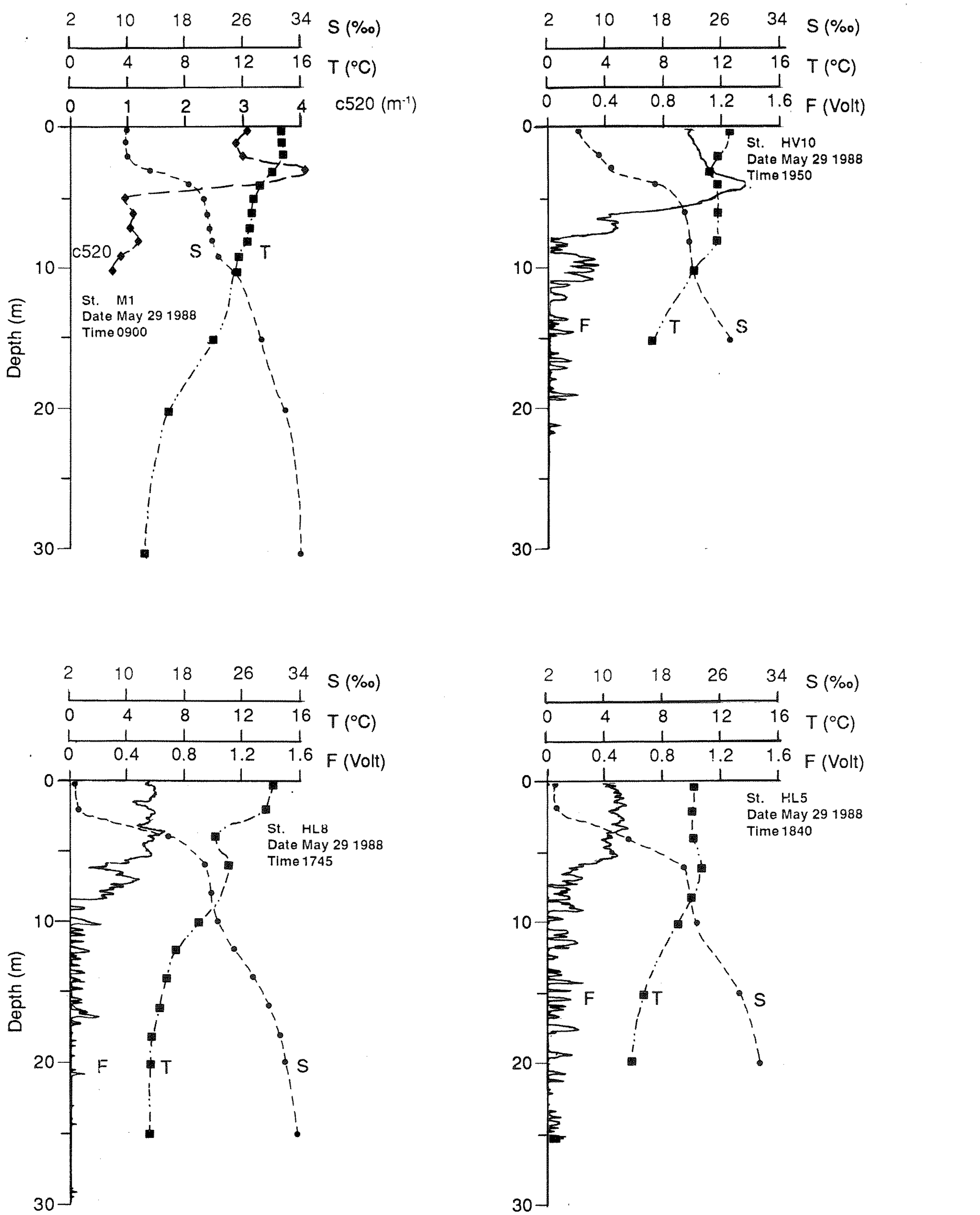
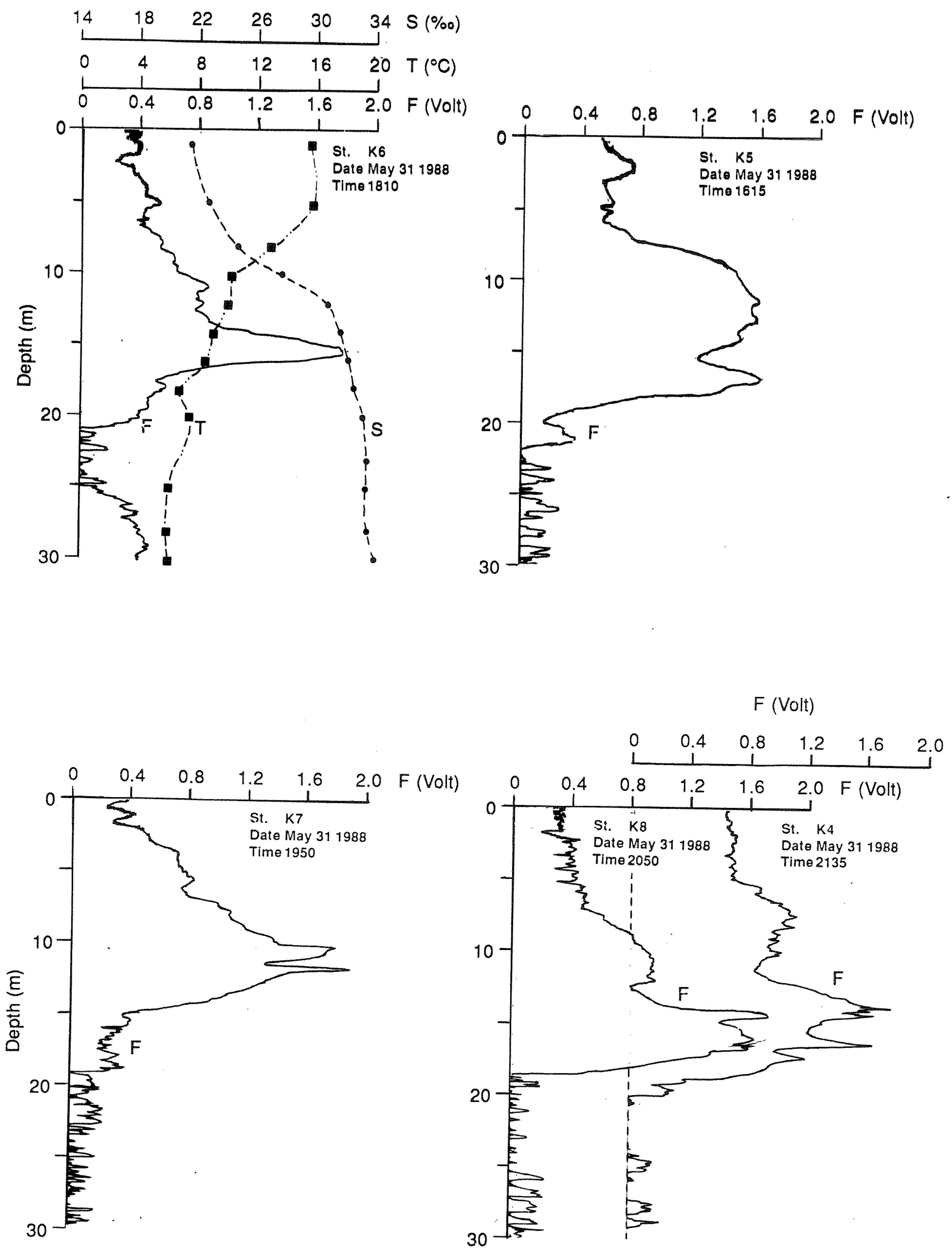
Appendix A



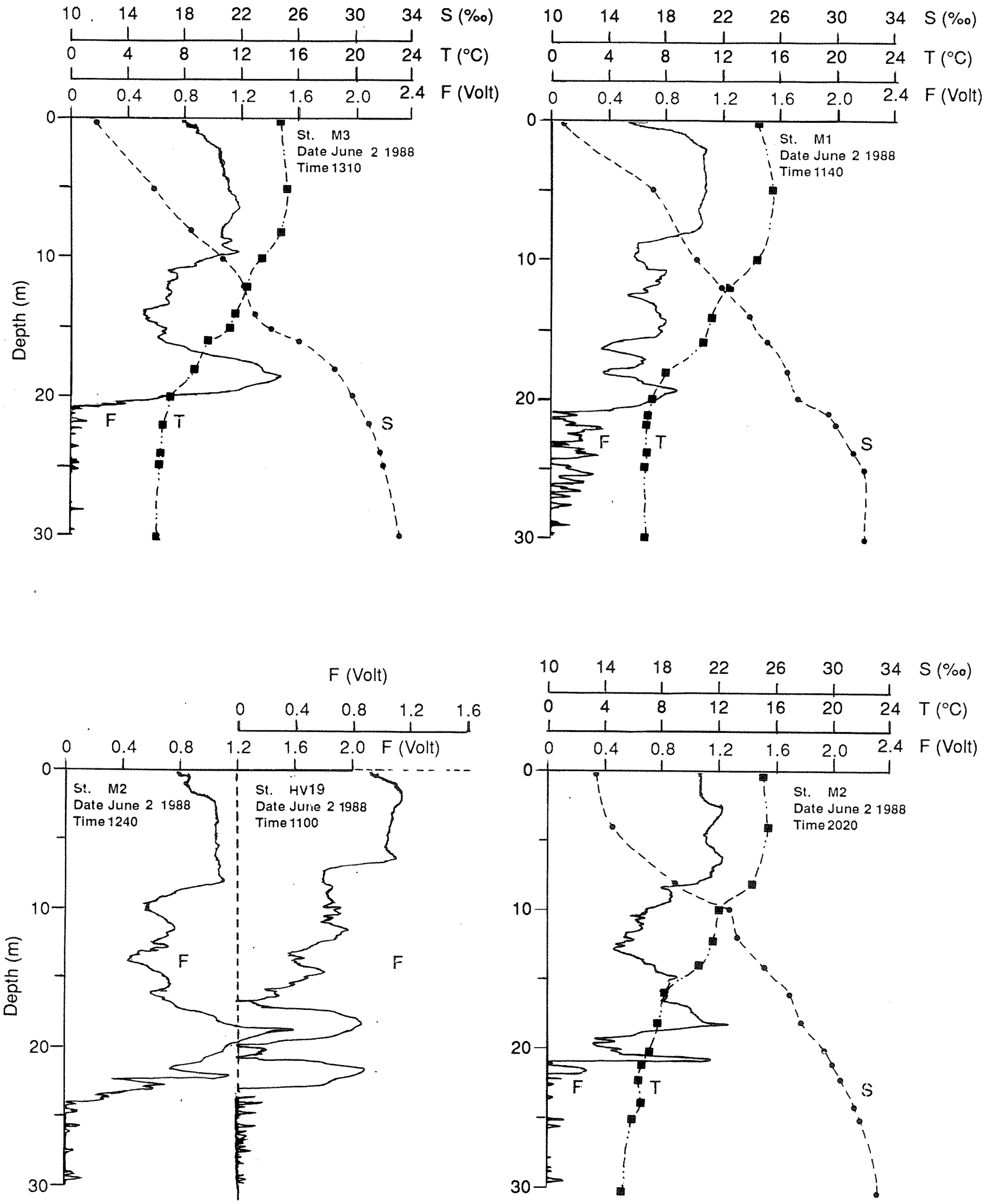
A.1. Vertical distribution of relative (logarithmic) chlorophyll-a fluorescence (F), temperature (T) and salinity (S) in the Torbjørnskjœr and Glomma outlet area on May 29,1988



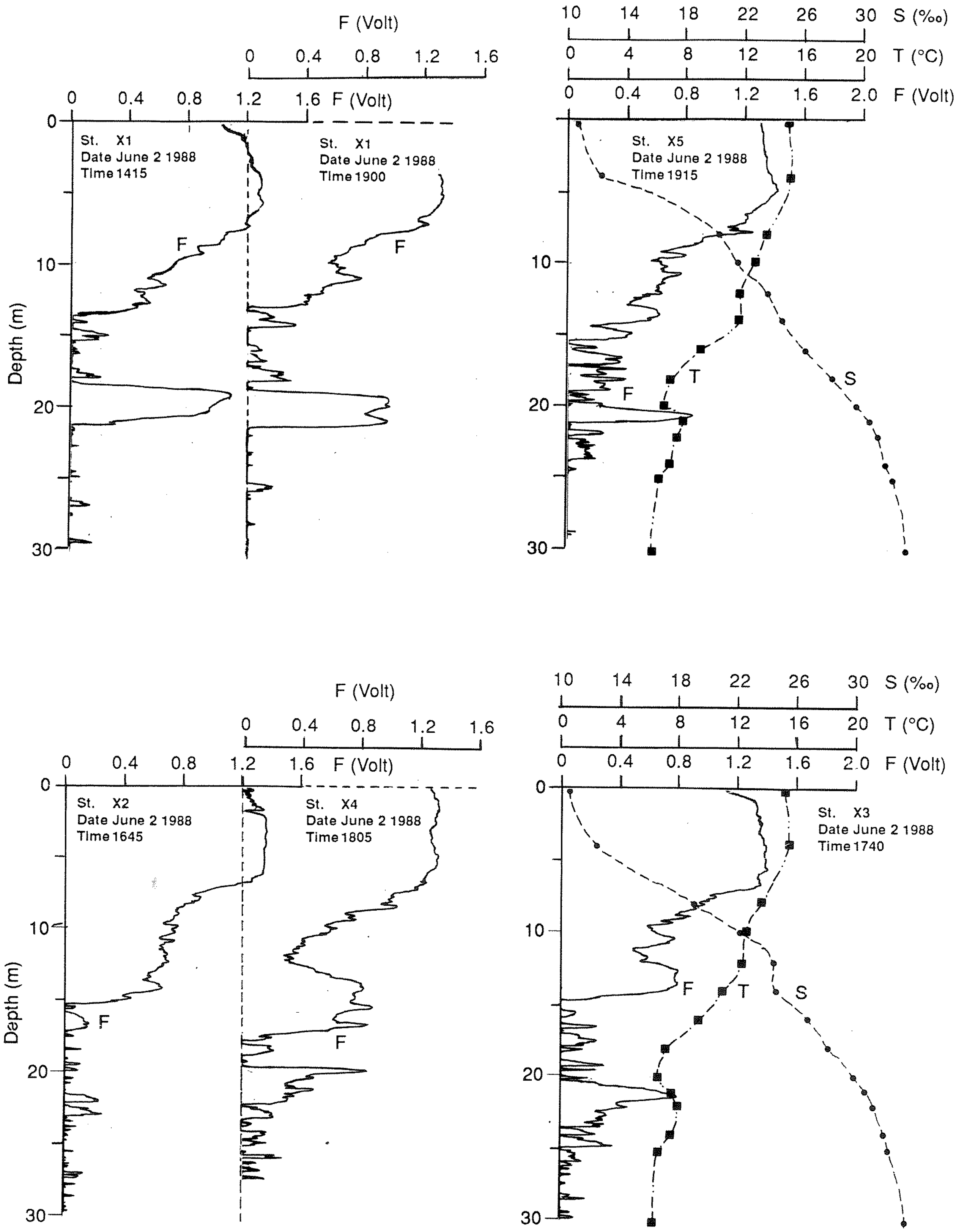
A.2. Vertical distribution of light beam attenuation (c520), relative (logarithmic) chlorophyll-a fluorescence (F), temperature (T), and salinity (S) in the Missingen and Hvaler area on May 29, 1988.



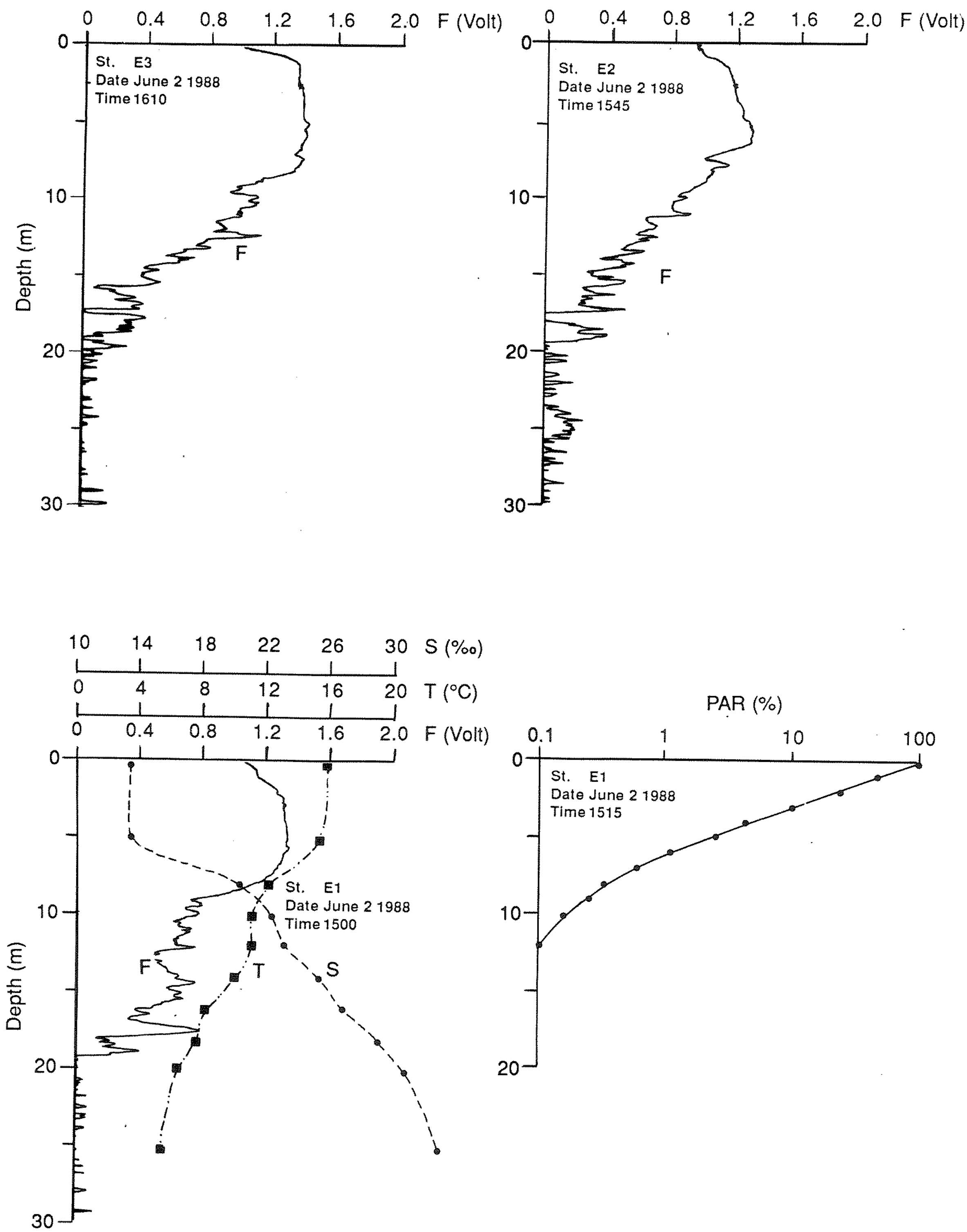
A.3. Vertical distribution of relative (logarithmic) chlorophyll-a fluorescence (F), temperature (T) and salinity (S) in the Koster/Skagerrak area on May 31, 1988.



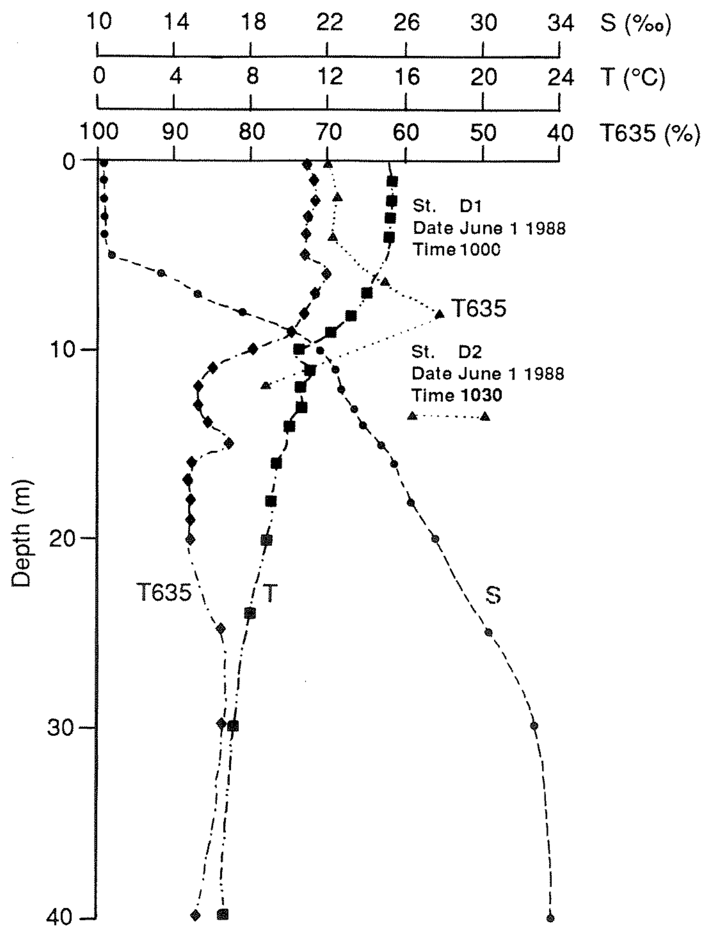
A.4. Vertical distribution of relative (logarithmic) chlorophyll-a fluorescence (F), temperature (T) and salinity (S) in the Missingen-Fulehuk area, June 2, 1988.



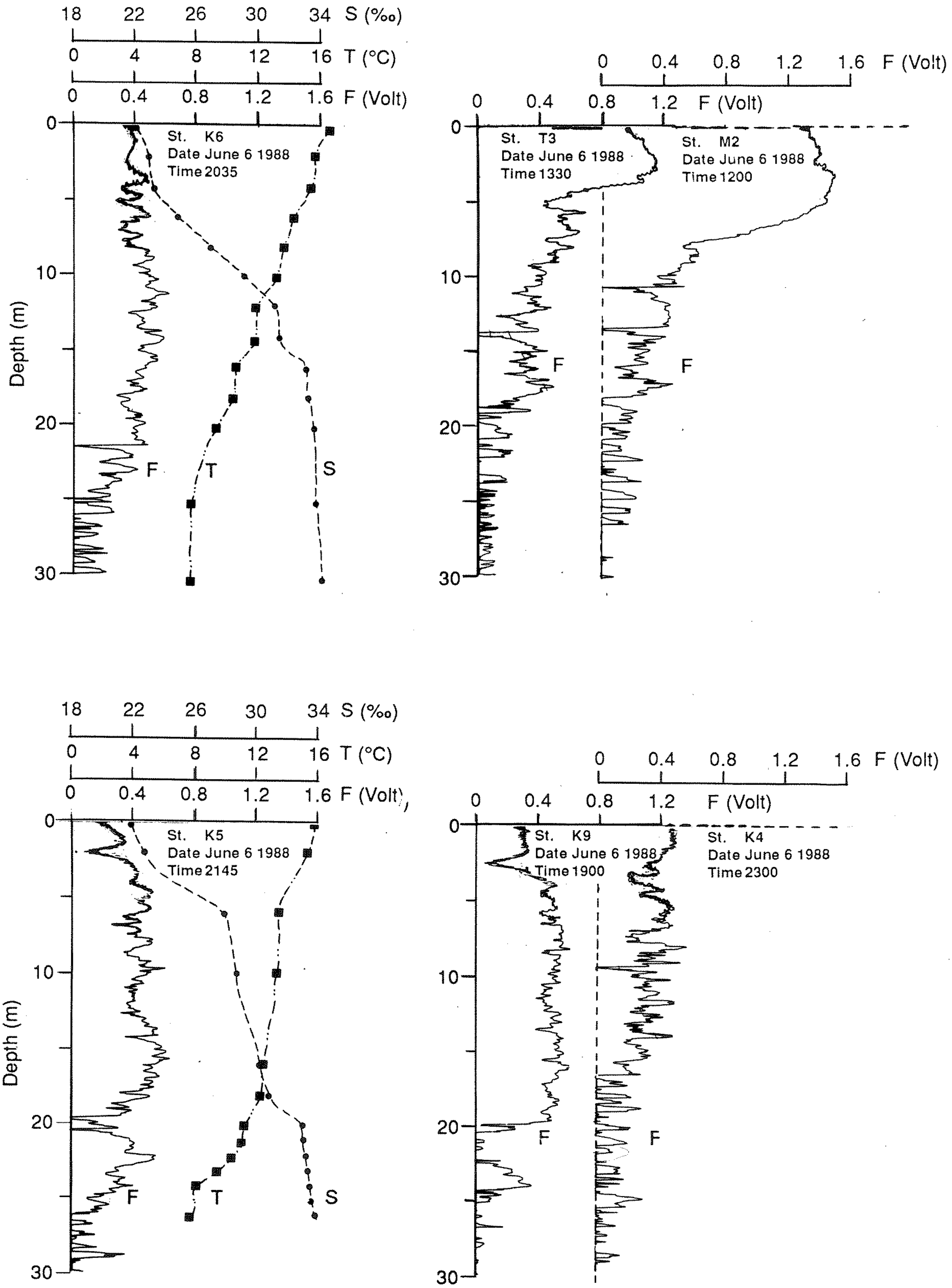
A.5. Vertical distribution of relative (logarithmic) chlorophyll-a fluorescence (F), temperature (T) and salinity (S) in the Slagentangen-Missingen area on June 2,1988.



A.6. Vertical distribution of relative (logarithmic) chlorophyll-a fluorescence (F), temperature (T) and salinity (S) and photosynthetic active radiation (PAR) in the Slagentangen- Eldøya area on June 2, 1988.



A.7. Vertical distribution of transmission of light at 635 nm (T635), temperature (T) and salinity (S) at stations D1 and D2 in Dröbak area, June 1. 1988.



A.8. Vertical distribution of relative (logarithmic) chlorophyll-a fluorescence (F), temperature (T) and salinity (S) in the Outer Oslofjord and Koster area, June 6, 1988.

Appendix B

The number of *Chrysochromulina polylepis* and *Skeletonema costatum* in samples from Outer Oslofjord and Skagerrak May 29 and June 2, 1988.

Date	Station		Depth	C. polylepis	S. costatum
	No.	Name	m	mill./litre	mill./litre
880529	M1	Missingen	8,0	0,25	
	T1	Torbjørnskjær (west)	18,0	15,7	
	HX3	Torbjørnskjær (south)	0-2	0,19	Dominating
			17,0	2,71	
	HL18	Torbjørnskjær (east)	0-2	0,09	Dominating
			13,0	3,84	
	HL16	Hvaler/Glomma (outlet)	0-2	0	
			11,0	0,78	
	HL8	Hvaler/Glomma (east)	7,0	0,04	
	HL5	Hvaler/Glomma (east)	5,0	0,02	
	HV10	Hvaler/Glomma (west)	0-2	0,11	5,04
			4,0	0,32	Dominating
			10,0	0,64	
880602	HV19	Missingen/Glomma (west)	22,0	0,06	
	M1	Missingen	19,5	0,16	
	M2	Missingen (Time1240)	19,0	0,66	
	M2	Missingen (Time 2000)	18,0	0,58	
	M3	Fulehuk (Time 1320)	18,5	2,33	
	X1	Outer Oslofjord	19,5	0,66	
	X2	Outer Oslofjord	14,0	0,14	
	X3	Outer Oslofjord	0-2	0.03	25,3
			6,0	0,1	Dominating
			10,5	0,48	
			13,5	0,86	Traces
			21,5	0,5	
	X4	Outer Oslofjord	15,0	0,41	
			21,5	0,04	
	X5	Outer Oslofjord	20,5	0,06	
	E1	Eldøya	17,5	0,14	
	E3	Slagentangen	18,0	0,28	

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