TOXIC ALGAL BLOOM IN SCANDINAVIAN WATERS, MAY-JUNE 1988

By I. Dundas, O.M. Johannessen, G. Berge and B. Heimdal

SINCE 1966, a number of blooms of toxic dinoflagellates have been reported along the southern coast of Norway. Most were caused by the species *Gyrodinium aureolum*, which produces toxins that can cause fish kills. Another common species is *Prorocentrum minimum*, which produces toxins that may accumulate in filter feeding animals (e.g., mussels) without necessarily causing harm to these animals; however, the accumulated toxins may render them toxic to consumers (Tangen, 1983).

Recently the recreational interest in coastal areas has increased markedly, causing a heightened public awareness of algal blooms. With the advent of aquaculture, toxic blooms causing shellfish poisoning or loss of valuable cultured fish have achieved the status of media events. In 1988, the alga *Chrysochromulina polylepis* had a massive and unpredicted bloom during May and June in the Skagerrak-Kattegat area, where it occasionally outgrew all other algae. Four weeks after its outbreak in the eastern Skagerrak, the bloom covered major parts of the Kattegat and the Skagerrak, causing kills of both wild and caged fish. The bloom spread northwards with the Norwegian Coastal Current (NCC) along the western coast of Norway to about 60°N.

In spite of the high concentrations of cells (up to 100 million cells per liter, Berge, *et al.*, 1988), the bloom was not very striking visually, partly because maximal algal populations often were found at some depth. The bloom was mainly noticed by its lethal effect on caged fish in fish farms along the coast. About 500 tons of caged fish with a market value of approximately $5 million US were lost along the southern coast of Norway before precautions were taken.

Because of the observed beneficial effects of low salinity, sea farm cages were relocated by towing them from the bloom-exposed coastal region to relative safety in the brackish waters of the inner parts of the fjords. There was some concern about possible negative effects on the caged fish by the towing procedure, but in spite of infrequent reports in the popular press about high casualties during the exodus, the general impression was that careful towing did not harm or stress the fish. Some fish farmers even insisted that the towing procedure had a beneficial effect on the general condition of the caged salmon.

On the west coast of Norway, some 200 sea farms, containing fish with a value of approximately $200 million US were evacuated during the bloom. Relocation of salmon cages was thus shown to be a feasible safeguarding procedure in similar future bloom incidents. Some concern was voiced about the localization of cages with cultured salmon close to river mouths, due to possible interference with the upriver migration of the native salmon population, but in no case was any such deleterious interference documented.

The Area

The surface water of the Kattegat is influenced by the outflowing brackish water from the Baltic Sea. In the eastern Skagerrak, this water mixes with water from the central and southern North Sea entering via the North Jutland Current (NJC). The mixture flows along the entire Norwegian coastline from the eastern Skagerrak into the Barents Sea, forming the NCC (Fig. 1, p. 10). Remote sensing studies (Johannessen, *et al.*, 1983; Johannessen *et al.*, 1989b) have established that the NCC is characterized by a complex pattern of shifting meanders and eddy structures. The surface water of the central Skagerrak originates mainly from North Sea water overriding Atlantic water brought in via the Norwegian Trench. The anticlockwise circulation in the area favors upwelling of deeper, nutrient-rich water in the central part of the Skagerrak (Svanson, 1975), a mechanism of great importance for the productivity of this area. In addition, advective transport of nutrients into this system adds to the natural fertilization of the coastal waters and is a potential source for an increasing number of blooms.

In the Skagerrak area, about 90 species of fish are recorded, of which about 30 have commercial importance. Lobster, crab, shrimp and mussels are also harvested commercially in the area. The total annual commercial catch of all species amounts to 400-500 thousand tons (Hognestad, 1984). In addition, the

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sheltered areas of the Swedish fjords and the fjords along the entire Norwegian coast offer excellent sites for a rapidly growing fish farming industry, with an annual production value approaching $750 million US.

The *Chrysochromulina* Bloom, its Monitoring and Forecasting

The first documented indication of this toxic bloom was a report on May 9, 1988, from fish farms on the west coast of Sweden. Dead wild fish were first observed May 13. The bloom progressed along the west coast of Norway where it culminated in early June. During the bloom, algal concentrations were measured up to a maximum of 100 million cells per liter. The highest concentrations could often be found in a thin layer between the relatively nutrient-poor surface water and the nutrient-rich deeper water. Here, the cell density could be high enough to be registered by sonar as an echo scattering layer (Horstmann and Jochem, 1988).

Fish with a value of approximately $200 million US were evacuated during the bloom.

In response to the algal bloom, an expert group with members from the University of Bergen, the Institute for Marine Research, and the Nansen Remote Sensing Center was formed, with the responsibility of coordinating the monitoring of the algal distribution and relevant environmental conditions (Berge and F¢yn, 1988). Daily forecasts of the position of the algal front were distributed by the Director of Fisheries to the radio, television and newspapers. Very little was previously known about the algae concerned, and investigations of its physiology and its effect on other organisms were carried out concomitantly with the monitoring efforts. The forecasts were used by the fish farming industry and its insurance companies for formulating advice on precautionary evacuation of caged fish. The Seafarming Sales Association in Trondheim established its own monitoring group to assist its members. Several research vessels, smaller speed boats, remote sensing aircraft, drifting Argos oceanographic buoys, as well as real-time NOAA satellite data, were at the disposal of both groups.

The propagation of the algal front, defined as a concentration between 0.5 - 1.0 million cells per liter, indicates the advance and retreat of the bloom along the southern and southwestern coast of Norway from May 21 to June 3. (Fig. 2, p. 11). After the species had been identified as *C. polylepis*, its concentration was determined with a ship-based flow cytometer and by direct counting of unpreserved water samples in light microscopes (Berge and F¢yn, 1988). The early observations indicated a close correlation between

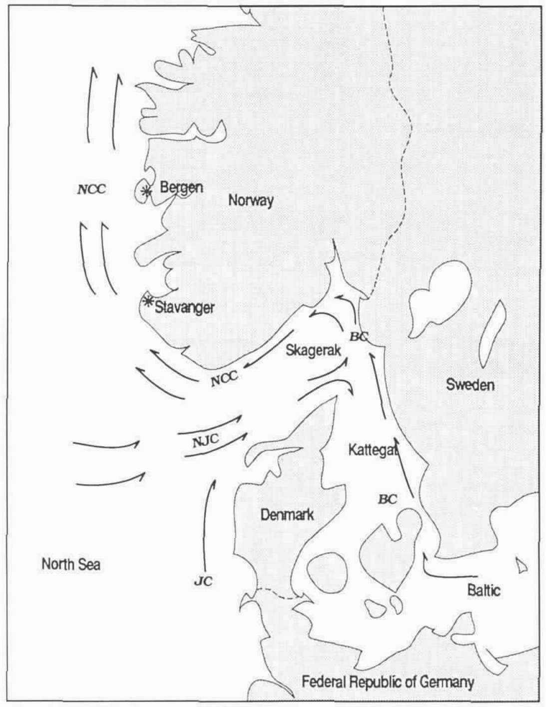

Fig. 1: Surface circulation in the North Sea, Skagerrak and Kattegat area. The Baltic Current: BC; The North Jutland Current: NJC; The Jutland Current: JC; The Norwegian Coastal Current: NCC.

the algal front and the satellite-derived surface warm water front. The spreading and advection of the algae was thus indirectly monitored by satellite infrared (IR) surface temperature data, during cloud free periods (Fig. 3, p. 12). Between May 15 - 21, the algal front moved southwestward at an average speed of 5 km d^{-1}, while between May 21 - 22 the westward advection of the front rapidly increased to about 30 km d^{-1}. On May 30 the IR image showed that a narrow front, close to the coast, had reached Stavanger, indicating a mean advection speed of about 25 km d^{-1}. *In situ* mapping of the sea surface temperature field, current measurements, and also the algal concentrations registered off Stavanger verified these satellite observations.

Synoptic satellite and *in situ* observations, data from the monitoring program, and historical data from a previous research program on the NCC were used in the production of daily forecasts of the algal front movement. In addition, numerical model simulation was done in support of the forecasts, using a two layer quasi-geostrophic model with a grid scale of 5 km (Ikeda, *et al.*, 1989). The model includes the

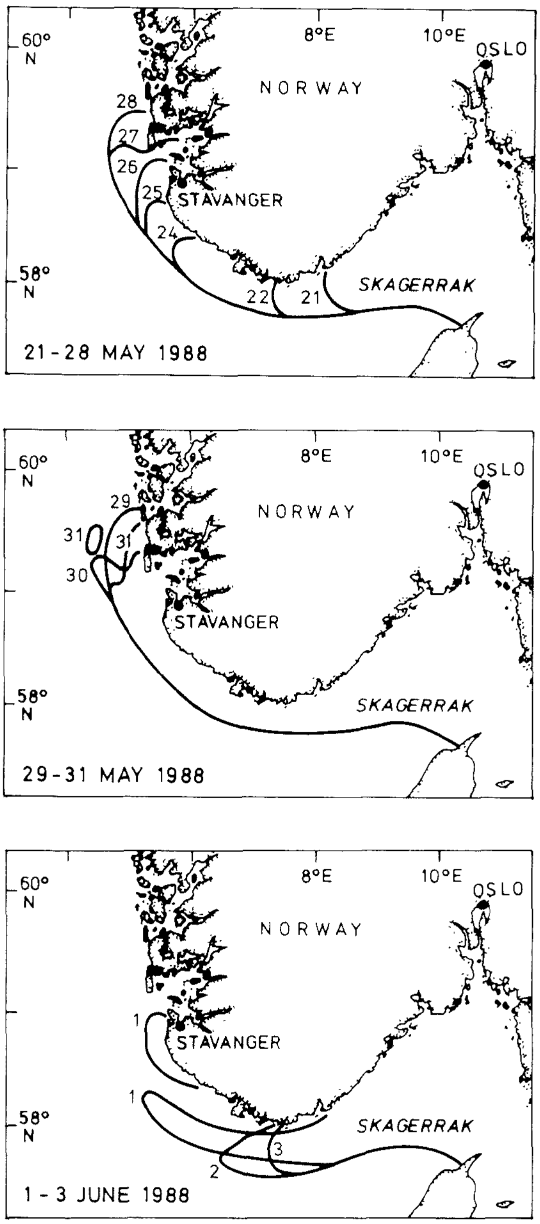

***Fig. 2:** Summary of the observed algal front including both advance and retreat in the Norwegian Coastal Current from May 21 to June 3 defined by 0.5-1.0 million algal cells per liter.*

effects of instabilities in the NCC and interactions with an idealized bottom topography. Wind effects and fjord and coastal exchange processes were not included. The model was initialized with the IR-derived surface temperature field from May 22 and later compared to IR images, current measurements, and algal observations, until June 1 (Johannessen *et al.*, 1989a). Neglecting local growth or death, the algae were assumed to drift passively with the NCC. Streamlines of the flow pattern for the upper layer in the model on June 1 are shown in Fig. 4 (p. 13). During this period the wind was modest, supporting the omission of wind effects from the model.

In the model calculation, the initial meander from the May 22 IR image developed into two vortex pairs on June 1, one pair off Stavanger and a second pair farther north. Assuming that the algae drift passively, the advection of a simulated algal front was included in the model from May 26 to June 1. The downstream evolution of the algae trajectories showed a meander-like propagation pattern in agreement with the vortex pair off Stavanger June 1. The central part of the front propagated downstream at an average speed of 20-25 km per day. Model particles simulating the algal front, placed nearshore, initially followed a clockwise path towards the coast, whereas particles placed on the offshore edge of the jet-like current followed cyclonically curved trajectories in accordance with the formation of the cyclonic eddy off Stavanger. The impression from the model is that particles remained trapped in the cyclonic feature.

The anticlockwise circulation in the area favors upwelling of deeper, nutrient-rich water in the central part of the Skagerrak.

The positions and configuration of the algal front on May 30, and the detached algal plume registered on May 31 (Fig. 2), are in good agreement with the results of the model tracer simulations, which demonstrates the impact that meander and eddy features may have on the dispersion of biological material. The algal front advected northwards with the NCC until the culmination of the bloom around May 30. Thereafter, the algal front retreated into the Skagerrak during the first three days of June (Fig. 2). Cessation of growth and possibly also algal mortality apparently caused the retreat of the algal front, and dominated over the effect of advection by the northward flow of the NCC.

Chrysochromulina Polylepis and its effects on other Organisms

Algae belonging to the genus *Chrysochromulina* are characterized by having a special threadlike appendage, the haptonema. The great majority of the *Chrysochromulina* species are single cells, motile by means of two whip-like flagella. They are identified on the basis of the shape and size of the cell, the length and morphology of the flagella and the haptonema, and especially by the morphology of the different

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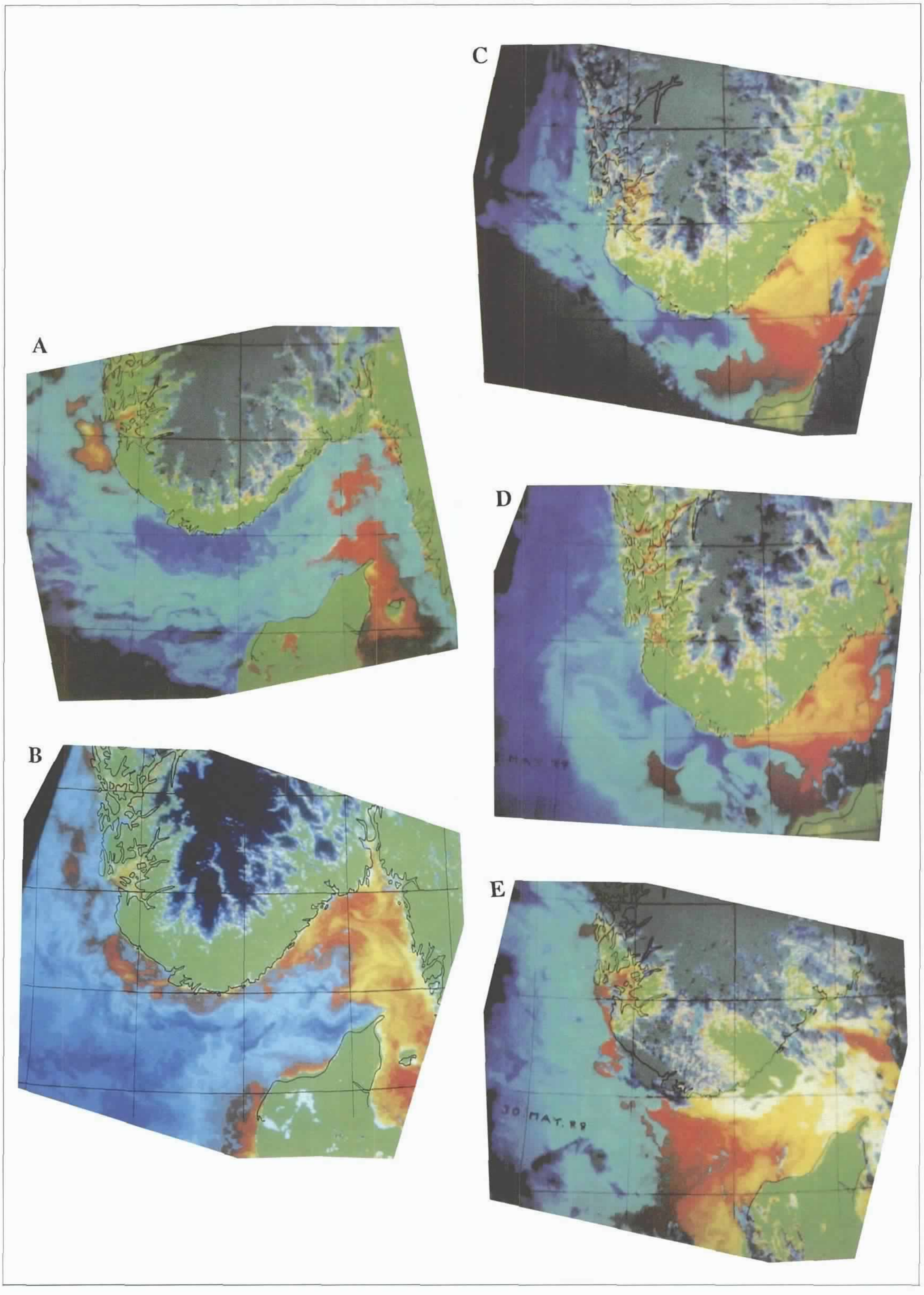

Fig. 3: *Color coded sea surface temperature field of the North Sea, Skagerrak and Kattegat derived from the NOAA Advanced Very High Resolution Radiometer (AVHRR) infrared (IR) channel in April and May 1988. Yellow represents warm water with temperature above 10°C, dark blue represents temperature below 6°C. Land is coded green, with snow/glaciers grey, while clouds are dark. The satellite data were received at Tromsø Telemetry Station, Norway. Data tapes were received at Nansen Remote Sensing Center, Bergen, Norway about 6 hours later, and uncalibrated infrared (IR) radiation data were converted to geometrically corrected and calibrated surface temperature values on the Context Image Processing System. The* Chrysochromulina polylepis *is correlated with the yellow color, representing water with temperature of more than 10°C. A: April 28, B: May 15, C: May 21, D: May 22, E: May 30.*

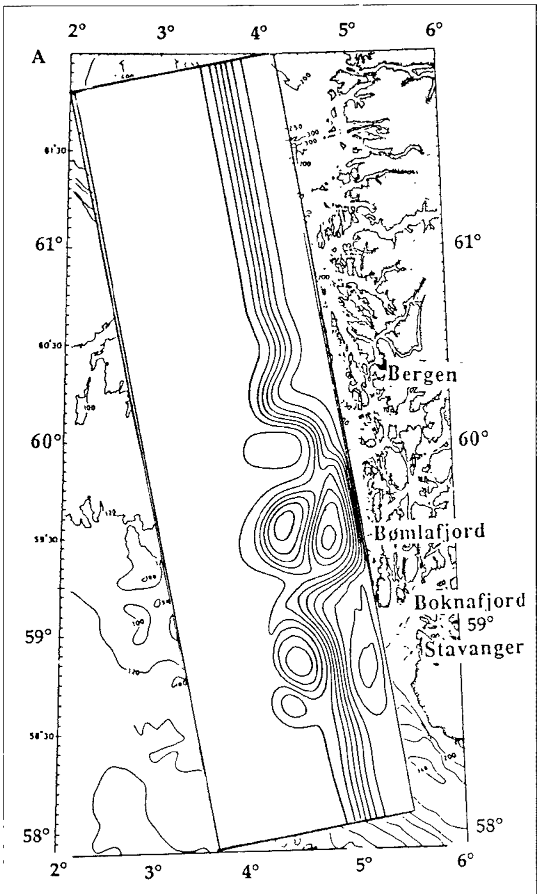

***Fig. 4:** The model streamfunction in the upper layer predicted for June 1.*

types of scales covering the cell body (Leadbeater, 1972).

Blooms of *C. polylepis* have not previously been connected to deleterious or toxic effects on other organisms, the sole exception being a culture experiment that showed it to be harmful for the bryozoan *Electra pilosa* (Jebram, 1980). The toxic effects observed during the *C. polylepis* bloom resemble those described for the closely related alga *Prymnesium parvum* (Hibberd, 1980). The taxonomic identification of *C. polylepis* as the algae responsible for the bloom and the awareness of its taxonomic relatedness to *P. parvum* made it possible to benefit from published data in studying the unknown toxic substance produced by *C. polylepis*.

During the 1988 bloom, fish farmers in the Gullmar fjord on the Swedish west coast reported that rainbow trout exposed to the algal bloom were showing signs similar to oxygen deficiency distress in spite of good oxygenation of the water (O. Lindahl, personal communication). Two days later the trout started to die. Observations of mucus covering gills of affected fish lead to the misconception that fish kills were the result of clogging of the gills. Instead, the toxic effect seems to be due to a breakdown of the salt-regulating activity by the gills of affected fish, as evidenced by an increase of blood chloride on exposure of the fish to the algae (Leivestad and Serigstad, 1988). Symptoms in other affected organisms were also consistent with a breakdown of membrane osmoregulation. *Chrysochromulina polylepis* itself is rather osmotically fragile, the cells becoming nonviable at about 10 ppt salinity. Loss of cell integrity at this salinity was demonstrated by microscopy. Experimental field work showed that toxic effects also were dependent on water salinity. Concentrations between 5 and 10 million cells per liter at salinities of about 30 ppt were sufficient to kill caged trout and salmon. In water of some 20 ppt salinity, algal concentrations above 20 million cells per liter were lethal to salmon, rainbow trout, and even cod, which seems to be the most resistant of these species (Leivestad and Serigstad, 1988). No fish kills were reported at salinities below 13 ppt regardless of algal concentration, and no kills have been reported at algal concentrations below one million cells per liter, regardless of water salinity.

Duration of exposure to the algae was obviously important. In several cases fish that started to show distress on exposure to the bloom recovered on being transferred to water with lower salinity or low algal concentrations. While some toxicity of blue mussels was registered after exposure to the algal bloom, no toxicity of fish flesh was detected (Berge *et al.*, 1988). Observations on wild populations were made during and after the bloom, both by experimental fishing and by an extensive program of diving surveys. Larger wild fish seemed to be able to avoid contact with the algal bloom, except in areas of shallow depth, where some mortality on flatfish and cod were recorded (Horstmann and Jochem, 1988). Effects on wild populations were mainly noted where the littoral had been exposed to high algal concentrations along the Norwegian coast chiefly in the Kattegat and the Skagerrak. Deleterious effects were observed on sessile plants (red and brown seaweed), molluscs (bivalves and snails), and echinoderms (sea stars and sea urchins), while crustaceans (crabs) seemed less affected. Survival depended on length of exposure and sub-lethal effects seemed to be reversible. Lethal effect on wrasses was extensive. Obser-

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vations after the algal bloom indicated severe local changes, of at least temporal importance, in population abundances. Populations of stickleback were locally abnormally high and commercial catches of eel were unusually high a month after the incident, while the wrasse population seemed severely depleted, as were the populations of snails (Berge *et al.*, 1988). During the bloom it was found that much of the 0-year group of cod, whiting, pollock and saithe exposed to the bloom was dead or dying (Berge, 1988; Horstmann and Jochem, 1988).

Concluding Remarks

The observed *C. polylepis* bloom of May 1988 came after the normal spring bloom of diatoms in the Skagerrak. While the situation in the central Skagerrak was normal for the month of May, with low concentrations of nutrients in the euphotic zone, there was a high influx of nitrates to the Kattegat where concentrations of phosphate and particularly silicate were quite low.

Unusual climatic conditions during the previous winter, with high precipitation resulting in increased land runoff, may represent a significant contribution both directly from the areas around Kattegat and indirectly by the Jutland Current. High nitrate concentrations, obviously originating in the eutrophic waters of the German Bight, were registered along the western coast of Denmark. The large discharge from the Baltic may have had an effect by causing entrainment into the euphotic zone of nutrient-rich underlying water.

While the *C. polylepis* bloom was most severe in areas and at depths with unusually high concentrations of nitrate and an abnormal ratio of nutrients, particularly nitrate against silicate, the abnormal nutrient concentrations alone can not explain the population explosion of *Crysochromulina*. The dominance of *C. polylepis* over all other algae must be explained on the basis of the autecology of this species, its environmental requirements, and its physiological responses. The motility of *C. polylepis*, which enables it to position itself on top of the unusually nitrate-rich deeper water, and its ability to supplement photosynthesis and/or nutrient uptake with phagotrophy of smaller microorganisms, undoubtedly give this alga a competitive edge. During photosynthesis it also produces oxygen needed for utilizing organic nutrients, minimizing the possibility of oxygen deficiency stress. One intriguing question concerns the production of lytic toxins by *C. polylepis* and the effect this may have had in giving this alga an additional advantage over other microorganisms in its environment.

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