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Toxic and noxious phytoplankton in Big Glory Bay, Stewart Island, New Zealand

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Abstract

Diurnal vertical profile sampling of the water column, during a fish killing bloom of the raphidophycean alga *Heterosigma akashiwo*, revealed a phytoplankton population otherwise composed almost entirely of a variety of dinoflagellates. Of these *Glenodinium danicum, Dinophysis acuta, Polykrikos schwartzii, Ceratium furca* and *Gyrodinium spirale* were predominant. The distribution of the major species within the phytoplankton were documented and evidence of synchronous vertical migration of *H. akashiwo, G. danicum* and *P. schwartzii* was observed. Extracts of shellfish obtained during the bloom and tested by mouse bioassay showed no PSP toxicity but a marginal degree of DSP toxicity. During a subsequent one year phytoplankton monitoring programme another potentially noxious species (*Chaetoceros convolutus*) appeared and the seasonal reoccurrence of species present during the bloom (e.g. *H. akashiwo*) was observed. Important year to year differences in the summer phytoplankton (diatom versus flagellate dominated populations) were apparent and analysis of climate data showed that these differences related to different weather conditions prevailing during the two summer periods sampled. The data suggest the fish killing bloom was giving a chance to develop by a prolonged period of warm, calm weather (during which several heavy rainfall events occurred) leading to stable hydrographic conditions (i.e. stratification) and an increase in the retention time of water within the bay.

Introduction

Big Glory Bay is a semi enclosed body of water (area; 11.9 km^2, mean depth; 16 m) in a native rain forest catchment on New Zealand's most southern major island (Stewart Island, Fig. 1). Because of the pristine nature of the environment, the temperature range of the sea waters (10–16 °C) and the shelter from wave action, this bay has been seen as an ideal location for aquaculture activities. Since the first farm was established in Big Glory Bay 1982, the sea cage rearing of Quinnat salmon (*Onchorynchus tshawytscha*) has become an important part of the island's economy and although currently only small quantities of shellfish (mussels and oysters) are cultivated, expansion of this activity is planned.

During mid summer (January) of 1989, an algal bloom occurred in the bay that caused devastating fish kills (> 800 tonnes) on the salmon farms and resulted in substantial financial losses (Boustead *et al.*, 1989). The bloom first became noticeable because of the unusual colour (red/brown) of the surface waters in the first week of

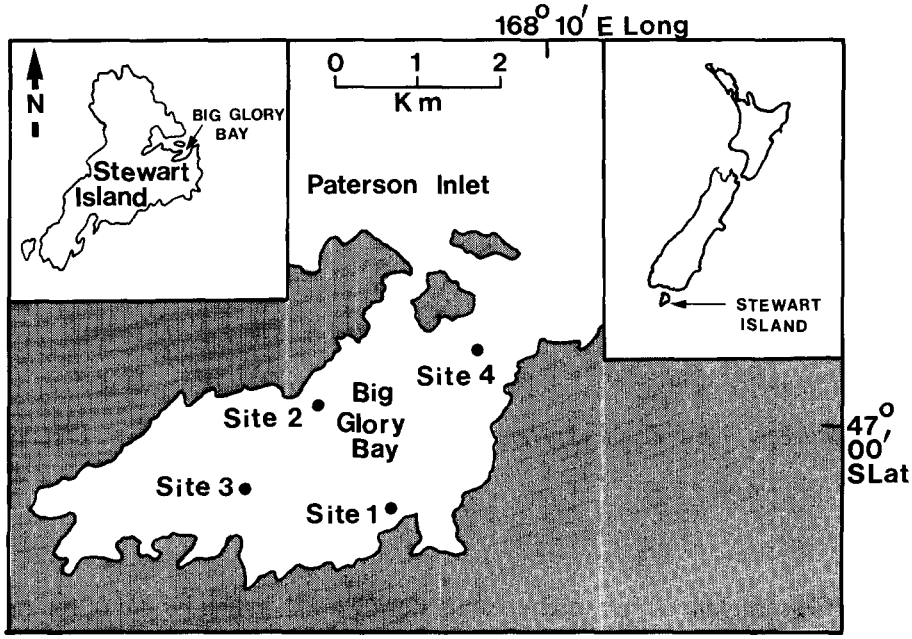


Fig. 1. Sampling sites and geographical location of Big Glory Bay, Stewart Island, New Zealand.

January 1989. Some farms were hit with mass mortalities days before others at different locations within the bay. Ultimately all were severely affected and fish began to die in increasing numbers during the second week of January. By the end of the first week, the micro-alga responsible for the fish deaths had been identified as *Heterosigma akashiwo*. (F. H. Chang, New Zealand Oceanographic Institute, Wellington, pers. comm.). The study reported here was aimed at examining the vertical distribution of *H. akashiwo* over a diurnal cycle, and describing in detail other components of the phytoplankton associated with it, insofar as this might provide clues as to why the fish kill bloom arose. Also, because of an increased awareness in New Zealand over the last few years of the potential risk that toxin producing phytoplankton such as PSP causing *Alexandrium* spp. (Hallegraeff *et al.*, 1988), and DSP causing *Dinophysis* spp. (Lee *et al.*, 1989) may pose to the shellfish cultivation industry and public health, attention was also focused on species with the potential to cause these problems.

As a result of the bloom an industry funded phytoplankton monitoring programme was begun in May 1990. This is designed to provide a routine diagnosis of the species composition and abundance of the phytoplankton and hence an early warning of the development of populations that may be hazardous to aquaculture activities. The results of the first year of this monitoring programme are reported here. Over the long term it is hoped that this will establish an information base upon which a predictive capability can be developed.

Methods

Diurnal sampling

Samples were taken at 5 metre intervals within the water column (27 m) with a PVC Van Dorn bottle, every three hours between 0100 h and 2200 h on 13 January 1989 at Site 1 (Fig. 1). This site was the location of a large sea cage installation from which all the fish had been harvested or disposed of a day or so previously. Sunrise and sunset were at 0510 h and 2042 h respectively.

Phytoplankton samples were preserved with

Lugol's iodine and subsequently examined and counted under an inverted microscope Phytoplankton carbon biomass was estimated from cell volumes obtained by calculation or scale models of cells. The equations of Strathman (1967) for diatoms, Eppley *et al.* (1970) for other phytoplankton and Beers & Stewart (1970) for microzooplankton were used in the calculation of specific carbon biomass.

Dissolved oxygen profiles were obtained with a YSI (model 5739) dissolved oxygen probe. Temperature could not be measured at the time due to a malfunction of the instrument, however extensive water column temperature data was collected by other investigators (F. H. Chang, pers. comm.) the previous day. Samples were collected for the subsequent analysis of salinity using an inductively coupled salinometer (Autolab, model 601). A soluble iron analysis (Franson, 1985) was carried out on stream water (low flow) entering the bay near Site 1.

Shellfish toxicity

Samples of cultivated mussels (*Perna canaliculus*) and oysters (*Tiostrea lutaria*) were taken from culture ropes near to Site 1 on 14th Jan 89. The mussel sample was taken from specimens occupying the top 2 m of the water column and the oysters from 5–10 m depth. These shellfish were tested by mouse bioassay for the presence of paralytic shellfish toxins (Helrich, 1990; AOAC, Official method) and diarrhetic shellfish toxins (Yasumoto, 1981).

To determine whether zinc toxicity might cause an artifact in the PSP bioassays (McCullough *et al.*, 1989) samples of mussel and oyster flesh were analysed for Zn using an atomic absorption technique.

Phytoplankton monitoring

Samples from four sites in Big Glory (Fig. 1) were collected at weekly to fortnightly intervals over a fourteen month period from 7 May 1989 to 23 July 1990. At each site an integrated (whole water column) sample was taken to a depth of 20–25 m with a hose pipe sampler and surface, mid water and near bottom samples were collected. All samples were immediately preserved with Lugol's iodine. Measurements of temperature at 3 m and 10 m were made at Site 1 from September 1989 onwards.

Climate records were obtained from the NZ meteorological service from data collected at a station at Halfmoon Bay, Stewart Island, approximately 5 km from Big Glory Bay.

Results

Diurnal sampling; physical and chemical properties

Differences in salinity between surface and bottom waters (33.8–34.3‰; Fig. 2) were relatively minor but a significant degree of vertical stratification existed. A body of lower salinity water (33.8–33.9‰) within the top 5 m was present between 0100 h and 1300 h after which surface waters became more saline. There was therefore a general change in the hydrographic character of the water mass that moved past the sampling point over this period. The temperature of the water column throughout the bay was very uniform (15–15.5 °C) at this time. The secchi depth ranged from 5 metres at 0700 h to less than 1 metre during the interval 1030 h–1600 h.

Dissolved oxygen concentrations decreased markedly with depth at Site 1 (Fig. 2). Concentrations ranged from 9.8 mg l^{-1} at the surface to 2.0 mg l^{-1} 1–2 metres from the bottom. The concentrations of dissolved oxygen increased (8.0–9.8 mg l^{-1}) in surface waters at midday during the period when surface algal biomass was highest. Stream water entering the bay was acidic (ph 4–5), was deeply stained with humic materials, and had a soluble iron content of 0.8 mg l^{-1}.

Diurnal sampling; the phytoplankton

Heterosigma akashiwo did not preserve perfectly in Lugol's iodine, cells lost their shape and

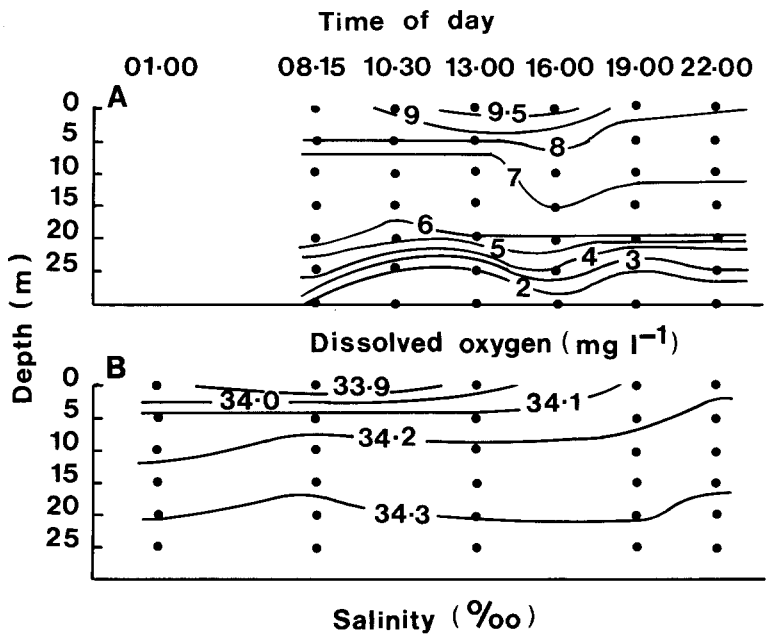


Fig. 2. Salinity and dissolved oxygen profiles measured during diurnal sampling at a Site 1. Big Glory Bay, 13 January 1989. Fig. 2A. Salinity (‰); Fig. 2B. Dissolved oxygen (mg · l^{-1}). The time of day is New Zealand summer daylight saving time. Sunrise 0510 h, sunset 2042 h.

flagella, though they remained intact and were easily identified and counted (Fig. 3). *H. akashiwo* was present in all the individual depth profile samples taken at Site 1 with a maximum of 5.9×10^6 cells l^{-1} and a minimum of 3.0×10^3 cells l^{-1} at the surface (1300 h) and 15 m, (2200 h) respectively. Highest cell numbers $> 4.0 \times 10^6$ cells l^{-1} persisted at the surface between 1030 h and 1600 h after which time a dramatic decline in numbers throughout the water column took place (Fig. 4A). The highest cell concentration observed (4.5×10^7 cells l^{-1}) was in a sample obtained from a patch of discoloured surface water about 30 m from Site 1 at 1015 h. The overall mean and standard deviation of the cell concentrations of all samples counted was $6.3 \times 10^5 \pm 11.3 \times 10^5$ cells l^{-1}. Several days prior to this sampling occasion, fish mortalities were observed to increase dramatically during mid day concurrent with visibly discoloured water. The cell concentrations of *H. akashiwo, Glenodinium danicum* and *Polykrikos schwartzii* showed similar patterns of vertical distribution with large increases in surface waters from mid morning to mid afternoon (Fig. 4A–4C) whereas *Dinophysis acuata* maintained a position within mid water column (10–15 m) throughout the sampling period (Fig. 5D). Other dinoflagellates (*Ceratium furca, Gyrodinium spirale*, and a variety of small *Gymnodinium* species) while displaying varying degrees of stratification showed little evi-

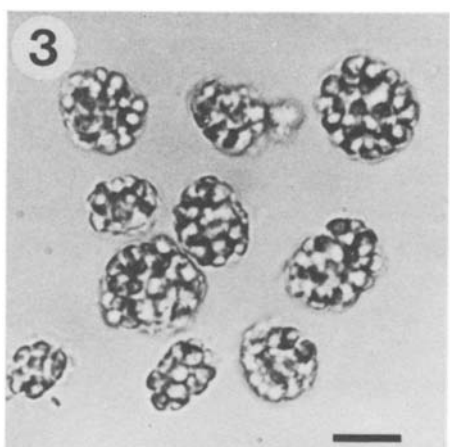


Fig. 3. Heterosigma akashiwo. Lugol's iodine preserved specimens. Scale bar = 10 μm.

dence of vertical migration (Fig. 4E–4G). *Skeletonema costatum*, was the only diatom that occurred in significant numbers (Fig. 4H) though it only contributed a small portion (1–2%; Fig. 5) of the total biomass. *H. akashiwo, G. danicum* and *P. schwartzii* (Fig. 5) dominated the biomass (60–90%) though their relative abundance varied. *D. acuta* and *C. furca* became proportionately more important in 1900 h and 2200 h samples. Total phytoplankton biomass in surface waters ranged between 0.7–2.4 mg C l^{-1} and averaged over the water column as a whole between 0.14–0.60 mg C l^{-1} (Fig. 6).

Cells of the small spherical thecate dinoflagellate *G. danicum* (Figs. 7–12) all existed as solitary individuals, with an equatorial cingulum displaced by its own width and a prominent apical pore complex (Fig. 9–10). This structure was surrounded by a circle of small perforations and lines of pores running parallel to the margins of the girdle and sulcus could be seen in most specimens. At the antapex of the cell a hexagonal perforated scar could be seen in SEM images and the margins of the sulcus displayed small lists (Fig. 11–12). The junction of the girdle and sulcus and location of the flagella pores were obscured by the overlap of the margins of adjacent plates though little of the thecal plate structure could be described in detail due to the small size of the cells and the faint delineation of the plate sutures.

Within all samples containing large (65–70 × 40–45 μm) *D. acuta* specimens (Fig. 13), a second, morphologically distinct form of *Dinophysis* occurred (Fig. 14). These cells were smaller (40–45 × 20–25 μm) with lists of a delicate appearance, more nearly parallel dorsal and ventral margins and a rounded antapex with occasionally a hint of a ventral edge concavity. These specimens most closely resembled descriptions of *Dinophysis dens* (Pavillard).

Shellfish toxicity assays

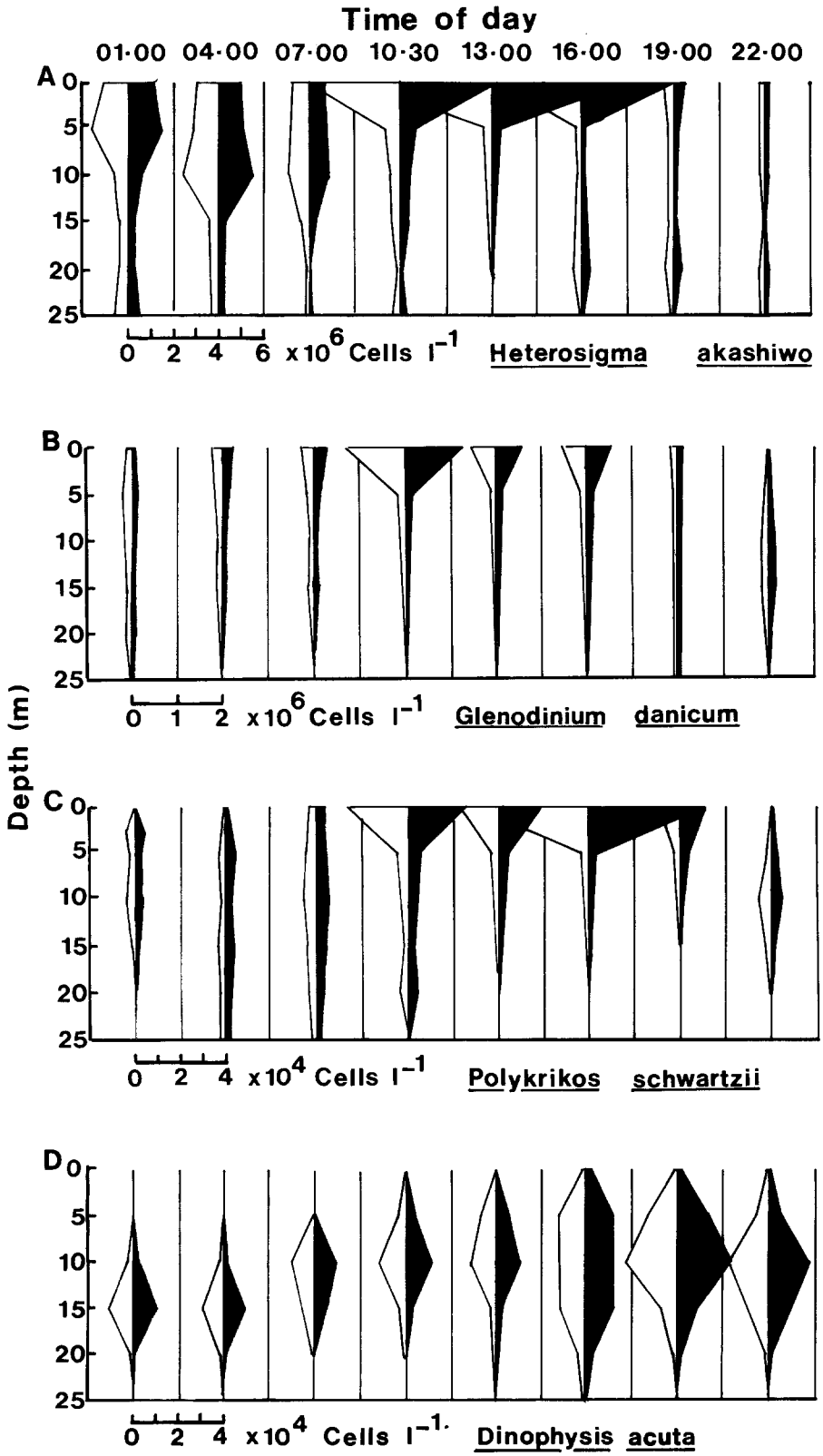
PSP toxicity: Mouse bioassays of extracts of mussels and oysters showed negative results as far as displaying the typical symptoms of PSP poisoning are concerned. All mice inoculated with extracts were unharmed by the treatment. On the other hand all mice inoculated with oyster extracts died within 24 hours with symptoms of slow debilitation unlike those characteristic of PSP poisoning. The zinc content of mussels and oysters were 12.4 and 40.7 μg g wet Wt^{-1} respectively.

DPS toxicity: Three out of six mice inoculated with lipid extracts of mussels hepatopancreas died within 24 hours. 1 : 1 and 1 : 2 dilutions of the extract showed no response. These tests indicate a marginal DSP toxin level exceeding the acceptable level of 0.05 mouse units (MU) g wet Wt^{-1} of whole flesh. Oyster extracts showed no response.

Zooplankton: There were a variety of unidentified ciliate species in the plankton and except at 1300 h when *H. akashiwo* numbers were at their peak, ciliate biomass was highest at the surface (Fig. 6). Although ciliate abundance increased towards the end of the sampling period as the phytoplankton biomass decreased, no clear relationship was apparent. Estimates of total ciliate biomass at the surface and averaged over the water column were 0.01–0.06 mg C l^{-1} and 0.02–0.03 mg C l^{-1} respectively. Proportionately this compared to 1–14% of the total phytoplankton biomass. Within the zooplankton very low numbers of copepods were observed though there was an abundance of larger species (especially salps and medusae).

Phytoplankton monitoring: May 1989–July 1990

The spatial distribution of species showed a high degree of variability between sites (Fig. 15A–15B), however, the sampling method was a rapid and economical strategy that provided a good general picture of species succession despite this. Diatom dominated populations were always more homogenously distributed than flagellate dominated assemblages. Although maximum cell numbers of stratified flagellate communities were


Time of day
01·00 04·00 07·00 10·30 13·00 16·00 19·00 22·00
A
0
5
10
15
20
25
0 2 4 6 x10^6 Cells l^-1 Heterosigma akashiwo
B
0
5
10
15
20
25
0 1 2 x10^6 Cells l^-1 Glenodinium danicum
Depth (m)
C
0
5
10
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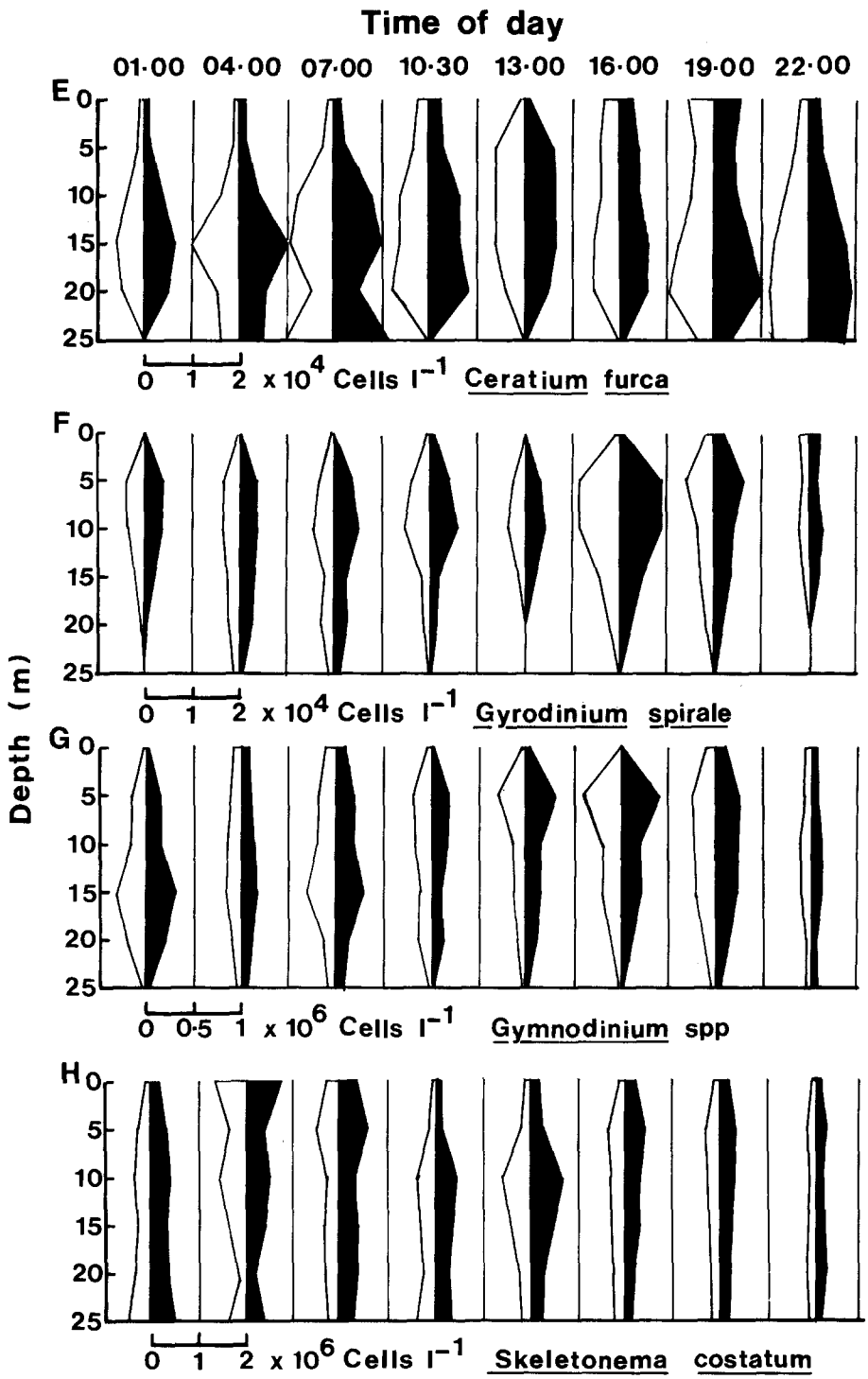


Fig. 4. Vertical distribution of phytoplankton species (cells l^{-1}) over the diurnal sampling period at Site 1, Big Glory Bay, 13 January 1989. The time of day is New Zealand summer daylight saving time. Sunrise 0510 h, sunset 2042 h. The abundance scales refer to the shaded areas only. Fig. 4A. *Heterosigma akashiwo;* Fig. 4B. *Glenodinium danicum;* Fig. 4C. *Polykrikos schwartzii;* Fig. 4D. *Dinophysis acuta;* Fig. 4E. *Ceratium furca;* Fig. 4F. *Gyrodinium spirale;* Fig. 4G. *Gymnodinium* spp.; Fig. 4H. *Skeletonema costatum.*

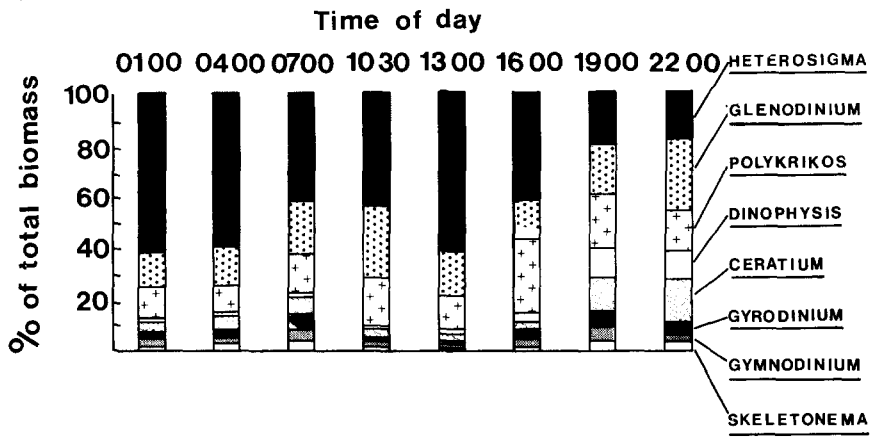


Fig. 5. The percentage contribution of the major species to the total phytoplankton biomass within the water column at Site 1, Big Glory Bay 13 January 1989.

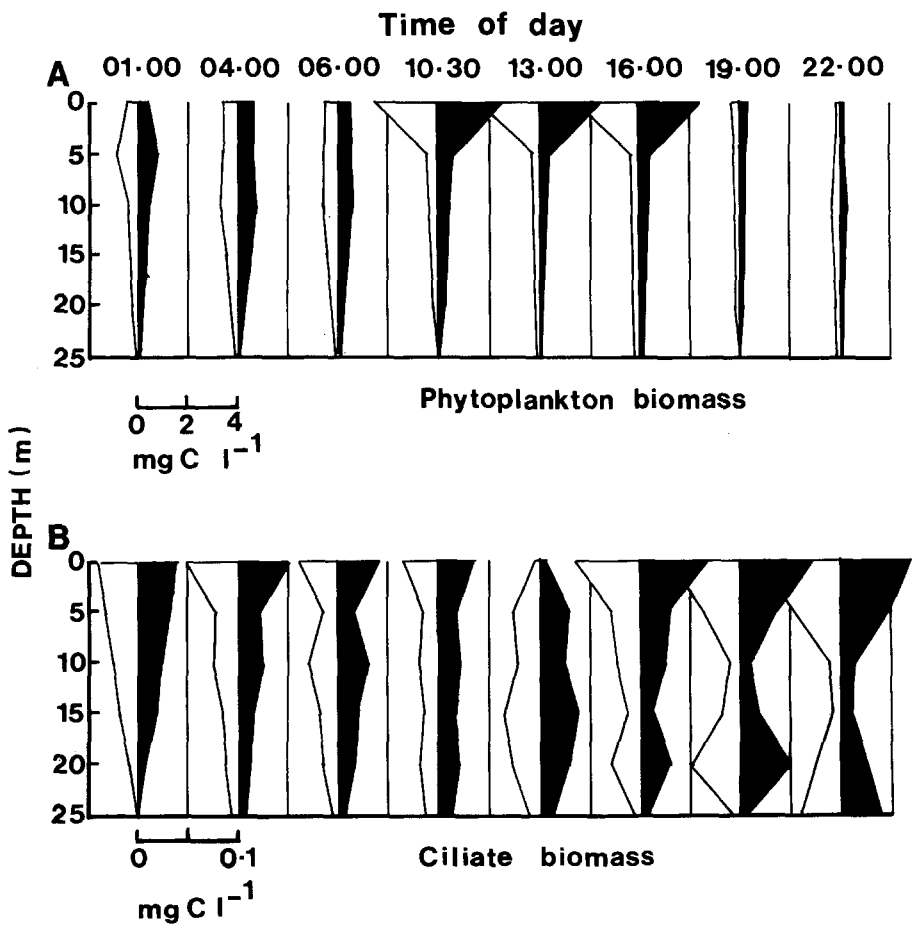
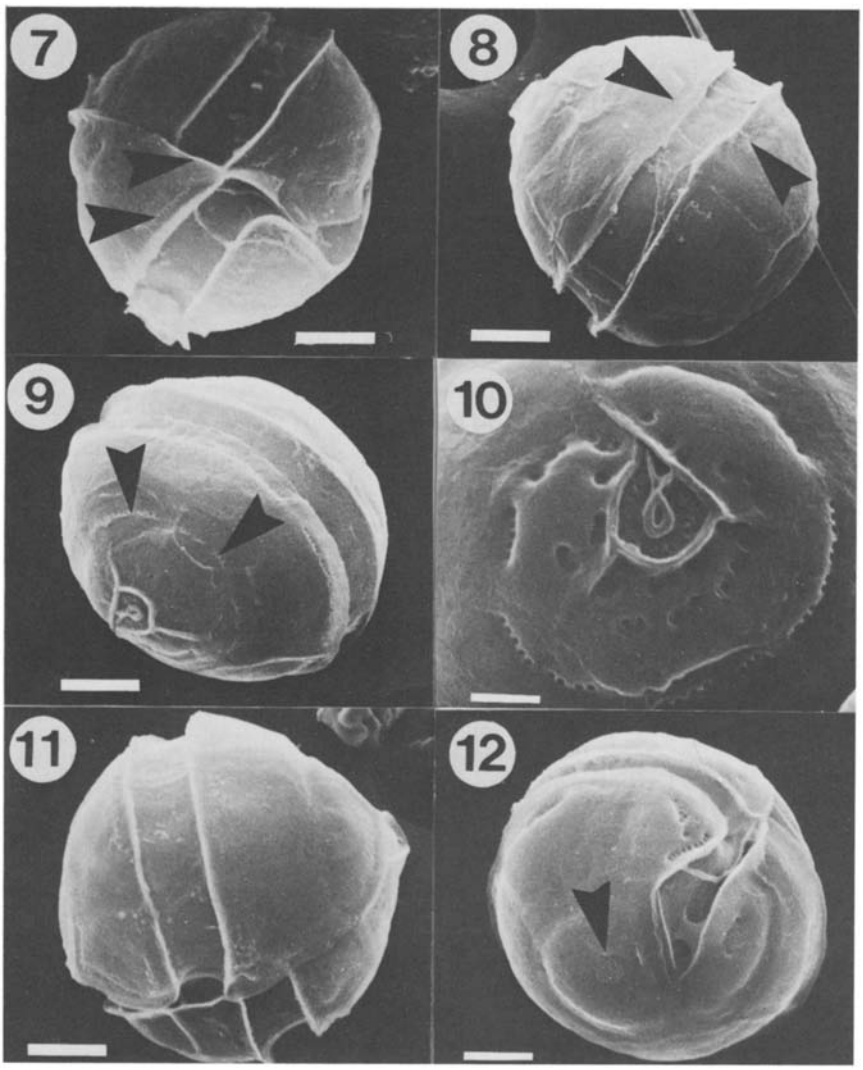


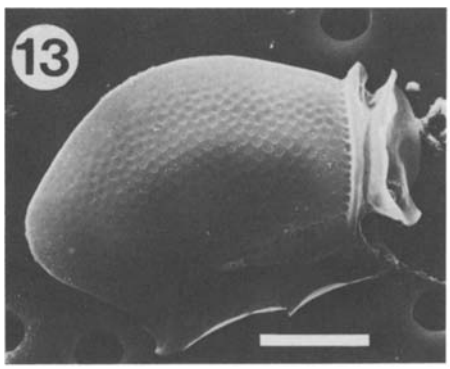
Fig. 6. Phytoplankton and microzooplankton (ciliate) biomass estimates (mg C l^{-1}) at Site 1. Big Glory Bay 13 January 1989. The time of day is New Zealand summer daylight saving time. Sunrise 0510 h, sunset 2042 h.

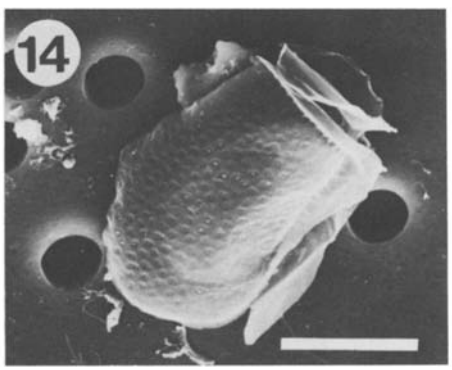


Figs. 7–12. Glenodinium danicum, Big Glory 13 January 1989. Fig. 7 Ventral view. The arrows indicate the epithecal plate margin overlap, and the lines of pores parallel to the girdle. Scale bar = 4 μm. Fig. 8 Dorsal view. The arrows indicate the lines of pores. Scale bar = 4 μm. Fig. 9 Oblique apical view of the dorsal side showing the prominent apical pore complex. The arrows indicate the circle of pores. Scale bar = 4 μm. Fig. 10 Close up view of apical pore complex. Scale bar = 2 μm. Fig. 11 Oblique view of right hand side of theca. Scale bar = 4 μm. Fig. 12 Antapical view of theca. The arrow indicates the hexagonal perforated scar. Scale bar = 4 μm.

usually considerably underestimated, the examination of the integrated samples was a sufficiently sensitive technique for detecting the development of blooms. Examination of surface, mid water and near bottom samples provided some information regarding the degree of vertical stratification of phytoplankton.

Alternating dominance by flagellate versus diatom dominated populations were evident during the monitoring period (Fig. 15). Several months of low phytoplankton biomass during the winter of 1989 were followed by a spring bloom (dominated by *Chaetoceros* spp., *Eucampia zoodiacus* and *Leptocylindricus* sp.) that peaked in late September (Fig. 15E). Thereafter the diatom biomass declined through late spring and early summer as flagellate abundance increased. *C. furca* served as a useful indicator of conditions





Figs. 13–14. Dinophysis spp. Big Glory 13 January 1989. Fig. 13 *Dinophysis acuta*. Scale bar = 20 μm. Fig. 14 *Dinophysis* cf *dens* Scale bar = 20 μm.

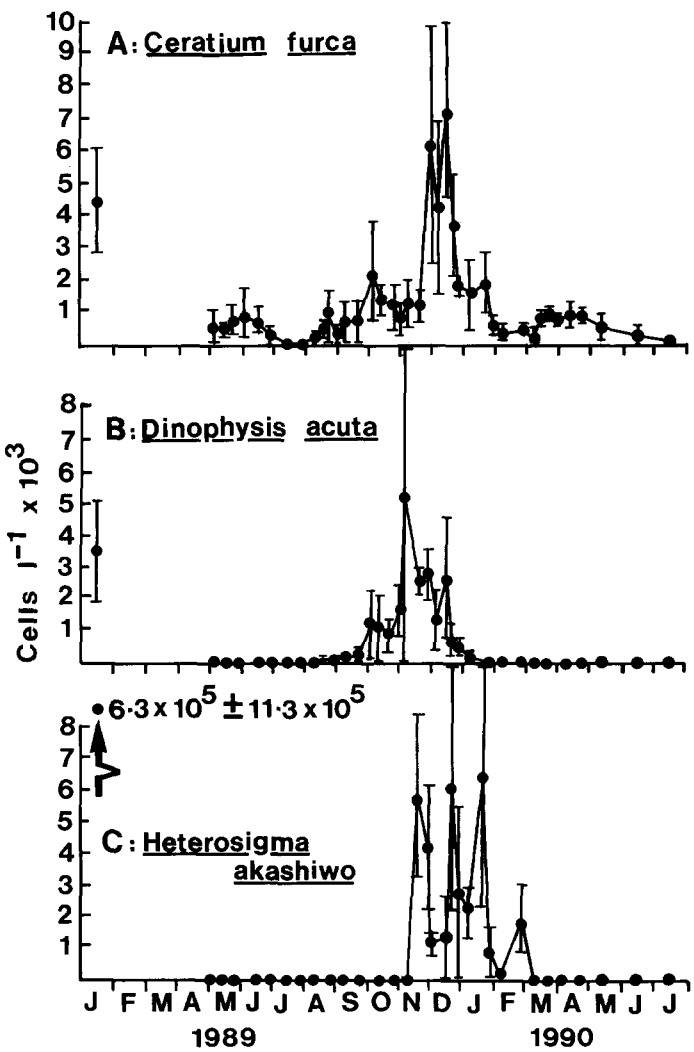


Fig. 15.

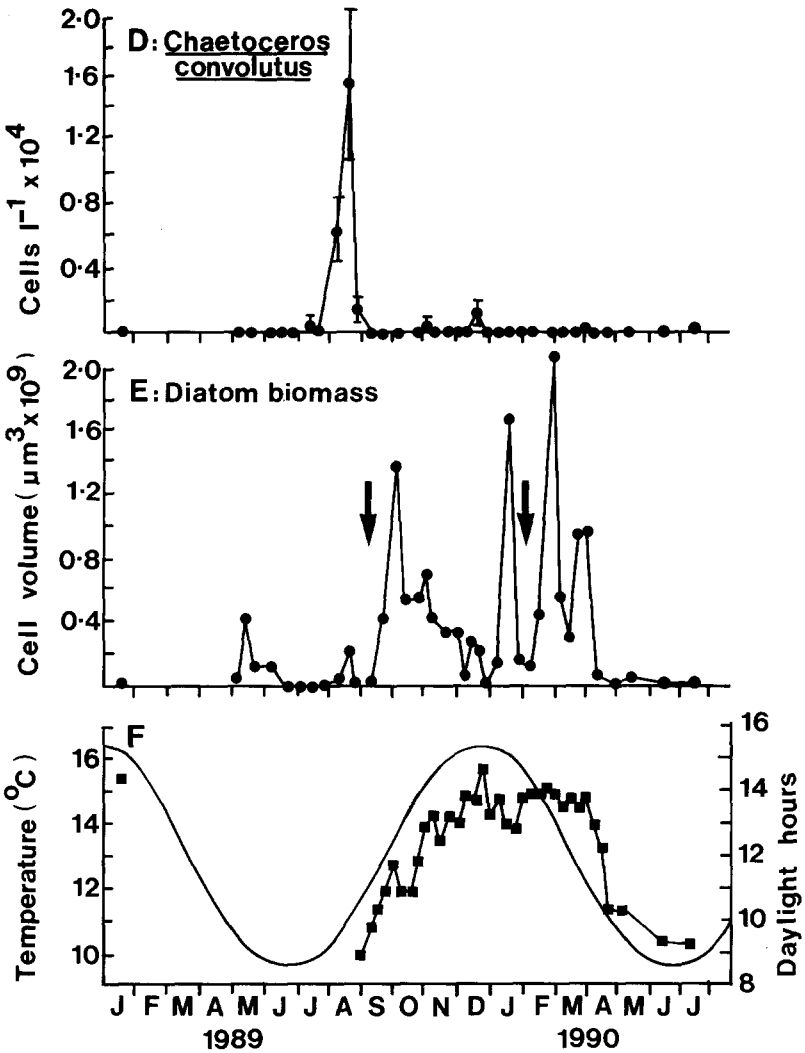


Fig. 15. The abundance of selected phytoplankton groups and species at Sites 1–4 Big Glory Bay 6 May 1989–23 July 1990. In Figs. 15A–15D the points are the mean values (cells $l^{-1} \times 10^3$) averaged over the four sites. The error bars represent the standard deviation around the mean. In Fig. 15E the points are the calculated total diatom cell volume ($\mu m^3 \times 10^9$) at Site 1 only. The arrows indicate *M. rubrum* bloom periods. Fig. 15F illustrates the day length periods at the latitude of Stewart Island and 3 m and 10 m averages sea water temperatures.

most suitable for the proliferation of other flagellates. A peak in the abundance of *C. furca* (Fig. 15A) during November and December 1989 (late spring/early summer) coincided with the appearance of low numbers ($< 1.3 \times 10^4$ cells l^{-1}) of *H. akashiwo* (Fig. 15C) and was immediately preceded by and co-occurred with the development of an abundant *Dinophysis acuta* community (Fig. 15B). These species all showed some degree of vertical stratification. In the case of *H. akashiwo*, cell numbers were highest in surface samples whereas with *C. furca* and *D. acuta* highest numbers were usually found in mid water (15 m) samples (maximum cell numbers of 1.9×10^4 and 3.8×10^4 cells l^{-1} respectively). The appearance of *D. acuta* coincided with the appearance of the smaller *D. dens*-like morphotype. Except when numbers were very low (< 100 cells l^{-1}) these small cells were always present in samples containing *D. acuta*, though

the proportion (16–45% total cell numbers) varied. Both forms disappeared simultaneously from the plankton in mid January 1990.

An abrupt change in species composition occurred with the development of a diatom bloom (*Lauderia* sp., *Thallasiosira hyalina*) during mid summer, (January) 1990 (Fig. 15E). Following a period of heavy rainfall this was replaced by an intense bloom of the photosynthetic ciliate *Mesodinium rubrum* during which vivid red surface waters were visible throughout the bay and cell concentrations up to 1.6×10^6 cells l^{-1} were observed. During the latter stages of the *M. rubrum* bloom it co-occurred with high numbers ($>4.0 \times 10^5$ cells l^{-1}) of the small dinoflagellate *Prorocentrum triestinum* which persisted for some time after the declined of *M. rubrum* and itself lent a red/brown hue to surface waters. No noxious effect on fish or shellfish by these species were observed. The remainder of the summer through until early autumn (March) was dominated by a succession of diatom species (*Chaetoceros* spp., *Lauderia* sp., *Leptocylindricus* spp, *Rhizosolenia* spp.), after which the phytoplankton biomass declined substantially (Fig. 15E).

Chaetoceros convolutus (Fig. 16) appeared in the plankton several times during the monitoring period with a peak in abundance during August (late winter), 1989, preceding the main spring diatom bloom (Fig. 15D). Cell numbers at this time ranged from $1.0–2.0 \times 10^4$ cells l^{-1} and were uniformly distributed throughout the water column. Chains of up to 14 cells were observed, though pairs and single cells were common, and detached setae were also present in the samples. The cells possessed large robust setae (2.5×150.0 μm) containing many chloroplasts and with a covering of small spines. *C. convolutus* comprised about 20% of the *Chaetoceros* spp. population but the total diatom biomass was low compared to that present during subsequent bloom periods (Fig. 15E). Low numbers (5.0×10^3 cells l^{-1}) of *C. convolutus* also occurred during December (summer) within a population dominated by *Nitzschia* sp. also at a time when the total diatom biomass was again comparatively low. Despite the appearance of this potential nuisance species no unusual salmon mortalities occurred.

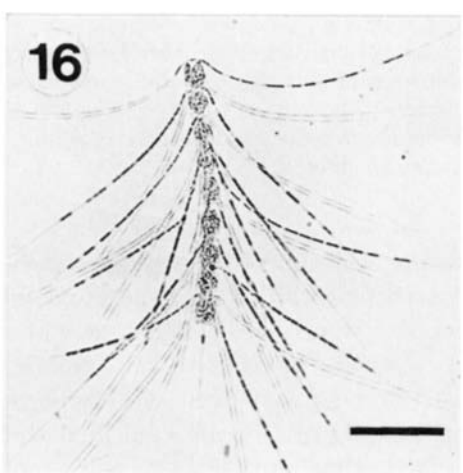


Fig. 16. Chaetoceros convolutus. Big Glory Bay, 23 August 1989. Light micrograph of a chain of cells. The scale bar = 60 μm.

The climate

The early to mid summer intervals (Dec–Jan) of 1988/89 were basically different in terms of the weather patterns that prevailed during these periods (Fig. 17). All measurements of air temperature (dry bulb, wet bulb, maximum, minimum; New Zealand Meteorological Service records) showed that these were consistently higher (1–2 °C) during December and January 1988/89, than during the same period the succeeding summer. The higher air temperatures were result of extended periods of light winds primarily from the easterly quarter from mid December, 1988. Conversely although winds were relatively light during early December, 1989, these were mainly westerlies and from the 20 December became very persistent and of increasing strength. During the first two weeks of January 1989, while the flagellate bloom was developing, Big Glory Bay experienced several episodes of intense rainfall under conditions of light to moderate winds. During January, 1990, on the

other hand, periods of high rainfall were accompanied by gale force westerly winds (Fig. 17B).

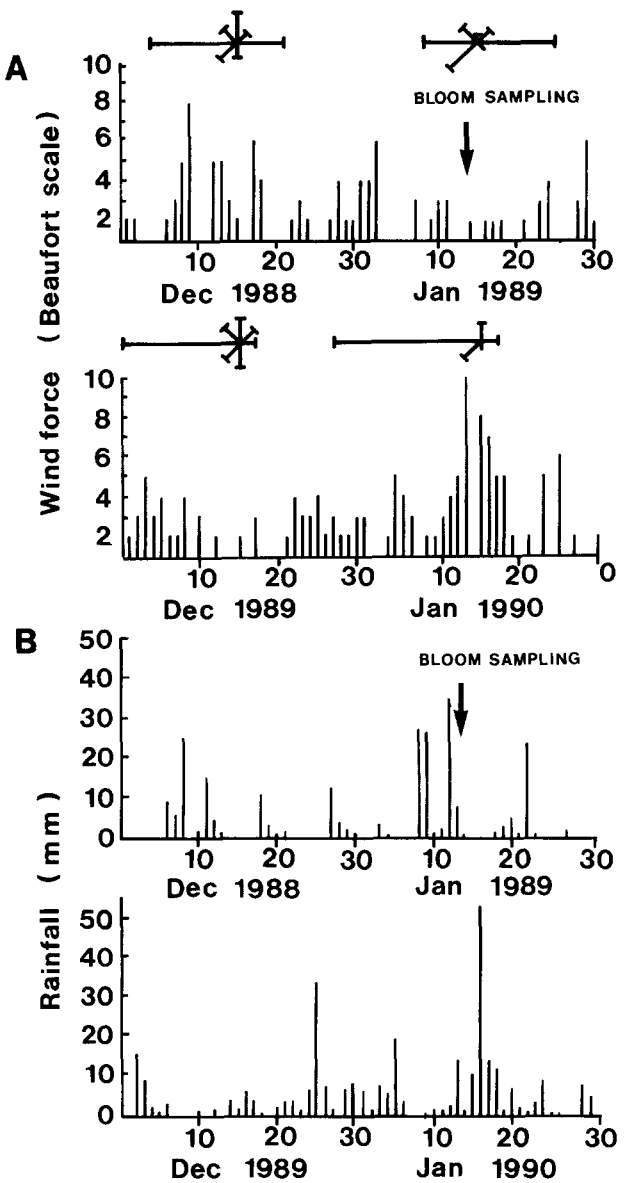


Fig. 17. Climate records for December and January 1988/89 and 1989/90, Halfmoon Bay, Stewart Island; Fig. 17A Rainfall (mm); Fig. 7B Surface wind force (Beaufort scale) and direction. The direction is represented by the bars. These are proportional to number of days in each month that the wind blew from the various compass directions.

Discussion

Mass mortalities of sea cage reared fish due to blooms of raphidophycean flagellates of the genera *Chattonella* and *Heterosigma* have been a chronic problem for the Japanese fish farming industry for many years (Okaichi, 1989). With the establishment of the sea cage rearing of fish (especially salmonids) elsewhere in the world, the same problem has arisen and major blooms, resulting in substantial losses have occurred in Canada, the USA and Chile (Rensel *et al.*, 1989; Taylor, 1989). Prior to the January 1989 bloom in Big Glory Bay *Heterosigma akashiwo* had not been documented in New Zealand coastal waters though since that time low numbers have been observed at a variety of locations around the coast (MacKenzie, unpublished data). At these locations *H. akashiwo* has mainly appeared during mid summer though occasionally a few cells have been observed at other times. The relatively small cell size of *H. akashiwo*, their usually low numbers, poor preservation qualities and the few detailed studies on the phytoplankton in New Zealand coastal waters are probably the reasons why it has not been recorded previously.

Though *H. akashiwo* was associated with other prominent flagellate species in the bloom because the observed mass salmon mortalities within water coincided with very high *H. akashiwo* cell numbers it was clearly the organism responsible for the lethal effect on the caged fish. Little is known of the mechanism by which *H. akashiwo* has this lethal effect though it is presumably similar to that exerted by related species of the genus *Chattonella* in which the production of bioactive agents (free polyunsaturated fatty acids and super oxide; Okaichi *et al.*, 1989) which cause abnormal secretion of mucous and destruction of the gill lamellae are believed to be involved. The mass mortalities within the Big Glory Bay seacages were consistent with this mechanism. They occurred rapidly with the production of copious quantities of mucilage from the gills and signs of asphyxiation (gasping) and disorientation (non avoidance of obstacles) although dissolved oxygen concentrations in discoloured waters were

high. Some fish were able to recover from these symptoms and fish of different age and sex differently affected.

Despite the mass mortalities within the sea cages, there was little evidence of effects on other flora and fauna. Scuba and shoreline observations revealed an abundance of fish (including wild salmon) and healthy invertebrate life; shellfish seemed to be unaffected. It appeared that these species could either avoid dense concentrations of the algae or were adapted to resist their effects. Throughout the duration of the bloom there were only rare accounts of the death of other species besides salmon and without the presence of the sea cages the event would probably have gone unnoticed.

The sporadic nature of the fish kills occurring at different locations during the bloom and the data presented here suggests *H. akashiwo* was very patchily distributed within the bay. *H. akashiwo* was most abundant within near surface lower salinity water and exhibited a diurnal vertical migration behaviour pattern that led to dense concentrations of cells rising through the sea cages. Similar diel vertical migration rhythms of *H. akashiwo* populations have frequently been observed under field and laboratory conditions. Watanabe *et al.* (1988) and Yamochi and Abe (1984) have described the ecological significance of these rhythms in natural populations attributing these movements to a strategy to optimise nutrient uptake in deeper nutrient enriched layers and photosynthesis near the surface. Salinity, dissolved oxygen and temperature profiles (15 °C @ Om, 15.5 °C @ 25 m; F.H. Chang pers. comm.) measured during the bloom revealed that although the physical impediment to mixing of the water column was not extreme, conditions were such that a stable stratified water column existed at this time.

It is conceivable that the high dissolved iron concentrations in the humic acid laden freshwater inflows of the bay may have played a significant role in enhancing the dominance of flagellates during the bloom (e.g. cf. Graneli and Moreira, 1990). Yamochi (1989) has demonstrated the importance of chelated iron as a crucial factor in the initiation of *H. akashiwo* red tide blooms in Japan. Likewise the low numbers of copepods in the plankton during the bloom is interesting in the light of a recent study (Uye and Takamatsu, 1990) that has demonstrated a chemically mediated rejection of *H. akashiwo* as a food source by copepods suggesting that this may be an important factor in the development of blooms.

The most notable feature of the phytoplankton population apart from *H. akashiwo* was the diversity and abundance of the dinoflagellate community which in many individual samples dominated the biomass. Because many of these species (e.g. *D. acuta*) probably have relatively long generation times, conditions conducive to their proliferation must have been in existence for quite some time prior to the *H. akashiwo* mediated fish kills occurring. It is hoped that these dinoflagellates will serve as useful indicator species for the development of potentially hazardous conditions in the bay.

The observation of the small spherical dinoflagellate ascribed to *Glenodinium danicum* in the Big Glory Bay plankton is a new taxonomic record within New Zealand coastal waters, however its small size and inconspicuous appearance makes identification difficult and it may be common. Although under SEM examination the cells have a number of distinctive features (e.g. the apical pore complex), little is revealed of the thecal plate structure and as a consequence the species has yet to be properly described (J.D. Dodge pers. comm.). The absence of PSP symptoms in mice inoculated with aqueous extracts prepared from shellfish exposed to high cell densities of the *G. danicum* presumably indicates that this organism does not have toxigenic properties. The cause of the slow mice deaths when inoculated with the oyster extracts is unknown. Though the symptoms were similar to those attributed to zinc toxicity (McCulloch *et al.*, 1989), the levels of zinc within the tissues (40.7 μg g wet Wt.$^{-1}$) were an order of magnitude below that of the reported zinc toxicity threshold (900 μg g wet Wt.$^{-1}$).

A variety of species of the genus *Dinophysis* (Ehrenberg) are common in New Zealand waters (Burns & Mitchell, 1982), of which *D. acuminata*

and *D. acuta* are the most frequently encountered. The cell numbers of *D. acuta* observed during the summer 88/89 bloom and the peak in abundance (Spring, 1989) during the subsequent monitoring period are the highest so far recorded in New Zealand. The marginal toxicity of lipid extracts of the mussels may have been an indication of DSP toxicity within the shellfish due to the relatively high *D. acuta* cell densities to which they were exposed. This species has been shown to be responsible for outbreaks of DSP intoxication due to the production of okadaic acid and *Dinophysis* toxin 1 (DTX1) (Edler & Hageltorn, 1989; Lee *et al.*, 1989). These results illustrate the difficulty in relating phytoplankton cell numbers to shellfish toxicity. The low degree of toxicity could be due to the low specific toxicity of local strains, the dilution effect caused by the abundance of non toxic species in the population (Sampayo *et al.*, 1989) or a possible indirect effect caused by *H. akashiwo* on the feeding activity of the mussels (Ward & Targett, 1989).

The appearance of *Chaetoceros convolutus* in the Big Glory Bay plankton constitutes a new record within New Zealand coastal waters. *C. convolutus* and the related species *C. concaricorne* have been implicated in considerable economic losses due to mass mortalities of sea cage reared solmonids on the West Coast of the USA and Canada though estimates of the cell numbers resulting in fish kills vary widely ($7.0 \times 10^3 - 1.8 \times 10^7$; Rensel *et al.*, 1989; Taylor F.J.R., pers. comm.). No salmon mortalities were observed during the period of maximum abundance (2.0×10^4 cells l^{-1}) of *C. convolutus* in Big Glory Bay. It is believed (Bell, 1961) that it is the apically orientated barbs on the setae of *C. convolutus* (and related species) that are the primary reason why these became lodged within fish gills resulting in mortalities. However, most specimens of *C. convolutus* that were examined here possessed very inconspicuous barbs that were only visible after SEM examination. It is unknown whether the elaboration of the setae barbs varies according to temporal changes in environmental conditions; if it does the noxious character of this species may vary from time to time.

Big Glory Bay is a large body of water with only a narrow avenue for exchange with more oceanic waters and it is known that the strength and persistance of westerly winds has a important effect on the residence time of sea waters within the bay. Rutherford *et al.* (1988) found that under conditions of light winds little of the water leaving the bay on the ebb tide escaped completely, most returned on the flood tide. Under conditions of moderate to strong westerlies, however, a strong surface flow of water left the bay and a deep, compensating, counter current developed that persisted throughout the tidal cycle. These effects resulted in estimated residence times of 10–13 days under light winds, to 7–9 days during periods of moderate westerly winds. The period from 2–13 January, 1989, during which the bloom developed and fish kills occurred was characterised by warm air and sea water temperatures, long daylight hours, light to moderate winds from an easterly quarter and an episode of intense rainfall. These conditions would result in runoff from the catchment being retained within the bay resulting in fertilization of the water and contributing towards the establishment of a stable stratified water column. These conditions were clearly suitable for the development of a flagellate dominated population. Conversely the same period the following year was characterised by cool air and sea water temperatures, the same day-length (but probably lower solar radiation), and moderate to strong winds from the west accompanied by intense cool rainfall. These conditions would have induced current flows (Rutherford *et al.*, 1988) that would have reduced the retention time, mixed and flushed out of the bay runoff from the catchment, promoted turbulence and prevented the establishment of a stratified water column. These conditions may have prevented the repetition of the flagellate bloom of the previous summer by inducing the development of a diatom dominated population instead.

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