# Seasonal Variation of Nearshore Antarctic Microalgae and Environmental Factors in Marian Cove, King George Island, 1996

## Sung-Ho Kang*, Jae-Shin Kang, Kyung-Ho Chung, Mi-Young Lee, Bang-Yong Lee, Hosung Chung, Yeadong Kim, and Dong-Yup Kim

*Polar Research Center, Korea Ocean Research & Development Institute, Ansan PO Box 29, Seoul 425-600, Korea*

ABSTRACT. Nearshore microalgal assemblages and physicochemical factors (meteorological parameters, sea water properties, and macronutrients) have been measured daily from January to December 1996 at a nearshore shallow-water in Marian Cove, King George Island in the maritime Antarctic. Microalgal biomass (size-fractionated at 20 $\mu$m) and the environmental factors all exhibited clear seasonal variability. Seasonal variation of nearshore microalgal biomass was affected by the combination of the environmental factors, and increase of microalgal biomass during austral summer affected on bacteria and macronutrients. Chlorophyll $a$ determinations demonstrated a marked seasonality in microalgal biomass. The summer peak of microplankton chlorophyll was dominated by large diatoms. Peak concentrations of pico- and nanoplankton chlorophyll, predominantly from flagellates, were much lower but the bloom lasted longer and winter biomass was higher than in the microplankton. The summer increases of nearshore planktonic microalgae have not been the result of *in situ* production and growth of phytoplankton, but attributed to resuspension of benthic microalgae by wind and tidal currents. The resuspension seems to be an important mechanism to affect the diversity of nearshore phytoplankton assemblages. The tychoplanktonic forms from the intertidal and subtidal diatom communities seem to contribute substantially to important carbon source to sustain the nearshore ecosystem of Marian Cove.

*Key Words: Antarctic, microalgae, seasonal variation*

## Introduction

To understand the response of a marine ecosystem to any environmental change it is necessary to determine the extent to which ecological variations are driven by environmental fluctuations (Murphy *et al.* 1995). As a first step in investigating the response of marine ecosystems to environmental change we need to characterize the variability spectrum of the environment. Any long-term environmental change may be resolved with investigation of suitable time series for determining the natural variability of the marine ecosystem (Clarke *et al.* 1988; Clarke and Leakey 1996; Whitehouse *et al.*

1996).

Antarctic nearshore ecosystem has been threatened by environmental changes such as ozone depletion, global warming, and anthropogenic pollution. Microalgae in nearshore areas can be used as an important biological parameter to detect and monitor the environmental change and pollution. Antarctic microalgae have been adapted in low light and temperature. Thus small-scale changes in their environment such as UV radiation and temperature can result in affecting structure of microalgae (Karentz *et al.* 1991). Microalgae are major primary producer to sustain Antarctic marine ecosystem, thus their change means change of whole marine ecosystem (Davidson and Marchant 1992).

The food chains which sustain components of the Antarctic marine ecosystem ultimately depend upon

autotrophic production. The distribution of biomass and rates of production are highly seasonal. Over the past two decades, most of the research on microalgal populations in the Antarctic regions has been constrained for logistic or financial reasons to the open-water summer months. The interpretation of population and food web dynamics may be biased if the seasonal component of biological and physicochemical factors are neglected (Rivkin 1991; Barnes and Clarke 1994; Delille et al. 1996; Clarke and Leakey 1996).

Microalgae in Antarctic nearshore areas have been studied mainly during austral summers (Dayton et al. 1986; Perrin et al. 1987; Klöser et al. 1993; Brandini and Rebello 1994; Ahn et al. 1997). Relatively little attention has been paid to seasonal variation of nearshore microalgae in relation to environmental factors which affect on structure and function of microalgal assemblages (Krebs 1983; Clarke et al. 1988; Clarke and Leaky 1996; Kopczynska 1996; Moline and Prézelin 1996; Schloss et al. 1997).

King Sejong Station is good place for long-term observation of microalgae because it is located at nearshore area in Marine Cove. Marian Cove is not affected directly from waters from the Bransfield Strait and the southern Drake Passage (Chang et al. 1990). Locally forming effects such as tide, ice berg movement, wind are more important environmental factors for determining structure of microalgae in this area. During summer time melt of sea ice, snow, and glacier which makes surface water column fresher (hence stable) and wind which causes water column unstable have been thought to major factors on growth of phytoplankton in nearshore waters (Krebs 1983; Klöser et al. 1993, 1994; Brandini and Rebello 1994). Krebs (1983) observed seasonal variation of phytoplankton near Palmer Station in Anvers Islands. He found that physical factors such as wind and tide are more important to affect structure of phytoplankton than biological factor such as grazing pressure. Structural patterns of microalgae such as succession, species composition, and biomass in relation to the seasonal variations of the physicochemical factors may be used as baseline data to understand long-term variations of environ-

ment change.

In this paper, data collected over a 366 day period, from the beginning of January through the end of December 1996, was used to 1) describe the seasonal cycles of nearshore microalgal assemblages (size-fractionated at <20 μm, pico- and nanoplankton chlorophyll a and >20 μm, microplankton chlorophyll a) and physicochemical factors such as wind velocity, wind direction, air temperature, barometric pressure, solar radiation, UV radiation, water temperature, salinity, density, and nutrients such as ammonia, nitrate, phosphate, and silicate, 2) understand relationships between biological components such as nearshore bacteria and microalgae and the physicochemical factors, 3) understand importance of microalgae as important carbon source to sustain nearshore ecosystem.

## Materials and Methods

### Study site

This study was undertaken in Marian Cove and the eastern part of Maxwell Bay (Fig. 1), close to the Korean Ocean Research and Development Institute (KORDI) research station (King Sejong) at King George Island, South Shetland Islands (62°13′ S, 58°47′ W). Maxwell Bay is a typical U-shaped fjord characterized by a deep sill (Choi et al. 1990) and a relatively small amount of freshwater input (Chang et al. 1990). The bay is about 18 km long and 6 to 14 km wide, and surrounded by King George Island and Nelson Island which belong to South Shetland Islands. To the northwestern end of the bay, between King George and Nelson Islands, lies Fildes Strait which is 400-800 m wide and connected to Drake Passage. The mouth of the bay is open to Bransfield Strait. Water depth gently increases from the coastline to 200 m depth, but sharply increase from 200 m to 400 m. The central part of the bay is relatively flat, ranging from 400 m to 500 m in depth. King George Island is in the maritime Antarctic and its position close to the northwestern edge of Weddell/Scotia Confluence region means that there are large interannual variations superim-
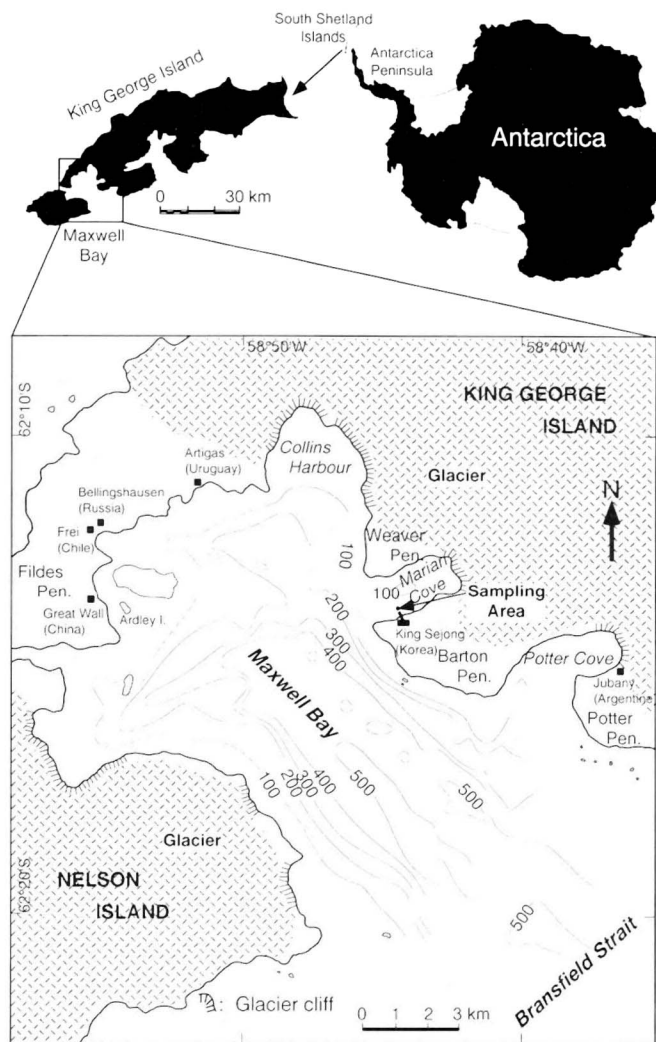
**Fig. 1**. Location of the study area in Marian Cove, King George Island.

posed on the seasonal cycle of wind speed, wind direction, seawater temperature, sea-ice cover, and microalgal biomass (Murphy *et al.* 1995). At this latitude, daylength varies from a summer maximum of 19 h in December to a winter minimum of 5 h in June.

Marian Cove is a tributary inlet of Maxwell Bay, one of the two big fjords at King George Island. The bottom of Marian Cove and the adjacent open coasts consist of hard substrata (boulders, stones, pebbles, gravel, sand) with a macroalgal vegetation of changing density (Chung *et al.* 1991, 1994). Bottom sediments are poorly sorted and mixed with a considerable amount of terrigenous sand and gravel (Ahn and Kang 1991). The cove is divided into mouth and inner part. The mouth area is not deeper than about 60 m and barred by a sill of about 20 m depth in

southwestern part of the cove (Kim and Baek 1995). The bottom of inner part lies between 100 m and 130 m. Glacier cliff reaches the cove in the east.

### Sampling and analysis

This study was conducted from 1 January to 31 December 1996 at a fixed station in front of King Sejong Station. At this station the water depth is about 10 m and the water column is well mixed by wind and tidal currents. Water samples (0.5 m) were taken with a PVC bottle, and water temperature and salinity were measured with Sea-Bird 911 plus CTD. Water samples were transferred to the research station immediately after collection and were used to measure chlorophyll *a* concentration, microscopic analysis of microalgae, protozoa, and bacteria, particulate matter, and macronutrients.

*Chlorophyll a.* Turner Design field fluorometer (Model 10-005R) was used for *in vivo* chlorophyll *a* (chl-*a*) measurement in sea water. The *in vivo* fluorescence values were calibrated with absolute chl-*a* values measured with spectrophotometer. The linear relation (y=0.81x-0.11, n=55) between *in vivo* and absolute values was used to measure chl-*a* concentrations ($\mu$g chl-*a* l$^{-1}$). Size-fractionated study of chl-*a* was conducted with 20-$\mu$m nylon mesh. Cells passed the net were considered as pico- and nanoplankton chlorophyll (<20 $\mu$m cells passing the 20-$\mu$m mostly flagellates, small diatoms, very small cells, cyanobacteria, and cell fragments) and rest cells as microplankton chlorophyll (>20 $\mu$m cells retained by the 20-$\mu$m nylon mesh essentially colonial forms, chain-forming species and large single diatoms).

*Particulate matter.* One liter of sea water was filtered on pre-dried and weighed GF/F filter, and the filter was dried in 60°C drying oven for 24 h and weighed. Total particulate matter was value of the filtered GF/F minus the pre-dried and weighed GF/F filter.

*Macronutrients.* Two 20 ml vials were stored in a freezer (-20°C) for macronutrient measurement. Macronutrients ($NO_3$, $PO_4$, $SiO_2$) and ammonia were analyzed using an autoanalyzer (LACHAT QuickChem AE) and standard seawater methods

(Grasshoff *et al.* 1983).

*Bacteria.* Glutaraldehyde-fixed samples were DAPI stained, filtered onto 0.2-$\mu$m polycarbonate filters and counted in UV excitation light by epifluorescent microscopy (Porter and Feig 1980). At least 300 cells per slide were counted. A cell carbon content of 20 fg C cell$^{-1}$ was assumed for calculating the carbon production (Lee and Fuhrman 1987).

*Weather data.* Global solar radiation (285-3000 nm), infrared radiation (3000-50000 nm), UV radiation (290-385 nm), UV-B radiation (295-320 nm), air temperature, barometric pressure, wind speed, and wind direction were measured at automatic weather station in King Sejong.

*Statistical analysis.* The SYSTAT 5 statistics package for the Macintosh was used to see the correlations between biological and physicochemical parameters (Pearson correlations) and to extract descriptive summary statistics.

## Results and Discussion

Seawater chlorophyll *a* concentration (size-fractionated at 20 $\mu$m) and physicochemical and environmental variables have been measured daily from January to December 1996 at a nearshore shallow-water station in Marian Cove, King George Island in the maritime Antarctic. This study shows the complex nature of the Antarctic nearshore marine ecosystem and emphasizes the need for year-round meteorological, oceanographic, and physicochemical studies in the highly seasonal Antarctic marine environment.

### Seasonal variation of solar radiation

The maximum day length in Marian Cove in 1996 was about 19 h and was attained in late December. The minimum number of daylight hours, approximately 5 h, occurred in late June. Solar radiation was clearly changed with season (Fig. 2A). Most of radiation was concentrated between October and March. Solar radiation started to decrease from April, showed lowest during winter (May-August), and increased from September (Fig. 3A). Maximum

monthly mean incident global solar radiation occurred in December (15485 kJ m$^{-2}$ day$^{-1}$) and the minimum in June (677 kJ m$^{-2}$ day$^{-1}$). Major factor to induce seasonal variation of microalgae is solar radiation (Krebs 1983). During winter the radiation is not enough to grow microalgal cells. When austral spring comes the solar radiation increases and sea ice, snow, and glacier starts to melts and water temperature starts to increase. It results in forming low density surface water. Microalgae survived in the ice and winter water are inoculated with melting of ice or resuspended from sediments, and selectively fast growing species become dominant species in this area (Krebs 1983; Clarke and Leakey 1996).

Total UV radiation showed similar pattern with solar radiation (Fig. 2C). Due to the ozone depletion starting from October, increase of biologically harmful UV radiation was observed. The seasonal variation in the UV-B estimates is shown in Fig. 3D. Monthly means of UV-B ranged from 0.03 kJ m$^{-2}$ day$^{-1}$ in June to 6.26 kJ m$^{-2}$ day$^{-1}$ in November. After February UV-B declined, reaching levels below 1 kJ m$^{-2}$ day$^{-1}$ from April to August. Winter levels were lower, with a minimum of 0.03 kJ m$^{-2}$ day$^{-1}$ in June. There was a slight increase in monthly mean of UV-B during September (1.33 kJ m$^{-2}$ day$^{-1}$). The UV-B then started to increase in October (2.93 kJ m$^{-2}$ day$^{-1}$), and abruptly increased in November (6.26 kJ m$^{-2}$ day$^{-1}$), continued until December (6.13 kJ m$^{-2}$ day$^{-1}$).

### Air temperature

The study period was "warm year" showing annual mean air temperature (-0.7°C) which was about 1.3°C higher than mean of last 8 years from 1988 to 1995 (avg. -2.0°C) measured at King Sejong Station (KORDI, 1997a). It was about 2.3°C higher than the coldest year of 1991 (avg. -3.0°C). Interannual variations of air temperatures seem to be varied according to dominance of wind directions. Warmer years (annual mean air temperature of >1.0°C) were usually associated with northerly wind dominated years (1989, 1993, and 1996), whereas colder years were coincided with southerly wind dominated years (1988, 1990-92, 1994-95) during winter time (KORDI, 1997b).

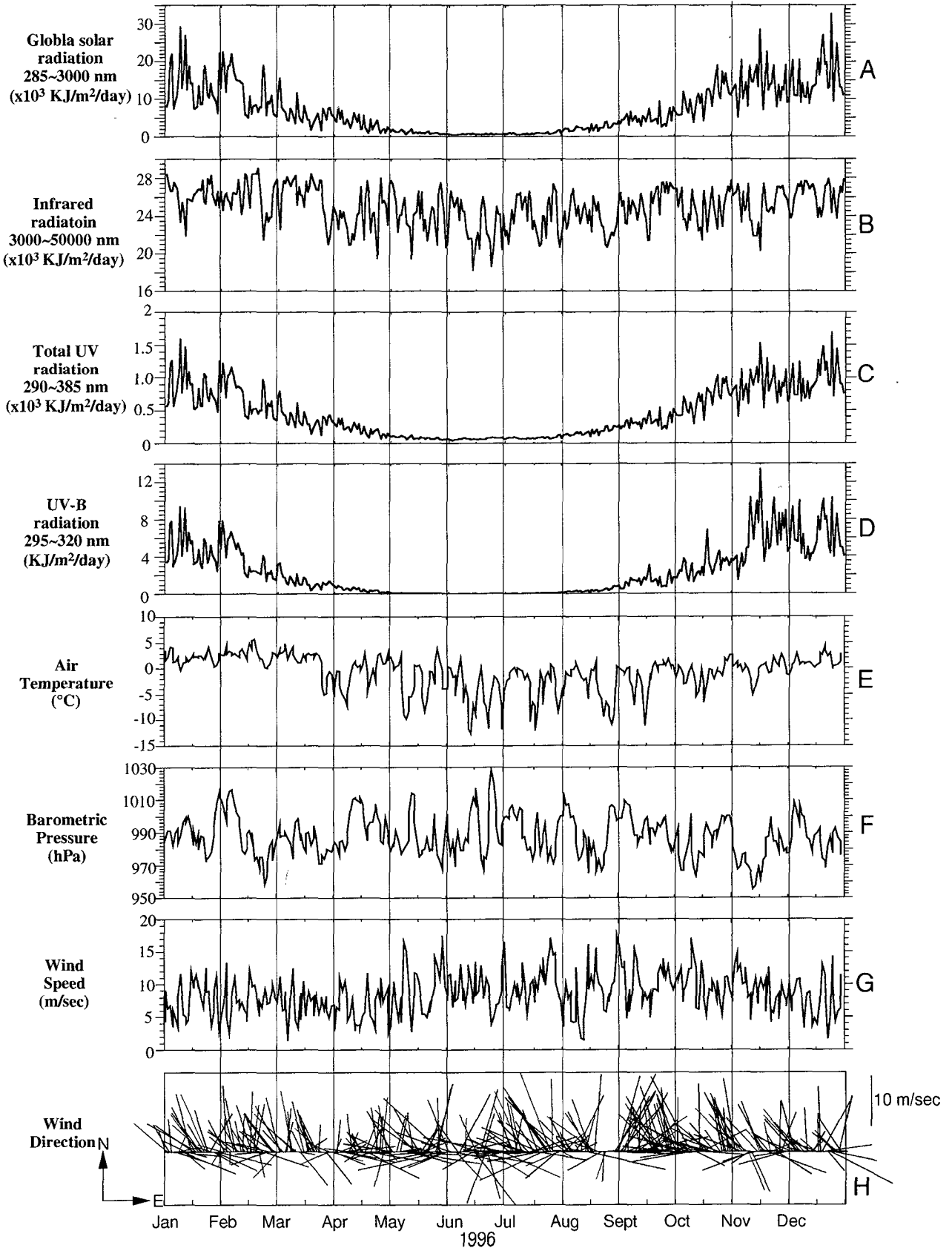## Meteorological Observations at King Sejong Station



**Fig. 2.** Seasonal variation and time series of global solar radiation (n=366), infrared radiation (n=366), total UV radiation (n=366), UV-B radiation (n=366), air temperature (n=366), barometric pressure (n=366), wind speed (n=366), wind direction (n=366) measured at automatic weather station in King Sejong, 1996.
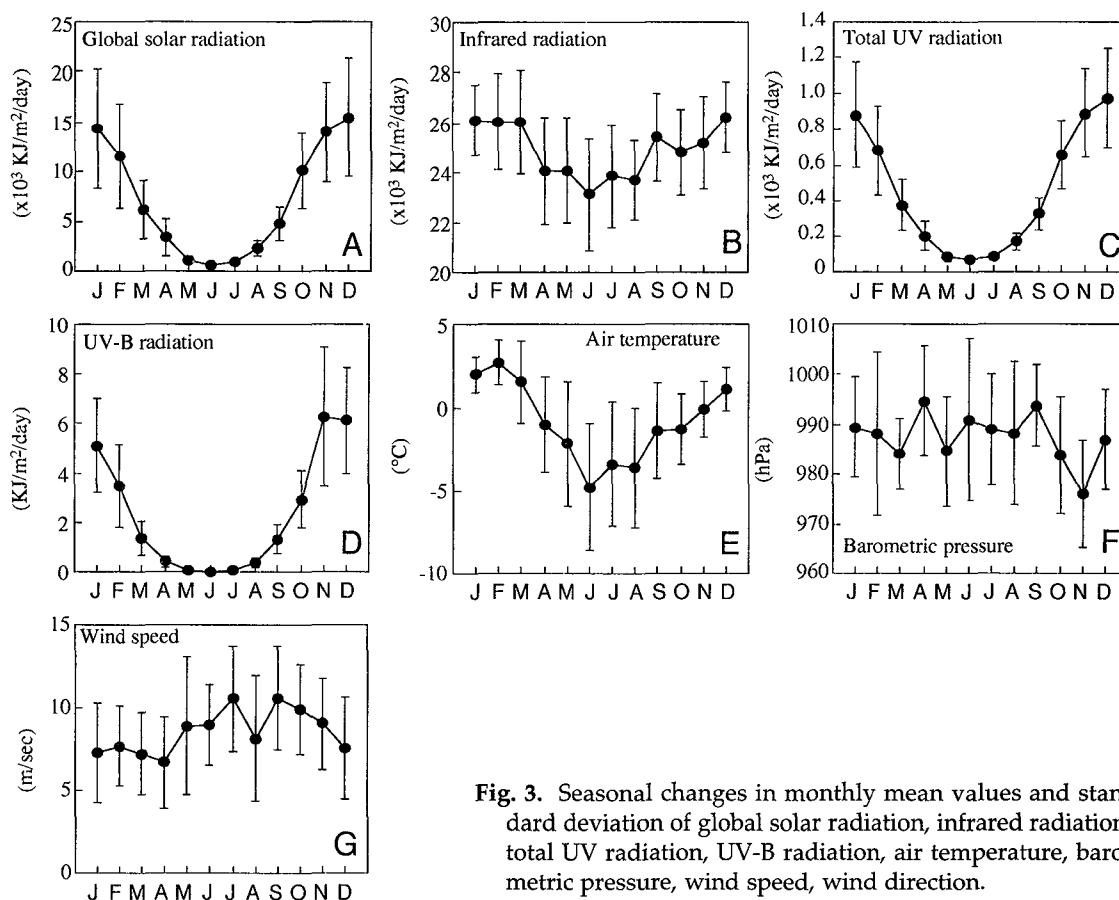
**Fig. 3.** Seasonal changes in monthly mean values and standard deviation of global solar radiation, infrared radiation, total UV radiation, UV-B radiation, air temperature, barometric pressure, wind speed, wind direction.

The seasonal variation in the air temperature estimates during 1996 is shown in Fig. 2E. The maximum and minimum monthly mean air temperatures were 2.7°C and -4.8°C and occurred in February and June, respectively (Fig. 3E). The maximum daily mean air temperature in 1996 was 5.6°C and was recorded on February 19, while -12.7°C was the minimum and occurred on June 14. The lowest temperature was during June (avg. -4.8°C), which was about 7.5°C higher than the highest temperature during February (avg. 2.7°C).

*Wind speed and direction*

The coastal regions of the South Shetland Islands are known to be among the stormiest of the continent (Gordon et al. 1978). The austral winter of 1996 in Marian Cove was windier than the summer, and that July and September (>10.5 m sec$^{-1}$) were particularly windy months (Fig. 2G). These months also correspond to the beginning of intense vertical mixing, which so characterizes oceanographic conditions in Marian Cove during the winter.

Annual mean wind speed was 8.5 m sec$^{-1}$. Wind speed and direction changed seasonally (Fig. 2H) with seasonally changing barometric pressure (Fig. 2F). Monthly mean wind speeds from January to April ranged from 6.7 m sec$^{-1}$ to 7.7 m sec$^{-1}$ (Fig. 3G). Wind was getting stronger from May (avg. 8.9 m sec$^{-1}$) and strongest during July (avg. 10.2 m sec$^{-1}$). In August weaker winds (avg. 8.1 m sec$^{-1}$) were formed. From September (avg. 10.5 m sec$^{-1}$) stronger winds were blown again, and it continued until November. In December wind speed was weakened. Overall wind speeds during summer and autumn (December-April) were weaker (avg. 7.3 m sec$^{-1}$) than during spring and winter (May-November, avg. 9.1 m sec$^{-1}$).

The wind field during the sampling period has been plotted in the form of stick vectors based on daily measurements of wind speed and direction (Fig. 2H). Winds were predominantly northwesterly, northerly, and northeasterly. The winds in this area are strong (mean >8 m sec$^{-1}$), and show frequent reversal of direction with the passing of low pressure systems (annual mean of 987 hPa in 1996; Fig. 3F). The seasonal variation in the wind direction is
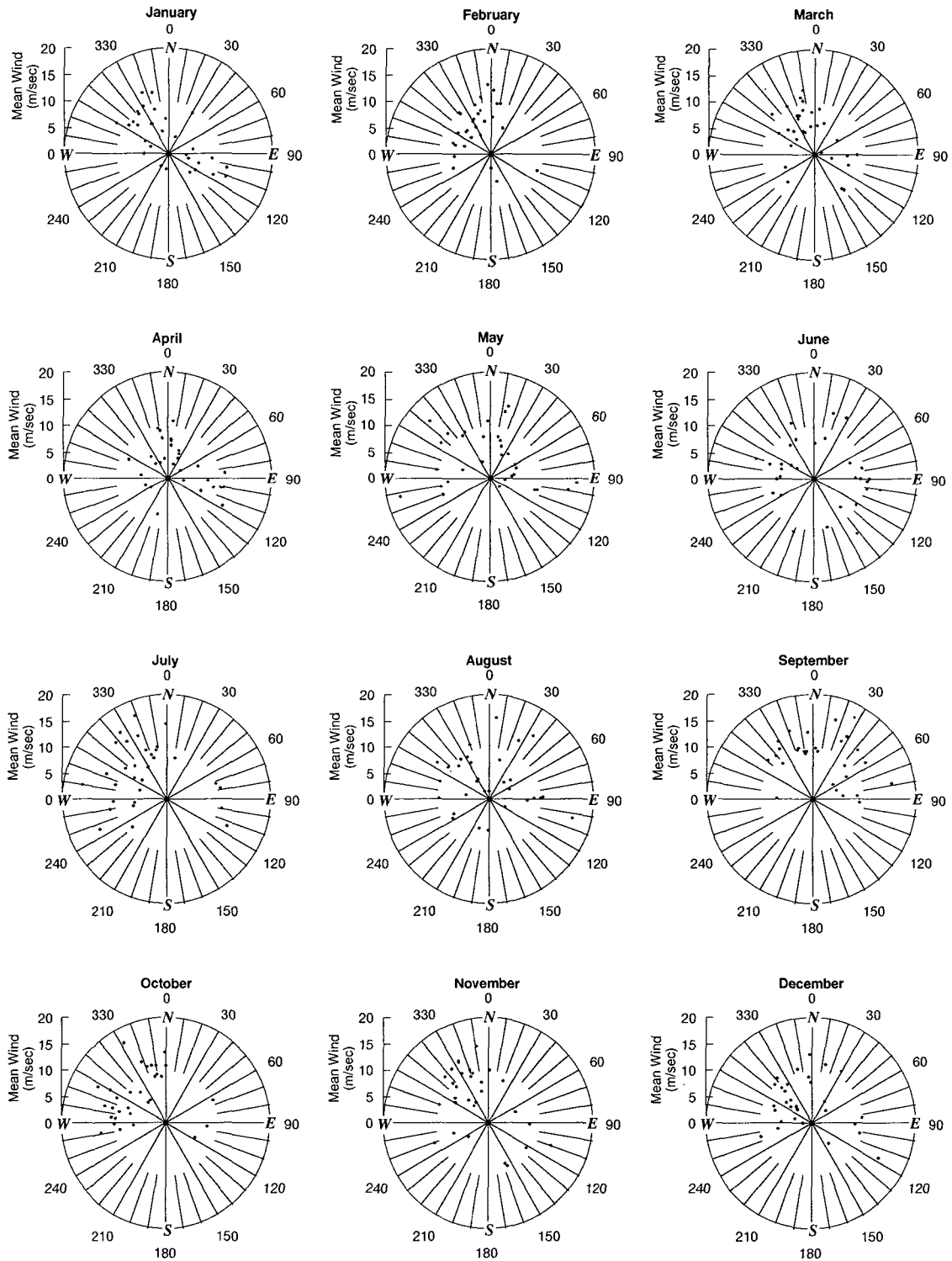
**Fig. 4.** Monthly velocity of wind in relation to wind direction.

shown in Fig. 4. Northerly and easterly were major wind direction from December to March. During transitional period (April and May) from summer to autumn, northerly, easterly, and westerly were dominant wind directions. During mid-winter periods (June-August) strong winds (>8.5 m sec⁻¹) from

north, northwest, northeast, and east were formed continuously. With increase of solar radiation from September strong northeasterly was main wind direction. From October most winds came from northwest.
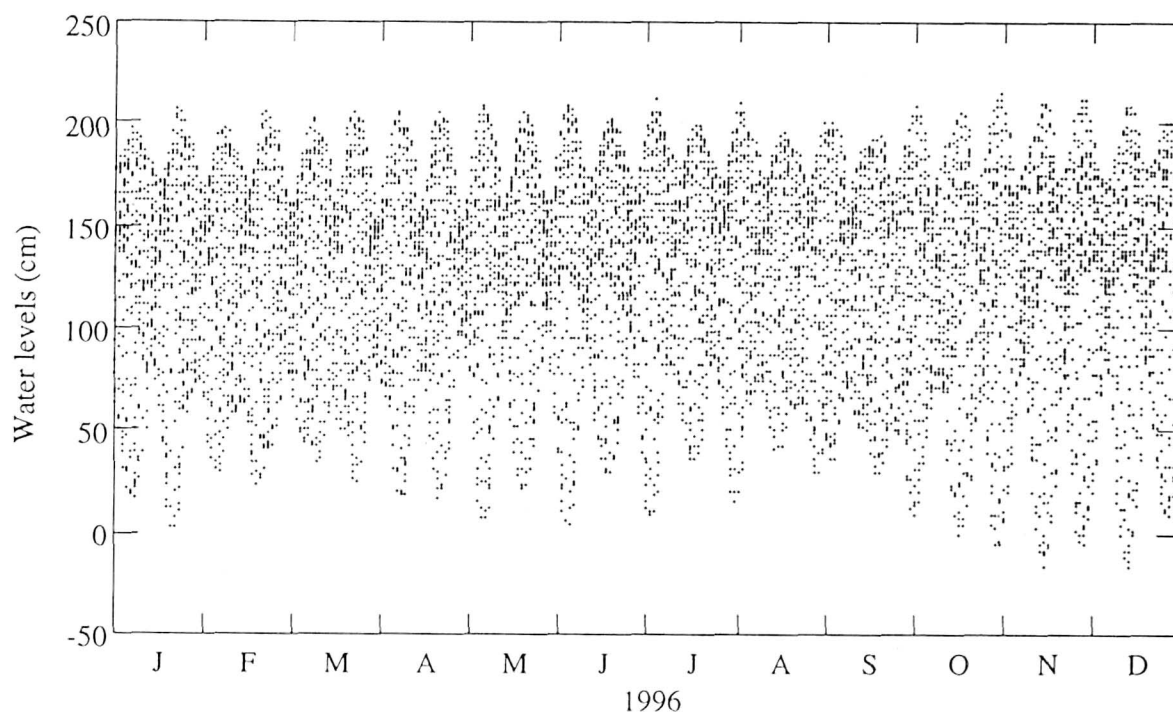
**Fig. 5.** The predicted water levels (cm) at the King Sejong Station (62°13' S, 58°47' W) during 1996.

*Sea ice*

King George Island is well within the zone of seasonal coverage by winter sea-ice, and its position at the edge of Weddell/Scotia Confluence zone means that there is considerable year-to-year variability in ice duration (Murphy *et al.* 1995). The duration of sea ice in Marian Cove varied from year to year. In 1996, sea ice did not form due to warmer air temperature blowing from north, only intermittent pack ice clogged the coastal region during winter time. However, frazil ice, early stage of sea ice formation, was observed during winter.

Sea-ice formation seems to be linked to wind direction and wind speed. In 1996 warm northerly wind dominated during winter, and storms from north resulted in all the local fast-ice blowing out and broken up by wind and wave action. The sea ice was rapidly driven out of the cove by the winds, no important melting could take place.

It should be noted here that ice conditions can be highly variable: for example, in 1989 and 1993 no persistent ice cover occurred at all like 1996 (this study period). These differences are of considerable significance to the underlying biological communities since sea ice influences light transmission and water column stability (Clarke *et al.* 1988). When sea

ice is present the underlying water is very stable and most of the particulate matter sediments out. If the sea ice breaks out wind-induced turbulence can once more turn over the water column and resuspend bottom material.

*Tide*

In the vicinity of King Sejong Station, two diel tidal currents exist (KORDI 1997a), which may make benthic diatoms regularly available for benthic suspension feeders (Ahn 1994; Ahn *et al.* 1994; Klöser *et al.* 1994; Gili *et al.* 1996). Hydrodynamic resuspension processes such as wind mixing and tidal currents may be the key factors in the availability of food to benthic suspension feeders. Tides are usually recognized as the principal source of mechanical energy for vertical mixing (Demers *et al.* 1987). The influence of the tides which are irregular at King George Island (KORDI 1997a) may be the main agent of water exchange in this area.

The intertidal and shallow subtidal zones of Marian Cove consist of hard substrata (boulders, stones, pebbles, gravel, sand). Bottom sediments are poorly sorted and mixed with a considerable amount of terrigenous sand and gravel (Ahn and Kang 1991). According to KORDI (1997b), the inter-
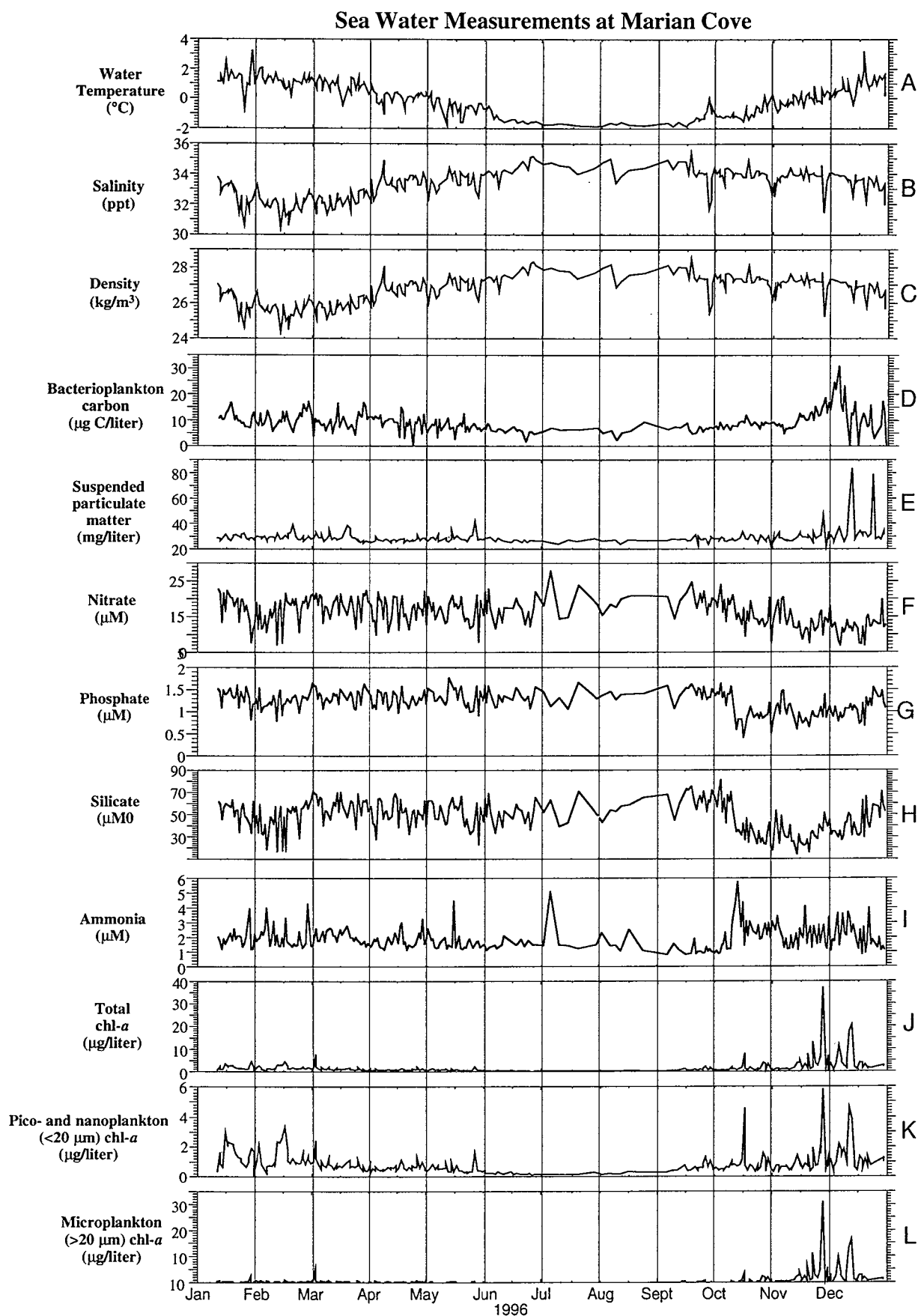
## Sea Water Measurements at Marian Cove



**Fig. 6.** Seasonal variation and time series of water temperature (n=272), salinity (n=272), density (n=272), bacterioplankton carbon (n=268), suspended particulate matter (n=272), nitrate (n=272), phosphate (n=272), silicate (n=272), ammonia (n=272), total chl-*a* (n=268), pico- and nanoplankton chl-*a* (n=268), microplankton chl-*a* (n=268) measured at the nearshore station, 1996.
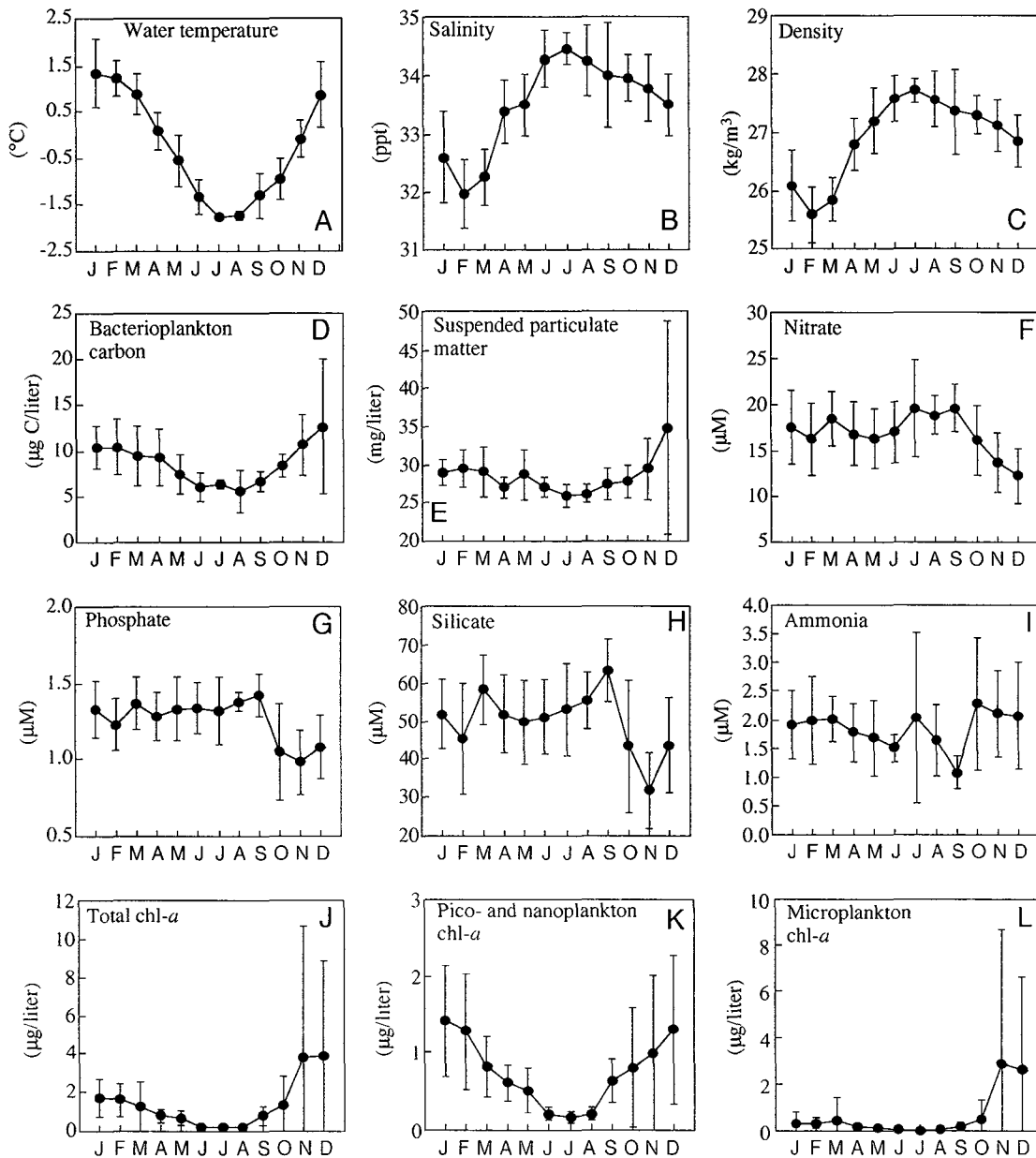
**Fig. 7.** Seasonal changes in monthly mean values and standard deviation of water temperature, salinity, density, bacterioplankton carbon, suspended particulate matter, nitrate, phosphate, silicate, ammonia, total chl-*a*, pico- and nanoplankton chl-*a*, microplankton chl-*a*.

tidal vertical range is about 1 m and is characterized by luxuriant benthic diatom growth during the austral summer. The diatom growth is absent during the austral winter when the intertidal zone is buffeted by waves and occasionally covered by sea ice. Strong tidal currents have been observed. Annual tidal ranges in Marian Cove during 1996 show that the lowest daily difference between high and low tide was about 50 cm and the highest was about 200 cm (Fig. 5). Especially higher intertidal differences were observed between October an December. Tide

was an important factor to affect microalgal assemblages and distribution in intertidal zone of Marian Cove. We observed that benthic microalgae were tychoplanktonic species that were temporally detached from their substrates such as macroalgae, mud, and rock after strong wind and tidal movement.

## Water temperature

Annual mean water temperature was -0.28°C, which was about 0.4°C higher than air temperature (avg. -

0.7°C). Seasonal variation of the water temperature was similar with air temperature (Fig. 6A). However, water temperature increased and decreased slowly without abrupt daily fluctuation, whereas air temperature showed some daily fluctuation (Fig. 2E).

The seasonal variation in monthly mean water temperature is shown in Fig. 7A. Monthly mean water temperatures varied from -1.78°C (July) to 1.33°C (January) and were above 0°C (0.08-1.33°C) from December to April, decreasing to below 0°C from May (avg. -0.55°C) and to near freezing point (-1.78°C and -1.75°C) in July and August, respectively. Temperature started to rise in September-October, showing highest monthly mean value in January (1.33°C). The rise in water temperature was mainly due to warming of surface water heated by increase of incoming solar radiation (Fig. 2A). Summer increases of water temperature to 2.48°C in 15 January and 3.28°C in 29 January were measured in Marian Cove. Monthly mean water temperature did not rise up to 2°C during the whole summer, which is coincident with measurements in Potter Cove and Marian Cove (Chang *et al.* 1990; Hong *et al.* 1991; Klöser *et al.* 1993).

*Salinity*

Annual mean salinity of sea water was 33.5 ppt. Seasonal variation of salinity is shown in Fig. 6B. Higher salinities (34.01-34.46 ppt) were formed during winter (June-September) due to saline ejection during sea ice formation, intrusion of higher salinity water, and no melt water formation. With increase of solar radiation melt water of snow, glacier, and ice started to be introduced from October, which resulted in getting lower salinity of sea water. The lowest salinity was formed during February (avg. 31.97 ppt) that was about 2.5 ppt lower than the highest in July (34.46 ppt). Termination of meltwater flow in April coincided with a slight increase in average salinity. Another general increase in salinity occurred in June due to the formation of sea ice at that time. The year's lowest salinity was 30.43 ppt in 13 February. The recorded high was 35.36 ppt and was found in 19 September.

The air temperature data reveal that maximum monthly means were above freezing in January through March and December (Fig. 3E). This defines a period of high runoff of glacial meltwater, which has been estimated to be about 20% of the ice loss at Anvers Island (Krebs 1983). Our data indicate that runoff increases through the austral summer (January-March), reaches a maximum in the February, and then ends abruptly in April (Fig. 7B). This meltwater discharge into Marian Cove was important in the stabilization of the nearshore water column. Salinity remained above 34 ppt from June until end of September. When meltwater discharge increased, maximal reduction of salinity in February and March yielded values between 31.97 ppt and 32.26 ppt, respectively. During that period, high amounts of terrigenous materials were introduced into the cove, resulting in visible coloration of the surface water.

*Water density*

The temporal distribution of sea-water density mirrors that of salinities (Figs. 6B and C). Changes in density regimes coincided with salinity fluctuations that were caused by runoff into Marian Cove. The cessation of runoff of glacier meltwater in April and the continued decline in air temperature increased sea-water density near the surface. This phenomenon plus high winds induced a general mixing of the water column in early May and resulted in a vertical homogeneity of sea water temperature that persisted through the winter months. Annual mean density was 26.75 kg m$^{-3}$. The lowest density water was formed in February (25.59 kg m$^{-3}$) and the highest was in July (27.74 kg m$^{-3}$) as the salinity (Figs. 7B and C). The lowest density value, 24.36 kg m$^{-3}$, was recorded in 13 February, whereas a high value of 28.47 kg m$^{-3}$ was found in 19 September. The density calculations are in general agreement with those obtained elsewhere from nearshore Antarctic regions (Krebs 1983) and support the contention that salinity was major factor to control density of water in low temperature (-1.78~1.33°C) and narrow temperature range (3°C).

## Bacterioplankton

The seasonal variation of bacterial biomass estimates is shown in Fig. 6D. Monthly means of bacterial biomass ranged from 5.6 $\mu$g C l$^{-1}$ in August to 12.6 $\mu$g C l$^{-1}$ in December (Fig. 7D). After April bacterial biomass declined, reaching levels below 7 $\mu$g C l$^{-1}$ from June to September. Winter levels were lower, with a minimum of 5.6 $\mu$g C l$^{-1}$ in August. There was a slight increase in monthly mean of bacterial biomass during October (8.4 $\mu$g C l$^{-1}$). The bloom then started in late October (10.7 $\mu$g C l$^{-1}$), increased abruptly during early November (12.6 $\mu$g C l$^{-1}$) and peaked in 5 December (30.9 $\mu$g C l$^{-1}$). The seasonal bacterial biomass estimates in Marian Cove during 1996 are comparable with other seasonal field data that are available for the Antarctic Ocean (Karl et al. 1991; Vosjan and Olanczuk-Neyman 1991; Lee et al. 1995) but are relatively higher when compared to some values reported in the Geologie Archipelago (Dellile 1993).

Although seasonal variation of bacterial biomass was smaller than variation of microalgae, bacteria also showed similar seasonal pattern with microalgae (Figs. 6D and J). Increase of bacteria followed microalgal biomass increase. In Marian Cove bacteria were actively growing after bloom of microalgae in early December. Maximum bacterial biomass was reached after the bloom of microalgae. Bacterial utilization of carbon substrates and uptake of DOC may form an important link to higher trophic levels during microalgal blooms.

It is speculated that microalgae may be major source of dissolved organic matter in Marian Cove. The dissolved organic material (DOM) released during photosynthesis or upon cell lysis is the primary substrate for bacterial growth (Cole et al. 1988). Thus, bacteria typically "bloom" after phytoplankton (Scavia and Laird 1987). The delay between the substrate production by phytoplankton and the bacterioplankton peak at a single sample site was found to be about one month in Antarctic waters (Davison and Marchant 1992). Our data showed a one week delay between the peak concentrations of microalgae and bacteria. The discrepancy in microalgae and bacterioplankton biomass indicates that bacterial

response to substrate availability in this waters was delayed.

## Suspended particulate matter

Annual mean value of suspended particulate material (SPM) including organic and inorganic matter was 29.05 mg l$^{-1}$. Organic source of SPM was bacteria, microalgae, and protozoa, and inorganic source of SPM was suspended clay mineral and clay particles formed from melting of glacier and snow. Seasonal variation of SPM is shown in Figs. 6E and 7E. The SPM was about 3 mg l$^{-1}$ higher during spring and summer (avg. 30.30 mg l$^{-1}$ from November to March) than autumn and winter (avg. 27.21 mg l$^{-1}$ from April and October) due to increased primary production and a strong predominance of the inorganic fraction by melt water introduction.

The SPM was supplied by different sources. Important sources were the meltwater streams, resuspension of benthic material, and subglacial discharge during summer. The most important source seemed to be the resuspension of benthic materials. Concentration of SPM, which consisted of >80% inorganic matter (mostly sediment) in Marian Cove (Ahn et al. 1997), seems to be influenced not only by wind-driven resuspension of particulate matter from sea bottom but also by terrigenous suspended sediment input from meltwater runoff, whereas diatom biomass is influenced mainly by wind-driven resuspension of epiphytic diatoms. Resuspension of sublittoral deposits has been shown to be an important process in Antarctic coastal environments (Krebs 1983; Berkman et al. 1986; Everitt and Thomas 1986; Dunbar et al. 1989; Gilbert 1991; Klöser et al. 1994; Brandini and Rebello 1994; Ahn et al. 1997). The increase of benthic diatom species in the water during November and December confirms resuspension of benthic material as a sediment source during these days.

## Macronutrients (nitrate, phosphate, and silicate)

The concentrations of nitrate, dissolved inorganic phosphate and dissolved silicate increased throughout the year until September. The concentrations of

nitrate, phosphate, and silicate fell sharply with increase of microalgal biomass in early October (Figs. 6F-H). The annual mean value of nitrate was about 17 $\mu$M, phosphate was 1.3 $\mu$M, and silicate was 49.9 $\mu$M.

The seasonal variation of macronutrient concentrations is shown in Figs. 7F-H. The pattern of depletion of the macronutrients was similar. Monthly mean levels of nitrate from January to September were quite high, ranging from 16.3 $\mu$M to 19.6 $\mu$M (Fig. 7F). Once the microalgal bloom started developing in October, nitrate levels dropped to 16.1 $\mu$M and then dropping rapidly in November (13.7 $\mu$M) and December (12.6 $\mu$M).

A similar pattern was shown by phosphate, showing higher monthly mean levels from January to September ranging from 1.23 $\mu$M to 1.42 $\mu$M (Fig. 7G). Once the bloom started in early October phosphate levels decreased rapidly to monthly mean minimum (0.98 $\mu$M) in November.

Silicate levels were also high from January to September, with a maximum monthly mean value of 63.35 $\mu$M in September (Fig. 7H). Silicate started to fall as early as October and had reached a minimum by November (31.76 $\mu$M), and the depletion continued until December. It would thus appear that macronutrients were being utilized while the microalgal bloom got underway from early October.

Lower concentrations of nitrate, phosphate, and silicate at the surface during February followed the decrease in salinity (Fig. 7B). In February input from glacier melt and runoff melt was high, producing decrease in salinity (31.97 ppt), dilution may play a role in reducing seawater nutrient concentrations at this site. Other researchers were also observed dilution effect of macronutrients, which may be mainly attributed to melting of glaciers and higher fresh water inputs into the bay (Lipski 1987; Brandini and Rebello 1994).

## Ammonia

Seasonal macronutrient patterns suggested a preferential utilization of ammonium at the late winter and start of spring (September) followed by a major utilization of nitrate, phosphate, and silicate by the

summer microalgal bloom. Ammonia levels started to decrease much earlier than other macronutrients (Fig. 6I). There was significant ammonium utilization during September (1.08 $\mu$M). This early spring decrease in ammonium occurred at a time when other macronutrient levels remained high as Clarke and Leakey (1996) observed in Signy Island. They speculated that the early phases of the summer microalgal bloom may be fueled primarily by ammonium rather than nitrate. During the period of low nitrate, phosphate, and silicate levels from October to December, ammonium levels increased (Fig. 7I), which may be mainly due to regeneration processes in sediment microbial activity and remineralization in the water column. Excretion by infauna, epifauna, and zooplankton can return significant quantities of ammonia to the nearshore marine ecosystem.

## Seasonal dynamics of microalgae

The microalgal population at a shallow Antarctic coastal site was monitored throughout 1996. Annual mean total chl-*a* concentration in surface water was 1.38 $\mu$g l$^{-1}$. A feature of microalgal biomass in Marian Cove was multimodal distribution of standing crop during the study period (Figs. 6J-L). Chlorophyll *a* (chl-*a*) determinations demonstrated a marked seasonality in microalgal biomass (Figs. 7J-L). Monthly means of chl-a concentrations in January and February were 1.74 $\mu$g l$^{-1}$ and 1.61 $\mu$g l$^{-1}$, respectively. After March (1.28 $\mu$g l$^{-1}$) the chl-*a* declined rapidly, reaching levels below 1 $\mu$g l$^{-1}$ in April (0.80 $\mu$g l$^{-1}$). Winter levels were very low, with a minimum of 0.19 $\mu$g l$^{-1}$ in July. There was a slight increase in monthly mean of chl-*a* during September (0.80 $\mu$g l$^{-1}$). The bloom then started in October (1.33 $\mu$g l$^{-1}$), increased abruptly during November (3.82 $\mu$g l$^{-1}$) and peaked in December (3.90 $\mu$g l$^{-1}$). The peak chl-*a* concentration was 36.9 $\mu$g l$^{-1}$ in 28 November.

Chl-*a* value (avg. 2.28 $\mu$g l$^{-1}$) between October and March accounted for 82% of total chl-*a* and was about 5 times higher than chl-a value (0.49 $\mu$g l$^{-1}$) between April and September. More than 46% (avg. 3.9 $\mu$g l$^{-1}$) of chl-*a* was concentrated during November and December. Although microalgal pro-
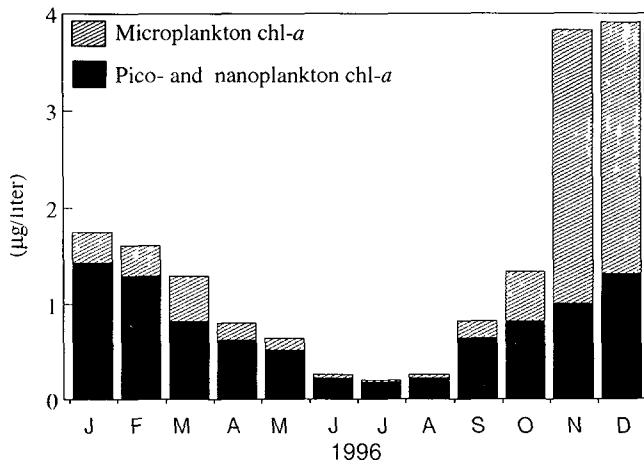
**Fig. 8.** Seasonal variation of microplankton and pico- and nanoplankton chl-*a*.

duction was much lower during autumn and winter, small amount of pico- and nanoplankton (<20 μm) chl-*a* kept existing in sea water. Whereas the bulk of the microalgal production occurred during spring and summer, but much of this was microplankton (>20 μm) chlorophyll. Microplankton chl-a showed summer peaks >5 μg l⁻¹ and low winter chlorophyll standing crops (Fig. 7L).

The pico- and nanoplankton (nanoplankton) chlorophyll and microplankton chlorophyll accounted for 54% (0.75 μg l⁻¹) and 46% (0.63 μg l⁻¹) of total chl-*a*, respectively. The nanoplankton chl-*a* existed in Marian Cove year-round. From January to October the nanoplankton contributed most of the chl-*a* (>70%) in water column (Fig. 8). Chl-*a* in nanoplankton fraction exhibited a clear seasonal variation. During spring and summer monthly means of nanoplankton chlorophyll increased to over 0.8 μg l⁻¹ and peaked at 1.42 μg l⁻¹ in January. In winter (April-September), monthly means of nanoplankton chlorophyll concentrations were between 0.17 μg l⁻¹ in July and 0.63 μg l⁻¹ in September. The nanoplankton bloom tended to last longer than the microplankton bloom. The nanoplankton chlorophyll exceeded that of the microplankton for 10 months except November and December (Fig. 8).

The summer peak of microplankton chlorophyll was dominated by large diatoms such as *Corethron criophilum, Licmophora* spp., and *Fragilaria* spp. Peak

concentrations of pico- and nanoplankton chlorophyll, predominantly from flagellates, were much lower but the bloom lasted longer and winter biomass was higher than in the microplankton (Fig. 8). Planktonic diatom, *Corethron criophilum*, dominated the phytoplankton in November and then benthic diatoms such as *Licmophora* spp. and *Fragilaria* spp. dominated in the nearshore area from December. Small phytoflagellates (<20 μm) were more abundant during January through October. During winter, mainly pico- and nanoplankton chl-a contributed to microalgal assemblages. Autotrophic flagellates such as *Cryptomonas* spp., *Pyraminomas* spp., *Phaeocystis antarctica* (motile stage), and deflagellated monads were dominant nanoplankton assemblages. Kopczynska (1996) observed similar pattern in Admiralty Bay.

The winter (June, July, and August) in Marian Cove is characterized by a homogeneity of biological and physicochemical conditions. Due to the low sunlight, higher winds, chilling of the surface layers, and cessation of runoff during the winter, winter microalgal standing crop was minimal, often <0.2 μg l⁻¹ for the larger size fractions (>20 μm) and <0.6 μg l⁻¹ for the smaller size fractions (<20 μm). Winter minima were reached in June and July. During that time, however, a seed assemblage of microalgae may survive in the plankton. This seed assemblage could give rise to microalgal blooms when conditions again became favorable.

### Microalgal biomass in relation to environmental factors

In order to see the relation between the physicochemical factors and microalgae, we used pearson correlation matrix based on monthly mean values (Table 1). We have tried to find statistically significant correlations between the chl-*a* and other physicochemical factors. The r values shown in this table indicate statistically significant when *p* values are less than 0.05. Other asteroid marks indicate that r values are no significant. Total chl-*a* was significantly correlated with air temperature, solar radiation, water temperature, suspended particulate matter, bacteria, and macronutrients. The macronutri-

**Table 1.** Pearson correlation matrix based on monthly average values. R values shown are significant (n = 12; $P \le 0.05$); * indicates that r values are not significanat ($P > 0.05$). Correlation coefficients between wind speed (WIND), air temperature (ATEMP), global solar radiation (RAD), total UV radiation (UV), UV-B radiation (UVB), water temperature (WTEMP), salinity (SAL), density (DEN), suspended particulate matter (SS), bacterioplankton (BAC), nitrate (NIT), phosphate (PHO), silicate (SIL), total chl-*a* (TCHL), nanoplankton chl-*a* (NACHL), microplankton chl-*a* (NECHL)

| | WIND | ATEMP | RAD | UV | UVB | WTEMP | SAL | DEN | SS | BAC | NIT | PHO | SIL | TCHL | NACHL | NECHL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WIND | 1 | | | | | | | | | | | | | | | |
| ATEMP | * | 1 | | | | | | | | | | | | | | |
| RAD | * | 0.792 | 1 | | | | | | | | | | | | | |
| UV | * | 0.762 | 0.998 | 1 | | | | | | | | | | | | |
| UVB | * | 0.695 | 0.977 | 0.982 | 1 | | | | | | | | | | | |
| WTEMP | -0.740 | 0.928 | 0.713 | 0.678 | 0.634 | 1 | | | | | | | | | | |
| SAL | 0.677 | -0.876 | * | * | * | -0.899 | 1 | | | | | | | | | |
| DEN | 0.690 | -0.899 | * | * | * | -0.914 | 0.993 | 1 | | | | | | | | |
| SS | * | 0.637 | 0.733 | 0.731 | 0.745 | 0.676 | | | 1 | | | | | | | |
| BAC | * | 0.861 | 0.871 | 0.854 | 0.841 | 0.883 | -0.634 | -0.670 | 0.836 | 1 | | | | | | |
| NIT | * | * | -0.661 | -0.667 | -0.720 | * | * | * | -0.793 | -0.741 | 1 | | | | | |
| PHO | * | * | -0.680 | -0.698 | -0.723 | * | * | * | * | -0.613 | 0.833 | 1 | | | | |
| SIL | * | * | -0.595 | -0.604 | -0.667 | * | * | * | * | * | 0.827 | 0.92 | 1 | | | |
| TCHL | * | 0.614 | 0.874 | 0.882 | 0.930 | 0.584 | * | * | 0.833 | 0.859 | -0.844 | -0.783 | -0.712 | 1 | | |
| NACHL | * | 0.930 | 0.927 | 0.909 | 0.863 | 0.889 | -0.719 | -0.751 | 0.746 | 0.908 | * | * | * | 0.749 | 1 | |
| NECHL | * | * | 0.712 | 0.731 | 0.814 | * | * | * | 0.742 | 0.701 | -0.836 | -0.80 | -0.733 | 0.955 | * | 1 |

ents such as nitrate, phosphate, and silicate were negatively correlated with chl-*a*, which probably reflects microalgal uptake. Nanoplankton chl-*a* showed no significant correlation with macronurients, but microplankton chl-*a* was negatively correlated with all the nutrients (Fig. 9). It means that the intense increase of microplanktonic microalgae significantly affected on decrease of nutrients. Whereas nanoplanktonic microalgae was not significantly correlated with nutrients.

The relations between physicochemical factors and chl-*a* were different depending on microalgal size. The contrast in the timing, intensity, and duration of the microplankton (>20 μm, diatoms) and nanoplankton (<20 μm, phytoflagellates) blooms is of profound ecological importance (Barnes and Clarke 1994; Clarke and Leakey 1996). Previous studies in Antarctic nearshore waters revealed that benthic micro-sized microalgae are an important food source for water column and benthic herbivores when other food sources are scarce (Rivkin and Putt 1987; Gilbert 1991; Ahn *et al.* 1997), and suspension-feeding organisms adapted to feed on nanoplanktonic cells may experience a longer annu-

al feeding period than those feeding on microplanktonic cells (Clarke and Leakey 1996).

Nanoplankton chl-*a* was significantly correlated with water column properties such as temperature, salinity, and density which reflects water column stability, whereas microplankton chl-*a* was not significantly correlated with water temperature, salinity, and density (Fig. 9). It means that nanoplanktonic microalgae was more affected by sea water structure such as increase of water column stability due to higher temperature and lower salinity. However, micro-sized tychoplanktonic microalgae was not significantly affected by physical properties of water column such as temperature, salinity, and density. We speculate that local wind mixing and intertidal movement would be more important physical mechanisms to increase of microplankton. These chlorophyll increases have been attributed to resuspension of benthic microalgae. This resuspension mechanism is presumed important since, for a large part of the summer growing season, planktonic biomass is very low in the water column. We observed the increase of microplankton was after local wind mixing and intertidal movement, especially during
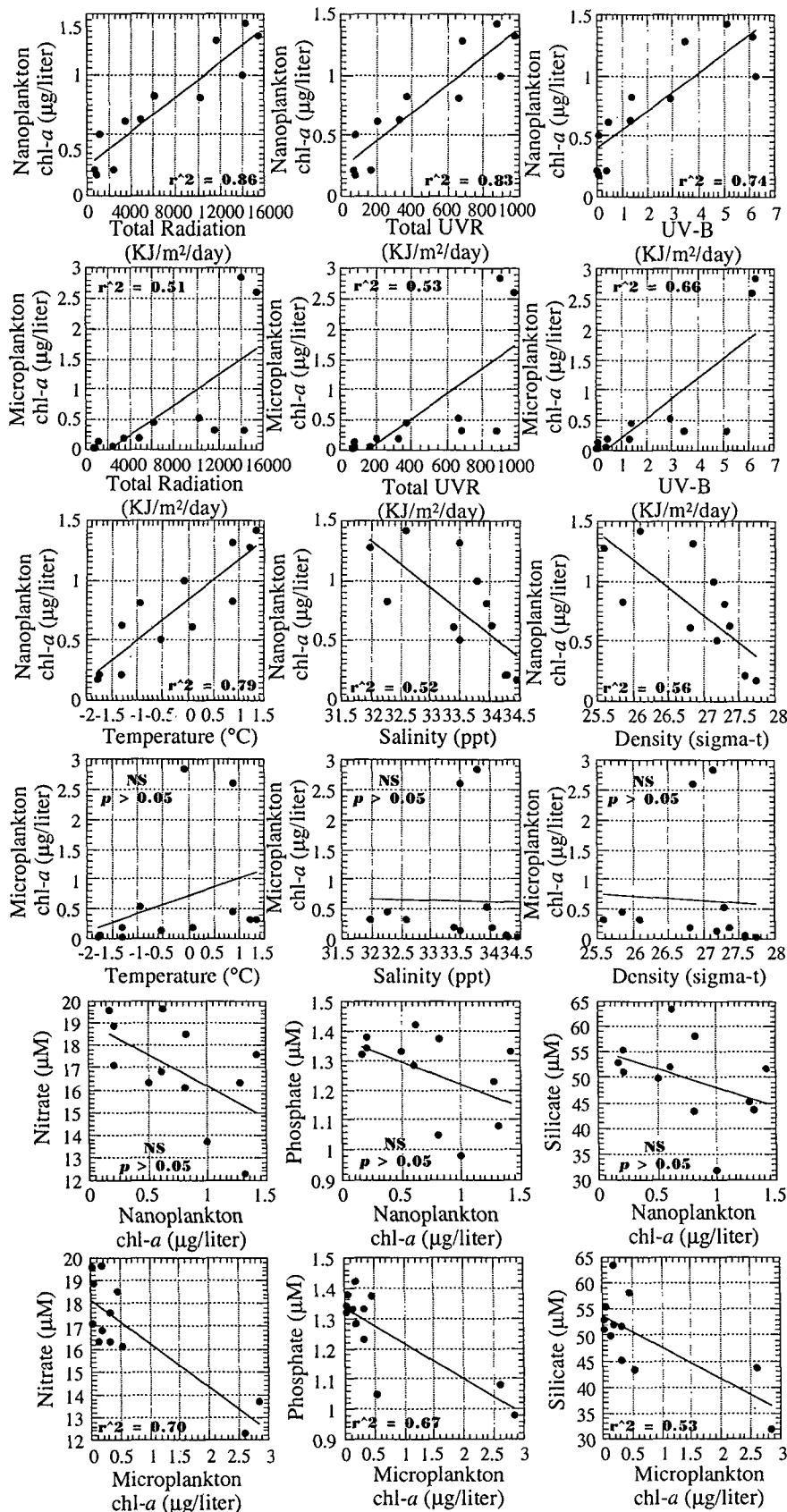
**Fig. 9.** Relation between the physicochemical factors and microalgae (microplankton and nanoplankton). Correlation matrix based on monthly mean values was used to find statistically significant correlations between the chl-a and other physicochemical factors. The $r^2$ values shown in this figure indicate statistically significant when $p$ values are less than 0.05. NS indicates that $r^2$ values are no significant.

low tide.

The origin and composition of the carbon source for benthic animals may be changed seasonally with planktonic production and resuspension of benthic microalgae by tidal currents and local wind mixing at the sediment-water interface. During early to late-November, the chl-*a* concentrations increased from <1 $\mu$g l$^{-1}$ to >5.0 $\mu$g l$^{-1}$ in a few days (Fig. 7J). This increase in microalgal biomass was not the result of *in situ* production and growth of phytoplankton, rather, resuspension of tychoplanktonic benthic diatoms were likely happened. Intertidal and shallow subtidal microalgal growth in Marian Cove began during November and December as a brown film and quickly developed into filamentous colonies that resembled thick, brown fur. These species were found to attach densely on macroalgae (Kang, J.-S., personal observation). The benthic diatoms were washed out of the intertidal zone and transported to the subtidal waters by tides or wind-generated waves and were detached from the benthic substrates and resuspended by wind- and tide-generated waves. The resuspension of benthic microalgae may be an important factor affecting the secondary production in Antarctic nearshore areas. Kang *et al.* (1997) listed many benthic species in the phytoplankton collections of Marian Cove and Maxwell Bay. The resuspension seems to be an important mechanism to affect the diversity of nearshore phytoplankton assemblages. The tychoplanktonic forms from the intertidal and subtidal diatom communities seem to contribute substantially to important carbon source to sustain the nearshore ecosystem of Marian Cove.

Monitoring the dynamic picture of environmental and microalgal fluctuations and various parameters in Marian Cove during 1996, a "warm" year for that region, has provided general conclusions about the interaction of biological and environmental events. Seasonal variation of nearshore microalgal biomass was mainly affected by light and water temperature. Increase of microalgal biomass affected on bacteria and nutrients. As Clarke & Leakey (1996) pointed out, we need continuous and interdisciplinary year-round studies to understand the highly seasonal and complex nature of the nearshore marine ecosystem.

## References

Ahn I.-Y. 1994. Ecology of the Antarctic bivalve *Laternula elliptica* (King and Broderip) in Collins Harbor, King George Island: Benthic environment and an adaptive strategy. *Mem. Natl. Inst. Polar Res. Spec. Issue* **50**: 1-10.

Ahn I.-Y. and Kang Y.C. 1991. Preliminary study on the macrobenthic community of Maxwell Bay, South Shetland Islands, Antarctica. *Korean J. Polar Res.* **2**: 61-71.

Ahn I.-Y., Chung H., Kang J.-S., and Kang S.-H. 1994. Preliminary studies on the ecology of neritic marine diatoms in Maxwell Bay, King George Island, Antarctica. *Korean J. Phycol.* **9**: 37-45.

Ahn I.-Y., Chung H., Kang J.-S., and Kang S.-H. 1997. Diatom composition and biomass variability in nearshore waters of Maxwell Bay, Antarctica, during the 1992/1993 austral summer. *Polar Biol.* **17**: 123-130.

Barnes D.K.A. and Clarke A. 1994. Seasonal variation in the feeding activity of four species of Antarctic bryozoan in relation to environmental factors. *J. Exp. Mar. Biol. Ecol.* **181**: 117-133.

Berkman P.A., Marks D.S., and Shreve G.P. 1986. Winter sediment resuspension in McMurdo Sound, Antarctica and its ecological implications. *Polar Biol.* **6**: 1-3.

Brandini F.P. and Rebello J. 1994. Wind field effect on hydrography and chlorophyll dynamics in the coastal pelagial of Admiralty Bay, King George Island, Antarctica. *Antarct. Sci.* **6**: 433-442.

Chang K.I., Jun H.K., Park G.T., and Eo Y.S. 1990. Oceanographic conditions of Maxwell Bay, King George Island, Antarctica (austral summer 1989). *Korean J. Polar Res.* **1**: 27-46.

Choi D.L., Nam S.H., and Oh J.K. 1990. Marine geology of the Maxwell Bay in King George Island by using 3.5kHz seismic profiles. *Korean J. Polar Res.* **1**: 19-26.

Chung H., Yang J.S., and Chung C.S. 1991. Seawater properties and macroalgal growth in littoral zone of Barton Peninsula, King George Island, Antarctica. *Korean J. Polar Res.* **2**: 51-60.

Chung H., Oh Y.S., Lee I.K., and Kim D.-Y. 1994. Macroalgal vegetation of Maxwell Bay in King George Island,

Antarctica (austral summer 1989). *Korean J. Phycol.* **9**: 47-58.

Clarke A., Holmes L.J., and White M.G. 1988. The annual cycle of temperature, chlorophyll, and major nutrients at Signy Island, South Orkney Islands, 1969-82. *Br. Antarct. Surv. Bull.* **80**: 65-86.

Clarke A. and Leakey R.J.G. 1996. The seasonal cycle of phytoplankton, macronutrients, and the microbial community in a nearshore Antarctic marine ecosystem. *Limnol. Oceanogr.* **41**: 1281-1294.

Cole J.J., Findlay S., and Pace M.L. 1988. Bacterial production in fresh and saltwater ecosystem: A cross-system overview. *Mar. Ecol. Prog. Ser.* **43**: 1-10.

Davidson A.T. and Marchant H.J. 1992. Protist abundance and carbon concentration during a *Phaeocystis*-dominated bloom at an Antarctic coastal site. *Polar Biol.* **12**: 387-395.

Dayton P.K., Watson D., Palmisano A., Barry J.P., Oliver J.S., and Rivera D. 1986. Distribution patterns of benthic microalgal standing stock at McMurdo Sound, Antarctica. *Polar Biol.* **6**: 207-213.

Delille D. 1993. Seasonal changes in the abundance and composition of marine heterotrophic bacterial communities in an Antarctic coastal area. *Polar Biol.* **13**: 463-470.

Delille D., Mallard L., and Rosiers C. 1996. Inter-annual variability in marine coastal Antarctic bacterioplankton. *Polar Biol.* **16**: 19-25.

Demers S. and Therriault J.-C. 1987. Resuspension in the shallow sublittoral zone of a macrotidal estuarine environment: Wind influence. *Limnol. Oceanogr.* **32**: 327-339.

Dunbar R.B., Leventer A.R., and Stockton W.L. 1989. Biogenic sedimentation in McMurdo Sound, Antarctica. *Mar. Geol.* **85**: 155-179.

Everitt D.A. and Thomas D.P. 1986. Observations of seasonal changes in diatoms at inshore localities near Davis Station, East Antarctica. *Hydrobiologia* **139**: 3-12.

Gilbert N.S. 1991. Microphytobenthic seasonality in nearshore marine sediments at Signy Island, South Orkney Islands, Antarctica. *Estuar. Coast. Shelf Sci.* **33**: 89-104.

Gili J.M., Alvà V., Pagès F., Klöser H., and Arntz W.E. 1996. Benthic diatoms as the major food source in the sub-Antarctic marine hydroid *Silicularia rosea. Polar Biol.* **16**: 507-512.

Gordon A.L., Molinelli E., and Baker T. 1978. Large-scale relative dynamic topography of the Southern Ocean. *J. Geophys. Res.* **83**: 3023-3032.

Grasshoff K., Ehrhardt M., and Kremling K. 1983. *Methods of Seawater Analysis.* Verlag Chemie, Weinheim.

Hong G.H., Kim D.-Y., Chung H., and Pae S. 1991. Coastal and inshore water interaction, mixing and primary productivity in the Bransfield Strait, Antarctica during austral summer 1989/1990. *Korean J. Polar Res.* **2**: 43-59.

Kang J.-S., Kang S.-H., Lee J.H., and Lee M.-Y. 1997. Antarctic net- and nano-phytoplankton assemblages in the surface water of Maxwell Bay during the 1997 austral summer. *Korean J. Polar Res.* **8**: this volume.

Karentz D., Cleaver J.E., and Mitchell D.L. 1991. Cell survival characteristics and molecular responses of Antarctic phytoplankton to ultraviolet-B radiation. *J. Phycol.* **27**: 326-341.

Karl D.M., Holm-Hansen O., Taylor G.T., Tien G., and Bird D.F. 1991. Microbial biomass and productivity in the western Bransfield Strait, Antarctica during the 1986-87 austral summer. *Deep-Sea Res.* **38**: 1029-1055.

Kim Y.K. and Baek W.D. 1995. Bathymetric and topographic measurements around King Sejong Station, King George Island, Antarctica (II). *In: The Studies on Natural Environment and Conservation of Antarctica.* KORDI Report, BSPN 00258-822-7. p. 825-846.

Klöser H., Ferreyra G., Schloss I., Mercuri G., Laturnus F., and Curtosi A. 1993. Seasonal variation of algal growth conditions in sheltered Antarctic bays: The example of Potter Cove (King George Island, South Shetlands). *J. Mar. Sys.* **4**: 289-301.

Klöser H., Ferreyra G., Schloss I., Mercuri G., Laturnus F., and Curtosi A. 1994. Hydrography of Potter Cove, a small fjord-like inlet on King George Island (South Shetlands). *Estuar. Coast. Shelf Sci.* **38**: 523-537.

Kopczynska E.E. 1996. Annual study of phytoplankton in Admiralty Bay, King George Island, Antarctica. *Polish Polar Res.* **17**: 151-164.

KORDI 1997a. *Overwintering of the 8th Korean Antarctic Research program (KARP), November 1994-December 1995.* KORDI Report, BSE 520001-982-7. p. 69-88.

KORDI 1997b. *Wintering report of the 9th Korean Antarctic Research Program at King Sejong Station, December 1995-December 1996.* KORDI Report, BSE 520001-982-7. p. 124-189.

Krebs W.N. 1983. Ecology of neritic marine diatoms, Arthur Harbor, Antarctica. *Micropaleontology* **29**: 267-297.

Lee S. and Fuhrman J.A. 1987. Relationships between biovolume and biomass of naturally derived marine bacterioplankton. *Appl. Environ. Microbiol.* **53**: 1298-1303.

Lee M.-Y., Kang S.-H., Lee S., Chung K.-H., and Choi J.K. 1995. Distribution and biomass of phytoplankton and bacterioplankton: Relationships to environmental parameters during an Antarctic austral summer in the Bransfield Strait. *Korean J. Polar Res.* **6**: 31-47.

Lipski M. 1987. Variations of physical conditions, nutrients nd chlorophyll a contents in Admiralty Bay (King George Island, South Shetland Islands). *Polish Polar Res.* **8**: 307-332.

Moline M.A. and Prézelin B.B. 1996. High-resolution time-series data for 1991/1992 primary production and related parameters at a Palmer LTER coastal sites: Implications for modeling carbon fixation in the Southern Ocean. *Polar Biol.* **17**: 39-53.

Murphy E.J., Clarke A., Symon C., and Priddle J. 1995. Temporal variation in Antarctic sea-ice: Analysis of a long term fast-ice record from the South Orkney Islands. *Deep-Sea Res.* **42**: 1045-1062.

Perrin R.A., Lu P., and Marchant H.J. 1987. Seasonal variation in marine phytoplankton and ice algae at a shallow Antarctic coastal site. *Hydrobiologia* **146**: 33-46.

Porter K.G. and Feig Y.S. 1980. The use of DAPI for identifying and counting aquatic microflora. *Limnol. Oceanogr.* **25**: 943-948.

Rivkin R.B. 1991. Seasonal patterns of planktonic production in McMurdo Sound, Antarctica. *Amer. Zool.* **31**: 5-16.

Rivkin R.B. and Putt M. 1987. Photosynthesis and cell division by Antarctic microalgae: Comparison of benthic, planktonic and ice algae. *J. Phycol.* **23**: 223-229.

Scavia D. and Laird G.A. 1987. Bacterioplankton in Lake Michigan: Dynamics, controls, and significance to carbon flux. *Limnol. Oceangr.* **32**: 1017-1033.

Schloss I. , Klöser H., Ferreyra G., Curtosi A., Mercuri G., and Pinola E. 1997. Factors governing phytoplankton and particulate matter variation in Potter Cove, King George Island, Antarctica. *In*: Battaglia B., Valencia J., and Walton D.W.H. (*eds*), *Antarctic Communities: Species, Structure, and Survival*. Cambridge Univ. Press, Cambridge. p. 135-141.

Vosjan J.H. and Olanczuk-Neyman K.M. 1991. Influence of temperature on respiratory ETS-activity of micro-organisms from Admiralty Bay, King George Island, Antarctica. *Neth. J. Sea Res.* **28**: 221-225.

Whitehouse M.J., Priddle J., and Symon C. 1996. Seasonal and annual change in seawater temperature, salinity, nutrient and chlorophyll a distributions around South Georgia, South Atlantic. *Deep-Sea Res.* **43**: 425-443.