Polar Biol (2015) 38:207–220
DOI 10.1007/s00300-014-1579-6

ORIGINAL PAPER

# Large contribution of small phytoplankton at Marian Cove, King George Island, Antarctica, based on long-term monitoring from 1996 to 2008

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Received: 27 March 2014 / Revised: 5 September 2014 / Accepted: 7 September 2014 / Published online: 13 September 2014


**Abstract** To detect and monitor coastal marine ecosystem responses to current environmental changes, the phytoplankton assemblage, salinity, and macro-nutrients were monitored daily at a fixed coastal site in Marian Cove, Antarctica, from 1996 to 2008. The monthly average water temperature at the site was highest (2.14 ± 0.36 °C) during the summer period (December–February) and lowest (−1.80 ± 0.22 °C) during the winter period (July–September). The salinity levels exhibited the opposite trend with the lowest values (30.9 ± 0.68 psu) during summer and the highest values (35.2 ± 1.15 psu) during winter. The concentrations of major nutrients were always high enough for phytoplankton growth, indicating the nutrients are not a main controlling factor for phytoplankton growth. Total chlorophyll-*a* generally started to increase from late November with a peak (1.14 ± 1.41 mg chl-*a* $m^{-3}$) around January when the water temperature was the warmest during the year. Within the phytoplankton communities, the average contribution of small (nano- plus pico-) phytoplankton (<20 μm) to the total chl-*a* concentration was high (62.9 %) throughout the study period, which supports the observation that small phytoplankton contributed 85.7 % to the cell numbers and 56.4 % to the biovolume of the total phytoplankton. The high contribution of small phytoplankton is a general characteristic at Marian Cove and may be expected to increase under future warming conditions.

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**Keywords** Phytoplankton · Marian Cove · Chlorophyll-*a* · Antarctica

## Introduction

The Antarctic Peninsula has been identified as one of the regions experiencing the fastest rate of global climate change (Rückamp et al. 2011). Over the past several decades, rapid physical changes have occurred in the marine ecosystem along the western continental shelf region of the Antarctic Peninsula (Ducklow et al. 2007). Antarctic marine ecosystems have responded differently to climate change (e.g., sea-ice extent, rapid atmospheric warming) in different regions (Montes-Hugo et al. 2009). Montes-Hugo et al. (2009) found regional changes in the response of chl-*a* concentrations to rapid changes in climate along the Western Antarctic Peninsula which have induced changes in krill and penguin populations. Antarctic nearshore ecosystems are vulnerable to environmental changes, such as global warming, ozone depletion, and anthropogenic pollution (Kang et al. 1997). According to Moline et al. (2004), increasing air temperatures reported along the Antarctic Peninsula will increase glacial melting, which could increase the contribution of small phytoplankton; the Antarctic food web may consequently be altered because small phytoplankton have different nutritional conditions as potential food source to higher trophic levels in regard to quality and quantity (Lee et al. 2009; Kim et al. 2014).

The Antarctic Peninsula where King George Island is located is one of the most rapidly warming locations with more than a 1.5 °C increase in the mean annual temperature (Clarke et al. 2007). Recently, the ice cliff in Marian Cove was found to be retreating rapidly (Fig. 1). This retreating ice cliff might alter the marine environmental

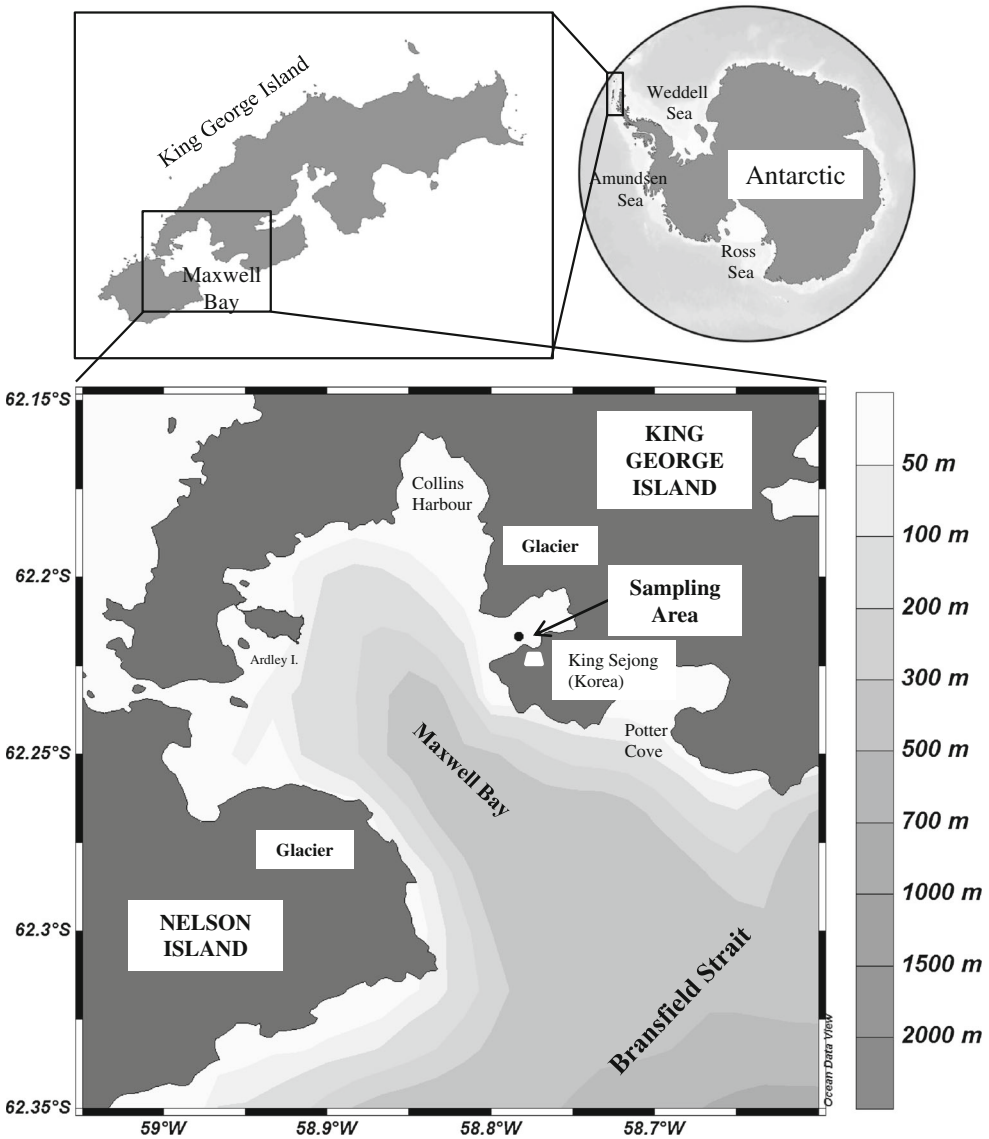


**Fig. 1** The location of the sampling sites (*open circles*) at the King Sejong Station in Marian Cove, Antarctica

conditions and eventually the local marine ecosystem. Therefore, it is necessary to determine the extent to which variations in the marine ecosystem of Marine Cove are driven by the current environmental fluctuations to anticipate ecosystem responses to future environmental change (cf. Murphy et al. 1995). This is particularly important for the phytoplankton, which make a major contribution to the primary production in the Marian Cove marine ecosystem and can be used to detect and monitor marine ecosystem responses to environmental changes.

In Antarctic coastal environments, most phytoplankton studies have been undertaken during summer (December–February) for logistical reasons because this is a period of maximum change in planktonic algal assemblages (Dayton et al. 1986; Fiala and Delille 1992; Brandini and Rebello 1994; Kang et al. 1997, 2002). These previous studies have generally been based on short-term observations of only several years, and continuous year-round monitoring studies have rarely been conducted in Antarctic coastal stations (Clarke et al. 1988; Kopczyńska 2008; Montes-Hugo et al. 2009).

In this study, we conducted year-round monitoring of biological, chemical, and physical parameters from 1996 to 2008 to examine the long-term intra- and inter-annual variability in biomass and species composition of phytoplankton at a coastal site near the Korean King Sejong Station at Marian Cove in Maxwell Bay, King George Island, Antarctica (Fig. 1). In particular, we aimed to focus on the interannual variations in species composition of phytoplankton during peak chlorophyll-*a* (chl-*a*) concentrations

(mostly during the spring bloom) to determine the long-term responses of this coastal marine ecosystem to the current changes in environmental conditions.

## Materials and methods

### Study location

The Korean King Sejong Station (62°13′S, 58°47′W) is located in Marian Cove, which is a tributary inlet of Maxwell Bay, one of the largest fjords on King George Island. King George Island is located in the South Shetland Islands archipelago (Fig. 1). Maxwell Bay is a typical *U*-shaped fjord characterized by a deep sill with a maximum depth of approximately 500 m and a relatively small amount of freshwater input based on an inconspicuous surface mixing layer and the presence of a halocline (Choi et al. 1990; Chang et al. 1990). Marian Cove is strongly influenced by the general circulation in Maxwell Bay (Roese and Drabble 1998). A cyclonic circulation usually prevails with an efficient renewal of the waters in the southern sector of the cove due to the massive entry of waters from Maxwell Bay (Klöser et al. 1994). Two main creeks, Matias and Potter, discharge into the cove, and this freshwater input varies seasonally and annually. When free water inputs occur, the discharge varies from 0.03 to 0.11 $m^3\ s^{-1}$ and from 0.08 to 3.8 $m^3\ s^{-1}$ in the Matias and Potter creeks, respectively (Varela 1998).

### Sampling of physical, chemical, and biological parameters

Surface seawater temperature and salinity were measured daily with a YSI model 30 at a fixed coastal site near the Korean King Sejong Station from 1996 to 2008, with the exception of 1997. The water depth is approximately 5–10 m at this station, and the water is generally well mixed by wind and tidal currents. Water samples from the surface (approximately 0.5 m water depth) at the site were collected daily for total and size-fractionated chl-*a* and species composition of phytoplankton. The chl-*a* concentration was estimated by the spectrophotometric method of Parsons et al. (1984). Water samples for total (pico- and nano-phytoplankton and micro-phytoplankton) chl-*a* concentration were collected on 25-mm glass fiber filters (GF/F; 0.7 μm pore size), and the filters were then extracted in 90 % acetone at 4 °C under dark conditions. Size-fractionated chl-*a* concentration was conducted with 20-μm nylon mesh. Cells that passed through the net were considered as pico- and nano-phytoplankton chl-*a* (<20 μm), whereas those that were retained in the net were considered to be micro-phytoplankton chl-*a* (>20 μm). Water samples for macro-nutrient analysis (nitrate, phosphate, and silicate) were collected daily from 2001 to 2003 and frozen until analysis in the laboratory in Korea. For macro-nutrient concentrations, water samples (500 mL) were filtered through a 47 mm GF/F (0.7 μm pore size) and the filtrates were stored frozen (at −45 °C) in polyethylene bottles (125 mL) that were cleaned with acid. The samples were kept frozen with dry ice during transport to the Korea Polar Research Institute (KOPRI). Nutrient concentrations were determined using a Lachat Autoanalyzer, according to the manufacturer's manual.

### Identification, counts, and biovolume of phytoplankton

Aliquots of 100-mL water samples were preserved with glutaraldehyde (final concentration 1 %) and then filtered through Gelman GN-6 Metricel filters (0.45 μm pore size, 25 mm diameter). The filters were mounted on microscope slides with water-soluble-embedding media HPMA (2-hydroxypropyl methacrylate). HPMA slides were prepared daily at the Korean station and later brought back to the laboratory in Korea for microscopic analyses. HPMA slides were used to estimate cell abundance following the method of Kang (1993) based on Crumpton (1987). HPMA slides, which provide a relatively permanent record of the sample, are ideal for obtaining accurate, quantitative estimates of pico- and nano-size microalgae that can be distinguished by morphological characteristics using a light microscope multiple optical modes of contrast and an epifluorescent microscope (450–490 blue filter). For this study, only species compositions at the highest chl-*a* peaks ($n = 13$) from 1998 to 2008 were analyzed to detect general dominant species compositions and any change in composition over a long-term period. Approximately 300 cells were enumerated using a lighted microscope (BX51, Olympus) at 400× for micro-phytoplankton (>20 μm) and a combination of light and epifluorescence at 1,000× for pico- and nano-phytoplankton (<20 μm) (Booth 1993). Cell counts were converted to cell concentrations ($L^{-1}$) as previously described by Kang and Fryxell (1991) and Kang (1993).

Cell dimensions of dominant phytoplankton species were measured to the nearest 1 μm for subsequent estimations of biovolume using appropriate geometric shapes (Strathman 1967; Sun and Liu 2003). Linear dimensions were measured by light microscopy (BX51, Olympus) and SEM (JSM-5600LV, JEOL). A minimum of thirty individual cells was measured to avoid bias in the results. However, for some rare species, a minimum of 20 cells was measured. The information on taxa and linear dimensions were then transferred to a Microsoft Excel worksheet, and biovolume was calculated according to Sun and Liu (2003).

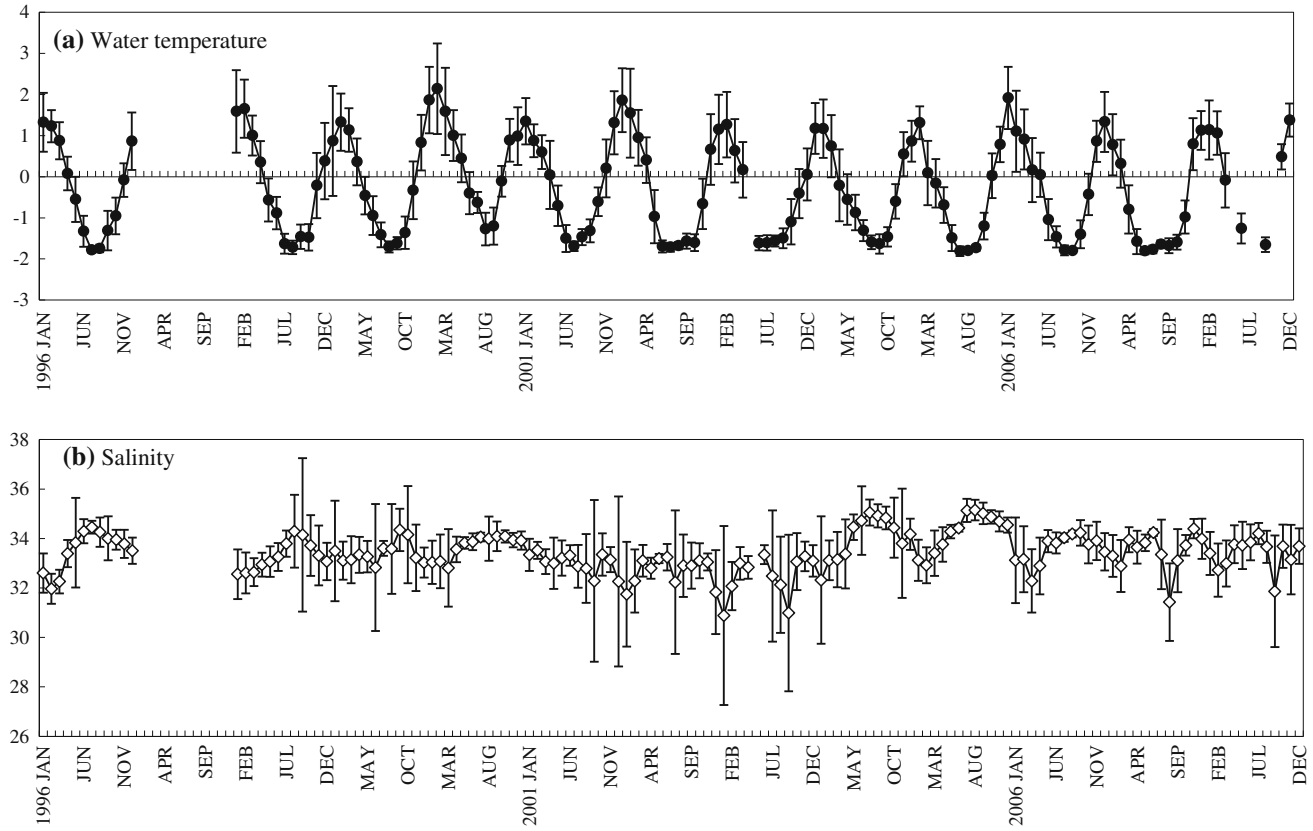


**Fig. 2** Annual patterns of surface water temperature (**a**) and salinity (**b**) at the sampling site, averaged monthly from 1996 to 2008

Statistical analyses

Pearson's correlation analysis was used to estimate the correlation between chl-*a* concentrations and the environmental factors measured in the water samples. Student's *t* test was applied to identify differences in the phytoplankton composition among the samples collected at different sampling times.

## Results

Seasonal and annual patterns of temperature, salinity, and inorganic nutrients

In general, the monthly average surface water temperature at the sampling site in Marian Cove was lowest (−1.80 °C) during winter (July–September) and highest (2.14 °C) during summer (December–February; Fig. 2a). Under normal conditions, temperature started to increase from September to November. The monthly average surface salinity had the opposite trend with a range between 30.9 psu during summer and 35.2 psu during the winter (Fig. 2b). The annual mean water temperature at the site ranged from −0.48 °C in 2005 to 0.49 °C in 2000, with a relatively short duration (during winter) of lower temperatures. Generally, the annual mean surface salinity ranged from 32.5 psu in 2003 to 34.3 psu in 2005. The salinity slightly increased from 2003 to 2005, but has been relatively stable at approximately 34.0 psu since 2005.

Macro-nutrient concentrations were high during the winter (July–September) and low during the phytoplankton growth season from December to January (Fig. 3). The monthly average concentrations of nitrate and silicate ranged from 24.5 to 30.1 μM and from 63.0 to 90.9 μM, respectively. During the spring growth season, the nitrate concentration exhibited a small decrease (approximately 5 μM), whereas the silicate concentration exhibited a large decrease (approximately 28 μM). In comparison, the phosphate concentration was relatively low, ranging from 1.8 to 2.4 μM with only small seasonal variability.

Seasonal and annual patterns of chlorophyll-*a* concentration

The monthly average total chl-*a* concentration ranged from <0.09 to 5.29 mg chl-*a* $m^{-3}$ at the sampling site (Fig. 4), although the daily total chl-*a* concentration reached up to 37.0 mg chl-*a* $m^{-3}$ in November 1996 (data not shown) during the study period. In most years, the total chl-

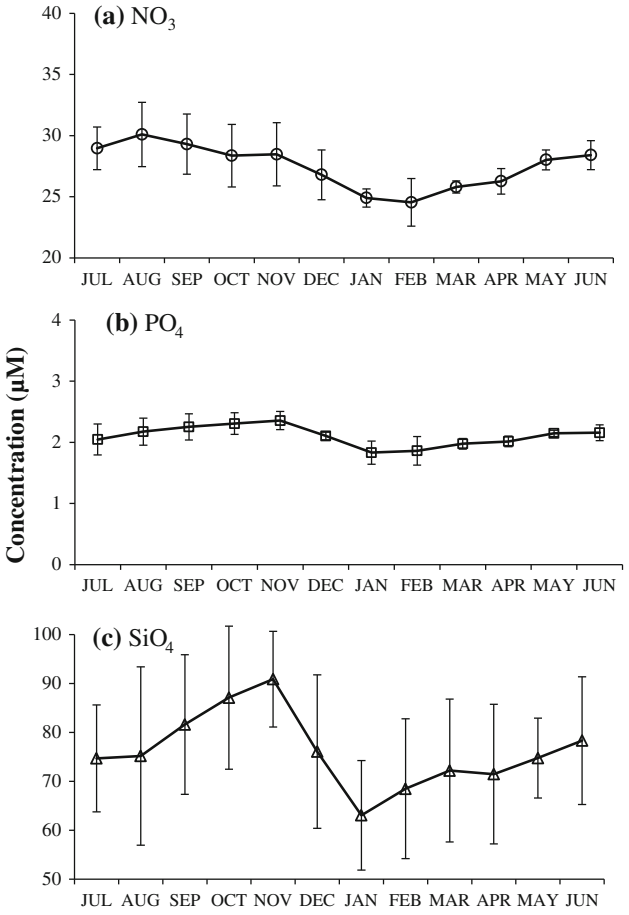


**Fig. 3** Major nutrient concentrations (μM) averaged monthly from 2001 to 2003

*a* concentration began to increase in late November, with the highest chl-*a* peaks mostly observed during December, January, and February; however, high peaks were also found in November and March during several years (Fig. 5). The highest annual peak in total chl-*a* concentrations ranged from 0.90 mg chl-*a* $m^{-3}$ in 2004 to 5.29 mg chl-*a* $m^{-3}$ in 2006 (Fig. 4a) with an average of 1.90 mg chl-*a* $m^{-3}$ (SD = ±1.42 mg chl-*a* $m^{-3}$). After February, the chl-*a* concentration continued to decrease until July. The overall monthly average total chl-*a* concentration ranged from a low of 0.18 mg chl-*a* $m^{-3}$ (SD = ±0.08 mg chl-*a* $m^{-3}$) in July to 1.14 mg chl-*a* $m^{-3}$ (SD = ±1.41 mg chl-*a* $m^{-3}$) in January during the study period (Fig. 6). Generally, the seasonal patterns of chl-*a* concentrations of large (>20 μm) and small (<20 μm) phytoplankton were similar to that of the total chl-*a* concentration. The overall contribution of small phytoplankton to the total chl-*a* concentration was highest in January (mean ± SD = 70.4 ± 22.1 %) and lowest in September (mean ± SD = 54.2 ± 22.8 %) based on the monthly average contributions over 11 years. However, the contribution of small phytoplankton was not significantly different between summer (October–March) and winter (April–September). Pearson's correlation analysis showed strong positive significant relationships between water temperature and total ($r = 0.480$, $n = 131$, $p < 0.01$) and different size-fractionated chl-*a* concentrations ($r = 0.475$, $n = 131$, $p < 0.01$ for small; $r = 0.283$, $n = 131$, $p = 0.01$ for large) (Table 1). In addition, small phytoplankton had a strong negative correlation with nitrate concentration ($r = -0.380$, $n = 35$, $p < 0.05$). The total chl-*a* concentration was strongly correlated with small phytoplankton (<20 μm; $r^2 = 0.8334$, $p < 0.01$), but exhibited a lower correlation with large phytoplankton (>20 μm; $r^2 = 0.516$, $p < 0.01$) (Fig. 7).

## Species compositions of phytoplankton at chlorophyll-*a* peaks

The number of phytoplankton species ranged from 4 to 12 species (mean ± SD = 8.9 ± 2.8) without including unidentified nano-phytoplankton (2–20 μm) and pico-phytoplankton (0.7–2 μm) at the highest chl-*a* peaks from 1998 to 2008 (Table 2). The highest number of phytoplankton species was found in February 2002, and the lowest number was found in February 2001. Generally, no specific trend in the number of phytoplankton species was found over the decade from 1998 to 2008.

The total phytoplankton cell abundance at the chl-*a* peaks ranged from 5.5 × $10^5$ cells $L^{-1}$ in March 2008 to 5.6 × $10^6$ cells $L^{-1}$ in February 2005, with an average of 2.7 × $10^6$ cells $L^{-1}$ (SD = ±1.8 × $10^6$ cells $L^{-1}$) (Table 2). The largest contributors to total phytoplankton cell abundance were unidentified pico-phytoplankton (0.7–2 μm) (mean ± SD = 43.7 ± 21.8 %) and unidentified nano-phytoplankton (2–20 μm) (mean ± SD = 31.7 ± 17.6 %) (Table 3). They were mostly cone-shaped flagellates with 2–4 flagella. The next major contributors were diatoms (mean ± SD = 13.5 ± 13.4 %); the contributions of *Cryptomonas* sp. and *Pyramimonas* sp. were 10.5 % (SD = ±12.5 %) and 6.6 % (SD = ±4.2 %), respectively. Total phytoplankton cell abundance was highest in February 2005 during the period from 1998 to 2008, although the chl-*a* concentration was highest in January 2006 (Fig. 4). In February 2005, unidentified pico-phytoplankton contributed >80 % to the total cell abundance. By contrast, the contribution of large diatoms, mainly *Thalassiosira* spp. (e.g., *T. antarctica* and *T. eccentrica*), was relatively higher in January 2006 (Table 2); these diatoms are typically planktonic organisms.

Regarding the biovolume of phytoplankton, the contribution of small phytoplankton (<20 μm; mainly unidentified nano- and pico-phytoplankton) to the total phytoplankton biovolume at chl-*a* peaks ranged greatly from a minimum of 17.1 % in February 2002 to 94.3 % in

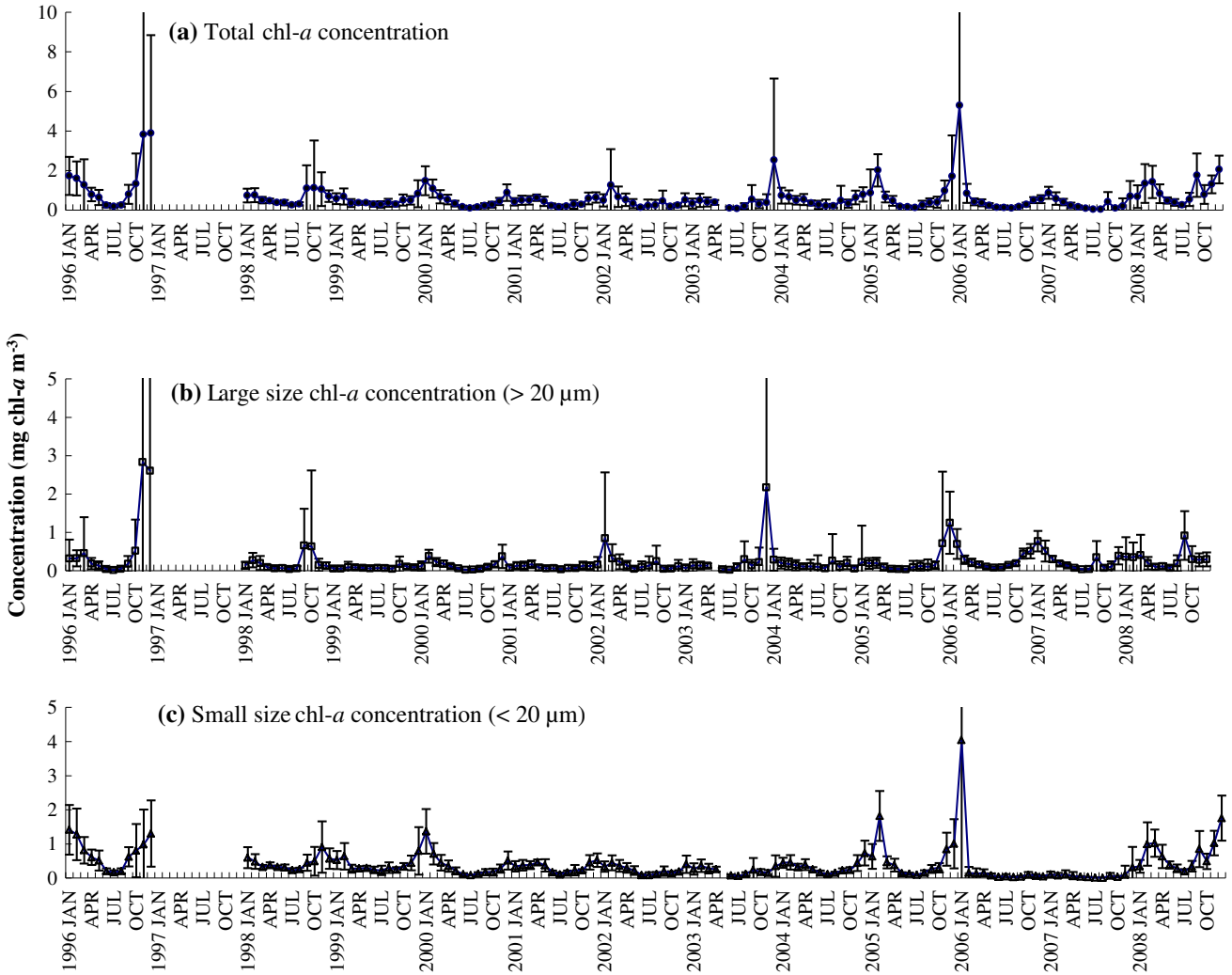


**Fig. 4** Seasonal patterns of surface chlorophyll-*a* concentrations (mg chl-*a* $m^{-3}$) of total (**a**), large >20 µm (**b**), and small <20 µm (**c**) phytoplankton from 1996 to 2008. *Points* show monthly averages of daily samples with *error bars* (±SD)

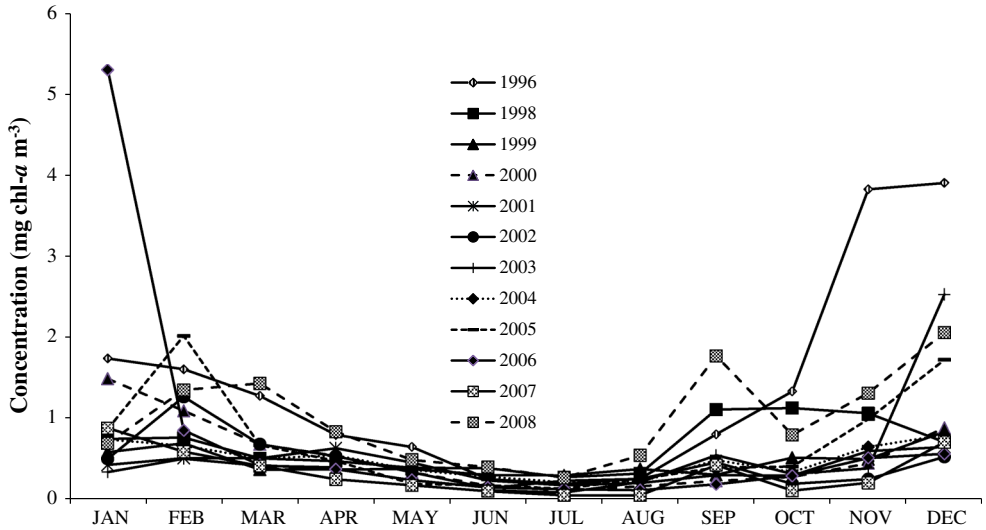


**Fig. 5** Annual patterns in surface chlorophyll-*a* concentrations (mg chl-*a* $m^{-3}$) of total phytoplankton from 1996 to 2008

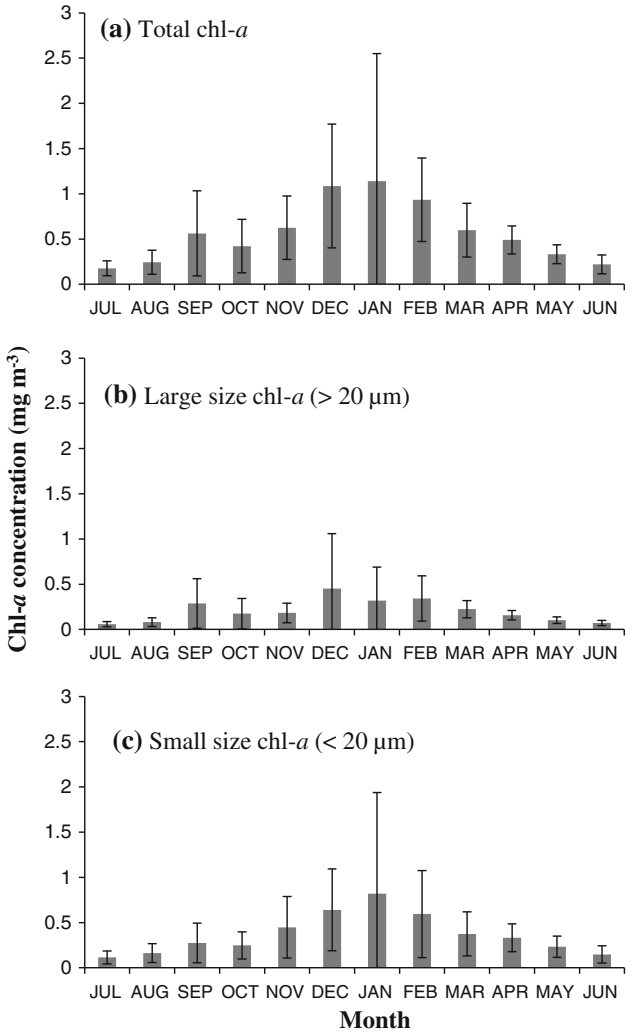


**Fig. 6** Annual patterns of surface chlorophyll-*a* concentrations of total (**a**), large >20 µm (**b**), and small <20 µm (**c**) phytoplankton averaged monthly from 1996 to 2008

February 2005 (Table 4). However, the overall average biovolume contribution of small phytoplankton was 54.4 % (SD = ±27.1 %) to the total biovolume. The inclusion of other small phytoplankton such as *Cryptomonas* sp. and *Pyramimonas* sp. slightly increased the contribution (mean ± SD = 56.4 ± 29.1 %).

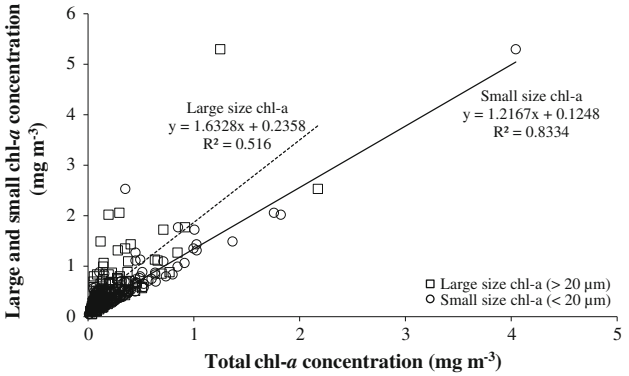


**Fig. 7** Relationship between chlorophyll-*a* concentrations of total, large (>20 µm), and small (<20 µm) phytoplankton fractions

## Discussion and conclusions

The monthly and annual mean water temperatures at the sampling site near the Korean King Sejong Station located in Marian Cove showed a low level of variability, ranging from −1.80 to 2.14 °C and from −0.48 to 0.49 °C, respectively (Fig. 2). The annual mean water temperature (mean ± SD = − 0.26 ± 1.17 °C) in this study was almost identical to that reported previously from the same site by Kang et al. (1997), i.e., −0.28 °C. Considering the sampling site is located on the coast, the monthly surface salinity had a low variability, ranging from 30.9 psu in summer to 35.2 psu in winter. The range of the annual mean water salinity was small (32.5–34.3 psu from 1996 to 2008), which is consistent with the annual mean salinity (33.5 psu) reported by Kang et al. (2002). Recently, Rückamp et al. (2011) reported large changes in the mass of the King George Island ice cap, with an approximately 1.6 % loss of ice from the island between 2000 and 2008. The fast retreat of the ice cliff in Marian Cove has also been recorded recently (Kyu-Cheul, pers. comm.). However, these glacial changes do not appear to have affected the surface water salinity at our sampling site thus far.

Macro-nutrients were generally abundant throughout the season and were relatively higher than those reported previously in other Antarctic coastal regions (Nelson et al.

**Table 1** Pearson's correlation analysis (*r* and *p* values shown) of chlorophyll-*a* and environmental conditions

| | Nitrate | Phosphate | Silicate | Temperature | Salinity |
|---|---|---|---|---|---|
| Total chl-*a* | −0.322, 0.059 | −0.205, 0.238 | −0.157, 0.369 | 0.480, <0.001** | −0.136, 0.115 |
| Small chl-*a* | −0.380, 0.024* | −0.219, 0.206 | 0.025, 0.889 | 0.475, <0.001** | −0.112, 0.204 |
| Large chl-*a* | −0.243, 0.160 | −0.158, 0.365 | −0.187, 0.282 | 0.283, 0.001** | −0.132, 0.132 |

Nutrient data from 2001 to 2003. Small chlorophyll-*a* <20 µm, large chlorophyll-*a* >20 µm

* Correlation is significant at the 0.05 level (two-tailed)

** Correlation is significant at the 0.01 level (two-tailed)

**Table 2** Cell abundance (cells $L^{-1}$) of phytoplankton at the highest chlorophyll-*a* peaks from 1998 to 2008

| Species | 1998_11_21 | 1999_02_12 | 2000_01_16 | 2001_02_14 | 2002_02_09 | 2003_02_15 |
|---|---|---|---|---|---|---|
| Bacillariophyceae | | | | | | |
| *Achnanthes* spp. | 650 | 1,756 | 1,756 | 1,756 | 3,512 | 15,802 |
| *Coconeis costata* | 9,755 | 5,267 | 19,314 | | | 19,314 |
| *Corethron pennatum* | | | | | | |
| *Corethron* sp. | | | | | 3,512 | |
| *Coscinodiscus* spp. (*oculoides*) | | | 1,756 | | | |
| *Fragilaria* sp. | 2,926 | 3,512 | | | | 38,628 |
| *Fragilariopsis cylindrus* | 65,844 | | 47,407 | | | 109,739 |
| *Fragilariopsis pseudonana* | | | | | | 32,922 |
| *Fragilariopsis ritscheri* | | 3,512 | | | | |
| *Fragilariopsis* sp. | 10,974 | 180 | | 65,844 | 21,948 | 21,948 |
| *Licmophora* sp. | 1,971 | 20 | 220 | 8,779 | 80 | 66,722 |
| *Minidiscus* spp. | 21,948 | | | | 21,948 | |
| *Navicula glaciei* | 4,877 | | | | | |
| *Navicula* sp. | 2,601 | 126,200 | 5,267 | | | 5,267 |
| *Nitzschia* sp. | 325 | 120,713 | 5,267 | | | |
| *Rhizosolenia antennate f. semispina* | | | | | 20 | |
| *Rhizosolenia* sp. | | | | | 120 | |
| *Thalassiosira antarctica* | | | 26,337 | | 103,594 | |
| *Thalassiosira eccentrica* | | | | | 36,872 | |
| *Thalassiosira gracilis* | | | | | 94,815 | |
| *Thalassiosira gravida* | | | | | 19,314 | |
| *Thalassiosira* spp. | | 1,756 | 7,023 | | 101,838 | |
| Cryptophyceae | | | | | | |
| *Cryptomonas* spp. | 230,453 | | 120,713 | 460,905 | | |
| Dictyochophyceae | | | | | | |
| *Dictyocha speculum* | | | | | 1,756 | |
| Prymneosiophyceae | | | | | | |
| *Phaeocystis* sp. | 76,818 | | 98,765 | | | |
| Prasinophyceae | | | | | | |
| *Pyramimonas* spp. | | 142,661 | | | | |
| Unidentified spp. (nano-size) | 592,593 | 669,410 | 2,973,937 | 493,827 | 427,984 | 493,827 |
| Unidentified spp. (pico-size) | 3,972,565 | 1,481,481 | 1,657,064 | 998,628 | 230,453 | 680,384 |
| Number of taxa | 14 | 12 | 13 | 6 | 15 | 10 |
| Standing crops (cells $L^{-1}$) | 4,994,299 | 2,556,469 | 4,964,829 | 2,029,739 | 1,067,765 | 1,484,554 |

| Species | 2003_12_12 | 2004_01_23 | 2005_02_05 | 2006_01_12 | 2007_12_23 | 2008_03_24 | 2008_12_14 |
|---|---|---|---|---|---|---|---|
| Bacillariophyceae | | | | | | | |
| *Achnanthes* spp. | | 3,512 | 3,512 | | 207,187 | 7,023 | 3,512 |
| *Coconeis costata* | 29,849 | | 5,267 | | 7,023 | 19,314 | 1,756 |
| *Corethron pennatum* | 100 | 260 | | | | | |
| *Corethron* sp. | | | | | | | |
| *Coscinodiscus* spp. (*oculoides*) | | | | | | | |
| *Fragilaria* sp. | | 10,535 | 3,512 | | 190,508 | 49,163 | 3,512 |
| *Fragilariopsis cylindrus* | | | | | | 65,844 | |
| *Fragilariopsis pseudonana* | | | | | 208,505 | | |
| *Fragilariopsis ritscheri* | | | | | | | |
| *Fragilariopsis* sp. | 32,922 | 21,948 | | | | 32,922 | 12,291 |
| *Licmophora* sp. | 160 | 60 | 100 | | 135,897 | 140 | 20 |

**Table 2** continued

| Species | 2003_12_12 | 2004_01_23 | 2005_02_05 | 2006_01_12 | 2007_12_23 | 2008_03_24 | 2008_12_14 |
|---|---|---|---|---|---|---|---|
| *Minidiscus* spp. | | | | | | | |
| *Navicula glaciei* | | | | | 24,582 | | |
| *Navicula* sp. | | 1,756 | | | 28,971 | 3,512 | |
| *Nitzschia* sp. | | 3,512 | | | 3,512 | | |
| *Rhizosolenia antennate f. semispina* | | | | | | | |
| *Rhizosolenia* sp. | | | | | | | |
| *Thalassiosira antarctica* | 43,896 | 15,802 | | 215,967 | | | |
| *Thalassiosira eccentrica* | | | | | | | |
| *Thalassiosira gracilis* | 63,210 | | | | | | |
| *Thalassiosira gravida* | 3,512 | | | 170,316 | | | |
| *Thalassiosira* spp. | 57,942 | 10,535 | | 108,861 | | | |
| Cryptophyceae | | | | | | | |
| *Cryptomonas* spp. | 120,713 | | 230,453 | 21,948 | 208,505 | 10,974 | 1,009,602 |
| Dictyochophyceae | | | | | | | |
| *Dictyocha speculum* | | | | | | | |
| Prymneosiophyceae | | | | | | | |
| *Phaeocystis* sp. | | | | | 21,948 | | |
| Prasinophyceae | | | | | | | |
| *Pyramimonas* spp. | 65,844 | 131,687 | 384,088 | 76,818 | 43,896 | | 340,192 |
| Unidentified spp. (nano-size) | 164,609 | 449,931 | 460,905 | 1,437,586 | 3,445,816 | 230,453 | 318,244 |
| Unidentified spp. (pico-size) | 131,687 | 757,202 | 4,499,314 | 2,315,501 | 636,488 | 131,687 | 1,042,524 |
| Number of taxa | 12 | 12 | 8 | 7 | 13 | 10 | 9 |
| Standing crops (cells $L^{-1}$) | 714,444 | 1,406,740 | 5,587,151 | 4,346,996 | 5,162,837 | 551,032 | 2,731,652 |

1989; Fiala and Delille 1992). The lowest concentrations of nitrate (24.5 μM), phosphate (1.8 μM), and silicic acid (63.0 μM) normally occurred during the phytoplankton growth season from December to January (Fig. 3). Fiala and Delille (1992) reported that the concentration ranges in the vicinity of the coast of Terre Adélie were 20 to 25 μM, 2 to 2.5 μM, and 45 to 60 μM for nitrate, phosphate, and silicate, respectively. However, the range of the nutrient concentrations reported in this study (with the exception of particularly low nitrate concentrations; 12.1 μM in December 2003; data not shown) was more similar to those from two sampling sites in Borge Bay, Signy Island, from 1969 to 1982 (Clarke et al. 1988). They reported 13–30, 1.2–2, and 65–85 μM for nitrate, phosphate, and silicate, respectively, with a large seasonal variation in nitrate driven by phytoplankton uptake (Clarke et al. 1988). Given these consistently high ambient nutrient concentrations, the growth of phytoplankton in Antarctic coastal waters is unlikely to be limited by major inorganic nutrients (Schloss et al. 2002). In this study, based on Pearson's correlation analysis, the nitrate concentration was negatively correlated with small-sized phytoplankton (Table 1). In fact, several other studies have also shown that small phytoplankton largely depend on ammonium as a source of nitrogen, whereas large phytoplankton depend on nitrate (Probyn 1985; Koike et al. 1986; Lee et al. 2008).

Although there were somewhat large interannual variations, no distinct decadal changes in the seasonal pattern or the magnitude of surface chl-*a* concentrations were found (Fig. 5). The seasonal patterns of chl-*a* concentration were similar to those at Signy Island from 1969 to 1982 (Clarke et al. 1988). The overall annual mean of the surface total chl-*a* concentration was 0.57 mg chl-*a* $m^{-3}$ (SD = ±0.59 mg chl-*a* $m^{-3}$) in this study, which coincides with the lower range of chl-*a* concentration reported in the vicinity of the coast of Terre Adélie by Fiala and Delille (1992). The annual mean of the total surface chl-*a* concentration in this study was lower than that of Kang et al. (2002) (1.38 mg chl-*a* $m^{-3}$) from the same site based on data from 1996. Generally, no exceptionally large phytoplankton blooms were found between 1996 and 2008, except for December 1996 and January 2006 when chl-*a* concentrations reached 3.90 and 5.29 mg chl-*a* $m^{-3}$, respectively (Fig. 4). Although the highest daily chl-*a* concentration reached up to 37.0 mg chl-*a* $m^{-3}$ in November 1996, which have been caused by ice algae

**Table 3** Contributions of different phytoplankton species to the total cell abundance at the highest chlorophyll-*a* peaks from 1998 to 2008

| Species | 1998_11_21 | 1999_02_12 | 2000_01_16 | 2001_02_14 | 2002_02_09 | 2003_02_15 | 2003_12_12 | 2004_01_23 | 2005_02_05 | 2006_01_12 | 2007_12_23 | 2008_03_24 | 2008_12_14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bacillariophyceae | 2.44 % | 10.28 % | 2.30 % | 3.76 % | 38.17 % | 20.90 % | 32.42 % | 4.83 % | 0.22 % | 11.39 % | 15.61 % | 32.29 % | 0.77 % |
| Cryptophyceae | 4.61 % | | 2.43 % | 22.71 % | | | 16.90 % | | 4.12 % | 0.50 % | 4.04 % | 1.99 % | 36.96 % |
| Dictyochophyceae | | | | | 0.16 % | | | | | | | | |
| Prymneosiophyceae | 1.54 % | | 1.99 % | | | | | | | | 0.43 % | | |
| Prasinophyceae | | 5.58 % | | | | | 9.22 % | 9.36 % | 6.87 % | 1.77 % | 0.85 % | | 12.45 % |
| Unidentified spp. (nano) | 11.87 % | 26.18 % | 59.90 % | 24.33 % | 40.08 % | 33.26 % | 23.04 % | 31.98 % | 8.25 % | 33.07 % | 66.74 % | 41.82 % | 11.65 % |
| Unidentified spp. (pico) | 79.54 % | 57.95 % | 33.38 % | 49.20 % | 21.58 % | 45.83 % | 18.43 % | 53.83 % | 80.53 % | 53.27 % | 12.33 % | 23.90 % | 38.16 % |
| Total chl-*a* (mg chl-*a* $m^{-3}$) | 2.70 | 2.17 | 3.60 | 1.21 | 9.24 | 1.32 | 14.99 | 1.50 | 3.49 | 19.80 | 3.73 | 4.66 | 4.23 |
| Standing crops (cells $L^{-1}$) | 4,994,298 | 2,556,469 | 4,964,829 | 2,029,739 | 1,067,765 | 1,484,554 | 714,444 | 1,406,740 | 5,587,151 | 4,346,996 | 5,162,837 | 551,032 | 2,731,652 |

released from melting sea ice or the resuspension of benthic microalgae by wind or tidal currents (Kang et al. 2002), the monthly average chl-*a* magnitude of phytoplankton bloom in this study was very low compared with those measured by Clarke et al. (1988) at the coastal sites in Borge Bay, Signy Island, which reached above 40 mg chl-*a* $m^{-3}$ in January. Generally, the monthly average chl-*a* concentrations in this study were highest during summer, whereas the lowest values occurred during winter (June–August) (Fig. 6). The sum of the chl-*a* concentrations from all size fractions between December and January contributed approximately 32 % to the total annual chl-*a* concentration from 1998 to 2008. Previously, Kang et al. (2002) estimated that the chl-*a* concentrations during November and December contributed more than 45 % to the annual chl-*a* concentration at the same sampling site. In addition, summer chl-*a* concentrations between October and March contributed 70 % to the annual chl-*a* concentration in this study, whereas Kang et al. (1997) reported that the summer chl-*a* contribution was 82 % at the same sampling sites. This discrepancy between studies can be attributed to the different observation periods. However, their results were based on the measurements from only 1 year (1996), and our study assimilates 12 years of measurements.

The size fractionation study from 1996 to 2008 demonstrated that the largest contributors to chl-*a* concentrations in Marian Cove throughout the year were the small phytoplankton (<20 μm) (mean ± SD = 62.9 ± 4.1 %). At the highest chl-*a* peaks during the observation period, small phytoplankton (nano- and pico-phytoplankton) remained as the largest contributors to the total phytoplankton cell abundance (Table 2). This is supported by the observation that the total chl-*a* concentration was more positively correlated with the small phytoplankton concentration ($r^2 = 0.8334$, $p < 0.01$) than with the large (>20 μm) phytoplankton ($r^2 = 0.516$, $p < 0.01$) (Fig. 7). The second most abundant group found at every peak was large diatoms (>20 μm), which contributed approximately 0.2–38.2 % to the total cell abundance. Kopczyńska (2008) reported that *Chaetoceros* spp. were only observed from January to March 2003 at the open water site in Admiralty Bay, King George Island, during a 6-year study, but no *Chaetoceros* spp. were found in our study (Table 2). By contrast, *Cryptomonas* spp. was often abundant when the diatom abundance was low (Table 2). Several silicoflagellates (Dictyochophyceae; ~0.2 %) were found at the February peak in 2002, whereas Prasinophyceae became abundant (ranging from 1.8 % to 12.5 %) at the chl-*a* peaks from 2003 onward, with the exception of 2008. We did not find *Phaeocystis* spp. in the chl-*a* peaks in this study, with the exception of November 1998 and January 2000 (Table 2); these results do not support the findings of Kang et al. (2002) at the same site. They found that the

**Table 4** Biovolume contributions of different species of phytoplankton to the total phytoplankton at the highest chlorophyll-*a* peaks from 1998 to 2008

| Species | 1998_11_21 | 1999_02_12 | 2000_01_16 | 2001_02_14 | 2002_02_09 | 2003_02_15 | 2003_12_12 |
|---|---|---|---|---|---|---|---|
| Bacillariophyceae | | | | | | | |
| *Achnanthes* spp. | 0.22 | 0.19 | 0.12 | 0.69 | 0.36 | 4.60 | |
| *C. costata* | 0.47 | 0.08 | 0.19 | | | 0.78 | 0.96 |
| *C. pennatum* | | | | | | | 0.09 |
| *Corethron* sp. | | | | | 1.38 | | |
| *Coscinodiscus* spp. (*oculoides*) | | | 5.39 | | | | |
| *Fragilaria* sp. | 0.84 | 0.21 | | | | 6.13 | |
| *F. cylindrus* | 2.18 | | 0.78 | | | 7.34 | |
| *F. pseudonana* | | | | | | 0.93 | |
| *F. ritscheri* | | 0.20 | | | | | |
| *Fragilariopsis* sp. | 0.35 | 0.01 | | 13.15 | 1.14 | 3.26 | 3.89 |
| *Licmophora* sp. | 0.57 | 0.00 | 0.01 | 2.85 | 0.01 | 16.12 | 0.03 |
| *Minidiscus* spp. | 0.08 | | | | 0.02 | | |
| *N. glaciei* | 0.65 | | | | | | |
| *Navicula* sp. | 0.35 | 27.42 | 0.75 | | | 3.05 | |
| *Nitzschia* sp. | 0.35 | 41.28 | 1.18 | | | | |
| *R. antennate f. semispina* | | | | | 0.14 | | |
| *Rhizosolenia* sp. | | | | | 0.87 | | |
| *T. antarctica* | | | 6.64 | | 37.16 | | 35.96 |
| *T. eccentrica* | | | | | 8.96 | | |
| *T. gracilis* | | | | | 9.83 | | 14.97 |
| *T. gravida* | | | | | 2.16 | | 0.90 |
| *Thalassiosira* spp. | | 0.39 | 1.01 | | 20.84 | | 27.09 |
| Cryptophyceae | | | | | | | |
| *Cryptomonas* spp. | 1.94 | | 0.21 | 4.45 | | | 0.69 |
| Dictyochophyceae | | | | | | | |
| *D. speculum* | | | | | 0.01 | | |
| Prymneosiophyceae | | | | | | | |
| *Phaeocystis* spp. | 0.51 | | 0.14 | | | | |
| Prasinophyceae | | | | | | | |
| *Pyramimonas* spp. | | 0.30 | | | | | 0.29 |
| Unidentified spp. (nano-size) | 78.93 | 28.43 | 82.50 | 75.24 | 16.89 | 55.96 | 14.84 |
| Unidentified spp. (pico-size) | 12.57 | 1.50 | 1.09 | 3.62 | 0.22 | 1.83 | 0.28 |

| Species | 2004_01_23 | 2005_02_05 | 2006_01_12 | 2007_12_23 | 2008_03_24 | 2008_12_14 |
|---|---|---|---|---|---|---|
| Bacillariophyceae | | | | | | |
| *Achnanthes* spp. | 1.18 | 1.46 | | 10.25 | 4.21 | 1.98 |
| *C. costata* | | 0.31 | | 0.05 | 1.62 | 0.14 |
| *C. pennatum* | 0.34 | | | | | |
| *Corethron* sp. | | | | | | |
| *Coscinodiscus* spp. (*oculoides*) | | | | | | |
| *Fragilaria* sp. | 1.93 | 0.80 | | 8.73 | 16.07 | 1.08 |
| *F. cylindrus* | | | | 0.00 | 9.08 | |
| *F. pseudonana* | | | | 1.00 | | |
| *F. ritscheri* | | | | | | |
| *Fragilariopsis* sp. | 3.76 | | | 3.78 | 10.07 | 3.54 |
| *Licmophora* sp. | 0.02 | 0.03 | | 7.87 | 0.07 | 0.01 |
| *Minidiscus* spp. | | | | | | |

**Table 4** continued

| Species | 2004_01_23 | 2005_02_05 | 2006_01_12 | 2007_12_23 | 2008_03_24 | 2008_12_14 |
|---|---|---|---|---|---|---|
| *N. glaciei* | | | | 0.47 | | |
| *Navicula* sp. | 1.17 | | | 0.56 | 4.19 | |
| *Nitzschia* sp. | 3.69 | | | 0.25 | | |
| *R. antennate f. semispina* | | | | | | |
| *Rhizosolenia* sp. | | | | | | |
| *T. antarctica* | 18.77 | | 43.53 | | | |
| *T. eccentrica* | | | | | | |
| *T. gracilis* | | | | | | |
| *T. gravida* | | | 10.72 | | | |
| *Thalassiosira* spp. | 7.14 | | 12.52 | | | |
| Cryptophyceae | | | | | | |
| *Cryptomonas* spp. | | 2.36 | 0.03 | 0.25 | 0.16 | 14.07 |
| Dictyochophyceae | | | | | | |
| *D. speculum* | | | | | | |
| Prymneosiophyceae | | | | | | |
| *Phaeocystis* spp. | | | | 0.02 | | |
| Prasinophyceae | | | | | | |
| *Pyramimonas* spp. | 0.85 | 3.08 | 0.08 | 0.04 | | 3.71 |
| Unidentified spp. (nano-size) | 58.80 | 74.64 | 31.89 | 66.43 | 53.80 | 70.01 |
| Unidentified spp. (pico-size) | 2.35 | 17.32 | 1.22 | 0.29 | 0.73 | 5.45 |

major carbon sources in January 1996 were the nanoflagellate, *P. antarctica*, and other unidentified nano-phytoplankton (Kang et al. 2002). Overall, the number of phytoplankton species was found to be relatively lower (mean ± SD = 8.9 ± 2.8) than that reported by Jeon (2014). Our lower number of taxa could be due to species composition analysis being performed only at the highest chl-*a* peaks when several species were predominant. In addition, there were several taxa included in the category of "unidentified" nano- (2–20 μm) and pico-phytoplankton (0.7–2 μm) that were major contributors to the total phytoplankton community.

Although there have been a number of previous reports on cell size composition demonstrating a dominance of nano-phytoplankton compared with micro-phytoplankton in open ocean waters around the Antarctic (Hewes et al. 1985; Weber and El-Sayed 1987; El-Sayed 1988), the large contribution of small phytoplankton (<20 μm) in this study is unusual for phytoplankton communities from Antarctic coastal sites, as they are normally dominated by large phytoplankton (>20 μm) (Holm-Hansen et al. 1989; Fiala and Delille 1992; Fiala et al. 1998; Wright et al. 2009). Holm-Hansen et al. (1989) reported that nano-phytoplankton (<10 μm) accounted for only 28 % of the total phytoplankton biomass in the vicinity of Palmer Station, Antarctica. Particularly, during Antarctic spring and summer blooms, micro-phytoplankton dominated by large diatoms and autotrophic dinoflagellates contributed significantly (>60 %) to the high biomass of total phytoplankton (Fiala et al. 1998). The different contributions of small cell sizes to the total chl-*a* concentration appear to be highly seasonal and regional (Wright et al. 2009). Fiala et al. (1998) reported that large phytoplankton (>10 μm) contributed 60 % of the total biomass during summer blooms, whereas small cells (<10 μm) contributed 80 % of the total chl-*a* biomass and were dominated by pico-phytoplankton during winter at the Kerfix Station, located off the Kerguelen Islands, Antarctica. Considering regional variation, Varela et al. (2002) studied three different regions in the Gerlache and south Bransfield Straits during summer 1995–1996; the two sites were dominated by small (<10 μm) phytoplankton (>65 % of chl-*a*), and one site was dominated by large (>10 μm) diatoms (80 % of chl-*a*). However, our sampling site (with similar sampling water depths, times, etc.) in Marian Cove and the high contribution (>60 %) of small phytoplankton (<20 μm) were consistent across seasons from 1996 to 2008.

Wright et al. (2009) noted that conventional filter fractionation techniques have several over- and/or underestimation problems when applied to estimations of the biomass of small phytoplankton in Antarctic waters. Small cells can be trapped on the filter due to clogging, which causes an underestimation of small phytoplankton contribution; they can also be overestimated when larger spindle-

shaped diatoms and cell fragments of dinoflagellates, diatoms, and cryptophytes pass through the 20-μm filter (Wright et al. 2009). Therefore, the failure to conduct microscopic confirmation could lead to misleading estimates of the contribution of small phytoplankton to the total chl-*a* in Antarctic waters (Wright et al. 2009). Based on microscopic analysis of phytoplankton from the highest chl-*a* peaks each year, the high contribution (mean ± SD = 62.9 ± 4.1 %) of small phytoplankton to the total chl-*a* concentration is consistent with the total cell numbers and biovolumes of phytoplankton in this study (Tables 2, 4). Small phytoplankton contributed approximately 61.8–99.8 % (mean ± SD = 85.7 ± 14.2 %) to the total phytoplankton numbers (Table 3) when the chl-*a* concentrations were highest during the seasons from 1998 to 2008 (Fig. 4). Regarding the biovolume, small phytoplankton contributed 56.4 % to the total phytoplankton biovolume, although there was a large interannual variation in the contribution of small phytoplankton (Table 4). Based on 1 year of microscopic analysis, Jeon (2014) reported that small phytoplankton were predominant throughout the season in 2010 at the same location near the Korean King Sejong Station. In fact, Kopczyńska (2008) also reported that pico-sized cells and nanoflagellates were dominant groups contributing >85 % to the total cell concentrations in Admiralty Bay, King George Island. Based on our observations, we assert that the high contribution of small phytoplankton to total phytoplankton community was not a seasonal or annual feature but a general characteristic of Marian Cove throughout the year.

Different grazing pressures by zooplankton on larger phytoplankton might be one of the reasons for the high contribution of small phytoplankton in this study (Kopczyńska 1996, 2008). Large cells (mainly diatoms) dominated when grazing pressure was low during the early developmental stages of a high-latitude spring bloom in the vicinity of Palmer Station, Antarctica (Holm-Hansen et al. 1989). In Arctic coastal waters, strong grazing pressure on large phytoplankton resulted in a difference in the contributions of large and small phytoplankton to primary production; primary production was generally dominated by large phytoplankton, whereas standing stock was dominated by small phytoplankton (Legendre et al. 1993). Future studies on the zooplankton grazing will be needed for a better understanding of the relative contributions of small and large phytoplankton to the total phytoplankton community in Marian Cove.

Among the physicochemical environmental factors, water temperature was positively correlated with total and different size-fractionated chl-*a* concentrations in our study area (Table 1), which is consistent with the finding by Kopczyńska (1996). The author reported that temperature was one of the major factors affecting the bloom magnitude of all phytoplankton including small flagellates in Admiralty Bay. Therefore, total phytoplankton biomass and abundance may be expected to increase under ongoing warming conditions around the Antarctic Peninsula. At Marian Cove, our data suggest that this will be driven by the contribution of the small phytoplankton community, because a stronger correlation was found between the abundance of small phytoplankton and total phytoplankton (Fig. 7). To better understand the importance of the size fractions to the total phytoplankton community, and therefore the marine ecosystem, we suggest two approaches:

1. Size-fractionated phytoplankton studies should be further extended outside Marian Cove to obtain an better regional perspective and
2. Studies on seasonal variations of grazing zooplankton as top-down regulators will be needed to improve the understanding of long-term changes in the marine coastal ecosystem at King George Island, Antarctica.

**Acknowledgments** We sincerely thank the members of the overwintering Korean teams at the Korean King Sejong Station for their scientific support. We especially thank the anonymous reviewers who greatly improved an earlier version of the manuscript. This work was supported by a grant from the Korea-Polar Ocean in Rapid Transition (K-PORT; PM13020) program of the Korea Polar Research Institute funded by the Ministry of Oceans and Fisheries, Korea.

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