

# Seawater nutrient and chlorophyll $\alpha$ distributions near the Great Wall Station, Antarctica

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Received 30 June 2014; accepted 2 March 2015

**Abstract** We examined the influences upon nutrient, temperature, salinity and chlorophyll  $a$  distributions in Great Wall Cove (GWC) and Ardley Cove (AC), near the Chinese Antarctic Great Wall Station, using measurements taken in January 2013 and other recent data. Nutrient concentrations were high, with phosphate concentrations of 1.94 (GWC) and 1.96 (AC)  $\mu\text{mol}\cdot\text{L}^{-1}$ , DIN(dissolved inorganic nitrogen) concentrations of 26.36 (GWC) and 25.94 (AC)  $\mu\text{mol}\cdot\text{L}^{-1}$  and silicate concentrations of 78.6 (GWC) and 79.3 (AC)  $\mu\text{mol}\cdot\text{L}^{-1}$ . However, average concentrations of chlorophyll  $a$  were low (1.29  $\mu\text{g}\cdot\text{L}^{-1}$ , GWC and 1.08  $\mu\text{g}\cdot\text{L}^{-1}$ , AC), indicating that this region is a high-nutrient and low-chlorophyll (HNLC) area. Nutrient concentrations of freshwater (stream and snowmelt) discharge into GWC and AC in the austral summer are low, meaning freshwater discharge dilutes the nutrient concentrations in the two coves. Strong intrusion of nutrient-rich water from the Bransfield Current in the south was the main source of nutrients in GWC and AC. Low water temperature and strong wind-induced turbulence and instability in the upper layers of the water column were the two main factors that caused the low phytoplankton biomass during the austral summer.

**Keywords** nutrient, chlorophyll  $a$ , Great Wall Cove, Ardley Cove, Antarctica

**Citation:** Gao S Q, Jin H Y, Zhuang Y P, et al. Seawater nutrient and chlorophyll  $a$  distributions near the Great Wall Station, Antarctica. Adv Polar Sci, 2015, 26: 63-70, doi:10.13679/j.advps.2015.1.00063

## 1 Introduction

Nutrients(N, P and Si) are essential elements for phytoplankton growth in marine ecosystems. Antarctic coastal waters are usually considered productive areas<sup>[1-2]</sup>. However, some shallow coastal areas are known to be high-nutrient and low-chlorophyll (HNLC) systems, where despite favorable conditions for phytoplankton growth, phytoplankton biomass remains low<sup>[3-4]</sup>. The concentrations of nutrients in Antarctic waters are generally very high<sup>[5-6]</sup> because of the combination of strong and continuous upwelling of nutrient-rich Upper Circumpolar Deep Water (UCDW) at the Antarctic Divergence coupled with relatively

low rates of biological uptake. However, except for some highly productive coastal or marginal ice environments<sup>[7]</sup>, Antarctic waters, especially shallow areas, can show very low phytoplankton biomass and productivity<sup>[3-4]</sup> with chlorophyll  $a$  rarely exceeding 3  $\mu\text{g}\cdot\text{L}^{-1}$ <sup>[8-9]</sup>. The low rate of biological uptake of nutrients is due to low phytoplankton biomass and low growth rates. Different hypotheses have been suggested to explain the low biomass: grazing pressure<sup>[10]</sup>, light limitation related to deep mixing<sup>[11]</sup>, lack of iron<sup>[12]</sup> and strong wind activity<sup>[4, 13]</sup>.

King George Island in the West Antarctica is one of the most rapidly warming regions on Earth<sup>[14-15]</sup>. Monthly air temperature recorded at the Chinese Antarctic Great Wall Station increased on average by 0.62°C over the period 1985–2008<sup>[15]</sup>. Increased air temperatures in West Antarctica have

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been associated with retreating glacier fronts and increased ice mass loss from land glaciers<sup>[16]</sup>. This aerial warming is favorable to phytoplankton growth, but the resultant meltwater intensifies water column stratification<sup>[14]</sup>, especially in shallow coastal environments of the Western Antarctic Peninsula. Meltwater and glacier run-off also transport high particle loads. This affects the amount of light penetration within the water column, and the conditions under which photosynthesis occurs in these coastal areas<sup>[1,17]</sup>. Coastal marine environments are ecosystem boundaries between land and offshore marine waters. These systems undergo an intense transfer of matter and energy flowing in both directions and their hydrographical and biological conditions are strongly influenced by both local processes and global trends<sup>[1,16-17]</sup>.

Previous observations and studies of the marine ecological conditions near the Great Wall Station mainly focused upon primary productivity<sup>[18]</sup>, the variation in the concentrations of chlorophyll  $\alpha$ <sup>[8,19-20]</sup> and surface water nutrient concentrations<sup>[21]</sup>. Sampling stations and observed parameters were insufficient to permit a comprehensive discussion of nutrient conditions relative to the physical and biological characteristics in this area. In this paper we present a discussion of seawater nutrient conditions, chlorophyll  $\alpha$  distributions and physical characteristics of the water column near the Great Wall Station, and their relationships to air temperature and climate forcing.

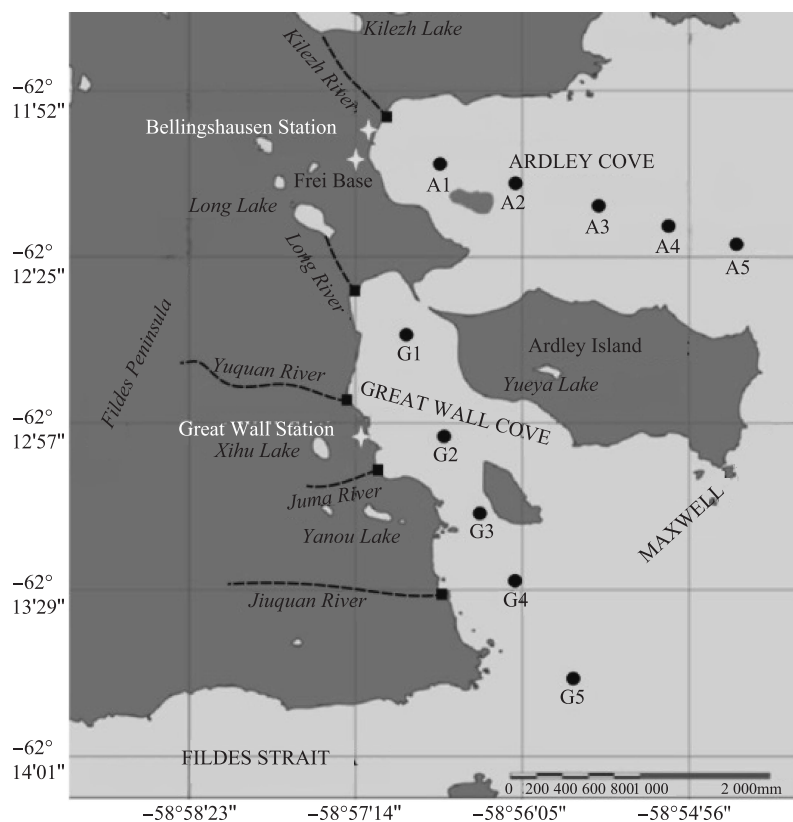
## 2 Materials and methods

### 2.1 Study area

Observations were carried out in January 2013 during the twenty-ninth Chinese National Antarctic Research Expedition (29th CHINARE), in Great Wall Cove (GWC) and Ardley Cove (AC) of King George Island, one of the South Shetland Islands of Antarctica. These two coves are located on the western side of Maxwell Bay, which connects to the Bransfield Strait (Figure 1). The two coves are separated by Ardley Island, which is the habitat of a great number of penguins and other sea birds. The western tip of Ardley Island is connected to the Fildes Peninsula by a sand bar during times of low tide, but at high tide, this sand bar is submerged and two coves are connected. During the austral summer, several streams along the coasts discharge into GWC and AC. The coasts are glacier-free, with isolated snow-bound areas remaining only in the mountainous regions of the island.

### 2.2 Sampling and analysis

Water samples were taken in GWC and AC with a 5-L Niskin sampler on 17 and 23 January 2013. A hand winch was used to deploy the sampler from an inflatable rubber boat. Water



**Figure 1** Location of sampling stations in Great Wall Cove and Ardley Cove.

samples were taken along transects from the inner to outer cove (stations 1, 2, 3, 4, 5) at depths of 0.5, 5, 10, 20, and 30 m (Figure 1). All samples were kept cold after collection and transported to the Great Wall Station laboratory within 4 h. Water samples were also collected from streams and lakes around the two coves (Figure 1).

Water samples were filtered through glass fiber (Whatman GF/F) filters, which were frozen and sent to Second Institute of Oceanography, SOA, Hangzhou for analysis, along with subsamples of water for determining nitrate and silicate concentrations. Phosphate, nitrite and ammonia were analyzed at the Great Wall Station using phospho-molybdenum blue for phosphate, diazo-azo for nitrite and phenol-hypochlorite for ammonia, according to the Chinese “Specification for Oceanographic Survey”<sup>[22]</sup>.

Nitrate and silicate were measured using an Automatic Nutrient Analyzer (SkalarSan<sup>++</sup>). All analytical data were calibrated by Standard Solution of Nutrients (Center of Standard Material, SOA).

The filters were extracted in 90% acetone and kept at  $-20^{\circ}\text{C}$  in the dark. Chlorophyll *a* concentrations were determined according to fluorescence readings using a Turner

10-AU fluorometer.

Seawater temperature and salinity were measured in situ with a CTDI fast (RBR concerto). Meteorological data was obtained from the Chinese Polar Scientific Expedition Management Information System.

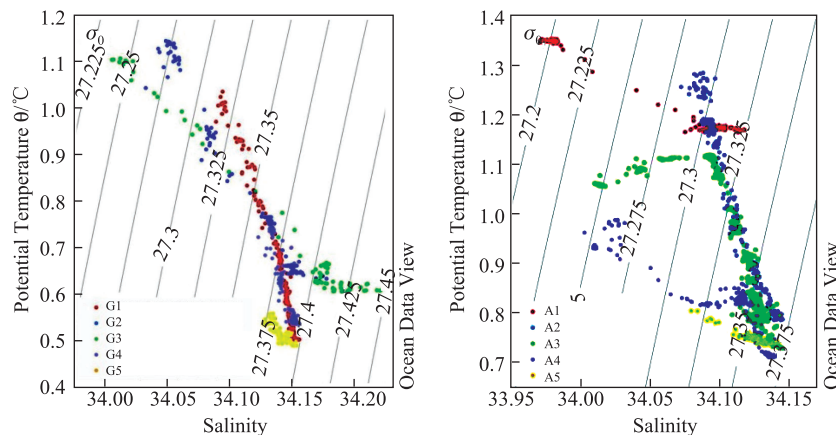
### 3 Results

#### 3.1 Temperature and salinity

Water temperature was in the range of  $0.49^{\circ}\text{C}$ – $1.15^{\circ}\text{C}$  (average  $0.72^{\circ}\text{C}$ ) in GWC and  $0.72^{\circ}\text{C}$ – $1.36^{\circ}\text{C}$  (average  $1.02^{\circ}\text{C}$ ) in AC (Table 1). Surface water temperatures were higher than bottom waters. There was an overall pattern of decreasing temperature from the inner to outer cove and from surface to bottom (Figure 3). Thermal stratification was only observed in the upper 10 m in GWC, but reached as deep as 30 m in AC. Stratification was not obvious in the outer regions of either cove. The maximum temperature measured in GWC was  $1.15^{\circ}\text{C}$  (station G2), with a maximum of  $1.36^{\circ}\text{C}$  in AC (station A1). Average water temperature in AC was  $0.23^{\circ}\text{C}$  higher than in GWC. Mean air temperature at AC increased during the observation period.

**Table 1** Environmental parameters of Great Wall Cove and Ardley Cove

Parameters	Great Wall Cove			Ardley Cove		
	Number	Average	Range	Number	Average	Range
T/ $^{\circ}\text{C}$	17	0.72	0.49–1.15	19	1.02	0.72–1.36
S/psu	17	34.13	34.02–34.21	19	34.08	33.97–34.14
$\text{PO}_4^{3-}/\mu\text{M}$	17	1.94	1.86–2.01	19	1.96	1.89–2.01
$\text{NO}_3^- + \text{NO}_2^-/\mu\text{M}$	17	25.12	24.19–26.24	19	25.13	24.41–25.72
$\text{NH}_4^+/\mu\text{M}$	17	1.24	0.87–1.99	19	0.81	0.42–1.74
DIN/ $\mu\text{M}$	17	26.36	25.50–28.22	19	25.94	25.20–27.45
$\text{SiO}_3^{2-}/\mu\text{M}$	17	78.61	77.56–80.26	19	79.32	78.52–80.14
Chl. <i>a</i> /( $\mu\text{g}\cdot\text{L}^{-1}$ )	17	1.29	0.42–3.08	19	1.08	0.81–1.49
N/P	17	13.6	13.1–14.0	19	13.2	12.8–13.8
Si/P	17	40.5	39.2–41.9	19	40.4	39.1–41.6



**Figure 2** Temperature-salinity diagrams of Great Wall Cove section (left) and Ardley Cove section (right).

Salinity ranged from 34.02 to 34.21 psu in GWC and from 33.97 to 34.14 psu in AC (Table 1). Surface salinity was low in mid-January because of the intense snow melting and increased freshwater run-off into the two coves, with a minimum of ~34 psu. Strong stratification was observed in the upper layers (0–10m) in the inner coves, but was nearly absent in the outer coves.

The temperature-salinity (T-S) structures in GWC and AC (Figure 2) represent mixing of Bransfield Current waters and freshwater from river discharge and snowmelt. The degree of mixing depends upon the distance of the sampling station from the river mouth. Stations G2 and G3 in GWC are considerably influenced by the Yuquan and Juma rivers, showing lower salinity and higher temperature in surface waters. Station G5 was dominated by Bransfield Current waters<sup>[23]</sup>, with lower temperature and higher salinity. High-salinity bottom water at station G3 in GWC was assumed to indicate water that had remained since winter, while lower-salinity waters in the upper layers at stations A3 and A4 of AC were probably influenced by melting of small pieces of glacier-derived ice, which drift into the cove from the north-eastern coast. The average surface water temperature in 2013 was lower than in 2000 and 2011, whereas the salinity was slightly higher than that in the year 2000 and 2011<sup>[24–25]</sup>.

### 3.2 Nutrients

The dissolved inorganic nitrogen (DIN) concentrations ranged from 25.20 to 28.22  $\mu\text{mol}\cdot\text{L}^{-1}$ , with an average concentration of 26.36  $\mu\text{mol}\cdot\text{L}^{-1}$  in GWC and 25.94  $\mu\text{mol}\cdot\text{L}^{-1}$  in AC. The variations in DIN concentration were small, with no significant difference ( $P < 0.01$ ) between the two coves except that the average concentration of ammonia in GWC was slightly higher than in AC (Table 1). Vertical distributions of DIN were similar in the two coves, with high DIN in the bottom water of the outer coves and low DIN in surface waters (Figures 3e and 3f). The DIN concentrations of the surface water in AC were slightly lower than those in GWC surface waters, and concentrations of surface DIN in AC were low throughout the transect, while low values of surface DIN in GWC were only observed in the inner cove.

Phosphate concentrations ranged from 1.86 to 2.01  $\mu\text{mol}\cdot\text{L}^{-1}$ , with average concentrations of 1.94 in GWC and 1.96 in AC. Silicate concentrations ranged from 77.56 to 80.26  $\mu\text{mol}\cdot\text{L}^{-1}$ , with average concentrations of 78.61  $\mu\text{mol}\cdot\text{L}^{-1}$  in GWC and 79.32  $\mu\text{mol}\cdot\text{L}^{-1}$  in AC (Table 1). The differences in phosphate and silicate concentrations between the two coves were not significant either horizontally or vertically.

The distribution patterns of phosphate and silicate were similar to those of DIN in GWC, increasing gradually from the inner to outer cove and from the surface to the bottom except for the high silicate value at the surface at station G5. However, in AC, phosphate and silicate distributions showed some differences from DIN (Figures 3f, 3h and 3j). A high phosphate concentration was observed at the surface at station

A2, with high silicate concentration in the subsurface layer at station A3. The lowest levels of phosphate (1.89  $\mu\text{mol}\cdot\text{L}^{-1}$ ) and silicate (78.53  $\mu\text{mol}\cdot\text{L}^{-1}$ ) were found in the subsurface, rather than the surface layer, at station A5, which was most likely caused by mixing of waters from the outer cove.

N/P ratios in both of the coves were close to, or slightly lower, than the Redfield ratio of 16:1<sup>[26]</sup>, and they were similar to the values observed in Admiralty Bay, King George Island<sup>[13]</sup>. The ranges of Si/P ratios were 39.2–41.9 for GWC and 39.1–41.6 for AC. These Si/P ratios were slightly higher than that of Admiralty Bay, but lower than the values of Bransfield Current waters<sup>[23]</sup>.

### 3.3 Chlorophyll $\alpha$

Average concentrations of chlorophyll  $\alpha$  were 1.29  $\mu\text{g}\cdot\text{L}^{-1}$  in GWC and 1.08  $\mu\text{g}\cdot\text{L}^{-1}$  in AC (Table 1). The range of chlorophyll  $\alpha$  concentrations in GWC (0.42–3.08  $\mu\text{g}\cdot\text{L}^{-1}$ ) was greater than that in AC (0.81–1.49  $\mu\text{g}\cdot\text{L}^{-1}$ ). It can be seen from Figures 3k and 3l that the distributions of chlorophyll  $\alpha$  throughout the water profile are markedly different. In GWC, there were two sites of high chlorophyll  $\alpha$  concentration: 3.08  $\mu\text{g}\cdot\text{L}^{-1}$  in the surface at station G4 and 2.12  $\mu\text{g}\cdot\text{L}^{-1}$  in the bottom at station G1. Minimum values of chlorophyll  $\alpha$  occurred in the bottom water at station G5. Overall, concentrations of chlorophyll  $\alpha$  increased gradually from the surface waters to the bottom waters, with the highest value observed close to the bottom layer of the inner region of GWC. A similar distribution pattern of chlorophyll  $\alpha$  in inner Great Wall Cove was observed in January 1989<sup>[8]</sup> and in December 1992 and 1994<sup>[20]</sup>.

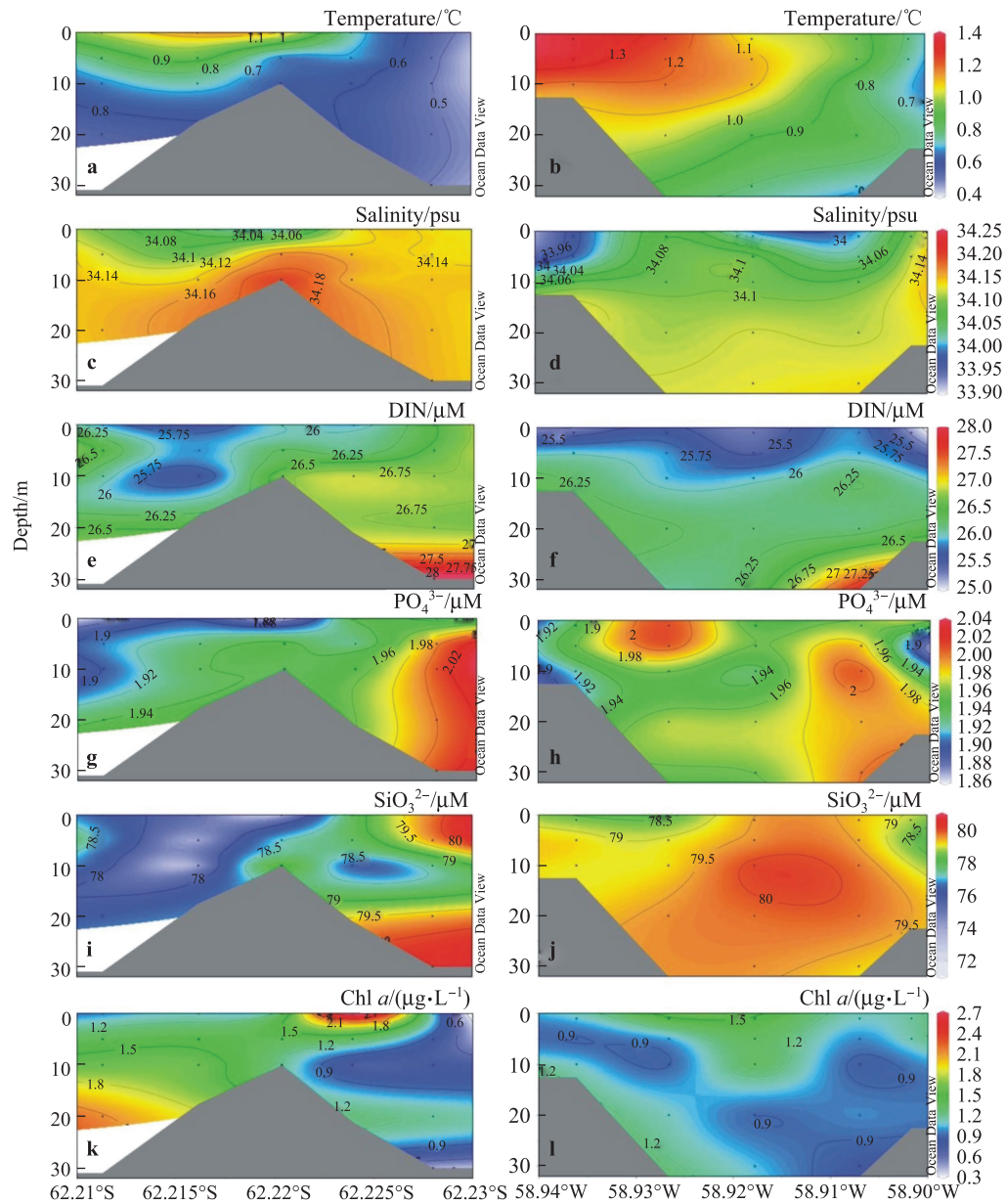
In AC, high concentrations of chlorophyll  $\alpha$  were observed at the surface at stations A3 (1.49  $\mu\text{g}\cdot\text{L}^{-1}$ ) and A2 (1.48  $\mu\text{g}\cdot\text{L}^{-1}$ ). Low values of chlorophyll  $\alpha$  (<0.9  $\mu\text{g}\cdot\text{L}^{-1}$ ) were observed in the bottom waters of the outer cove and in the subsurface layer of the inner cove. The variation in chlorophyll  $\alpha$  concentrations throughout the cove was not significant (Figure 3l).

## 4 Discussion

### 4.1 Nutrients in Great Wall Cove and Ardley Cove

High concentrations of DIN, phosphate and silicate were found in GWC and AC. It was previously thought that high concentrations of nutrients in these coves came mainly from riverine input during the austral summer. However, the concentrations of phosphate and DIN in freshwaters flowing into GWC and AC are generally low (Table 2) because of limited anthropogenic activity in these areas. Silicate concentrations of the freshwater input were also much lower than that of seawater in GWC and AC. Additionally, there was a strong positive correlation between nutrients and salinity in both coves (Figure 4). These results indicate that the riverine and snowmelt waters play a diluting role in nutrient concentrations in these two coves.

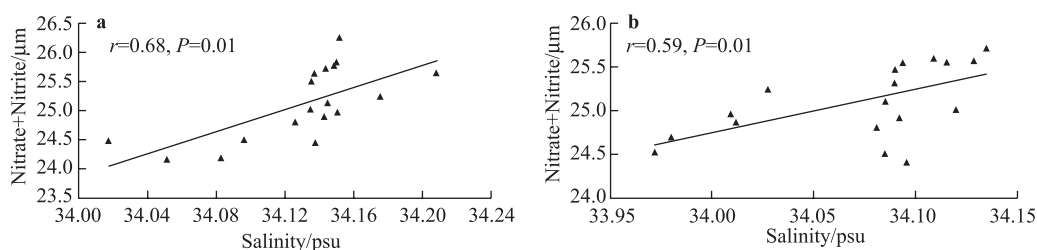




**Figure 3** Profile distributions of environmental parameters in Great Wall Cove (left panel) and Ardley Cove (right panel).

**Table 2** Concentrations of nutrients in freshwaters flowing into Great Wall Cove and Ardley Cove

Freshwater	$\text{PO}_4^{3-}/(\mu\text{mol}\cdot\text{L}^{-1})$	$\text{NO}_2^-/(\mu\text{mol}\cdot\text{L}^{-1})$	$\text{NH}_4^+/(\mu\text{mol}\cdot\text{L}^{-1})$	$\text{NO}_3^-/(\mu\text{mol}\cdot\text{L}^{-1})$	$\text{SiO}_3^{2-}/(\mu\text{mol}\cdot\text{L}^{-1})$
Kitezh river	0.12	0.06	1.38	3.10	39.02
Long river	0.18	0.03	2.15	2.90	28.17
Yuquan river	0.09	<0.01	0.37	0.95	19.32
Juma river	0.09	0.71	0.96	2.94	23.68
Jiuquan river	0.21	0.09	1.41	2.82	27.36
Kitezh lake	0.11	0.05	0.90	2.79	37.96
Xihu lake	<0.01	0.03	1.15	1.38	23.28
Yanou lake	0.09	<0.01	0.51	0.82	23.85
Yueya lake	1.07	0.05	0.45	0.41	1.77



**Figure 4** Correlations of (nitrate+nitrite) vs. salinity. **a**, Great Wall Cove; **b**, Ardley Cove.

The two coves are adjacent to Maxwell Bay, which connects to the Bransfield Strait. The Bransfield Current flows north-east at the surface with a rotation in a northerly direction at greater depths. Both tidal currents and wind-induced transport lead to the intrusion of the Bransfield Current into both GWC and AC through Maxwell Bay<sup>[27]</sup>. Because of the strong and continuous upwelling of nutrient-rich Upper Circumpolar Deep Water (UCDW), Bransfield Current waters contain very high nutrient concentrations<sup>[23, 28]</sup>. The strong incursion of the nutrient-rich Bransfield Current in the south enriches the waters of both GWC and AC and is the main source of nutrients in the two coves.

Another source of nutrients is decomposition of penguin and other bird guano on Ardley Island. A great number of penguins and other sea birds perch and breed on the north-eastern shore of Ardley Island, and deposits of guano formed from their excreta are washed into the coves during times of high precipitation or strong wave activity<sup>[29-30]</sup>. The results showed that there were very high concentrations of phosphate

( $5.32 \mu\text{mol}\cdot\text{L}^{-1}$ ) and DIN ( $214.6 \mu\text{mol}\cdot\text{L}^{-1}$ ) in gully water on Ardley Island, and high concentrations of phosphate ( $2.81 \mu\text{mol}\cdot\text{L}^{-1}$ ) and DIN ( $29.78 \mu\text{mol}\cdot\text{L}^{-1}$ ) were measured in the north-eastern shallow waters of Ardley Island. Decomposition of the guano deposited on Ardley Island resulted in an increase of fertility in the near-shore waters along the north-eastern shore of Ardley Island and is also a source of DIN and phosphate in the two outer coves.

The decay of macroalgae deposited on the coasts also contributes to increased nutrient levels in some other coastal areas near the study region<sup>[30]</sup>, but any contribution to nutrient levels in GWC and AC from macroalgae would be minimal because of the limited amount of macroalgae present in the two coves.

The low phytoplankton biomass in these two coves results in a low rate of nutrient utilization. Table 3 shows previous observations of chlorophyll *a* concentrations and water temperature in GWC and AC. Although the concentrations of chlorophyll *a* vary slightly, the previous

**Table 3** Chlorophyll *a* concentrations and water temperature in Great Wall Cove and Ardley Cove in different surveyed years

Region	Date of observation	Depths/ m	Water temperature/°C	Chl. <i>a</i> concentrations /( $\mu\text{g}\cdot\text{L}^{-1}$ )		Literature
				Average	Range	
Great Wall Cove	Nov. 1985–Feb. 1986	surface	−1.4–2.2	1.66	0.50–4.91	31
	Mar. 1988–Feb. 1989	surface	−0.8–2.9(summer)	0.44	0.16–1.33	8
	Jan. 1989	0–25	1.4–2.2	0.94	0.66–1.19	19
	Jan. –Feb. 1991	Surface	0.5–3.0	1.72	0.96–2.61	32
	Dec. 1992–Mar. 1993	Surface	0.7–3.8	3.79	1.41–11.51	20
	Dec. 1993–Mar. 1994	Surface	−0.73–1.63	1.80	0.18–6.75	20
	Dec. 1994–Mar. 1995	Surface	no data	1.20	0.82–3.23	20
	Dec. 1999–Mar. 2000	Surface	1.6–3.2	0.71	0.10–2.40	24
	Jan. 2013	0–30	0.50–1.15	1.29	0.42–3.08	This paper
Ardley Cove	Jan. 2013	0–30	0.72–1.36	1.08	0.81–1.49	This paper

results, also recorded during the austral summer, are similar to the observations from this study.

## 4.2 Factors affecting phytoplankton growth

Antarctic coasts are usually considered productive areas as they have excess nutrients, sufficient dissolved iron (due to additional terrestrial inputs or atmospheric transport of land

weathering products)<sup>[33]</sup>, and adequate solar radiation for photosynthesis during the austral summer. However, despite the high concentrations of nutrients and favorable nutrient structures in the waters of GWC and AC, phytoplankton biomass is low, even during summer bloom periods.

It is unlikely that macronutrients (N, P, Si) or micronutrients (e.g. Fe) are limiting phytoplankton growth;

rather, physical processes appear to be the main factors controlling phytoplankton accumulation<sup>[1]</sup>. Wu et al.<sup>[8]</sup> and Zhu et al.<sup>[20]</sup> suggested that light availability and water temperature were two major factors affecting phytoplankton growth in GWC. In these shallow waters, light limitation (due to high turbidity)<sup>[1,4]</sup> and the strong mixing throughout the water profile caused by strong winds<sup>[13]</sup> have also been suggested to control phytoplankton growth.

Given that the two coves receive high levels of solar irradiation during the austral summer and the high transparency of the water bodies during the survey period, it is unlikely that light was a major limiting factor upon phytoplankton growth. However, there were significant positive correlations between chlorophyll  $a$  biomass and water temperature in GWC ( $r=0.75$ ,  $P<0.01$ ) and AC ( $r=0.76$ ,  $P<0.01$ ) except for stations G1, G2 and A1, A2 of the inner coves; indeed, the inner region of GWC exhibited an inverse correlation ( $r=-0.89$ ,  $P<0.01$ ) between the two parameters. This demonstrates that water temperature plays an important role in phytoplankton photosynthesis, with higher water temperature more favorable for phytoplankton growth and hence biomass accumulation in the coves. Furthermore, this indicated that other factors affected phytoplankton growth. Unusual relationships between chlorophyll  $a$  concentrations and water temperature in the inner region of GWC were presumably related to dilution of chlorophyll  $a$  concentrations in the surface and subsurface layers resulting from high discharge of freshwater. The comparative stability of the water bodies at depths close to the bottom was beneficial to phytoplankton growth<sup>[20]</sup>.

The annual air temperature at the Great Wall Station ranges from 10.3°C to -27.7°C<sup>[15]</sup>. The annual range of water temperature in GWC was much smaller (4.5°C) than that of air temperature<sup>[34]</sup>. The water temperature in GWC was generally low throughout the year, with minimal (<3°C) seasonal variation. Even during the austral summer, the mean water temperature in these two coves rarely exceeded 2°C and was variable daily. This impeded the development of large bloom sizes in these areas, with consequent low nutrient utilization.

Wind was another major influence upon phytoplankton growth in GWC and AC. The austral summer brings strong and more frequent north-western winds<sup>[14,35]</sup>. Coastal waters are constantly subjected to strong wind-induced turbulence carrying algal cells into deeper water where the light conditions are less favorable for photosynthesis<sup>[9]</sup>. Even though the sea-ice had diminished in GWC during the sampling period, all the lakes near the two coves were still covered by ice. Air temperature at the Great Wall Station was 1.4°C, and the average water temperature in GWC was 0.7°C. Observations in AC were conducted several days later, and air temperature had increased to 2.4°C. Increased run-off from streams resulted in an increase in water temperature and reduction in salinity in the inner region of AC (Figures 3b and 3d). Despite higher water temperature during the observation period in AC compared with GWC (Figures 3a and 3b), the

overall chlorophyll  $a$  levels in AC were lower than those in GWC (Figures 3k and 3l). This was because daily mean wind speed over the 4 days before sampling in Ardley Cove was much stronger (7.5 m·s<sup>-1</sup>) than that in Great Wall Cove (<4.5 m·s<sup>-1</sup>). The strong wind caused excessive turbulence and instability in the upper layers of the water column, influencing biomass buildup. The coastal waters near the Great Wall Station are constantly subjected to strong winds, with highly variable wind speed and direction, even during the austral summer<sup>[14, 35]</sup>. The low water temperatures, along with strong wind-induced turbulence and instability in the surface waters, were the main factors that led to a generally low phytoplankton biomass in the seawater near the Great Wall Station, despite the high levels of inorganic nutrients.

## 5 Conclusions

(1) The concentrations of phosphate (>1.86  $\mu\text{mol}\cdot\text{L}^{-1}$ ), DIN (>25.0  $\mu\text{mol}\cdot\text{L}^{-1}$ ) and silicate (>77.5  $\mu\text{mol}\cdot\text{L}^{-1}$ ) in the seawaters of GWC and AC were very high. However, average concentrations of chlorophyll  $a$  were relatively low (GWC: 1.29  $\mu\text{g}\cdot\text{L}^{-1}$  and AC: 1.08  $\mu\text{g}\cdot\text{L}^{-1}$ ), giving rise to high-nutrient and low-chlorophyll  $a$  (HNLC) conditions in this area.

(2) Nutrient concentrations of the freshwater flowing into GWC and AC during the austral summer generally were very low, resulting in these waters playing a diluting role in the nutrient concentrations of the two coves.

(3) Strong intrusion of nutrient-rich Bransfield Current from the south was the main source of nutrients in GWC and AC waters.

(4) Low water temperature and strong wind-induced turbulence and instability in the upper seawater layers near the Great Wall Station during the austral summer were the main factors impeding phytoplankton growth, with a resultant low rate of nutrient uptake.

**Acknowledgments** We are grateful to Mr. Ma Xindong and Mrs. Li Huirong for assistance with the *in situ* sampling, as well as to all our colleagues working at Great Wall Station of the 29th CHINARE in 2012/2013. This study was supported by the Chinese Polar Environmental Comprehensive Investigation & Assessment Programs (Grant nos. CHINARE 2014-04-01-07, CHINARE 2014-02-01-05), and the Chinese Polar Science Strategy Research Foundation (Grant no. 20120104).

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