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Glacial melting pulses in the Antarctica: Evidence for different responses to regional effects of global warming recorded in Antarctic bivalve shell (*Laternula elliptica*)

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A B S T R A C T

Meltwater history of the Antarctic bivalve *Laternula elliptica* in Maxwell Bay, King George Island near the Antarctic Peninsula was reconstructed during the shell growth. High resolution trace elemental and stable isotopic compositions along the aragonite outer part of the shell together with growth bands shows that the shell lived for 9 years with distinct annual cycles. Also oxygen and carbon isotope values reveal the local meltwater history in Antarctic Peninsula region. More negative oxygen isotope values than the predicted equilibrium values clearly show that oxygen isotope depletion is due to lower salinity of seawater by glacial melting. This is also confirmed by the similar trend of low carbon isotope values as well as monitored sea surface salinity values. Comparing $\delta^{18}O$ values of previous results using the same bivalve species, more negative values from the Antarctic Peninsula (Maxwell Bay) during the austral winter than from East Antarctica (Syowa Coast and Ross Sea) suggests that perennial glacial melting influenced seawater $\delta^{18}O$ composition near the peninsula. Also, more negative and variable bivalve $\delta^{18}O$ values during austral summer indicate that meltwater pulses fluctuated greatly in the study area. Distinctively different trends in bivalve $\delta^{18}O$ profiles between the Antarctic Peninsula and East Antarctica may reflect differential responses to regional warming with regard to the recent global warming over the past few decades.

1. Introduction

Global warming has become a threat to our society over the past few decades. In particular, the Antarctic Peninsula (AP) has experienced a warming trend over the 20th century (Jones, 1990; Jones et al., 1993; Barrand et al., 2013; Turner et al., 2014; Wouters et al., 2015). Special attention has been paid to global sea-level rise due to massive melting of glaciers in polar region. About 87% of the marine glacier fronts on the AP and associated islands have retreated over the past 50 years, and the rate of retreat has increased since the beginning of the 21st century (Cook et al., 2005). Maxwell Bay located in the northern tip of AP also shows a similar trend. The glacier front of Marian Cove in the bay has retreated > 683 m from 1956 to 1994 (Park et al., 1998) and over about 1100 m from 1956 to 2013 (Moon et al., 2015).

Previous studies have shown that the oxygen isotopic compositions ($\delta^{18}O$) of pectenids (*Adamussium colbecki*) and bivalves (*Laternula elliptica*) reflect the seasonal input of meltwater in Antarctica as well as growth laminae (Barrera et al., 1994; Berkman, 1994; Brey and Mackensen, 1997; Tada et al., 2006). Similar suggestions were made from analysis of barnacle shells (Burgess et al., 2010). The Antarctic soft-shelled clam, *Laternula elliptica* is endemic to the Antarctic and widely distributed in nearshore waters around the Antarctic continent and islands It occurs as dense patches of tens to hundreds of individuals per m^2 in shallow subtidal waters (~50 m), being one of the most conspicuous species in the nearshore waters (Stout and Shabica, 1970; Hardy, 1972; Zamorano et al., 1986; Ahn, 1993 & 1994; Ahn et al.,

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2001; Mercuri et al., 1998). *L. elliptica* likely feeds on a variety of food particles suspended in the water including organic detritus, benthic diatoms resuspended from the bottom substrates as well as phytoplankton (Ahn, 1993 & 1994; Ahn and Shim, 1998). It has a relatively long lifespan of more than 10 years or occasionally much longer (Urban and Mercuri, 1998). All these characteristics of *L. elliptica* appear to render this species a suitable indicator or model species for tracking climate-induced changes in the Antarctic coastal areas, the sites most vulnerable to ice sheet changes (Brey et al., 2011; Agüera et al., 2017).

In this study, we analysed the stable isotopic and elemental compositions of the calcareous skeleton of the bivalve *Laternula elliptica*. We compared the geochemical composition of the shell with monitoring data instrumentally measured near the King Sejong Station (the Antarctic Research Base of Korea) on King George Island to delineate AP meltwater history.

2. Study area

The study area is located near the tip of the Antarctic Peninsula. Maxwell Bay is a deep fjord between King George Island and Nelson Island in the South Shetland Islands, West Antarctica and is comprised of three small embayments (Collins Harbour, Marian Cove and Potter Cove) (Fig. 1). The South Shetland Islands are separated from the AP by the Bransfield Strait, formed by back-arc spreading over the last 1.4 Ma (Smellie et al., 1984). The islands are mostly covered by snow and ice throughout the year and are affected by glaciomarine processes. The hydrographic regime of the Maxwell Bay in austral summer is characterized by two distinct water masses: the temperature maximum and temperature minimum layers (Chang et al., 1990). The intense temperature minimum (< 0.0 °C) layer in 100-m water depth shows characteristics of Antarctic Surface Water, the product of the remnant surface water in austral winter and ice melting in austral summer (Chang et al., 1990). In case of Marian Cove, it was observed that the surface water in surface mixed layer (< about 70 m water depth) became warmer and less saline by the active melting during the summer from 1996 to 2000 (Yoo et al., 2015).

3. Methods

A living bivalve sample was collected by scuba diving at a water depth of about 25 m in Collins Harbour on January 7, 2002 (Fig. 1; 62°09′55.6″S/58°49′06.8″W). The size of bivalve shell was about 8.2 cm in length and 4.8 cm in height (Supplementary Fig. S1a). In order to investigate the composition and microstructure of the bivalve shell, X-ray diffraction (XRD) and scanning electron microscope (SEM) examinations were carried out. The shell was composed of aragonite, with outer crossed lamellar and inner nacreous microstructures (Supplementary Fig. S2). Powder samples were micro-drilled from the umbo to the ventral margin along the maximum growth axis by drilling only the outer layer at a spacing of about 450 μm (Supplementary Fig. S1).

After removing the organic matter with H_2O_2 for 24 h, the oxygen and carbon isotopic compositions of the powder samples was measured at the Leibniz-Laboratory for Radiometric Dating and Isotope Research in Kiel University, Germany. The powder samples were reacted with 100% orthophosphoric acid at 75 °C within a carbonate preparation device (Kiel I prototype). The isotopic composition of the evolved CO_2 gas was analysed using a Finnigan MAT 251 mass spectrometer connected to the preparation device. The precision of measured $\delta^{18}O$ and

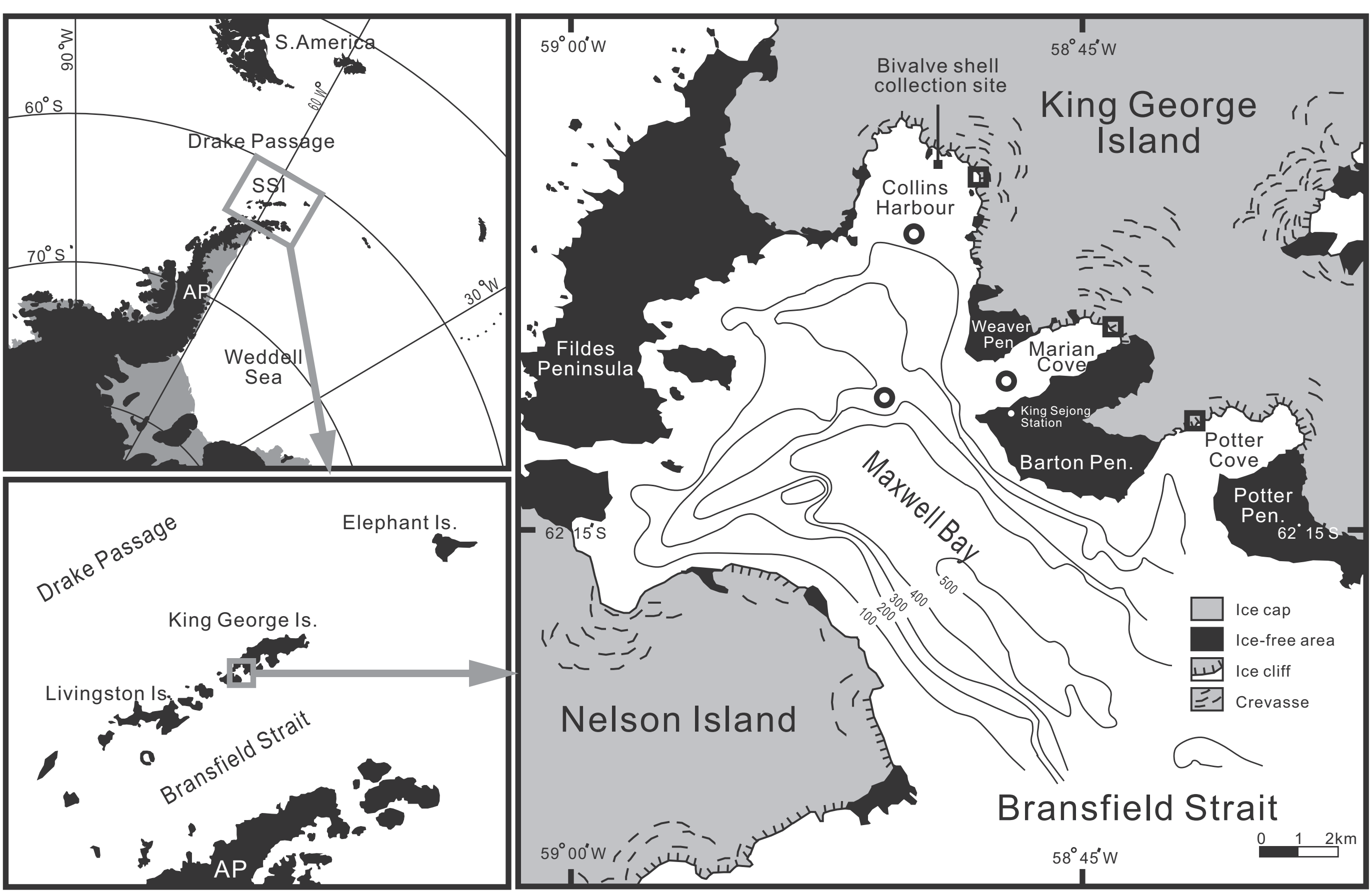

Fig. 1. Map showing the study area and bivalve shell collection site. Air temperature, sea surface temperature (SST), and sea surface salinity (SSS) were monitored from the surface seawater at the King Sejong Station near the entrance to Marian Cove. Sampling sites for seawater and meltwater are marked with circles and squares, respectively. The collecting site of the bivalve shell in Collins Harbour is also indicated.

$\delta^{13}C$ values was controlled by running on daily routine different laboratory internal carbonate standards and one international carbonate standard (NBS-19). Isotope ratios were converted to the Vienna Pee Dee Belemnite (VPDB) scale using the carbonate standard NBS-19. External standard errors for performing carbonate standards with the Kiel I prototype carbonate preparation device connected to the MAT 251 are better than ± 0.08‰ for $\delta^{18}O$ and ± 0.05‰ $\delta^{13}C$. Elementary analysis was carried out using a laser ablation-ICP-mass spectrometer (X7 equipped UP 123) by measuring the slab surface at the Korea Basic Science Institute. Elemental measurement of Sr and Mg (in cps) was made with a spacing of about 110 μm at the points and a distance of about 80 μm from the shell surface (Supplementary Fig. S1b&c).

Air temperature was measured at the King Sejong Station daily from 1996 to 2007. Daily sea surface temperature (SST) and sea surface salinity (SSS) recorded twice a day (neap and spring tides) near the pier of the station (62°13′22.4″S/58°47′13.8″W) in Marian Cove in 1996 and from 1998 to 2007 were measured using a water quality meter (YSI 610D) (Supplementary Tables S1 & S2).

Meltwater samples were collected during austral summer from glacial-runoff in Collins Harbour (62°10′04.3″S/58°47′57.3″W) and Marian Cove (62°12′00.1″S/58°43′39.2″W), and from creek water formed by glacial melting in Potter Cove (62°13′41.0″S/58°41′38.1″W) in January 2009 to measure the stable isotopic composition (Supplementary Fig. S3). Seawater samples were also collected at the same period from water depths of 0, 10, and 25 m in Collins Harbour (62°10′56.2″S/58°49′46.5″W), Marian Cove (62°12′53.8″S/58°46′53.8″W), and Maxwell Bay (62°13′14.2″S/58°50′42.1″W) (Fig. 1). Stable isotopic composition of collected meltwater and seawater was measured in the Korea Basic Science Institute. Oxygen and hydrogen isotopic compositions were analysed in water samples ($\delta^{18}O_{MW}$ and δD_{MW} from meltwater and $\delta^{18}O_{SW}$ and δD_{SW} from seawater, in Standard Mean Ocean Water, SMOW). 0.3 ml of water were allowed to equilibrate with dilute CO_2 at 25 °C according to the H_2O-CO_2 equilibrium method (Epstein and Mayeda, 1953) and installed immediately the mass spectrometer (Optima) for the measurement of oxygen isotope composition. The repeatability of the standard sample is ± 0.1‰. Hydrogen gas produced by reaction of 0.2 μl of water with Cr in on-line hydrogen pretreatment system (PyrOH) according to the method proposed by Morrison et al. (2001) were installed the mass spectrometer (Isoprime) for the measurement of hydrogen isotope composition. The repeatability of the standard sample is ± 1.0‰.

Carbon isotope analysis was performed for dissolved inorganic carbon (DIC) in water ($\delta^{13}C_{MW\text{-}DIC}$ and $\delta^{13}C_{SW\text{-}DIC}$ from DIC of meltwater and seawater, respectively, in VPDB). The separation of DIC was carried out according to the method of Atekwana and Krishnamurthy (1998). After separation of DIC, carbon isotope compositions were measured using a mass spectrometer (Optima). The repeatability of the standard sample is ± 0.2‰.

4. Results

4.1. Age determination of the bivalve shell

Bivalve shell has annual bands produced by alternate deposition of skeletal material of different density or structure. The alternation is triggered either by changes in environmental factors, such as temperature, salinity, oxygen content or food supply, and by internal factors, such as reproduction. These annual growth laminae were reported for the same bivalve species (*L. elliptica*) from a nearby area, King George Island (Brey and Mackensen, 1997). The bivalve shell in this study also has numerous growth laminae, with about 10 estimated annual bands. However, it is difficult to determine the exact age of the bivalve shell from growth bands alone because annual growth bands are not very distinctive due to small seasonal SST variations. Another common method to determine the age of bivalve shell is based on sequential oxygen isotope variations along the growth axis, as bivalve shell commonly displays seasonal temperature variation if the $\delta^{18}O$ of seawater is relatively constrained. However, this cannot be applied to the bivalve shell in this study because the $\delta^{18}O$ of seawater has been continuously influenced by meltwater input. As a result, the bivalve shell does not show clear enough seasonal $\delta^{18}O$ trends to determine its growth period.

Because of these difficulties, age determination of the bivalve shell in this study was made in four steps: 1) overall age was determined based on annual Sr and Mg variations; 2) this estimate was confirmed by comparison with the $\delta^{18}O_{Shell}$ profile; 3) the age estimate was confirmed and calibrated by the positions of densely spaced growth laminae; and 4) finally, it was confirmed by comparing the size of bivalve shell with the observed growth curve for this species by Urban and Mercuri (1998).

Numerous studies showed that the Sr/Ca and Mg/Ca ratios of various calcareous skeletons, including bivalves, are directly related to the seawater temperature during its growth. Mg/Ca ratios are commonly proportional to the temperature of growth (Lea et al., 2000), whereas Sr/Ca ratios can be proportional or inversely proportional (Gillikin et al., 2005), even though Sr and Mg contents may also vary with growth rate (Lorrain et al., 2005) or ontogenic effects (Freitas et al., 2009). In this study, high resolution profiles of the Sr and Mg contents are used to determine the precise lifespan of the bivalve because the three-point averaged Sr and Mg contents show distinctive seasonal trends that are directly related to air temperature and SST variations (Fig. 3a–c). Sr contents show 12 distinctive peaks ranging from 1500 to 1900 cps, with three and two peaks clustered in the middle and dorsal part, respectively. Between the peaks a few relatively smaller peaks were present ranging from 1100 to 1300 cps. Mg contents show 16 peaks ranging from 70 to 270 cps. Like the Sr values, a few Mg peaks are clustered, probably reflecting minor environmental changes or metabolic effects. Overall, Mg content increased with the age of the shell, probably due to ontogenic aging effects (Fig. 3c).

Sr and Mg peaks are almost coincident, except that three Sr peaks in the middle are overlapped by two Mg peaks. Also, smaller Mg peaks do not always follow the positions of smaller Sr peaks. Overall Sr and Mg peak positions and compositional variations are very cyclic and consistent, showing that these trends did reflect environmental changes. This can be confirmed by the coincidence between these cyclic Sr and Mg variations and measured SST variations in Marian Cove. Sharp increases in Sr content were present when SST values reached their highest values during austral summer. The rest of the Sr values are low. Similar trends can be observed in the Mg variations, except that the Mg peaks have relatively gentler slopes. These overall trends strongly indicate that Sr and Mg contents were mostly influenced by SST variations (Fig. 3b&c). The cluster of the three Sr peaks and two Mg peaks in the middle part is interpreted to have formed during a single winter because these peaks are closely clustered (Fig. 3c), and only one densely spaced growth band could be observed on the surface of the bivalve shell (triangular marks on the bottom of Fig. 3). Thus, it can be estimated that the bivalve lived for 9 years from the austral autumn of 1993 to the austral summer of 2002 (Fig. 3).

Urban and Mercuri (1998) collected 195 bivalves of *Laternula elliptica* from King George Island and measured their shell size and growth rings, and suggested the growth curve of the von-Bertalanffy growth-function (VBGF) estimated from shell ring reading. According to their growth curve, a 9-year-old bivalve shell may have a size of ca. 85.6 mm in length. The bivalve shell size in this study is 82.0 mm, and it followed the observed growth curve of Urban and Mercuri (1998) for this species (Supplementary Fig. S4).

4.2. Stable isotopic compositions of the bivalve shell

Monthly mean air temperature over 12 years (1996–2007) varied from −11.4 °C (austral winter) to 3.0 °C (austral summer), with an annual mean of −1.5 °C (Fig. 2a, Supplementary Table S1). Monthly

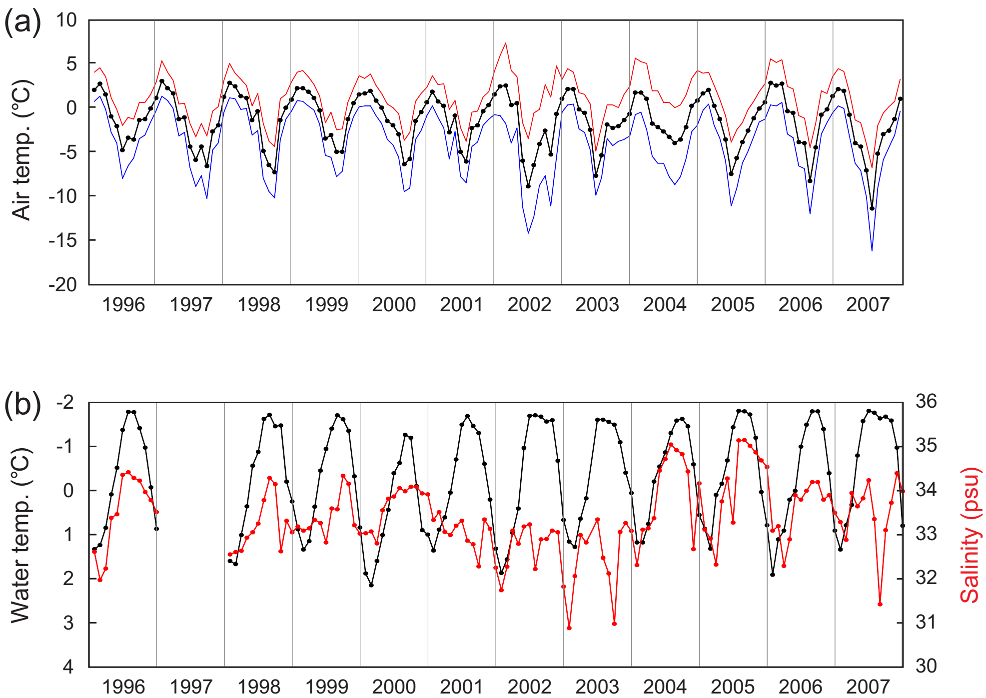

Fig. 2. (a) Monthly mean air temperature measured at the King Sejong Station from 1996 to 2007. Black, red, and blue lines indicate mean, maximum, and minimum temperatures, respectively. (b) Monthly mean SST (black line) and SSS (red line) observed near the pier of the Station in 1996 and from 1998 to 2007.

mean SSTs varied from −1.8 (austral winter) to 2.1 °C (austral summer) and monthly mean SSSs from 30.9 (austral summer) to 35.2 (austral winter) psu (Fig. 2b, Supplementary Table S2). The seasonal variation of monthly averaged SSTs in Marian Cove was relatively small (from −1.68 to +1.53 °C, with a range of about 3.21 °C; Fig. 2b, Supplementary Table S2).

Due to year-round cold SSTs and little seasonal change, the bivalve $\delta^{18}O_{Shell}$ would not show distinctive seasonal variations (greater than ~1‰). The seawater $\delta^{18}O_{SW}$ in Maxwell Bay, Marian Cove, and Collins Harbour range between −0.41 and −0.17‰, with an average of −0.29‰ (Table 1). Using the isotopic paleo-temperature equation of aragonite (Grossman and Ku, 1986), the bivalve $\delta^{18}O_{Shell}$ should be between +3.83 and +4.52‰, with a seasonal range of about 0.69‰. However, the bivalve $\delta^{18}O_{Shell}$ showed more negative values and a much wider range, from −2.07 to +3.67‰, with a difference of about 5.74‰. Excluding two sharply negative peaks near the tip of the shell, they ranged from +0.79 to +3.67‰, with a seasonal range of about 2.88‰ (Fig. 3e).

It is notable that the bivalve $\delta^{18}O_{Shell}$ values in austral summer were quite variable even though austral winter values were constant. Highly variable austral summer values reflected the variable rate of meltwater input from year to year. Salinity variations during austral summer are susceptible to climatically induced meltwater influx and glacier calving in the proximal glacial zone, whereas those during austral winter depend upon the degree of sea-ice formation. Thus, the fresh peaks in austral summer may have resulted from increased meltwater influx caused by increased air temperature. The seasonal SSS variation from 2001 to 2003 displayed the remarkably notable pattern: surface water was relatively fresh throughout those years. The increased atmospheric temperature may yield active calving of glaciers around the northernmost AP, and the consequent floating ice may exist around Maxwell Bay throughout the year. The relatively low salinity (< 33.5 psu) in austral autumn and austral winter seems to be influenced by the floating ice outside of the bay or abrupt increase in glacial melting nearby.

Significant declines in SSS and corresponding decreases in bivalve $\delta^{18}O_{Shell}$ were observed every other austral summer from early 1996 to early 2002 (early 1996, early 1998, early 2000, and early 2002). During

Table 1
Oxygen, hydrogen, and carbon isotopic values of the meltwater and seawater from Collins Harbour, Marian Cove, Potter Cove, and Maxwell Bay.

Location	Sample no.	$\delta^{18}O_{SW}$ (‰, SMOW)	δD_{SW} (‰, SMOW)	$\delta^{13}C_{SW\text{-}DIC}$ (‰, VPDB)
		Seawater		
Collins Harbour	CH-SW1 (10 m)	−0.36	−4.5	0.2
	CH-SW1 (25 m)	−0.17	−3.0	0.1
	CH-SW2 (0 m)	−0.32	−3.1	0.2
	CH-SW2 (10 m)	−0.31	−4.5	0.1
	CH-SW2 (25 m)	−0.25	−4.2	0.1
Marian Cove	MC-SW1 (10 m)	−0.33	−3.9	0.1
	MC-SW1 (25 m)	−0.33	−4.6	0.2
	MC-SW2 (10 m)	−0.41	−4.9	0.2
	MC-SW2 (25 m)	−0.36	−5.0	0.2
Maxwell Bay	MX-SW1 (10 m)	−0.17	−3.8	0.1
	MX-SW1 (25 m)	−0.23	−4.6	0.2
Average		−0.29	−4.2	0.2
		Meltwater		
Collins Harbour	CH-MW1	−8.45	−64.6	−6.6
	CH-MW2	−8.65	−63.9	
	CH-MW3	−8.83	−65.6	−6.1
Marian Cove	MC-MW1	−8.59	−65.5	−8.5
	MC-MW2	−8.85	−69.1	
	MC-MW3	−9.07	−68.1	−7.1
Potter Cove	PC-MW1	−9.96	−74.3	−6.4
	PC-MW2	−8.82	−67.0	−3.7
	PC-MW3	−9.61	−70.9	−3.4
Average		−8.98	−67.7	−6.0

these intervals, SSS declined to about 31.0 psu, and the bivalve $\delta^{18}O_{Shell}$ also decreased to about +1‰ (Fig. 3d&e, yellow bars in Fig. 3). However, the SSS descents were relatively smaller at other summer (early 1999 and early 2001), as low as about 33.0 psu, and were accompanied by bivalve $\delta^{18}O_{Shell}$ value decreases to +2‰. (Fig. 3d&e, gray bars in Fig. 3). The sharp drops of SSS (about 30.0 to 33.0 psu) are observed except for the austral summers (late 1998, middle 1999, late

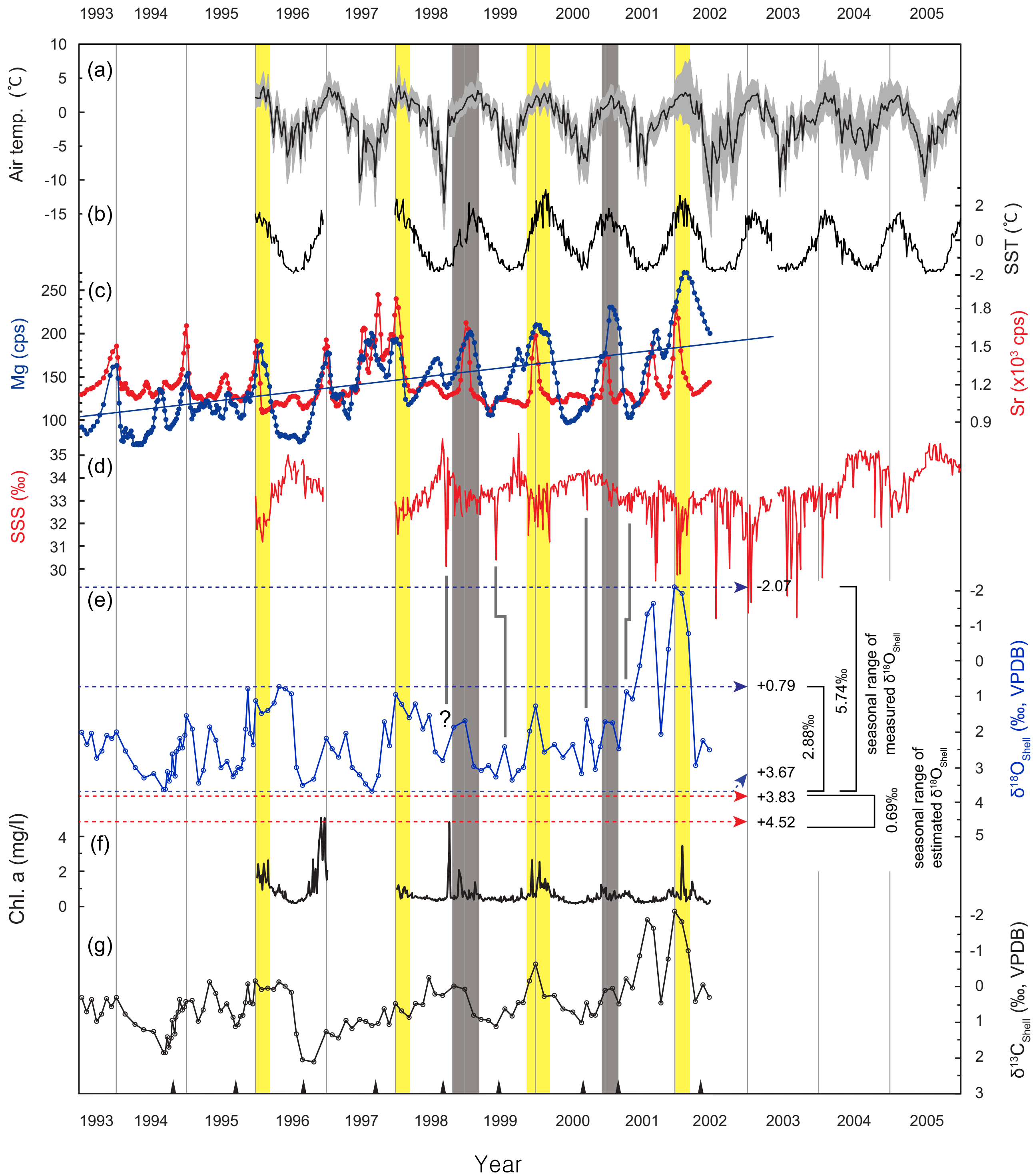

Fig. 3. (a) Five-day averaged air temperature measured at the King Sejong Station from 1996 to 2005. (b) Five-day averaged SST measured near the pier of the Station in 1996 and from 1998 to 2005. (c) Three-point averaged Mg and Sr content of the bivalve shell in this study. High-resolution Mg and Sr contents were used for age determination. Note that high Mg and Sr peaks match well with monitoring data of the air temperature and SST. (d) Five-day averaged SSS measured near the pier of the Station in 1996 and from 1998 to 2005. (e) Oxygen isotopic compositions of the bivalve shell. Bivalve $\delta^{18}O_{Shell}$ coincides well with SSS in terms of peak intensity and timing. Note the salinity-decrease peaks, which have matched bivalve $\delta^{18}O_{Shell}$. Yellow bars show the intervals of the SSS and the $\delta^{18}O_{Shell}$ decrease to about 31 psu and +1‰, and grey bars show the intervals of the SSS and the $\delta^{18}O_{Shell}$ decrease to about 33 psu and +2‰, respectively. Red dotted lines indicate the estimated $\delta^{18}O_{Shell}$ of the aragonite (+3.83 in austral summer and +4.52‰ in austral winter) using the equation of Grossman and Ku (1986). Blue dotted lines indicate the measured $\delta^{18}O_{Shell}$ of the shell (+0.79 in austral summer and +3.67‰ in austral winter) and the unusual value of two sharply negative peaks (−0.27‰). (f) Chlorophyll *a* concentration measured near the pier of the Station in 1996 and from 1998 to 2002. (g) Carbon isotopic compositions of the bivalve shell. Bivalve $\delta^{13}C_{Shell}$ showed the opposite trend with chlorophyll *a* and exactly the same trend with bivalve $\delta^{18}O_{Shell}$ except for 1997. Densely spaced growth laminae are indicated by triangular marks on the x-axis.

2000, and early 2001). These abrupt events lasted < 1 week and could not be correlated with bivalve $\delta^{18}O_{Shell}$ in this study, although a few drops in bivalve$\delta^{18}O_{Shell}$ are also present during the same intervals (Fig. 3d&e, gray lines in Fig. 3).

Primary productivity as indicated by chlorophyll concentration in Maxwell Bay varies seasonally depending upon the amount of sunlight incident into the area (Kim et al., 1998), and it rises with increasing sunlight during austral summer (Kang et al., 1997). Standing stock of phytoplankton can be estimated by chlorophyll-*a* content of the surface water, and it was always high (> 3 mg/l) during the austral summer between 1996 and 2002 (Fig. 3f). This should have resulted in increased seawater $\delta^{13}C_{SW\text{-}DIC}$, which should, in turn, be reflected in bivalve $\delta^{13}C_{Shell}$ as a seasonal cyclic signal. However, the bivalve $\delta^{13}C_{Shell}$ showed the opposite trend and tended to be more negative during austral summer (Fig. 3f&g). This means that bivalve $\delta^{13}C_{Shell}$ was affected by other factors in addition to primary productivity.

The most notable pattern was that overall bivalve $\delta^{13}C_{Shell}$ data showed exactly the same trend as bivalve $\delta^{18}O_{Shell}$ during the bivalve growth period for not only peak positions but also in intensity, except for 1997 (Fig. 3e&g). Unfortunately, the lack of monitoring results during 1997 made further interpretation difficult. However, the high value ($R^2 = 0.7855$) of the correlation coefficient between bivalve $\delta^{18}O_{Shell}$ and $\delta^{13}C_{Shell}$ can clarify the considerable interrelationship of both isotopic compositions (Fig. 4a). To confirm meltwater influence on seawater $\delta^{13}C_{SW\text{-}DIC}$, seawater and meltwater samples were collected and analysed. The seawater $\delta^{18}O_{SW}$ and $\delta^{13}C_{SW\text{-}DIC}$ ranged from −0.41 to −0.17‰ and from 0.06 to 0.25‰, respectively, whereas those of meltwater $\delta^{18}O_{MW}$ and $\delta^{13}C_{MW\text{-}DIC}$ were −9.96 to −8.45‰ and −8.53 to −3.44‰, respectively (Fig. 4b, Table 1). Both isotopes in meltwater were significantly more negative than those in seawater, but meltwater $\delta^{13}C_{MW\text{-}DIC}$ showed wider range than meltwater $\delta^{18}O$ $_{MW\text{-}DIC}$. It is interesting that meltwater $\delta^{13}C_{MW\text{-}DIC}$ was relatively clustered from area to area (Fig. 4b). This means that meltwater $\delta^{13}C_{MW\text{-}DIC}$ may vary depending upon the local source of organic carbon on land and bivalve $\delta^{13}C_{Shell}$ may well be influenced by the amount of meltwater input, as shown by the bivalve $\delta^{18}O_{Shell}$ trend. The degree of variability between bivalve $\delta^{18}O_{Shell}$ and $\delta^{13}C_{Shell}$ differs because the source of carbon in meltwater may vary.

5. Discussion

5.1. *Influence of glacial meltwater on stable isotope compositions*

Two characteristics could be recognised in the bivalve $\delta^{18}O_{Shell}$ profile: 1) Firstly, measured bivalve $\delta^{18}O_{Shell}$ was more negative than the estimated bivalve $\delta^{18}O_{Shell}$ by isotopic paleo-temperature equation of aragonite based on SST regardless of season. During austral winter they were more negative by about 0.85‰, (measured vs. estimated value = 3.67 vs. 4.52‰), and during austral summer, by about 3.04‰ (0.79 vs. 3.83‰). Secondly, estimated bivalve $\delta^{18}O_{Shell}$ ranges based on seasonal SST changes were ca. 0.69‰ (3.83–4.52‰; red dotted lines in Fig. 3e), whereas measured $\delta^{18}O_{Shell}$ showed larger variations of ca. 2.88‰ (0.79–3.67‰; blue dotted lines in Fig. 3e), even excluding two strongly negative peaks between 2001 and 2002.

Table 2
Minimum SST in austral summer and maximum SST in austral winter at Marian Cove and $\delta^{18}O$ of seawater from Maxwell Bay, Syowa Coast, and Ross Sea. The SST in Maxwell Bay is instrumentally measured, averaged SST values from water depth of 5 to 10 m. The SST in Syowa Coast and Ross Sea are obtained from bottom water temperatures in Lützow-Holm Bay (Fukuchi et al., 1985; Watanabe et al., 1986; Matsuda et al., 1987) and from water depth of 10 m in McMurdo Sound (Littlepage, 1965; Stockton, 1984; Alexander and DcLrlca, 1987; Barry and Dayton, 1988; Schwarz et al., 2003; Kapsenberg et al., 2015).

Location	Seawater temperature (°C)			$\delta^{18}O_{SW}$ (‰, SMOW)
	Austral summer	Austral winter	Average	
Maxwell Bay	1.53	−1.68	−0.08	−0.29
Syowa Coast	−1.37	−1.91	−1.76	−0.11
Ross Sea	−1.90	−2.04	−1.69	−0.12

Obvious discrepancies between measured and estimated $\delta^{18}O_{Shell}$ indicate that the bivalve $\delta^{18}O_{Shell}$ was affected by seawater $\delta^{18}O_{SW}$ in addition to SST variation. This means that seawater $\delta^{18}O_{SW}$ during bivalve growth must have been lower than the collected and measured seawater $\delta^{18}O_{SW}$ (−0.29‰; Table 2). The most probable cause for low seawater $\delta^{18}O_{SW}$ is meltwater input into the area in which the bivalve lived because the study area is extensively surrounded by glaciers (Fig. 1). Comparison of the bivalve $\delta^{18}O_{Shell}$ profile with SSS variations revealed that all the low-SSS peaks coincided with more negative bivalve $\delta^{18}O_{Shell}$ peaks (Fig. 3d&e). Increase in meltwater input during austral summer instantaneously resulted in SSS decrease, and these low-SSS peaks were invariably accompanied by low bivalve $\delta^{18}O_{Shell}$ (yellow and gray bars in Fig. 3). Of note were the sharp SSS drops, to about 30.0 to 33.0 psu, for this period except during the austral summers (gray lines in Fig. 3). Two significant and sharp negative peaks in SSS and bivalve $\delta^{18}O_{Shell}$ were present between late 2001 and early 2002 (Fig. 3d&e). Extremely negative bivalve $\delta^{18}O_{Shell}$ indicated that the amount of meltwater input was significantly larger than during other episodes. Air-monitoring results near King Sejong Station (Marian

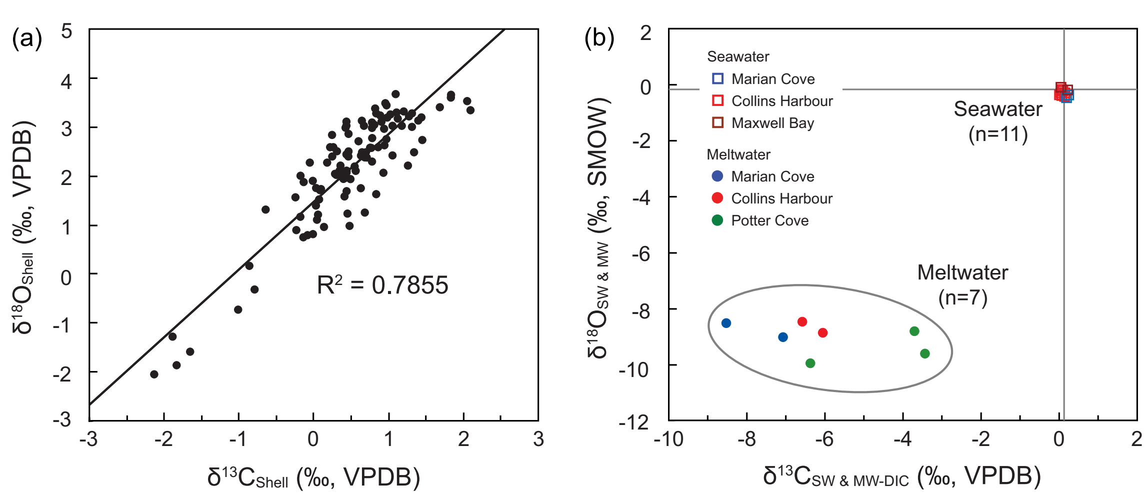

Fig. 4. (a) Bivalve $\delta^{13}C_{Shell}$ vs. $\delta^{18}O_{Shell}$ plots (R2 = 0.7855). (b) $\delta^{13}C_{SW\ \&\ MW\text{-}DIC}$ vs. $\delta^{18}O_{SW\ \&\ MW}$ plots of seawater and meltwater from Collins Harbour, Marian Cove, Potter Cove, and Maxwell Bay.

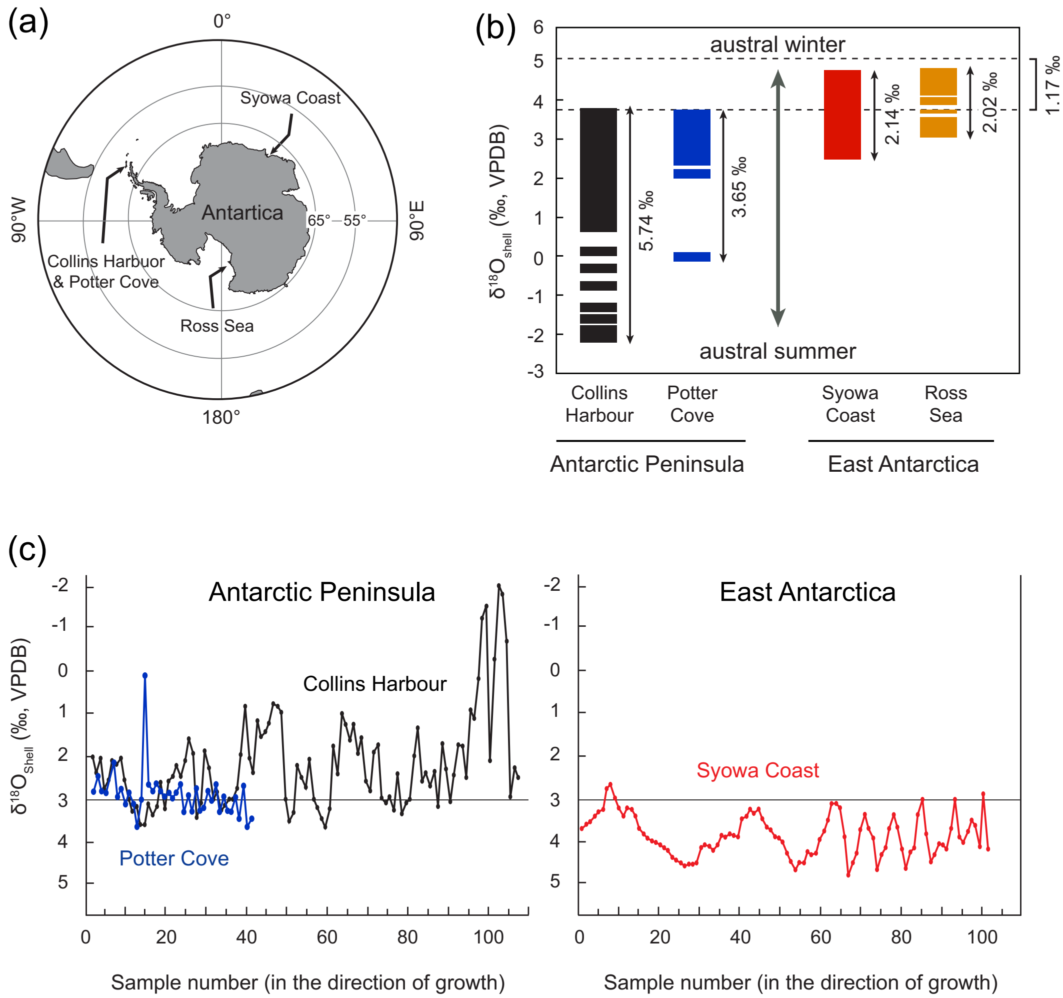

Fig. 5. (a) A map of Antarctica with the locations of Collins Harbour, Potter Cove, the Syowa Coast, and the Ross Sea. Oxygen isotopic ranges (b) and profiles (c) of four and three bivalve shells (*Laternula elliptica*). Data were compiled from this study for Collins Harbour, from Barrera et al. (1994) for the Ross Sea, from Brey and Mackensen (1997) for Potter Cove, and from Tada et al. (2006) for the Syowa Coast.

Cove) revealed that the maximum monthly averaged temperature during austral summer from late 2001 to early 2002 was much higher than in previous years (Figs. 2a & 3a).

Overall bivalve $\delta^{13}C_{Shell}$ profile showed exactly the same trend as bivalve $\delta^{18}O_{Shell}$ except for 1997 and a high linear relationship (Figs. 3g &e, 4a), strongly suggesting that both bivalve $\delta^{18}O_{Shell}$ and $\delta^{13}C_{Shell}$ were influenced by amount of meltwater input. Meltwater has more negative values than seawater by ca. 9‰ for $\delta^{18}O_{MW}$, but more variable values for $\delta^{13}C_{MW\text{-}DIC}$ by 3 to 8‰ (Fig. 4b, Table 1). This confirms that bivalve $\delta^{13}C_{Shell}$ may well be influenced by the amount of meltwater input, as shown by the bivalve $\delta^{18}O_{Shell}$ trend.

5.2. Implications for contrasting melting rate between AP and EA

The $\delta^{18}O_{Shell}$ data from the same bivalve species from the AP (Collins Harbour and Potter Cove) and East Antarctica (EA, Syowa Coast and Ross Sea) are compared (Fig. 5a). It may be a little challenging to compare the meltwater trend between AP and EA based on stable isotope data of a few bivalve shells because the shells may imply only local meltwater effects. However, it is believed that the implications for meltwater history of both regions are feasible due to the following reasons: 1) we have a nice matching trend of coordinated textural, stable isotopic, and trace elemental data, which can be well combined with independent monitoring data from the different locality in AP. In this study oxygen and carbon isotopes show the similar meltwater trends even though these two proxies are influenced by independent controlling factors; and 2) the meltwater history during the shell growth is reconstructed in Maxwell Bay near the tip of Antarctic Peninsula, which can be considered to be a part of the open ocean (Fig. 1). Thus regional changes of physical and chemical properties of seawater due to geographic isolation are not likely.

Three points can be noted: 1) The maximum bivalve $\delta^{18}O_{Shell}$ are more negative in the AP (Fig. 5b); 2) Bivalve $\delta^{18}O_{Shell}$ ranges from the AP show a much wider range than that from EA (Fig. 5b); and 3) overall bivalve $\delta^{18}O_{Shell}$ trends in the AP (Collins Harbour and Potter Cove) did not show distinctive seasonal cycles, whereas such cycles were more prominent in the EA (Syowa Coast; Fig. 5c). Maximum bivalve $\delta^{18}O_{Shell}$ should indicate austral winter seasons, and similar austral winter SST values between AP (−1.68 °C) and EA (−1.93 °C) suggest that the amount of sea-ice formation may be similar in the two growth locations of the bivalves (Table 2). Because sea-ice formation influence seawater $\delta^{18}O_{SW}$ very little and because SST values are similar between AP and EA, the difference in bivalve $\delta^{18}O_{Shell}$ (about 1.17‰; maximum bivalve $\delta^{18}O_{Shell}$ from AP vs. EA in Fig. 5b) should reflect different seawater $\delta^{18}O_{SW}$, indicating that the AP was influenced by meltwater input even during austral winter. This also implies that the AP is perennially influenced by meltwater input. The range of bivalve $\delta^{18}O_{Shell}$ from the EA was about the same (2.02 and 2.14‰ from Syowa Coast and Ross Sea), whereas those from the AP ranged from 3.65 to 5.74‰ (Fig. 5b) reflecting the amount of meltwater input during austral summer. Similar ranges between two separate and distant regions in the EA (Syowa Coast and Ross Sea) suggest that the amount of meltwater input into these regions during austral summer is about the same. However, large differences between two adjacent regions in the AP (Collins Harbour and Potter Cove) indicate that the amount of meltwater input can be quite variable.

The bivalve $\delta^{18}O_{Shell}$ trend from the Syowa Coast in EA showed a regular pattern with clear seasonal cycles indicating that seasonal SST, SSS, and meltwater pulses were regular and constant (Fig. 5c). In contrast, cyclic patterns of the bivalve $\delta^{18}O_{Shell}$ from the Collins Harbour and Potter Cove in the AP were quite irregular due to different amounts of meltwater input and glacial coverages. Different rates of meltwater input between EA and AP can be inferred that the melting rate of glaciers has increased more recently due to regional as well as global warming.

Even though it appears that global warming has had a significant influence on the melting of Antarctic glaciers, the exact mechanism to explain the different melting behaviour of glaciers between EA and AP is not yet completely clear (Turner et al., 2005; Steig et al., 2009). Steig et al. (2009) suggested faster warming for West Antarctica, including the AP, based on monitoring and modelling results. These results are consistent with bivalve $\delta^{18}O_{Shell}$ results from both regions. Other data have shown a strong correlation between the atmospheric circulation and temperature in AP (Meredith and King, 2005). Anomalously cyclonic conditions over the Amundsen-Bellingshausen region are associated with increased warm air advection and thus warmer AP austral winters, whilst anomalously anticyclonic conditions are associated with decreased warm air advection and colder AP austral winters. Stronger cyclonic circulation is mainly a result of stratospheric ozone depletion, which has strengthened austral autumn wind speeds around the continent, deepening the Amundsen Sea Low through flow separation around the high coastal orography (Turner, 2009). This temperature trend could result from the increase in the strength of the westerlies driven by both global warming on the one hand and ozone changes in the stratosphere on the other hand (Thompson and Solomon, 2002). The strengthened winds result from the Southern Annular Mode having become more positive in recent decades, primarily because of the combined effects of increasing greenhouse gases and the development of the Antarctic ozone hole (Arblaster and Meehl, 2006). With respect to the warming of the AP, it is also evident that the El Nino-southern oscillation is transmitted by Ross by waves from the tropical Pacific Ocean to the Antarctic (Turner et al., 2005). It is not clear how that signal is itself affected by global warming, but it does serve to warm the AP periodically. Evidently, the effect of global warming on climate changes between EA and AP needs further scrutiny.

6. Conclusions

High resolution trace elemental contents (Mg and Sr) together with growth band positions, stable isotopic compositions and the shell size suggest that the bivalve (*Laternula elliptica*) grew for 9 years from the austral autumn of 1993 to the austral summer of 2002. Based on the comparison between monitoring field data and stable isotopic compositions of the shell, significant drops in SSS and corresponding decreases in bivalve $\delta^{18}O_{Shell}$ and $\delta^{13}C_{Shell}$ are due to meltwater pulses during austral summer. The intensity of meltwater invasion is clearly demonstrated by different ranges of both stable isotopic compositions. The comparison of the $\delta^{18}O_{Shell}$ data from the same species of bivalve from the AP (Collins Harbour and Potter Cove) and EA (Syowa Coast and Ross Sea) may imply the different rates of meltwater input between AP and EA, being more affected in AP. This may have resulted from different atmospheric circulation patterns between two regions due to global warming. However, more data from EA are necessary to confirm this hypothesis.

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