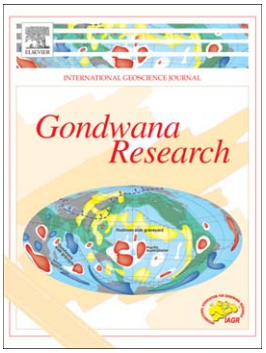

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An early-middle Eocene Antarctic summer monsoon: evidence of 'fossil climates'

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Absract

A warmer and mostly ice-free South polar region prevailed during the early-middle Eocene, indicative of a low latitudinal temperature gradient. Climatic models mostly fail to reconstruct such a low gradient, demonstrating our poor understanding of the mechanisms involved in heat transfer. Here we describe a new phenomenon that shaped the southern high latitude climate during the early-middle Eocene: the Antarctic summer monsoon. Our palaeoclimatic reconstruction is based on 25 morphotypes of fossil dicotyledonous leaves from the early-middle Eocene fossil leaf assemblage of Fossil Hill from King George Island, the Antarctic Peninsula. We use a novel CLAMP (Climate Leaf Analysis Multivariate Program) calibration which

includes new climatic parameters that allow us to characterise better the seasonality in precipitation. Our reconstruction indicates a warm humid temperate climate with strong seasonality in temperature and precipitation. Seasonality in precipitation indicates a rainfall rate of 6.4 ± 1.30 mm/day during summer (summer daily rate of precipitation; SDR) and a summer precipitation representing more than 60.3 ± 8.28% of annual rainfall (ratio of summer precipitation; RSP), which fulfills the definition of a summer monsoon in the modern world. This implies a seasonal alternation of high- and low-pressure systems over Antarctica during the early-middle Eocene. Such a climate regime would have impacted upon global atmospheric circulation and heat transfer. This climatic regime presents a challenge for climatic models and their ability to reconstruct accurately palaeoclimates at high southern latitudes and thereby understand latitudinal heat transfer in a 'greenhouse Earth' regime.

Keywords

Antarctic, Eocene, monsoon, leaf physiognomy, paleoclimate.

1. Introduction

The presence of Cenozoic floras in Antarctica has been known for a long time since the work by Dusén (1908) in the early twentieth century. They are mostly from the Antarctic Peninsula and neighbouring islands, including Seymour Island, Alexander Island and King George Island, which have yielded many fossil sites (Dusén, 1908; Barton, 1964; Orlando, 1964; Thomson and Burn, 1977; Case, 1988; Askin, 1989; Birkenmajer and Zastawniak, 1989; Li, 1994; Doktor et al., 1996; Gandolfo et al., 1998; Poole et al., 2000, 2001, 2003, 2005; Francis and Poole, 2002; Hunt and Poole, 2003; Cantrill and Poole, 2005; Poole and Cantrill, 2006; Francis et al., 2008a). The fossil record of the Antarctic Peninsula is represented mostly by its wood (Poole and Cantrill, 2006); other organs: leaves, palynomorphs, seeds and fruits, flowers; however, have also been discovered and reported.

The Antarctica Peninsula was a continental-margin magmatic arc during the Mesozoic and early Cenozoic (Storey and Garrett, 1985). Paleogene deposits of King George Island are therefore typically those associated with of active volcanism, of a mixed-effusive type (Smellie et al., 1984; Shen, 1994; Xue et al., 1996; Dutra and Batten, 2000). Antarctica was already at a high latitude during the Paleogene, slightly higher than 60°S (Lawver et al., 1992; Wilford and Brown, 1994; Lawver and Gahagan, 2003).

In this study, we focus on the Eocene climate of this marginal region of Antarctica. The palaeoclimate of the early-middle Eocene Fossil Hill flora from the King George Island is reconstructed quantitatively using physiognomic methods. In the studied flora more than 40 leaf morphotypes have already been described, belonging to pteridophytes, gymnosperms and angiosperms (Zhou and Li, 1994a, 1994b; Li, 1994; Li and Zhou, 2007). Many morphotypes were only attributed to dicots without further

resolution of affinities (some of them may represent extinct groups). Nothofagaceous leaves are dominant (Li, 1992). Most of the morphotypes show affinities with the neotropics and the southern part of South America (Li, 1992, 1994).

This vegetation, coupled with volcanic activity, is typical of a Valdivian environment now found in southern Chile (Poole et al., 2001, 2003). The vegetation mostly consists of Myrtaceae, Araliaceae, Podocarpaceae, and Cupressaceae, along with the Nothofagaceae. The Valdivian vegetation is characterised by catastrophic events which allow it to be maintained (Veblen and Ashton, 1978; Veblen et al., 1980). On King George Island during the Eocene, volcanism induced this disturbance (Poole et al., 2001, 2003). Because the diversity of the Fossil Hill Flora assemblage is quite high, it is unlikely to represent early pioneering stages but was probably derived from mature vegetation typical of later serial stages (Poole et al., 2001).

The presence of plant fossils in this now snow world is enough to demonstrate that the climate was warmer in the Eocene and widely distributed data show that globally this was a time of marked warmth (Zachos et al., 2001). Faunal (Reguero et al., 2002) and sedimentary (Dingle and Lavelle, 2000) proxy data also indicate a temperate climate for the Antarctic Peninsula during the early-middle Eocene. The middle Eocene palaeoclimate of King George Island has been reconstructed at several locations based either on wood or leaf fossils indicating a warm temperate climate with high precipitation (Birkenmajer and Zastawniak, 1989; Hunt and Poole, 2003; Poole et al., 2005; Francis et al., 2008b; Reguero and Marenssi, 2010; Table 1). In this ‘greenhouse world’, climatic conditions at high latitudes were markedly warmer than they are today and point to distinctive climatic heat transfer mechanisms compared to today and is suggestive of a weak meridional gradient (Korty et al., 2008). Climatic models mostly fail to reconstruct such a low gradient, demonstrating our poor

understanding of the mechanisms involved in heat transfer (Korty et al., 2008). The general discrepancy between models and proxies for this geological time, and generally for periods with greenhouse climates (Korty et al., 2008), requires new mechanisms to explain heat transfer between low and high latitudes. Detailed reconstructions are needed to discuss the climatic mechanisms.

In this study, we have three aims: to develop a new method to reconstruct the seasonality in precipitation; to reconstruct the palaeoclimate of the Fossil Hill flora; to describe possible climatic mechanisms at high latitudes during a 'greenhouse Earth' regime.

2. Material and Methods

2.1. Fossil locality

The plant fossils studied here were collected from the Fossil Hill Formation of Fossil Hill (62°12'S, 58°57'W), the Fildes Peninsula, southernmost part of King George Island (Fig. 1; Li, 1994), during two Chinese expeditions to Antarctica. The Fossil Hill Formation was dated to early-middle Eocene (52±1 - 43±2 Ma) based on K/Ar and Rb/Sr isotopic dating (Li et al., 1989). Some radiometric dates from King George Island are controversial (Hunt and Poole, 2003). However, the composition of the flora is indicative of a Paleogene age (Torres, 2003) and thus consistent with the radiometric age.

2.2. Fossil assemblage

The Fossil Hill flora consists of 25 morphotypes of dicotyledonous leaves (Fig. 2) that are complete enough for CLAMP study. Twenty species are already published (Li, 1994; Li and Zhou, 2007); five morphotypes are still unpublished. Nothofagaceae are

dominant in the vegetation with six species represented: *Nothofagus oligophlebia* Li 1994, *Nothofagofolia zastawniakiae* (Dutra) Li and Zhou 2007, *N. carpinoides* Li and Zhou 2007, *N. betulifolia* (Dutra) Li and Zhou 2007, *N. multinervis* Li and Zhou 2007, *N. sp.* Other species are: *Lomatia mirabilis* (Dusén) Li 1994, *Pentaneurum dusenii* (Zastawniak) Li 1994, *Oreopanax guinazui* Berry 1938, *Rhoophyllum nordenskjoeldi* Dusén 1899, *Myrtiphyllum bagnalense* Dusén 1899. Several morphotypes have less clear affinities, *Dicotylophyllum latitrilobatum* Zastawniak 1989, *D. elegans* Li 1994, *D. sp.* 1, *D. sp.* 2, *D. sp.* 3, *D. sp.* 4, *D. sp.* 5, *D. sp.* 6, *D. sp.* 9, *D. sp.* 10 (Li, 1994). All fossil species are kept in Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences.

2.3. Palaeoclimate reconstruction

Two methods based on fossil leaves can be applied to reconstruct comprehensive palaeoclimate: Nearest Living Relative (NLR)-based techniques and physiognomic techniques. Antarctic Paleogene floras belong to the 'palaeoflora mixta' that group plants with NLR growing under different climate of Southern hemisphere, temperate and tropical conditions (Romero, 1978). Therefore, the NLR-based techniques, like the coexistence approach (CoA) (Mosbrugger and Utescher, 1997), cannot be applied. Among the physiognomic techniques, CLAMP (Climate Leaf Analysis Multivariate Program; Wolfe, 1993) gives the most comprehensive climate reconstructions (Kennedy et al., 2002). In its most widely used form CLAMP links 31 physiognomic characters from leaves of woody dicots with 11 climatic parameters and is calibrated on modern floras (Wolfe, 1993; Spicer, 2000).

Although the standard CLAMP analysis indicates seasonality of precipitation, it does not reveal whether the wet season occurs in winter or in summer. The Eocene climate

of Antarctica exhibited high seasonality as indicated by sedimentology (Dingle and Lavelle, 2000) and by palaeobotany (Poole et al., 2005). To characterise better seasonality of precipitation we established a new CLAMP calibration by including new climatic parameters: the summer daily rate of precipitation and the summer ratio of precipitation to that of the whole year. The summer is defined as including five months: MJJAS for the northern hemisphere and NDJFM for the southern hemisphere (Zhang and Wang, 2008). In our calibration we include 10 climatic parameters: MAT (mean annual temperature), WMMT (warm month mean temperature), CMMT (cold month mean temperature), LGS (length of the growing season), GSP (growing season precipitation), MMGSP (mean monthly growing season precipitation), 3-WET (precipitation during the three wettest months), 3-DRY (precipitation during the three driest months), SDR (summer daily rate of precipitation), RSP (ratio of summer precipitation). We used a calibration primarily based on the PhysgAsia1 dataset (Jacques et al., 2011). However, we used a different source for meteorological data: primary monthly precipitation data and monthly temperatures for all modern sites were extracted from a global gridded dataset (Hijmans et al., 2005). This was done using the geographical information system software ArcGis 9.3. The gridded meteorological maps have a resolution of 30-arc-seconds and are freely available online (www.worldclim.org). Temperatures were corrected using a global average altitudinal cooling rate (0.5 °C/100 m). The different climatic parameters used in this calibration were then calculated from these primary parameters. Specific humidity, relative humidity and enthalpy are other parameters often used in CLAMP calibrations. However, as they are not included in the global dataset we used, we did not include them in this calibration. This meteorological calibration file is called GRIDMetMonsoon1.

Analyses were carried out using Canonical Correspondence Analysis (CANOCO v.4.0). Regression equations for the CLAMP vector scores against the observed climate parameters were calculated in Axes 1-4 space using SPSS 17.0.

One analysis was carried out using PhysgAsia1 and GRIDMetAsia1, the original gridded meteorological dataset for PhysgAsia1 (Jacques et al., 2011), for comparison with the new calibration.

All modern sites were used as active for the calibration and the analysis; the Fossil Hill flora was included as passive in the analysis.

The scoresheet for the fossil flora, the physiognomic spreadsheet, the meteorological spreadsheet, and the new calibration spreadsheet are given as supporting files.

Palaeoclimate reconstruction followed the CLAMP procedure (http://clamp.ibcas.ac.cn/).

3. Results

3.1. Palaeoclimate reconstruction

In the morphospace resulting from the canonical correspondence analysis, the Fossil Hill flora plotted within the cloud of calibration sites (Fig. 3-4). Palaeoclimate reconstruction (Table 2) indicated a warm temperate climate (MAT 11.5 °C), with high seasonality and freezing temperatures in winter. The palaeoclimate was wet (GSP 1259.3 mm), with high seasonality (3-DRY is less than a third of 3-WET). The summer was wet with 6.4 mm of rainfall per day on average, and the summer precipitation represented 60.3% of the annual rainfall. The results obtained with the new calibration and PhysgAsia1 calibration are very similar, and generally fall within the standard error.

3.2. Physiognomic comparison

The calibration files contain sites from North America, Puerto Rico, the Fijis, Japan and New Caledonia. The Fossil Hill flora plots outside the area occupied by sites in America and within that of sites in Japan and close to those from northern China (Fig. 3-4). The physiognomy of the Fossil Hill leaves is similar to those from sites in Japan; an archipelago experiencing the South-East Asian monsoon, but surrounded by an ocean that tempers dry season water stress.

4. Discussion

4.1. Evaluation of the new calibration

The new calibration (based on GRIDMetMonsoon1 and PhysgAsia1) gives similar standard deviations for temperature-related variables compared with the PhysgAsia1 calibration, but slightly higher uncertainties for precipitation-related variables (Table 2). This is because we use a simpler lapse rate altitude correction compared to previous calibrations; precisely, we only corrected monthly mean temperatures. The new calibration can therefore be used with confidence.

4.2. Palaeoclimatic reconstruction under high CO_2 level.

The atmospheric CO_2 concentrations were far higher in the Eocene than they are today (Berner and Kothavala, 2001; Lowenstein and Demicco, 2006; Bijl et al., 2010; Grein et al., 2011), namely 853-1033 ppm (Grein et al., 2011). As leaf stomata play an important role in CO_2 exchange, one might think there would be a strong response by leaf physiognomy to changes in CO_2 levels. Such a response may influence the results of analyses using leaf physiognomy. However, the response is not so simple. Jordan (1997) explained that the response of overall physiognomy to changes in CO_2 levels is

completely unknown. Gregory (1996), however, noticed that only three of the eleven genera studied changed in leaf size with increasing CO_2 levels. She concluded that the error introduced by elevated CO_2 is less than the CLAMP standard error for precipitation. Moreover, the response of the physiognomy of trees to high CO_2 levels is often less than that observed for herbaceous plant (Norby et al., 1999). Indeed, leaf physiognomy adapts to many environmental constraints and not only to CO_2. "For example, CO_2-induced reductions in stomatal conductance and (at least temporally) transpiration should contribute to an increase in leaf temperature. This increase in leaf or needle temperature exerts negative feedback on transpiration, and rates of transpiration may therefore increase after partial stomatal closure" (Norby et al., 1999: p. 706). Moreover, for the Lower Cretaceous when CO_2 was also high, CLAMP results are similar to those of isotopic data (Spicer and Hermann, 2010). Therefore, results of leaf physiognomy are valid even in high CO_2 regimes.

4.3. Early-middle Eocene climate of King George Island

Whichever calibration dataset was used (Physg3brcAZ with GRIDMet3br or PhysgAsia1 with GRIDMetMonsoon1), our results indicate a warm temperate humid climate (Table 2). Earlier studies indicated a cool to warm temperate climate for the late Paleocene-middle Eocene of King George Island based on four sites: Mount Wawel, Dragon Glacier, Fossil Hill, and Collins Glacier (Francis et al., 2008a; Poole et al., 2005; Table 1). Our results confirm that the winter temperatures were often below freezing in the Antarctic Peninsula during the early-middle Eocene (Francis et al., 2008a). In the late Paleocene-middle Eocene, the vegetation was typically mesothermal in both northern and southern high latitudes (Askin and Spicer, 1995). Our results indicate a growing season of 6.8 months (Table 2), which fits well with

high latitudes where the growing season is mostly controlled by light availability.

4.4. Summer monsoon rainy season

Our results indicate a strong seasonality in precipitation (Table 2). This seasonality is also suggested by the smectite/kaolinite ratio (Dingle and Lavelle, 2000), and by previous studies of fossil plants (Poole et al., 2005; Francis et al., 2008b). The distribution of precipitation throughout the year is also important: does the rainy season occur in summer or in winter? Our results indicate a summer daily rate of precipitation of 6.4 mm/day and summer precipitation represents 60.3% of annual precipitation. This clearly indicates a summer rainy season. A summer rainy season, in turn, suggests a monsoon regime. Several criteria have been proposed to define a monsoon regime based on precipitation. A uniform criterion can be used, for example a rainy season with a rainfall rate exceeding 6 mm/day (Lau and Yang, 1997). A multi-criteria approach has also been defined: (1) the summer rainfall rate should be equal to or over 3 mm/day, (2) the ratio must be greater than 55%, the summer in the Southern Hemisphere is defined as NDJFM (Zhang and Wang, 2008). The early-middle Eocene climate of Fossil Hill fulfills both criteria for a summer monsoon rainy season.

There are six monsoon domains on Earth today: the Asian summer monsoon, the Indonesian and Australian summer monsoon, the North African summer monsoon, the South African summer monsoon, the North American summer monsoon, and the South American summer monsoon (Zhang and Wang, 2008). These regions are mostly tropical and subtropical, and none extend to high latitudes. Our results indicate an early-middle Eocene southern high latitude rainfall regime that can be regarded as monsoonal when compared with any of these domains, i.e. SDR over 3 mm and RSP

over 55 % (Zhang and Wang, 2008). This clearly represents a 'fossil climate', as high latitude summer monsoons are not a feature of our present climate system.

The monsoon indicated by the Fossil Hill flora is similar to that found today in Japan (Fig. 3-4). That the Fossil Hill flora does not plot within the cloud of modern Chinese monsoon sites can be explained by 1) the Chinese sites with a strong monsoon signal are in subtropical regions with high temperatures (Jacques et al., 2011), whereas the Fossil Hill flora comes from cooler high latitudes (the proximity of some sites in north China confirm this), and 2) the Fossil Hill flora is situated on King George Island, part of the Southern Shetland archipelago, and its monsoon regime is likely to have been tempered by the influence of the surrounding ocean similar to that for Japan today.

4.5. Climate models

Climate models, including coupled models and general circulation models, usually reconstruct cold and dry climates for Antarctica during the Eocene (e.g., Shellito et al., 2003; Huber and Goldner, 2012). Proxies, either biological or chemical, indicate that the climate was warmer than that indicated by the model reconstructions (Korty et al., 2008). Because of the laws of physics, the water content of the atmosphere diminishes with temperature. Therefore, cold climates are dry. Because the models reconstruct colder climates than the proxies at high latitudes, they will also tend to reconstruct drier climates than the proxies, including the present palaeobotanical proxy. Other palaeoclimatic reconstructions of Eocene Antarctica sites (Poole et al., 2005; Francis et al., 2008b) also indicate a warm and humid climate (Table 1).

Most of the climate models fail to simulate seasonal alternations of high- and low-pressure systems at polar regions (Hay et al., 2005). The importance of ice-sheet

and vegetation cover in the context of climate feed-back is clearly demonstrated (Ogura and Abe-Ouchi, 2001; DeConto and Pollard, 2003; Thorn and DeConto, 2006). In summer, the Antarctic region receives a large amount of solar radiation. During early-middle Eocene, the Antarctic ice-sheet was absent (Zachos et al., 2001), even if some mountain glaciers might have occurred (Birkenmajer et al., 2005). In the absence of an ice sheet, the albedo will be low, and the continent will be warmer than the surrounding ocean in the summer (Hay et al., 2005). The Antarctic landmass, with its low heat capacity, will be colder than the surrounding ocean during the winter (Hay et al., 2005). This seasonal variation in temperature results in a low-pressure system during the summer and a high-pressure system during the winter (Fig. 5). This in turn would have caused reversals in airflow and seasonality in precipitation, as reconstructed from the Fossil Hill flora (humid summer compared to relatively dry winter). Such an alternation has not been demonstrated in models (Hay et al., 2005). Some models show a more global distribution of monsoon systems during the Eocene, but without mentioning Antarctica specifically (Huber and Goldner, 2012). Nevertheless, our results constitute strong evidence in support of this alternation. The Fossil Hill flora was situated on an island in the path of strong monsoonal winds created by the seasonally alternating Antarctic pressure systems, in the same way as the modern day Philippines and Japanese archipelagos are under the influence of the South-East Asian monsoon.

4.6. The Valdivian model

The Paleogene floras of the Antarctic Peninsula have been compared to the Valdivian forest (Poole et al., 2001, 2003). The climate of the Valdivia region is totally different from that of King George Island during the early-middle Eocene (Table 2). Even if the

MATs are similar, the seasonality in temperature is clearly less pronounced than for the Fossil Hill flora. In Valdivia, summer is the dry season, with summer precipitation only accounting for 19.2% of annual precipitation, and averaging 3.1 mm/day, clearly excluding a monsoon climate. Even if the modern Valdivia province and the early-middle Eocene King George Island experience a strong influence of volcanic catastrophic events, they differ through their climate. The Valdivian model well reflects some environmental conditions of the early-middle Eocene King George Island ecosystem but does not give a good picture of its climate.

5. Conclusions

Our study of the Fossil Hill flora reveals an early-middle Eocene summer monsoon in Antarctica. At the present day, there is no such climate at high latitudes; therefore, we interpret it as representing a 'fossil climate'. We invite climatologists to study how this early-middle Eocene Antarctic monsoon may have affected the global climate at that time and specifically heat transfer at high southern latitudes. Our study, together with those of other possible fossil climates will help to understand better 'greenhouse Earth' climate regimes.

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Table 1. Comparison of Fossil Hill with other floras. MAT, mean annual temperature; MAP, mean annual precipitation; GSP, growing season precipitation; LMA, leaf margin analysis; CLAMP, climate leaf analysis multivariate program; WP, wood physiognomy. Data from Poole et al. (2005), except * from this study.

Parameter	Method	Dragon Glacier	Fossil Hill	James Basin	Ross
MAT (°C)	LMA	10.5	8.8		
	CLAMP	10.6	11.5*		
	WP		11.7	10.9	
MAP (mm)	LMA	1039	1059		
	WP		3707	3889	
GSP (mm)	CLAMP	885	1259.3*		

Table 2. **Climate values of Fossil Hill during the Eocene and at present day.** Modern values come from Bellingshausen station on Fildes Peninsula at 62°12'S 58°56'W (www.aari.aq) and from Mueller (1996) for Valdivia. Standard deviation of the residuals are used for standard errors.. NA, not applicable.

Parameter	Eocene		Modern	
	GRIDmetMonsoon1	GRIDMetAsia1	King George	Valdivia
MAT (°C)	11.5±1.39	10.7±1.25	-2.3	11.3
WMMT (°C)	24.8±1.58	23.6±1.51	1.8	17
CMMT (°C)	-0.5±2.45	-0.5±2.57	-8.0	7
LGS (months)	6.8±0.73	6.2±0.74	0	7
MAP (mm)	NA	NA	698.4	2489
GSP (mm)	1259.3±309.1	1080.6±217.7	0	809
MMGSP (mm)	176.6±32.1	165.6±25.3	0	115.6
3-WET (mm)	661.4±150.9	627.7±139.0	202.9	1165
3-DRY (mm)	217.9±57.7	169.7±41.2	147.1	241
SDR (mm)	6.4±1.30	NA	1.9	3.2
RSP (%)	60.3±8.3	NA	41.2	19.2

Figure captions

Fig. 1. Location of Fossil Hill fossil sites (62°12'S, 58°57'W), the Fildes Peninsula, southern end of King George Island, Antarctic Peninsula. A, general map of Antarctica; B, detailed map of Antarctica Peninsula; C, detailed map of King George Island.

Fig. 2. Selected morphotypes of the Fossil Hill flora. A. *Dicotylophyllum elegans* Li (PB16663); B. *Dicotylophyllum* sp. 1 (PB16664); C. *Dicotylophyllum* sp. 2 (PB16666); D. *Dicotylophyllum latitrilobatum* Zastawniak (PB16679); E. *Dicotylophyllum* sp. 9 (PB14251); F. *Dicotylophyllum* sp. 3 (PB16668); G. *Lomatia mirabilis* (Dusén) Li (PB16658); H. *Dicotylophyllum* sp. 10 (PB16676); I. *Pentaneurum dusenii* (Zastawniak) Li (PB16656); J. *Nothofagofolia multinervis* Li et Zhou (PB20805); K. *Nothofagofolia betulifolia* (Dutra) Li et Zhou (PB20817); L. undescribed species; M. *Dicotylophyllum* sp4 (PB16669); N. *Rhoophyllum nordenskjoeldi* Dusén (PB15452); O. *Nothofagofolia carpinoides* Li et Zhou (PB20819); P. *Nothofagofolia zastawniakiae* (Dutra) Li et Zhou (PB20823). Scale bar=1 cm.

Fig. 3. Position of the Fossil Hill flora in physiognomic space. Physiognomic space is represented in the first three dimensions of Canonical Correspondence Analysis. All available modern sites in PhysgAsia1 were used as active; Fossil Hill flora as passive. Fossil Hill flora plots near sites in Japan, not far from some sites in northern China, and well away from sites in America. The physiognomy of the Fossil Hill flora is similar to that of modern sites from an archipelago experiencing the South-East Asian monsoon (Japan). The Fossil Hill flora was situated on an island belonging to the Southern Shetland archipelago.

Fig. 4. Position of the Fossil Hill plant assemblage in physiognomic space. Vectors

represent climatic parameters: MAT, mean annual temperature; WMMT, warm month mean temperature; CMMT, cold month mean temperature; LGS, length of the growing season; GSP, growing season precipitation; MMGSP, mean monthly growing season precipitation; 3-WET, precipitation during the three wettest months; 3-DRY, precipitation during the three driest months; SDR, summer daily rate of precipitation; RSP, ratio of summer precipitation.

Fig. 5. Schematic view of the seasonal air pressure reversal over Antarctica during the Eocene. Arrows represent the movement of air masses. In summer (left), long insulation and low albedo result in an overheating of the continent compared to the ocean. The low continental pressure induces winds bringing humidity from the ocean. In winter (right), the absence of light induces a rapid cooling of the continent compared to the ocean. The high pressure over the continent is responsible of winds towards the ocean preventing humidity to come on the continent.

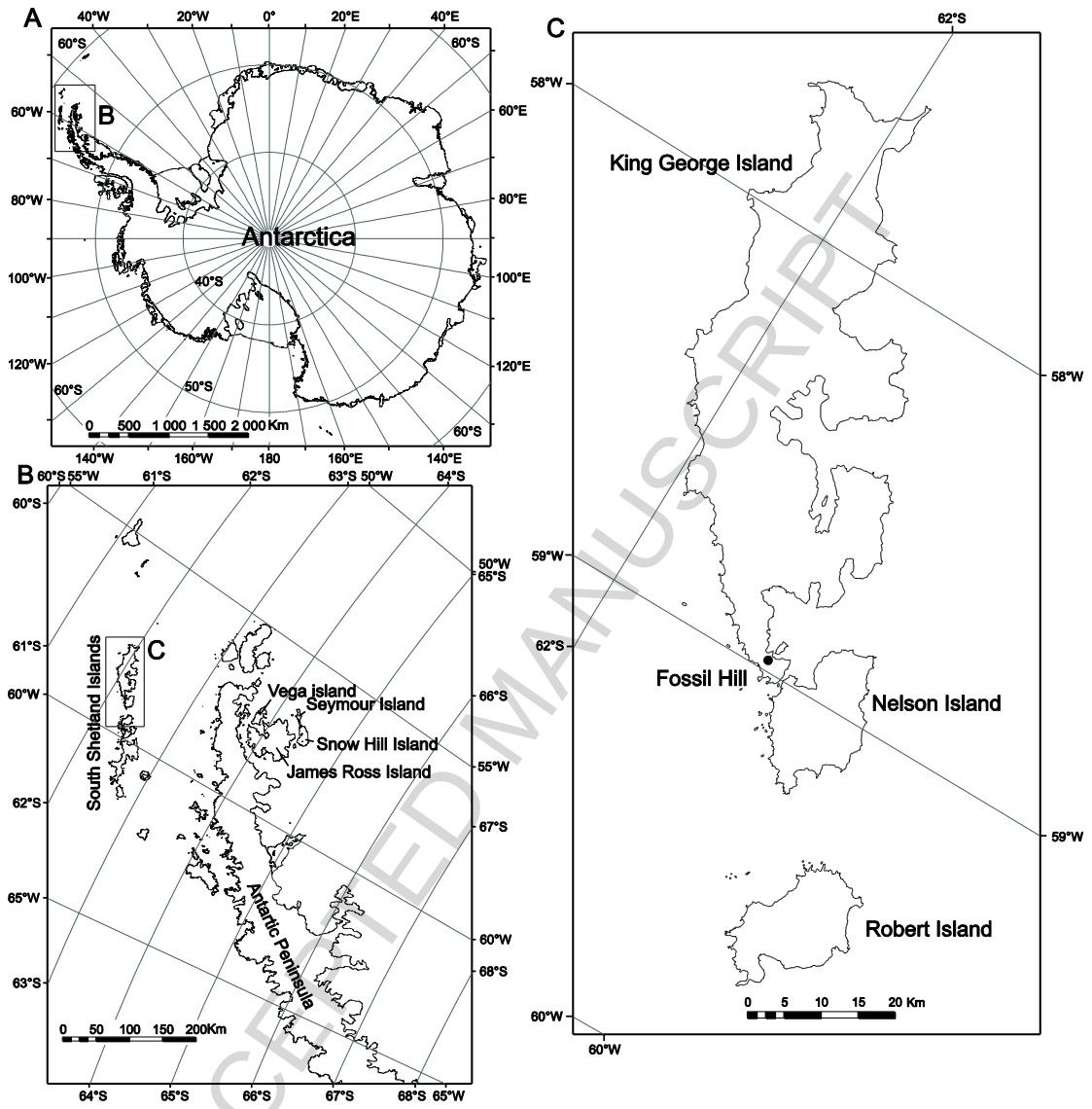


Fig. 1

Fig. 2

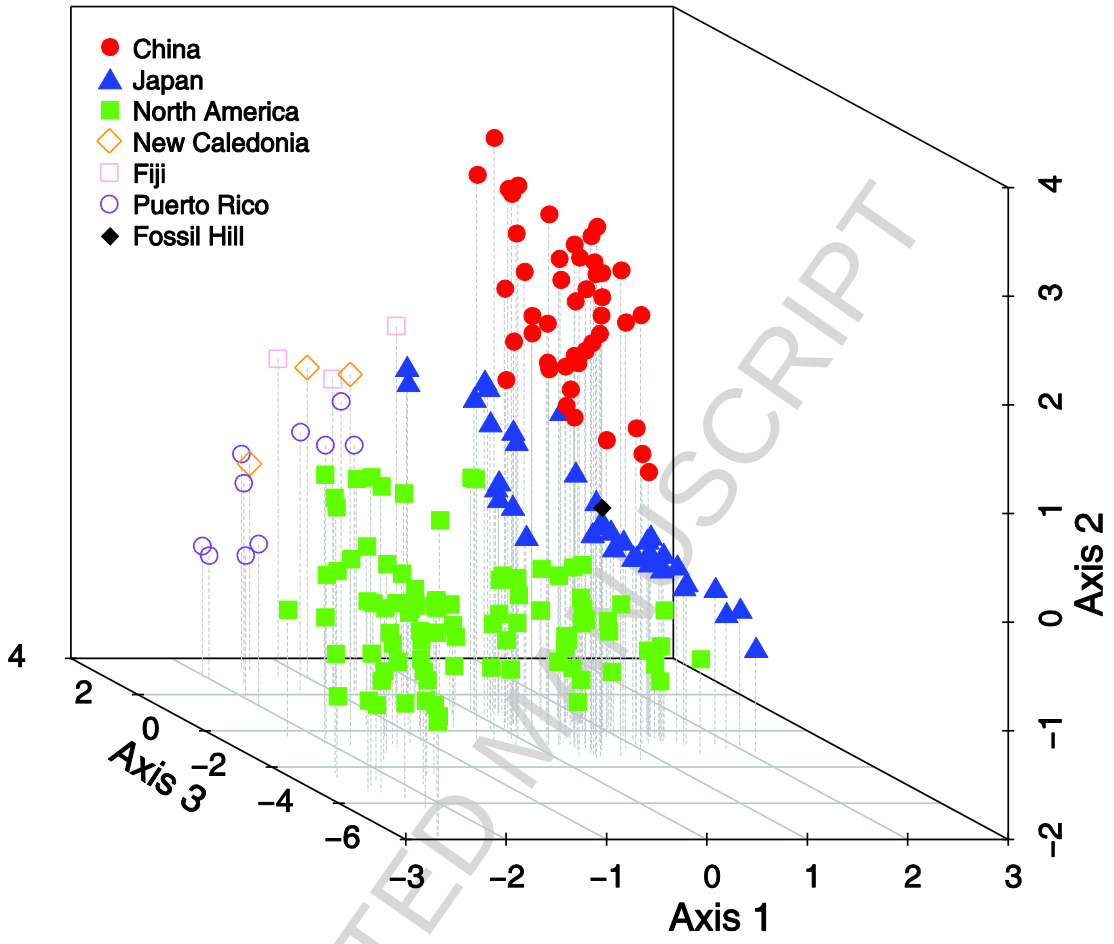


Fig. 3

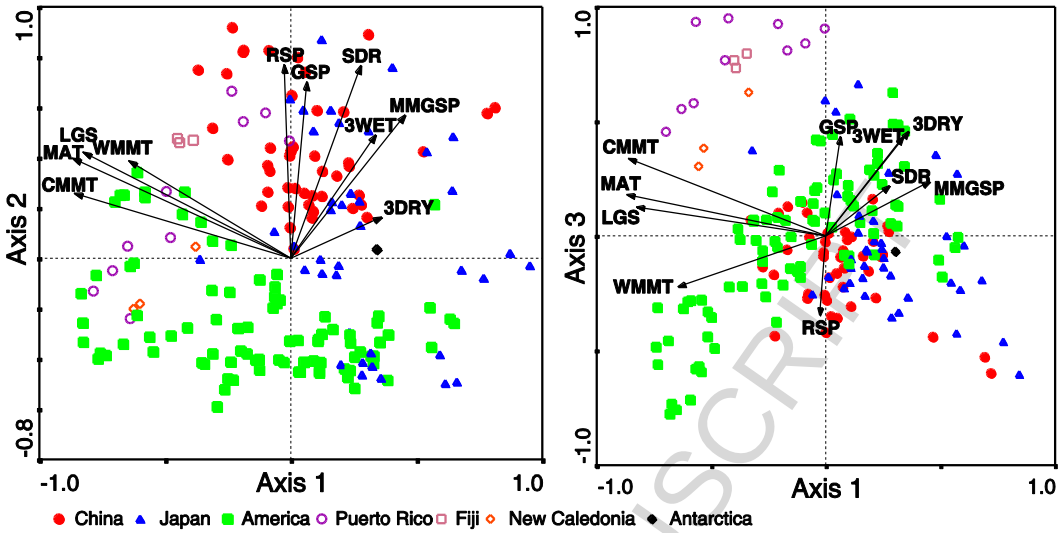


Fig. 4

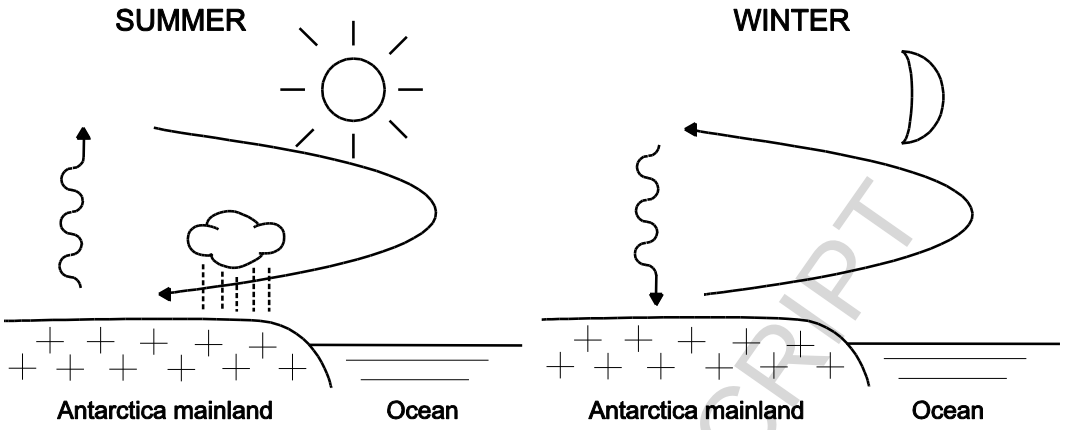
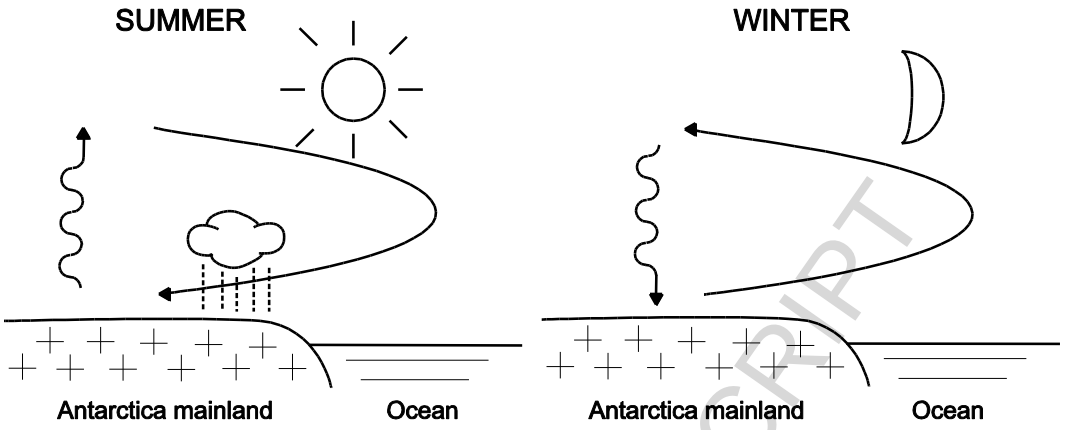


Fig. 5



Graphical abstract

Highlights

- A new CLAMP calibration including new climatic parameters was developed.
- The Eocene climate of the King George Island, Antarctica, was warm and humid.
- The Eocene climate of Antarctica was characterized by a monsoon regime.