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Antarctic deglacial pattern in a 30 kyr record of sea surface temperature offshore South Australia

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[1] Comparison of ice cores from Greenland and Antarctica shows an asynchronous two-step warming at these high latitudes during the Last Termination. However, the question whether this asynchrony extends to lower latitudes is unclear mainly due to the scarcity of paleorecords from the Southern Hemisphere. New data from a marine core collected off South Australia (~36°S) allows a detailed reconstruction of sea-surface temperatures over the Last Termination. This confirms the existence of an Antarctic-type deglacial pattern and shows no indication of cooling associated with the Northern Hemisphere YD event. The SST record also provides a new comparison with the more extensive paleoclimatic data available from continental Australia. This shows a strong climatic link between onshore and offshore records for Australia and to Southern Hemisphere paleorecords. We also show a progressive SST drop over the last ~6.5 kyr not seen before for the Australian region. **Citation:** Calvo, E., C. Pelejero, P. De Deckker, and G. A. Logan (2007), Antarctic deglacial pattern in a 30 kyr record of sea surface temperature offshore South Australia, *Geophys. Res. Lett.*, *34*, L13707, doi:10.1029/2007GL029937.

1. Introduction

[2] Comparison of climate records from Greenland and Antarctic ice cores, with the exception of the coastal Antarctic site of Taylor Dome, has provided evidence for an asynchronous pattern in the evolution of air temperatures during the last ice age and Termination I [*Blunier and Brook*, 2001]. During the last deglaciation, the Antarctic Cold Reversal (ACR), that interrupted the deglacial warming in Antarctica, coincided with the warm Bølling-Allerød in Greenland and occurred ~1 kyr before its northern hemisphere cold counterpart, the Younger Dryas (YD) event [*Jouzel et al.*, 1995]. This north-south asymmetry is consistent with the bipolar seesaw hypothesis which proposes a response to changes in the thermohaline circulation and heat transport, causing Antarctica to cool when Greenland warms and vice versa [*Broecker*, 1998]. While it appears that climate changes in Greenland ice cores have been synchronously recorded in most Northern Hemisphere latitudes, evidence from the Southern Hemisphere is sparse. In a compilation of SST records from the Pacific Ocean [*Kiefer and Kienast*, 2005], only one SST record presented a clear Antarctic pattern during the deglaciation [*Pahnke et al.*, 2003]. The only other record from the Southern Hemisphere with enough temporal resolution to show an ACR was a δ^{18}O record from the South Atlantic [*Charles et al.*, 1996] and more recently a $U^{k'}_{37}$ SST record from the SE Pacific [*Kaiser et al.*, 2005].

[3] Here we present a new alkenone-derived sea-surface temperature (SST) record from offshore southern Australia, which covers the last deglaciation and the Holocene in detail. These new data provide support for the idea that deglacial SSTs in the mid latitudes of the Southern Hemisphere evolved in synchrony with Antarctica. They also offer a detailed Holocene marine record, still very scarce in this area, to compare with the more extensive climatological information from continental Australia.

2. Materials and Methods

[4] Sediment gravity core MD03-2611 (36°44′S, 136°33′E, 11.97 m long) was recovered from the Murray Canyons area, off Kangaroo Island, South Australia during the AUSCAN 2003 cruise (Figure 1) [*Hill and De Deckker*, 2004]. The site is located at 2,420 m water depth on a small plateau over a ridge, avoiding the processes of erosion and sediment redistribution that occur within the main canyons. It is more than 200 km away from the present mouth of the Murray River and ~50 km away from the present 100 m depth contour, which roughly delimits the broad continental shelf, and sedimentation is mostly pelagic. A description of the core and its mineralogical content is available in the work of *Gingele et al.* [2004].

[5] Alkenone analyses on selected core samples were performed following published methods [*Calvo et al.*, 2003] and alkenone-derived SSTs were reconstructed using the relationship $U^{k'}_{37} = 0.033 \times \mathrm{SST} + 0.044$ [*Müller et al.*, 1998], which provides annually averaged SSTs. The accepted error bar is of the order of 1°C. The core-top estimate provides a SST of 17.6°C, slightly warmer than the modern annual mean of 16.5°C at 0 m depth [*Conkright et al.*, 2002]. This difference is probably due to the absence of the most recent sediments from the top of the gravity core as confirmed by a ^{14}C AMS date of the core-top sediment, which provides a calibrated age of 683 years. A preferential alkenone production during summer/autumm, when upwelling develops along the coast of of the southern Eyre Peninsula [*Kämpf et al.*, 2004], could also slightly bias the reconstructed SSTs towards warmer values (SSTsummer = 18.4°C; SSTautumm = 17.1°C).

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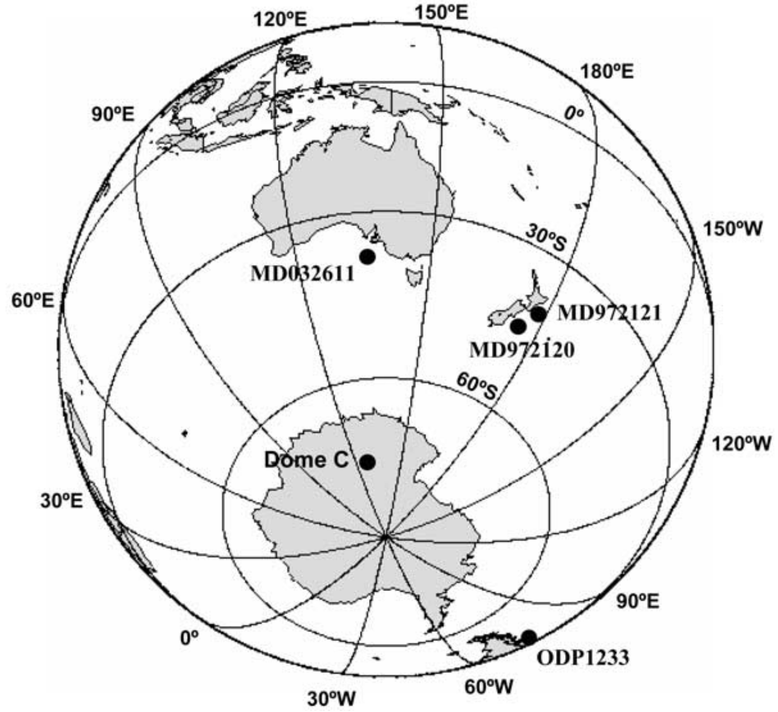

Figure 1. Map showing location of marine core MD03-2611 (36°44′S, 136°33′E). Also displayed other marine and ice cores discussed in the text.

[6] Oxygen isotopes were analysed on the planktonic foraminifera *Globigerinoides bulloides* on a Finnigan MAT251 mass spectrometer at GEOMAR (Germany). This species was also used to establish the age model by means of 16 AMS ^{14}C dates. From 0 to 26 cal kyr BP, radiocarbon ages were converted into calendar ages using the Calib 5.01 software and the marine calibration dataset MARINE04 [*Hughen et al.*, 2004], which includes a marine reservoir correction of 400 years. The oldest ^{14}C age (24860 ^{14}C yr) was calibrated using the CALPAL program and the CalPal 2005 SFCP calibration curve (available at http:/www.calpal.de). According to this age model, the 765 cm analysed in this study cover the last 30 kyr and sedimentation rate averaged ~27.6 cm/kyr. Thus, the 10-cm sampling interval provides a time resolution of ~360 years for the alkenone record. The δ^{18}O record also present the same time resolution for the top 400 cm of the core. For the bottom 350 cm (between 16.8 and 30 kyr), we sampled every 25 cm which provides a time resolution of ~890 years.

3. Results

[7] The alkenone-derived SST record shows a large deglacial warming, up to 8°C, from 11°C at ~19 cal kyr BP (the coldest SST recorded during the Last Glacial Maximum (LGM: 21 ± 2 kyr [*Mix et al.*, 2001]) to 19.3°C at the beginning of the Holocene (Figure 2). A similar amplitude was found using amino-acid racemization in emu eggshells from Central Australia with a deglacial average air temperature increase of 9°C [*Miller et al.*, 1997]. SST amplitudes of 7–10°C were also found along the Chilean margin at 35°S [*Romero et al.*, 2006] and in subantarctic waters southeast of New Zealand [*Barrows et al.*, 2000]. However, this change of 8°C is still considerable when compared with other mid-latitude SST records of the Southern Hemisphere (Figure 3). It is likely that the present influence of the Leeuwin Current, which brings warm and low-salinity waters from the Indian Ocean to the southern Australian coast as far east as 130°E [*Rochford*, 1986], was much reduced or absent during the LGM. This, together with a greater influence of cold Southern Ocean waters during the LGM would cause a larger SST amplitude than expected for these latitudes.

[8] The deglacial warming is accomplished in two steps, with an interruption between 15 and 13.3 kyr BP, which is also captured by the δ^{18}O record. The first warming (~5°C) occurred between 19 and 15.5 kyr BP and the second (3.5°C) between 13.3 and 11 kyr BP. After a small cooling (0.6°C) at 11 kyr BP, SSTs exhibited a broad maximum between 5.5 and 8 kyr BP, reaching the highest values of the whole record (19.8°C) at 7.5 kyr BP. The record shows small SST variability during this Holocene broad thermal maximum, a period followed by a gradual decrease of ~2°C towards modern SST values.

[9] The δ^{18}O record closely follows the glacial and deglacial pattern displayed by the alkenone record, with a 2.2‰ change between glacial and Holocene sections (Figure 2). Considering that the ice volume contribution to this change is about 1‰ [*Schrag et al.*, 1996], the remaining 1.2‰ should reflect changes in local SST and salinity. Given the ~8°C warming recorded by the $\mathrm{U}_{37}^{k'}$ index, seawater δ^{18}O is expected to change by ~1.6‰ over the deglaciation [*Bemis et al.*, 2002]. Accordingly, the 0.4‰ isotopic difference is ascribed to an increase in local salinity of about 0.8 units since the last glacial period (assuming a change of 0.5‰ per 1 salinity unit). The decrease in salinity during the LGM may be related to a northward displace-

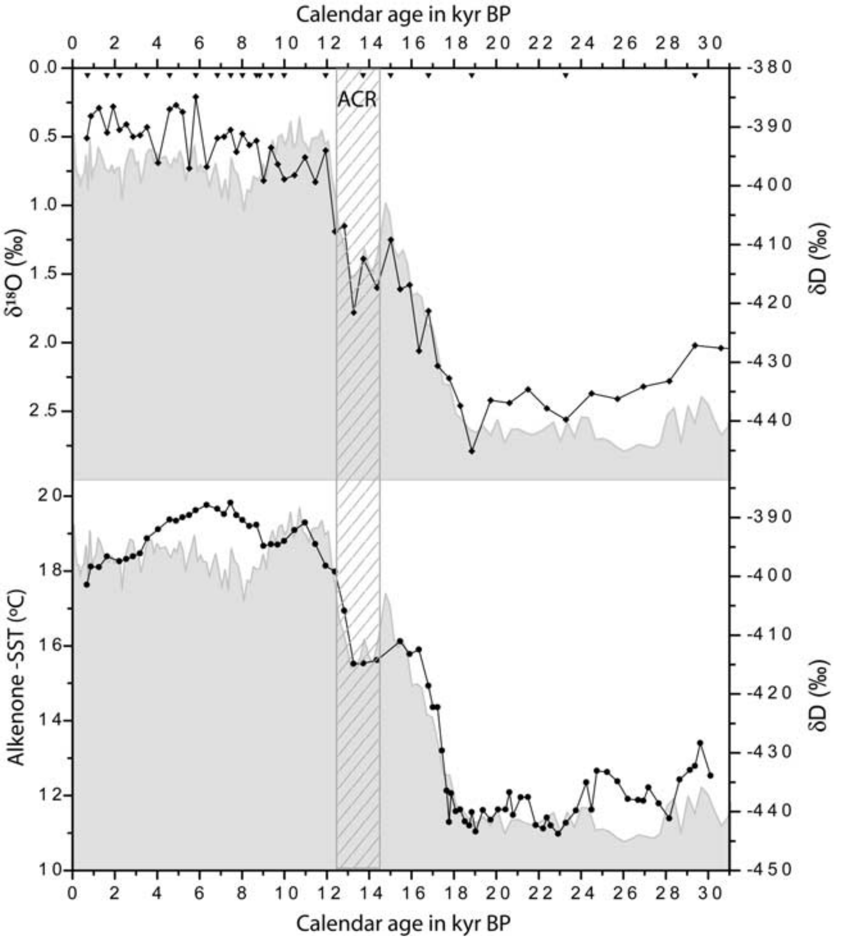

Figure 2. (top) *G. bulloides* δ^{18}O record and (bottom) alkenone-derived SST record from core MD03-2611. Also plotted Antarctica air temperatures, δD (shaded area [*EPICA Community Members*, 2004]). The vertical bar indicates the Antarctic Cold Reversal (ACR).

ment of the Subtropical Front (STF: present location between 38–40°S) and its associated salinity gradient. *Pahnke et al.* [2003] also found a consistent decrease in salinity during glacial times east of New Zealand, which was attributed to a major influence of fresher subantarctic waters from the south of the STF. Alternatively, the exposure of the shallow shelf during the sea level drop at the LGM may have also prevented the formation of the high salinity surface waters that are formed today in the Spencer Gulf, north of Kangaroo Island, as a result of strong summer evaporation [*Lennon et al.*, 1987].

[10] During the late Holocene, however, the evolution of the δ^{18}O and alkenone records differs significantly. The consistent cooling observed in the alkenone record for the last 6 kyr is not identified in the isotope record. Instead, the δ^{18}O measurements reach Holocene values at about 12 kyr BP and then follow a progressive depletion towards the lowest δ^{18}O values of the whole record at the top of the core. The contrasting evolution of the two proxies suggests a significant influence of salinity in the planktonic δ^{18}O record at this time.

4. Discussion

[11] The deglacial warming at site MD03-2611 closely resembles the atmospheric temperature evolution reconstructed in Antarctica since the end of the LGM, both in timing and structure (Figure 2). The clear reversal in SST and δ^{18}O observed during the deglaciation is synchronous with the ACR described in Antarctic ice cores around 14–12.5 kyr BP [*Jouzel et al.*, 1995], suggesting a close coupling between mid- and high-southern latitudes. After this reversal, SSTs increased gradually to the Holocene, providing no evidence of any cooling associated with the YD cold event (12.9–11.5 kyr BP). Whether this event, which is characteristic of the Northern Hemisphere, also affected the Southern Hemisphere has been the subject of considerable debate. *Denton and Hendy* [1994] reported an advance of the Franz Josef Glacier in New Zealand during the YD, pointing to inter-hemispheric deglacial symmetry. However, other terrestrial reconstructions from New Zealand provided contrasting results, more indicative of asymmetry between hemispheres [i.e., *Turney et al.*, 2003]. In the mid to high latitudes of South America, studies on the existence of cooling related to the YD are also contradictory [i.e., *Glasser et al.*, 2004].

[12] An Antarctic-type deglacial pattern has been reported in high resolution marine sediment cores using alkenone- and Mg/Ca-SST methods from the southeast Pacific and east of New Zealand [*Kaiser et al.*, 2005; *Lamy et al.*, 2004; *Pahnke et al.*, 2003]. In Figure 3, we compare our MD03-2611 SST record with the three high resolution

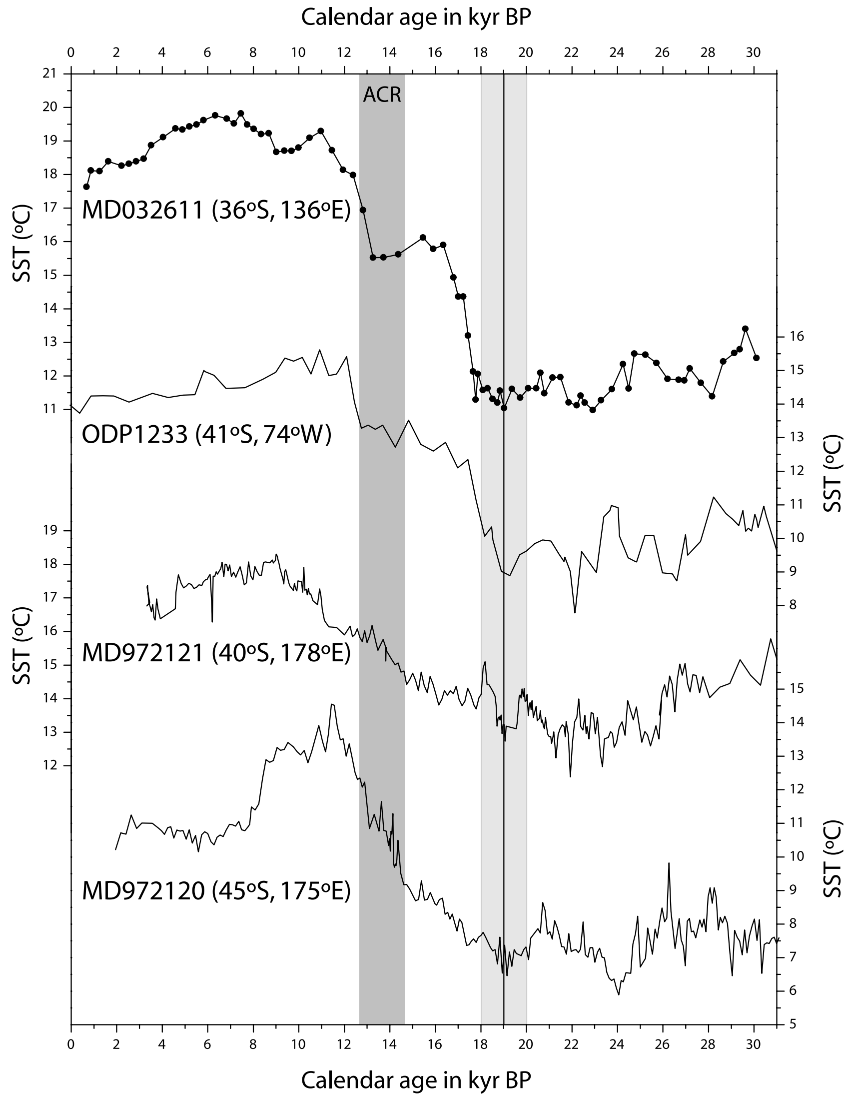

Figure 3. Comparison of high resolution alkenone-derived SST records available from the mid-latitudes of the Southern Hemisphere [*Kaiser et al.*, 2005; *Pahnke and Sachs*, 2006]. See Figure 1 for location of the marine cores. ACR is the Antarctic Cold Reversal. Light shaded bar indicates the onset of deglacial warming at 19 ± 1 kyr.

and radiocarbon-dated alkenone-derived SST records available from these mid-latitudes of the Southern Hemisphere. All four SST records show a synchronous onset of deglacial warming at ~19 kyr, comparable with the start of deglaciation in Antarctica and SST records from tropical and subtropical latitudes of the Pacific Ocean [*Kiefer and Kienast*, 2005]. With the exception of core MD97-2121, from north of Chatman Rise, all records display cooling associated to the ACR. This cooling is clear in cores MD03-2611 and ODP1233, off Chile, but only represents an interruption of the warming in core MD97-2120, east of New Zealand. However, Mg/Ca data from the same core show a 1.5°C cooling during the ACR [*Pahnke et al.*, 2003]. There is no evidence of cooling associated to the YD cold event in any of the alkenone-derived SST deglacial records. This contrasts with recent results from planktonic foraminifera δ^{18}O in two studies, which have been interpreted as evidences of cooling associated to the YD in the mid to high latitudes of the Southern Hemisphere. These studies reported δ^{18}O enrichments at the time of the YD for a core also retrieved South of Australia [*Andres et al.*, 2003] and for two cores from South of New Zealand, close to the Ross Sea [*Morigi et al.*, 2003]. Given the compilation of alkenone-derived SST data described above (Figure 3) and that foraminifera δ^{18}O is influenced by other parameters in addition to SST, we suggest that the isotopic enrichment may not solely be related to sea surface cooling.

[13] Considering that higher SST promotes evaporation, formation of clouds and precipitation, alkenone-derived SSTs in core MD03-2611 agree with the present knowledge of the history of rainfall and moisture in continental Southern Australia during the Holocene. The cold temperatures of the last 4 kyr coincide with a period of increased aridity in southeastern Australia [*Cupper*, 2005; *Harrison*, 1993]. Drier conditions have also been inferred from the mineralogical and isotopic study of the terrestrial component of MD03-2611 [*Gingele et al.*, 2007]. The δ^{18}O record, however, show the lightest values of the whole record during the late Holocene, indicating the existence of low salinity water masses. Salinity changes can be driven by

changes in the evaporation-precipitation balance and also by the vertical/horizontal mixing of different water masses. The arid conditions that prevailed in the area at that time cannot account for these low salinity waters. Thus, changes in the water masses bathing our core site is the most likely explanation. A plausible mechanism to explain the cold SSTs shown by the $U^{k'}_{37}$ and the low salinities recorded by the oxygen isotopes is a greater influence of Southern Ocean waters versus the tropical waters of the Leeuwin Current. Interestingly, marine cores from the western tropical Pacific also show a similar trend during the Holocene, with δ^{18}O decreasing from 10 ka to the present and Mg/Ca ratios recording the lowest SSTs during the late Holocene [*Stott et al.*, 2004]. It may well be that the decrease in salinity of the latter part of the Holocene is then a wider feature across the Pacific Ocean, as already suggested by *Stott et al.* [2004].

[14] Warmer SSTs coincide with higher precipitation during the mid-Holocene, between 8 and 6 kyr BP, as recorded in southeastern Australia lake levels [*Bowler*, 1981; *Stanley and De Deckker*, 2002] and in the history of a swamp from the Fleurieu Peninsula [*Bickford and Gell*, 2005]. On the other hand, the progressive decrease in SST from 6.5 kyr BP to modern times parallels other alkenone-derived SST records from the mid latitudes of the Southern Hemisphere, as recently reviewed by *Lorenz et al.* [2006]. Thus, our data gives support to the general finding that Holocene SSTs experienced a warming in the tropics but a cooling in the extratropics after 7 kyr BP.

5. Conclusions

[15] The reconstructed SSTs from core MD03-2611 represent the first continuous record of high temporal resolution for the Australian region over the last deglaciation. The SST record shows significant colder conditions during the Last Glacial Maximum, with temperatures ~8°C lower than during the early Holocene. This study confirms the existence of a cold reversal during the last deglaciation that coincides with the ACR described in Antarctic ice cores. It also provides no evidence of any cooling associated with the northern hemisphere YD event. Thus, this new alkenone-derived SST record corroborates the close link between mid- and high-southern latitudes. Finally, the SST evolution during the Holocene compares well with information on hydrological and vegetation changes from southeastern Australia showing a warm early Holocene at a time of generally wetter conditions and a subsequent decrease in temperature at a time of increasing aridity after ~6.5 ka.

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