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Insolation dependence of the southeastern Subtropical Pacific sea surface temperature over the last 400 kyrs

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Abstract. The present study describes the first sea surface temperature (SST) reconstruction in the southeastern Subtropical Pacific Ocean, offshore the South American coast. The obtained record encompasses the last 400 kyr and follows the characteristic glacial/interglacial pattern defined by global ice volume. However, SST leads the $\delta^{18}O$ isotopic record reflecting the role of the low latitudes areas in driving climate change. SST in the Holocene is lower by about 0.5-0.8°C than maximal SST in stages 5e, 7, 9 and 11. SST in stages 2-4 is lower by about 0.6-1.3°C than minimal SST in stages 6, 8 and 10. These features are similar to SST records obtained in the South Atlantic Ocean pointing to a general inter-basinal behaviour at these low latitudes. For most of the record, the observed long-term SST evolution is well correlated with the orbital parameter of eccentricity, which modulates the insolation at low latitudes. However, at low eccentricity values (Stages 11 – 9 and Termination I), SST is driven by obliquity, exhibiting a dependence from high latitude climatic responses.

Introduction

The oceanic circulation of the southeastern Subtropical Pacific Ocean along the south american coast is mainly controlled by the Peru-Chile Current system as a part of the South Pacific Subtropical gyre (Fig. 1). This system, flowing from the Southern Hemisphere high latitudes towards the equator, transports cold waters into the equatorial current system and prevents, depending on its strength, the advection of warm equatorial waters to the south american coast. In addition, the southeast trade winds strongly influence the general oceanic circulation north of about 20°S, driving the major currents to the west. Changes in this circulation pattern may be dependent on Southern Hemisphere insolation variability [*Imbrie et al.*, 1992].

Sea surface temperature (SST) data from the area under direct influence of the Chile Current may provide relevant information on the climatic variation of this system and its relation to insolation forcing. Unfortunately, the extremely low sedimentation rates and poor carbonate preservation in this area (most of the southeastern Pacific sea floor is deeper than 4000 meters, the approximate present carbonate compensation depth [*Weber et al.*, 1995]) have prevented the elaboration of paleoceanographic reconstructions. For this reason, sediments deposited on the ridges are probably the only chance to overcome calcium carbonate dissolution problems. In this sense, the present work is devoted to study a core located in the Nazca Ridge at 3120 m water depth and therefore above the present depth of the lysocline.

Core TG7 is situated under the influence of the cold waters carried by the Chile Current and, to a lesser extent, the subtropical water mass from the Peru Countercurrent (Fig. 1). C_{37} alkenones have been analyzed to reconstruct sea surface temperatures (SST) for the last 400 kyr by means of the $U^{K'}_{37}$ index. This method has been extensively used in a wide variety of oceanographic locations over glacial to interglacial timescales [e.g., *Prahl et al.*, 1993; *Schneider et al.*, 1995; Villanueva *et al.*, 1998; *Cacho et al.*, 1999; *Pelejero et al.*, 1999]. The present study represents the first $U^{K'}_{37}$ - SST reconstruction performed in the southeastern Pacific Ocean. These results are evaluated in relation to planktonic $\delta^{18}O$ data as an ice volume proxy with the finding of some dephasings between both proxies. Furthermore, the SST changes are also discussed by reference to insolation forcing.

Materials and Methods

Gravity core TG7 (17°14.7'S, 78°6.3'W, 3120 m water depth, 4 m long) was recovered in the Nazca Ridge, in the eastern boundary of the Subtropical South Pacific, during the PALEOPAC campaign in March 1996 on board of the R/V BIO-Hespérides (Fig. 1).

Oxygen isotopic analyses were performed at the Scripps Oceanographic Institution. Between 12 to 15 specimens of the

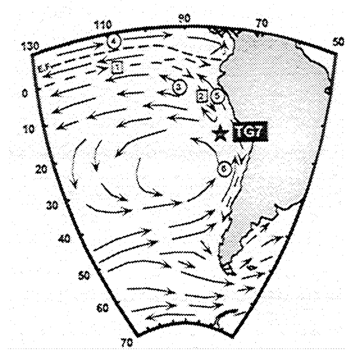

Figure 1. Map showing core TG7 location together with the general southeastern subtropical Pacific Ocean circulation according to [*Molina-Cruz*, 1978]. Continous and discontinous arrows correspond to superficial and sub-superficial currents, respectively. 1) Equatorial Undercurrent current; 2) Peru Countercurrent; 3) Peru Oceanic Current; 4) South Equatorial Current; 5) Peru Coastal Current; 6) Chile Current; E.F.) Equatorial Front.

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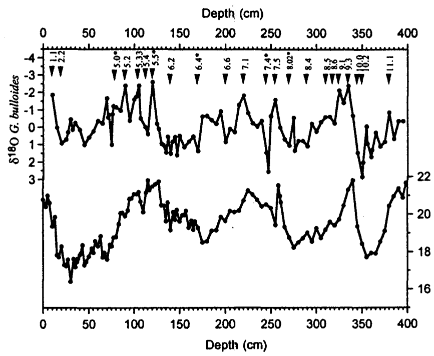

Figure 2. $\delta^{18}O$ of planktonic foraminifera *G. bulloides* and alkenone SST profiles from core TG7 vs depth. Arrows indicate the age control points derived from correlation with the SPECMAP stacked record [*Imbrie et al.*, 1984; *Martinson, et al.*, 1987]). * indicates age data points supported by nannofossil biostratigraphy (J.A. Flores, unpublished data).

planktonic foraminifera *Globigerina bulloides*, from the 250-350 µm size fraction, were picked for each isotopic determination. The age scale for this core was obtained by tuning the $\delta^{18}O$ curve to the SPECMAP reference time series (Fig. 2; [*Imbrie et al.*, 1984; Martinson *et al.*, 1987]). This age model is consistent with data on nannofossil biostratigraphy (J.A. Flores, unpublished data).

Thus, core TG7 covers the last four glacial-interglacial cycles reaching as far as Stage 11, which implies an average sedimentation rate of about 1.1 cm/kyr. The sampling of this core has been performed every 2-3 cm for the first 170 cm and every 5 cm for the rest of the core, which corresponds to a time resolution of 1.9 and 4.5 kyr, respectively.

The analytical procedure for the determination of $U^{K'}_{37}$ is described elsewhere [*Villanueva et al.*, 1997]. The $U^{K'}_{37}$ values were calculated using the $U^{K'}_{37} = C_{37:2}/(C_{37:2}+ C_{37:3})$ index [*Prahl et al.*, 1988] where $C_{37:2}$ and $C_{37:3}$ are the concentrations of di- and tri-unsaturated C_{37} alkenones, respectively. SST measurements were obtained using the global core-top calibration of *Müller et al.* [1998]: $SST(°C) = (U^{K'}_{37} - 0.044)/0.033$.

Results and Discussion

The SST value (20.8°C) obtained for the surface sediment of a multicore retrieved in the same location than core TG7 (Multicore MC7) matches almost exactly the modern annual mean temperature for the surface waters of this area (20.3°C; [*Levitus*, 1994]). As a general trend, the SST profile follows the typical glacial/interglacial pattern, with low and high values during glacial and interglacial periods, respectively. The SST evolution also displays the general saw-tooth pattern, exhibiting abrupt warmings near Terminations IV, III and, to a lesser degree, Termination I, and more gradual temperature changes towards glacial conditions.

SST values range from 16.4 to 21.9°C, implying a total amplitude of about 5.5°C. SST changes in all warmings from glacial to interglacial stages, including the Last Glacial Maximum (LGM) to Holocene transition, are about 3-4°C. This difference between LGM - modern times is greater than the one predicted by the CLIMAP LGM SSTs in low to mid-latitudinal oceanic regions [*CLIMAP*, 1981]. However, the $U^{K'}_{37}$-based temperature amplitude is consistent with those estimated from radiolarian assemblages in a nearby core (Core Y71-6-12: 16°S, 77°W; [*Pisias and Mix*, 1997]). Moreover, this larger SST difference is also in agreement with that observed in the subtropical South Atlantic for the same latitude using the C_{37} alkenone method [*Schneider et al.*, 1995].

SST estimates registered during interglacial Stages 5e, 7, 9 and 11 are always slightly higher (0.5 - 0.8°C) than in the Holocene. The highest values, 21.8°C, are observed in Stages 5 and 9. The warmer conditions that prevailed during Stage 5e seem to be a global feature, since they have also been observed in different alkenone SST records [*Schneider et al.*, 1995; *Rostek et al.*, 1997; *Villanueva et al.*, 1998; *Kirst et al.*, 1999; *Pelejero et al.*, 1999]. In Stage 7, SST maxima (substage 7.5) is recorded as a short and well defined peak followed by a sudden cooling of about 3°C characteristic of cold substage 7.4.

Apart from the typical glacial/interglacial pattern of this temperature record, core TG7 SSTs present two significantly different features when comparing with the planktonic $\delta^{18}O$ record. First, glacial SST minima show higher values in glacial Stages 6, 8 and 10 (18.5°C, 18.2°C and 17.7°C, respectively) than during the last glacial period, Stages 2-4 (17.2°C as average). Warmer SSTs in stage 6 than stage 2 have also been observed in some locations of the North [*Villanueva et al.*, 1998] and South Atlantic Ocean [*Schneider et al.*, 1995]. The shifts between these glacial minima in core TG7 are in the order of 0.6-1.3°C, involving higher temperature differences than those observed between the above described interglacial SST maxima. Second, the minimal glacial SST estimates were recorded well before the global ice volume maxima, which implies an initial warming prior to the retreat of the Northern Hemisphere ice caps. This lead of SST over the $\delta^{18}O$ was about 10 kyr for Termination I and 20 kyr for

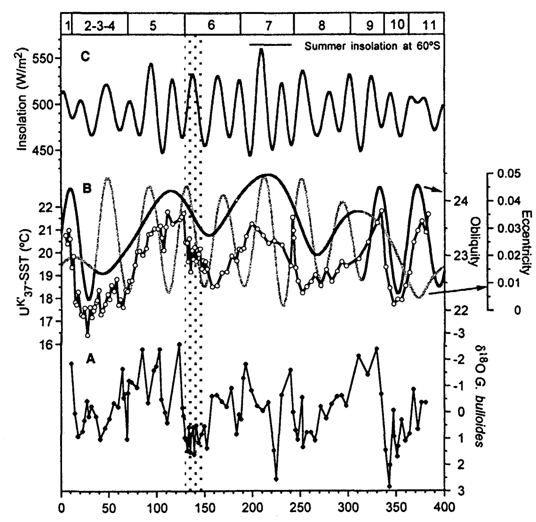

Figure 3A. $\delta^{18}O$ of planktonic foraminifera *G. bulloides* plotted versus age. **3B.** $U^{K'}_{37}$-SST from core TG7 compared with eccentricity and obliquity, which have been obtained using the Analyseries program [*Paillard et al.*, 1996]. **3C.** Summer insolation at 60°S is also represented. Note the close parallelism between the TG7 SST and eccentricity for most of the record (black eccentricity curve) and the switch to an SST-obliquity relationship (black obliquity curve). Eccentricity and obliquity are grey coloured when they do not exhibit parallelism with the SST record.

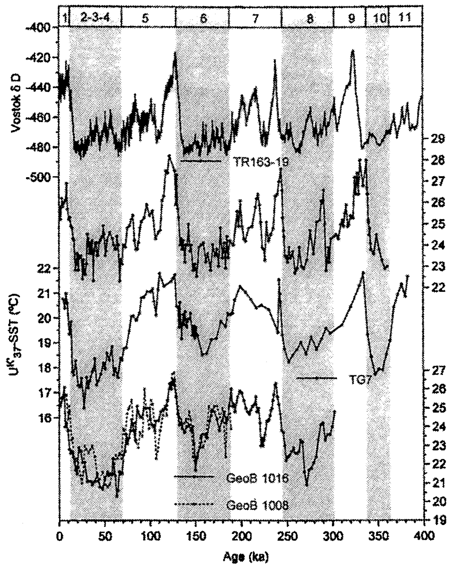

Figure 4. Comparison of the $U^{K'}_{37}$-SST records from cores TG7, GeoB 1016 and GeoB 1008 (data from [*Schneider et al.*, 1999]) with Mg/Ca-based SST from core TR163-19 ([*Lea et al.*, 2000]) and Vostok δD record ([*Petit et al.*, 1999]). Shaded areas represent glacial periods. Specially remarkable are the coldest temperatures recorded in all records about 10 to 20 kyr before the beginning of the terminations.

Termination II (Fig. 3B,C). These results are coincident with those recently obtained by [*Lea et al.*, 2000] in a core located further north of core TG7 (TR163-19; 2°2'N 89°5'W; Fig. 4). In this sense, paleotemperatures estimations based on Mg/Ca measurements also show that SST changes precede those in ice volume (e.g. SST minimum of stage 6, at about 150 kyr), suggesting the importance of tropical SSTs changes in driving ice-age climate. The close resemblance between both records is more striking if we consider the total independence of the age models. Moreover, preliminary results based on alkenones in core TR163-19 also show a remarkably agreement between proxies, including the lead of SSTs over $\delta^{18}O$ [*Herbert*, 2000].

The same climatic pattern has also been observed in several alkenone SST records from the Atlantic, the Indian and the Pacific oceans indicating a global and typical feature for low latitude sites (for a review see [*Schneider et al.*, 1999]), mainly those located under the influence of eastern boundary currents flowing from high Southern Hemisphere latitudes to the equator [*McIntyre et al.*, 1989]. The agreement of the TG7 SST record with this global imprint is illustrated in Figure 4 where it is compared with the alkenone SST records from the Congo fan and Angola basin [*Schneider et al.*, 1995], which span over the last 200 and 300 kyr, respectively. All three records are highly similar (over the last 200 kyr the linear correlation R coefficient between TG7 and GeoB 1016 is 0.86, n = 81), pointing to a similar SST evolution over glacial to interglacial periods between the South Pacific and the South Atlantic subtropical oceans, both in terms of timing and glacial/interglacial SST range. Moreover, the short-term variability in both oceans is also very closely related, the high temperatures presented during Termination II and late Stage 6 in all three cores are specially remarkable. At this transition, whereas the oxygen isotope records of these cores display the onset of Termination II at about 132 kyr (according to SPECMAP isotope chronology) the rising in SST begins well before, at about 150 kyr.

Previous observations in the Southern Hemisphere [*Pichon et al.*, 1992; *Bard, et al.*, 1997; *Mashiotta et al.*, 1999] are consistent with these results which suggest a significant SST lead over global ice volume. Moreover, this warming of the surface ocean is synchronous with warming in the Antarctic atmosphere, as revealed by the deuterium record of Vostok ice core [*Petit et al.*, 1999] (Fig. 4). This warming of the Southern Hemisphere corresponds to the timing of maximal summer insolation in this hemisphere (Fig. 3A, B), which has been suggested to be one of the possible causes for this SST lead [*Broecker and Henderson*, 1998]. The higher temperatures for this period could indicate the influence of warm subtropical waters to the area, as consequence of a weakening of the Chile Current and/or intensification of the Peru Countercurrent.

Furthermore, the warming towards interglacial conditions of Stage 5e is not gradual, showing a two-step deglaciation mode, interrupted by a Younger Dryas-type oscillation. After a first warming of about 1°C, the SSTs remain fairly constant between 132 and 150 kyr BP before further warming till interglacial values. Many terrestrial, lacustrine and marine records over different world areas also support the existence of a Younger Dryas-style cooling in the penultimate deglaciation [*Seidenkrantz et al.*, 1996]. Recently, sea level estimations derived from coral reef terraces at Huon Peninsula have revealed a drop in sea level of about 60 to 80 meters right after the initial sea level rise at about 140 kyr, pointing towards a return to almost full glacial conditions at this time [*Esat et al.*, 1999].

These dissimilarities between SST and planktonic foraminifera $\delta^{18}O$ in core TG7 points to a "type I" site, according to the classification of *Schneider et al.* [1999], a pattern observed in other low latitude records. In this type of alkenone SST pattern, the coldest SST values of glacial times occurred about 15-20 kyr before maximum glaciation (maxima $\delta^{18}O$ values), and stage 6 was warmer than stage 2. According to these authors, the close parallelism between SSTs and eccentricity in these cases was interpreted as a response to low latitude insolation forcing, where eccentricity exerts its major influence ([*Schneider et al.,* 1999]). However, the eccentricity – SST parallelism fails at eccentricity minima within the 400 kyr period (c.a. Stages 11 – 9 and Termination I; Fig 3B). Interestingly, during these periods, SST is driven by obliquity, as shown by the well defined parallelism between SST and this solar periodicity (Fig. 3B): maxima in obliquity are coincident with SST maxima. Since changes in obliquity have minor influence in the global heat distribution at low latitudes, a response to climatic change induced from high latitudes seems to have dominated SST changes in the periods of time when the eccentricity cannot account for the SST evolution. At these times, this high latitude signal could be transferred to the low latitudes of core TG7 via the Chile current, which transports cold waters from the high southern hemisphere latitudes and could modulate the SST variations of the eastern subtropical Pacific.

Conclusions

The SST record reconstructed in the southeastern Subtropical Pacific Ocean follows the characteristic glacial-interglacial pattern defined by the global ice volume changes, although two major dissimilarities are observed: The warmer SSTs in Stages 6, 8 and 10 by about 0.6-1.3°C compared to

Stages 2-4, and the glacial SSTs leading global ice volume minima by about 10 kyr and 20 kyr in Termination I and II, respectively. This same pattern is also registered in two Atlantic cores from similar latitudes, pointing towards a global inter-oceanic climatic response. Comparison with the orbital parameters shows that most of the thermal record seems to be forced by low latitude insolation related to eccentricity. However, during Stages 11-9 and Termination I, the SST – obliquity concordance suggests a major control from high latitudes.

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