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Abstract

The lack of temporal resolution and accurate chronology of Southern Ocean marine cores has hampered comparison of glacial millennial-scale oscillations between the Southern Ocean, Antarctic ice and other records from both hemispheres. In this study, glacial climate variability is investigated over the last 50 ka using a multi-proxy approach. A precise chrono-stratigraphy was developed on the high-sedimentation rate core MD94-103 (Indian Southern Ocean, 45°35'S; 86°31'E, 3560 m water depth) by geomagnetic synchronization between the later core and NAPIS75, and ^{14}C dates. High-resolution time-series of $\delta^{18}O$ in planktonic foraminifera *G. bulloides* and *N. pachyderma,* and sea surface temperatures (SSTs) estimated from the alkenone $U^{K'}_{37}$ index and foraminifera assemblages have been generated. Temporal evolution of the two temperature *proxy* records is notably different during the last glacial period. While foraminifera data indicate a consistent cooling towards the last glacial maximum, anomalous warm glacial alkenone temperatures suggest a strong advection of <warm> "detrital" alkenones by surface waters of the Agulhas current. Superimposed to this general trend, during Heinrich events, foraminiferal SSTs points to warmer surface waters, while concurrent alkenone SSTs exhibit apparent coolings probably caused by enhanced local

alkenone production. By analogy to modern observations, possible influence of ENSO-like conditions on the subantarctic Southern Ocean SSTs is discussed.

1. Introduction

The millennial-scale oscillations of the last glacial period (Heinrich and Dansgaard-Oeschger events) [1,2,3] have been the subject of numerous publications over the last decade. These events, first described in Greenland ice [4] and North Atlantic sediments [5], are characterized by a fast warming completed in a few decades, followed by a slow cooling lasting for several centuries and a final collapse to full glacial conditions. Their initial cause is attributed to major collapses of the Laurentide and Arctic ice sheets [6,7] and associated melt water events in the northern Atlantic and Arctic seas [6,8], and their impact on the meridional overturning circulation [9-11]. Similar temperature excursions have since been documented in marine sediments with a wide spatial coverage (reviewed by Voelker et al. [12]), suggesting a rapid transmission of the North Atlantic climate to distant regions of the northern Hemisphere. While, it is now clearly demonstrated that millennial scale glacial variability is hemispheric in extent, inter-hemispheric climate links are still poorly understood. Paleo-records from Antarctic ice and marine sediments show apparently connected patterns, but with different temporal responses [13-16]. However, the lack of high-resolution SST records from the Southern Ocean contributed to prevent from a comprehensive understanding of the role of this important component of the global climate system.

This paper presents the first continuous alkenone SST time series from the Indian sector of the Southern Ocean (core MD94-103; 45°35'S; 86°31'E, see Fig. 1) over the last 50 ka, and chrono-stratigraphically linked to the Northern hemisphere records by high-resolution magnetostratigraphy [17] and ^{14}C dating. Alkenone paleothermometry [18] is combined to lower resolution temperatures derived from planktonic foraminiferal assemblages using the

Modern Analog Technique (MAT) [19] and planktonic foraminifera oxygen isotopes. Furthermore, high glacial sedimentation rates (on average 25 cm/kyrs) at this location of the South Indian Ridge provide the temporal resolution needed to resolve glacial climate variability.

2. Methodology and results

Alkenones were extracted from freeze-dried sediments in a mixture of 1:3 (v/v) methanol:dichloromethane. They were isolated from the total lipid extract by silicagel chromatography prior to gas chromatography analyses preformed on a Varian 3400 Series. The oven was temperature programmed from 100°C to 300°C at a rate of 10°C/min. The alkenone temperature record presented here is the first continuous time series obtained at 30 to 100 year resolution in the Southern Indian Ocean. It extends the 30-50 ka BP record that has been presented in [17]. The precision on the relative temperature change is estimated to be 0.5°C [20].

SSTs were also estimated from foraminifera micropaleontology using MAT, expanding the record presented in [17]. Resolution within the 30-50 ka period has been increased with respect to [17] and new data generated for the last 30 ka. The reference database used is composed of 28 species of planktonic foraminifera determined in 245 surface sediments from the Southern Ocean. The mean uncertainty of each individual determination is $\pm$1.3°C. Temperatures could not be estimated between 38.2 and 36.5 ka because of the lack of foraminifera or high fragmentation. Oxygen stable isotope records for the planktonic foraminifera *Globigerina bulloides* (250-315 μm) and *Neogloboquadrina pachyderma* (left coiling, 200-250μm) are original. Analyses were done on a Finnigan MAT 251 mass spectrometer and calibrated *vs* NBS19 and NBS18 [21]. Mean temporal resolution for isotope determinations is about 350 years.

The age model between 30 and 50 ka is described in details in [17]. It is derived from a geomagnetic correlation between core MD94-103 and NAPIS-75 [22], a paleointensity record obtained from North Atlantic cores placed on the GISP2 age scale. Best correlation was obtained in the 30-45 ka B.P. interval, which includes Heinrich event H4. In this interval, the correlation with SAPIS, a paleointensity stack obtained from the South Atlantic [23] gives close results, with an average age difference of 0.46 kyr. For the last 22 kyrs, the age model was constrained by 10 original accelerator mass spectrometry ^{14}C dates on 9 sediment horizons, performed on monospecific foraminifera *G. bulloides* and *N. pachyderma* (On-line Table 1). ^{14}C ages were converted to calendar ages (expressed in ka throughout the text) using the Calib 4.3 software, the marine calibration Marine 98.14c and a modern local reservoir age of 600 years [24]. Uncertainties in the reservoir age estimates for the deglaciation [25] have no implication on our discussion, focussed on the glacial period. The depth to age conversion was obtained by linear interpolation between age constrained levels [26] (On-line Table 1). There has been no further adjustment by graphical tuning of any of the *proxy* records developed here. Based on our age model, we estimated the temporal resolution for alkenone temperature to 30-50 years between 50 to 15 kyrs, thus resolving glacial climate at a temporal resolution sometimes better than the Vostok ice core.

The core has been sampled on a protected shoulder of the upper southern slope of the South Indian Ridge, out of reach for long-distance bottom sediment advection [27]. However, high-sedimentation rate is occurring as a result of local sediment focusing [27]. The stability of the focusing factor Φ has been studied following François et al. [28] by comparison of the expected flux of ^{230}Th from the overlying water column to the down-core determinations of decay-corrected unsupported ^{230}Th. Sediment digestion was performed using the protocol adapted from [29]. About 1.5 g of dried sediment were spiked with yield monitors (^{232}U, ^{228}Th) before being digested in mixtures of HCl, HNO_3, $HClO_4$, and HF. The radionuclides of interest were purified by ion exchanges on anionic resins. Thereafter, ^{238}U, ^{234}U, ^{232}Th, ^{230}Th have been measured by α spectrometry (mean 1 σ error: 4%). Activities of ^{230}Th were determined in 28 samples to derive Φ values and evaluate potential bias that focusing may introduce in our records. Values of Φ over the data set exhibit a limited range of variation (mean value 13.4 ±5.3) between two focusing regimes (Φ around 9 and 17) (On-Line Table 2).

3. Results and discussion

This discussion is based on the data presented in Figure 2 and On-line Table 3 values. The temporal evolution of the two temperature *proxy* records based on alkenones (SST_{alk}) and foraminifera (SST_{foram}) (Figs. 2 b,c; on-line Table 3) differs notably with a more pronounced deviation between 17 to 32 ka. The foraminifera data (SST_{foram} and $\delta^{18}O$) show the expected cooling and the gradual isotopic increase with increasing ice volume of the last glacial period in this area (Figs. 2 d,e) [30]. Over the same time interval, the alkenone record highlights an overall warming trend from 7 to 13°C between 38 to 26 ka followed by a 5°C decrease ending at 14.5 ka. The observed difference between the two signals is less pronounced in the older part of the record (50-35 ka BP) and the Holocene, but it is quite large at the time of maximum sea ice extent (18-27 ka) as reconstructed by diatoms in this basin [31].

3.1. Long-term changes

The temperature difference between the SST_{alk} and the lower resolution SST_{foram} records in the 30-50 ka interval (about 4°C) was earlier interpreted as possibly reflecting different growth seasons or depth habitats [17]. In the extended record presented here, this difference increases up to 9°C between 18-25 ka, a value that cannot be accounted by ecological factors and thus requires another explanation. While core-top value (8.5°C) is consistent with Levitus SSTs at this latitude in summer, the main season of alkenone production in the Southern Ocean [32,33], glacial SST_{alk} reach similar to the Holocene optimum (13°C). Warm SST_{alk} between 15 and 40 ka shows a similar profile as documented in the subantarctic waters of the South East Atlantic Cape Basin by [34,35]. This result from the South Atlantic was interpreted by the advection of alkenones produced in warmer waters to the North and subsequent transport to drifts in the South [34,35]. The similarity of the Southern Indian Ocean SST_{alk} curve during MIS3 suggests a common control of SST_{alk} at our site. As discussed earlier and by [17], long-distance advection of bottom sediments from the North to the core site, located up on the southern flank of the South Indian Ridge, is unlikely. Advection by strong surface currents provides a more plausible mechanism to explain the observed temperature deviation. Alkenones are mainly synthesized in the surface ocean by the calcareous coccolithophorid *Emiliania huxleyi* and are thus carried by fine particles. They can thus undergo transport under vigorous surface current conditions, such as those encountered in the Southern Ocean. At the tip of south Africa, the Antarctic Circumpolar Current is fed by the warm waters of the Agulhas Current and its retroflection on the Agulhas plateau heading eastward [36], thus supplying warm waters at mid-latitude Indian Ocean. Warmer than expected SST_{alk} during MIS3 could thus result from a strong advection of <warm> alkenones in the subantarctic zone by surface waters of the Agulhas current. This interpretation is supported by higher focusing factors at warmer SST_{alk} and lower ones when they are colder, as shown in on-line figure 1.

Modern ocean data from the western Argentinean Basin indicates that surface water lateral advection does occur today and can strongly influence the sedimentary alkenone record [37]. In this area, the Malvinas current, flowing northwards, brings cold waters from high productivity areas to the South. Estimated temperatures from $U^{K'}_{37}$ determined in surface suspended particles are significantly lower (by 2 to 3°C) than measured water temperatures, whereas there is no offset between alkenone temperature and measured water temperature, outside this region. Furthermore, core top $U^{K'}_{37}$ ratios are consistently lower than expected from overlying surface water temperatures [38]. We hypothesize that, similarly, advection of <warm> “detrital” alkenones from the Agulhas Current has occurred during the last glacial in the Subantarctic Indian Ocean, where productivity and temperature gradients also exist. Intensification of the Agulhas Current, today the most vigorous western boundary current of the Southern hemisphere, would be responsible for the strong supply of <warm> alkenones to our core site. A reduction of the Agulhas leakage in the Subantarctic Atlantic Ocean as recently documented by [39,40,41] is also possible and could also have contributed to increase recirculation of the Agulhas water back into the Indian Ocean.

3.2. Millennial-scale variations

Superimposed on the general trend, several millennial-scale temperature oscillations of 2 to 4°C are recorded by both *proxy* records, but again foraminifera and coccolithophorid provide different responses. As reported earlier by [17], comparison between SST_{alk} and $\delta^{18}O$ variability in GISP2, linked by paleomagnetic correlations, indicates a progressive temperature decrease at the time of H4 and H5. In the new portion of the record, well-expressed cooling episodes are also recognized during H1, H3 and during H2a and H2b, previously described by [42]. During these time intervals, increase SST_{foram} are associated to lighter $\delta^{18}O$ values in planktonic foraminifera *G. bulloides* and *N. pachyderma*, indicating that $\delta^{18}O$ primarily reflects temperature changes. Therefore, while SST_{foram} evidence that the surface ocean was warmer during Heinrich events, the apparent decline of SST_{alk} would be suggestive of a decrease of <warm> "detrital" alkenone transport. However, enhanced local production by increasing the relative fluxes of <cold> alkenones could also account for the observed coolings. This interpretation is supported by the recent report of enhanced alkenone production during Heinrich events in the Pacific sector (Chatham Rise; core MD97-2120, 45°S; 174E) and Atlantic sector (Cape Basin, core TN057-21-PC2, 41°S; 7°E) of the Subantarctic Southern Ocean, over the last 70 ka by [43]. According to [43], possible causes for production increase could involve enhanced iron supply and/or stronger stratification of the upper ocean during phytoplankton growth season. Warmer SST_{foram} data in our core would favor the assumption of greater stratification during Heinrich events rather than enhanced micro-nutrient inputs. Both increase solar radiation and/or reduced wind stress contribute to warm the upper ocean. Recent modern observations have shown warm anomalies in the southern Indian Ocean during marked ENSO years, and higher primary production than during normal years [44]. Models simulate such positive anomalies in the South Indian and Southeast Pacific sectors under ENSO conditions [45]. They also suggest a control by solar radiation and cloud cover due to changes in atmospheric large-scale circulation [46]. According to [44], a reduction of the cloud cover by increasing available light could have promoted phytoplankton growth during ENSO years. Recent paleo-data from the western tropical Pacific Ocean have shown that salinity shifts similar to those observed during modern ENSO conditions, occurred during Heinrich events, leading to the Super ENSO hypothesis during cold periods [47]. It is thus tempting to speculate that the hydrological (warmer SST_{foram}) and biogeochemical (higher local primary production) changes observed in the subantarctic

Indian Ocean during Heinrich events could be linked to Super ENSO conditions through atmospheric teleconnection.

Finally, we note that the MD94-103 SST_{foram} record is the only published Southern Indian ocean signal correlated at millennial time scale during that time period to the Greenland-Byrd synchronized ice time scales [17]. It is therefore difficult to conclusively ascertain if the observed lead-lag relationship between SST_{foram} and the $\delta^{18}O$ ice record at Byrd (Fig. 2f) is representative of the SSTs of Antarctic precipitation sources. However, the earlier interpretation by [17] of a cooling of the Antarctic water sources during A1 and A2 events based on the SST_{alk} record only, needs to be re-assessed taking into account the results presented here. Additional interactions involving the Antarctic ice dynamic and/or deep-water exchange and thermohaline circulation (as proposed by [48]) are necessary to explain the Antarctic ice record.

4. Conclusions

We have shown that the SST *proxy* record (SST_{alk} and SST_{foram}) in core MD94-103 exhibit different temporal patterns during the last glacial period. Foraminifera isotope data and SST_{foram} display the expected cooling during the last glacial period, while <warm> glacial SST_{alk} are explained by alkenones advected by stronger Agulhas current surface waters retroflecting into the Indian Ocean. Superimposed to this dominant long-term signal, apparent SST_{alk} coolings at the time of Heinrich events could express enhanced local production of <cold> alkenones. Warmer SST_{foram} suggest stronger stratification of the upper ocean caused by weaker winds and/or enhanced solar radiation. We speculate that surface ocean warming during Heinrich events could be caused by a change in the cloud cover as suggested by modeling studies [45,46]. These conditions would have stimulated phytoplankton growth resulting in higher <cold> alkenone fluxes and apparent cooling SST_{alk}. By analogy to modern observations, we hypothesize that during Heinrich events, ENSO-like conditions could have induced important changes in the Southern Ocean upper layer through the atmosphere bridge.

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Figure captions

Figure 1: Location of core MD94-103, with the general bathymetry of the area and overprinted with sea surface temperatures (purple to green represents for polar to sub-polar waters while the yellow to red represents for sub-Antarctic to sub-tropical waters).

Figure 2: Records of Sea Surface Temperatures (SSTs) and isotope data in the sediment core MD94-103 (43°32'S; 86°32'E, 3560 m water depth), and isotopes in ice cores GISP2 and Byrd over the last 50,000 years. **a**, Oxygen isotope from GISP2. **b,** SSTs derived from alkenone $U^{K'}_{37}$ index (SST_{alk}) in MD94-103. Black diamonds represent horizons where ^{14}C dates have been determined. **c**, Temperature estimates from foraminifera transfer function using the modern analog technique (SST_{foram}). The temperature record is interrupted between 38.2 and 36.5 ka because of the lack of foraminifera or high fragmentation within this interval. **d**, $\delta^{18}O$ values of N. *pachyderma* (left coiling, 200-250μm). **e,** $\delta^{18}O$ values of G. *bulloides* (250-315 μm). **f,** Oxygen isotope from Byrd ice core. Vertical grey bars indicate Heinrich events following Bond's correlation [3]; the blue vertical bar indicates the time of the Laschamp excursion.