Late Quaternary changes in biogenic opal fluxes in the Southern Indian Ocean

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Abstract

Late Quaternary sedimentary and paleoenvironmental conditions in the southern Indian Ocean have been reconstructed from radioisotope and proxy element profiles (biogenic opal and organic carbon) measured on five sediment cores taken along a transect across the Indian sector of the Antarctic Circumpolar Current. Dissolution-corrected opal rain rates were used to reconstruct past changes of opal productivity for this region. Records from these five cores indicate that opal productivity during glacial periods was lower than presently recorded south of the Antarctic Polar Front (APF), probably due to increased ice cover. North of APF, opal productivity was slightly greater during glacial periods than during the Holocene, probably in response to (1) the northward migration of the APF by approximately 5° latitude, (2) a northward transport of Si from the Antarctic Zone, and (3) an increase of Fe, necessary for opal-producing organisms, via upwelling and the erosion of the Kerguelen Plateau. We also invoke a decoupling between opal burial and organic carbon flux to the seabed to explain the variation in buried Si/C ratio between glacial and interglacial sediment. This decoupling is principally explained by better organic carbon preservation in the glacial sediments due to strong sediment focussing. An increase in glacial export paleoproductivity is not supported by the data, implying that bioproductivity variations in the Southern Indian Ocean are unlikely to have contributed to the glacial drawdown of atmospheric CO2 inferred from ice core data.

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1. Introduction

In order to understand biogenic silica produc-
occurs mostly at the sediment–water interface rather than deeper down core in the pore water (Broecker and Maier-Reimer, 1992). The extent of dissolution of biogenic silica depends on a number of factors including the residence time of biogenic silica in the diffusion layer, the bulk accumulation rate, dilution by other components, and the assemblage composition because some diatom species are more prone to dissolution than others (Pichon et al., 1992). Second, opal accumulation rates in sediments cannot distinguish between changes in accumulation resulting from variations in productivity controlling vertical rain rate and those resulting from variations in sediment redistribution by currents. In the Southern Ocean, the latter uncertainty is especially significant because of the presence of relatively strong currents associated with the Antarctic Circumpolar Current (ACC) and Antarctic Bottom Water (François et al., 1993; Dezileau et al., 2000; Frank et al., 2000).

Because sediment redistribution is common in the Southern Ocean, we use the $^{230}$Th-normalization procedure to derive regional average pelagic rain rates preserved in the sediments from five cores taken along a transect across the ACC from 54°S to 43°S. We also use a transfer function to quantify silica dissolution in sediments developed by Pichon et al. (1992) in order to correct opal fluxes for dissolution. Using these cores, Bareille et al. (1991) attempted to reconstruct biogenic accumulation rates in order to estimate the opal paleoproductivity of this area. However, discrepancies between sediment accumulation rates and vertical rain rates require that the paleoproductivity reconstructions of Bareille et al. (1991) be reinterpreted.

Past changes in productivity may be assessed, in principle, from the record of biogenic detritus buried in the seabed. Diatoms largely drive the export of organic carbon and nutrients to the deep sea in the Southern Ocean. Thus, opal rain rates are expected to reflect the productivity of overlying surface waters. However, recent studies indicate that the carbon flux/opal flux ratio in glacial sediments of the Southern Ocean differs from the corresponding ratio in interglacial sediments (Kumar et al., 1995; Anderson et al., 1998; Bareille et al., 1998). Hence, in this paper we will also report a comparison between vertical opal rain rates and organic carbon rain rates in order to study the buried Si/C ratio.

The first aim of this paper is to estimate and discuss the variations in glacial/Holocene opal productivity in the Southern Indian Ocean using variations of dissolution-corrected opal rain rates as a proxy. The second aim is to study the evolution of the buried Si/C ratio between glacial and Holocene periods.

2. Materials and methods

2.1. Oceanography and core material

Today, the Southern Ocean can be divided into different zones defined by a succession of three meridional frontal structures. The first front, located around 40°S in the Indian sector and known as the Subtropical Front (STF), constitutes the northern border of the Southern Ocean. It is characterized by a narrowing of the isotherm contained between 12°C and 14°C (Deacon, 1966; Belkin and Gordon, 1996). The second front, near 45°S in the Indian sector, is named the Subantarctic Front (SAF). This front is characterized by a pronounced minimum in the salinity of its subsurface water (Whitworth and Nowlin, 1987) and is difficult to distinguish from the STF around the Kerguelen sector. The third front, near 52°S in Indian sector, is the Antarctic Polar Front (APF). It consists of a narrowing isotherm contained between 3°C and 5°C during summer (Park et al., 1991; Belkin and Gordon, 1996). The APF is at the northern limit of wind-driven upwelling of deep water and is characterized by a pronounced gradient in dissolved silica (Van Bennekum et al., 1988). Besides a small southward increase in dissolved nitrate and phosphate, a drastic increase in dissolved silica gives way to enhanced opal productivity. The area delimited by the STF and SAF is usually called the ‘Subantarctic Zone’ (SAZ) and that delimited by the SAF and APF is known as the ‘Polar Frontal Zone’ (PFZ). The Antarctic Zone (AZ) is the entire region south of the APF (Fig. 1). To study the
changes in biological productivity for the Indian sector of the Antarctic Ocean, it is necessary to sample the various subsystems of the ocean. For this reason, we selected five cores that characterize each of the three major zones, the SAZ, the PFZ and the AZ.

Five gravity cores from the southern flank of the Southeast Indian Ridge (Fig. 1; Table 1) were collected between 3000 and 3500 m water depth beneath the eastward-flowing ACC. Core MD 88773 was previously studied by François et al. (1997). We also examined one core from the Kerguelen Plateau (MD 84552), which was collected at 1800 m water depth. All cores were recovered during the APSARA II (1984) and IV (1988) and PACIMA (1994) ocean drilling programs.

The gravity cores were sampled and then split into separate slices with a resolution between 5 and 25 cm per sample depending on macroscopic changes in lithology and previously determined stratigraphy. The measurement of each sample represents the average value for the corresponding core section.

2.2. Stratigraphic framework and age model

A combination of results derived from oxygen isotope measurements, siliceous microfossil bio-fluctuation, and AMS 14C ages was used to establish the stratigraphy of each core (Dezileau et al., 2000).

2.3. Analytical methods

U and Th isotopes were measured by α spectrometry following chemical preparation as described in Dezileau et al. (2000). All data have been previously published in Dezileau et al. (2000). The biogenic opal data (Table 2) used in this study have been previously published in Ba-

Table 1
Location of the gravity cores

<table>
<thead>
<tr>
<th>Cores</th>
<th>Latitudes (°S)</th>
<th>Longitudes (°E)</th>
<th>Water depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD 94-102</td>
<td>43.5</td>
<td>79.8</td>
<td>3205</td>
</tr>
<tr>
<td>MD 94-104</td>
<td>46.5</td>
<td>88.1</td>
<td>3460</td>
</tr>
<tr>
<td>MD 88-769</td>
<td>46.1</td>
<td>90.1</td>
<td>3420</td>
</tr>
<tr>
<td>MD 88-770</td>
<td>46</td>
<td>96.5</td>
<td>3290</td>
</tr>
<tr>
<td>MD 88-773</td>
<td>52.6</td>
<td>109.5</td>
<td>2460</td>
</tr>
<tr>
<td>MD 84-552</td>
<td>54.9</td>
<td>73.8</td>
<td>1780</td>
</tr>
</tbody>
</table>
Dezileau et al. (2000). The opal content has been obtained by chemical dissolution following the procedure of Mortlock and Froelich (1989) with a general precision better than 2%. The organic carbon data (Table 2) used in this study are from Bareille et al. (1998). Organic carbon determinations were made after decarbonatation using a Leco carbon–sulfur analyzer.

### 3. Results

#### 3.1. Past changes in sea surface temperatures

In order to understand past variations in hydrology, Huston (1980) and Prell (1985) have developed a method allowing evaluation of past sea surface temperature (SST), based on counting foraminifera found in deep-sea sediments. Labeyrie et al. (1996), Salvignac (1998) and Lemoine (1998) have used this method on sediment cores MD 94102 (43°S), MD 88769 (46°S), MD 88770 (46°S) and MD 84552 (55°S) to reconstruct past SST variations for the central part of the Indian sector of the Southern Ocean (from 60°E to 100°E in longitude). The results of these reconstructions are shown in Fig. 2a,b.

Each figure shows the typical increase in SST from the Last Glacial Maximum (LGM) to the Holocene period. Moreover, if we compare the SST obtained from core MD 88769 and MD 88770 (Fig. 2a), located roughly at the same latitude (46°S), we observe large differences in SST for most part of marine isotope stage 3 (MIS 3), reaching more than 2.5°C (around 5.5°C for core MD 88769 and 3.0°C for core MD 88770). These large SST differences indicate that synchronous global temperature variations do not occur in the studied area. The differences in SST imply the existence of a large meridional gradient in temperature and suggest the presence of a frontal pattern, very similar to modern day APF, between cores MD 88769 and MD 88770. During MIS 2,
the SST gradient between cores MD 88769 and MD 88770 was lower. This is probably due to the presence of the APF at the location of the two cores. During the Holocene period, we can identify a short warming episode from 12 to 9 kyr BP from the SST reconstruction for core MD 84552 (Fig. 2b) that is not synchronous with the global warming following the LGM recorded by core MD 88770. Lemoine (1998) attributed this warming episode to a temporary southward incursion of the APF. In conclusion, these data support the idea that a thermal frontal structure, similar to the modern day APF, has persisted over the last 60 kyr with a northward shift of the APF of about 5° latitude during the glacial period compared with the Holocene. These results are consistent with those from other studies of the Atlantic and Indian Oceans (Charles et al., 1991; Mortlock et al., 1991; Bareille et al., 1998). Some workers argue that the fronts could not have migrated significantly because their position is constrained by interaction of the flow of the ACC with bottom topography throughout much of Southern Ocean (Moore et al., 2000; Anderson et al., 2002). This argument is unlikely to have influence in our case, because most cores are located away from large topographic features (with the exception of the core MD 84552), and are located above the South Indian Basin. In the area represented by these cores, a northward shift in the mean location of the APF during the last glacial period is considered possible. For this reason, throughout this paper, reference to the location of the APF implies that it is 5° latitude north during glacial periods and at its present-day position during the Holocene.

This has an implication on the position of the Southern Westerlies because ocean circulation and the position of the APF are directly related to the mean position of these winds. Our results suggest a northward shift of the Southern Westerlies during MIS 2/3 compared with the Holocene. The direction of Late Pleistocene shifts of the westerly wind belt – either equatorward (e.g. Heusser, 1989) or poleward (Markgraf, 1989) – has been debated. The Southern Andean region is ideal for monitoring late Quaternary paleoclimate at mid-latitudes in the Southern Hemisphere, because it is one of the few land areas crossed by the Southern Westerlies. Therefore, palaeocontinental and paleoceanographic records along a meridional transect can be used to track the ice-age history of the Southern Westerly stormtracks. Recent results based on paleoclimatic modelling (Hulton et al., 1994), glacier fluctuations (Clapperton et al., 1995), palynological paleoclimatic studies (Moreno, 1997; Moreno et al., 1999) and marine sediments (Lamy et al., 2000, 2001, 2002) suggest an equatorward shift of the Southern Westerlies during the LGM in
These results which are not consistent with the majority of climate models (Wyroll et al., 2000; Valdes, 2000) are consistent with our data.

3.2. Reconstruction of opal rain rates corrected for dissolution

3.2.1. Reconstruction of opal rain rates: $^{230}$Th method

The $^{230}$Th-normalization procedure used here is described in detail by Bacon (1984), Suman and Bacon (1989) and François et al. (1990). Briefly, $^{230}$Th is produced at a rate of $2.63 \times 10^{-3}$ dpm cm$^{-3}$ kyr$^{-1}$ in the oceanic water column from the radioactive decay of dissolved $^{234}$U in seawater. Because of the long (4 $\times$ 10$^5$ a) residence time of U in the ocean, its concentration in seawater shows no significant geographical variations (Ku et al., 1977). Since Th is strongly adsorbed by marine particulate matter, its residence time in the water column is short (< 40 a), and the rate of $^{230}$Th delivery to the sediments is practically equal to the production rate, i.e. none of the $^{230}$Th is lost by decay in the water column. Measurements of $^{230}$Th with deep-sea sediment traps (Anderson et al., 1983; Yu et al., 2001) and a study of the global distribution of $^{230}$Th flux to ocean sediments constrained by GCM modelling (Henderson et al., 1999) have confirmed that the production and the vertical flux of $^{230}$Th carried by settling particles are nearly in balance. Exceptions have been found in areas where advection of water masses with short residence times occur, such as the case shown for the Atlantic sector of the Southern Ocean (Rutgers van der Loeff and Berger, 1993; Walter et al., 1997). Thorium-$^{230}$Th normalized flux calculations are based on the assumption that the flux of $^{230}$Th to the seafloor is constant and equal to the production rate (Bacon, 1984; Suman and Bacon, 1989; François et al., 1990). Excess $^{230}$Th activity in settling particulates is then inversely related to total mass flux. Excess $^{230}$Th activities (decay- and ingrowth-corrected) in sediments can thus be used as reference against which the vertical flux of other sedimentary components can be calculated:

$$F_i = \frac{\beta Z f_i}{^{230}Th_{ex}}$$

where $F_i$ is the rain rate of the sedimentary component $i$; $\beta$ is the constant production rate of $^{230}$Th in the water column ($2.63 \times 10^{-3}$ dpm cm$^{-3}$ kyr$^{-1}$); $Z$ is the water depth; $f_i$ is the wt% of sedimentary component $i$; $^{230}Th_{ex}$ is the activity of decay- and ingrowth-corrected excess $^{230}$Th in sediment.

This approach has been successfully applied where lateral re-sedimentation is important (Suman and Bacon, 1989; François et al., 1993, 1997; Kumar et al., 1995; Anderson et al., 1998, 2002; Frank et al., 2000; Dezileau et al., 2000; Chase et al., 2003).

Down-core records of opal rain rate (corrected for sediment redistribution but not opal dissolution) are shown in Fig. 3. Application of Eq. 1 to $^{230}Th_{ex}$ data reveals relatively low opal rain rates for the four northern cores with values below 0.15 g cm$^{-2}$ kyr$^{-1}$ throughout the Holocene (Fig. 3). In cores MD 88769, MD 94104 and MD 88770 opal rain rates are modestly higher during MIS 2 and 3 than during the Holocene (0.2–1 g cm$^{-2}$ kyr$^{-1}$). In core MD 84552, which is located on the Kerguelen Plateau, opal rain rates during the Holocene are represented by values of up to 3 g cm$^{-2}$ kyr$^{-1}$ while lower values are evident during glacial periods. For core MD 88773 (not shown on Fig. 3) relatively high opal rain rates (around 1 g/cm$^2$ kyr) are recorded throughout the investigated period of time (François et al., 1997).

3.2.2. Comparison between the opal accumulation rate and the opal rain rate

In Fig. 4, a comparison of the average opal accumulation and the opal rain rate for the Holocene, MIS 2 and MIS 3 along the transect of this study is presented to illustrate the importance of correcting for sediment redistribution when reconstructing particle fluxes in the past.

Without correction for sediment redistribution, the pattern of opal accumulation suggests that an area of high particle fluxes remained at a position south of the APF during the past 40 kyr (Fig. 4). In a previous study (Dezileau et al., 2000), we investigated the effects of circulation of water masses on deep marine sedimentation. We showed that lateral transport of biogenous and detrital material contributes 50–90% of sediment input.
at the base of the South East Indian Ridge (SEIR) with lateral input increasing during glacial periods. This suggests that, although most of the material found on the seafloor comes initially from surface water production, the sedimentation in the South Indian Basin is mainly controlled by redistribution by deep ocean currents. The pattern of opal rain rates is not very different after correction for sediment redistribution (Fig. 4b), except that opal rain rates are much lower than opal accumulation rates for the South Indian Basin. The variation of Holocene opal rain rates with latitude is consistent with the known present-day trends in biological productivity (Pondaven et al., 2000a, b), i.e. relatively high rain rates found south of the APF and minimum values occurring at the SAF (Fig. 4b). We notice that opal rain rates in the PFZ for the last glacial period were slightly higher than during the Holocene. The high opal rain rates during MIS 2 and 3 in the Antarctic zone were modestly lower than those found during the Holocene in MD 88773 (François et al., 1997), and significantly lower than those of the Holocene recorded in the core from the Kerguelen Plateau (MD 84552).

After correction for sediment redistribution, the opal rain rate variations can be explained by changes in two factors: biogenic opal productivity and/or dissolution. Pichon et al. (1992) studied and attempted to quantify opal dissolution in cores located in the Southern Indian Ocean. In our study the importance of the two factors is assessed.

### 3.2.3. Reconstruction of dissolution-corrected opal rain rate

Bareille (1991) and Pichon et al. (1992) have established a transfer function to quantify the dissolution of diatom silica in Southern Ocean sediments. The relationship between the amount of silica dissolution and changes in diatom species distribution was built by controlled progressive dissolution of biogenic silica in recent sediment samples from box-core tops, each representative of modern diatom species assemblages. In each experiment, the amount of dissolved silica was measured. Factor analysis (Q-mode) identified four factors accounting for 83% of the variance. The first three factors are controlled by surface water properties (mostly temperature). The fourth factor (F4) is the only one correlated with loss of silica in the reference samples ($R = 0.9$). Pichon et al. (1992) then defined an empirical relationship between the F4 value and the percentage of dissolved silica. Because dissolution experiments start with surface sediment that has already suf-
ferred dissolution of opal, it is postulated that the % dissolution obtained by using the empirical relationship determined by Pichon et al. (1992) is a minimum. However, by comparing opal fluxes in sediment trap (Pondaven et al., 2000a,b) to 230Th-normalized accumulation rates of opal in the POOZ Dezileau et al. (2003) have shown that the percent of opal dissolution is underestimated by only 14%.

The intensity of dissolution of Bareille (1991) and Pichon et al. (1992) was estimated for each sediment level in cores MD 88770 (PFZ), MD 88773 (AZ) and MD 84552 (AZ) and for each marine isotopic stages in cores MD 94102 (SZ), MD 88769 (PFZ) and MD 94104 (PFZ). Both the corrected and uncorrected opal rain rates used in this study are published in Dezileau et al. (2003) but their significance was not discussed.

3.2.3.1. Subantarctic Zone (North of 45°S). For core MD 94102, low opal rain rates (< 0.1 g/cm² kyr) are recorded throughout the investigated period of time (Fig. 5). Estimating opal dissolution by applying the diatom transfer function of Pichon et al. (1992) reveals a difference in opal dissolution from 60% in the last glacial to only 30% in the Holocene. After correcting for dissolution, the dissolution-corrected opal rain rates in the SAZ remain at values lower than 0.2 g/cm² kyr (Fig. 5). Thus, the low opal fluxes observed during the investigated period of time are apparently due to low productivity of biological opal.
3.2.3.2 Polar Frontal Zone. For cores MD 94104, MD 88769 and MD 88770, low opal rain rates are recorded throughout the Holocene and are modestly higher during the glacial stages. The glacial opal rain rates (0.2–1 g/cm² kyr) are up to a factor of 3 higher than the Holocene ones (0.07–0.2 g/cm² kyr). Opal dissolution estimates did not reveal a significant difference between glacial (30–45%) and Holocene values (30–58%). The higher dissolution-corrected opal rain rates (up to 1.7 g/cm² kyr in core MD 88770) observed during glacial periods indicate a quite significant increase of production of siliceous organisms compared to the Holocene.

3.2.3.3 Antarctic Zone. For core MD 84552, located on the Kergulen Plateau, high opal rain rates, between 0.7 and 2.6 g/cm² kyr, were determined for the Holocene and low values (0.4 g/cm² kyr) for the glacial period (Fig. 5). Estimates of opal dissolution from a diatom transfer function reveal an increase in opal dissolution from 51% in the Holocene to 74% during MIS 2, and 75% during MIS 3. Dissolution-corrected opal rain rates are still generally higher during the Holocene (between 0.9 and 3.7 g/cm² kyr) than during MIS 2 (0.8–1.3 g/cm² kyr). Low dissolution-corrected opal fluxes recorded during glacial stages reflect a decrease in the production of siliceous organisms. For core MD 88773 (not shown on Fig. 5) relatively high opal rain rates (around 1 g/cm² kyr) are recorded throughout the inves-
tigated period of time (François et al., 1997). Estimates of opal dissolution (Bareille, 1991) did not reveal any clear difference between glacial and Holocene, which remained static at a value around 55% throughout the investigated period of time. Thus, the relatively high values of dissolution-corrected opal rain rates (2 g/cm² kyr) observed during both the Holocene and MIS 2 and 3 indicate a constant high productivity of opal in this region over time.

4. Discussion

4.1. Paleoceanographic implications

In the following we discuss changes in dissolution-corrected opal rain rates to the seafloor in the Indian sector of the Southern Ocean from MIS 2 to the Holocene. Glacial conditions in this region can be seen more clearly (Fig. 6) by comparing a latitudinal transect of dissolution-corrected opal rain rate for the Holocene with the same transect for MIS 2.

At sites well to the south of the APF, represented by cores at ~53 and 55°S in Fig. 6, dissolution-corrected opal rain rates during MIS 2 were lower than during the Holocene. These results are consistent with those from other studies in the Atlantic and Pacific Ocean (François et al., 1997; Frank et al., 2000; Anderson et al., 2002; Chase et al., 2003) and suggest that diatom productivity during MIS 2 was lower than during the Holocene at latitudes south of the APF. Lower diatom productivity during MIS 2 south of APF may have been driven either by a reduced supply of Si to surface waters via upwelling, by less efficient use of upwelled Si by diatoms, or by an increase in sea-ice cover. Considering different hypotheses, recent studies have shown that the rate of upwelling to Southern Ocean surface waters during the LGM was not lower than that existing today (see Anderson et al., 2002). Moreover, silicon stable isotope measurements suggest that the percentage utilization of silicic acid by diatoms in the Southern Ocean during the last glacial period was diminished relative to the Holocene (De La Rocha et al., 1998). Consequently, increased coverage of this area by sea-ice during glacials could explain the concurrent drop in both opal productivity and silicic acid use during MIS 2. This is consistent with an estimate from diatom-based reconstructions that annual sea-ice cover persisted for 4 months (X. Crosta, pers. commun., 2000) during MIS 2 in the southernmost core MD 84552. However, Gersonde and Zielinsky (2000) established that a longer period of ice cover is needed to explain our low rates of opal sedimentation. There are discrepancies between the approaches to reconstruct sea-ice extent used by Crosta et al. (1998) and the one proposed by Gersonde and Zielinsky (2000). Chase et al. (2003) have presented a relationship between the average number of ice free days per year and the $^{238}$Th-normalized opal burial during the Holocene. If we
use this relationship, we estimate that annual sea-ice cover persisted for 6 months. During these 4–6 months, snow covered sea-ice reduced the availability of light in the surface waters at 55°S (Fig. 6), which was probably the most significant factor limiting opal productivity in this area.

At sites north of the actual position of the APF, represented by cores at 46 and 46.5°S in Fig. 6, dissolution-corrected opal rain rates during the MIS 2 (between 0.3 and 0.8 g/cm² kyr) were slightly higher than during the Holocene (between 0.1 and 0.3 g/cm² kyr). These results are consistent with those from other studies of the Pacific Ocean (Anderson et al., 2002; Chase et al., 2003) and suggest that diatom productivity would have been only modestly greater during MIS 2 compared to the Holocene. There is a clear difference in the Atlantic sector where opal rain rates were as high north of the actual position of the APF during the MIS 2 as the maximum rates observed south of the APF during the Holocene ( > 2 g/cm² kyr; Frank et al., 2000). Higher diatom productivity during MIS 2 north of the actual position of the APF in the Indian sector may have been driven either by an increase supply of Si to surface waters and/or by an increase in Fe. This is discussed below.

SSTs, at ~ +3°C, calculated using foraminiferal transfer functions (Lemoine, 1998), suggest that cores at ~46°S (particularly core MD 88770) were close to the APF (Figs. 2 and 6). Thus, the increase of opal productivity during MIS 2 compared to the Holocene is probably a consequence of an increase supply of Si to the surface waters in this area due to a northward migration of the APF by approximately 5° of latitude. In this case, the APF during MIS 2 stayed as today both as a physical water mass boundary and an ecological boundary. This is in contrast to the interpretations of Moore et al. (2000), Anderson et al. (2002) and Chase et al. (2003) who suggest that the two likely became uncoupled at the LGM.

During MIS 2, extensive sea-ice cover limited diatom productivity and silicic uptake south of the APF (Anderson et al., 2002; Chase et al., 2003). Upwelled Si that went unused south of the APF because of ice cover was transported northward, permitting enhanced opal productivity in the region.

With Si but not Fe being supplied to waters north of the actual position of the APF during MIS 2, primary producers in this region are limited. Diatoms in the Indian sector have probably received some Fe from the erosion of the basaltic hence Fe-rich Kerguelen Plateau by strong currents associated to the ACC (Dezileau et al., 2000), from upwelled Fe that went unused south of the APF because of ice cover, and also may be from Patagonian dust. As opal productivity was clearly more important in the Atlantic sector than in the Indian sector north of the actual position of the APF during MIS 2, we suggest that Fe fluxes in the Atlantic sector were greater than in the Indian sector. This is consistent with the decreasing Atlantic-Pacific gradient dust flux estimated by Mahowald et al. (1999) and the interbasin gradient of lithogenic fluxes estimated by Chase et al. (2003). Bopp et al. (2003) have assessed the impact of dust deposition rates on marine biota and atmospheric CO₂ using a state-of-the-art ocean biogeochemistry model. The model results suggest that the glacial increase in Patagonian dust deposition was most likely insignificant for increasing Fe supply to the Indian sector of the Southern Ocean. Thus, most likely Fe was supplied via upwelling and the erosion of the Kerguelen Plateau by strong currents associated to the ACC.

Opal productivity was lower during MIS 2 than during MIS 3 (Fig. 5) although Fe was probably more important during MIS 2 than during MIS 3. This result can be explained by an unfavorable light-mixing regime during MIS 2. Pondaven et al. (2000b) found that present-day high wind conditions prevailing during winter (average 14 m s⁻¹) would keep algal biomass at low levels, whereas decreased wind speed in summer (7 m s⁻¹) would allow moderate stratification (mixed layer depth 50–100 m), leading to a moderate increase in biomass and major nutrient utilization. An intensification of the Westerlies is supported by the increased wind strengths during MIS 2 inferred from the concentrations of dust and sea salt extracted from the Vostok ice core (Petit et al., 1999). An intensification of the ACC probably due to an increase in westerly wind strengths may
also be deduced from marine sediment studies (Dezileau et al., 2000). Thus, the mixed layer (wind-dependent) was probably deeper during MIS 2 than during MIS 3 inducing an high-iron low biomass case (Blain et al., 2001) during MIS 2. This process could also explain the modest increase and not a high increase of opal productivity during MIS 2 relative to the Holocene.

At site MD 94102 (43°S), located in the northern part of the PFZ, i.e. close to the Subantarctic Front (Fig. 6), dissolution-corrected opal rain rates during MIS 2 were similar to those recorded during the Holocene. Low dissolution-corrected opal rain rates (0.2 g/cm² kyr) recorded in this region are presumably due to unfavorable SST conditions and low concentration of dissolved silica. Burckle et al. (1987) argued that the northern limit of high productivity by diatoms is controlled by temperature, which effects the metabolic processes of diatoms. Burckle et al. (1987) noticed a general decrease in diatom abundance in the surface waters of the Southern Ocean when SSTs are higher than 8°C. Fiala and Oriol (1990) found that Antarctic diatoms could not survive in temperatures above 6–9°C. Reconstructed SSTs (Salvignac, 1998) for core MD 94102 are higher than 8°C throughout the investigated period of time. These SST values may have prevented Antarctic diatoms from extending north of 43°S in the Indian sector. The other important factor that needs to be mentioned is the concentration of dissolved silica. At present, the northern part of the PFZ is characterized by a low concentration of dissolved silica. Reconstructed SSTs (Salvignac, 1998) for core MD 94102 clearly show that the APF does not reach this latitude (Fig. 2a) throughout the investigated period of time. Thus, we suggest that the diatom abundance has been limited by a low supply of Si to surface waters via upwelling in this region.

The low productivity of siliceous organisms in this northernmost core may therefore be explained by SSTs which have been always above 8°C and low supply of Si to surface waters via upwelling. Low opal fluxes recorded throughout MIS 2 for this northernmost core confirm that the siliceous belt, which has probably been associated with the APF, did not reach this latitude. This is a very similar situation to the one found by Asmus et al. (1999) in the eastern Atlantic sector of the Southern Ocean.

4.2. Variations in biogenic silica and organic carbon rain rates

Here we discuss changes in dissolution-corrected opal rain rates and organic carbon rain rates to the seafloor in the Indian sector of the Southern Ocean from MIS 2 to the Holocene. Our aim is to determine whether dissolution-corrected opal rain rates represent a reliable proxy of export paleoproductivity or whether there was a glacial decoupling of organic carbon and biogenic opal accumulation (Kumar et al., 1995; Anderson et al., 1998; Bareille et al., 1998).

During the Holocene period, maximum biogenic opal and organic carbon deposition has occurred in the AZ of the Southeast Indian sector (Fig. 7). During glacial times, the belt of biogenic opal and organic carbon rain rates shifted northwards. A closer comparison of last glacial and Holocene patterns suggests that there are significant differences between the two periods. First, glacial biogenic opal rain rates (1.1 g/cm² kyr) never reach values as high as those observed in the Holocene accumulation belt (1.8 g/cm² kyr). During glacial times the average dissolution-corrected opal rain rates is equal to 0.94 g/cm² kyr (n = 5) corresponding to a 20% reduction compared to the Holocene (1.20 g/cm² kyr). The glacial increase of biogenic silica rain rates in the PFZ–SAZ does not compensate glacial Antarctic decrease south of the present position of the PFZ. Secondly, during glacial times the average organic carbon rain rate is equal to 6.5 mgC/cm² kyr (n = 5) corresponding to a 25% increase compared to the Holocene (5.3 g/cm² kyr). Although the spatial coverage of cores for which opal and organic carbon burial rates have been reconstructed remains too limited to attempt a quantitative budget for opal and carbon burial during MIS 2, if our results are representative of the entire South-eastern Indian Basin, then we can suggest that this region is characterized by a reduction in opal rain rates that is not recorded by organic carbon rain rates. One way to reconcile these ob-
servations is to invoke a decoupling between opal rain rates and organic carbon fluxes to the sea bed.

Kumar et al. (1995), Anderson et al. (1998) and Bareille et al. (1998) have reached a similar conclusion in the Atlantic and Indian sectors of the Southern Ocean. What is the origin of this decoupling? Either organic carbon was delivered to glacial sediments of the PFZ with reduced amounts of opal, or there is a differential change in the degradation/preservation of the biogenic components, or both. These two scenarios are discussed further below.

Firstly, the scenario involving the delivery of organic carbon to glacial sediments of the PFZ together with reduced amounts of opal. There are two possible hypotheses to explain this decoupling. An ecological shift of dominant species assemblages away from diatoms to phytoplankton without siliceous shells (coccolithophorids; Anderson et al., 2002) could contribute to the observed decoupling between carbon flux and opal accumulation in the Indian sector. Moreover, diatom assemblages have lower Si/C ratios during MIS 2 north of the actual position of the APF. Recently, Hutchins and Bruland (1998) have shown that Fe plays a crucial role in the control of the Si/C ratio, and during times of increased Fe inputs diatom assemblages exhibit lower Si/C ratios (production of less silicified organisms). We suggest that the increased Fe fertilization of surface waters during MIS 2 (Martin, 1990; Kumar et al., 1995) may have resulted in decreased Si/C ratios north of the present-day position of the APF.

Secondly, the scenario of change in the preservation of organic matter. Decoupling between opal and organic carbon accumulation can be explained by more efficient organic carbon preservation in the PFZ during glacial times. Dezileau et al. (2000) have clearly shown an increase in sediment focusing in the PFZ during glacial times. Consequently, we suggest that the preservation of organic carbon during glacial times has been controlled by intense sediment focusing in the PFZ. Even if these effects on the organic carbon preservation are not quantifiable, we suggest that this effect may explain a major part of the strong decoupling between opal rain rates and organic carbon fluxes to the sea bed.

In conclusion, the origin of the decoupling between C and Si during glacial times in the PFZ can be explained as the result of a combination of factors including: a change in phytoplankton communities, the influence of Fe on the Si/C ratio in diatoms and, most likely, a better preservation of organic components in the sediment.

During glacial times, in the Indian sector of the Southern Ocean the average biogenic opal rain rate showed a 20% reduction and the average organic carbon rain rate showed a 25% increase compared to the Holocene. In this area, the increase of the average organic carbon rain rate does not necessarily mean an increase in export production of 25%. This result may be due to a better preservation of organic carbon in the sediment. In this case, if we consider only the organic carbon flux we overestimate export production. On the other hand, the decrease of the average opal rain rate does not necessarily mean a decrease in export production of 20%. Indeed, it is possible that there was a change in the composition of phytoplankton communities or a change in the Si/C ratio during glacial times. In this case if we consider only the opal flux, we underestimate export production. Finally, in the Indian sector of the Southern Ocean, we conclude that the range in past variability of export production is between −20 and +25% during glacial times compared to the Holocene. This relatively small difference between the two estimates of export productivity suggests there has little change between glacial times and the Holocene in the Indian sector.

The export paleoproductivity of the Atlantic sector of the Southern Ocean during MIS 2 has also been found to be similar to today (Frank et al., 2000) while in the Pacific sector paleoproductivity was lower than today (Chase et al., 2003). An increase in export paleoproductivity during glacial periods is not supported by the data, implying that bioproduction variations within the Southern Ocean are unlikely to have contributed to the glacial drawdown of atmospheric CO2 inferred from ice core data.
5. Conclusions

Radioisotope and proxy element profiles were measured on five sediment cores forming a transect across the Southern Indian Ocean of the ACC. Records of opal and organic carbon fluxes to the seafloor were obtained by normalization to $^{230}$Th.

During glacial periods, we observe that dissolution-corrected opal rain rates are slightly greater than during the Holocene in the PFZ. This is probably a consequence of the northward migration of the frontal system by approximately 5° latitude, a northward transport of Si from the AZ and an increase in Fe via upwelling and the erosion of the Kerguelen Plateau by strong currents associated to the ACC. In the Antarctic zone, glacial biogenic opal rain rates were similar to the Holocene except for the Kerguelen Plateau where rates have decreased. We suggest that the availability of light in surface waters above the Kerguelen Plateau was reduced during the last glacial period by snow covered sea-ice, which would have significantly limited opal productivity in the area. The results of our study favor an interpretation that overall opal productivity for the Indian sector of the Southern Ocean is slightly lower during glacial periods.

As far as export paleoproduction is concerned, dissolution-corrected opal rain rates were lower during the glacial period by up to 20% while organic carbon rain rates were higher by up to 25%. One way to reconcile these apparently contradictory observations is to invoke a decoupling between opal burial and organic carbon flux to the sea bed during the last glacial period. This decoupling can be explained by a number of factors, including a change in the composition of phytoplankton communities (other than diatoms), a change in the Si/C ratio in siliceous planktonic organisms due to increased Fe input in the Southern Ocean, and, most importantly, by a better preservation of organic components in the sediment. The results of our study indicate that the evolution of export production ranges between −20 and +25% during glacial times compared to the Holocene in the Indian sector of the Southern Ocean. This small range means that glacial export productivity was similar to Holocene values in the Indian sector of the Southern Ocean.

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References


Blain, S., Tréguer, P., Belviso, S., Bucciarelli, E., Denis, M., Desabre, S., Fiala, M., Martin-Jezéquel, V., LeFèvre, J.,


Mahowald, N., Kohfeld, K., Hansson, M., Harrison, S.P., Prentice, I.C., Schulz, M., Rodhe, H., 1999. Dust sources and deposition during the last glacial maximum and current climate: A comparison of model results with paleodata from...