

Interactive comment on “Contribution of changes in opal productivity and nutrient distribution in the coastal upwelling systems to late Pliocene/early Pleistocene climate cooling” by J. Etourneau et al.

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Major Comments:

1. Alkenone-derived SST and alkenone MAR records of Sites 1082 and 1084 have been added to the figure 3 (3B and 3E). *T. antarctica* and *Chaetoceros* spores records cannot be added to the figure because they are not available. Lange et al. (1999) and Marlow et al. (2000) described qualitatively the diatom assemblages throughout the ODP Sites 1082 and 1084 sediment. We can only base our comparison on the one performed by these authors.

Silicic acid and nitrate export may have reached the Benguela region via three mech-
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anisms: (1) an enhanced equatorward surface water advection, (2) a gradual shoaling of the thermocline and nutricline, or (3) a strengthening of coastal upwelling activity. Etourneau et al. (2009) has demonstrated that possibility (1) is unlikely because the $\delta^{15}\text{N}$ signature is not consistent with the one measured in the polar frontal system. Lange et al. (1999) and several other studies (Berger et al., 2002; Dupont et al., 2006; Etourneau et al., 2009; Marlow et al., 2000; Perez et al., 2001) reported that the upwelling activity was weak during the MDM and restricted to the south as shown by diatom assemblages, SST gradient, pollen data, and others. We propose that dissolved silicic acid and nitrate largely transported by SAMW and AAIW fed the biological production through shoaling of the thermocline combined with the sporadic equatorward advection through the Benguela Current and upwelling in the south of the BUS. On the one hand, the diatom species (*T. antarctica*) dominating the MDM probably migrated through the water column to feed in the nutricline where SAMW and AAIW prevailed. On the other hand, other phytoplankton species (e.g. coccolithoporphids), that cannot migrate through the water column like diatoms, were likely fed by nitrate through surface water advection and upwelling activity in the south of the BUS. We explain in the manuscript the mechanisms related to the atmospheric circulation (high pressure atmospheric cells located south) that controlled the upwelling activity in the BUS. One paragraph explaining this mechanism has been added to the manuscript as follow:

‘According to this line of evidence, we therefore emphasize that nutrient feeding the biological production in the BUS originated from SAMW and AAIW. The diatom species (*T. antarctica*) dominating the MDM probably mostly migrated through the water column to abundantly feed, in response to global cooling, from shallow thermocline and nutricline waters (Etourneau et al., 2009; Philander and Fedorov, 2003) where the silicate and nitrate-rich SAMW and AAIW circulated. In addition, the growth of diatoms and other phytoplankton species (e.g. coccolithoporphids), that were not able to migrate through the water column like diatoms, may have also been sporadically fueled by brief seasonal episodes of mixing supplying nutrients to the surface as well as surface water advection through the Coastal Benguela Current transporting nutrients from the active

upwelling cells located south of the BUS.'

2. See also response 1. We modified the text as follow:

'For most of the time, on both decadal scales but probably also during the annual cycle, stratification prevailed within the eastern boundary currents between 2.7 and 2.4 Ma but was interrupted by most likely short seasonal episodes of mixing supplying nutrients, thus fuelling bioproductivity in the low latitude upwelling systems and thereby increasing atmospheric CO₂ uptake. The long seasonal period of stratified conditions probably prevented significant upwelling of dissolved CO₂-enriched waters to the surface, which diminished the CO₂ flux from the ocean to the atmosphere in these regions. Given the extremely high opal production in these regions, we infer that the uptake of CO₂ was probably considerably enhanced and higher in flux than release from the deep ocean to the atmosphere via upwelling.'

3. During the late Pliocene/early Pleistocene cooling between 2.8 and 2.4 Ma, the opal fluxes in the different regions changed as follows (assuming the data at each ODP sites as reflecting the regional flux): High latitudes (the opal MAR records have been added to figure 4): North Pacific: 6 to 1 g.cm-2.ka-1 Southern Ocean: - North of the Polar front: 0.5 to 1.0 g.cm-2.ka-1 - South of the PF: 4.0 to 1.0 g.cm-2.ka-1 Low latitudes: BUS: 0.5 to 4.0 g.cm-2.ka-1 California: 0.5 to 4.0 g.cm-2.ka-1 Mauritania: 0.5 to 6.0 g.cm-2.ka-1 whereby any effects of changes in opal dissolution and sediment redistribution (focusing) potentially affecting all these records have not been taken into account because they cannot be quantified for this period of time.

We do not claim that the biological pump was necessarily more active between 2.8 and 2.4 Ma than prior to 2.8 Ma. We argue that the biological production pumping atmospheric CO₂ remained active despite its low activity in the polar oceans because it was matched by enhanced production in the low-latitude regions. This is illustrated by the opal fluxes reported above. The main difference with the period preceding the MDM resides in the fact that in addition to this active biological production, the combined

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stratification of the Southern Ocean due to the extension of ice cap and the weak upwelling activity in the low-latitude regions as a result of weak (Hadley) atmospheric circulation most likely strongly increased the CO₂ storage to the deep ocean. The poorly ventilated global ocean probably resulted in significantly lowered atmospheric CO₂ concentration and therefore contributed to late Pliocene/early Pleistocene cooling.

Fe dust fertilization in the Southern Ocean that plays an important role on the Si:N ratio and therefore on the nutrient distribution from the high to the low-latitudes during the last glacial period was quite different from the period between 3.0 and 2.0 Ma. The supply of Fe to the Southern Ocean during this latter period of time was poor (Martinez-Garcia et al., 2011), again as a probable result of a weakly developed atmospheric circulation. In the text, an additional sentence has been added as follow:

'However, it must be noticed that the major difference between the last glacial and the late Pliocene/early Pleistocene cooling periods resides in the fact that Fe dust fertilization did unlikely play a significant role on nutrient utilization in the Southern Ocean during the MDM, and therefore on nutrient distribution towards the low-latitudes upwelling regions, as Fe remained poorly transported to the surface waters between 3.0 and 2.0 Ma (Martinez-Garcia et al., 2011) probably as a result of a weak atmospheric circulation and a displacement south of the South Atlantic atmospheric high pressures cells (Etourneau et al., 2010; Martinez-Garcia et al., 2010; this study).'

The work proposed by Horn et al. (2011) is focused on Southern Ocean. The method to calculate the Si supply in the BUS as suggested by the referee cannot be applied in a similar manner as in Horn et al. (2011). In the latter study, the Southern Ocean d₃₀Si values were never below 0.6‰ contrary to the BUS where d₃₀Si can reach values as low as 0‰. For such low values, the calculated %Si(OH)₄ consumed and the resulting estimated Si supply is negative when considering 1.7‰ as the isotopic signature of upwelled Si(OH)₄ (Cardinal et al. 2005) and -1.1‰ as the isotopic enrichment factor (De LaRocha et al. 1997). Obviously, the Si supply cannot be negative, especially when regarding the high silica supply required for promoting such opal production.

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This method of calculation is therefore not adaptable to our study.

Moreover, we can also not estimate the relative utilization of Si(OH)_4 in the BUS (as we would wish) following the integrated product of the Rayleigh fractionation equation (Altabet and Francois, 1994) and our $\delta^{30}\text{Si}$ values ($\delta^{30}\text{Si}_{\text{diatom}} = \delta^{30}\text{Si}(\text{Si(OH)}_4)_{\text{initial}} + f/(1-f) \times e \times \ln(f)$ where f is the fraction of the initial silica pool remaining and e the fractionation factor) because there are no studies which offer an estimate of the $\delta^{30}\text{Si}(\text{Si(OH)}_4)_{\text{initial}}$ in the modern BUS (this has been specified in the 3rd paragraph of the discussion). We thus at present do not have any available data to quantitatively estimate the percentage of unused (or used) silica pool and future work on the modern BUS and to estimate the $\delta^{30}\text{Si}(\text{Si(OH)}_4)_{\text{initial}}$ supplying the BUS is needed.

4. The major difference between the two periods of time (last deglaciation (Brzezinski et al., 2002) and late Pliocene/early Pleistocene cooling (this study)) is that the Southern Ocean was probably poorly fertilized by Fe during the MDM (e.g. Martinez-Garcia et al., 2011). The latter nutrient was probably not the main factor controlling Si and N utilization in the Southern Ocean prior to 2.4 Ma and did not impact on the nutrient distribution from the polar ocean to the low-latitudes but was instead governed by drastic hydrological and atmospheric changes (stratification vs upwelling) related to the global cooling. Our new data do not provide evidence for changes in the balance between coccolithophorids and diatoms. Alkenone and biogenic opal MARS were both enhanced in the coastal upwelling regions during the MDM as a result of a high nutrient availability and favorable oceanic conditions for phytoplankton growth (a shoaling of the thermocline, brief episodes of local upwelling and nutrients resurgence added to an active upwelling activity in the south of the BUS). Although we cannot assert by how much the pCO_2 concentration might have precisely decreased due to this nutrient redistribution between the ocean basins and the poorly ventilated ocean (we write that we propose a 'possible' scenario), the coherence between the increase in biological production concomitantly with surface water stratification in the global ocean and pCO_2 decline suggest a strong link. However, future work including more data on nutri-

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ent utilization and especially modeling studies are therefore needed to further evaluate the impact of the MDM on global climate as now mentioned in the revised version of the manuscript.

Minor Comments:

- Planktic foraminifera-derived pCO_2 records of Bartoli et al. (2011), Hönisch et al. (2009) and Seki et al. (2010) have been added to the figure 4 and reveal the same decreasing pattern between 2.7 and 2.4 Ma, within methodological and age uncertainties. Other records (not shown here) (Pagani et al., 2010; Tripathi et al., 2010) similarly reproduce this pattern.

- The text has been adjusted according to the referee comment ('not completely understood').

- We infer that siliceous organisms other than diatoms (e.g. radiolarians) cannot significantly influence the $\delta^{30}\text{Si}$ values as the diatom amount in each sample was greater than 90%. On the microscope pictures below the dominance of diatom fragments in the samples after extraction and purification steps is shown. We did not quantitatively count radiolarians but every sample was controlled under the microscope (see picture attached) and the abundance of these organisms is clearly so low, especially within the size fraction of the diatoms considered here (11-23 μm), that it is unlikely that the abundance of siliceous organisms other than diatoms affected our $\delta^{30}\text{Si}$ values. In addition, on fig. d, during the MDM (2.19 Ma), the presence of pennate diatoms (stick shaped diatoms) of the *Thalassiothrix* species is by far more important than on the 3 other pictures taken at other periods of time. Therefore, the $\delta^{30}\text{Si}$ values measured on those samples reflect the isotopic signal associated with the MDM.

Figure caption Pictures taken at 4 different ages (a, 1.588 Ma; b, 1.696 Ma; c, 1.974 Ma; 2.19 Ma) where 4 different $\delta^{30}\text{Si}$ values were obtained (0.7 ‰ 1.2 ‰ 1.3 ‰ and 1.7 ‰ respectively), before analysis. The scale bar is about $\sim 20 \mu\text{m}$. Note that most of the diatoms are broken due to the treatment (extraction and purification steps).

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Fig.3. A, BSi content (%) at the Benguela Sites 1082 (green) and 1084 (black) (Etourneau et al., 2009; Lange et al., 1999; Pérez et al., 1999; Robinson et al., 2002). B, Alkenone-derived SST records at Sites 1082 (green) (Etourneau et al., 2009) and 1084 (black) (Marlow et al., 2000). C, $\delta^{30}\text{Si}$ (‰) (red) (this study) and BSi mass accumulation rate (MAR) ($\text{g}/\text{cm}^2/\text{ka}$) (light green) (Etourneau et al., 2009), (D) Alkenone MAR record (blue) (Etourneau et al., 2009), (E) bulk $\delta^{15}\text{N}$ (black) (Etourneau et al., 2009) and diatom-bound $\delta^{15}\text{N}$ (black squares) (Robinson et al., 2002) records at Site 1082. The solid lines for each records corresponds to the smoothed curve. Age models of Sites 1082 and 1084 are described in Etourneau et al. (2009). In Fig.3B, the long-term reproducibility of the $\delta^{30}\text{Si}$ measurements is indicated by the error bar.

Fig.4. BSi MAR at Sites (A) 882 (Maslin et al., 1996), (B) 1018 (Janecek, 2000), (C) 1082 (Etourneau et al., 2009), (D) 1091 (Cortese et al., 2004) and (E) 1096 (Hillenbrand and Fütterer, 2001). F, Atmospheric pCO_2 estimate derived from planktic foraminifera (blue line (Seki et al., 2010); blue square (Bartoli et al., 2010; Hönlisch et al., 2009)) and alkenones (grey and red (Seki et al., 2010)) at the Caribbean Site 999. The grey zone corresponds to the period of increasing siliceous productivity and decreasing pCO_2 as illustrated by the black arrows. The dashed line indicates the maximum biogenic opal production during the MDM. The associated map shows the respective locations of the different sites and the major opal centres shifts, from the Southern Ocean and the North Pacific (blue) to the low-latitudes upwelling regions (green) around 3.0-2.7 Ma, and from the latter to the Atlantic sector of the Southern Ocean (orange) around 2.4-2.0 Ma (modified from Cortese et al., 2004).

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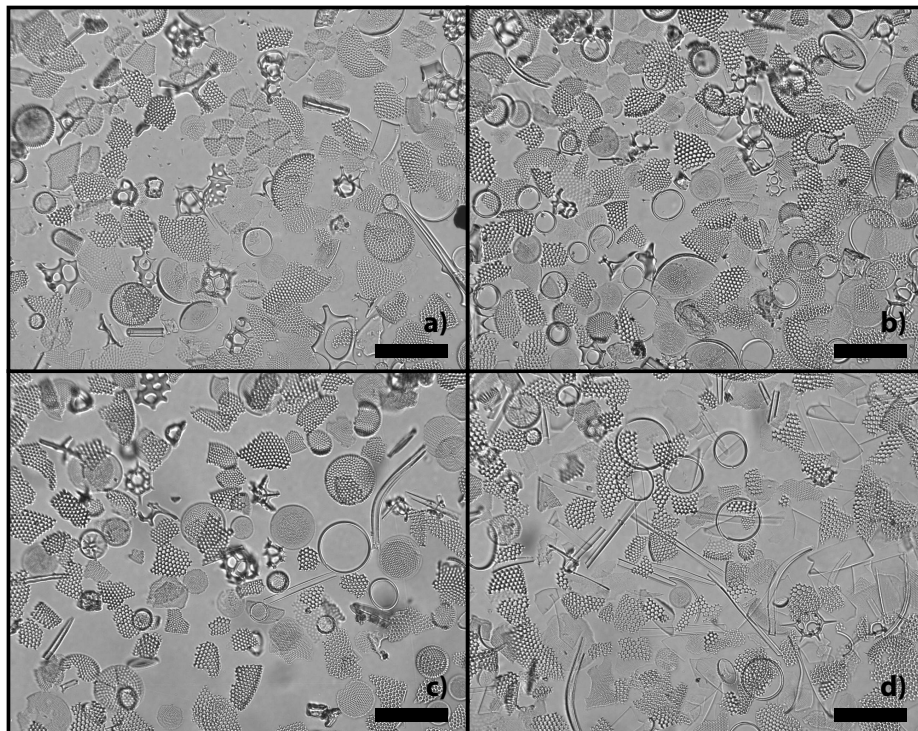


Fig. 1. Pictures taken at 4 different ages (a, 1.588 Ma; b, 1.696 Ma; c, 1.974 Ma; d, 2.19 Ma) where 4 different $\delta^{30}\text{Si}$ values were obtained (0.7 ‰, 1.2 ‰, 1.3 ‰ and 1.7 ‰ respectively).

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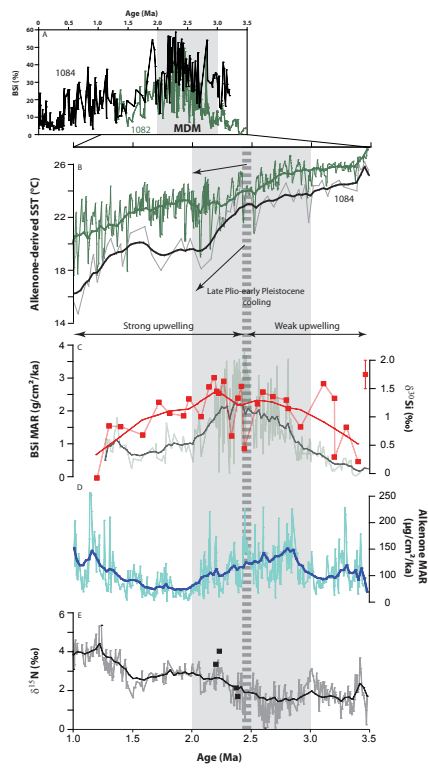


Fig. 2. Figure 3 of the revised manuscript

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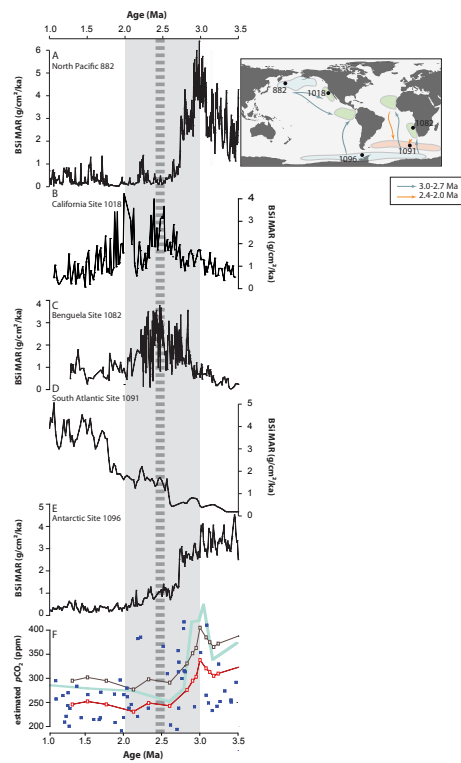


Fig. 3. Figure 4 of the revised manuscript

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