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Climate of the Past Discussions

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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P672 L1 In all the cited tropical and subtropical upwelling areas (e.g. California), the alkenone-derived SSTs declined by about 3-4°C between 3.0 and 2.4 Ma while productivity increased. Contrary to the BUS, no diatom assemblages have been reconstructed in the other regions. In contrast, the combination of the reconstructed SST gradients and other evidence (e.g. intensification of denitrification) suggest a weak upwelling activity in all the eastern boundary current regions during the MDM. Our assumptions are therefore based on an ensemble of indications describing the state of the upwelling conditions in other tropical/subtropical areas. Some words have been added to the text

('at which a similarly dramatic SST decline of about 3-4°C was recorded in all these three areas (Dekens et al., 2007; Etourneau et al., 2009; Herbert et al., 1998; Liu et al., 2008; Marlow et al., 2000)').

P672 L5 Some hypotheses have been indeed invoked to unravel the causes of the MDM in the BUS. However, the recent addition of records including the comparison between d30Si and d15N allow for the first time to accurately assess nutrient distribution, biological production and hydrological conditions changes in the BUS during this period of time. It is a paradox that upwelling activity was not the primary cause of the MDM while it should have brought more nutrients and hence stimulated local primary productivity. This is obviously not the case and we can show this from the comparison of all the records.

P675 L9 ++ We definitely consider this a valid statement. We added to the figure 3 a smoothed curve for each record. Nevertheless, in order to show the measured d30Si variability in line with the other records, we do prefer to also keep a connecting red line between the data points.

P676 L8(+16) It is true that there is not a single shift from mixed diatom species to exclusively T. antarctica species at 3.0 Ma ago. However, despite the minor presence of other species during some short time intervals, Lange et al. (1999) concluded that this polar species dominated the assemblages globally and was a feature of the MDM in the BUS. But indeed, the brief appearance of such species shifts might have accompanied the excursions to low d30Si values during the MDM as observed during episodes of low BSi MARs (lines 308-309 in the revised version of the manuscript). However, according to our low-resolution d30Si record, we discuss here the general trend and not the glacial/interglacial variability where the other species might appear. For this reason, we do not claim that the upwelling activity of the BUS ceased, but probably on a mean annual basis was not intense, and mostly restricted to the south, at least south of Site 1082. This is clearly supported by the low SST gradient between Sites 1084 and 1082 (Etourneau et al., 2009; 2010) (the corresponding SST records have been added to figure 3). Because T. antarctica and Chaetoceros spores records cannot be added to the figure as they are not available, we base our assumptions on the work of Lange et al. (1999), Marlow et al. (2000) and others. One sentence has been added to the text about the presence of other diatom species during the MDM as follow:

'Very few other diatom species (e.g. Chaetoceros radicans and C. cinctus) that developed under strong upwelling conditions sporadically appeared during the MDM and might have accompanied the excursions to light δ30Si as recorded during episodes of BSi MAR low between 3.0 and 2.0 Ma. However, those species remained globally rare and were more abundant in the south than in the north of the BUS (Lange et al., 1999). The distribution of these diatom species along the Namibian coast implies that developed upwelling cells were restricted to the south of the BUS that corroborates the low presence or absence of T. antarctica in the southern BUS (Lange et al., 1999).'

P676 L13++ There is indeed a peak in the d30Si record (2 consecutive data points, several times controlled) between 3.2 and 3.0 Ma while the d15N and the diatom production remained low. Contrary to the MDM, this period probably corresponded to the unique interval during which the system behaved as 'expected' with a high utilization of Si accompanied by a low opal productivity and at the same time a low utilization of nitrate within a warm and weak BUS. This primary productivity was probably limited by silicic acid availability. We added one sentence as follow:

'This is probably the case for the period between 3.2 and 3.0 Ma during which the system behaved as 'expected' with a high utilization of Si (high δ30Si values) accompanied by a low opal productivity and at the same time a low utilization of nitrate (low d15N values) within a warm BUS. During this time interval, the local primary productivity was probably limited by silicic acid availability owing to a weak upwelling activity.'

However, considering our low-resolution record and the topic we aim to discuss in this paper (the causes of the onset and end of the complex MDM and its impact at a global scale on the late Pliocene/early Pleistocene climate), we do not believe it is worth to

discuss further these two data points in the manuscript in detail. However, it might be of particular interest in the future to focus at a higher resolution on this time interval, the so-called PLIOMAX, considered by many Pliocene researchers as the most recent period of time resembling modern climate the most.

P677 L25++ We distinguish in the Southern Ocean two regions: the polar frontal system zone (north of the polar front (PF)) and south of the PF, surrounding Antarctica. In the first region, carbonate producers mostly dominated between 3.0 and 2.4 Ma (e.g. Sites 1091, 1089 or 1092 where the carbonate content ranged between 50 and 100% of the sediment) which suggest weak silica utilization. In contrast, from 2.4 Ma onwards, carbonate was progressively replaced by silica as shown at Site 1091 (see revised figure 4 in the manuscript and Fig 2. of Hillenbrand and Cortese (2006)), implying enhanced silica utilization and switch to siliceous productivity. According to Cortese et al. (2004) and Hillenbrand and Cortese (2006) – the latter reference has been added to the revised version of the manuscript – the southern part of the Southern Ocean, at sites of more than 5 gravity cores and ODP Sites was characterized by strong changes in biogenic opal MAR at around 2.8 Ma (see Fig 2. of Hillenbrand and Cortese (2006)). Before 2.8 Ma, biogenic opal content in the Southern Ocean sediment was between 15 and 60% which is a high level of deposition compared to nowadays. Records from some coastal sites (e.g. ODP Site 1096/1095) clearly show a strong decline in biogenic opal from 2.8 Ma, thus implying as a consequence a strong decrease of silica production. This decline was associated to developing stratification and large sea ice extent (Sigman et al., 2004). This event concurred with the onset of the MDM in the BUS. Taken all these observations together, we infer that the MDM was caused by unused silica from the entire Southern Ocean to low-latitude upwelling system through intermediate and mode water circulation and transport. In the manuscript, we slightly modified the text as follow:

'Today, the BUS is mainly supplied with Si from the Southern Ocean waters through equatorward advection and upwelling of SAMW and AAIW (Fig.1). During the MDM, the polar frontal system regions where these water masses are presently formed, may have been poorly developed prior to 2.1 Ma (Liu et al., 2008). We therefore suspect that the two water masses might have originated either further south or from a wider area during the MDM. The extension of the Antarctic ice cap and the progressive stratification of the 'warm' Southern Ocean at ~3.0-2.7 Ma (Haug et al., 1999; Martinez-Garcia et al., 2010) likely favoured the delivery of Si to the BUS through SAMW and AAIW, and unlikely from surface water advection. Indeed, the lack of coherency between the d15N values from the BUS and the polar frontal region do not support surface water advection as a possible source of nutrients along the southwestern African coast (Etourneau et al., 2009). The hydrological changes in the Southern Ocean most likely allowed the transfer of a large amount of unused Si in the Southern Ocean to the low-latitude upwelling systems (Cortese et al., 2004; Hillenbrand and Cortese, 2006). The presence of diatom species typical for Southern Ocean waters in the BUS (Berger et al., 2002; Lange et al., 1999; Pérez et al., 2001) confirms the close connection between the two regions during the MDM. According to sedimentary archives, productivity during the MDM was mostly dominated by carbonate producers in the polar frontal (PF) region of the Southern Ocean (e.g. ODP Site 1090 (Gersonde et al., 1999)). In addition, very few diatoms or other opal producers were found south of the PF at that time (e.g. ODP Sites 1095 (Hillenbrand and Cortese, 2006) and 1096 (Hillenbrand and Fütterer, 2001)), which supports the conclusion that the original silica pool feeding the BUS was poorly utilized. This observation therefore minimizes potential effects of diatom dissolution in the Southern Ocean water column potentially affecting the δ30Si values advected waters to the BUS because this process, as previously observed in culture experiments (Demarest et al., 2009), should have led to low δ30Si signatures in the BUS and not the high ones observed.'

P678 L4+ We perfectly agree. The nutrient leakage from both North Pacific and Southern Ocean towards the low-latitude upwelling systems between 3.0 and 2.4 Ma does not have the same origin as from the low-latitudes upwelling systems to the Southern Ocean from 2.0 Ma onwards. On the one hand, the reconstructed nutrient leakage

at 3.0 Ma likely resulted from surface water stratification and sea ice extent in polar regions that favored the export of unutilized nutrient to the low-latitudes. On the other hand, the shift of the centres of opal deposition from low latitudes to the Southern Ocean may instead have been linked to changes in hydrological conditions in the Southern Ocean (namely the development of the polar frontal system) accompanied by an increase in Fe fertilization via dust (Martinez-Garcia et al., 2011) tied to the intensification of atmospheric circulation (Etourneau et al., 2010), causing an enhanced consumption of nutrient in the Southern Ocean and thus limiting its export to the low-latitudes upwelling regions.

In the manuscript, we do not assert that it was similar. The similarity only concerns the comparison between the North Pacific and the Southern Ocean sea ice extension and the resulting reorganization of nutrient cycling in response to this phenomenon. In the absence of d30Si records in the Southern Ocean, we can only assume that it was relatively similar to the North Pacific as they both evolved in a similar way. We therefore argue that d30Si values shift in the Southern Ocean accompanying the onset of stratification around about 2.7 Ma might have been on the same order than those of the North Pacific and could not explain the BUS values.

P680 L8++ Sentence has been reworded as suggested ('Compared to the high silicate utilization, the supply of nitrate in the BUS between 3.0 and 2.4 Ma was probably surpassing the nitrate demand of primary producers in the BUS (Etourneau et l. 2009), as suggested by the reconstructed light d15N values (Fig. 3).').

P681 L5+ Chaetoceros species are not a large contributor of biogenic silica compared with T. antarctica. Although other species were also found in the sediment, only the dominant species were discussed as Marlow et al. (2000) reported.

P681 L7+ Uk'37 can present indeed some differences with other SST proxies (TEX86 or Mg/Ca). This has recently been highlighted in Leduc et al. (2010) for the Holocene/Eemian but also in several other studies. However, other studies point to coherent variations (e.g. during the penultimate climate cycle (Huguet et al., 2011)). Contrary to the other proxies, the alkenone calibration is based on the most extensive dataset for a SST proxy, and this is particularly true for the BUS (Müller et al., 1998; Conte et al., 2006) where numerous core-tops have been analyzed. In addition, although the seasonality might be the main issue when using a SST proxy, Schneider et al. (2010) used satellite data for mapping the existing relationship between the annual cycle of SST and local primary productivity. The authors developed a seasonality index for the BUS which broadly depicts an increased primary productivity when SSTs are below the mean-annual value because the biological production is stimulated by enhanced upwelling of cool and nutrient-rich waters. Based on this study, we assume that the alkenone-derived SST of the BUS can be used as a reliable marker for SST changes as recently supported by Leduc et al. (2010) in this region.

P683 L21++ The impact of the shift of the centres of opal deposition along with the reorganization of nutrient cycling remains difficult to precisely assess. A detailed modeling study may help to complete this work. However, the shift occurred between the North Pacific and Southern Ocean with the low-latitudes upwelling regions (California, Mauritania and BUS) as well as the equatorial upwelling in the Pacific (see Cortese et al. 2004). It is also possible that other regions were affected by this transition but the lack of records does not allow us to evaluate this. In contrast, from several studies, it seems clear that a large nutrient leakage from high to low latitudes may have had a significant impact on global CO2 through an enhanced efficiency of the biological pump under weak upwelling conditions (the transport from the upper ocean to the sediment surpassing the transport from the deep ocean to the atmosphere in these regions). Here, we provide a possible scenario that links both low latitude primary productivity and atmospheric CO2 given that synchronous variations in BSi and CO2 occurred. Moreover, the increasing productivity in the upwelling regions between 3.0 and 2.4 Ma associated with a reduced CO2 release from the deep ocean to the atmosphere in polar regions due its abrupt stratification and extent of the polar ice cap probably had a strong combined effect on global climate that remains difficult to estimate without a

comprehensive modeling study. Some words have been added to the text ('Although further (modeling) studies are required to precisely quantify the impact of the MDM on global climate').

P684 L23 Here, without considering Fe dust fertilization, we just give an information about the impact of silica leakage on CO2 levels. Of course, aeolian Fe supply in the Southern Ocean must be taken into account when considering the impact of such a reorganization on the carbon cycle. This has been specified in the revised version of the manuscript as follow:

'For comparison, a large silica transfer during the last glacial periods between a stratified Southern Ocean and intensive low-latitude upwelling systems would have accounted for a reduction of the atmospheric CO2 by 60 ppm (Brzezinski et al., 2002). 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).'

FIGURES FIG 1 Vertical transects have been added to the Figure 1.

FIG 3 T. antarctica and Chaetoceros spores cannot be added to the figure because they are not available. Lange et al. (1999) and Marlow et al. (2000) qualitatively described the diatom assemblages of the sediments of ODP Sites 1082 and 1084. We can only base our comparison to the one performed by these authors.

FIG 4 The two records from both high latitudes have been added to revised figure 4.

Interactive comment on Clim. Past Discuss., 8, 669, 2012.

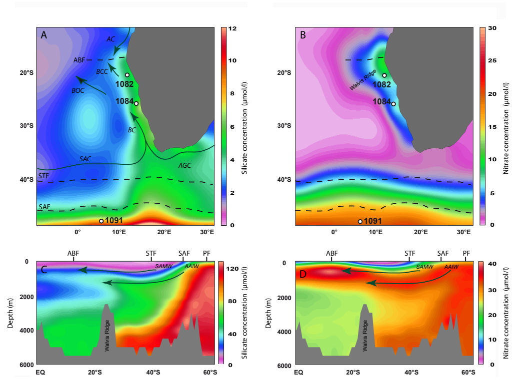

Fig. 1. Figure 1 of the revised manuscript

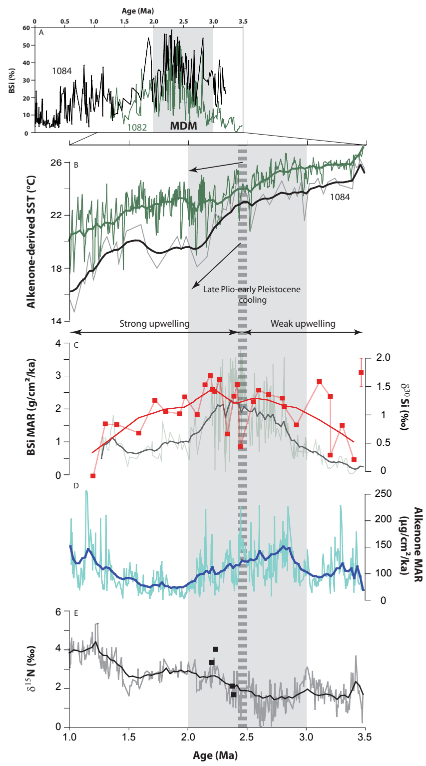

Fig. 2. Figure 3 of the revised manuscript

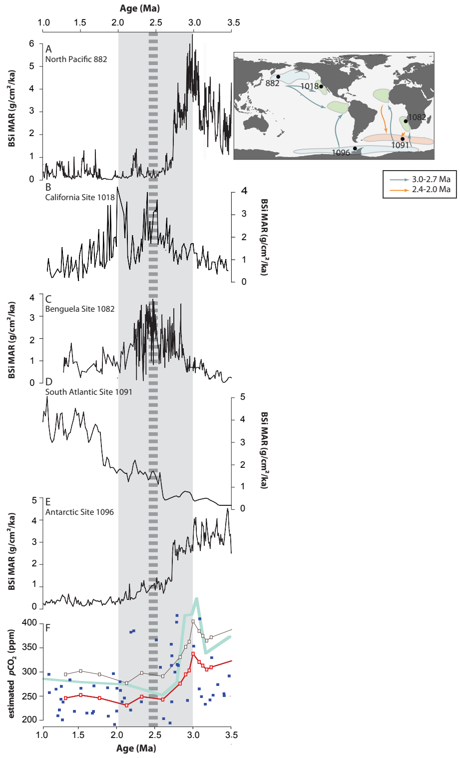

Fig. 3. Figure 4 of the revised manuscript