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Interactive comment on "Miocene–Pliocene stepwise intensification of the Benguela upwelling over the Walvis Ridge off Namibia" *by* S. Hoetzel et al.

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We thank the reviewer for the thoughtful comments to our paper. We repeat the reviewers comments between <>.

GENERAL COMMENTS

<This paper is an interesting study to elucidate the evolution of the northern part of the Benguela upwelling system along the west coast of Africa since the Miocene. In the present climate the Benguela system is a major region of upwelling in the Atlantic Ocean, where mostly cold and nutrient rich water comes to the surface and hence influences surface water conditions. The authors produced a new record from ODP site

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1081 on organic-walled dinoflagellate cysts, and infer past surface water conditions from the varying distribution of several species and the total organic carbon content. The paper is very well written and methods are clearly explained. I cannot fully judge how complete the interpretation of the record is based on all available literature, as my expertise lies mostly in ocean and climate modeling, but I had similar concerns as referee 1 as to the interpretation of the data seems somewhat narrow. My major concern, however, lies one step further in the interpretation of the data: Throughout the paper statements are made that in fact are a mix of what the data really say (which is mostly based in nutrient availability) and what that might imply for the conditions and circulation in the (global) ocean and atmosphere. The latter sort of statements should be substantiated by referring to either present-day oceanographic data/simulations and/or past climate model studies. This is an important issue, which needs to addressed and sorted out more elaborately before final publication.>

We try to avoid this type of confusion. We first describe the Results (4). After that, we discuss the sequence in steps (sections 5.2 to 5.6), each time beginning with the cyst record and after that the interpretation in terms of upwelling. Concerning the ABF and the AC we refer to oceanographic literature. Only in section 5.4, did we not strictly follow this scheme. We'll correct that in the revision by shifting the first paragraph of section 5.4 to the middle of the section. The last three paragraphs of section 5.4 refer to other paleoceanographic literature. At section 5.5 we refer to a recent modelling study about the influence of uplift on the BUS. After the stepwise discussion of the developments in the BUS, a separate section (5.7) places our results in a global context. Apart from a few too bold statements in the Abstract and Conclusions, which will be deleted, we separated results and interpretation of the data from implications in a global context.

SPECIFIC COMMENTS

<It is mentioned in the introduction that the Benguela upwelling system is thought to have initiated in the Late Miocene. I think this is a too general statement. Large-scale ocean upwelling systems exist because of the general distribution of wind patterns in

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the atmosphere, and so does the BUS.>

We'll change the sentence into: "Cold water upwelling in this system is supposed to have initiated in the early Late Miocene (∼10-15 Ma) (Siesser, 1980; Diester-Haass et al., 1990; Heinrich et al., 2011; Rommerskirchen et al., 2011) during a phase of global cooling."

The literature does speak of "initiation". From the abstract of Siesser (1980 in Science): "Deep Sea Drilling Project cores collected at site 362/362A suggest the time of initiation of the Benguela upwelling system. . .. . .that major, sustained upwelling began in the early late Miocene." and from the abstract of Diester-Haass et al (1990 in Paleoceanography): "In the middle Miocene the Benguela Current had not yet reached the Walvis Ridge, and consequently, no local upwelling occurred."

<It is difficult to imagine a completely absent BUS in a situation where Africa is at about the same position as today and trade winds and westerlies at mid-latitudes exist. What can vary, is the strength of the upwelling (depending on wind strength) and the properties of the upwelled waters (depending on the global ocean circulation, in particular deep sea conditions). The winds are the main reason for upwelling in the ocean, and while the wind pattern of course is related to meridional temperature gradients this is not a simple relationship. Interpreting the dinoflagellate cyst distributions in terms of meridional temperature gradients appears too far going in my view.>

We agree that upwelling at the Eastern ocean boundaries depends primarily on the existence of a continent to the East and strong winds blowing parallel to the coast depending on the position and strength of the subtropical anticyclone. However, also essential for the wind strength and its direction parallel to the coast is the steep coastal orography and the zonal land-sea thermal contrast, which is increased through the presence of African mountains (both points are discussed).

Apart from the strength of the upwelling and the properties of the upwelled waters the location of the BUS might shift, following strength and position of the subtropical

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anticyclone. Hence upwelling might not have been completely absent along the west coast of Southern Africa, but it is possible that it was strongly limited in latitudinal extent (and also weaker, with a weaker SAA).

Therefore we write:

“A weak meridional temperature gradient would shift the ABF southwards and allow the AC to penetrate southwards over the Walvis Ridge creating Benguela Niño like conditions (sensu Shannon et al., 1986). Conversely, increase of the meridional gradient (Billups, 2002) would have resulted in a northward shift of the ABF, northward migration of the BUS (Diester-Haass et al., 1992), stronger currents and vigorous trade winds.”

and:

“Since 3.2 Ma the intensification of the Northern Hemisphere glaciations and the introduction to a bi-polar icehouse would have shifted the Inter-Tropical Convergence Zone southwards to its average modern position (Billups et al., 1999). The southward shift probably caused an intensified meridional temperature gradient (in the Southern hemisphere) and further intensification of the low-level winds driving upwelling, which affected the dinoflagellate cyst assemblages.”

<In the interpretation of the data a clear distinction should be made between the above mentioned two processes: Is this a consequence of stronger/weaker upwelling or rather different water properties upwelled? The distinction might not be unique at all times, but at least an attempt should be made.>

In section 5.4 we make the attempt where we write:

“The period of warm subsurface waters at Site 1085 (southern BUS) coincides with the increased representations of B. hirsuta (Site 1081) suggesting that the downward mixing affected the quality of upwelled waters at the northern BUS creating special and non-recurring conditions.

"Berger et al., (2002a) argued that the quality of the coastal upwelling waters at the

BUS is linked to the deep water circulation and the strength of the NADW. Increasing NADW formation brings, until a critical point, more silica from the Northern Ocean into the Southern Ocean and eventually changes the chemistry of the upwelled waters at the BUS (enabling the Matuyama Diatom Maximum). Changes of the silica content might have affected dinoflagellates indirectly via ecological competition with algae or other microorganisms or via changes in food supply and sources. The latter one is important for the heterotrophic species since they feed on diatoms which are highly depending on silica contents.

"A further change of the quality of the upwelled waters could be caused by a poleward undercurrent flowing south from the Angola dome along the African margin transporting silica-rich, phosphate-rich and oxygen depleted waters (Berger et al., 1998) and increasing the fertile thermocline. A strengthening of this undercurrent and a higher silica content of the waters representing a mixing of the intermediate water and this poleward undercurrent is indicated by a radiolarian peak from 5.8 Ma until 5.25 Ma at ODP Site 1085 (Diester-Haass et al., 2002) coinciding with the younger B. hirsuta maximum. The peak in radiolarian might explain lower H/A ratios since radiolarian might have competed with heterotrophic dinoflagellates."

and again at section 5.6:

"Between 4.4 and 3.4 Ma, the H/A ratios show minima during dinoflagellate cyst flux maxima indicating again a change in the quality of upwelled waters corresponding to a northward shift of diatom assemblages to the central BUS area (Marlow et al., 2000). These changes may be linked to a stronger influence of Antarctic Intermediate Water."

<Section 5.1 should contain much more information on how dinoflagellates are distributed in the present BUS.>

To cover this point the following will be inserted:

"Of the extant species L. machaerophorum, Impagidinium spp., N. labyrinthus, O. centrocarpum, Brigantedinium spp., S. quanta and Spiniferites spp. are the more important taxa found at ODP Site 1081. The following features of the distributions are after Zonneveld and Marret (2013). L. machaerophorum is restricted to the subtropical-equatorial regions of the Southern Hemisphere and has now almost disappeared from the BUS. Impagidinium species are found in fully marine and often oligotrophic environments. They are not very abundant in modern sediments of the BUS except where other cysts are subject to oxygenic degradation. Also N. labyrinthus is found under fully marine conditions. O. centrocarpum is a cosmopolitan species abundant in the modern BUS. Brigantedinium species are cosmopolitan and thrive under nutrient rich conditions of upwelling. They are dominant in the modern BUS. S. quanta appears in coastal and marine sites near frontal systems. It has been observed in relation with enhanced opal flux. Many Spiniferites species are found relatively near the coast. They are not particularly abundant in the modern BUS."

<I cannot believe the Benguela Nino conditions to be directly related to the appearance of certain dinoflagellate species. Again, there should be steps in between to substantiate this interpretation.>

We believe our phrasing in the discussion to be quite cautious:

"Outside the inner neritic zone, L. machaerophorum has been considered an indicator for stratified warm nutrient-rich waters, e.g. after upwelling relaxation (Marret and Zonneveld, 2003; Zonneveld et al., 2013, and references therein) suggesting that periods with stratified water conditions were more frequent and/or longer than today. I. paradoxum and N. labyrinthus which are more frequent in waters around the ABF (Dale et al., 2002; Zonneveld et al., 2013) also may indicate a southern position of the ABF at least 3° of latitude further south than today. At present, the ABF shifts southwards on inter-annual timescales during Benguela Niños (Shannon et al., 1986). Under these special conditions, the waters over the Walvis Ridge receive a contribution of the Angola Current (Petterson and Stramma, 1991; Florenchie et al., 2004; Mohrholz et al., 2004; Richter et al., 2010). It is possible that these Benguela Niño events were more common during Miocene times when the SAA and the trade winds were weaker."

We agree, however, that the phrase in the conclusion about the Benguela Niños is not warranted and will be deleted.

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