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Climate of the Past Discussions

Interactive comment on "From Monsoon to marine productivity in the Arabian Sea: insights from glacial and interglacial climates" *by* Priscilla Le Mézo et al.

Anonymous Referee #1

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Recommendation This paper investigates how changes in orbital parameters and ice sheets during Âăthe last glacial-interglacial cycle impact Arabian Sea productivity through changes in the monsoon intensity and spatial pattern. This is an important topic, since productivity estimates from Arabian Sea cores are usually interpreted as proxies of the monsoon intensity. Using numerical simulations with a earth system model, this study shows that the relationship between monsoon intensity and productivity is non trivial, because spatial shifts in the monsoon jet axis influence both wind stress and its curl, which both control the influence of the coastal upwelling. The paper topic is interesting, and the analyses are scientifically sound. I however suggest a couple of additional diagnostics, re-arangement of some results, additional critical discussion of the model, which should improve the clarity of the paper and make it more convincing (see general comments below).

General comments 1. I feel that some diagnostics on the intensity of the upwelling (eg SST anomaly in the coastal box relative to the Indian Ocean average and/or vertical velocities and/or depth of the thermocline – and nutricline-) would be helpful to relate the changes in nutrients with changes in the upwelling intensity. A bit more validation of the upwelling characteristics in the present-day simulation also would not harm. 2. There is no discussion of how the biases of the model for the current-day climate (e.g. its underestimated productivity) may influence the overall results of the study. 3. The abstract could be improved (suggestions below). It may also be beneficial to show and discuss Fig. 14 much earlier in the paper, in order to describe the relative effects of alongshore stress and near-shore Ekman pumping in the present-day climate ahead of the past climates discussion. 4. I am not sure that it is worth discussing the central Arabian Sea region (Figures 6 and 9). A reason for that is that this region is usually viewed as highly influenced by what happens in the coastal upwelling region. I hence feel that focussing on the coastal box is enough. If you want to keep this central Arabian Sea box, a diagnostic as that of figure 14, which relates the interannual variability of productivity to wind stress (here an indicator of vertical mixing) and wind stress curl would be helpful. 5. It may be useful to show maps of the JJAS climatological wind stress and Ekman pumping values for all the simulations, to more visually relate how the changes in low pressures over the continent relate to changes in the monsoon flow.

Detailed comments P1, L1: maybe "the current-climate Indian monsoon. . ." P1, L5-10: I think that the abstract could be clarified. Maybe mention explicitly that coastal upwelling is fuelled by a combination of alongshore stress intensity and upward Ekman pumping to the west of the jet axis. There is however strong downward Ekman pumping to the east of the jet axis, so that changes in coastal alongshore stress / curl depend both on the jet intensity and position. You can then relate changes in the intensity and position to the exact position of the low pressure over Tibet, with astronomical parameters having impact mostly on the intensity and changes in ice sheets rather influencing the jet position. P1, L18: Another useful reference here is McCreary et al. (2009) (see full reference below). P1, L24: maybe indicate “upward” Ekman pumping. It may be interesting to mention offshore downward pumping to the right of the jet axis. P2, L5: Also mention the specific role of eddies, quoting Resplandy et al. (2011). P2, L9-11: Recent studies indicate that, due to changes in atmospheric stability, an increase in rainfall is not necessarily associated with an increase of the associated circulation (e.g. Held and Soden J. Clim. 2006 in the context of anthropogenic climate change). P2, L24: Be more specific: change of ice sheet heights in which regions? Same comment for ice volume L27. P3, L14 and following: “the LMDZ5A atmospheric general circulation model” (and likewise for the other components) P4, L30-34: A recent study (Keerthi et al. 2016, see below for full ref) shows that, in winter (when the cloud cover over the Arabian Sea is low), there is a good agreement between various satellite datasets for the Northern Arabian sea, but large differences in terms of amplitude. You may hence want to add a cautionary note about uncertainties of the observational estimate. P5, L1: vertical mixing is more specifically due to convective overturning in presence of strong southward winds that bring dry, cold continental air. P5, L11: typo: ? -> ‘. How is productivity computed from SeaWifs? P5, L18-19: It is also likely that the absence of eddies in the model solution contributes to a weaker offshore export than in observations (but you note it a bit later on p6). The consequences of this underestimated productivity on your results has to be thoroughly discussed at the end of the paper. P5, L25-35: Time series of the mean seasonal cycle of alongshore wind-stress, near-shore wind stress curl and of an indicator of the upwelling (e.g. SST) would allow a more quantitative validation of the model than the existing figures. P6, L10: Is “pathway’ appropriate in this context? P6, L23-25: You should refer to fig4 to justify this diagnostic better. I am surprised by the position of the black start on figure 4e: it is on the edge of the region with SLP anomalies < -5 hPa, which is surprising for a barycentre. Is there a gridpoint with a very large negative SLP anomaly? Or maybe I’m colorblind: you should probably highlight the -5 hPa contour on that figure. P8, L5-16: I generally agree with the interpretation, but I feel that the explanation takes twists and turns. I would reorganize as follows: the shift of the Tibetan low leads to a poleward shift of the monsoon jet (5c). This leads to weaker alongshore winds in the Somalia and stronger alongshore winds in the oman upwelling (5c). But this also brings the Ekman downwelling to the right of the jet axis closer to both Oman and Somalia coasts (5e). Both factors (alongshore, and offshore curl) contribute to a Somalia upwelling reduction, while the wind stress curl change seems to overwhelm the increased alongshore winds in the Oman region, leading to overall upwelling reduction and less nutrients (5b). The reduced wind stress also reduces the mixed layer depth in the Southern Arabian Sea (5d) but I'm not sure it's so relevant to show this here. Rather, showing SST (which characterizes the upwelling intensity) and/or vertical velocities in the model would allow to better characterize physical changes. Showing the depth of the nutricline would also be really helpful. Finally, I wonder why nutrient reduction is larger in the Oman region than in the Somalia region. Is it an effect of changes in biological uptake? P8, L17-23: This figure is relevant for the coastal box, but is it so relevant for the offshore box, for which a lot of the productivity changes are most likely a consequences of changes in the coastal upwelling, exported offshore by the circulation. For the coastal box, it indicates that the curl change (favouring downwelling) wins over the change in coastal winds (favouring upwelling and enhanced vertical mixing). This would be confirmed by looking at the thermocline (and nutricline) depth and/or to vertical velocities, i.e. looking at physical indicators of the intensity of the upwelling. Another interest of this plot relies on the fact that productivity is decreased for all years: i.e. the change that you see is statistically significant. Finally the last interest of this plot is that it allows to evaluate the respective roles of Ekman pumping and alongshore wind stress for interannual variability: although not very clear with the current choice of color scale for panel a, there is a tendency for a weaker decrease in productivity for strong alongshore stress, as would be expected. We would also expect to see a stronger decrease in productivity for larger negative wind stress curl anomaly. If you confirm this (i.e. by performing a bilinear fit of the productivity on the stress & curl), illustrating the competition between those two effects for interannual variability will strengthen your case for explaining changes between CTL and EH. Nota: I later came to realize that you actually show this as figure 14, but it may be interesting to show it at an earlier stage in the paper. P9, L9-10: This statement is more confusing than helpful (where exactly in the Central AS?) P9, L11: Figure 8 would be usefully complemented by scatterplots between some of the variables (and the associated correlations): alongshore wind stress is strongly controlled by DTT (panels a and b); nutrients exert a (weaker) control on productivity (b and c): I would combine these scatterplot with Figure 9a (again, I don't think that figure 9b is so relevant, because wind stress is not really an upwelling driver away from the coast and productivity changes in the central Arabian Sea may not be the result of local processes). P9, L24-25: Doing a scatterplot of alongshore wind stress vs. coastal wind stress curl would also be helpful to characterize the relations of the two parameters that control the upwelling. I would not say they are entirely independent: it seems that there is a tendency for a negative correlation. P10, L15-20: It may be better to start by explaining the links between the low pressure position and the wind stress and curl, and then discussing the consequences on the productivity. To understand better the links between the low pressure position and wind stress intensity / curl, it would be good to add a figure with maps of the JJAS wind stress (vectors) and its curl (colors), with the position of the barycentre indicated. P10, L23: simply point out that the latitude of the barycentre exerts a strong control on the coastal wind stress amplitude. P10, L28: In general, in this section mention "increase of productivity with the central longitude of the Tibetan low". P11, L1-10: I'm not that familiar with those orbital parameters. Wouldn't it be simpler to directly relate the position of the low pressure to the annual (or JJAS) solar heat flux properties over the region, and then describe more qualitatively how orbital parameters control this value? Or at least remind how these parameters influence insolation and hence the low (e.g. copy the text at lines 30-31 here). P11, L14: Âăremove only P13, L8-9: can you explain this choice? P13, L17: you could locate this core, e.g. on figure 7. P14, L9: provide a reference in support of this statement. P14, L11-17: in the model. P15, L9-19: This is nice. I would move this much earlier in the paper, because it allows to explain better the relative roles of wind strees and its curl at interannual timescales before moving to applying these explanations for climates of the past. P15: a through discussion on the possible consequences of the present-day climate biases in the model on the results of this study is needed.

Figures Fig. 2: also draw the Northern box. Fig 3: left panels of b, c, d have some spurious horizontal lines on them. Some smoothing or median filter would not harm on the sat. wind stress intensity & curl. On d, also avoid saturating the colorscale. Panel b: use the same spacing between vectors for the model and data. Fig 5: it would be useful to materialize the boxes that you use for integrated diagnostics on this figure. Fig 7: draw the coastal box. Figure 8: describe the whiskers in the caption. I imagine it is a confidence interval: at what significance level? How is it computed? What are the small circles on this figue (and on figure 12). Figure 10: draw the boundaries of panels b, c, d on panel a. You can re-organize the panels into 2 x 2 to save space. Figure 12: it would be nice to locate the core / box that are used for figure 12 on another plot, e.g. figure 7. Clarify in the caption which panels are model results. Figure 13: I don't find this picture very clear. I would do it upside down: start it by changes in orbital parameters / ice sheet driving changes in the Tibetan plateau low, which impact the intensity / pattern, stress / curl, the upwelling of nutrients, etc… Materiaize the direction of arrows connecting boxes.

References McCreary, J. P., R. Murtugudde, J. Vialard, P. N. Vinayachandran, J. D. Wiggert, R. R. Hood, D. Shankar, and S. R. Shetye, 2009: Biophysical processes in the Indian Ocean, In: Indian Ocean Biogeochemical Processes and Ecological Variability, J.D.Wiggert, R.R. Hood, S.W.A. Naqvi, S.L. Smith, and K.H. Brink (ed.), American Geophysical Union, Washington, D. C, pp 9-32. Keerthi et al. 2016: Physical control of the interannual variations of the winter chlorophyll bloom in the northern Arabian Sea. Biogeosciences discussions, available at http://www.biogeosciences-discuss.net/bg-2016-153/

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Discussion paper

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