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Ocean Science Discussions

Interactive comment on "The relationship between Arabian Sea upwelling and Indian monsoon revisited" *by* X. Yi et al.

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We thank the reviewer for the detailed reading of the manuscript and for the constructive suggestions. In the following, we sketch how we plan to eventually revise this manuscript to address these suggestions.

The title and the focus of our study is to revisit the connection between the Indian Monsoon and upwelling in the Arabian Sea in the context of a high-resolution ocean simulation. The ocean model we are analyzing (MPI-OM) has been used in many other applications, it is also included as a component in ensemble of models of the Climate Model Intercomparison project used by the IPCC. The difference here is the high spatial resolution of the model version we have used for our study. The simulation with the

high-resolution version has been analyzed globally in other studies conducted at the Max-Planck-Institute for Meteorology (von Storch et al., 2012). It is known that coastal upwelling in the real world is driven by the wind-stress, and it is very reasonable to assume that this link will be well represented in the ocean model. The physics of coastal upwelling is well known, so there would be very little added value to show a detailed analysis that this ocean model also reproduces the connection between upwelling and wind stress. We do briefly show, however, that the statistical link between simulated upwelling and the wind-stress is the expected one. The focus of the study is to test the assumption that upwelling in the Arabian Sea is connected to the Indian Monsoon, as it has been assumed in different papers cited in the manuscript. With this focus in mind it is unavoidable that the manuscript has a strong statistical character, since the physical mechanism are already known. The concept of Monsoon, although also well known, is more difficult to quantify, as there are different definitions and therefore different indices, for instance based on Indian precipitation or based on spatial averages of the zonal wind over different regions of South Asia. These Monsoon indices are themselves not 100% correlated, indicating that they capture different aspects of the Indian Monsoon. To disentangle what is the connection between Arabian Sea upwelling and Indian Monsoon we have to explore several Monsoon indices available, but this does not mean that we are assuming that upwelling is physically driven by precipitation, for instance. Upwelling is also not physically driven by zonal wind over land. But both indices have been used to describe the intensity of the Monsoon. In our study we explore how strong the statistical connection is between upwelling and these Monsoon indices. However, coastal upwelling will be always immediately driven by the coast-parallel wind, there cannot be no new physics in this regard. The rationale of using an ocean simulation is that, for instance in paleoclimate studies based on ocean sediment cores, the location of the proxy records is distributed over the Arabian Sea. These records are, therefore, only indirect measures of upwelling, as the reviewer correctly points out. The question that we want to address is to what extent these records are representative enough to upwelling and even then, to what extent these records can be also interpreted as indicators of Monsoon. Since there are very little, if any, time series of ocean vertical velocities, the use of a climate simulation driven by the observed atmosphere in the last decades seems the best substitute one can think of. Of course, the conclusions depend on the realism of the ocean model, but this is a well tested model - albeit admittedly less so in the very high resolution version. Since there are very little direct measurements, a direct comparison of simulated upwelling with observations is almost impossible. On the other hand, upwelling dynamics driven by the wind-stress is not such a complex process, so that it can be reasonably assumed that the ocean model will not be very far from reality.

General comments: Dynamical mechanism analysis: We will eventually include the analysis of more variables simulated by the model, but the physical mechanism that links upwelling and wind-stress cannot be better illuminated nor new mechanisms can be identified.

Specific comments: Bakun hypothesis: We agree with the reviewer that Bakun's hypothesis is contested, however, it continues to be so far the framework that explains the response of upwelling to external radiative forcing. We are not testing Bakun's hypothesis. The text is just summarizing the state-of-the-art. We will expand this part to include recent challenges to Bakun's hypothesis

Wind stress: We thank the reviewer for pointing out the erroneous description of the equation in the text. In the analysis itself, the correct equation was used. The updated equation is τ_SW=·C_D·$\sqrt{}$(uˆ2+vˆ2)·(u·cosα+v·cosβ). We are aware that the description of the equation was also misleading. What we were trying to say is exactly the same as the reviewer suggests, namely that alpha and beta are the angles between the wind speed components and the coastal orientation. The text will be rephrased. Concerning the estimation of wind stress from the NECP/NCAR wind speed instead of using directly the wind stress product from NCEP/NCAR is that we were trying to be consistent with the other wind dataset CCMP for which only wind data are available.

Averaging upwelling over the upper 200m: The coastal upwelling extends to 200-300m of the upper water (Brock et al., 1992) so we would like to cover more information by averaging the upwelling velocity over the upper 200m. We also agree with the reviewer and in the revised version we will select the upwelling velocity at around the averaged mixed layer depth.

Section 6 We acknowledge that the analysis presented this section is incomplete and needs improvement. The correlation patterns between the leading EOF of upwelling with temperature and SLP display certain areas with positive and negative values. The a posteriori selection of those areas to construct an index entails circularity and does not reveal new information. The revision of this section will include an analysis of why these correlation patterns arise and what are the physical mechanisms that may be involved in these correlations. So far the analysis was focused on establishing the statistical differences between the patterns that drive Monsoon and those patterns that drive upwelling, but a deeper discussion of why these differences arise needs to be included

Trend and detrending: We mean that the long-term trend was small compared to the mean upwelling velocity. As suggested by the reviewer, we performed a significance test on the trend, obtaining a p-value of 0.1954 for the null hypothesis of no trend. The trend is, therefore, not statistically significant at the 90% or 95% level. However, statistical significance does not mean that the trend itself is small. It means that, in the data set analyzed, it may have arisen by chance although process that generates the time series is itself trendiness. Statistical significance is, therefore, determined by the size of the trend and by the length of the time series, among other factors. When calculating the correlation between the two series, it is advisable to take into account the role of the long-term trend. The correlation between two series exhibiting a long-term trend is influenced by this trend. In some cases, it may result in large values of the trend although the year-to-year variations may be unrelated. This is the rationale of detrending the series before calculating the correlation. Other statistical solutions are possible, but they are more cumbersome, and for this analysis not really needed.

Model validation: The model validation is necessary. As we stated before, the validation of upwelling is hindered by the lack of direct measurements of vertical velocity. Following the suggestions of the reviewer, we will extend the validation by comparing the model SST and the AVHRR satellite SST.

Correlation analyses between Monsoon with averaged upwelling. It is not clear to us why the reviewer is suggesting this pint. Actually, the spatially resolved correlation between Monsoon and upwelling is one of the points that we wanted to highlight, namely that the correlation is not spatially homogeneous and that the interpretation of one single proxy record as indicator of monsoon variability is not straight forward. The correlation with the spatially averaged upwelling would lose this information.

Technical details: Area for wind stress: The wind stress is averaged over the entire ocean area on fig.1d because the upwelling region is rather narrow and the resolution of the wind data is not sufficient for us to calculate the wind stress at a fixed distance.

Two-dimensional correlation: This colour code plot helps to convey the strength of the correlation between one index and a two-dimensional field in a single plot. The correlation of the index to each component of the wind is used to define a two-dimensional vector. The square root of the sum of squares of these two components is just the size of this vector. This number is not used in any further analyses, it is only used in the plot to summarize the correlations with the u and v components of the wind

Ocean color help validate results: Ocean color can also be interpreted as an indirect indicator of upwelling, since we lack the direct upwelling observational data. Ocean colour is related to photosynthetic activity, to primary production and therefore, indirectly to the upwelling of nutrients.

Interactive comment on Ocean Sci. Discuss., 12, 2683, 2015.