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Interactive comment on "Oxygen minimum zone of the open Arabian Sea: variability of oxygen and nitrite from daily to decadal time scales" *by* K. Banse et al.

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We thank the referee for his constructive comments. Our specific response to each comment/suggestion is as follows. Please note that the comment identifier '15472: 12' denotes 'Pg. 15472, Line 12'.

15458: 9 ff. (not "15457: 10"): We write now, '.... appears to be a decade or less (Naqvi, 1987: ∼4 y; Olson et al., 1993: about ten years, for 100-1,000 and 200-1,000 m, respectively). Residence time is not the same as age of water estimated by, e.g. freon (CFC-11 or 12). We treat only the residence time. The difference between the two concepts is acknowledged by Olson et al. (1993: 679) whose residence time is not

based on freon data. Regarding the NO2- turnover time of 49 + 20 y for 100-1,000 m in Lam et al. (2011:Table 1B), since the upper OMZ is of concern herein, the relatively higher NO2- inventory for 100 to about 350 m depth due to the SNM would be divided by a greatly enhanced, measured NO2- production rate (Lam et al., Fig. 4c) yielding a low residence time. We neither use the average CFC ages of 3 y by Howell et al. (1997) for 150-350 m depth (much longer at greater depths) nor 20-26 y for ∼150-500 m near 10oN, 65oE by Fine et al. (2008). With a likely residence time of about a decade, temporal O2 changes should be discernible in historical data sets.'

The reviewer drew our attention to Fine et al. (1998). Dr. Fine wrote us that there is no article by her of that year about the Arabian Sea, but noted her paper of 2008, cited below, to which we refer above.

Fine, R.A. , Smethie, Jr., W.M, Bullister, J.L., Min, D-H., Warner, M.J., Rhein, M., Poisson, A. and Weiss, R.F. (2008) Decadal ventilation and mixing of Indian Ocean waters, Deep-Sea Res. I, 54, PAGES doi: 10.1016/j.dsr.2007.10.002.

15472: 15-20 (actually, L. 18-20). These lines are dropped Next not-numbered paragraph of the review (15479: 1-11) about contradictory results. On lines 7-9, we stated that previous papers, including one of the two cited by the reviewer, were based either on cruises for differing seasons or on different cruises during one year. Hence, they could not distinguish between seasonal and interannual changes. In the next lines we describe the new, multi-decadal climatology for our meridional swath, which includes these papers revealing the seasonal differences described in our paper. The trends observed by us, therefore, may not necessarily be the same as those reported by de Sousa et al. based on three cruises in differing seasons of successive years. Sarma's results are not relevant since he modeled the water exchange from coast to coast along 10oN and, to obtain residence time, he divided the volume to the north between 100 and 1,000 m depthby the modeled annual influx of water.

15478 (not 15488): 10. No, that cannot be concluded since time is not involved in the plot. (Figure 3 shows that below the pycnocline near 200 m depth, mixing plus advection differ substantially from the regime near 300-500 m.)

15484:15. In the preceding lines, we stated ‘that is difficult to distinguish interannual from seasonal changes or those from those caused by smaller scale spatio-temporal variability’. We rephrase: ‘Nevertheless, there is some suggestion of significant inter-annual changes from our data (e.g. compare profiles from cruises SS136 and SK209 coming from almost the same time of the year (Suppl. S.1.2).’

15488:5. We drop the erroneous ‘(total)’. Thank you.

15491: 25. The summary as advised by the referee is as follows .

‘Summary and Conclusions

We looked for changes in the upper OMZ of the central Arabian Sea (150-500 m depth) within 12o-21oN latitudes and 64-68oE longitudes using all available discrete and acceptable historical O2 data that were collected by the Winkler method with visual end-point detection. Similarly we studied the concomitant NO2- records collected between 1959 and 2004, which largely come from the secondary nitrite maximum (SNM). Additional data from latitudes 8o-10oN were used to a limited extent. For O2 and NO2-, as well as salinity we offer climatologies.

Within the OMZ, the medians of O2 for four horizons (200, 300, 400 and 500 m) range between 0.04 and 0.15 mL L-1 (mean, 0.11 mL L-1, $\sim$ 5 μmol kg-1). During the four decades O2 shows significant declines with time between 12o and 20oN, but an increasing trend near 21oN. There is significant seasonality, with higher values occurring during the NE monsoon and spring inter-monsoon as compared to the SW monsoon season. Close to the upper boundary of the OMZ, near 150-200 (250?) m diapycnal re-supply of O2 appears to be important but at 300-500 m most of the presumably annual re-oxygenation is by isopycnal inputs.

An unknown but probably substantial uncertainty in our analysis comes from the error

associated with titrimetric O2 measurements on which almost all of the historical data are based, as evident from the two to three orders-of-magnitude lower concentrations determined by the recently developed STOX sensor in oceanic OMZs. Our data on NO2-, which only appears within OMZs when the dissolved O2 is < 0.05 μmol kg-1 ($\sim$ 0.001 mL L-1), do not show clear seasonal or secular patterns. Thus, based on the measurements made so far it is not possible to say unequivocally whether or not the OMZ of the Arabian Sea has intensified in recent decades. The spatial and temporal variability at drift stations is high and seasonal change of hydrography is marked even at 500 m. Therefore, any assumption of a steady state for the upper OMZ will not be valid, and estimates of elemental budgets or rates of biogeochemical transformations must not be based on a single cruise or data for only one season.

We make two recommendations for future work. First, an observation system to monitor key hydrographic and biogeochemical variables at high temporal and spatial resolutions must be put in place in this ecologically and biogeochemically important oceanic region. For detecting secular change, parts of the system have to be laid out for long-term observations. Also, greater application of the STOX sensor is certain to change our views about oceanic OMZs, including the Arabian Sea. But as NO2- can be analyzed far more easily and with great precision, it should be used as a proxy for identification and mapping of possible functionally anoxic waters.

Secondly, in 79 % of our 707 OMZ samples with > 0.02 μM NO2-, O2 must have been <0.05 μmol kg-1 ($\sim$ 0.001 mL L-1; onset of NO3- reduction), rather than our mean overall O2 of $\sim$ 0.1 mL L-1. These samples largely represent the SNM. Live copepods, however, are being collected by fine nets towed in the SNM. Do animals actually co-occur with elevated NO2-, or have the nets fished in water of the 21% samples without NO2-, which are interspersed in the SNM? To clarify whether there is resident metazoan life at such extraordinarily low O2 levels we suggest sampling of meso-zooplankton with 100-liter bottles from which NO2- can routinely be drawn as substitutes for elaborate STOX measurements.

Interactive comment on Biogeosciences Discuss., 10, 15455, 2013.