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Interactive comment on "Seasonal and interannual variations of the nitrogen cycle in the Arabian Sea" *by* T. Rixen et al.

T. Rixen et al.

tim.rixen@zmt-bremen.de

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General comments I suggest to the authors that as part of revision process that they give a careful read of their ms. There are a number of indications (i.e., odd grammar; logic jumps that rely too much on the reader to intuit the intended meaning) that suggest a quickly developed document that was not subjected to a careful final editing pass prior to submission. I have noted a number of these occurrences, but authors should make concerted effort to fully identify and rectify these. Overall, this is a very interesting line of research and I look forward to seeing it appear in the literature. I believe it will be very well-received by the Indian Ocean research community.

Response The referee #2 provides a variety of very helpful comments in order to present our arguments and results more clearly. We followed all suggestions. Please

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see below:

Page 19542, lines 1-3. Please clarify this statement. It could be interpreted to mean that the paleo record preserves signature of N2.

Response: the sentence: The Arabian Sea is strongly influenced by the Asian monsoon and plays an important role as a climate archive and in the marine nitrogen cycle, because bio-available NO−3 is reduced to dinitrogen gas (N2) in its mid-water oxygen minimum layer (OMZ)

was rephrased: The Arabian Sea plays an important role in the marine nitrogen cycle because of its pronounced mid-water oxygen minimum layer (OMZ) in which bio-available NO3- is reduced to dinitrogen gas (N2). As the nitrogen cycle can respond fast to climate-induced changes in productivity and circulation the Arabian Sea sediments are an important paleoclimatic archive.

Page 19542, lines 8 and 9. This statement is a bit awkward. First, should say "was 63% larger : : :". Also a bit unclear on the date. I consider the meaning to be that based on JGOFS data from 1995, the SNM was 63% larger than a similarly determined estimate based on all pre-JGOFS (or is it largely IIOE-period) observations. Also, please make it clear whether the 63% increase is reflecting the areal extent of the 2-D expression of denitrifying waters (i.e,. Fig. 1) or a volumetric estimate. This statement is drawn directly from the text (page 19554, lines 16-18), so need to modify both similarly.

Response: The sentence: Our results imply that the area characterized by a pronounced secondary nitrite maximum (SNM) was by 63% larger in 1995 than before.

was change into: The data comparison showed that the area characterized by a pronounced secondary nitrite maximum (SNM) was 63% larger in 1995 than a similarly determined estimate based on all pre-JGOFS data prior to 1993.

Page 19543, line 18. Specify that this is oceanic. I.e., "global ocean's water-column ..". OMZ is not defined in the text at this point, just in the abstract.

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Response: The sentences: Approximately 30% of the global water-column denitrification occurs in the OMZ of the central and eastern Arabian Sea (Bange et al., 2000; Bulow et al., 2010; Codispoti 20 et al., 2001; Devol et al., 2006; Naqvi, 1987; Nicholls et al., 2007; Ward et al., 2009).

was changed into: Approximately 30% of the global ocean's water-column denitrification occurs in the oxygen minimum zone (OMZ) of the central and eastern Arabian Sea (Bange et al., 2000; Bulow et al., 2010; Codispoti et al., 2001; Devol et al., 2006; Naqvi, 1987; Nicholls et al., 2007; Ward et al., 2009).

Page 19544, line 3. Should clarify by noting " these additional reactions : : :". Minor point but would reduce reader's need to successfully interpret.

Response: Done: According to Jensen et al, (2011) these additional reactions can be described as follows:

Page 19544, line 24. This description is confusing. How do SE winds become the southwesterly winds of the SW Monsoon that flow over the Arabian Sea? The cited figure (Fig. 1) does not show sea surface wind vectors and does not extend down to the equator.

Response: In summer (SW monsoon) the strong heating forms an atmospheric low over Asia that attracts the SE trade winds blowing as SW winds over the Arabian Sea after crossing the equator (Fig. 1).

was changed into: In summer (SW monsoon) the strong heating forms an atmospheric low over Asia that attracts the SE trade winds of the southern hemisphere. After crossing the equator the SE winds turn to SW winds forming a low-level-cross equatorial jet stream (Findlater, 1977). This so-called Findlater Jet cause upwelling off Somalia and Oman (Brock et al., 1992; Brock et al., 1991) and is indicated by enhanced wind speeds over the Arabian Sea (Fig. 1).

Page 19545, lines 1-4. The SWM can not be said to replace the NEM (or vice versa).

The transition one to the other and back both occur through _ 2-month Intermonsoon. I realize authors are fully aware of this monsoonal cycle, it is just that the description here needs to be more carefully and precisely stated. Simplest fix would be to say SWM represents a reversal of the winds from NEM period, or something to that effect.

Response: The SW winds (SW monsoons) replace the NE winds (NE monsoon) prevailing during winter, reverse the surface ocean circulation including the Somali Current carrying ICW into the western Arabian Sea (Fischer et al.,1996), and . . .

was changed into: During winter the prevailing NE winds (NE monsoon) reverse the surface ocean circulation including the Somali Current.

Page 19545, lines 7-11. Suggest splitting this sentence into two. It is rather complex and a challenge to follow in current form, and information is in a disjointed order. The point is to note that the core OMZ is not directly beneath the most productive waters.

Response: During the remineralization of organic matter, oxygen is consumed in the mid-waters, but the lowest mid-water oxygen concentrations occur in the north-eastern Arabian Sea, contrary to the expectations, spatially separated from the highly productive zones in the western and northern Arabian Sea.

was changed into: Contrary to expectations the OMZ is spatially separated from the highly productive zones in the western and northern Arabian Sea and is most pronounced in the north-eastern Arabian Sea (Morrison et al., 1999). This spatial separation is caused by the oceanographic conditions characterised by a strong propagation of Indian Ocean Central Water (ICW) through the Socotra Strait into the western Arabian Sea (Fischer et al., 1996b; Stramma et al., 1996).

Page 19545, lines 3-20. The characteristics of the ICW needs to be clearly and carefully documented here. A bit more comprehensive background from the cited literature would be useful. It is particularly unclear from what is stated here whether the ICW is oxygen-enriched (line 12) or oxygen-depleted (line 16) when their influence on SNM

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manifests. Narrative suggests that ICW evolves toward oxygen-depleted state as it progresses eastward

Response: has been documented in more comprehensive way: The ICW originates by convective mixing in the southern Indian Ocean (Sverdrup et al., 1942) and mixes with Indonesian Throughflow and Subtropical Subsurface Water (SSW) prior to its entry into the Arabian Sea (Schott and McCreary, 2001). Overall the ICW contributes approximately 25% to the thermocline waters in the upper OMZ (water-depth < 500) of the Arabian Sea (Rixen and Ittekkot, 2005).. In addition to the ICW also Red Sea and Arabian Sea High Salinity Water contributes to the formation of the thermocline water refereed to as the North Indian High Saliniy Intermediate Water (NIHSIWMorrison et al., 1998; Schott and McCreary, 2001; You, 1997).

And more information on this topic were added to the discussion: Mass balance calculations indicate on the other hand side that the degree to which the northwards propagating ICW is oxygen-depleted is crucial for maintaining the OMZ in the Arabian Sea (Pichevin et al., 2007; Rixen and Ittekkot, 2005; Sen Gupta et al., 1975; Warren, 1994). According to the World Ocean Atlas 2009 the oxygen concentration in the Socotra Strait averaged between 10 and 11 N and 51 – 53 E and at water-depth between 200 and 400 m, is with approximately 52 μmol kg-1 undersaturated with respect oxygen (Garcia et al., 2010). In the western Indian Ocean the mid-water oxygen concentration decrease from the equator towards the north, so that the ICW is compared to water masses in Arabian Sea oxygen-enriched and compared to water masses in the equatorial Indian Ocean oxygen-depleted. Since we are interested in the Arabian Sea, the ICW is considered as oxygen-enriched in our discussion.

Page 19545, lines 20-22. This statement on IODW impact to water mass balance is an interesting injection and has relevance vis a vis maintenance of the OMZ. A bit of an expansion could be useful as a way to provide global consequence and linkage of IO to global ocean, and past/early efforts (e.g., (Warren 1994)).

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Response: Upwelling of Indian Ocean Deep Water is of course interesting but these process is probably much too slow to be of relevance for the seasonal and interannual variability of processes at water-depth < 300 m. Furthermore we are not aware of any information on changes in the water mass composition in the deep Arabian Sea which could be linked to e.g. monsoon variability or changes in the global THC for which there is, as far as we know, also no clear evidence. However aspects mentioned by Warrn 1994 have been considered in the discussion

Page 19545, line 24. Would be useful here to re-state the time frame of this cruise.

Response: was done: During the RV Meteor cruise M74/1b from September 18th to October 4th to the Arabian Sea, water samples for the determination of nutrients (NO3-, NO2-, PO43-) were obtained from an "Oceanic" rosette water sampler provided with 18 sample bottles.

Page 19547, line 17. "concentrations increase within : : :" would be better stated as "concentrations increase in conjunction with : : :" or something similar.

Response: was done: Bulow et al. (2010) found a linear correlation between denitrification rates and NO2- concentrations in the SNM suggesting that NO2- concentrations increase in conjunction with rising denitrification rates.

Page 19548, line 13. "support currently" would be better stated as "lend support to".

Response: was done: The NO3–deficit which can be explained by the mean residence time of Olson et al. (1993) and the denitrification rates measured by Bulow et al. (2010), Ward et al. (2009) and Devol et al. (2006), lend support to the original concept of Naqvi (1991) who used the occurrence of the SNM to map the spatial extension of the denitrifying zone.

Page 19549, line 27. Statement seems incomplete. Seems that meaning is "an increase in N* of : : :" is what is intended.

Response: During the JGOFS cruises an oxygen decrease of approximately 0.45

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μmolO2 kg-1 is associated with an increase of the of 2.2 μmolNkg-1 (Fig. 5a).

was changed into: During the JGOFS cruises an oxygen decrease of approximately 0.45 μmol O2 kg-1 was associated with an increase of the NO3–deficit of 2.2 μmol N kg-1 (Fig. 5a). The nitrate deficit is expressed as N* which is the deviation of the nitrate to phosphate ratio form the oceanic average (Gruber and Sarmiento, 1997).

Page 19551, line 15. The last portion of this sentence is confusing, but seems to be through a need for some punctuation (i.e,. insertionof commas -> "and, until the peak of the SWM, also in (the) SNM."). I would also suggest that authors follow up this statement to reinforce/clarify whether what they are reporting is that the SNM oxygen concentration is augmented by ICW or that the westward expansion of SNM signature is inhibited. Basically, the current statement may be attempting to convey several messages that get confused when kept in a consolidated statement.

Response: This implies in line with model studies (Anderson et al., 2007) that a reinforced propagation of oxygen-enriched ICW through the Strait of Socotra into the region off Oman prevents the westwards expansion of SNM by increasing the oxygen concentration in the western Arabian Sea and until the peak of the SW monsoon also in SNM.

was changed into: This implies in line with model studies (Anderson et al., 2007) that despite high organic carbon fluxes a reinforced propagation of oxygen-enriched ICW through the Strait of Socotra into the region off Oman increased the oxygen concentration in the western Arabian Sea and inhibited the westwards expansion of SNM (Fig. 4).

Page 19552, lines 3-4. This sentence needs revising so that its meaning is clear.

Response: To compare the 1995 and the 2007 expeditions only those JGOFS stations will be considered in the following discussion, which were revisited in 2007 (Fig. 3c and d).

was changed into: During the expedition in 2007 ten JOGFS stations were revisited (Fig. 3). The data obtained at these ten stations will be use study the interannual variability of the SNM (Fig. 3 c, d). The comparison of this data show that the spatial expansion of the denitrifying zone during the SW monsoon in 2007 was much larger than during the SW monsoon in 1995 (Fig. 7).

Page 19553, line 1. Please give the time frame used in performing the SST averaging. Documenting precisely how this cooling index was determined will be very interesting for readers interested in using this method to further explore the climate - monsoon intensity connection in their own endeavors.

Response: Done: Therefore satellite-derived records on SST from 1982 to 2007, were averaged for the upwelling influenced western Arabian Sea between 13 and 23 °N and 55 and 65°E. For each year of the resulting time-series the mean inter- and SW monsoon SSTs were calculated by averaging the SSTs between April and May as well as between June and September. Between 1982 and 2007 the SST were on average 1.82°C lower during the SW monsoon than during the spring intermonson. The decade between 1997 and 2007 was in general characterized by SW monsoons all revealing a cooling above this average (Fig. 9).

Page 19554, line 12. End of this sentence seems incomplete. Please fix.

Response: This part of the paper has been changed because a new chapter on the Holocene were additionally included into the ms as recommended.

Page 19554, line 26. The low oxygen waters are from open water OMZ as well as Indian shelf waters I would think. Clarification needed here.

Page 19555, lines 1-9. The concepts here are really intriguing and need to be precisely/ clearly articulated for the reader's benefit.

Response: Conclusion was changed: Based on the JGOFS data from 1995 the area of the SNM, characterized by an NO2- concentration > 2 μmol kg-1 was by 63% larger

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than a similarly determined estimate based on all pre-JGOFS data. However, the database is still too small to distinguish between trends and the pronounced seasonal and interannual variability seen in the spatial expansion of the core of the denitrifying zone. Seasonal variations mainly follow the monsoon-driven seasonal reversal of the current regime. During the NE monsoon the SNM expands westward because of the reversal of the current regime. The prevailing transport towards the west seems to carry additional denitrification signals from the Indian shelf into the open Arabian Sea. During the SW monsoon the SNM retreats eastward due to the inflow of oxygen-enriched ICW. Within the eastwards retreating SNM the upwelling-driven enhanced organic carbon export increases the denitrification rates. On an interannual time scale a stronger SW monsoon enhances denitrification rates but the associated increased inflow of ICW from the equatorial Indian Ocean lowers the accumulation of denitrification tracers by reducing the residence time of water in the SNM. This finding is supported by paleoclimatic studies showing that the enhanced preservation of accumulative denitrification tracers in marine sediments of the Arabian Sea is accompanied by a weakening of the monsoon during the last 8 to 9000 years. Since the monsoon strength controls the inflow of ICW into the Arabian Sea and denitrification rates in the SNM it is suggested that NO3- supply from the equatorial Indian Ocean compensates NO3- losses in the SNM during weaker and stronger monsoons.

I would suggest fleshing out the paleo climate connections. In particular, during weaker monsoon there would also be reduced production and export, and therefore, oxygen demand at depth. How does this feedback into the scenarios considered in these closing remarks?

Response: This was done: Paleo-data were included in order to see if our findings form 1995 and 2007 holds true and can be used to explain variability seen in the past. In order to keep things simple and more straightforward we restricted the discussion to the Holocene. A new chapter and a new figure on the Holocene was included in to the ms:

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Holocene records δ15N of NO3- is as discussed before another denitrification tracer (Fig. 2). Since phytoplankton utilizes NO3- and forms organic matter that is export into the deep sea, the δ15N signatures preserved in sediments are used as indicators of past changes in denitrification rates in the Arabian Sea (Altabet et al., 2002; Altabet et al., 1999; Suthhof et al., 2001). The only almost complete Holocene sedimentary records of δ15N are from the upwelling region off Oman (RC-2723, Altabet et al., 2002) and from the Makran coast (Pakistan) close to the SNM (MD-04 2876, Pichevin et al., 2007, Fig. 1). These two cores show increasing δ15N values during the Holocene, which were assumed to be caused by increasing denitrification rates. Since sedimentary proxies point towards a reduced productivity, the increasing Holocene denitrification were explained by reduced ventilation in conjunction with a reorganization of the ICW and the NIHSIW during the Holocene sea level rise (Pichevin et al., 2007). A decreasing productivity is also in line with paleoclimatic records on moisture conditions derived from Himalayan lakes, indicating a weakening of the monsoon from the mid to the late Holocene (Herzschuh, 2006). The Holocene weakening of the monsoons follows the decreasing solar insolation at 30°N (Berger and Loutre, 1991), which is assumed to be one of the main forces controlling the monsoon strength (Kutzbach, 1981; Ruddiman, 2006). The current sea level was reached at about 6000 BP (Arz et al., 2007; Bard et al., 1990; Fairbanks, 1989; Siddall et al., 2003) and the δ15N continued to rise (Fig. 1). Our results indicate that a weakening of the monsoon associated with enhanced accumulation of denitrification signals is caused by a reduced inflow of ICW, which increases the residences time of water within the SNM. A further consequence of a weaker monsoon should also be a larger gradient of denitrification signals between the upwelling region and the SNM. A direct comparisons of δ15N data obtained form the two regions, in order to estimate such a difference, is difficult because of the isotopic fractionation during the decomposition of organic matter in surface sediments (Gaye-Haake et al., 2005). This isotopic fractionation increases with increasing sedimentation rate and could raise the δ15N values by 2 to 3 ‰.High sedimentation rates off Pakistan indicate that effects of the isotopic fractionation can be ignored whereas they need to be considered off Oman due to lower sedimentation rates (Pichevin et al., 2007). Assuming a diagenitic enrichment of 2 ‰ suggest that the differences between δ15N measured off Oman and off Pakistan increase in conjunction with the weakening of the monsoons. This further supports our hypothesis that increasing δ15N reflects a longer residence time and a lower inflow of ICW. A lower inflow of ICW imply also reduced NO3- inputs to balance NO3- losses caused a by lower denitrifictrion rates and monsoons-driven export fluxes.

Figure 1. (a) Holocene sea level changes obtained from Sidall et al (2003, black squares), Fairbanks (1989, blue squares), and Bard et al (2000, red squares), Arz et al. (2007, red squares). The black line is the mean calculated out of all data points. The blue curve shows the solar irradiation at 30°N obtained from Berger and Loutre (1991). (b) The red curve reveals the effective moisture index representing monsoon strength obtained from Herzschuh (2006). The black line shows the δ15N record from the core RC27-23 (Altabet et al., 2002), which was corrected for the isotopic fractionation and the blue curve reveals the δ15N records from the core MD-04 2876 (Pichevin et al., 2007).

) “An associated reinforced propagation of ICW increases the transport of accumulative denitrification tracers from the SNM into the upwelling region : : :”. Transport of accumulative denitrification tracers here means that stronger ICW will fuel surface productiowith subsequent export and oxygen utilization -> DNF at depth for the SNM waters being drawn into the coastally upwelled waters??

Response:

By including the Holocene the links became more clear: We suggest that: a weaker monsoon decreases the inflow of ICW and therewith the oxygen and nitrate inputs into the Arabian Sea. An associated weaker upwelling lowers carbon export fluxes, reduces oxygen consumption in the OMZ, and prevents therewith the establishment of anoxic conditions. A reduced carbon inputs into the denitrifying zone lowers denitrification rates, and reduced N losses can be balanced by the lower N inputs from the south. In the other hand the lower residence time increases the accumulation of denitrification tracers in the OMZ as indicated by increasing d15N values associated with a weakening of the monsoon intensity.

2) “from Indian Ocean into the Arabian Sea.”. Need to refine this statement, since Arabian Sea is part of the Indian Ocean. More specific geographic descriptors are needed to set the source of these ICW waters.

Response: done

Figure comments Figure 7. Suggest enhancing the labeling on the SWM panels for clarity. For the distribution shown from the 2007 cruise, the label in lower left is “late 2007”, which could be confused to mean latter part of year rather than late SWM as intended. Including SWM and year in all of these distributions (i.e., early SWM (1995) etc.) would make this straightforward to follow.

Response: done

Suggested References Warren, B. A. (1994). "Context of the suboxic layer in the Arabian Sea." Proceedings of the Indian Academy of Sciences-Earth and Planetary Sciences 103(2): 301-314.

Response: done

Interactive comment on Biogeosciences Discuss., 10, 19541, 2013.

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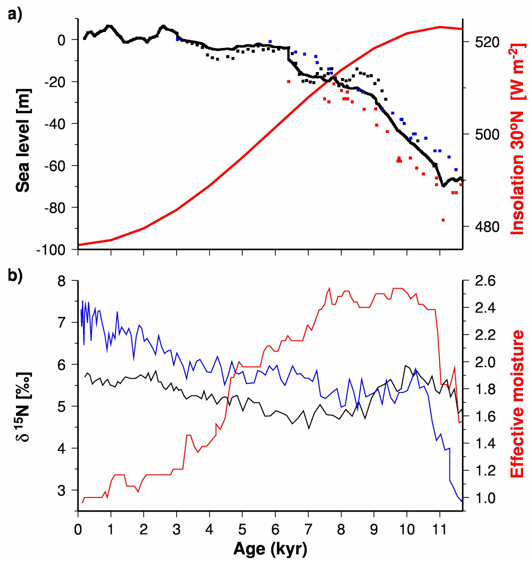

Fig. 1.