

REPLY BY AUTHORS

Reply to the comments on “Monsoon related changes in sea surface productivity and water column denitrification in the Eastern Arabian Sea during the last glacial cycle”

V. K. Banakar, T. Oba, A. R. Chodankar, T. Kuramoto, M. Yamamoto, M. Minagawa

Refer: Marine Geology, V. 219, pp. 99-108, 2005.

1/6b. “Age Model”: Ramesh and Tiwari (hereafter ‘RT’) have comments on ages and associated peaks reported by us (Banakar et al., 2005, hereafter ‘Bea’). We had no ^{14}C ages available for the studied core, hence adopted tropical stack of oxygen isotope stratigraphy of Bassinot et al. (1994) to define climate stage boundaries and chronology as clearly been spelt out in first paragraphs of sections 2 and 3 (see also Bea Figure 2; please note that m should cm in this figure). Second (see RT-6b), we compared our data to published data with a slightly different age model. Therefore, the minimum $\delta^{15}\text{N}$ at e.g. ~60 ka (Bea-Figure 5, GC08 and RC27-16) occurs at ~67 ka for NIO-464. However, corresponding intervals are clearly indicated by arrows in our figure. Thus no discrepancy or even anti-correlation occurs as suggested in RT-6.

2. The basis for assuming Holocene mean-SST as 28 °C has been described in the last paragraph of section 2 (‘Material and methods’). If we would have had AMS- ^{14}C dates and a few more SST data points between 12 and 11 ka, we might have interpreted the lowest SST at ~11.3 ka as combined effect of Younger Dryas and locally enhanced upwelling due to hydrographic perturbations caused during LGM-Holocene climate transition. Except for that one-indeed intriguing-data point, the lowest SSTs (~26 °C) in ‘Bea’ are concentrated around peak-LGM (~18 ka). Sonzogni et al. (1998) also recorded lowest LGM-SSTs between ~17 and 20 ky B.P. (see their Tables 3: ~25.7 °C and 4: ~24.7 °C), not at ~21 ka as

mentioned by RT. Hence there is no discrepancy in our assumed Holocene- or measured LGM-mean SST.

3-5. We did not get in to the issue of organic matter preservation as they form part of ongoing debate. The C/N ratios of Holocene organic matter in our sediment core are around the expected Redfield ratio of ~7 for marine organic matter. Secondly, RT must be aware of their own colleagues' work (Sarkar et al., 1993) that suggested near anoxic conditions through the entire last glacial cycle in the deep Eastern Arabian Sea (>2500 m depth). If such was the environment then organic matter deposited in the deep Eastern Arabian Sea during the last glacial cycle should be faithful.

All three organic proxies in 'Bea' indicate higher LGM-productivity compared to Holocene-productivity. It should be noted that MIS3 was part of the last glacial cycle, hence had lesser warmth than the Holocene as evident in moderate enrichment of $\delta^{18}\text{O}$. Interestingly, the minimum SSTs in 175 ka time-series reported by Rostek et al. (1993) are not at ~21 ka as observed by RT, but are at ~45 ka (see their Figure 2). Therefore, the productivity in MIS3 is expected to be higher than during the Holocene in accordance with our hypothesis. Higher content of C_{org} in MIS3 section than in LGM section is because of lower sedimentation rate during the former period. As the C_{org} flux represents organic matter input over unit area and unit time, it eliminates bias in absolute concentration caused due to variable sedimentation rates, when sedimentation rate is governed by non-organic material input to the seafloor. Further, the organic matter oxidation theoretically should lead to abnormal enrichment of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}_{\text{org}}$ because it may lead to preferential fractionation of lighter-isotopes out of the sedimentary organic system. The $\delta^{15}\text{N}$ (6 to 9 ‰) and $\delta^{13}\text{C}_{\text{org}}$ (–20 to –18 ‰) presented in 'Bea' do not exhibit such abnormalities. Hence, organic proxies utilized in our study have not been greatly affected by preservation problems.

RT proposes diagenesis as an alternative explanation for C/N ratio variation recorded by our study. Although diagenesis cannot be ruled out, we think it is very difficult to isolate relative importance of diagenesis and terrestrial organic matter input through time to the study region. We emphasized the latter possibility, because; a) the studied core location is near to the landmass, and b) the winter winds blow from land towards sea, in addition to preceding observations. All these conditions suggest that the observed variations in C/N ratio time-series are due to changes in marine versus terrestrial organic matter input.

6. RT assumed a linear relationship between denitrification and productivity, which is questionable. In addition, the past water column denitrification is also being debated (see Devol, 2002). The relative importance of thermocline ventilation, productivity, and nitrogen fixation in determining the water column denitrification are yet unclear (see e.g., Altabet et al., 1995; Emmer and Thunell, 2000; Ganeshram et al., 2002; 2000; Reichart et al., 2002). Relating past denitrification directly to past productivity alone requires thermocline oxygenation to be nearly constant over glacial-interglacial time-scale, which is unlikely. We demonstrate here decoupling of denitrification from productivity not only in the Eastern Arabian Sea but also in Northern Arabian Sea (see Figure A). This clearly suggests that the local hydrography (thermocline ventilation) must also have played a vital role.

In summary, the comments of 'RT' on our paper ('Bea') appear to have emerged from misunderstanding of our age-model and the hypothesis describing productivity and denitrification time-series. However, we thank RT for forcing us to put-up decoupling of the above biogeochemical parameters more convincingly.

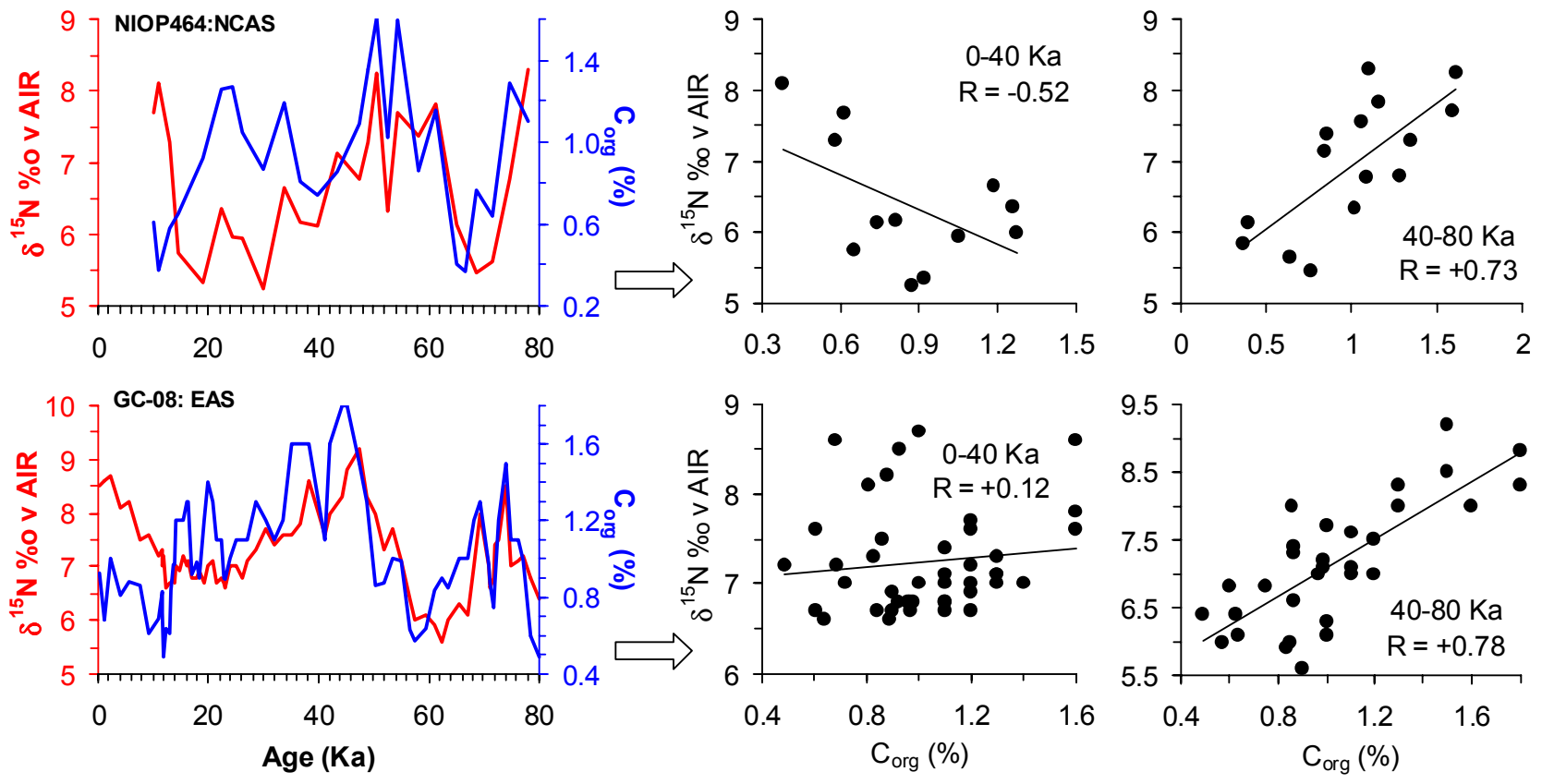
References:

- Altabet, M. A., Francois, R., Murray, D. W. and Prell, W. L., 1995. Climate related variation in denitrification in the Arabian Sea from sediment $^{15}\text{N}/^{14}\text{N}$ ratios. *Nature*, 373: 506-509.
- Banakar, V. K., Oba, T., Chodankar, A. R., Kuramoto, T., Yamamoto, M. and Minagawa, M., 2005. Monsoon related changes in sea surface productivity and water column denitrification in the Eastern Arabian Sea during the last glacial cycle. *Mar. Geol.*, 219: 99-108.
- Bassinot, F. C., Labeyrie, L. D., Vincent, E., Quidelleur, X., Shackleton, N. J. and Lancelot, Y., 1994. The astronomical theory of climate and the age of Brunhes-Matuyama magnetic reversal. *Earth Planet. Sci. Lett.*, 126: 91-108.
- Devol, A. H., 2002. Getting cool with nitrogen. *Nature*, 415: 131-132.
- Emmer, E. and Thunell, R. C., 2000. Nitrogen isotope variation in Santa Barbara Basin: implications for denitrification in the eastern tropical north Pacific during the last 50,000 years. *Paleoceanography*, 15: 377-387.
- Ganeshram, R. S., Pederson, T. F., Calvert, S. E. and Francois, R., 2002. Reducing nitrogen fixation in the glacial oceans inferred from changes in marine nitrogen and phosphate. *Nature*, 415: 156-159.
- Ganeshram, R. S., Pederson, T. F., Calvert, S. E., McNeill, G. W. and Fontugne, M. R. 2000. Glacial-interglacial variability in denitrification in the world oceans: Causes and consequences. *Paleoceanography*, 15: 361-376.
- Reichart, G. J., Nortier, J., Versteegh, G. and Zachariasse, W. J., 2002. Periodical breakdown of the Arabian Sea oxygen minimum zone caused by deep convective mixing. In: P. D. Clift, D. Kroon, C. Gaedicke, J. Craig (eds), *The tectonic and climate evolution of the Arabian Sea region*. Geol. Soc. London, Spl. Pub., 195, pp. 407-409.
- Rostek, F., Ruhland, G., Bassinot, F.C., Muller, P. J., Labeyrie, Lancelot, Y. and Bard, E., 1993. Reconstructing sea surface temperature and salinity using $\delta^{18}\text{O}$ and alkenone records. *Nature*, 364: 319-321.
- Sarkar, A., Bhattacharya, S. K. and Sarin, M. M., 1993. Geochemical evidence for anoxic deep water in the Arabian Sea during the last glaciation. *Geochim. Cosmochim. Acta*, 57: 1009-1016.
- Sonzogni, C., Bard, E. and Rostek, F., 1998. Tropical sea-surface temperatures during the last glacial period: A view based on alkenones in Indian ocean sediment. *Quat. Sci. Rev.*, 17: 1185-1201.

(This is NIO-contribution No.....)

Caption to Figure A

Organic-carbon and $\delta^{15}\text{N}$ variation during the past 80 ka, recorded in the Arabian Sea sediments. GC-08 is from Eastern Arabian Sea (our paper) and NIOP-464 is from North Central Arabian Sea (Water Depth = 1470 m: Reichart et al., 1998). Their respective X-Y scatter plots of $\delta^{15}\text{N}$ versus C_{org} for two time-slices (0-40 and 40-80 ka) are presented on right hand side. Note insignificant or negative correlation between productivity and denitrification during the former time-slice and very strong positive correlation during the latter time-slice.



Banakar et al (Reply: MARGO3201R1): Figure A