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Climate of the Past Discussions

Interactive comment on "Cyclone trends constrain monsoon variability during Late Oligocene sea level highstands (Kachchh Basin, NW India)" *by* M. Reuter et al.

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We appreciate the constructive review of referee 2. His major concern is that we rely on the effect of vertical wind shear in controlling cyclone activity over the Arabian Sea. Evan et al. (2011, 2012) proposed that Arabian Sea tropical cyclones have become stronger over the last 30 years owing to a reduction in vertical wind shear brought about by radiative forcing from aerosols. Wang et al. (2012) argue in a brief communication that was arising from this paper that the decline in vertical wind shear more likely results from a systematic shift in the onset of the summer monsoon, which may be caused by enhanced land-sea thermal contrast between the Asian landmass and the equatorial

Indian Ocean either due to anthropogenic warming or as part of a natural cycle. The stratigraphic resolution of the studied tempestite sequence from the Kachchh Basin is not high enough to contribute to this discussion since it does not allow resolving climate seasonality during the Oligocene. Anyway, an anthropogenic influence can be clearly excluded for the Late Oligocene and both authors agree that the effect of vertical wind shear is the major agent for cyclone activity over the Arabian Sea. Moreover, Wang et al. (2012) propose that there are natural causes related to global warming (increased land-sea thermal contrast between the Asian landmass and equatorial Indian Ocean, variability of the Interdecadal Pacific Oszillation), which can influence the vertical wind shear over the Arabian Sea. This is consistent with our findings. Aside from the vertical wind shear other factors exist such as sea surface temperature and humidity, which are also important for quantifying tropical cyclone activity. The comparison of our results with the oxygen isotope curve of Zachos et al. (2008) implies that the strength of the Late Oligocene monsoon over northern India was not mainly controlled by the sea surface temperature since the storm activity at 24 Ma was lower than at 26 Ma despite of a globally warmer climate (Fig. 5). Monsoon-related upwelling of cold deep-water in the northwestern Arabian Sea had also no effects on Late Oligocene cyclogenesis since it was not established before 5.5–5.0 Ma BP (Kroon et al., 1991). Although the physical mechanisms that determine tropical cyclone intensity are not well understood, it is hypothesized that the environmental relative humidity is one controlling factor and the entrainment of dry desert air from the surrounding environment into a storm would overwhelm the effect of warm sea surface water and low vertical wind shear (Hill and Lackman, 2009; Evan and Camargo, 2011). Accordingly, modeling experiments suggest that the presence of dry air from the Sahara region may result in lower averaged humidity and weaker tropical monsoons in the Atlantic compared to the Pacific, but additional investigation would be needed to test this speculation (Hill and Lackmann, 2009). For the studied time interval no data exist about air humidity over the Arabian Sea. Potential sources for dry air are the Arabian and Sahara deserts. Similar to the present-day situation generalizing palaeoclimatic maps indicate a relative arid

Oligocene climate in North Africa and the Middle East region (Scotese, 2002). Additionally, John et al. (2003) consider that episodes of Antarctic cooling (Mi events) probably resulted in a stronger thermal gradient between the southern and northern hemisphere, which would have induced a northward shift of the ITCZ during the Middle Miocene. Hence, the tropical rainbelt would have moved further south over northern Africa during non-Mi event times like the Late Oligocene warming. Otherwise, large parts of the Arabian Peninsula and Middle East region, which are covered by deserts at present-day, were part of the shallow marine Tethyan Seaway during this time providing a source for humid oceanic air (Rögl 1998; Popov et al. 2004). This applies also for large parts of central Asia, which were covered by the Paratethys Sea. Desertification of this region was associated with the shrinkage of this shallow epicontinantal sea in the Miocene (Ramstein et al., 1997). Despite of all uncertainties regarding the Late Oligocene climate, it is important to note that we refer to a single outcrop, which records 3rd-order sea level highstands only. Therefore, regional effects and climatic variability during a glaciation cycle are assumed as to be insignificant for our interpretation of large scale cyclone trends off NW India during the Late Oligocene. Although the resolution of our data cannot fulfill all required requests of the referee we intend to integrate his suggestions in respect of cyclone and monsoon dynamics in the revised version of the manuscript.

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