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Contrasting sea surface temperature of summer and winter monsoon variability in the northern Arabian Sea over the last 25 ka

Anna Böll [a,*], Hartmut Schulz [b], Philipp Munz [b], Tim Rixen [a,c], Birgit Gaye [a], Kay-Christian Emeis [a,d]

[a] Institute of Geology, University of Hamburg, Bundesstr. 55, 20146 Hamburg, Germany
[b] Department of Geosciences, University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany
[c] Leibniz Center for Tropical Marine Ecology, Fahrenheitstr. 6, 28359 Bremen, Germany
[d] Institute of Coastal Research, Helmholtz Center Geesthacht, Max-Planck-Str. 1, 21502 Geesthacht, Germany

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ABSTRACT

The seasonal monsoon cycle with winds from the southwest (SW) in summer and from the northeast (NE) in winter strongly impacts on modern regional sea surface temperature (SST) patterns in the Arabian Sea (northern Indian Ocean). To reconstruct the temporal and spatial variation in the dynamically coupled winter and summer monsoon strength over the last 25 ka, we analyzed alkenone-derived SST variations in one sediment core from the northwestern Arabian Sea, that is influenced by the summer monsoon (SST affected by upwelling processes), and in one core from the northeastern Arabian Sea, where SST is mainly governed by the winter monsoon (no upwelling). Comparison of the SST records reveals an antagonistic relationship of summer and winter monsoon strength throughout the late deglaciation and the Holocene. Upwelling along the Arabian Peninsula associated with peak SW monsoonal wind strength was strongest during the early Holocene climate optimum between 11 and 8 ka, and coincided with the northernmost position of the Intertropical Convergence Zone (ITCZ) marked by maximum precipitation over northern Oman. The SW monsoon weakened over the middle to late Holocene, while the NE monsoon gained strength. This different evolution was caused by the southward displacement of the ITCZ throughout the Holocene. Superimposed over the long-term trend are variations in northeast monsoon wind strength at time scales of centuries that were synchronous with late Holocene climate variations recorded on the Asian continent and in the high-latitude Northern Hemisphere. Their likely driving forces are insolation changes associated with sunspot cycles. Enhanced by feedback mechanisms (e.g. land-sea thermal contrast) they enforced centennial scale fluctuations in wind strength and temperature in the northern Arabian Sea monsoon system.

1. Introduction

The oceanic environment and surface ocean properties of the Arabian Sea are directly coupled to the seasonal monsoon cycle. Alternating wind directions with low-level winds from the southwest (SW) in summer and from the northeast (NE) in winter cause regional differences in Arabian Sea sea surface temperature (SST) patterns. South-westerly winds are generated by the atmospheric pressure difference between the cold southern Indian Ocean and the heat low over central Asia in spring and summer. They drive upwelling of cold, nutrient-rich waters along the coasts of Somalia, Oman and southwest India and wind-stress curl-driven upwelling offshore (Hastenrath and Lamb, 1979; Rixen et al., 2000). These upwelling regions exhibit sea surface cooling during Northern Hemisphere (NH) summer (Levitus and Boyer, 1994) and high rates of primary production by upwelled nutrients (Haake et al., 1993; Rixen et al., 1996). In the northeastern Arabian Sea off Pakistan, on the other hand, no upwelling occurs and SST remains warm during NH summer. The seasonal SST pattern in the northern Arabian Sea is furthermore governed by the NE monsoon in NH winter. During this part of the year moderately strong, cold and dry northeasterly winds (caused by the reversal of atmospheric pressure gradients between central Asia and the southern Indian Ocean in fall (Clemens et al., 1991)) prevail in this region. The resultant increase in evaporation rates together with a reduction in solar insolation lowers SST and increases the density of surface waters (Madhupratap et al., 1996; Prasanna Kumar and Prasad, 1996). Thus, while SSTs on the Pakistan Margin show a clear seasonal signal with high SST in summer (~28.5 °C) and low SST (~23.5 °C) in winter (Fig. 1C; Levitus and Boyer, 1994), this seasonal pattern is less pronounced on the Oman Margin due to upwelling induced cooling during the summer season (Fig. 1B).

The seasonally variable SST pattern of the Arabian Sea thus reflects monsoon dynamics and relative monsoon strength so that SST changes determined in sediment records track past variations in monsoon

* Corresponding author.
E-mail address: anna.boell@zmaw.de (A. Böll).

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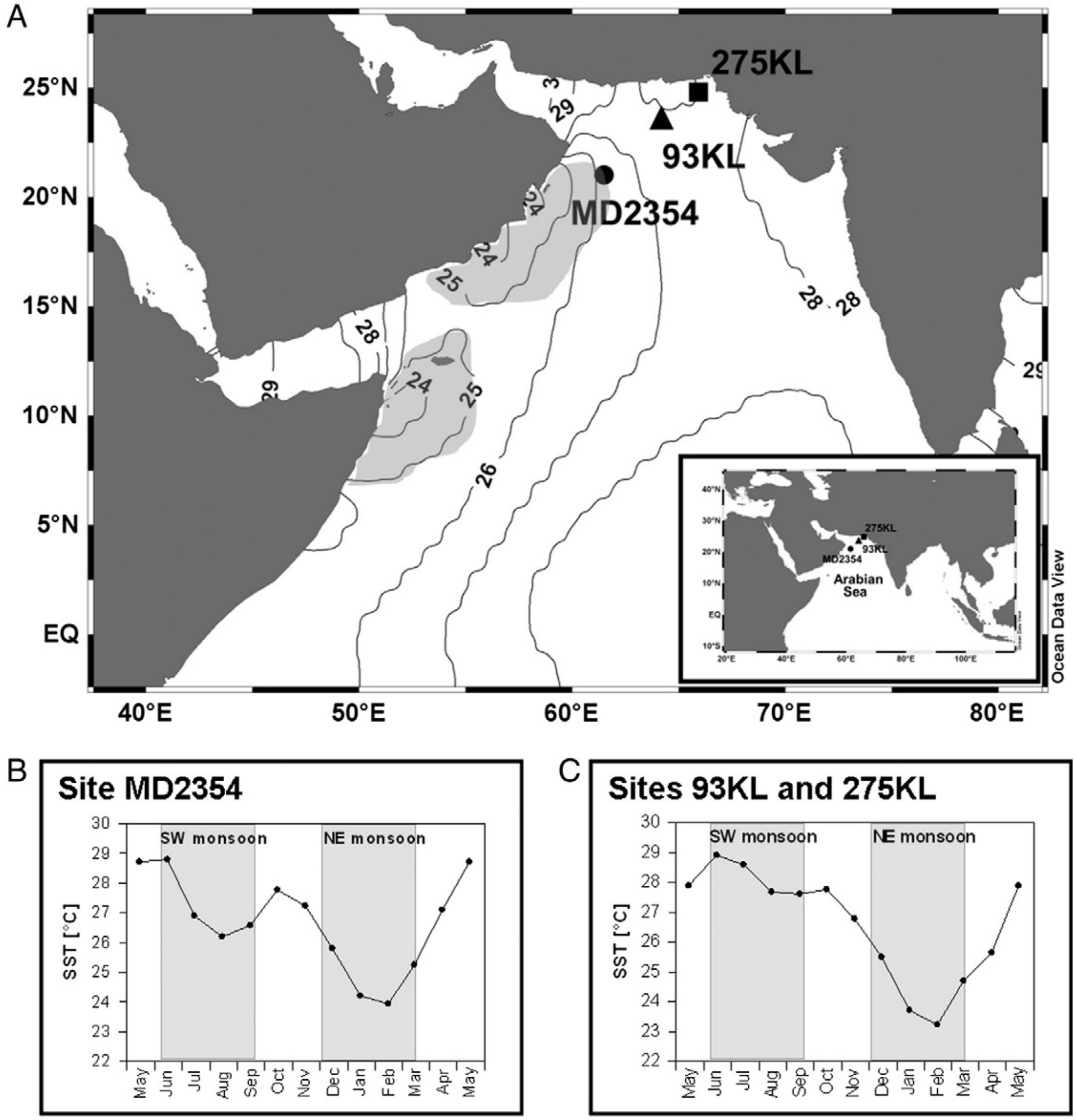

Fig. 1. A) Study area with core location MD00-2354 from the northwestern (NW) Arabian Sea and 93KL and 275KL from the northeastern (NE) Arabian Sea. Illustrated is the sea surface temperature pattern during the summer monsoon season (Jul–Sep). Shaded areas indicate regions of upwelling. This map was produced by using Ocean Data View (Schlitzer, 2013). B) Annual SST variability for site MD2354 and C) sites 93KL and 275KL extracted from the Wold Ocean Atlas (Levitus and Boyer, 1994).

strength over glacial/interglacial cycles (Emeis et al., 1995; Rostek et al., 1997; Schulte and Müller, 2001) and during the Holocene (e.g., Naidu and Malmgren, 2005; Dahl and Oppo, 2006; Huguet et al., 2006; Saher et al., 2007a; Anand et al., 2008; Saraswat et al., 2013). From these reconstructions, a general pattern emerged of increased NE monsoon strength during cold glacial stages and stadials, and vigorous SW monsoon strength during warm interglacials and interstadial periods (e.g., Rostek et al., 1997; Reichart et al., 1998; Schulz et al., 1998; Schulte and Müller, 2001; Wang et al., 2001). This change in wind patterns had consequences beyond SST: Interglacials and interstadials also marked productivity maxima and an expanded oxygen minimum zone (OMZ) with intense denitrification in the Arabian Sea subthermocline, as reflected in maxima of organic carbon burial and $\delta^{15}N$ in sediments (Suthhof et al., 2001; Altabet et al., 2002). Monsoon activity in the Arabian Sea region varied on Milankovitch and millennial time scales not only during the Pleistocene, but also (with smaller amplitude) during the Holocene (e.g., Sirocko et al., 1993; Overpeck et al., 1996; Lückge et al., 2001; Anderson et al., 2002, 2010; Gupta et al., 2003, 2011; Fleitmann et al., 2004). Strongest SW monsoon activity was recorded in the early Holocene insolation maximum when air temperatures (Marcott et al., 2013) and summer precipitation in Asia were high (Fleitmann et al., 2003; Herzschuh, 2006). Most of these studies aimed to reconstruct summer monsoon strength, that determines the state of the upwelling system in the western Arabian Sea (Naidu and Malmgren, 1996; Anderson et al., 2002, 2010; Gupta et al., 2003). Much less attention has been given to the response of the NE monsoon to changing mid-latitude glacial/interglacial boundary conditions, and the dynamic evolution of the coupled winter and summer monsoon throughout the Holocene (Reichart et al., 2002; Yancheva et al., 2007; Liu et al., 2009).

Since SST provide a signal for both monsoon seasons (i.e., determined by the intensity of summer upwelling versus deep winter mixing), several authors reconstructed time series of seasonal SST variations to distinguish between summer and winter monsoon strengths (Naidu and Malmgren, 2005; Saher et al., 2007b; Anand et al., 2008). An alternative approach was used by Dahl and Oppo (2006), who investigated the spatial SST history of the Arabian Sea basin for different time slices. These authors showed that comparing SST variations in areas today affected by upwelling with areas not affected by upwelling is a viable approach to distinguish sea surface cooling caused by SW monsoonal upwelling from cooling caused by the northeasterly winds of the winter monsoon.