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Monsoon variability and upper ocean stratification during the last ~66 ka over the Andaman Sea: Inferences from the $\delta^{18}O$ records of planktonic foraminifera

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ABSTRACT

Using new oxygen isotope ($\delta^{18}O$) data of three planktonic foraminiferal (*Globigerinoides ruber, Globigerinoides sacculifer* and *Globorotalia menardii*) species from a sediment core SK-234-60, collected from the Andaman Sea, we infer that summer monsoon was weaker during Marine Isotopic Stage-3 (MIS-3) than the early Holocene but was stronger than that during MIS-2. Further, an abrupt decrease in a monsoon during the mid-Holocene between ~7 and 4.5 ka is observed. The difference in $\delta^{18}O$ between species with different habitats depth also enables the reconstruction of past ocean stratification over the Andaman Sea. Distinct weak and strong freshwater-induced upper ocean stratifications are observed during the last ~66 ka. A weaker upper ocean stratification during the Last Glacial Maximum (LGM) and a stronger stratification during the early Holocene is observed. This is due to the prevailing positive and negative Evaporation minus Precipitation (E-P) conditions, respectively. Weaker stratifications during ~32 ka and early to mid-MIS-3 are observed, whereas the stratification was strong during ~42-39 ka. Stronger monsoon associated with higher upper ocean stratification was seen during ~62 ka. Likewise, weaker monsoon during the Heinrich events was associated with weaker stratification.

1. Introduction

The Indian Summer Monsoon (ISM) is primarily driven by the north-south movement of the Inter-Tropical Convergence Zone (ITCZ) across the equator (Meehl, 1994; Webster et al., 1998; Wang and Ding, 2008). It causes large-scale precipitation and controls local hydrological cycles that in turn directly affects water resources, agriculture and socio-economic well-being of the south Asian countries. The ISM is a primary source of freshwater to all major river systems of India, Bangladesh, Pakistan and Myanmar. As all these rivers finally debouch into Indian Ocean, it becomes an important region for studying the variations in the freshwater discharges (river runoff/direct precipitation) from the Indian subcontinent, which is largely modulated by the ISM (Milliman and Meade, 1983; Mohanty et al., 2008; Rashid et al., 2007). The Bay of Bengal (BoB) and the Andaman Sea (Colin et al., 1998, 1999) in the northeastern Indian Ocean get a major supply of their fresh water during summer from the rivers like Ganga, Meghna, Brahmaputra, Irrawaddy and Salween because of which the northern BoB is always fresher than the southern BoB (Subramanian, 1993, 1996) with a salinity gradient of ~0.2 (psu)/degree latitude (Sijinkumar et al., 2016). However, the seasonal reversal of surface winds, which drives the surface currents in the northern Indian Ocean transport high saline water from the Arabian Sea (AS) to the BoB during summer and low salinity water from the BoB to the AS in winter (Wyrtki, 1973; Akhil et al., 2014).

Planktonic foraminifera is one of the best proxies for paleoceanographic studies, as they are known to record the changes in the seawater conditions in their shells ($CaCO_3$) during their formation. The interpretation of planktonic foraminiferal oxygen isotope ($\delta^{18}O$) variation is mostly based on a combination of changing sea surface temperature (SST), monsoon runoff and the global ice-volume effect (Broecker, 1986). The previous studies from the Indian Ocean based on the observed $\delta^{18}O$ enrichment in planktonic foraminiferal tests from the BoB showed that the southwest monsoon was weaker during the Last Glacial Maximum (LGM; Duplessy, 1982) which led to the reduced influx of fresh water into the BoB. Similarly, Sarkar et al. (1990) showed that the winter monsoon was stronger than the present during the LGM. Based on upwelling indices such as the abundance of

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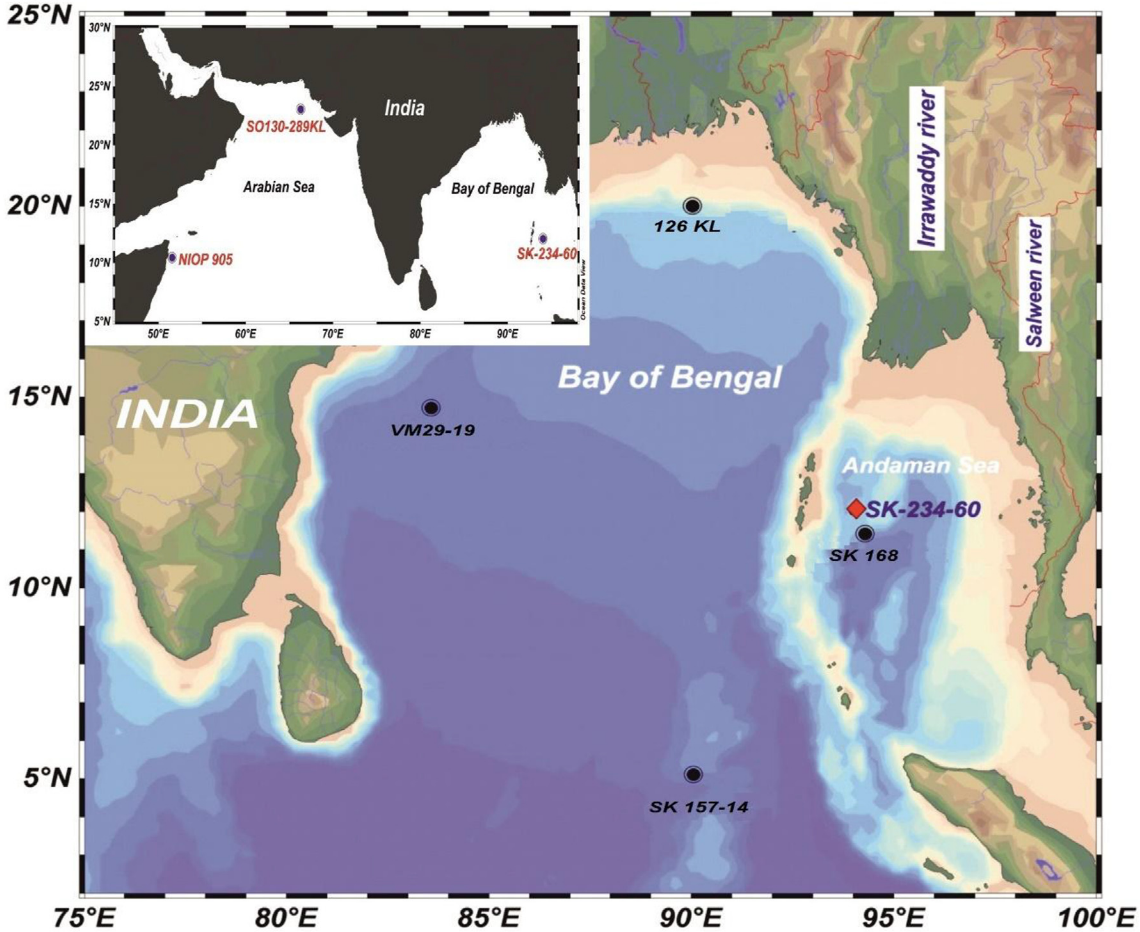

Fig. 1. Location of the sediment core SK-234-60 (filled diamond; red) used in this study, also shown are cores from the Bay of Bengal (126 KL: Kudrass et al., 2001; VM 29–19: Rashid et al., 2011; SK 157–14: Ahmad et al., 2012) and the Andaman Sea (SK 168: Sijinkumar et al., 2011) studied earlier. GRIP ice core (Grootes and Stuiver, 1997) NIOP-905 (Western Arabian Sea, Jung et al., 2009) and SO130-289 KL (northeastern Arabian Sea, Deplazes et al., 2013), are also used in this study (shown in inset). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

planktonic foraminiferal species (*e.g.*, *Globigerina bulloides*) and variability in eolian inputs, the strength and timing of the past monsoon winds were inferred from sediment records of the western AS (Gupta et al., 2003; Singh et al., 2016). A study by Kumar and Ramesh (2016) from the AS have shown that freshwater influx from the peninsular rivers to the BoB and later transported to the AS by the boundary currents (WICC, West India Coastal Current and EICC, East India Coastal Current) have great control on its surface water oxygen isotopic composition. Some paleo-monsoon studies based on sediment cores from the Andaman Sea (Naqvi et al., 1994; Colin et al., 1998, 1999; Ahmad et al., 2000, 2005; Rashid et al., 2007; Raza et al., 2014; Ali et al., 2015; Raza et al., 2017) have reported glacial-interglacial variations in the surface water characteristics of Andaman Sea (Ahmad et al., 2000, 2008). Fossil records from the Andaman Sea showed variations in the productivity and maximum abundance and good preservation of pteropods during stadial periods (Sijinkumar et al., 2010, 2015). Based on the paired Mg/Ca and $\delta^{18}O$ data on the planktonic foraminifer shells, Rashid et al. (2007) showed rapid changes in climate during the last deglaciation and Holocene including substantial changes in the Indian Ocean monsoon system. Based on a compilation of $\delta^{18}O$ and salinity variations in the BoB and the Andaman Sea, Sijinkumar et al. (2016) showed that the Andaman Sea was relatively fresher in comparison to BoB surface waters during LGM probably due to the semi-enclosed nature of the Andaman Basin or the fact that the Irrawaddy River alone accounts for ~428 km^3 of freshwater flux annually to the Andaman Sea (Milliman and Meade, 1983).

While there are a good number of studies aimed at reconstructing the paleo-monsoon from the foraminiferal $\delta^{18}O$ records from the Andaman Sea, very few studies tried to examine the relative differences of $\delta^{18}O$ between the species dwelling within the Mixed Layer Depth (MLD; *G. ruber* and *G. sacculifer*) and the Thermocline Depth (TD; *G. menardii*), which can give clues to the past changes in the upper ocean stratification (*e.g.*, Singh et al., 2016). Therefore, here we report new data of $\delta^{18}O$ of *G. sacculifer* (MLD species) and *G. menardii* (TD species) from a core SK-234-60 from the Andaman Sea, studied earlier by Awasthi et al. (2014). Inferences on the paleo-monsoon variation were made based only on the *G. ruber* $\delta^{18}O$ variation. With the additional data on two more planktonic species from different habitats depth, we are in a position to examine the freshwater-induced stratification in the Andaman Sea, and how it was related to paleo-monsoon intensity. We then compare the new and the previously published $\delta^{18}O$ records of planktonic foraminifera from different well-dated sediment cores of different regions of the northern Indian Ocean, where the spatial variation of observed $\delta^{18}O$ variability in planktonic foraminifera is studied.

2. Materials and methods

A ~4 m long marine sediment core (SK-234-60) was collected from the Andaman Sea (12.05°N, 94.05°E) from a water depth of 2000 m during the SK-234 expedition (Fig. 1). The chronology was reported earlier by Awasthi et al. (2014). Briefly, dating was based on the Accelerator Mass Spectrometer (AMS) radiocarbon analyses of mixed planktonic foraminifera from 10 different depths in the top 2 m, done at the AMS laboratory of the University of Arizona, USA. The dates