

Mid-Pleistocene Transition altered upper water column structure in the Bay of Bengal

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Abstract

The unique water column structure and seasonal change in the hydrodynamics make the Bay of Bengal an interesting area to understand the effect of monsoon on the water column stratification. We have reconstructed a 1.45 Myr record of planktic foraminifera assemblages and a 1.16 Myr (MIS 47- MIS 8) record of the difference in the stable oxygen isotopic ratio ($\Delta\delta^{18}\text{O}$) between the mixed layer dwelling *Globigerinoides ruber* and thermocline dweller *Neogloboquadrina dutertrei* from the IODP Site U1446 to understand the change in water column stratification and its relationship with the monsoon. From the glacial-interglacial shift in $\Delta\delta^{18}\text{O}$ and mixed layer and thermocline assemblages, we infer a stronger stratification during the warm interstadials and comparatively weaker stratification during the cold stadials. The strengthened summer monsoon induced high direct rainfall, and riverine influx inhibited mixing in the upper layer and created a shallow thermocline during the interstadials. We report a large variability in $\Delta\delta^{18}\text{O}$ prior to the mid-Pleistocene transition (MPT). Interestingly, the glacial-interglacial shift in $\Delta\delta^{18}\text{O}$ significantly decreased post MPT. A stronger upwelling and deeper mixed layer during the stadial periods reduced the glacial-interglacial shift in $\Delta\delta^{18}\text{O}$ post mid-Pleistocene transition. The strengthened summer monsoon during the post MPT period increased the stratification in the Bay of Bengal.

Keyword : Indian ocean, Indian monsoon, Planktic foraminifera, Oxygen isotope, Quaternary

1. Introduction

The water column structure strongly modulates the ocean's primary productivity, air-sea exchange and heat flux (Shanthi et al., 2016). The solar insolation, wind intensity and direction, precipitation and freshwater influx control the upper water column structure in the tropical oceans (Murtugudde et al., 2002; Sobarzo et al., 2007; Kantha et al., 2019). Therefore, the water column stratification records from the tropical oceans can provide information about the monsoon wind strength, dynamics of the ocean-atmosphere exchange, carbon burial capability and oceanic heat transport. The unique water column structure due to seasonal changes in the hydrodynamics make the Bay of Bengal, a part of the tropical Indian Ocean, an interesting area to understand the effect of monsoon on the upper ocean stratification. The seasonally reversing monsoon winds, direct overhead precipitation, riverine influx, eddies and the seawater exchange with the Arabian Sea, mainly control the upper water column structure in the Bay of Bengal (Narvekar and Prasanna Kumar, 2006; 2014; Thakur et al., 2019; Amol et al., 2020).

The stable isotopic composition of the planktic foraminifera has been widely used as a proxy to reconstruct the upper ocean vertical structure (Whitman and Berger, 1993; Ravelo and Shackleton, 1995; Mulitza et al., 1998; Rühlemann et al., 2001; Spero et al., 2003; Steph et al., 2006; Cléroux et al., 2007). The stable oxygen isotopic ratio ($\delta^{18}\text{O}$) of foraminifera primarily records the temperature and isotopic composition of the ambient water mass (Urey, 1947; McCrea, 1950; Epstein et al., 1953; Emiliani, 1955; Shackleton, 1974). Additionally, the seawater carbonate ion concentration, diagenetic changes and species-specific vital effects also affect the isotopic composition of the foraminiferal shells (Berger et al., 1978; Shackleton and Vincent, 1978; Spero et al., 1997; Bemis et al., 1998; Bijma et al., 1999; Schiebel et al., 2018). Different species of planktic foraminifera living at distinct depths in the water column record different $\delta^{18}\text{O}$ signatures in their calcite shell (Shackleton and Vincent, 1978; Fairbanks and Wiebe, 1980; Fairbanks et al., 1982; Ravelo and Fairbanks, 1992; Niebler et al., 1999; Mortyn and Charles, 2003; Lončarić et al., 2006; Lakhani et al., 2022). The difference between the $\delta^{18}\text{O}$ of planktic foraminifera living at different depths can be used as a proxy for vertical temperature and salinity gradient in the water column (Williams and Healy-Williams, 1980; Ravelo and Fairbanks, 1992; Mulitza et al., 1997; Patrick and Thunell, 1997; Ravelo and Andreasen, 1999; Niebler et al., 1999; Faul et al., 2000; Farmer et al., 2007). Therefore, the difference in the oxygen isotopic ratio between thermocline and surface-dwelling planktic foraminifera has been commonly used to reconstruct the upper ocean stratification through time (Ravelo and Shackleton, 1995; Tian et al., 2005; Steinke et al., 2010).

The oxygen isotopic ratio of the planktic foraminifera in the Bay of Bengal is mainly influenced by the seawater salinity (Saraswat et al., 2023a). The sea surface salinity depends on the monsoon-induced precipitation-evaporation budget (Cullen, 1981; Duplessy, 1982; Rashid et al., 2007; Govil and Naidu, 2011). The water column stratification changes in the past, have been reconstructed from several parts of the northern Indian Ocean (Bolton et al., 2013; Gebregiorgis et al., 2016; Kumar et al., 2018; Ota et al., 2019; Naik and Naidu, 2019; Gautam et al., 2021; Sijinkumar et al., 2021; Nilsson-Kerr et al., 2022). However, only three of these studies (Ota et al., 2019; Naik and Naidu, 2019; Nilsson-Kerr et al., 2022) are from the riverine influx dominated western Bay of Bengal and cover only the last 140 kyr. To better understand the effect of the Indian monsoon on the Bay of Bengal stratification on an orbital scale, we need longer records covering multiple glacial-interglacial cycles.

The mid-Pleistocene Transition (MPT) is one of the most significant events in the Quaternary considering its large-scale effect on the global climate (Maslin et al., 1998). The implications of the MPT have been reported in global sea level (Rohling et al., 2014), ice volume (Lisiecki and Raymo, 2005) and sea surface temperature (Herbert et al., 2010). The shift from 41 kyr periodicity to 100 kyr is a significant phenomenon associated with the MPT (Clark et al., 2006). The Indian monsoon system also went through a significant change during this period (Clemens et al., 2021; Bhadra and Saraswat, 2022). However, it will be interesting to see if this change in the Indian monsoon strength affected the upper water column structure in the Bay of Bengal or not.

In this paper, the effect of varying monsoon intensity on the thermocline and water column stratification in the Bay of Bengal, during the last 1.45 Ma is assessed by using the faunal abundance and the difference in the stable oxygen isotopic ratio ($\Delta\delta^{18}\text{O}$) between mixed layer dwelling *Globigerinoides ruber* (from Clemens et al., 2021) and thermocline dweller *Neogloboquadrina dutertrei*. We also have tried to understand the effect of the MPT on the monsoon-associated changes in the water column structure of the Bay of Bengal.

2. Regional Setting

The Bay of Bengal is a semi-enclosed basin surrounded by land masses from three sides. It experiences a seasonal reversal of monsoon winds associated with southwest and northeast monsoons during the summer and winter seasons (Thadathil et al., 2007). The southwest monsoon brings a huge amount of freshwater influx to the Bay of Bengal. Apart from the net positive precipitation over evaporation (Prasad, 1997), Bay of Bengal receives a huge amount of riverine influx ($\sim 1.85 \times 10^{12} \text{ m}^3/\text{yr}$) as well (Subramanian, 1993). The surplus of freshwater warms the Bay of Bengal surface layer and is also less saline, inhibiting vertical mixing and creating strong stratification. The monsoon-induced upwelling

in the western Bay of Bengal is restricted to a narrow band (Shetye et al., 1993). The restricted upwelling does not reach the surface and thus fails to break the stratification in large parts of the bay (Shenoi et al., 2002). The salinity has more control over the stratification by creating a barrier layer that does not allow mixing (Lucas et al., 2016). Therefore, the mixed layer remains shallow (Narvekar and Prasanna Kumar, 2006).

Site U1446 was drilled during the International Ocean Discovery Program (IODP) expedition 353. It is located at a water depth of 1441 m in the western Bay of Bengal, 75 km from the coast of Odisha, India (19°5.02' N; 85°44.08' E) (Figure 1). The drilled sediments are dominated by clay with nannofossils, biosilica and foraminifera. Except for the occasional presence of transported materials, the site is free from turbidite deposits (Clemens et al., 2016).

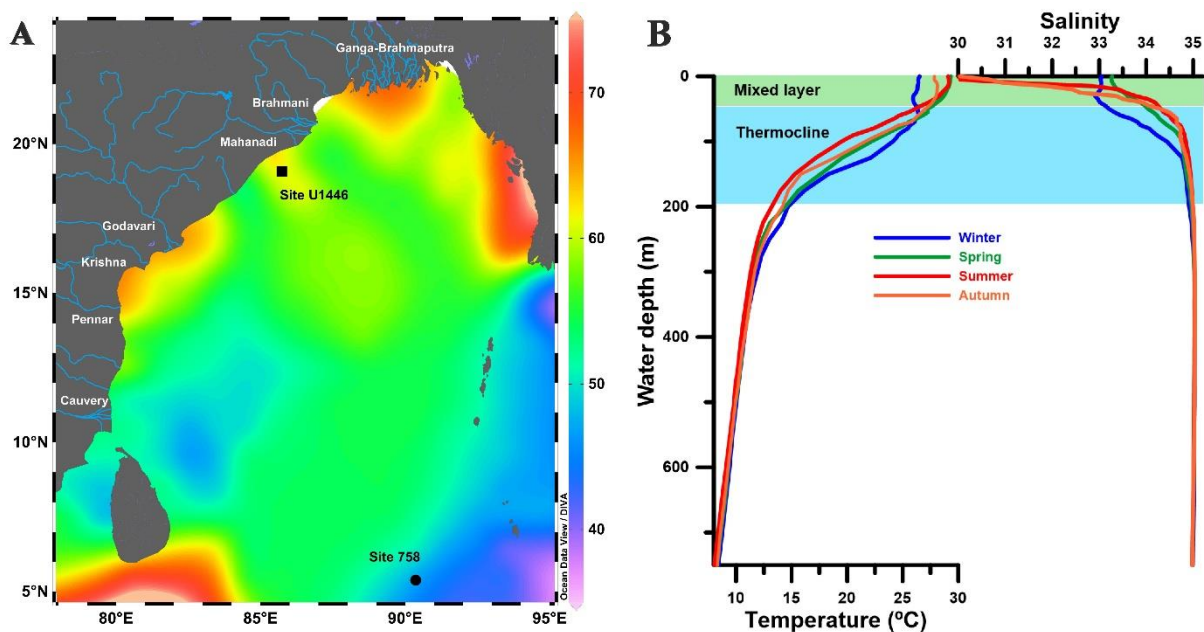


Figure 1: (A) The location of IODP Site U1446 and Site 758. The background contour is the annual average mixed layer depth in meters (Goyet et al., 2000). (B) The seasonal upper water column temperature and salinity variation at Site U1446. The data were obtained from the World Ocean Atlas-2018 (Locarnini et al., 2018; Zweng et al., 2019) using the Live Access Server of CSIR-National Institute of Oceanography, India. . The different colours represent different seasons. The mixed layer and thermocline depths have been shaded with different colours. The location map was prepared by Ocean Data View software (Schlitzer, 2022).

The thermocline and mixed layer depth was demarcated from the temperature data. The upper and lower limit of the thermocline was marked at the water depths indicating an abrupt temperature change (Figure 1). The annual average depth for the mixed layer and thermocline at Site U1446 ranges between 0-40 m and 40-180 m, respectively. The subsurface chlorophyll maxima, which occurs in the

upper thermocline, depends on the nitrate availability in the water column of the northwestern Bay of Bengal (Sarma and Aswanikumar, 1991).

3. Methodology

A total of 524 samples covering the entire 202 m drilled depth of the primary splice of Site U1446 have been used for this study. All the samples were processed following the standard procedure (Saraswat et al., 2023b). The sediment samples were freeze-dried. The dried samples were then soaked and subsequently wet sieved with water using a 63 μm sieve. The material retained on the sieve was dried, weighed and transferred to labelled plastic storage vials. A representative split aliquot of the fraction $>63 \mu\text{m}$ was sieved using a 125 μm sieve. Both the original fraction and the one obtained after dry sieving with 125 μm sieve, were weighed. A total of 328 samples were used for faunal analysis. A minimum of 300 planktic foraminifera were picked from the sieved fraction using an Olympus SZX12, stereozoom microscope. Only intact foraminiferal shells were picked. The species were identified by following Parker (1962) and Schiebel and Hemleben (2017). The number of different planktic foraminiferal species was counted. The relative abundance of the species was calculated in the total assemblage.

A total of 409 samples were used for the stable isotopic analysis. Five to fifteen specimens of *Neogloboquadrina dutertrei* were picked from 250-350 μm size fraction, obtained by sieving a part of the fraction $>63 \mu\text{m}$. The stable oxygen and carbon isotopes were measured using Isotope Ratio Mass Spectrometer (MAT 253; ThermoFisher Scientific, Germany) attached to a Kiel Carbonate device. Makrana marble (n=38) and NBS 19 (n=11), were used as standards during analysis. The standard deviation of Makrana marble over the measurement period was 0.1‰ for $\delta^{18}\text{O}$. The standard deviation for NBS 19 was 0.08‰ for $\delta^{18}\text{O}$. The isotopic values are reported in δ notation versus VPDB.

The $\delta^{18}\text{O}_{G. ruber}$ data were obtained from Clemens et al. (2021). The difference between the $\delta^{18}\text{O}_{G. ruber}$ and $\delta^{18}\text{O}_{N. dutertrei}$ was calculated and termed as $\Delta\delta^{18}\text{O}$ ($\Delta\delta^{18}\text{O} = \delta^{18}\text{O}_{G. ruber} - \delta^{18}\text{O}_{N. dutertrei}$). As $\delta^{18}\text{O}_{G. ruber}$ and $\delta^{18}\text{O}_{N. dutertrei}$ records were at different intervals of the same core, the $\delta^{18}\text{O}$ values were splined at a uniform 2 kyr interval to obtain a similar age for both the records. We want to state that using the isotopic values from different sections, although close by, may result in some variation. Therefore, we plotted the actual data with the splined data to find out if there is any significant difference between the two. We found that barring a few points, the splined data follows a trend very similar to that of the original data. Additionally, here, we have discussed the major shifts in the water column stratification, ignoring the stand alone individual data point peaks and lows. Therefore, we are

confident that the use of splined data provides a proper estimate of the difference in the mixed layer and thermocline signatures.

The age of the samples was determined by using the tie points provided by Clemens et al. (2021). There were 53 tie points, of which four were accelerator mass spectrometer (AMS) radiocarbon dates between 1.7 and 6.1 meters below sea floor (mbsf), one from the base of Toba ash at 15.6 m and the rest (48) from the comparison of benthic foraminifera oxygen isotopic ratio with the global isostack (Lisiecki and Raymo, 2005). The samples cover a time span of 1.183 Myr between ~270 ka and ~1453 ka. The average sample resolution for the faunal and isotopic analysis is ~4 kyr and ~3 kyr, respectively. The sedimentation rate varied between 5 and 20 cm/kyr (Clemens et al., 2021; Bhadra and Saraswat, 2022).

The planktic foraminiferal species were grouped into mixed layer assemblage (MLA) and thermocline assemblage (TA) to reconstruct the changes in the water column structure. Seventeen species, excluding those in low abundance, were used to prepare assemblages. The species were grouped into respective assemblages following their habitat preference described by Schiebel and Hemleben (2017). *Globigerinita glutinata*, *Globigerina bulloides*, *Globigerina falconensis*, *Globoturborotalita rubescens*, *Globoturborotalita tenella*, *Globigerinoides ruber*, *Trilobus sacculifer*, *Globigerinella calida*, *Neogloboquadrina incompta* and *Globoquadrina conglomerata* were included in the MLA, whereas *Pulleniatina obliquiloculata*, *Neogloboquadrina dutertrei*, *Globigerinella siphonifera*, *Globorotalia menardii*, *Globorotalia unguolata*, *Globorotaloides hexagonus* and *Globigerinoides conglobatus* have been included in the TA.

The wavelet and spectral analyses were done on $\delta^{18}\text{O}_{N. dutertrei}$, TA, and $\Delta\delta^{18}\text{O}$ to find out possible periodicities and assess the effect of the long-term periodic global climatic changes on the water column structure of the Bay of Bengal. The wavelet plots were generated through wavelet analysis for unequally spaced data. The spectral analysis was done with Past 4.03 (Hammer et al., 2001). The spectral analysis was done using the REDFIT algorithm with a Rectangle window. The dataset was divided into two parts to analyze the cyclicity changes following the MPT. Specifically, we focused on the period after MIS 23, which exhibited a noticeable shift in our $\Delta\delta^{18}\text{O}$ dataset. Therefore, we used 900 ka as a boundary to separate the record into two parts for spectral analysis. An oversample of 2 and a segment of 3 were taken as sub-parameters. Only in the case of TA (900 -1450 ka) a segment of 2 was taken because of the smaller number of data points in that interval.

4. Results

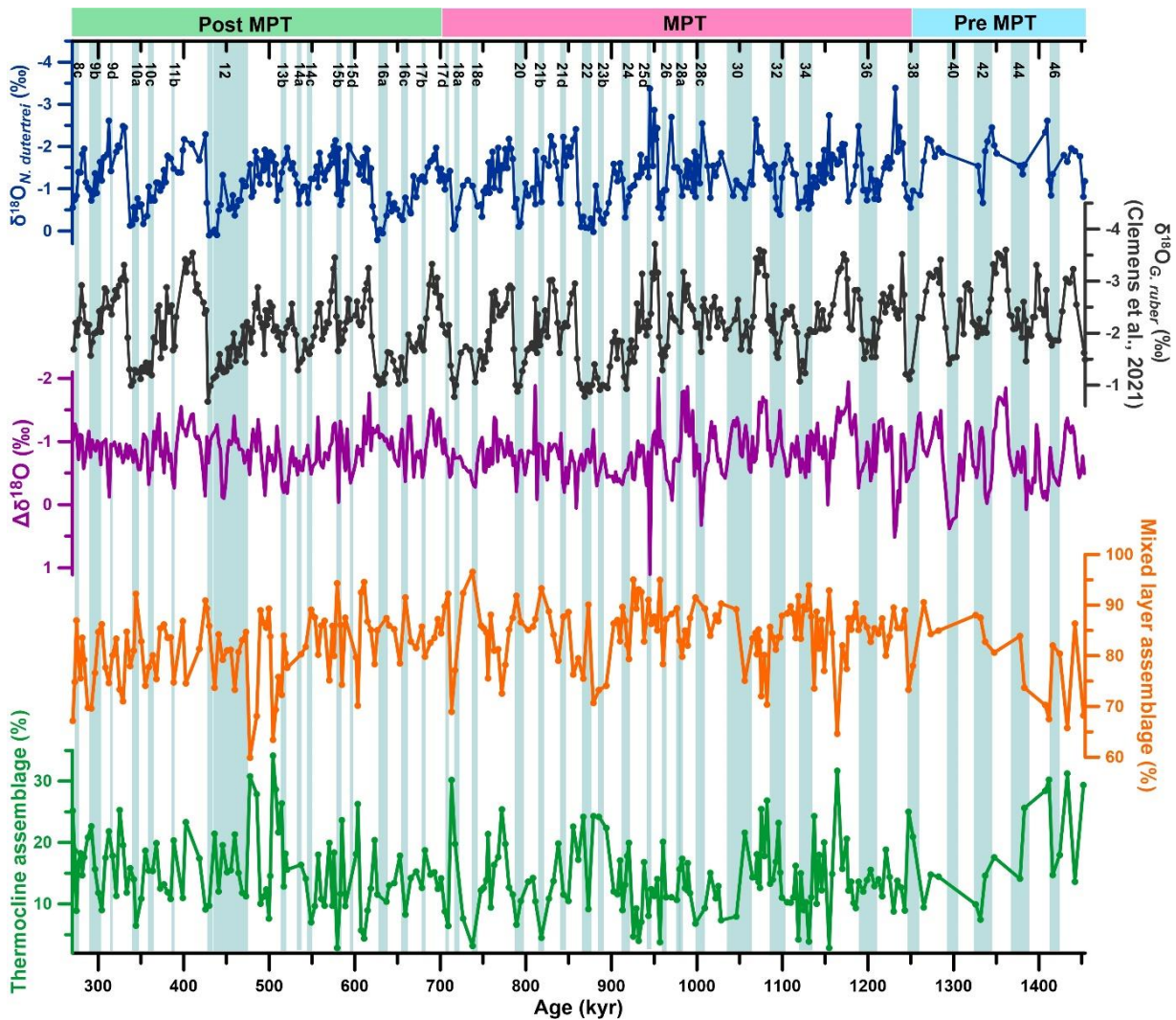


Figure 2: The variation in relative abundances of Mixed Layer Assemblage (MLA) and Thermocline Assemblage (TA), difference in the $\delta^{18}\text{O}$ between *N. dutertrei* and *G. ruber* ($\Delta\delta^{18}\text{O}$), $\delta^{18}\text{O}$ *G. ruber* and $\delta^{18}\text{O}$ *N. dutertrei* between MIS 47 and MIS 8. The light blue bands indicate stadials with respective MIS numbers marked on the top. The $\delta^{18}\text{O}$ *G. ruber* data have been obtained from Clemens et al. (2021).

The $\delta^{18}\text{O}_{N. dutertrei}$ record covered 1180 kyr between Marine Isotope Stage (MIS) 46 to MIS 8 (Figure 2). *Neogloboquadrina dutertrei* $\delta^{18}\text{O}$ varied between -3.39‰ and 0.22‰ and showed a clear glacial-interglacial pattern. The glacial-interglacial variation in $\delta^{18}\text{O}_{N. dutertrei}$ was more pronounced than the $\delta^{18}\text{O}_{G. ruber}$ (Clemens et al., 2021), though similar first-order variability can be seen in both records. $\Delta\delta^{18}\text{O}$ varied between 1.1 and -2.0‰ . It was more negative during the warm interstadials (e.g. MIS 10b, 13c, 21a, 28a, 31, 43) and moved towards positive during the cold stadials (e.g. MIS 9d, 15b, 25b, 28c, 40). The low and high peaks in the $\Delta\delta^{18}\text{O}$ match well with the low and high peaks in the thermocline assemblage, suggesting a similar variability (Figure 2).

The relative abundance of *N. dutertrei* varied from a minimum of 0.42% to a maximum of 27.98% (Figure 3). The average abundance was 8.84%. The abundance increased during the warm interstadials as compared to the cold stadials. The relative abundance of MLA (%), varied from 59.92% to 96.29% with an average of 80.37%, whereas the TA (%) varied from 3.12% to 36.29% with an average of 17.09%. During the interstadials, TA increased, and MLA decreased (e.g. MIS 3a, 9e, 17e, 31, 35), whereas during the glacial periods, MLA increased and TA decreased (e.g. MIS 2, 10a, 15b, 21b, 42) (Figure 3).

The wavelet analysis of $\delta^{18}\text{O}_{N. dutertrei}$ shows significant change from 41 kyr to 100 kyr cyclicity after 900 ka, whereas the 23 kyr cyclicity is intermittently present throughout (Figure 4). In the wavelet plot of TA, the 23 kyr cyclicity is more prominently visible during the post MPT period. The 41 kyr cyclicity is prominent in the $\Delta\delta^{18}\text{O}$ wavelet plot prior to 900 ka (Figure 4). The spectral analysis reveals that the $\delta^{18}\text{O}_{N. dutertrei}$ had a 41 kyr periodicity with a significance of 95% prior to 900 ka, whereas after 900 ka, it changed to 100 kyr periodicity with 95% significance and a 23 kyr periodicity with 99% significance (Figure 5). The 41 kyr periodicity was absent in other proxies. The 23 kyr periodicity was present in the thermocline assemblage throughout the studied time period with a significance of 99%. It was present in the $\Delta\delta^{18}\text{O}$ record after 900 ka with a significance of 90% (Figure 5).

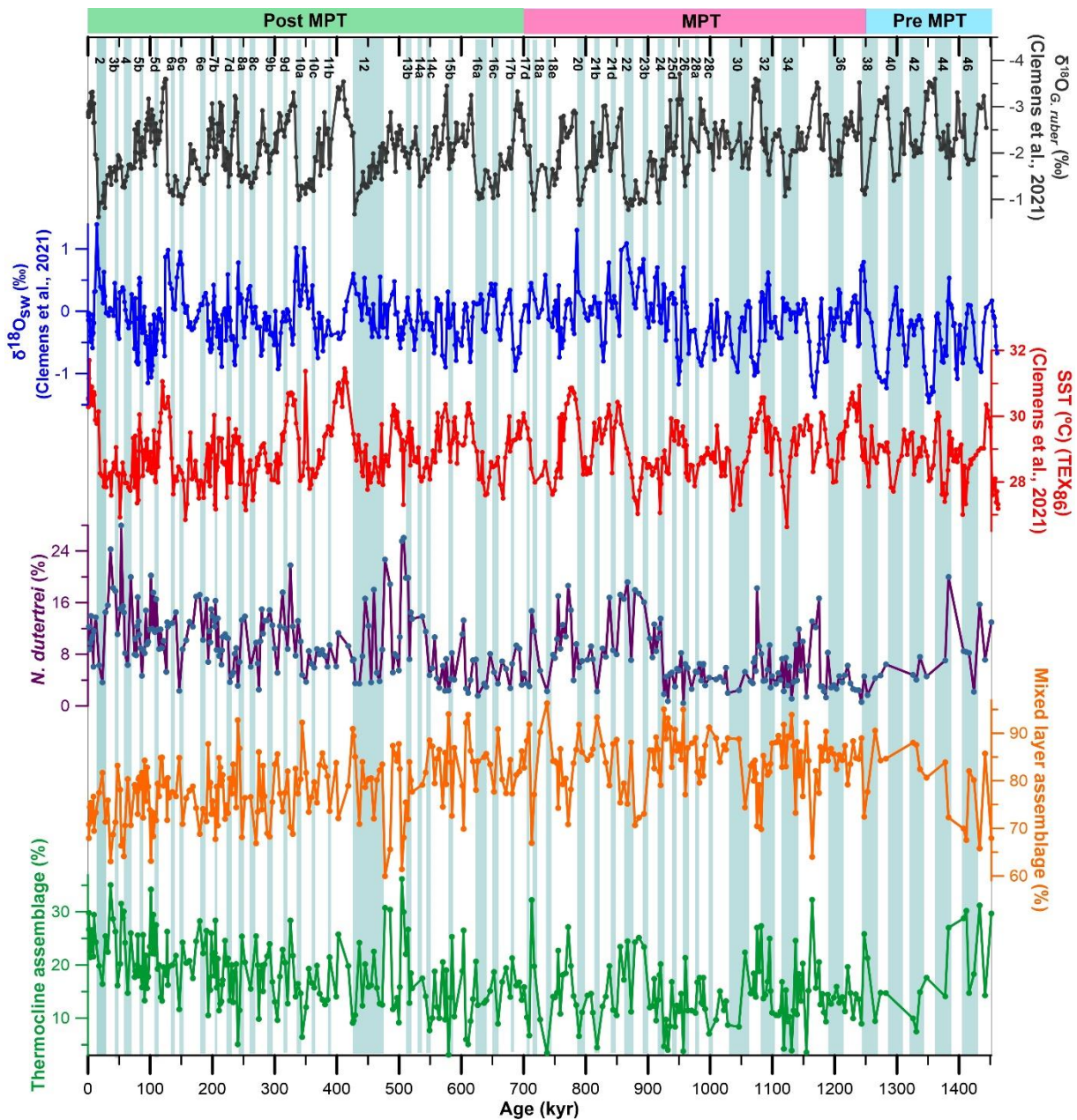


Figure 3: The variation in Mixed Layer Assemblage (MLA), Thermocline Assemblage (TA), the relative abundance of *N. dutertrei* (%), sea surface temperature (SST), $\delta^{18}\text{O}$ of seawater ($\delta^{18}\text{O}_{\text{sw}}$) and $\delta^{18}\text{O}$ *G. ruber* during the last 1.45 Myr. The light blue bands indicate stadials, with each MIS sub-stage marked at the top. The $\delta^{18}\text{O}$ *G. ruber*, $\delta^{18}\text{O}_{\text{sw}}$ and SST data have been obtained from Clemens et al. (2021).

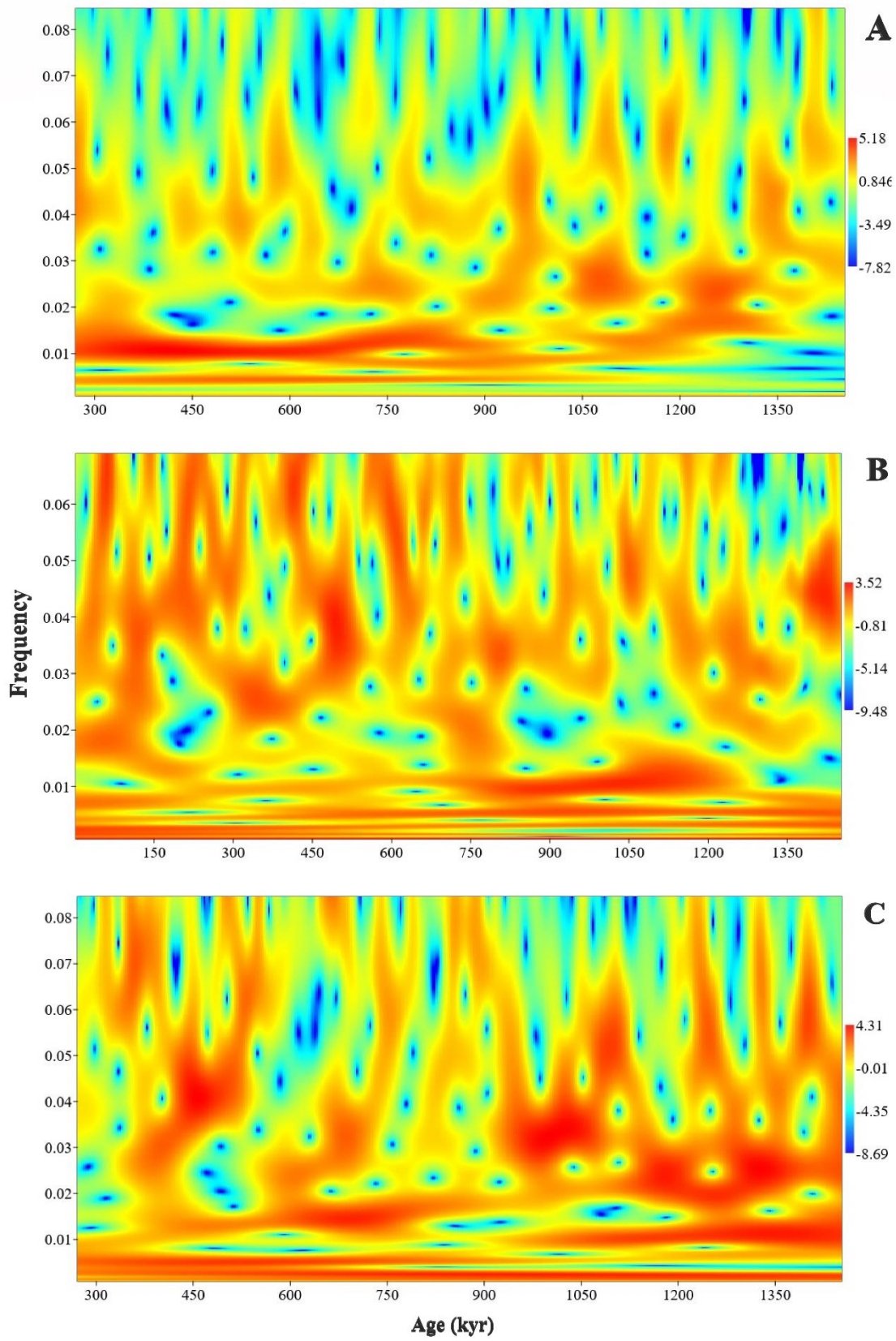


Figure 4: The wavelet analysis of (A) $\delta^{18}\text{O}$ *N. dutertrei* and (C) $\Delta\delta^{18}\text{O}$ during 271-1450 ka, and (B) Thermocline assemblage during 0-1450 ka. The y-axis is frequency, and the x-axis is age (kyr).

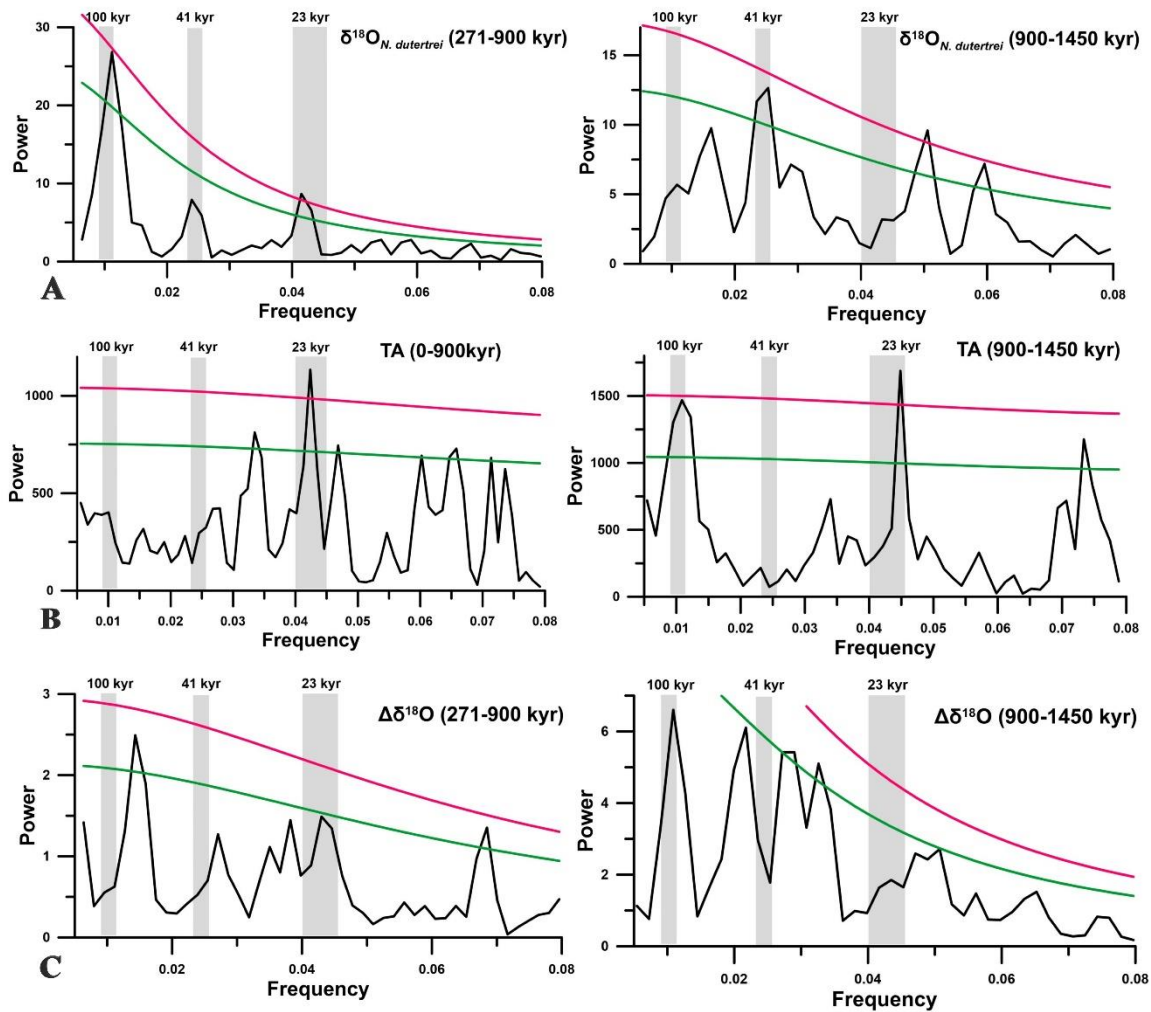


Figure 5: The spectral analysis of (A) $\delta^{18}\text{O}$ *N. dutertrei*, and (C) $\Delta\delta^{18}\text{O}$ during 271-900 ka and 900-1450 ka, and (B) Thermocline assemblage during 0-900 ka and 900-1450 ka. The pink and green line represents 99% and 95% significance, respectively. The y-axis is power, and the x-axis is frequency.

5. Discussion

5.1 Applicability of $\Delta\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{G. ruber} - \delta^{18}\text{O}_{N. dutertrei}$) as a proxy for stratification in the Bay of Bengal

As mentioned earlier, we have used the difference in the stable oxygen isotopic ratio of *G. ruber* and *N. dutertrei* in our study and denoted it as $\Delta\delta^{18}\text{O}$. As compared to Ota et al. (2019), where there is hardly any notable difference between the glacial-interglacial $\Delta\delta^{18}\text{O}$ during the last 80 kyr, we report a significant variation at Site U1446 (Figure 2). *Globigerinoides ruber* (white) is primarily a surface dweller and preferentially calcifies its shells within the mixed layer (Fairbanks et al., 1980; 1982; Hemleben et al., 1989; Niebler et al., 1999). On the other hand, *Neogloboquadrina dutertrei* preferably

lives and calcifies in the well-stratified photic zone within the thermocline, close to the subsurface chlorophyll maximum (Bé and Tolderlund, 1971; Fairbanks and Weibe, 1980; Fairbanks et al., 1982; Curry et al., 1983). *Neogloboquadrina dutertrei* calcifies at a colder temperature and has higher $\delta^{18}\text{O}$ than that of *G. ruber* (Tedesco et al., 2007). Both species are present throughout the year with more abundance during the summer monsoon (Guptha et al., 1997; Nilsson-Kerr et al., 2022). Therefore, the chances of long-term seasonal biases in $\delta^{18}\text{O}$ *G. ruber*, $\delta^{18}\text{O}$ *N. dutertrei* and $\Delta\delta^{18}\text{O}$ are minimal (Gebregiorgis et al., 2016). Moreover, though the depth habitat of *N. dutertrei* varies widely, it calcifies within a narrow range of temperatures (Curry and Matthews, 1981; Curry et al., 1983; Sautter and Thunell, 1991; Ravelo and Fairbanks, 1992; Field, 2004). Therefore, the $\Delta\delta^{18}\text{O}$ variability can be more apparently related to the change in the SST rather than the change in the thermocline temperature (Tedesco et al., 2007). The depth habitat of a particular species might not be constant through different timescales (Field, 2004; Rohling et al., 2004). However, *G. ruber* is reported to maintain a near-surface depth habitat irrespective of freshwater-induced changes (Schmuker and Schiebel, 2002; Rohling et al., 2004). Field (2004) reported only a small-scale response of *G. ruber* to the change in the temperature gradient and covariance of *N. dutertrei* abundance with the depth of a given isotherm within the thermocline. Only *sensu stricto* (ss) morphotype of *G. ruber* was used for the $\delta^{18}\text{O}$ (Clemens et al., 2021). As *G. ruber* ss preferably maintains a shallower and narrow depth habitat than *G. ruber sensu lato*, the $\Delta\delta^{18}\text{O}$ gives us a more appropriate stratification signal. Also, *N. dutertrei* was picked from a narrow size range (250-350 μm) following Kroon and Darling (1995) to avoid the gametogenesis-related bias.

The $\Delta\delta^{18}\text{O}$ between shallow and deep-dwelling planktic foraminifera has been related to the water column stratification, with large difference indicating increased stratification and vice versa (Mulitza et al., 1997; Venancio et al., 2018). The $\Delta\delta^{18}\text{O}$ is large when the thermocline is shallow, and a strong temperature gradient exists in the photic zone (Steph et al., 2009, 2010; Steinke et al., 2010). The salinity gradient induced by the changes in evaporation-precipitation can also affect the $\Delta\delta^{18}\text{O}$ (Rohling et al., 2004; Mohtadi et al., 2009; Steinke et al., 2010). Naik and Naidu (2019) and Sijinkumar et al. (2021) also used $\Delta\delta^{18}\text{O}_{G. ruber-N. dutertrei}$ as an indicator of salinity difference between the mixed layer and thermocline and reported higher stratification and shallower thermocline during the strengthening of the summer monsoon.

5.2 Glacial-interglacial stratification changes in the western Bay of Bengal

In the western Bay of Bengal, the riverine freshwater input during the summer monsoon season creates a shallow mixed layer and strong stratification. A barrier layer exists between the mixed layer and the thermocline (~30- 80 m) that resists mixing (Vinayachandran et al., 2002; Thadathil et al., 2007). On

the longer glacial-interglacial scale, the thermocline assemblage (TA) (%) peaks during the interstadials and is low during the stadials, whereas the mixed layer assemblage (MLA) (%) shows the opposite trend (Figures 2 and 3). This indicates that the mixed layer was shallow during the interglacial times and deep during the glacial period. The $\Delta\delta^{18}\text{O}$ was more negative (large difference) during the interstadials, suggesting more stratification and less mixing (Figure 2). The strengthened monsoon must have contributed to higher freshwater influx during the interstadials. The warm and low saline water acted as a cap inhibiting mixing and thereby creating a stronger vertical temperature gradient, which helped form a shallow mixed layer. The $\Delta\delta^{18}\text{O}$ is also affected by the salinity changes in the water column, with lower values indicating increased salinity differences. The vertical $\delta^{18}\text{O}$ profiles suggest a strong salinity gradient in the Bay of Bengal with low saline waters at the surface (Sengupta et al., 2013). The mixed layer-thermocline salinity gradient can increase due to the surface salinity decrease due to the increased freshwater influx due to strengthened monsoon (Steinke et al., 2010). The high SST and low $\delta^{18}\text{O}_{\text{sw}}$ (suggesting low salinity) during interstadials also corroborate the same (Clemens et al., 2021). The light limitation can also be a factor in this scenario, but the final interpretation will be the same. The increased cloud cover during the strong monsoon period would decrease the light availability, shifting the chlorophyll maxima to the upper water column. The chlorophyll maxima have been reported to occur at the boundary of the mixed layer and thermocline (Prasanna Kumar et al., 2004; Narvekar and Prasanna Kumar, 2006). As *N. dutertrei* is associated with the deep chlorophyll maxima, its habitat will shift and result in lighter oxygen isotopic value.

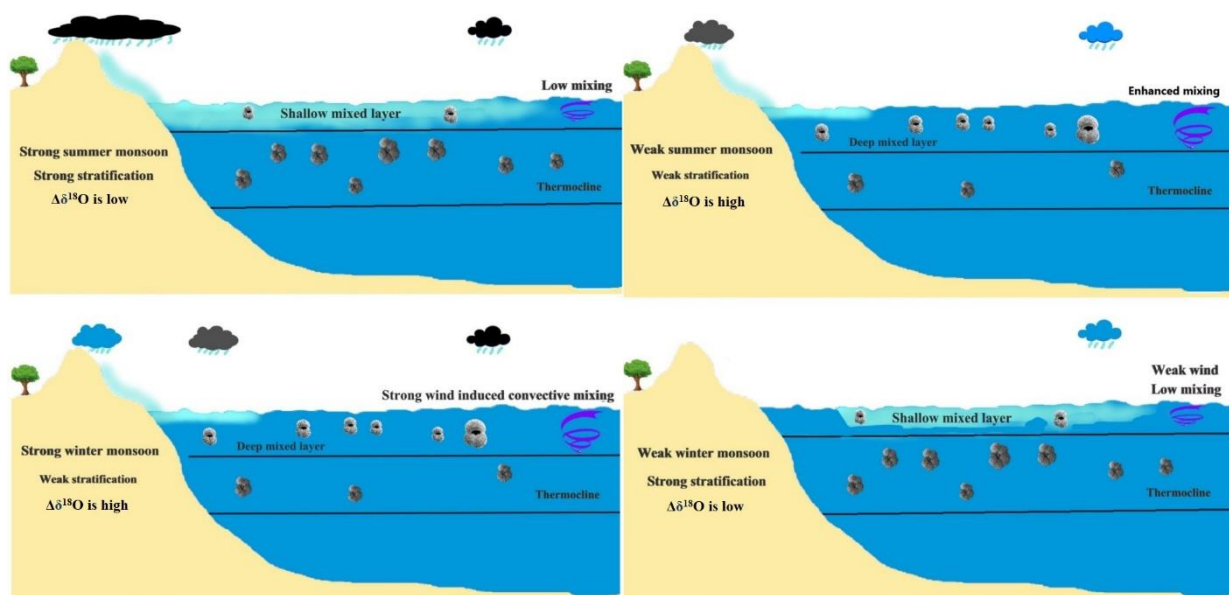


Figure 6: The schematic of the variation in $\Delta\delta^{18}\text{O}$ during the strong and weak summer monsoon and strong and weak winter monsoon. The low and high $\Delta\delta^{18}\text{O}$ in the figure signifies more and less negative $\Delta\delta^{18}\text{O}$ values, respectively.

During the stadial periods, however, the deep mixed layer could be because of the weakened summer monsoon, strengthened winter monsoon, or both. A weakened summer monsoon would imply less freshwater influx, resulting in a deeper mixed layer due to the absence of a low salinity cap. At the same time, a strengthened winter monsoon would induce more convective mixing, which can result in a deeper mixed layer (Figure 6). Previous studies from the Indian Ocean have also reported that the Indian summer monsoon (ISM) strengthened during the warm interglacials and weakened during the cold glacials (Clemens et al., 1991; Ivanova et al., 2003; Saraswat et al., 2014; Saravanan et al., 2020; Saraswat et al., 2020; Bhadra and Saraswat, 2022). Stainbank et al. (2021) also reported stronger stratification during the interglacial periods and less stratification during the glacials in the Maldives inner sea.

From the above discussion, it is clear and also important to note that whether the change in $\Delta\delta^{18}\text{O}$ is a result of the change in temperature or salinity in the water column, our conclusions of more stratification during the interstadials and less during the stadials don't change. To better assess whether the change in the water column stratification was triggered by the surface or subsurface changes, a subsurface temperature record is needed, which is limited by the current dataset and is beyond the scope of this manuscript.

5.3 Effect of the mid-Pleistocene transition on the water column stratification in the Bay of Bengal

The ice sheet growth and intensity of glacial periods started to increase around ~910 ka, much before the dominance of the 100 kyr cycles (650-725 ka) (Mudelsee and Schulz, 1997; Mudelsee and Statterger, 1997). However, there is a notable shift in the $\delta^{18}\text{O}_{N. dutertrei}$ towards lighter values after MIS 25d (Figure 2). A major change in $\Delta\delta^{18}\text{O}$ is also observed after MIS 26. The variability is very high in and prior to MIS 25d, whereas it becomes low after that. The $\Delta\delta^{18}\text{O}$ ranged between -0.05‰ and 2.00‰ after MIS 25d with only one value <0‰ and two values >1.5‰. The presence of most of the high and low peaks in $\Delta\delta^{18}\text{O}$ prior to MIS 24 indicates that the Bay of Bengal experienced large-scale glacial-interglacial stratification changes during the pre MPT period. The 900 kyr event in the MPT has been marked as a long-term cooling trend reduction and a climate threshold crossing (McClymont et al., 2013). The average $\Delta\delta^{18}\text{O}$ stays high (less negative) even during the interstadials between MIS 25 and MIS 23. The TA also shows a very low value during the MIS 25 (a-c) interstadial (Figure 2). It suggests there was reduced stratification in the Bay of Bengal just after the large variability across MIS 25-26 transition, which increased afterwards (MIS 22 onwards). MIS 23 was the one interglacial which did not see a strengthened Atlantic meridional overturning circulation (AMOC) (Peña and Goldstein, 2014; Dausmann et al., 2017). The global temperature dropped during MIS 24-22 (Raymo

et al., 2006; Prokopenko et al., 2006; McClymont et al., 2013). The SST of the Bay of Bengal also decreased (Figure 3). The Antarctic ice volume expanded (Elderfield et al., 2012), and the global thermohaline circulation weakened (Pena and Goldstein, 2014). This resulted in an increase in the cross-equatorial pressure gradient between the southern subtropical Indian Ocean and the Indian subcontinent paving the way for a strengthened ISM (Clemens et al., 1996; Elderfield et al., 2012; Farmer et al., 2019; Chen et al., 2020). The strengthened ISM-induced freshwater influx resulted in a stronger stratification

The period between MIS 22 and MIS 13 saw a variable stadial-interstadial change in the water column stratification of the Bay of Bengal. This is visible in the MLA, TA and $\Delta\delta^{18}\text{O}$ records (Figure 2). This period is considered as generally reduced overturning circulation (Schmieder et al., 2000; Kemp et al., 2010). Two of the three instances in the entire record where the TA (%) decreases below 4% are in this period. These stadials (MIS 15b and 18e) also had low peaks (less negative values) of $\Delta\delta^{18}\text{O}$. This suggests that MIS 15b and 18e were period of intense mixing indicating weakened summer monsoon and/or strengthened winter monsoon.

The scenario in MIS 13 is interesting. We observed a very small variability in the $\delta^{18}\text{O}_{N. dutertrei}$, whereas there is a large variation in TA, MLA and $\Delta\delta^{18}\text{O}$ across MIS 13 (Figure 2). The post MPT glacial-interglacial change in ice volume is the least prominent (Lisiecki and Raymo, 2005), which can be in the $\delta^{18}\text{O}_{N. dutertrei}$ as well. MIS 13 has been reported as a colder period compared to other interglacials in terms of lower atmospheric CO_2 and CH_4 concentrations (Loulergue et al., 2008; Luthi et al., 2008) and colder Antarctic temperature (Jouzel et al., 2007). However, our record indicates high variability in the water column stratification. There have been reports of strengthened East Asian summer monsoon during MIS 13 as well (Guo et al., 2000; Sun et al., 2006; Yin and Guo, 2008; Guo et al., 2009; Hao et al., 2015). Therefore, the large variation in the Bay of Bengal water column stratification could be a result of the prominent change in the ISM. As the $\delta^{18}\text{O}_{N. dutertrei}$ is controlled by the global ice volume change, temperature and changes in the regional evaporation-precipitation, it alone doesn't clearly show the effect of the change in ISM.

It is interesting to note that the stadial SSTs decreased after MIS 12 (Figure 3). This might be because of a possible decrease in winter monsoon, which will result in a cooler SST due to reduced freshwater influx as the summer monsoon was weak during the stadials. There has been report of strengthened ISM after the mid-Bruhnes event due to a weak Indian Ocean equatorial westerly wind and positive Indian Ocean dipole (IOD) (Gupta et al., 2010). However, our records suggest a longer-term change in the ISM strength. After MIS 25, the glacial-interglacial changes in the upper water column stratification have smoothed (Figure 2). There could be two possibilities for this, (1) the

interglacial stratification decreased or (2) the glacial mixing decreased. However, there is a slow and steady shift in $\Delta\delta^{18}\text{O}$ towards more negative values from MIS 24 to MIS 8c, and the trend is more noticeable for stadial values when compared to the pre MPT period. This trend can be more prominently seen in the thermocline assemblage (%), which continuously increases from MIS 24 to the present. Therefore, it is clear that the decreased mixing during the post MPT stadial periods resulted in limited variation in $\Delta\delta^{18}\text{O}$. The possible explanation for this could be an increased summer monsoon, decreased winter monsoon, or the coupled effect of both. The lack of $\Delta\delta^{18}\text{O}$ data of the last 270 ka, precludes a corroboration of the sharp increase in TA after MIS 8 with $\Delta\delta^{18}\text{O}$. However, this change is prominent from MIS 12 to MIS 8 in all three records ($\Delta\delta^{18}\text{O}$, MLA and TA), and it is likely that the covarying relationship between the three continues till the present. This indicates a continuous increase in the stratification in the western Bay of Bengal. We have plotted the $\delta^{18}\text{O}_{N. dutertrei}$ and $\Delta\delta^{18}\text{O}_{G. ruber-N. dutertrei}$ record from Site U1446 as an extension of our existing data till 70 ka, and it shows a decreasing trend in the $\Delta\delta^{18}\text{O}$ (Figure 7) (Nilsson-Kerr et al., 2022). The $\Delta\delta^{18}\text{O}_{G. ruber-N. dutertrei}$ record of Bolton et al. (2013) from the southern Bay of Bengal also shows a decreasing trend from MIS 12 to the present (Figure 7). All these studies corroborate our earlier inference of a continuous increase in stratification due to the strengthening of ISM in the post MPT period. The major ice sheet expansion caused by the continued global effects associated with the MPT resulted in a change in the Indian monsoon system (Bhadra and Saraswat, 2022). A similar strengthening of the East Asian summer monsoon has been reported after 550 ka from studies on Chinese and Japanese loess deposits in line with the uplift of the Tibetan plateau (An et al., 1990; Xiao and An, 1999). A higher $\Delta\delta^{18}\text{O}$ during the glacial terminations is reported in the equatorial Indian Ocean (Bolton et al., 2013). It was suggested that the inferred strong stratification during the termination events indicates a Southern Hemisphere control over the ISM variability on the millennial scale, possibly via modulation of the strength of the Southern subtropical Indian Ocean-Asia pressure gradient (An et al., 2011; Caley et al., 2013). A similar observation is evident in the Site U1446 record. Most of the peaks are during the termination events. Recently, Band et al. (2022) also linked the millennial scale ISM variability to a similar Southern Hemisphere forcing.

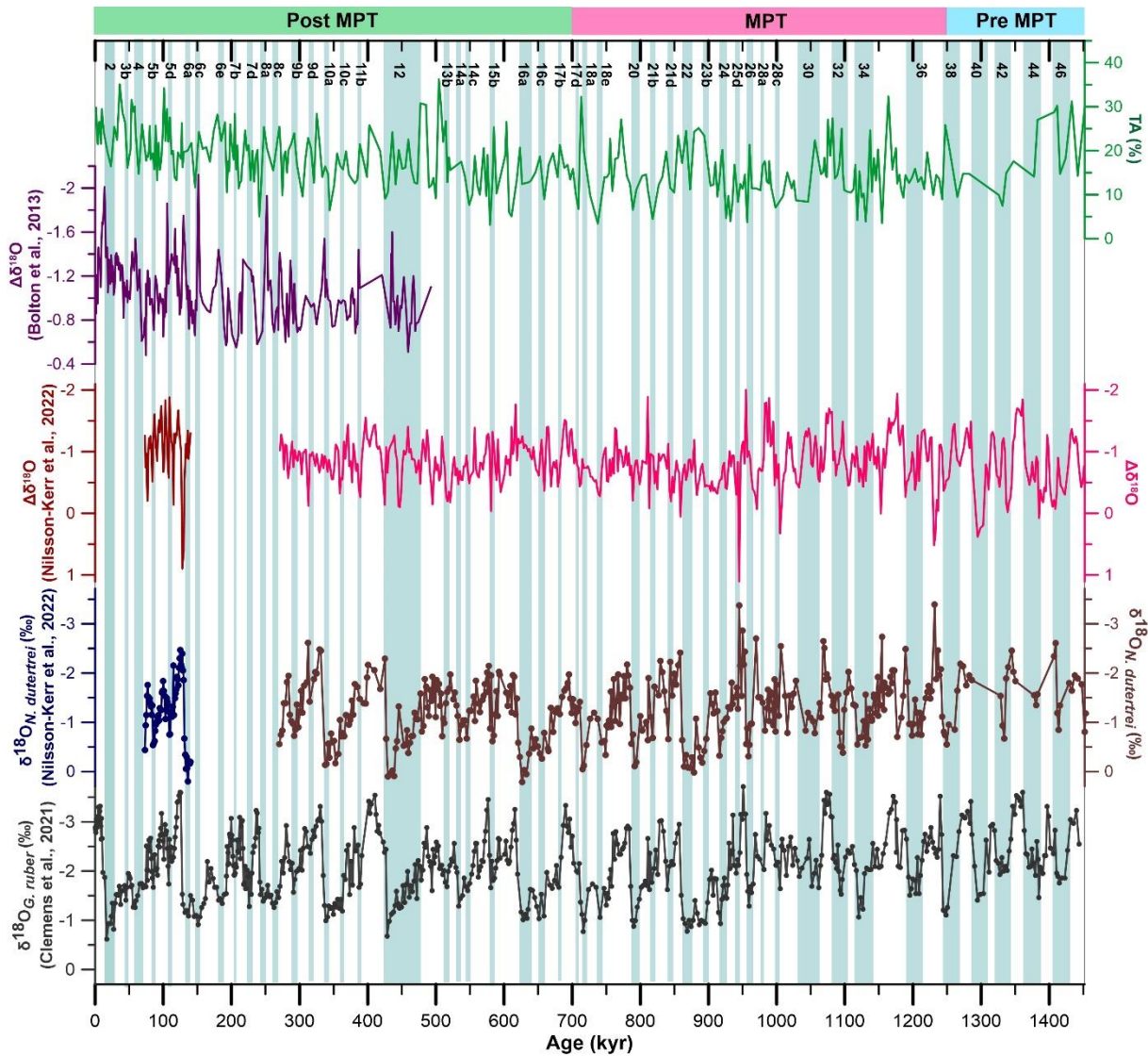


Figure 7: The variation in the $\delta^{18}\text{O}$ *G. ruber* (Clemens et al., 2021), $\delta^{18}\text{O}$ *N. dutertrei* (this study and Nilsson-Kerr et al., 2022), the difference in the $\delta^{18}\text{O}$ between *N. dutertrei* and *G. ruber* ($\Delta\delta^{18}\text{O}$) (this study and Nilsson-Kerr et al., 2022), $\Delta\delta^{18}\text{O}$ from Bolton et al. (2013) and Thermocline assemblage during the last 1.45 Myr. The light blue bands indicate stadials, with each MIS sub-stage marked at the top.

The relative abundance of *N. dutertrei* was high during the interglacials and continuously increased after MIS 25, which supports our earlier results regarding summer monsoon variability (Figure 3). The abundance of *N. dutertrei* usually increases at the deep chlorophyll maximum within the thermocline because of the light availability and high concentration of nutrients (Fairbanks and Wiebe, 1980; Peeters et al., 2002; Field, 2004; Lončarić et al., 2006; Triantaphyllou et al., 2010; Birch et al., 2013). Recently, the high relative abundance of *N. dutertrei* in the western Bay of Bengal was attributed to the deep chlorophyll maxima in the thermocline (Bhadra and Saraswat, 2021). This deep chlorophyll maximum is created by a strong density gradient caused by low salinity in the surface waters. Therefore, the high relative abundance of *N. dutertrei* was suggested as a low surface salinity

indicator. The relative abundance of *N. dutertrei* also shows a good correlation with summer monsoon-induced low salinity in the Bay of Bengal (Cullen, 1981). The high saline and dense water during the summer monsoon in the Bay of Bengal entrap the nutrients in the upper thermocline, thereby creating a subsurface chlorophyll maximum, a preferred habitat for *N. dutertrei*.

The $\delta^{18}\text{O}_{N. dutertrei}$ clearly shows a shift from 41 kyr periodicity to 100 kyr periodicity after 900 ka suggesting the effect of the MPT (Figure 5). However, this change isn't visible in any other proxy. This indicates that the obliquity and eccentricity forcing have little effect on the upper water column stratification of the Bay of Bengal. However, the precession signal is strongly visible in all the records indicating its dominant control on the stratification changes in the Bay of Bengal. The $\delta^{18}\text{O}_{N. dutertrei}$ is affected by the global ice volume changes and the local temperature-salinity effect. Therefore, it is possible that the 41 kyr and 100 kyr periodicities present in the $\delta^{18}\text{O}_{N. dutertrei}$ are the signal captured by only the global ice volume changes and don't have any contribution from local seawater properties. On the other hand, $\Delta\delta^{18}\text{O}$ and faunal assemblage reflect the stratification changes in the water column, which is controlled by the ISM as inferred from the previous sections. Therefore, the precession forcing has a larger control over the ISM than eccentricity or obliquity. The presence of 23 kyr signal in $\Delta\delta^{18}\text{O}$ after 900 ka and its absence before that suggests the precession control over the Indian monsoon has increased after the MPT. Previous studies have also reported the control of precession forcing on the Indian summer monsoon in the quaternary.

6. Conclusion

The faunal abundance and difference between $\delta^{18}\text{O}$ of *N. dutertrei* and *G. ruber* show a similar variability between MIS 45 and MIS 8. All the indices indicate a stronger stratification during the interstadials and comparatively weaker stratification during the stadials. The strengthened summer monsoon during the interstadials lowered the salinity of the surface layer in the western Bay of Bengal with high direct rainfall and riverine influx. This, in turn, inhibited mixing in the upper layer and created a shallow thermocline. The effect of the MPT on surface waters of the Bay of Bengal was large enough to change the water column structure. The strengthened monsoon post MPT period resulted in more shallowing of the thermocline. There is a strong precessional control over the summer monsoon induced stratification in the Bay of Bengal.

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Data availability

The data has been provided as supplementary material.

References

- Amol, P., Vinayachandran, P.N., Shankar, D., Thushara, V., Vijith, V., Chatterjee, A. and Kankonkar, A., 2020. Effect of freshwater advection and winds on the vertical structure of chlorophyll in the northern Bay of Bengal. *Deep Sea Research Part II: Topical Studies in Oceanography*, 179, p.104622.
- An, Z.S., Liu, T.S., Lu, Y.C., Porter, S.C., Kukla, G.J., Wu, X.H., and Hua, Y.M., 1990. The long-term paleomonsoon variation recorded by the loess–paleosol sequence in central China. *Quaternary International*, 7, pp.91–95.
- An, Z., Clemens, S.C., Shen, J., Qiang, X., Jin, Z., Sun, Y., Prell, W.L., Luo, J., Wang, S., Xu, H., Cai, Y., Zhou, W., Liu, X., Liu, W., Shi, Z., Yan, L., Xiao, X., Chang, H., Wu, F., Ai, L., and Lu, F., 2011. Glacial-interglacial Indian summer monsoon dynamics. *Science* 333, p.719e723.
- Band, S.T., Yadava, M.G., Kaushal, N., Midhun, M., Thirumalai, K., Francis, T., Laskar, A., Ramesh, R., Henderson, G.M. and Narayana, A.C., 2022. Southern hemisphere forced millennial scale Indian summer monsoon variability during the late Pleistocene. *Scientific Reports*, 12, pp.1-8.
- Bé, A.W.H., and Tolderlund, D.S., 1971. Distribution and ecology of living planktonic foraminifera in surface waters of the Atlantic and Indian Ocean. In: Funnell, B.M., et al. (Ed.), *Micropaleontology of Oceans*. Cambridge University Press, Cambridge, pp.105–149.
- Bemis, B.E., Spero, H.J., Bijma, J. and Lea, D.W., 1998. Reevaluation of the oxygen isotopic composition of planktonic foraminifera: Experimental results and revised paleotemperature equations. *Paleoceanography*, 13, pp.150-160.
- Berger, W.H., Killingley, J.S. and Vincent, E., 1978. Sable isotopes in deep-sea carbonates-box core erdc-92, west equatorial pacific. *Oceanologica Acta*, 1, pp.203-216.
- Berger, W.H. and Jansen, E., 1994. Mid-pleistocene climate shift-the Nansen connection. *The polar oceans and their role in shaping the global environment*, 85, pp.295-311.
- Bhadra, S.R. and Saraswat, R., 2021. Assessing the effect of riverine discharge on planktic foraminifera: A case study from the marginal marine regions of the western Bay of Bengal. *Deep Sea Research Part II: Topical Studies in Oceanography*, 183, p.104927.
- Bhadra, S.R. and Saraswat, R., 2022. A strong influence of the mid-Pleistocene transition on the monsoon and associated productivity in the Indian Ocean. *Quaternary Science Reviews*, 295, p.107761.

- Bijma, J., Spero, H.J. and Lea, D.W., 1999. Reassessing foraminiferal stable isotope geochemistry: Impact of the oceanic carbonate system (experimental results). In *Use of proxies in paleoceanography*, pp. 489-512. Springer, Berlin, Heidelberg.
- Birch, H., Coxall, H.K., Pearson, P.N., Kroon, D. and O'Regan, M., 2013. Planktonic foraminifera stable isotopes and water column structure: Disentangling ecological signals. *Marine Micropaleontology*, 101, pp.127-145.
- Bolton, C.T., Chang, L., Clemens, S.C., Kodama, K., Ikehara, M., Medina-Elizalde, M., Paterson, G.A., Roberts, A.P., Rohling, E.J., Yamamoto, Y. and Zhao, X., 2013. A 500,000 year record of Indian summer monsoon dynamics recorded by eastern equatorial Indian Ocean upper water-column structure. *Quaternary Science Reviews*, 77, pp.167-180.
- Caley, T., Malaizé, B., Kageyama, M., Landais, A., and Masson-Delmotte, V., 2013. Bihemispheric forcing of the Indo-Asian monsoon during glacial terminations. *Quaternary Science Reviews*, 59, pp.1-4.
- Chen, H., Xu, Z., Lim, D., Clift, P.D., Chang, F., Li, T., Cai, M., Wang, W., Yu, Z. and Sun, R., 2020. Geochemical records of the provenance and silicate weathering/erosion from the eastern Arabian Sea and their responses to the Indian summer monsoon since the Mid-Pleistocene. *Paleoceanography and Paleoclimatology*, 35, p. e2019PA003732.
- Clark, P.U., Archer, D., Pollard, D., Blum, J.D., Rial, J.A., Brovkin, V., Mix, A.C., Pisias, N.G. and Roy, M., 2006. The middle Pleistocene transition: characteristics, mechanisms, and implications for long-term changes in atmospheric pCO₂. *Quaternary Science Reviews*, 25, pp.3150-3184.
- Clemens, S., Prell, W., Murray, D., Shimmield, G. and Weedon, G., 1991. Forcing mechanisms of the Indian Ocean monsoon. *Nature*, 353, pp.720-725.
- Clemens, S.C., Murray, D.W. and Prell, W.L., 1996. Nonstationary phase of the Plio-Pleistocene Asian monsoon. *Science*, 274, pp.943-948.
- Clemens, S.C., Kuhnt, W., LeVay, L.J., Anand, P., Ando, T., Bartol, M., Bolton, C.T., Ding, X., Gariboldi, K., Giosan, L., Hathorne, E.C., Huang, Y., Jaiswal, P., Kim, S., Kirkpatrick, J.B., Littler, K., Marino, G., Martinez, P., Naik, D., Peketi, A., Phillips, S.C., Robinson, M.M., Romero, O.E., Sagar, N., Taladay, K.B., Taylor, S.N., Thirumalai, K., Uramoto, G., Usui, Y., Wang, J., Yamamoto, M., and Zhou, L., 2016. Site U1446. In Clemens, S.C., Kuhnt, W., LeVay, L.J., and the Expedition 353 Scientists, *Indian Monsoon Rainfall. Proceedings of the International Ocean Discovery Program*, 353.
- Clemens, S.C., Yamamoto, M., Thirumalai, K., Giosan, L., Richey, J.N., Nilsson-Kerr, K., Rosenthal, Y., Anand, P. and McGrath, S.M., 2021. Remote and local drivers of Pleistocene South Asian summer monsoon precipitation: A test for future predictions. *Science Advances*, 7, p.eabg3848.
- Cléroux, C., Cortijo, E., Duplessy, J.C. and Zahn, R., 2007. Deep-dwelling foraminifera as thermocline temperature recorders. *Geochemistry, Geophysics, Geosystems*, 8, p. Q04N11.
- Cullen, J. L., 1981. Microfossil evidence for changing salinity patterns in the Bay of Bengal over the last 20000 years, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 35, pp.315-356.

- Curry, W.B. and Matthews, R.K., 1981. Paleo-oceanographic utility of oxygen isotopic measurements on planktic foraminifera: Indian Ocean core-top evidence. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 33, pp.173-191.
- Curry, W.B., Thunell, R.C. and Honjo, S., 1983. Seasonal changes in the isotopic composition of planktonic foraminifera collected in Panama Basin sediment traps. *Earth and Planetary Science Letters*, 64, pp.33-43.
- Dausmann, V., Frank, M., Gutjahr, M. and Rickli, J., 2017. Glacial reduction of AMOC strength and long-term transition in weathering inputs into the Southern Ocean since the mid-Miocene: Evidence from radiogenic Nd and Hf isotopes. *Paleoceanography*, 32, pp.265-283.
- Duplessy, J.C., 1982. Glacial to Interglacial contrast in the northern Indian Ocean. *Nature*, 295, pp.494-498.
- Elderfield, H., Ferretti, P., Greaves, M., Crowhurst, S., McCave, I.N., Hodell, D. and Piotrowski, A.M., 2012. Evolution of ocean temperature and ice volume through the mid-Pleistocene climate transition. *Science*, 337, pp.704-709.
- Emiliani, C., 1955. Pleistocene temperatures. *The Journal of Geology*, 63, pp.538-578.
- Epstein, S., Buchsbaum, R., Lowenstam, H.A. and Urey, H.C., 1953. Revised carbonate-water isotopic temperature scale. *Geological Society of America Bulletin*, 64, pp.1315-1326.
- Fairbanks, R.G. and Wiebe, P.H., 1980. Foraminifera and chlorophyll maximum: vertical distribution, seasonal succession, and paleoceanographic significance. *Science*, 209, pp.1524- 1526.
- Fairbanks, R.G., Wiebe, P.H. and Bé, A.W., 1980. Vertical distribution and isotopic composition of living planktonic foraminifera in the western North Atlantic. *Science*, 207, pp.61-63.
- Fairbanks, R.G., Sverdrlove, M., Free, R., Wiebe, P.H. and Bé, A.W., 1982. Vertical distribution and isotopic fractionation of living planktonic foraminifera from the Panama Basin. *Nature*, 298, p.841.
- Farmer, E.C., Kaplan, A., de Menocal, P.B. and Lynch-Stieglitz, J., 2007. Corroborating ecological depth preferences of planktonic foraminifera in the tropical Atlantic with the stable oxygen isotope ratios of core top specimens. *Paleoceanography*, 22, p. PA3205.
- Farmer, J.R., Hönisch, B., Haynes, L.L., Kroon, D., Jung, S., Ford, H.L., Raymo, M.E., Jaume-Seguí, M., Bell, D.B., Goldstein, S.L. and Pena, L.D., 2019. Deep Atlantic Ocean carbon storage and the rise of 100,000-year glacial cycles. *Nature Geoscience*, 12, pp.355-360.
- Faul, K.L., Ravelo, A.C. and Delaney, M.L., 2000. Reconstructions of upwelling, productivity, and photic zone depth in the eastern equatorial Pacific Ocean using planktonic foraminiferal stable isotopes and abundances. *The Journal of Foraminiferal Research*, 30, pp.110-125.
- Field, D.B., 2004. Variability in vertical distributions of planktonic foraminifera in the California Current: Relationships to vertical ocean structure. *Paleoceanography*, 19, p. PA2014.
- Gautam, P.K., Narayana, A.C., Kumar, P.K., Bhavani, P.G., Yadava, M.G. and Jull, A.J.T., 2021. Indian monsoon variability during the last 46 kyr: isotopic records of planktic foraminifera from southwestern Bay of Bengal. *Journal of Quaternary Science*, 36, pp.138- 151.

- Gebregiorgis, D., Hathorne, E.C., Sijinkumar, A.V., Nath, B.N., Nürnberg, D. and Frank, M., 2016. South Asian summer monsoon variability during the last~ 54 kyrs inferred from surface water salinity and river runoff proxies. *Quaternary Science Reviews*, 138, pp.6-15.
- Govil, P., and Naidu, P.D., 2011. Variations of Indian monsoon precipitation during the last 32 kyr reflected in the surface hydrography of the western Bay of Bengal. *Quaternary Science Reviews*, 30, pp.3871-3879.
- Goyet, C., R. J. Healy, and J. P. Ryan. 2000. Global distribution of total inorganic carbon and total alkalinity below the deepest winter mixed layer depths. ORNL/CDIAC-127, NDP-076. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee.
- Guo, Z., Biscaye, P., Wei, L., Chen, X., Peng, S. and Liu, T., 2000. Summer monsoon variations over the last 1.2 Ma from the weathering of loess-soil sequences in China. *Geophysical Research Letters*, 27, pp.1751-1754.
- Guo, Z.T., Berger, A., Yin, Q.Z. and Qin, L., 2009. Strong asymmetry of hemispheric climates during MIS-13 inferred from correlating China loess and Antarctica ice records. *Climate of the Past*, 5, pp.21-31.
- Gupta, A.K., Sarkar, S., De, S., Clemens, S.C. and Velu, A., 2010. Mid-Brunhes strengthening of the Indian Ocean Dipole caused increased equatorial East African and decreased Australasian rainfall. *Geophysical Research Letters*, 37, p. L06706.
- Guptha, M.V.S., Curry, W.B., Ittekkot, V., Muralinath, A.S., 1997. Seasonal variation in the flux of planktic Foraminifera; sediment trap results from the Bay of Bengal, northern Indian Ocean. *Journal of Foraminiferal Research*, 27, pp.5–19.
- Hammer, Ø., Harper, D.A. and Ryan, P.D., 2001. PAST: Paleontological statistics software package for education and data analysis. *Palaeontologia Electronica*, 4, p.9.
- Hao, Q., Wang, L., Oldfield, F. and Guo, Z., 2015. Extra-long interglacial in Northern Hemisphere during MISs 15-13 arising from limited extent of Arctic ice sheets in glacial MIS 14. *Scientific Reports*, 5, pp.1-8.
- Hemleben, C., Spindler, M., and Anderson, O.R., 1989. *Modern Planktonic Foraminifera*. Springer, Berlin, p. 363.
- Herbert, T.D., Peterson, L.C., Lawrence, K.T. and Liu, Z., 2010. Tropical ocean temperatures over the past 3.5 million years. *science*, 328, pp.1530-1534.
- Imbrie, J., Berger, A., Boyle, E., Clemens, S.C., Duffy, A., Howard, W.R., Kukla, G., Kutzbach, J., Martinson, D.G., McIntyre, A. and Mix, A.C., 1993. On the structure and origin of major glaciation cycles 2. The 100,000-year cycle. *Paleoceanography*, 8, pp.699-735.
- Ivanova, E., Schiebel, R., Singh, A.D., Schmiedl, G., Niebler, H.S. and Hemleben, C., 2003. Primary production in the Arabian Sea during the last 135 000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 197, pp.61-82.

- Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J.M., Chappellaz, J. and Fischer, H., 2007. Orbital and millennial Antarctic climate variability over the past 800,000 years. *Science*, 317, pp.793-796.
- Kantha, L., Weller, R.A., Farrar, J.T., Rahaman, H. and Jampana, V., 2019. A note on modeling mixing in the upper layers of the Bay of Bengal: Importance of water type, water column structure and precipitation. *Deep Sea Research Part II: Topical Studies in Oceanography*, 168, p.104643.
- Kemp, A. E. S., Grigorov, I., Pearce, R. B., and Naveira Garabato, A.C., 2010. Migration of the Antarctic Polar Front through the mid-Pleistocene transition: Evidence and climatic implications. *Quaternary Science Reviews*, 29, pp.1993–2009.
- Kroon, D. and Darling, K., 1995. Size and upwelling control of the stable isotope composition of *Neogloboquadrina dutertrei* (d'Orbigny), *Globigerinoides ruber* (d'Orbigny) and *Globigerina bulloides* d'Orbigny; examples from the Panama Basin and Arabian Sea. *The Journal of Foraminiferal Research*, 25, pp.39-52.
- Kumar, P.K., Band, S.T., Ramesh, R. and Awasthi, N., 2018. Monsoon variability and upper ocean stratification during the last~ 66 ka over the Andaman Sea: inferences from the $\delta^{18}\text{O}$ records of planktonic foraminifera. *Quaternary International*, 479, pp.12-18.
- Lakhani, K.Q., Lynch-Stieglitz, J. and Monteagudo, M.M., 2022. Constraining calcification habitat using oxygen isotope measurements in tropical planktonic foraminiferal tests from surface sediments. *Marine Micropaleontology*, 170, p.102074.
- Lisiecki, L.E. and Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography*, 20, p. PA1003.
- Locarnini, M., Mishonov, A.V., Baranova, O.K., Boyer, T.P., Zweng, M.M., Garcia, H.E., Seidov, D., Weathers, K., Paver, C. and Smolyar, I., 2018. World ocean atlas 2018, volume 1: Temperature. In: A. Mishonov, Technical Editor. NOAA Atlas NESDIS 81, pp. 52.
- Lončarić, N., Peeters, F.J., Kroon, D. and Brummer, G.J.A., 2006. Oxygen isotope ecology of recent planktic foraminifera at the central Walvis Ridge (SE Atlantic). *Paleoceanography*, 21, p. PA3009.
- Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V., Blunier, T., Lemieux, B., Barnola, J.M., Raynaud, D., Stocker, T.F. and Chappellaz, J., 2008. Orbital and millennial-scale features of atmospheric CH₄ over the past 800,000 years. *Nature*, 453, pp.383-386.
- Lucas, A.J., Nash, J.D., Pinkel, R., MacKinnon, J.A., Tandon, A., Mahadevan, A., Omand, M.M., Freilich, M., Sengupta, D., Ravichandran, M. and Le Boyer, A., 2016. Adrift upon a salinity-stratified sea: A view of upper-ocean processes in the Bay of Bengal during the southwest monsoon. *Oceanography*, 29, pp.134-145.
- Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K. and Stocker, T.F., 2008. High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature*, 453, pp.379-382.
- Maslin, M.A., Li, X.S., Loutre, M.F. and Berger, A., 1998. The contribution of orbital forcing to the progressive intensification of Northern Hemisphere glaciation. *Quaternary Science Reviews*, 17, pp.411-426.

- Maslin, M.A. and Ridgwell, A.J., 2005. Mid-Pleistocene revolution and the 'eccentricity myth'. Geological Society, London, Special Publications, 247, pp.19-34.
- McClymont, E.L., Sostdian, S.M., Rosell-Melé, A. and Rosenthal, Y., 2013. Pleistocene sea-surface temperature evolution: Early cooling, delayed glacial intensification, and implications for the mid-Pleistocene climate transition. *Earth-Science Reviews*, 123, pp.173-193.
- McCrea, J.M., 1950. On the isotopic chemistry of carbonates and a paleotemperature scale. *The Journal of Chemical Physics*, 18, pp.849-857.
- Mohtadi, M., Steinke, S., Groeneveld, J., Fink, H.G., Rixen, T., Hebbeln, D., Donner, B. and Herunadi, B., 2009. Low-latitude control on seasonal and interannual changes in planktonic foraminiferal flux and shell geochemistry off south Java: A sediment trap study. *Paleoceanography*, 24, p. PA1201.
- Mortyn, P.G. and Charles, C.D., 2003. Planktonic foraminiferal depth habitat and $\delta^{18}\text{O}$ calibrations: Plankton tow results from the Atlantic sector of the Southern Ocean. *Paleoceanography*, 18, p. 1037.
- Mudelsee, M. and Stattegger, K., 1997. Exploring the structure of the mid-Pleistocene revolution with advanced methods of time-series analysis. *Geologische Rundschau*, 86, pp.499-511.
- Mudelsee, M. and Schulz, M., 1997. The Mid-Pleistocene climate transition: onset of 100 ka cycle lags ice volume build-up by 280 ka. *Earth and Planetary Science Letters*, 151, pp.117- 123.
- Mulitza, S., Dürkoop, A., Hale, W., Wefer, G., and Niebler, H.S. 1997. Planktonic foraminifera as recorders of past surface-water stratification. *Geology*, 25, pp.335–338.
- Mulitza, S., Rühlemann, C., Bickert, T., Hale, W., Pätzold, J. and Wefer, G., 1998. Late Quaternary $\delta^{13}\text{C}$ gradients and carbonate accumulation in the western equatorial Atlantic. *Earth and Planetary Science Letters*, 155, pp.237-249.
- Murtugudde, R., Beauchamp, J., McClain, C.R., Lewis, M. and Busalacchi, A.J., 2002. Effects of penetrative radiation on the upper tropical ocean circulation. *Journal of Climate*, 15, pp.470-486.
- Naik, S.S. and Naidu, P.D., 2019. Coupling of thermocline depth and strength of the Indian, summer monsoon during deglaciation. *Journal of Earth System Science*, 128, pp.1-6.
- Narvekar, J. and Prasanna Kumar, S., 2006. Seasonal variability of the mixed layer in the central Bay of Bengal and associated changes in nutrients and chlorophyll. *Deep Sea Research Part I: Oceanographic Research Papers*, 53, pp.820-835.
- Narvekar, J. and Prasanna Kumar, S., 2014. Mixed layer variability and chlorophyll a biomass in the Bay of Bengal. *Biogeosciences*, 11, pp.3819-3843.
- Niebler, H.S., Hubberten, H.W. and Gersonde, R., 1999. Oxygen isotope values of planktic foraminifera: a tool for the reconstruction of surface water stratification. *In Use of Proxies in Paleoceanography*, pp. 165-189.
- Nilsson-Kerr, K., Anand, P., Sexton, P.F., Leng, M.J. and Naidu, P.D., 2022. Indian Summer Monsoon variability 140–70 thousand years ago based on multi-proxy records from the Bay of Bengal. *Quaternary Science Reviews*, 279, p.107403.

- Ota, Y., Kuroda, J., Yamaguchi, A., Suzuki, A., Araoka, D., Ishimura, T., Expedition, N.G.H.P., Team, J.S. and Kawahata, H., 2019. Monsoon-influenced variations in plankton community structure and upper-water column stratification in the western Bay of Bengal during the past 80 ky. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 521, pp.138-150.
- Parker, F.L., 1962. Planktonic foraminiferal species in Pacific sediments. *Micropaleontology*, 8, pp.219-254.
- Patrick, A. and Thunell, R.C., 1997. Tropical Pacific sea surface temperatures and upper water column thermal structure during the last glacial maximum. *Paleoceanography*, 12, pp.649- 657.
- Peeters, F.J., Brummer, G.J.A. and Ganssen, G., 2002. The effect of upwelling on the distribution and stable isotope composition of *Globigerina bulloides* and *Globigerinoides ruber* (planktic foraminifera) in modern surface waters of the NW Arabian Sea. *Global and Planetary Change*, 34, pp.269-291.
- Pena, L.D. and Goldstein, S.L., 2014. Thermohaline circulation crisis and impacts during the mid-Pleistocene transition. *Science*, 345, pp.318-322.
- Prasad, T.G., 1997. Annual and seasonal mean buoyancy fluxes for the tropical Indian Ocean. *Current Science*, 73, pp.667-674.
- Prasanna Kumar, S., Nuncio, M., Narvekar, J., Kumar, A., Sardesai, D.S., De Souza, S.N., Gauns, M., Ramaiah, N. and Madhupratap, M., 2004. Are eddies nature's trigger to enhance biological productivity in the Bay of Bengal?. *Geophysical Research Letters*, 31, p. L07309.
- Prokopenko, A.A., Hinnov, L.A., Williams, D.F. and Kuzmin, M.I., 2006. Orbital forcing of continental climate during the Pleistocene: a complete astronomically tuned climatic record from Lake Baikal, SE Siberia. *Quaternary Science Reviews*, 25, pp.3431-3457.
- Rashid, H., Flower, B.P., Poore, R.Z. and Quinn, T.M., 2007. A~ 25 ka Indian Ocean monsoon variability record from the Andaman Sea. *Quaternary Science Reviews*, 26, pp.2586-2597.
- Ravelo, A.C. and Fairbanks, R.G., 1992. Oxygen isotopic composition of multiple species of planktonic foraminifera: Recorders of the modern photic zone temperature gradient. *Paleoceanography*, 7, pp.815-831.
- Ravelo, A.C. and Shackleton, N.J., 1995. Evolution of surface water circulation in the east equatorial Pacific over the past 2.0 Ma: Isotopic measurements from ODP Site 851. In *Proc. Ocean Drill. Program Sci. Results*, 138, pp. 503-514.
- Ravelo, A.C. and Andreasen, D.H., 1999. Using planktonic foraminifera as monitors of the tropical surface ocean. In *Reconstructing Ocean History*, pp.217-243. Springer, Boston, MA.
- Raymo, M.E., Lisiecki, L.E. and Nisancioglu, K.H., 2006. Plio-Pleistocene ice volume, Antarctic climate, and the global $\delta^{18}\text{O}$ record. *Science*, 313, pp.492-495.
- Rohling, E.J., Sprovieri, M., Cane, T., Casford, J.S., Cooke, S., Bouloubassi, I., Emeis, K.C., Schiebel, R., Rogerson, M., Hayes, A. and Jorissen, F.J., 2004. Reconstructing past planktic foraminiferal habitats using stable isotope data: a case history for Mediterranean sapropel S5. *Marine Micropaleontology*, 50, pp.89-123.

- Rohling, E.J., Foster, G.L., Grant, K.M., Marino, G., Roberts, A.P., Tamisiea, M.E. and Williams, F., 2014. Sea-level and deep-sea-temperature variability over the past 5.3 million years. *Nature*, 508, pp.477-482.
- Rühlemann, C., Diekmann, B., Mulitza, S. and Frank, M., 2001. Late Quaternary changes of western equatorial Atlantic surface circulation and Amazon lowland climate recorded in Cear a Rise deep-sea sediments. *Paleoceanography*, 16, pp.293-305.
- Saraswat, R., Nigam, R. and Correge, T., 2014. A glimpse of the Quaternary monsoon history from India and adjoining seas. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 397, pp.1-6.
- Saraswat, R., Kurtarkar, S.R., Yadav, R., Mackensen, A., Singh, D.P., Bhadra, S., Singh, A.D., Tiwari, M., Prabhukulskar, S.P., Bandodkar, S.R. and Pandey, D.K., 2020. Inconsistent change in surface hydrography of the eastern Arabian Sea during the last four glacial–interglacial intervals. *Geological Magazine*, 157, pp.989-1000.
- Saraswat, R., Suokhrie, T., Naik, D.K., Singh, D.P., Saalim, S.M., Salman, M., Kumar, G., Bhadra, S.R., Mohtadi, M., Kurtarkar, S.R. and Maurya, A.S., 2023a. Large freshwater-influx-induced salinity gradient and diagenetic changes in the northern Indian Ocean dominate the stable oxygen isotopic variation in *Globigerinoides ruber*. *Earth System Science Data*, 15, pp.171-187.
- Saraswat, R., Rajput, K.R., Bandodkar, S.R., Bhadra, S.R., Kurtarkar, S.R., Jo o, H.M., Suokhrie, T. and Kumar, P., 2023b. Persistent increase in carbon burial in the Gulf of Mannar, during the Meghalayan Age: Influence of primary productivity and better preservation. *Geological Magazine*, pp.1-18. doi:10.1017/S001675682200111X
- Saravanan, P., Gupta, A.K., Zheng, H., Majumder, J., Panigrahi, M.K. and Kharya, A., 2020. A 23000 year old record of paleoclimatic and environmental changes from the eastern Arabian Sea. *Marine Micropaleontology*, 160, p.101905.
- Sarma, V.V. and Aswanikumar, V., 1991. Subsurface chlorophyll maxima in the northwestern Bay of Bengal. *Journal of Plankton Research*, 13, pp.339-352.
- Sautter, L.R. and Thunell, R.C., 1991. Planktonic foraminiferal response to upwelling and seasonal hydrographic conditions; sediment trap results from San Pedro Basin, Southern California Bight. *The Journal of Foraminiferal Research*, 21, pp.347-363.
- Schiebel, R. and Hemleben, C., 2017. *Planktic foraminifers in the modern ocean*. Berlin: Springer.
- Schiebel, R., Smart, S.M., Jentzen, A., Jonkers, L., Morard, R., Meilland, J., Michel, E., Coxall, H.K., Hull, P.M., Garidel-Thoron, T., Aze, T., Quill ev er e, F., Ren, H., Sigman, D.M., Vonhof, H.B., Mart nez-Garc a, A., Kucera, M., Bijma, J., Spero, H.J., and Haug, G.H., 2018. Advances in planktonic foraminifer research: New perspectives for paleoceanography. *Revue de Micropaleontology*, 61, pp.113–138.
- Schlitzer, R., 2022. *Ocean Data View*. [Software]
- Schmieder, F., von Dobeneck, T., and Bleil, U., 2000. The Mid-Pleistocene climate transition as documented in the deep South Atlantic Ocean: Initiation, interim state and terminal event. *Earth and Planetary Science Letters*, 179, pp.539–549.

- Schmuker, B. and Schiebel, R., 2002. Planktic foraminifers and hydrography of the eastern and northern Caribbean Sea. *Marine Micropaleontology*, 46, pp.387-403.
- Sengupta, S., Parekh, A., Chakraborty, S., Ravi Kumar, K. and Bose, T., 2013. Vertical variation of oxygen isotope in Bay of Bengal and its relationships with water masses. *Journal of Geophysical Research: Oceans*, 118, pp.6411-6424.
- Shackleton, N.J., 1974. Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus *Uvigerina*: isotopic changes in the ocean during the last glacial, pp.203-209, *Colloques Internationaux du C.N.R.S.*, 219,
- Shackleton, N.J. and Vincent, E., 1978. Oxygen and carbon isotope studies in recent foraminifera from the southwest Indian Ocean. *Marine Micropaleontology*, 3, pp.1-13.
- Shanthi, R., Poornima, D., Naveen, M., Thangaradjou, T., Choudhury, S.B., Rao, K.H. and Dadhwal, V.K., 2016. Air-sea CO₂ flux pattern along the southern Bay of Bengal waters. *Dynamics of Atmospheres and Oceans*, 76, pp.14-28.
- Shenoi, S.S.C., Shankar, D. and Shetye, S.R., 2002. Differences in heat budgets of the near- surface Arabian Sea and Bay of Bengal: Implications for the summer monsoon. *Journal of Geophysical Research: Oceans*, 107, pp.5-1.
- Shetye, S.R., Gouveia, A.D., Shenoi, S.S.C., Sundar, D., Michael, G.S. and Nampoothiri, G., 1993. The western boundary current of the seasonal subtropical gyre in the Bay of Bengal. *Journal of Geophysical Research: Oceans*, 98, pp.945-954.
- Sijinkumar, A.V., Nath, B.N., Clemens, S., Gayathri, N.M. and Miriyala, P., 2021. Late Quaternary record of Indian summer monsoon-induced stratification and productivity collapse in the Andaman Sea. *Journal of Quaternary Science*, 36, pp.298-310.
- Sobarzo, M., Bravo, L., Donoso, D., Garcés-Vargas, J. and Schneider, W., 2007. Coastal upwelling and seasonal cycles that influence the water column over the continental shelf off central Chile. *Progress in Oceanography*, 75, pp.363-382.
- Spero, H.J., Bijma, J., Lea, D.W. and Bemis, B.E., 1997. Effect of seawater carbonate concentration on foraminiferal carbon and oxygen isotopes. *Nature*, 390, pp.497-500.
- Spero, H.J., Mielke, K.M., Kalve, E.M., Lea, D.W. and Pak, D.K., 2003. Multispecies approach to reconstructing eastern equatorial Pacific thermocline hydrography during the past 360 kyr. *Paleoceanography*, 18, p. 1022.
- Stainbank, S., Spezzaferri, S., Rüggeberg, A., Raddatz, J., de Leau, E.S., Yu, S.M., Zhang, M. and Kroon, D., 2021. Monsoon and tropical climate forcing on the physicochemical and thermocline characteristics of the Maldives Inner Sea: Insights from Marine Isotope stages 1–2 and 10–13. *Paleoceanography and Paleoclimatology*, 36, p.e2020PA004105.
- Steinke, S., Groeneveld, J., Johnstone, H. and Rendle-Bühring, R., 2010. East Asian summer monsoon weakening after 7.5 Ma: Evidence from combined planktonic foraminifera Mg/Ca and $\delta^{18}\text{O}$ (ODP Site 1146; northern South China Sea). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 289, pp.33-43.

- Steph, S., Tiedemann, R., Groeneveld, J., Sturm, A. and Nürnberg, D., 2006. Pliocene changes in tropical east Pacific upper ocean stratification: response to tropical gateways? In Proceedings of the Ocean Drilling Program: Scientific Results, 202, pp. 1-51.
- Steph, S., Regenberg, M., Tiedemann, R., Mulitza, S. and Nürnberg, D., 2009. Stable isotopes of planktonic foraminifera from tropical Atlantic/Caribbean core-tops: Implications for reconstructing upper ocean stratification. *Marine Micropaleontology*, 71, pp.1-19.
- Steph, S., Tiedemann, R., Prange, M., Groeneveld, J., Schulz, M., Timmermann, A., Nürnberg, D., Rühlemann, C., Saukel, C. and Haug, G.H., 2010. Early Pliocene increase in thermohaline overturning: A precondition for the development of the modern equatorial Pacific cold tongue. *Paleoceanography*, 25, p. PA2202.
- Subramanian, V., 1993. Sediment load of Indian rivers. *Current Science*, 64, pp.928–930.
- Sun, Y., Clemens, S.C., An, Z. and Yu, Z., 2006. Astronomical timescale and palaeoclimatic implication of stacked 3.6-Myr monsoon records from the Chinese Loess Plateau. *Quaternary Science Reviews*, 25, pp.33-48.
- Tedesco, K., Thunell, R., Astor, Y. and Muller-Karger, F., 2007. The oxygen isotope composition of planktonic foraminifera from the Cariaco Basin, Venezuela: Seasonal and interannual variations. *Marine Micropaleontology*, 62, pp.180-193.
- Thadathil, P., Muraleedharan, P.M., Rao, R.R., Somayajulu, Y.K., Reddy, G.V. and Revichandran, C., 2007. Observed seasonal variability of barrier layer in the Bay of Bengal. *Journal of Geophysical Research: Oceans*, 112, p. C02009.
- Thakur, R., Shroyer, E.L., Govindarajan, R., Farrar, J.T., Weller, R.A. and Moum, J.N., 2019. Seasonality and buoyancy suppression of turbulence in the Bay of Bengal. *Geophysical Research Letters*, 46, pp.4346-4355.
- Tian, J., Wang, P., Chen, R. and Cheng, X., 2005. Quaternary upper ocean thermal gradient variations in the South China Sea: Implications for east Asian monsoon climate. *Paleoceanography*, 20, p. PA4007.
- Triantaphyllou, M.V., Antonarakou, A., Dimiza, M. and Anagnostou, C., 2010. Calcareous nannofossil and planktonic foraminiferal distributional patterns during deposition of sapropels S6, S5 and S1 in the Libyan Sea (Eastern Mediterranean). *Geo-Marine Letters*, 30, pp.1-13.
- Urey, H.C., 1947. The thermodynamic properties of isotopic substances. *Journal of the Chemical Society (Resumed)*, pp.562-581.
- Venancio, I.M., Mulitza, S., Govin, A., Santos, T.P., Lessa, D.O., Albuquerque, A.L.S., Chiessi, C.M., Tiedemann, R., Vahlenkamp, M., Bickert, T. and Schulz, M., 2018. Millennial-to Orbital-Scale Responses of Western Equatorial Atlantic Thermocline Depth to Changes in the Trade Wind System Since the Last Interglacial. *Paleoceanography and Paleoclimatology*, 33, pp.1490-1507.
- Vinayachandran, P.N., Murty, V.S.N. and Ramesh Babu, V., 2002. Observations of barrier layer formation in the Bay of Bengal during summer monsoon. *Journal of Geophysical Research: Oceans*, 107, pp.SRF-19.

- Whitman, J.M. and Berger, W.H., 1993. Pliocene-Pleistocene carbon isotope record, site 586, Ontong Java Plateau. In Berger, WH, Kroenke, LW, Mayer, LA, et al., Proc. ODP, Sci. Results, 130, pp. 333-348.
- Williams, D.F. and Healy-Williams, N., 1980. Oxygen isotopic-hydrographic relationships among recent planktonic foraminifera from the Indian Ocean. *Nature*, 283, pp.848-852.
- Xiao, J. and An, Z., 1999. Three large shifts in East Asian monsoon circulation indicated by loess–paleosol sequences in China and late Cenozoic deposits in Japan. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 154, pp.179-189.
- Yin, Q.Z. and Guo, Z.T., 2008. Strong summer monsoon during the cool MIS-13. *Climate of the Past*, 4, pp.29-34.
- Zweng, M.M., Seidov, D., Boyer, T., Locarnini, M., Garcia, H., Mishonov, A., Baranova, O.K., Weathers, K., Paver, C.R. and Smolyar, I., 2019. World ocean atlas 2018, volume 2: Salinity. In: A. Mishonov, Technical Editor. NOAA Atlas NESDIS 81, pp. 50.