

## **A synthesis of paleomonsoon and associated processes from the unique depocenter, Andaman Sea**

**Rinu Fathima<sup>1,2</sup>, Rajeev Saraswat<sup>1\*</sup>**

<sup>1</sup>Micropaleontology Laboratory, Geological Oceanography Division,  
National Institute of Oceanography, Dona Paula, Goa, India

<sup>2</sup>School of Earth, Ocean and Atmospheric Sciences, Goa University, Goa, India

(\* For Correspondence: rsaraswat@nio.org)

### **Abstract**

The Andaman Sea is a unique deep basin with limited connectivity with the global ocean. The riverine influx from the major rivers draining from the surrounding Asian landmass combined with a large amount of rainfall during the summer monsoon season strongly affects the Andaman Sea. The biogenic carbonate-rich sediments with ample terrigenous material ensure the potential applicability of a wide range of proxies to reconstruct the past. Thus, the Andaman Sea is an excellent archive to reconstruct the past monsoon and associated processes. The isolated nature of the deeper regions provides a unique opportunity to understand deep water changes, without the usual influence of the Antarctica and North Atlantic Ocean. The presence of both the aerial and sub-marine volcanoes in the Andaman Sea makes it an interesting region to understand the temporal changes in the climate-tectonics interaction. Here, we synthesize the paleomonsoon and associated studies from the Andaman Sea. A majority of the paleoclimatic studies from this region are restricted to the last glacial-interglacial transition, with limited attention being paid to the long-term changes. The provenance of fresh water and sediments reaching the Andaman Sea varied during glacial-interglacial times. A few coral and speleothem based studies provide high-resolution records of the past monsoon from the Andaman region. The limited drilling during the last expedition to the Andaman Sea (Site U1447 and U1448), was restricted to a relatively shallow depth. The region requires both high-resolution and long-term paleoclimatic studies based on several more drill holes covering a range of depths and latitudinal zones.

**Keywords** - Andaman Sea, Monsoon, Foraminifera, Hydrography, Sediments.

## 1. Introduction

Global temperature will increase by 6°C due to the rapid anthropogenic emission of carbon dioxide (CO<sub>2</sub>) which is likely to double by the end of the 21<sup>st</sup> century (Beaulieu et al. 2012). The warming will affect the global hydrological cycle and hence monsoon intensity and distribution. More than 22% of the world's population depends on the South Asian summer monsoon (SAM) (Ashfaq et al. 2009) and by the year 2050, a total of 5 billion people will be directly influenced by any variation in SAM precipitation (Lutz and Kc 2011). Hence, any change in the monsoon pattern will have severe consequences for mankind. Therefore, understanding the factors responsible for monsoon variability is a topic of major scientific interest. The long-term monsoon records covering different boundary conditions can help us to understand the monsoon dynamics. Several previous studies reported monsoon variability using wind-driven upwelling records from the Arabian Sea. However, how much they represent changes in the rainfall component of the monsoon remains a question. The monsoon precipitation depends on the moisture content of the incoming winds and their transport pathways rather than the wind. Hence, when we look into the past rainfall pattern in regions with higher precipitation and run-off, like the Andaman Sea and the Bay of Bengal, we are likely to get better information about the monsoon. Andaman Basin is one of the sites, suitable to reconstruct the past climate due to its confined nature (the presence of island arcs that separate it from the Bay of Bengal). It preserves the large terrigenous input by the monsoon-fed rivers (Rodolfo 1969a; Miriyala et al. 2017; Huang et al. 2020). As the entire Andaman Sea is a part of the exclusive economic zone of the neighboring countries, a majority of the paleoclimatic studies from this region are done by workers from these countries. Several short gravity cores collected from different parts of the Andaman Sea have been used to reconstruct the changes in the monsoon-induced runoff and related processes in the past. A synthesis of these efforts can help to understand the gaps/lacuna in our understanding of this basin in the past. This work aims to provide a comprehensive review of the paleoclimate studies based on the sediments collected from the Andaman Sea so that the gaps in research in this particular area can be properly understood. Since, most of the studies from the basin focused on changes that happened during the last glacial-interglacial, the comparability and differences in the records and the possible reason for the differences, are discussed. Additionally, as the changes in the stable oxygen isotopic ratio of planktic foraminifera ( $\delta^{18}\text{O}$ ), are often used to reconstruct hydroclimate variability, the records from the basin are assessed on a common chronology to understand spatial changes in the monsoon and associated processes since the last glacial maximum (LGM).

## **2. Geological Setting of the Andaman Sea**

The Andaman Sea, a Neogene-Quaternary basin is an oblique convergence extensional basin formed by trans tension (Curry et al. 1979; Curry 1989; Raju et al. 2004). It is a marginal sea situated in the north-eastern part of the Indian Ocean (Sijinkumar et al. 2020a) and is enclosed by Myanmar in the north, Sumatra in the south, the Malay Peninsula in the east, and Andaman Nicobar Islands, which is an extension of the Andaman Nicobar ridge, in the west (Fig. 1a) (Raju et al. 2004). The basin has a maximum depth of 4400 m, an average depth of 1096 m, a length of 1200 km, and a width of 650 km. It covers a total area of 800,000 km<sup>2</sup> (Rodolfo 1969a). The prominent geomorphological features within the basin include the Nicobar Deep, Barren-Narcondam volcanic islands, Invisible Bank, and Alcock and Sewell seamount complexes (Rodolfo 1969b).

The Andaman Sea is part of an Island arc system formed as a result of anticlockwise rotation and subduction of the Indian plate beneath the Eurasian plate since the Cretaceous (Moore et al. 1980; Roy and Sharma 1993; Curry 2005; Roy et al. 2020). A two-phase opening history for the Andaman Sea was suggested and includes an initial rifting episode in Oligocene- early Miocene and active spreading in the post-middle Miocene (Curry et al. 1979). Khan and Chakraborty (2005) studied these two phases by drawing isochrones that indicated the deformation events. Early Miocene (~25 Ma) stretching and rifting of the overriding plate caused the separation of the Sunda and Burma plates and resulted in the formation of a spreading center in the late Miocene-early Pliocene (Curry 2005; Singh et al. 2013; Morley 2016). They could correlate their 11 Ma record with early rifting and stretching. However, the 4–5 Ma event was interpreted as the major forcing behind the spreading phase of the Andaman Sea. Based on the magnetic anomalies, it was suggested that the seafloor spreading in the Andaman Basin started before 4 Ma with opening rates of 1.6 cm/yr (Raju et al. 2004). A silica crash at ~6 Ma is attributed to the restriction of nutrient-rich waters from the western Pacific entering into the Andaman Sea due to the closure of Indonesian Throughflow (Cawthorn et al. 2014). Additionally, the variation in depth of deposition of benthic foraminifera in the Miocene and Pliocene indicates the uplift of the basin beginning in the middle Miocene and culminating in the Pliocene (Frerichs 1971).

## **3. Andaman Sea Oceanography and Water Circulation**

The water exchange takes place between the Andaman Sea and the Bay of Bengal via shallow channels. The Deep Prepares Channel, the Ten Degree Channel, and the Great Channel connect the Andaman Sea with the eastern Bay of Bengal, and the Malacca Strait connects it with the

South China Sea (Wyrcki 1971; Rizal et al. 2012; Chatterjee et al. 2017; Sebastian et al. 2019) (Fig. 1b). The oceanographic processes and water column structure (temperature, salinity, and dissolved oxygen) of the Bay of Bengal and the Andaman Sea are similar upto the sill depth (1200-1300 m). The presence of sills also limits intermediate and deep water circulation at greater depths (Babu and Sastry 1971; Naqvi et al. 1994). Beneath the sill depth, the Andaman Sea water is less saline, warmer ( $\sim 2^{\circ}\text{C}$ ), and has lower dissolved oxygen concentration as compared to the Bay of Bengal waters (Raju et al. 1981; Naqvi et al. 1994; Sijinkumar et al. 2016a). It was postulated that along with the confined nature of the basin (Rao and Jayaraman 1968; Sengupta et al. 1981), the  $2^{\circ}\text{C}$  increase in the temperature was due to the tide-induced vertical mixing which kept the water warmer (Jithin and Francis 2020). Additionally, Sarma and Narvekar (2001) documented that the Andaman Sea waters had lower total alkalinity and higher  $\text{pCO}_2$  (warmer waters) beneath the sill depth, as compared to the Bay of Bengal waters.

The average sea surface temperature (SST) in the Andaman Sea is quite uniform throughout the year and varies from  $27$  to  $30^{\circ}\text{C}$  (Babu and Sastry 1976; Kurian et al. 2008). The temperature remains constant up to a depth of 50 meters resulting in water stratification and this prevents vertical mixing (Sarma and Narvekar 2001). Raju et al. (1981) identified a mixed layer depth varying between 25 to 80 m. In a vertical profile, temperature varies from  $13^{\circ}\text{C}$  at 200 m to  $9^{\circ}\text{C}$  at depths of 500–600 m and further decreases to  $2.7$ – $3.0^{\circ}\text{C}$  at 4000 m. The total thermocline thickness is about 150 m (Fairbridge and Rodolfo 1974; Saidova 2008). The surface salinity is low in the Andaman Sea due to the large river influx and it increases southward (Rodolfo 1969a; Sebastian et al. 2019). During summer monsoons the surface salinity decreases due to the large amount of freshwater input from the Irrawaddy, Salween, and Sittang (ISS) river systems (Varkey et al. 1996). At depths of 200 m, salinity increases to 34.9–35.0, then further to 4000 m salinity remains almost constant (Saidova 2008). The dissolved oxygen content is uniform at the surface ( $\sim 4.6$  ml/l). At 50 m, it decreases to 2.2 to 4.4 ml/l and further decreases to 0.4 to 1.6 ml/l at 100 m. This large variability was suggested to be due to the convergences and divergences in the field of motion (Babu and Sastry 1976). A mid-depth intense oxygen deficient zone (ODZ) was reported at 150-800 m (Rodolfo 1969a; Sengupta et al. 1981). The primary productivity in the Andaman Sea is less than that in the Arabian Sea and higher than that of the Bay of Bengal (Sijinkumar et al. 2020a). The productivity in the offshore region is  $\sim 0.8$ – $1.0$   $\text{mgC}/\text{m}^2/\text{d}$  and  $<0.6$   $\text{mgC}/\text{m}^2/\text{d}$  in the coastal areas (Janekarn and Hylleberg 1989).

The direction of surface currents in the Andaman Sea reverses seasonally due to reversing monsoon winds (Wyrcki 1973) (Fig. 2). A three-dimensional model experiment on circulation

pattern in the Andaman Sea and Malacca strait found that the surface currents change seasonally, depending on two different monsoons (Rizal et al. 2012), and was in good agreement with previous field studies (Wyrtki 1961). The circulation pattern is cyclonic (west to east) during the summer monsoon (May–September) and anticyclonic (east to west) during the winter monsoon (December–February) (Potemra et al. 1991). The surface currents enter the Andaman basin through Preparaes and Ten Degree channel during the summer monsoon and flow towards the southeast, resulting in a clockwise circulation pattern and exit through the Great Channel. In the case of winter monsoon, the current pattern associated with Preparaes Channel is not clear. The currents are usually southwest exiting through the Ten Degree and Great Channels (Rizal et al. 2012; Ali et al. 2015). The surface circulation strongly regulates sediment dispersal in the Andaman Sea (Damodararao et al. 2016). The eastward currents during the summer monsoon, mix sediments from the northern Andaman shelf with Irrawaddy sediments, which are then transported eastward to mix with Salween sediments and finally deposited in the Gulf of Martaban and eastern shelf. During the winter, the westward current transports the sediments deposited on the shelf during the summer monsoon, to the eastern Bay of Bengal (Colin et al. 1999; Ramaswamy et al. 2004).

#### **4. Paleoclimate Archives from the Andaman Sea**

The Andaman Sea is an ideal site for paleoclimatic studies due to its confined nature and good carbonate preservation. It preserves signatures of monsoon variability in the sediments deposited by the monsoon-fed rivers (Rodolfo 1969a; Miriyala et al. 2017; Huang et al. 2020). Our understanding of the instrumental records of rainfall patterns and changes goes back to AD 1871 when a network of rain gauge stations were established in the nation. To further go back in time and understand monsoon changes in centennial, millennial, orbital, and tectonic time scales, people use indirect monsoon signatures preserved in natural archives. The climate archives explored from the Andaman Sea include sediments, corals, and speleothems.

##### **4.1 Sediments**

The sediments deposited in the deep sea environments are the major recorders of the paleoclimate and paleoceanographic conditions (Xu et al. 2022). The sediments can help to reconstruct both the fine and coarse resolution climate changes of the short and long time periods. The average sedimentation rate in the Andaman Sea was estimated to be ~13 cm/ky (Sijinkumar et al. 2020a). The highest sedimentation rate (~860 cm/ky) was at the mouth of the Irrawaddy River. The lowest sedimentation rate (~3.1 cm/ky) was in the western Andaman Sea. The sedimentation rate decreases from north to south due to the proximity of the northern part to the

Irrawaddy River (Sijinkumar et al. 2020a). In the western Andaman Sea, a late Miocene and Pliocene hiatus in sedimentation was observed (Flores et al. 2014). The sedimentation rate in the Andaman Sea varied with the strength of the monsoon. A very low sedimentation rate during Marine Isotopic Stage (MIS) 2 (3 cm/ky) was followed by an increase in the Holocene/MIS 1 (7.7 cm/ky) (Awasthi et al. 2014). Lal et al. (2022) also suggested a decline in sediment contribution during the Last Glacial Maximum (LGM) due to the weak Indian Summer Monsoon (ISM) and the large extent of glaciations.

### **Speleothem and Corals**

Several workers have used the speleothems and corals, commonly present in the Andaman region, to reconstruct the past monsoon variations. The speleothems are secondary carbonate precipitates that are a characteristic feature of a karst environment (Laskar et al. 2011). The oxygen isotopic composition of speleothems depends on the rainwater  $\delta^{18}\text{O}$  and the mean annual cave temperature (Yadava and Ramesh 2001, 2005; Laskar et al. 2013). Currently,  $\delta^{18}\text{O}$  in the Indian speleothems is used as a precipitation proxy, on time scales ranging from centuries to millennia (Laskar et al. 2011; Band and Yadava 2020). The carbon isotopic ( $\delta^{13}\text{C}$ ) changes of speleothems depend on the climate-driven vegetation changes and are often used along with  $\delta^{18}\text{O}$  (Genty et al. 2001; Cruz Jr et al. 2006). The advantage of using speleothem as a proxy includes their annual to decadal resolution and Uranium/Thorium (U/Th) dating that goes back to the late Pleistocene (Band and Yadava 2020). The Andaman Islands in the southern Indian Ocean receive the first and last shower of the monsoon. Thus, the speleothem records in Bartang caves of Andaman and Nicobar Islands serve as good proxies for paleomonsoon studies (Laskar et al. 2011). By studying the stalagmite of Bartang caves, Laskar et al. (2013) established the amount effect as the main factor causing an increase in  $\delta^{18}\text{O}$ . However, a study to understand atmospheric controls on isotopic variations indicated that  $\delta^{18}\text{O}$  is mainly controlled by integrated convective activities (Chakraborty et al. 2016). Further studies also suggested that the southwest monsoon is the main source of annual precipitation in the Andaman Islands (Laskar et al. 2011).

The reef-building corals also provide high-resolution information on the physical and chemical properties of the environments in which they lived during the last several centuries (Chakraborty et al. 2020). The oxygen isotopic composition of corals depends on seawater oxygen isotope composition and sea surface temperature (Dunbar and Wellington 1981; Chakraborty and Ramesh 1997). Additionally, elemental ratios (Sr/Ca, Mg/Ca, and U/Ca) in coral skeletons depend on the temperature-dependent distribution coefficients and thus help in the reconstruction of SST (Beck et al 1992; Wei et al. 2000). A coral colony (*Porites lutea*) south

of Port Blair on the Andaman Islands was studied to understand its response to monsoon changes between 1975 and 2006 by using  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  (Rixen et al. 2011). It was inferred that during the summer monsoon, the site is affected by high salinity Arabian Sea waters and by the Bay of Bengal waters during the winter monsoon. A decreasing influence of the summer monsoon current due to Northern Hemisphere warming was also suggested.

## **5. Modern Proxy Response in the Andaman Sea**

The prominent proxies commonly applied to infer the past climate from the Andaman Sea includes sediment characteristics and microfossils (foraminifera, pteropods, and coccolithophores). The proxy application depends on its sensitivity to different climate parameters. The proxy response to ambient conditions is evaluated by monitoring the modern distribution. Several authors have studied sediment characteristics and distribution of various microorganisms in the surface sediments to understand their relationship with various biophysico-chemical conditions to assess the applicability of these proxies.

### **5.1 Sensitivity of Sediment Characteristics to the Climate Change**

The terrigenous material is a potential source of information regarding weathering and erosion driven by monsoon variability in the source region (Colin et al. 1999; 2006). The terrigenous sediment-based proxies used in paleoclimatic studies include isotope geochemistry, magnetic susceptibility, clay minerals, elemental ratio, and grain size. Different source regions will have a particular isotope value due to different lithologies. Hence, the isotopic composition of the sediments can be applied to trace the sedimentary provenance (Colin et al. 1999; Awasthi et al. 2014; Damodararao et al. 2016). The more advanced tracers for sedimentary provenances are radiogenic isotopic compositions of neodymium (Nd), strontium (Sr), and lead (Pb) (Awasthi et al. 2014; Ali et al. 2015).

Monsoon variability can be reconstructed by using the dominant weathering mechanism. When chemical weathering dominates, it represents a humid and warm climate with a strong summer monsoon/weak winter monsoon. In the case of prominent physical weathering, we have a dry cold climate associated with weak summer monsoons and strong winter monsoons (Lee et al. 2020). The wet periods of summer monsoon are associated with chemical weathering in Irrawaddy plains, compared to physical erosion of Burman ranges during winter (NE monsoon) (Colin et al. 1999). This idea has been used to understand monsoon variability in the past. Rashid et al. (2019) suggested that  $\epsilon_{\text{Nd}}$  values change proportionally with changes in monsoon. The higher values indicate strengthening and smaller values indicate weakening of summer monsoon

in the Andaman region. The strontium isotope ratios were also used with lower  $^{87}\text{Sr}/^{86}\text{Sr}$  values indicating chemical weathering (Colin et al. 1999; Colin et al. 2006; Ali et al. 2015). The clay mineral composition also depends on source rock and type of weathering (pedogenic and detrital) and hence is used in provenance and paleoweathering/paleoclimatic studies in the Andaman Basin (Birkland 1974; Colin et al. 1999; Nagasundaram et al. 2014; Philips et al. 2014; Ali et al. 2015; Lee et al. 2020). The elemental ratios were also used to develop chemical weathering indices to understand the dominant mode of weathering in the basin (Miriyyala et al. 2017; Ota et al. 2017; Lee et al. 2020). Some workers used grain size end-member modeling with other geochemical proxies to understand changes in the monsoon pattern (Colin et al. 1998; Cao et al. 2015; Huang et al. 2020). The magnetic grain size studies by Colin et al. (1998) showed that smaller magnetic grain size is associated with intense summer monsoons and increased chemical weathering. The magnetic grain size and magnetite content in sediments from the northern and southern parts of the Andaman basin revealed differences in monsoon sensitivity of the source area of sediments and variations in weathering patterns during the Holocene and LGM. An isolated nature of the Andaman Sea during LGM due to lower sea levels was identified by rare earth element (REE) studies (Alagarsamy et al. 2010).

## **5.2 Sediment Provenances in the Andaman Sea**

Both, the Andaman Sea and the Bay of Bengal are associated with a large amount of riverine freshwater and sediment input. Irrawaddy and Salween river system contributes  $640 \text{ km}^3/\text{yr}$  of fresh water (Milliman and Farnsworth 2011). Irrawaddy contributes 360 million tonnes of sediments annually (Meade 1996; Robinson et al. 2007) and is the chief sedimentary source to the Andaman Sea (Rodolfo 1969a; Ramaswamy et al. 2004; Rao et al. 2005). The catchment and drainage of Irrawaddy consist of the western Indo-Burman Ranges, Myanmar central basin, and eastern syntaxis of the Himalayas. Salween and eastern tributaries of Irrawaddy drain through the sedimentary, acidic, and metamorphic rocks of the eastern Shan Plateau (Bender 1983; Curray 2005; Najman 2006; Socquet and Pubellier 2005; Robinson et al. 2007; Licht et al., 2013; Sebastian et al. 2019) (Fig. 1a). A proper understanding of the sedimentary sources and their fluxes to the Andaman basin is very crucial before interpreting the paleoclimatic data.

Several studies have been conducted to understand sediment sources in different parts of the Andaman Sea. Most of these studies suggested an Irrawaddy-dominated sediment source in the basin (Rodolfo 1969a; Colin et al. 1999; Miriyyala et al. 2017). However, the sediment provenance might vary depending on the location in the basin. The clay mineralogical and geochemical data from the western Andaman Sea shows that the Indo Burman Arakan ranges



(IBA), Andaman Islands (volcanic rocks), and Barren volcanoes are the prominent sediment sources (Sebastian et al. 2019). Ali et al. (2015) also suggested similar sediment sources including Indo-Burman ranges and central Myanmar with minor contributions from the Andaman Islands and Barren volcanoes. The clay mineralogical study from the same core (Philips et al. 2014) showed smectite as the most abundant clay mineral, indicating weathering of volcanic rocks along the Sunda Arc. The previous clay mineral distribution maps also show the occurrence of smectite in the western Andaman Sea (Rodolfo 1969a). The contribution of local sources to the west Andaman Sea was highlighted based on similar  $\epsilon_{Nd}$  values of the middle Andaman and Neil islands (Miriyala et al. 2017). About 60% of sediment contribution to the western part of the Andaman Basin comes from the Irrawaddy catchment and the western slopes of the IBA (Awasthi et al. 2014).

The Irrawaddy sources dominate the sediments in the central and eastern parts of the Andaman Sea. The sediment provenance studies from the Sewell seamount suggested Irrawaddy as the main sediment source (Colin et al. 1999). The Central Andaman Trough (CAT) sediment source can be traced back to ISS river systems (Miriyala et al. 2017). The Irrawaddy River is also the primary terrigenous sediment contributor to the southeastern continental slope of the Andaman Sea (Cao et al. 2015). Damodararao et al. (2016) identified sediment contribution to the Andaman Sea from the granitic ranges of western Thailand and southern Myanmar. The intense precipitation in this region results in erosion with the sediments being carried to the adjacent shelf by Tavoy and the Tanintharyi rivers. Based on the spade core samples collected from the Andaman Back arc basin, the altered basinal volcanic products and biogenic sources with river input, were found to constitute the main sediment sources (Kurian et al. 2008). Colin et al. (2006) used two different cores to understand the variability of sediment sources in various parts of the Andaman Sea. In the northern part of the basin, the sediments are contributed by the Burman ranges and Irrawaddy River, while in the south, Irrawaddy only provides the sediments.

The spatial variation in precipitation intensity can result in differences in the source regions that contributed sediments in the basin. Miriyala et al. (2017) studied sediment source variability in CAT and observed that during the glacial period with intensified northeast (NE) monsoon, Salween and Sittang rivers were the major sediment contributor while the Irrawaddy River and Arakan coast were the major sediment contributor during the interglacial period with an intense southwest monsoon. The variability in contribution from different source regions was also suggested by Awasthi et al. (2014). They suggested that during Northern Hemisphere cooling periods, a southward shift of the locus of southwest monsoon from the Himalayas to Myanmar,

resulted in a higher contribution from IBA and eastern Andaman, without any reduction in the monsoon intensity. Interestingly, a sediment core (NGHP-17) in the southwest of the core SK234 GC60 (Awasthi et al. 2014) showed differing results. The authors (Ali et al. 2015) documented a stable sediment contribution from the Indo-Burman Ranges and Central Myanmar for the past 60 ka. They postulated that changes in the sediment source of SK234 GC60 may be due to differences in transport when Ganga-Brahmaputra sediments from the Bay of Bengal were transported to the Andaman Sea. A stable sediment source in the Andaman Sea was also suggested by several others (Colin et al. 1999; 2006; Lee et al. 2020).

### **5.3 Foraminiferal Studies from the Andaman Sea**

Foraminifera, due to their abundance and widespread distribution in the marine realm, are widely used to reconstruct the past climate. Initial studies were focused to understand climate-induced changes in the abundance and diversity of foraminifera (Murray 1897; Pfleger 1948; Arrhenius 1952). Later, the potential of foraminiferal shells to record chemical and isotopic signals were found (Boyle 1981; Boyle and Keigwin 1985; Urey et al. 1951; Emiliani and Epstein 1953; Emiliani 1955). Since then, foraminiferal shells have been used as an excellent indicator of the seawater properties like temperature, salinity, dissolved oxygen, productivity, and sea level changes (Saraswat et al. 2015).

Detailed studies on foraminiferal distribution and their response to varying environments are still lacking from the Andaman Sea. A few studies used foraminiferal population density for environment monitoring in the basin (Pam and Mohan 2022; Mohan et al. 2013). The foraminiferal distribution in the Myanmar shelf region of the basin shows a higher diversity in the west compared to the east due to excessive terrestrial dilution in the east (Hla et al. 2021). Muruganantham and Mohan (2015) suggested a few benthic foraminifera as indicators of the monsoon and non-monsoon periods, based on their abundance. A qualitative classification of benthic foraminifera into eleven communities was done by Saidova (2008). The foraminiferal assemblage within the basin was used to separate pre-tsunami and tsunami sediments (Hawkes et al. 2007).

Both, the destructive and non-destructive foraminiferal proxies have been used to understand ISM variability in the Andaman Sea. The monsoon variability can be effectively studied by using planktic foraminiferal assemblage and abundances (Conan and Brummer 2000; Gayathri et al. 2022). In addition, *Pulleniatina* Minimum Events (PMEs) and *Globigerinoides ruber* morphotype abundance was also used to understand monsoon variability (Sijinkumar et al. 2011; Jayan et al. 2021). The planktic foraminiferal oxygen isotope ( $\delta^{18}\text{O}$ ) depends on SST, monsoon

runoff and the global ice-volume effect (Broecker 1986). A combination of oxygen isotopes and Mg/Ca ratio in foraminifera was used to reconstruct surface water temperature and salinity in the Andaman region (Ahmad et al. 2000; Rashid et al. 2007; Katz et al. 2010; Sijinkumar et al. 2010, 2015; Gebregiorgis et al. 2018; Kumar et al. 2018; Schiebel et al. 2018; Johnck et al. 2020; Nilsson Kerr et al. 2021). The difference in  $\delta^{18}\text{O}$  and Mg/Ca (temp) between the mixed layer species (*Globigerinoides ruber* and *Trilobatus sacculifer*) and thermocline species (*Globorotalia menardii*, *Pulleniatina obliquiloculata*) has been used to understand water stratification in the past (Bolton et al. 2013; Mohtadi et al. 2014; Gebregiorgis et al. 2016; Singh et al. 2016). The idea was that a larger  $\Delta\delta^{18}\text{O}_{\text{sw}}$  gradient/temperature gradient ( $\Delta T$ ) implies a shallower thermocline while a small  $\Delta\delta^{18}\text{O}_{\text{sw}}$  gradient/weak  $\Delta T$  indicates a deeper thermocline (Ravelo and Shackleton 1995; Steinke et al. 2010; Steph et al. 2009).

#### **5.4 Modern and Paleoclimatic Studies Based on Coccolithophores from the Andaman Sea**

The coccolithophores are calcareous nanoplankton, a dominant carbonate producer playing an essential role in the marine biogeochemical cycles. Their large diversity, good preservation, role in marine biogeochemical cycles, and faster turnover rates make them a potential proxy in paleoclimate studies (Choudhari et al. 2020). No studies have yet focused on the coccolith distribution in the Andaman Sea. The scarcity of data across the Andaman Sea on their modern distribution calls for further research to get a better idea regarding region-specific proxy behaviour, as it will further strengthen the application of coccolith-based proxies in paleoclimate interpretation.

Zhou et al. (2020) used coccolithophores to reconstruct productivity variations in the Andaman Sea during the last 26 ky. The productivity variations from 26-19 ka (drier period) were related to the nutrient discharge from ISS river system. However, during the last 19 ky (humid period), salinity stratification was the prominent factor controlling productivity. Cold events like Younger Dryas (YD) and Heinrich Event were associated with lower stratification and higher productivity. However, periods like Bolling-Allerod (B/A) and early-middle Holocene were characterized by higher precipitation, strong stratification, and lower productivity.

#### **5.5 Pteropod Distribution in the Surface and Sub-surface Sediments of the Andaman Sea**

Pteropods are aragonitic microfossils and their occurrence depends on the physical, chemical, and biological properties of the water masses (Berger 1984; Byrne et al. 1984). They are used to reconstruct bathymetry, productivity, upwelling, water circulation, aragonite compensation depth, dissolved oxygen, and monsoon intensity (Bhattacharjee 2005; Panchang et al. 2007;

Sreevidya et al. 2022). Saha et al., (1997) documented pteropods from different physiographic domains in the Andaman Sea and suggested their paleoceanographic significance. Most of the studies on pteropods in the Andaman Sea focused on reconstructing the nature and variation of Aragonite Compensation Depth (ACD), especially how it varied from LGM to present and its climatic implications (Adelseck and Berger 1975; Almogi Labin et al. 1988). The dependence of pteropod preservation on the carbonate chemistry of the ocean and the strength of ODZ was suggested by Almogi-Labin (1982). Based on pteropods preservation at different depths, Bhattacharjee et al. (2005) demarcated the aragonite compensation depth in the Andaman Sea at 1150 m. Panchang (2007) noted the lower preservation of pteropods in the shallower regions due to the influence of freshwater influx on the Myanmar shelf. A detailed study on the distribution and taxonomy of pteropods and benthic foraminifera was done on the Myanmar shelf by Panchang (2008). The low productivity means organic carbon minima, less intense oxygen deficient zone, high pH due to low CO<sub>2</sub> associated with less organic matter decomposition, and hence a deeper ACD. The paleo-ACD around Car Nicobar Island was reported at 1500 m (Bhattacharjee 2001). Pteropod distribution studies suggested that sea level changes during the past 1280 years remained the same (Panchang et al. 2007). Bhattacharjee (1997) used pteropod preservation spike (PPS) as a biozonation tool in the Quaternary marine sediments.

The sediment trap studies from the Arabian Sea and Bay of Bengal were quite useful in understanding the effect of monsoon variability on the sediment flux and composition as well as the abundance and diversity of the microfossils (Curry et al., 1992; Ramaswamy and Nair, 1994; Guptha et al., 1997; Unger et al., 2003, 2005; Stoll et al., 2007). However, such studies are rare in the Andaman Sea (Wall et al., 2012; Marimuthu et al., 2013).

## **6. Indian Monsoon Variability from the Andaman Region**

Monsoon is the annual reversal of surface winds leading to the rainy summer and dry winter seasons (Ramage 1971; Webster et al. 1999; Wang and Ding 2008). The Indian monsoon is a part of the South Asian monsoon and is driven by the changes in the land-sea thermal contrast and annual cycle of incoming solar radiation (Trenberth et al. 2000; Gebregiorgis et al. 2016). The Intertropical Convergence Zone (ITCZ) meridionally migrates in the monsoon regions and the low-level winds associated with it reverse the direction (Wang et al. 2017). Indian monsoon consists of summer monsoon or southwest monsoon (June-September) and winter monsoon (October-November). At present, the summer monsoon causes 80% of the precipitation in the Indian subcontinent (Gadgil 2003; 2006). This section includes a comprehensive review of the

studies on the past monsoon based on archives from the Andaman Sea, from longer to shorter time scales.

### **6.1 Orbital Scale Monsoon Variability**

One of the biggest advances in paleoclimate research was the introduction of the astronomical theory of climate, the Milankovitch cycles (100 kyr eccentricity cycle, 41 kyr obliquity cycle, and 23 kyr precession cycle) (Milankovitch 1941). It explained the orbital forcing of the glacial cycles and its control on the orbital scale of climate change across the globe (Ruddiman 2001). Several studies have tried to understand the orbital scale variability of the Indian Monsoon (Clemens et al. 1991; Clemens and Prell 2003, 2007; Ruddiman 2006; Clemens et al. 2008; Caley et al. 2011). An eccentricity phased seasonality and corresponding evolutionary changes in the coccolithophores that contributed to the 405000-year cyclicality in the global carbon cycle were inferred from the Andaman Sea (Beaufort et al., 2020). The studies on monsoon variability from the Andaman Basin, date back to the late Miocene. A late Miocene intensification of the South Asian monsoon due to Tibetan uplift has been suggested by many authors (Prell et al. 1992; Prell and Kutzbach 1997; Zhisheng et al. 2001; Gupta et al. 2015). However, a few others suggested a decrease in the rainfall strength during the same period (Clift et al. 2008; Molnar and Rajagopalan 2012; Tripathy et al. 2017). Lee et al. (2020) studied monsoon variability since the late Miocene in the Andaman region. A weakening of summer monsoon and strengthened winter monsoon since late Miocene was reported and attributed to global cooling. During the Miocene-Pliocene transition, the mixed layer temperature increased and a shift from precession to obliquity forcing was observed (Fig. 4). This obliquity forcing further increased the transport of heat and moisture from the Southern Hemisphere, resulting in an intense summer monsoon precipitation (Johnck et al. 2020). The obliquity is the main driver of SAM variability. It warms the Southern Hemispheric and increases the inter-hemispheric moisture transport during an obliquity minimum (Gebregiorgis et al. 2018) (Fig. 4). This aligns with the observations of Clemens and Prell (2003, 2007) that the latent heat influx from the Southern Hemisphere drives the monsoon variability. A 23 kyr periodicity signal representing summer rainfall variability was present in a core (Colin et al. 1998). It agrees with past studies that stated Northern Hemisphere summer insolation as the main driver of the Indian monsoon (Kutzbach 1981; Ruddiman 2006). However, records of the long-term orbital scale variation in the monsoon and other associated processes, are limited from the Andaman region.

## **6.2 Monsoon across Marine Isotope Stages (MIS)**

One of the most widely used system to differentiate between glacial and interglacial events are the marine oxygen isotope stages (Railsback et al. 2015). The global isostack LR04 is used to tune isotopic variation in foraminifera (Lisiecki and Raymo 2005). A few studies from the Andaman Sea focused on understanding monsoon variability across marine isotopic stages. An intense ISM rainfall throughout MIS 5 despite background cooling was observed (Nilsson Kerr et al. 2022) (Fig. 5). Also, this sustained rainfall transported moisture to the high latitudes resulting in ice sheet growth. This favors the idea that the low latitude processes control the global climate. Based on rainfall reconstruction from six tropical regions (Nilsson Kerr et al. 2021) across MIS 5, a heterogeneous dipole-like pattern with different loci of precipitation was observed. Further, it was noted that this pattern cannot be explained by the meridional shift in ITCZ. The higher carbon isotopic ratio during MIS 2 and 4 was associated with increased productivity and was attributed to the intensified northeast monsoon (Ahmad et al. 2000). The higher chemical weathering intensity, temperature, and precipitation was observed during MIS 3 and 1 and vice versa during MIS 2 indicating climate-driven weathering trends (Lee et al. 2020). Based on the oxygen isotope ratio of foraminifera, Kumar et al. (2018) also stated that the summer was strongest in the Holocene followed by MIS 3, then MIS 2, during the past 66 kyr.

## **6.3 Last Glacial Maximum (23-19 ka) and Early Deglacial (19-15 ka)**

The Last Glacial Maximum (LGM) was defined as the most recent time when global ice sheets reached the maximum integrated volume. It serves as an important period in paleoclimate studies due to its sensitivity in climate model studies, the equilibrium state of the climate, known boundary conditions, and within the range of radiocarbon age dating (Mix et al. 2001). Previous studies have indicated that the northeast monsoon was strong and the southwest monsoon was weak during LGM (Duplessey 1982; Fontugne and Duplessey 1986; Sarkar et al. 1990). The studies from the Andaman basin also showed similar results. The summer monsoon was very weak during the LGM, resulting in a cold and dry climate, and increased salinity (Ahmad et al. 2000; Gebregiorgis et al. 2016; Kumar et al. 2018). A 3°C colder temperature during LGM, compared to the Holocene was inferred, which deviates from CLIMAP values by 1-2°C (Rashid et al. 2007, Liu et al. 2021). During LGM to HS1 (Heinrich Stadials 1), there existed a large north-south productivity gradient, with the southern part of the basin being highly productive due to the winter monsoon and well-mixed water column (Gayathri et al. 2020).

The salinity in the basin remained similar during LGM due to the reduced mixing with the Bay of Bengal waters (isolation of the basin due to sea level fall) (Sijinkumar et al. 2016a). A

few others also suggested an isolated nature of the Andaman Basin during the LGM (Colin et al. 2006; Alagarasamy et al. 2010; Miriyala et al. 2017). However, a few other workers speculated the existence of currents from the Bay of Bengal to the Andaman Sea, hence proper connectivity between these two regions during LGM (Ahmad et al. 2005; Awasthi et al. 2014). A weak stratification and wind-driven deepening of the thermocline during LGM were attributed to the strong winter monsoon (Kumar et al. 2018). The modeling studies by Marzin et al. (2013) showed a teleconnection between abrupt North Atlantic Ocean climate events and a weakened Indian monsoon during glacial intervals. *Pulleniatina* Minimum Events (PMEs) were also observed during LGM, which might have been due to the reduced winter SST and deepening of the thermocline (Sijinkumar et al. 2011). A decrease in the abundance of low salinity-preferring species *Neogloboquadrina dutertrei* (weak summer monsoon) and increased productivity proxies due to convective mixing associated with winter monsoon was observed during LGM (Sijinkumar et al. 2021). The increased abundance of *Globigerinoides ruber* sensu lato was also found during LGM (Jayan et al. 2021). The well-preserved pteropods were a characteristic feature of the cold intervals YD, Heinrich Event (HE) 1, and LGM (Sijinkumar et al. 2010).

A gradual increase in the strength of monsoon was observed during the deglacial period. The 2 to 3 kyr early strengthening of the monsoon in the Andaman region during deglaciation as compared to the Arabian Sea, suggests regional variability and a more complex mechanism than the north-south displacement of ITCZ following insolation changes as the mechanism driving monsoon (Gebregiorgis et al. 2016). The deglacial warming in the Andaman Sea began at 18.5 ka (Liu et al. 2021) and the fluctuations were driven by the Southern Ocean and Antarctic warming trends, atmospheric CO<sub>2</sub> rise, and strength of the solar insolation during mid-summer. An increase in silicate weathering from deglacial to mid-Holocene was suggested (Miriyaala et al. 2017). This study proposed that the CO<sub>2</sub> consumption during weathering can change at a century to glacial-interglacial time scale where chemical weathering is not a later amplifier but worked together with global climate change. The early deglaciation was the driest interval in the last 25 kyr (Rashid et al. 2019), which parallels inferences from the Hulu cave  $\delta^{18}\text{O}$  variations (Wang et al., 2001).

The deglaciation was characterized by the abundance of mesopelagic pteropod forms over epipelagic forms indicating weak ODZ associated with winter monsoon and ventilation (Sijinkumar et al. 2010). Sijinkumar et al. (2015) suggested strong winter monsoon, deeper ACD, and lower CO<sub>2</sub> concentrations as possible mechanisms contributing to pteropod preservation during deglaciation. The changes in intermediate water circulation can be another probable factor

for better pteropod preservation during deglaciation (Sijinkumar et al. 2010). A better preservation of foraminifera during the deglacial period also suggested enhanced ventilation and deepening of the calcium carbonate compensation depth (CCD) (Sijinkumar et al. 2022).

#### **6.4 Bølling–Allerød (B/A) and Younger Dryas (YD)**

Bølling Allerød (B/A) is characterized by an abrupt and drastic warming event in Greenland (Buizert et al. 2014; Obase and Abe-Ouchi 2019). However, Younger Dryas (YD) was a millennial duration cooling episode that started at 12.9 ka in the European continent and punctuated the termination of the last glacial period (Alley 2000; Brauer et al. 2008; Broecker et al. 2010; Dansgaard et al. 1989; Isarin et al. 1998). The previous studies on Greenland ice cores in the high northern latitudes as well as the foraminiferal oxygen isotopic and elemental ratio studies from different parts of the world oceans have confirmed the global nature of YD cooling and temperature rise associated with B/A (Kallel et al. 1988; Kudrass et al. 1991; Anderson et al. 2006; Rasmussen et al. 2006). The results from the Andaman Sea are also comparable with the global data. The sea surface temperature increased with low salinity during B/A followed by cooler temperatures and higher salinity during YD (Ahmad et al. 2000; Sijinkumar et al. 2016a; Rashid et al. 2021). A study on the transition from B/A to YD showed an invasion of northern cold air masses to the Indo-China Peninsula due to the strengthening of the East Asian winter monsoon, resulting in the cooling of the Andaman Sea (Shi et al. 2022). The North Atlantic atmospheric teleconnection influence on ISM was put forth by Sijinkumar et al. (2016b) based on the well-preserved signatures of Heinrich events, LGM, YD, Dansgaard-Oeschger, and deglacial events. PMEs were observed in YD too, due to the similar reasons for their occurrence during LGM. ISM intensified during B/A followed by weakening during the YD (Gayathri et al. 2021; Sijinkumar et al. 2021). A higher dissolution of pteropod shells occurred during the B/A period as indicated by pits, cavities, fractures, and crevices (Sijinkumar et al. 2020b). The low pH due to higher productivity and remineralization during summer monsoon is thought to cause this increased dissolution (Sijinkumar et al. 2015; Sijinkumar et al. 2020b).

#### **6.5 Holocene**

Holocene, also known as the present interglacial started at 11.7 ka when the climate transitioned from the cooler Younger Dryas to a warmer state (Wanner et al. 2015). The early-mid Holocene was suggested to be the wettest period in the Andaman Sea (Rashid et al. 2007; Marzin et al., 2013; Cao et al. 2015; Gebregiorgis et al. 2016; Rashid et al. 2019). Huang et al. (2020) proposed that the Holocene ISM maximum started at ~9.1 ka, instead of the early Holocene. This delay has been attributed to the combined effects of the slowdown of the Atlantic Meridional



Overturning Circulation and the remnant Northern Hemisphere ice sheets during the early Holocene. A sudden decrease in the monsoon strength was reported during the early mid-Holocene (7.0-4.5 ka) (Kumar et al. 2018). Yang et al., (2022) found a significant lag in the maximum rainfall signal of the terrigenous proxy compared to the marine proxy. The marine proxies showed an early Holocene ISM maximum, while the terrigenous proxies suggested an intensification during the mid-Holocene. The authors suggested a south-to-north shift in the maximum precipitation for these differences. This shift was attributed to the combined effect of the ITCZ movement and El Niño Southern Oscillation activities. The sporopollen record from the same core (Yang et al., 2023) also showed similar results with a higher monsoon intensity during the early Holocene. Sijinkumar et al. (2021a) noted lower productivity and higher stratification in the early-mid Holocene suggesting a strong monsoon. Gayathri et al. (2022) found that during the early-mid Holocene, stronger water stratification due to intensified ISM resulted in low productivity with the northern part of the basin being least productive. Not much has been discussed about the 8.2 ka cooling event (Alley et al. 1997) from sediment cores in the Andaman Sea, except a weak period of ISM during 8.5 ka, which might be related to the cooling event (Gaythri et al. 2022).

During the mid-late Holocene, monsoon gradually weakened from 6.0 to 2.0 ka with strong monsoon intervals observed during 6.4 ka, 5.3 ka, and 3.3-3.0 ka (Achyuthan et al. 2014; Nagasundaram et al. 2014). A late Holocene weakening of ISM was also found, followed by strengthening during 2.0 to 1.2 ka (Gebregiorgis et al. 2016; Sijinkumar et al. 2021). The stalagmite oxygen isotope ratios revealed that monsoon decreased sharply during the Roman Warm Period (RWP) (2.1–1.8 ka). The most intense monsoon was observed during the Medieval Warm Period (MWP) (0.8–1.2 ka), followed by a decrease in monsoon during the transition from the MWP to Little Ice Age (450–800 yrs BP) (Laskar et al. 2013; Jaglan et al. 2020). The weakened summer monsoon during the 16<sup>th</sup> to 19<sup>th</sup> century CE might have been due to severe droughts and famines associated with lower rainfall (Jaglan et al. 2020). Further, monsoons intensified during the last 700 years (Ota et al. 2017). The lack or lower abundance of pteropods during the Holocene was attributed to the higher CO<sub>2</sub> concentration and shoaled CCD (Sijinkumar et al. 2015).

## **6.6 Monsoon Variability from the Oxygen Isotopic Ratio of Planktic Foraminifera**

The Andaman Sea is associated with a large river influx from the Irrawaddy, Salween, and Sittang rivers during the summer monsoons which results in low salinity in the northern part of the basin which further increases southward (Rodolfo 1969a; Varkey et al. 1996; Milliman and

Farnsworth 2011; Sebastian et al. 2019). We compiled the oxygen isotopic variation in mixed layer dwelling planktic foraminifera *Globigerinoides ruber* in cores collected from the Andaman Sea (Fig. 6). The spatial variability in the oxygen isotopic ratio of six cores (RVS 2, Sijinkumar et al. 2015; AAS 11, Ahmad et al. 2000; ADM 159, Liu et al. 2021; SK168 GC-01; Sijinkumar et al. 2010; SK234-60, Awasthi et al. 2014; RC12-344, Rashid et al. 2007) between 8°N to 12.5°N, was studied to understand how the river influx and hence monsoon varied during LGM to present (Fig. 6). The oxygen isotopic ratio of foraminiferal shells depends on the isotope ratio of the water from which it is precipitated, the temperature at the time of calcification, and to a lesser extent carbonate ion concentration (Pearson 2012). We assume that the temperature (Fig. 7) and the ice-volume effect remained the same throughout the basin. Thus, any variability in the oxygen isotopic ratio is mainly driven by salinity which can be correlated with the river runoff and precipitation.

A broad comparison of the Marine Isotopic stages shows that MIS 2 had the most enriched isotopic ratio, followed by MIS 3, and MIS 1. This can be correlated with the stronger ISM during MIS 1 and 3. The B/A warming and YD cooling event signatures are present in the cores with a good resolution. YD is associated with a higher salinity due to a weaker ISM and B/A shows lower values due to the stronger ISM. During both LGM and Holocene, the southern part of the basin had higher  $\delta^{18}\text{O}$  compared to the northern part. The clear north-south gradient can be explained by the proximity of the cores in the northern part of the basin to the river influx. LGM had higher  $\delta^{18}\text{O}$  suggesting cooler temperatures weaker summer monsoon, strong cool and dry winter monsoon resulting in high evaporation and high salinity along with global ice volume changes (Duplessey 1982; Sarkar 1990). The low  $\delta^{18}\text{O}$  during the Holocene was due to the warmer temperatures and intensified summer monsoon, leading to decreased evaporation–precipitation (E–P) and less saline waters (Kudrass et al. 2001; Govil and Naidu 2011). The period of most enriched  $\delta^{18}\text{O}$  during LGM and most depleted  $\delta^{18}\text{O}$  during the Holocene, ranges between 18-20 ka and 6-9 ka, respectively, across the basin without any characteristic patterns. A strong salinity gradient across the basin was reported during the mid-Holocene. This salinity gradient was attributed to the intensified summer monsoon. Although, a weaker salinity gradient during early LGM to early deglacial was suggested to be due to the isolated nature of the basin (Gayathri et al. 2022), such a trend couldn't be identified by spatial variation in  $\delta^{18}\text{O}$ . The signatures of 8.2 ka or 4.2 ka cooling events are not present in any record. It is most likely, due to the poor resolution of a majority of the records. Considering different sedimentary provenances, and varying river input, different parts of the basin will give interesting and

variable monsoon signatures. Hence, more high-resolution and longer-time scale studies are required in the Andaman basin.

## **7. Conclusion**

With global temperatures increasing rapidly there have been immense efforts to understand past climate changes. The idea of low latitude forcing of climate change, even though relatively new, has gained huge attention. This calls for more paleoclimatic studies in the lower latitudes. This review focuses on understanding the past monsoon variability from the Andaman Sea. The high sedimentation rates and enclosed nature makes the Andaman Sea an ideal site for paleoclimatic studies. However, due to its location within the exclusive economic zone of the adjoining nations, studies from the Andaman Sea are less as compared to the works from the Bay of Bengal and the Arabian Sea. One of the shortcomings in paleomonsoon studies from the Andaman region is the lack of long-term high-resolution Pliocene/Pleistocene records. This is essential to understand how orbital forcing influenced the monsoon variability in the region. Most of the short-term studies reported a strong winter monsoon during LGM and a strong summer monsoon during the Holocene with the early-mid Holocene being the wettest period. While some suggested an isolated nature of the basin due to lower sea level, others speculated the existence of currents from the Bay of Bengal to the Andaman Sea, hence proper connectivity during LGM. Therefore, a better understanding of the circulation pattern and connectivity with ocean basins during glacial-interglacial stages is required to interpret the data from the Andaman Sea. The Neogene - Quaternary basin is a tectonically active region and will be an interesting site to study tectonics and climate interaction. We can also understand the deep water changes in the basin without the effect of the North Atlantic and Antarctic waters. Even though several studies have been done on the Indian monsoon, there is no clarity on the forcing mechanisms, the corresponding responses, and its global teleconnection. Thus, this review calls for further high-resolution, multiproxy and modelling studies from the Andaman Basin.

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## References

- Achyuthan H, Nagasundaram M, Gurlan AT, Eastoe C, Ahmad SM, Padmakumari VM (2014) Mid- Holocene Indian summer monsoon variability off the Andaman Islands, Bay of Bengal. *Quat Int* 349:232-244. <https://doi.org/10.1016/j.quaint.2014.07.041>
- Adelseck CG, Berger WH (1975) On the dissolution of planktonic foraminifera and associated microfossils during settling and on the sea floor. *Spec Publ Cushman Found Foraminiferal Res* 13: 70-81.
- Ahmad SM, Patil DJ, Rao PS, Nath BN, Rao BR, Rajagopalan G (2000) Glacial-interglacial changes in the surface water characteristics of the Andaman Sea: Evidence from stable isotopic ratios of planktonic foraminifera. *J Earth Syst Sci* 109:153-156 <https://doi.org/10.1007/bf02719159>
- Ahmad SM, Anil Babu G, Padmakumari VM, Dayal AM, Sukhija BS, Nagabhushanam P (2005) Sr, Nd isotopic evidence of terrigenous flux variations in the Bay of Bengal: Implications of monsoons during the last~ 34,000 years. *Geophys Res Lett* 32. <https://doi.org/10.1029/2005gl024519>
- Alagarsamy R, You CF, Nath BN, Kumar AS (2010) Determination of rare earth, major and trace elements in authigenic fraction of Andaman Sea (Northeastern Indian Ocean) sediments by Inductively Coupled Plasma-Mass Spectrometry. *Microchem J* 94:90-97. <https://doi.org/10.1016/j.microc.2009.09.007>
- Ali S, Hathorne EC, Frank M, Gebregiorgis D, Statterger K, Stumpf R, Kutterolf S, Johnson JE, Giosan L (2015) South Asian monsoon history over the past 60 kyr recorded by radiogenic isotopes and clay mineral assemblages in the Andaman Sea. *Geochem Geophys Geosys* 16:505-521. <https://doi.org/10.1002/2014gc005586>
- Alley RB, Mayewski PA, Sowers T, Stuiver M, Taylor KC, Clark PU (1997) Holocene climatic instability: A prominent, widespread event 8200 yr ago. *Geology* 25:483-6. [https://doi.org/10.1130/0091-7613\(1997\)025<0483:hciapw>2.3.co;2](https://doi.org/10.1130/0091-7613(1997)025<0483:hciapw>2.3.co;2)
- Alley RB (2000) The Younger Dryas cold interval as viewed from central Greenland. *Quat Sci Rev* 19:213-26. [https://doi.org/10.1016/s0277-3791\(99\)00062-1](https://doi.org/10.1016/s0277-3791(99)00062-1)
- Almogi-Labin A (1982) Stratigraphic and paleoceanographic significance of Late Quaternary pteropods from deep-sea cores in the Gulf of Aqaba (Elat) and northernmost Red Sea. *Mar Micropaleontol* 7:53-72. [https://doi.org/10.1016/0377-8398\(82\)90015-9](https://doi.org/10.1016/0377-8398(82)90015-9)
- Almogi-Labin A, Hemleben C, Deuser WG (1988) Seasonal variation in the flux of euthecosomatous pteropods collected in a deep sediment trap in the Sargasso Sea. *Deep-Sea Res Part A* 35:441-464. [https://doi.org/10.1016/0198-0149\(88\)90020-9](https://doi.org/10.1016/0198-0149(88)90020-9)
- Andersen KK, Svensson A, Johnsen SJ, Rasmussen SO, Bigler M, Röthlisberger R, Ruth U, Siggaard-Andersen ML, Steffensen JP, Dahl-Jensen D, Vinther BM (2006) The Greenland Ice Core Chronology 2005, 15–42ka. part 1: Constructing the time scale. *Quat Sci Rev* 25:3246–3257. <https://doi.org/10.1016/j.quascirev.2006.08.002>

- Arrhenius G (1952) Analyses of ocean-floor sediment cores taken on the Swedish deep-sea expedition. *Geol Soc Am Bull* 63:515. [https://doi.org/10.1130/0016-7606\(1952\)63\[515:gaaos\]2.0.co;2](https://doi.org/10.1130/0016-7606(1952)63[515:gaaos]2.0.co;2)
- Ashfaq M, Shi Y, Tung WW, Trapp RJ, Gao X, Pal JS, Diffenbaugh NS (2009) Suppression of south Asian summer monsoon precipitation in the 21st century. *Geophys Res Lett* 36. <https://doi.org/10.1029/2008gl036500>
- Awasthi N, Ray JS, Singh AK, Band ST, Rai VK (2014) Provenance of the Late Quaternary sediments in the Andaman Sea: Implications for monsoon variability and ocean circulation. *Geochem Geophys Geosys* 15:3890-3906. <https://doi.org/10.1002/2014gc005462>
- Babu VR, Sastry JS (1971) Hydrography of the Andaman Sea during late winter. *J Mar Sci* 5:179-189.
- Band S, Yadava MG (2020) Addressing past monsoon variability from speleothems. *Curr Sci* 119:244-254. <https://doi.org/10.18520/cs/v119/i2/244-254>
- Beaufort L, Bolton C, Sarr AC, Sucheras-Marx B, Rosenthal Y, Donnadiou Y, Barbarin N, Bova S, Cornuault P, Gally Y, Gray E, Mazur JC, Tetard M (2020) Cyclic evolution of phytoplankton forced by changes in tropical seasonality. *Nature* 601:79-84. <https://doi.org/10.21203/rs.3.rs-100744/v1>
- Beaulieu E, Godd ris Y, Donnadiou Y, Labat D, Roelandt C (2012) High sensitivity of the continental-weathering carbon dioxide sink to future climate change. *Nat Clim Chang* 2: 346-349. <https://doi.org/10.1038/nclimate1419>
- Beck JW, Edwards RL, Ito E, Taylor FW, Recy J, Rougerie F, Joannot P, Henin C (1992) Sea-surface temperature from coral skeletal strontium/calcium ratios. *Sci* 257:644-647. <https://doi.org/10.1126/science.257.5070.644>
- Bender FK (1983) *Geology of Burma*. Science Publ, Berlin.
- Berger RH, Acre JG, Betzer PR, Feely RA, Castes MH (1984) Water column dissolution of aragonite in the Pacific Ocean. *Nat* 312:321-326. <https://doi.org/10.1038/312321a0>
- Byrne RH, Acker JG, Betzer PR, Feely RA, Cates MH (1984) Water column dissolution of aragonite in the Pacific Ocean. *Nat* 312:321-326. <https://doi.org/10.1038/312321a0>
- Bhattacharjee D (1997) Pteropod preservation spike and its significance in the Andaman Sea. *J Pal Soc India* 42:49-60.
- Bhattacharjee D (2001) Late Quaternary palaeodepth study around Narcondam Island in the Andaman Sea with the help of pteropod. *Geol Surv India, Spec Publ* 65:183-193.
- Bhattacharjee D (2005) Pteropod preservation profiles in seabed sediments off Middle Andaman Island in Andaman Sea. *Indian J Mar Sci* 34: 259-266.
- Birkland PW (1974) *Peodology, weathering and geomorphological research*. Oxford University Press, London.

- Bolton CT, Chang L, Clemens SC, Kodama K, Ikehara M, Medina-Elizalde M, Paterson GA, Roberts AP, Rohling EJ, Yamamoto Y, Zhao X (2013) A 500,000-year record of Indian summer monsoon dynamics recorded by eastern equatorial Indian Ocean upper water-column structure. *Quat Sci Rev* 77:167-80. <https://doi.org/10.1016/j.quascirev.2013.07.031>
- Boyle EA (1981) Cadmium, zinc, copper, and barium in foraminifera tests. *Earth Planet Sci Lett* 53:11-35. [https://doi.org/10.1016/0012-821X\(81\)90022-4](https://doi.org/10.1016/0012-821X(81)90022-4)
- Boyle EA, Keigwin LD (1985) Comparison of Atlantic and Pacific paleochemical records for the last 215,000 years: Changes in deep ocean circulation and chemical inventories. *Earth Planet Sci Lett* 76:135-150. [https://doi.org/10.1016/0012-821X\(85\)90154-2](https://doi.org/10.1016/0012-821X(85)90154-2)
- Brauer A, Haug GH, Dulski P, Sigman DM, Negendank JFW (2008) An abrupt wind shift in western Europe at the onset of the Younger Dryas cold period. *Nat Geosci* 1:520-523. <https://doi.org/10.1038/ngeo263>
- Broecker WS (1986) Oxygen isotope constraints on surface ocean temperatures. *Quat Res* 26:121-134. [https://doi.org/10.1016/0033-5894\(86\)90087-6](https://doi.org/10.1016/0033-5894(86)90087-6)
- Broecker WS, Denton GH, Edwards RL, Cheng H, Alley RB, Putnam AE (2010) Putting the Younger Dryas cold event into context. *Quat Sci Rev* 29:1078-1081. <https://doi.org/10.1016/j.quascirev.2010.02.019>
- Buizert C, Gkinis V, Severinghaus JP, He F, Lecavalier BS, Kindler P (2014). Greenland temperature response to climate forcing during the last deglaciation. *Sci* 345:1177–1180. <https://doi.org/10.1126/science.1254961>
- Byrne RH, Acker JG, Betzer PR, Feely RA, Cates MH (1984) Water column dissolution of aragonite in the Pacific Ocean. *Nat* 312:321-6. <https://doi.org/10.1038/312321a0>
- Caley T, Malaizé B, Zaragosi S, Rossignol L, Bourget J, Eynaud F, Martinez P, Giraudeau J, Charlier K, Ellouz-Zimmermann N (2011) New Arabian Sea records help decipher orbital timing of Indo-Asian monsoon. *Earth Planet Sci Lett* 308:433-44. <https://doi.org/10.1016/j.epsl.2011.06.019>
- Cao P, Shi X, Li W, Liu S, Yao Z, Hu L, Khokiattiwong S, Kornkanitnan N (2015) Sedimentary responses to the Indian Summer Monsoon variations recorded in the southeastern Andaman Sea slope since 26 ka. *J Asian Earth Sci* 114:512-525. <https://doi.org/10.1016/j.jseaes.2015.06.028>
- Cawthorn T, Johnson JE, Giosan L, Flores JA, Rose K, Solomon E (2014) A late Miocene–early Pliocene biogenic silica crash in the Andaman Sea and Bay of Bengal. *Mar Pet Geol* 58:490-501. <https://doi.org/10.1016/j.marpetgeo.2014.07.026>
- Chakraborty S, Ramesh R (1997) Environmental significance of carbon and oxygen isotope ratios of banded corals from Lakshadweep, India. *Quat Int* 37:55-65. [https://doi.org/10.1016/1040-6182\(96\)00028-6](https://doi.org/10.1016/1040-6182(96)00028-6)
- Chakraborty S, Sinha N, Chattopadhyay R, Sengupta S, Mohan PM, Datye A (2016). Atmospheric controls on the precipitation isotopes over the Andaman Islands, Bay of Bengal. *Sci Rep* 6. <https://doi.org/10.1038/srep19555>

- Chakraborty S (2020) Potential of reef building corals to study the past Indian monsoon rainfall variability. *Curr Sci* 119:273-281. <https://doi.org/10.18520/cs/v119/i2/273-281>
- Chatterjee A, Shankar D, McCreary JP, Vinayachandran PN, Mukherjee A (2017). Dynamics of Andaman Sea circulation and its role in connecting the equatorial Indian Ocean to the Bay of Bengal. *J Geophys Res Oceans* 122:3200-3218. <https://doi.org/10.1002/2016jc012300>
- Choudhari PP, Patil SM, Mohan R (2020) Use of coccolith based proxies for palaeoceanographic reconstructions. *Curr Sci* 119:307. <https://doi.org/10.18520/cs/v119/i2/307-315>
- Clemens S, Prell W, Murray D, Shimmield G, Weedon G (1991) Forcing mechanisms of the Indian Ocean monsoon. *Nat* 353:720-725. <https://doi.org/10.1038/353720a0>
- Clemens SC, Prell WL (2003) A 350,000 year summer-monsoon multi-proxy stack from the Owen Ridge, Northern Arabian Sea. *Mar Geol* 201:35-51. [https://doi.org/10.1016/s0025-3227\(03\)00207-x](https://doi.org/10.1016/s0025-3227(03)00207-x)
- Clemens SC, Prell WL (2007) The timing of orbital-scale Indian monsoon changes. *Quat Sci Rev* 26:275- 278. <https://doi.org/10.1016/j.quascirev.2006.11.010>
- Clemens SC, Prell WL, Sun Y, Liu Z, Chen G (2008) Southern Hemisphere forcing of Pliocene  $\delta^{18}\text{O}$  and the evolution of Indo-Asian monsoons. *Paleoceanogr* 23. <https://doi.org/10.1029/2008pa001638>
- Clift PD, Hodges KV, Heslop D, Hannigan R, Van Long H, Calves G (2008) Correlation of Himalayan exhumation rates and Asian monsoon intensity. *Nat Geosci* 1:875-80. <https://doi.org/10.1038/ngeo351>
- Colin C, Kissel C, Blamart D, Turpin L (1998) Magnetic properties of sediments in the Bay of Bengal and the Andaman Sea: impact of rapid North Atlantic Ocean climatic events on the strength of the Indian monsoon. *Earth Planet Sci Lett* 160:623-35. [https://doi.org/10.1016/s0012-821x\(98\)00116-2](https://doi.org/10.1016/s0012-821x(98)00116-2)
- Colin C, Turpin L, Bertaux J, Desprairies A, Kissel C (1999) Erosional history of the Himalayan and Burman ranges during the last two glacial–interglacial cycles. *Earth Planet Sci Letters* 171:647-660. [https://doi.org/10.1016/s0012-821x\(99\)00184-3](https://doi.org/10.1016/s0012-821x(99)00184-3)
- Colin C, Turpin L, Blamart D, Frank N, Kissel C, Duchamp S (2006) Evolution of weathering patterns in the Indo-Burman Ranges over the last 280 kyr: Effects of sediment provenance on  $87\text{Sr}/86\text{Sr}$  ratios tracer. *Geochem Geophys Geosys* 7. <https://doi.org/10.1029/2005gc000962>
- Conan SH, Brummer GJ (2000) Fluxes of planktic foraminifera in response to monsoonal upwelling on the Somalia Basin margin. *Deep Sea Res Part II* 47:2207-2227. [https://doi.org/10.1016/s0967-0645\(00\)00022-9](https://doi.org/10.1016/s0967-0645(00)00022-9)
- Cruz Jr FW, Burns SJ, Karmann I, Sharp WD, Vuille M, Ferrari JA (2006) A stalagmite record of changes in atmospheric circulation and soil processes in the Brazilian subtropics during the Late Pleistocene. *Quat Sci Rev* 25:2749-2761. <https://doi.org/10.1016/j.quascirev.2006.02.019>



- Curry JR, Moore DG, Lawver LA, Emmel FJ, Raitt RW, Henry M, Kieckhefer R (1979) Tectonics of the Andaman Sea and Burma: convergent margins. *Geological and Geophysical Investigations of Continental Margins*. <https://doi.org/10.1306/m29405c12>
- Curry JR (1989) The Sunda Arc: a model for oblique plate convergence. *Neth J Sea Res* 24:131-140. [https://doi.org/10.1016/0077-7579\(89\)90144-0](https://doi.org/10.1016/0077-7579(89)90144-0)
- Curry JR (2005) Tectonics and history of the Andaman Sea region. *J Asian Earth Sci.* 25:187-232. <https://doi.org/10.1016/j.jseaes.2004.09.001>
- Curry WB, Ostermann DR, Guptha MV, Ittekkot V (1992) Foraminiferal production and monsoonal upwelling in the Arabian Sea: Evidence from sediment traps. *Geol Soc London Spec Pub* 64: 93–106. <https://doi.org/10.1144/gsl.sp.1992.064.01.06>
- Damodararao K, Singh SK, Rai VK, Ramaswamy V, Rao PS (2016) Lithology, monsoon and sea-surface current control on provenance, dispersal and deposition of sediments over the Andaman continental shelf. *Front Mar Sci* 3:118. <https://doi.org/10.3389/fmars.2016.00118>
- Dansgaard W, White JW, Johnsen SJ (1989) The abrupt termination of the Younger Dryas climate event. *Nature* 339:532-534. <https://doi.org/10.1038/339532a0>
- Dunbar RB, Wellington GM (1981) Stable isotopes in a branching coral monitor seasonal temperature variation. *Nature* 293:453-455. <https://doi.org/10.1038/293453a0>
- Duplessy JC (1982) Glacial to interglacial contrasts in the northern Indian Ocean. *Nature* 295:494-498. <https://doi.org/10.1038/295494a0>
- Emiliani C, Epstein S (1953) Temperature variations in the Lower Pleistocene of southern California. *J Geol* 61:171-81. <https://doi.org/10.1086/626064>
- Emiliani, C (1955) Pleistocene temperatures. *J Geol* 63:538–578. <https://doi.org/10.1086/626295>
- Fairbridge RW, Rodolfo KS (1974) Andaman Sea, *Oceanographic Encyclopedia* 15–17.
- Flores JA, Johnson JE, Mejia-Molina AE, Álvarez MC, Sierro FJ, Singh SD, Mahanti S, Giosan L (2014) Sedimentation rates from calcareous nannofossil and planktonic foraminifera biostratigraphy in the Andaman Sea, northern Bay of Bengal, and eastern Arabian Sea. *Mar Pet Geol* 58:425-437. <https://doi.org/10.1016/j.marpetgeo.2014.08.011>
- Fontugne MR, Duplessy JC (1986) Variations of the monsoon regime during the upper Quaternary: evidence from carbon isotopic record of organic matter in North Indian Ocean sediment cores. *Palaeogeogr Palaeoclimatol Palaeoecolog* 56:69-88. [https://doi.org/10.1016/0031-0182\(86\)90108-2](https://doi.org/10.1016/0031-0182(86)90108-2)
- Frerichs WE (1971) Paleobathymetric trends of neogene foraminiferal assemblages and sea floor tectonism in the Andaman Sea area. *Mar Geol* 11:159-173. [https://doi.org/10.1016/0025-3227\(71\)90004-1](https://doi.org/10.1016/0025-3227(71)90004-1)
- Gadgil S (2003) The Indian monsoon and its variability. *Annu Rev Earth Planet Sci* 31:429-467. <https://doi.org/10.1146/annurev.earth.31.100901.141251>

- Gadgil S (2006) The Indian monsoon, GDP and agriculture. *Economic and political weekly* 25:4887-4895. <https://www.jstor.org/stable/4418949>
- Gayathri NM, Sijinkumar AV, Nath BN, Sandeep K, Wei KY (2022) A ~ 30 kyr sub-centennial to millennial Indian summer monsoon variability record from the southern Andaman Sea, northeastern Indian Ocean. *Palaeogeogr Palaeoclimatol Palaeoecolog* 590:110865. <https://doi.org/10.1016/j.palaeo.2022.110865>
- Gebregiorgis D, Hathorne EC, Sijinkumar AV, Nath BN, Nurnberg D, Frank M (2016) South Asian summer monsoon variability during the last~ 54 kyrs inferred from surface water salinity and river runoff proxies. *Quat Sci Rev* 138:6-15. <https://doi.org/10.1016/j.quascirev.2016.02.012>
- Gebregiorgis D, Hathorne EC, Giosan L, Clemens S, Nürnberg D, Frank M (2018) Southern Hemisphere forcing of South Asian monsoon precipitation over the past~ 1 million years. *Nat Commun* 9:4702. <https://doi.org/10.1038/s41467-018-07076-2>
- Genty D, Baker A, Massault M, Proctor C, Gilmour M, Pons-Branchu E, Hamelin (2001) Dead carbon in stalagmites: carbonate bedrock paleodissolution vs. ageing of soil organic matter. Implications for  $^{13}\text{C}$  variations in speleothems. *Geochim Cosmochim Acta* 65:3443-357. [https://doi.org/10.1016/s0016-7037\(01\)00697-4](https://doi.org/10.1016/s0016-7037(01)00697-4)
- Govil P, Naidu PD (2011) Variations of Indian monsoon precipitation during the last 32 kyr reflected in the surface hydrography of the Western Bay of Bengal. *Quat Sci Rev* 30:3871-3879. <https://doi.org/10.1016/j.quascirev.2011.10.004>
- Gupta AK, Yuvaraja A, Prakasam M, Clemens SC, Velu A (2015) Evolution of the South Asian monsoon wind system since the late Middle Miocene. *Palaeogeogr Palaeoclimatol Palaeoecolog* 438:160-167. <https://doi.org/10.1016/j.palaeo.2015.08.006>
- Guptha MV, Curry WB, Ittekkot V, Muralinath AS (1997) Seasonal variation in the flux of planktic foraminifera; sediment trap results from the Bay of Bengal, northern Indian Ocean. *J Foraminiferal Res* 27:5–19. <https://doi.org/10.2113/gsjfr.27.1.5>
- Hawkes AD, Bird M, Cowie S, Grundy-Warr C, Horton BP, Shau Hwai AT, Law L, Macgregor C, Nott J, Ong JE, Rigg J, Robinson R, Tan-Mullins M, Sa TT, Yasin Z, Aik LW (2007) Sediments deposited by the 2004 Indian Ocean tsunami along the Malaysia–Thailand Peninsula. *Mar Geol* 242:169–190.
- Hla KY, Aung DW, Zaw TT (2021) Middle shelf zone foraminiferas occurred in the sediments of northern part of the Andaman Sea. *J Myanmar Acad Arts Sci* 19.
- Huang Y, Xiao J, Xiang R, Liu S, Khokiattiwong S, Kornkanitnan N, Fan J, Wen R, Zhang S, Liu J (2020) Holocene Indian summer monsoon variations inferred from end-member modeling of sediment grain size in the Andaman Sea. *Quat Int* 558:28-38. <https://doi.org/10.1016/j.quaint.2020.08.032>
- Isarin RF, Renssen H, Vandenberghe J (1998) The impact of the North Atlantic Ocean on the Younger Dryas climate in northwestern and central Europe. *J Quat Sci: Published for the Quat Res Assoc* 13:447-453. [https://doi.org/10.1002/\(sici\)1099-1417\(1998090\)13:5<447::aid-jqs402>3.0.co;2-b](https://doi.org/10.1002/(sici)1099-1417(1998090)13:5<447::aid-jqs402>3.0.co;2-b)

- Jaglan S, Gupta AK, Cheng H, Clemens SC, Dutt S, Balaji S (2020) Indian summer monsoon variability during the last millennium as recorded in stalagmite from Baratang Mahadev cave, Andaman Islands. *Palaeogeogr Palaeoclimatol Palaeoecolog* 557:109908. <https://doi.org/10.1016/j.palaeo.2020.109908>
- Janekarn V, Hylleberg J (1989) Coastal and offshore primary production along the west coast of Thailand (Andaman Sea) with notes on physical chemical variables. *Phuket Mar Biol Centre Res Bull* 51:1–19.
- Jayan AK, Sijinkumar AV, Nath BN (2021) Paleoceanographic significance of *Globigerinoides ruber* (white) morphotypes from the Andaman Sea. *Mar Micropaleontol* 165:101996. <https://doi.org/10.1016/j.marmicro.2021.101996>
- Jithin AK, Francis PA (2020) Role of internal tide mixing in keeping the deep Andaman Sea warmer than the Bay of Bengal. *Sci Rep* 10. <https://doi.org/10.1038/s41598-020-68708-6>.
- Jöhnck J, Kuhnt W, Holbourn A, Andersen N (2020) Variability of the Indian monsoon in the Andaman Sea across the Miocene-Pliocene transition. *Paleoceanogr Paleoclimatolog* 35. <https://doi.org/10.1029/2020pa003923>
- Kallel N, Labeyrie LD, Arnold M, Okada H, Dudley WC, Duplessy JC (1988) Evidence of cooling during the Younger Dryas in the western North Pacific. *Oceanologica Acta* 11:369-75.
- Katz ME, Cramer BS, Franzese A, Honsch B, Miller KG, Rosenthal Y, Wright JD (2010) Traditional and emerging geochemical proxies in foraminifera. *J Foraminifer Res.* 40:165-192. <https://doi.org/10.2113/gsjfr.40.2.165>
- Khan PK, Chakraborty PP (2005) Two-phase opening of Andaman Sea: a new seismotectonic insight. *Earth Planet Sci Lett* 229:259-271. <https://doi.org/10.1016/j.epsl.2004.11.010>.
- Kudrass HR, Erlenkeuser H, Vollbrecht R, Weiss W (1991) Global nature of the Younger Dryas cooling event inferred from oxygen isotope data from Sulu Sea cores. *Nature* 349:406-409. <https://doi.org/10.1038/349406a0>
- Kudrass HR, Hofmann A, Dose H, Emeis K, Ostseeforschung I (2001) Modulation and amplification of climatic changes in the Northern Hemisphere by the Indian summer monsoon during the past 80 k.y. *Geology* 29:63–66. [https://doi.org/10.1130/0091-7613\(2001\)029](https://doi.org/10.1130/0091-7613(2001)029)
- Kumar PK, Band ST, Ramesh R, 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. *Quat Int* 479:12- 18. <https://doi.org/10.1016/j.quaint.2018.03.025>
- Kurian S, Nath BN, Ramaswamy V, Naman D, Rao TG, Raju KK, Chen (2008) Possible detrital, diagenetic and hydrothermal sources for Holocene sediments of the Andaman backarc basin. *Mar Geol* 247:178-193. <https://doi.org/10.1016/j.margeo.2007.09.006>
- Kutzbach JE (1981) Monsoon climate of the early Holocene: climate experiment with the earth's orbital parameters for 9000 years ago. *Science* 214:59-61. <https://doi.org/10.1126/science.214.4516.59>

- Lal MS, Sijinkumar AV, Nath BN, Sandeep K, Badesab F (2022) Environmental magnetic records of the sediments from the Andaman Sea: Evidence for late Quaternary changes in provenance and monsoon. *Oceans 2022-Chennai 2022* 1-9. <https://doi.org/10.1109/oceanschennai45887.2022.9775135>
- Laskar AH, Raghav S, Yadava MG, Jani RA, Narayana AC, Ramesh R (2011) Potential of stable carbon and oxygen isotope variations of speleothems from Andaman Islands, India, for paleomonsoon reconstruction. *J Geol Res* 2011:1-7. <https://doi.org/10.1155/2011/272971>
- Laskar AH, Yadava MG, Ramesh, Polyak VJ, Asmerom Y (2013) A 4 kyr stalagmite oxygen isotopic record of the past Indian Summer Monsoon in the Andaman Islands. *Geochem, Geophys, Geosys* 14:3555-3566. <https://doi.org/10.1002/ggge.20203>
- Lee J, Kim S, Lee JI, Cho HG, Philips SC, Khim BK (2020) Monsoon-influenced variation of clay mineral compositions and detrital Nd-Sr isotopes in the western Andaman Sea (IODP Site U1447) since the late Miocene. *Palaeogeogr Palaeoclimatol Palaeoecol* 538:109339. <https://doi.org/10.1016/j.paleo.2019.109339>
- Licht A, France-Lanord C, Reisberg L, Fontaine AN, Soe, Jaeger JJ (2013) A palaeo Tibet–Myanmar connection? Reconstructing the Late Eocene drainage system of central Myanmar using a multi-proxy approach. *J Geol Soc* 170:929-939. <https://doi.org/10.1144/jgs2012-126>
- Lisiecki LE, Raymo ME (2005) A Pliocene-Pleistocene stack of 57 globally distributed benthic  $\delta^{18}\text{O}$  records. *Paleoceanogr* 20. <https://doi.org/10.1029/2004pa001071>
- Liu Z, Colin C, Huang W, Le KP, Tong S, Chen Z, Trentesaux A (2007) Climatic and tectonic controls on weathering in south China and Indochina Peninsula: Clay mineralogical and geochemical investigations from the Pearl, Red, and Mekong drainage basins. *Geochem, Geophys Geosys* 8. <https://doi.org/10.1029/2006gc001490>
- Liu S, Ye W, Cao P, Zhang H, Chen MT, Li X, Li J, Pan HJ, Khokiattiwong S, Kornkanitnan N, Shi X. (2021) Paleoclimatic responses in the tropical Indian Ocean to regional monsoon and global climate change over the last 42 kyr. *Mar Geol* 438:106542. <https://doi.org/10.1016/j.margeo.2021.106542>
- Lutz W, Kc S (2011) Global human capital: Integrating education and population. *Science* 333:587-592. <https://doi.org/10.1126/science.1206964>
- Marimuthu N, Jerald Wilson J, Vinithkumar NV, Kirubakaran R (2012) Coral reef recovery status in South Andaman Islands after the bleaching event 2010. *J Ocean Universit China*. 12:91–96. <https://doi.org/10.1007/s11802-013-2014-2>
- Marzin C, Kallel N, Kageyama M, Duplessey JC, Braconnot P (2013) Glacial fluctuations of the Indian monsoon and their relationship with North Atlantic climate: new data and modelling experiments. *Clim Past* 9:2135-2151. <https://doi.org/10.5194/cp-9-2135-2013>
- Meade RH (1996) River-sediment inputs to major deltas. Sea-level rise and coastal subsidence: Causes, consequences, and strategies. *Coastal Systems and Continental Margins* 63-85. [https://doi.org/10.1007/978-94-015-8719-8\\_4](https://doi.org/10.1007/978-94-015-8719-8_4)
- Milankovitch MM (1941) Canon of insolation and the ice age problem. Royal Serbian Academy Special Publication 132.

- Milliman JD, Farnsworth KL (2011) River discharge to the Coastal Ocean. Cambridge University Press.
- Miriyala P, Sukumaran NP, Nath BN, Ramamurthy PB, Sijinkumar AV, Vijayagopal B, Ramaswamy V, Sebastian T (2017) Increased chemical weathering during the deglacial to mid-Holocene summer monsoon intensification. *Sci Rep* 7:1-11. <https://doi.org/10.1038/srep44310>
- Mix AC, Bard E, Schneider R (2001) Environmental processes of the ice age: land, oceans, glaciers (EPILOG). *Quat Sci Rev* 20:627-657. [https://doi.org/10.1016/s0277-3791\(00\)00145-1](https://doi.org/10.1016/s0277-3791(00)00145-1)
- Mohan PM, Dhivya P, Narayanamurthy K (2013). Distribution of live planktonic and benthic foraminifera in the shelf off Port Blair and Hut Bay, Andaman Group of Islands, India. Ecology and Conservation of Tropical Marine Faunal Communities, 19:42. [https://doi.org/10.1007/978-3-642-38200-0\\_2](https://doi.org/10.1007/978-3-642-38200-0_2)
- Mohtadi M, Prange M, Oppo DW, De Pol-Holz R, Merkel U, Zhang X, Steinke S, Lückge A (2014) North Atlantic forcing of tropical Indian Ocean climate. *Nature* 509:76-80. <https://doi.org/10.1038/nature13196>
- Moore GF, Curray JR, Moore DG, Karig DE (1980) Variations in geologic structure along the Sunda fore arc, northeastern Indian Ocean. *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands. Geophysical Monograph Series* 23:145-160. <https://doi.org/10.1029/gm023p0145>
- Morley CK (2016) Cenozoic structural evolution of the Andaman Sea: evolution from an extensional to a sheared margin. *Geol Soc, London, Special Publications* 431:39-61. <https://doi.org/10.1144/SP431.1>
- Molnar P, Rajagopalan B (2012) Late Miocene upward and outward growth of eastern Tibet and decreasing monsoon rainfall over the northwestern Indian subcontinent since ~10 Ma. *Geophys Res Lett* 39. <https://doi.org/10.1029/2012gl051305>
- Murray J (1897). On the distribution of the pelagic foraminifera at the surface and on the floor of the ocean. *Natural Science (Ecology)*, 11:17-27.
- Muruganatham M, Mohan PM (2015) First report of three benthic foraminifera from the waters of Andaman Islands, India. *Biodiversity J* 6:789-794.
- Nagasundaram M, Achyuthan H, Ahmad SM (2014) Monsoonal changes inferred from the Middle to Late Holocene sediments off landfall island, North Andaman. *Arab J Geosci.* 7:3513-3523. <https://doi.org/10.1007/s12517-013-1010-6>
- Najman Y (2006) The detrital record of orogenesis: A review of approaches and techniques used in the Himalayan sedimentary basins. *Earth Sci Rev* 74:1-72. <https://doi.org/10.1016/j.earscirev.2005.04.004>
- Naqvi WA, Charles CD, Fairbanks RG (1994) Carbon and oxygen isotopic records of benthic foraminifera from the Northeast Indian Ocean: implications on glacial-interglacial atmospheric CO<sub>2</sub> changes. *Earth Planet Sci Lett* 121:99-110. [https://doi.org/10.1016/0012-821x\(94\)90034-5](https://doi.org/10.1016/0012-821x(94)90034-5)

- Nilsson-Kerr K, Anand P, Holden PB, Clemens SC, Leng MJ (2021) Dipole patterns in tropical precipitation were pervasive across landmasses throughout Marine Isotope Stage 5. *Comm Earth Environ* 2:64. <https://doi.org/10.1038/s43247-021-00133-7>
- Nilsson-Kerr K, Anand P, Sexton PF, Leng MJ, Naidu PD (2022) Indian summer monsoon variability 140–70 thousand years ago based on multi-proxy records from the Bay of Bengal. *Quat Sci Rev* 279:107403. <https://doi.org/10.1016/j.quascirev.2022.107403>
- Obase T, Abe-Ouchi A (2019) Abrupt Bølling-Allerød warming simulated under gradual forcing of the last deglaciation. *Geophys Res Lett* 46:11397-11405. <https://doi.org/10.1029/2019gl084675>
- Ota Y, Kawahata H, Murayama M, Inoue M, Yokoyama Y, Miyairi Y, Aung T, Hossain HZ, Suzuki A, Kitamura A, Moe KT (2017) Effects of intensification of the Indian summer monsoon on northern Andaman Sea sediments during the past 700 years. *J Quat Sci* 32:528-539. <https://doi.org/10.1002/jqs.2947>
- Pam B, Mohan PM (2022) Distribution of larger benthic foraminifera (lbf) in selected islands of Marine National Park, Port Blair, South Andaman, India. *Open J Mar Sci* 12:141–160. <https://doi.org/10.4236/ojms.2022.124009>
- Panchang R (2008) Ecology and distribution of benthic foraminifera off Myanmar. Doctoral dissertation, Goa University.
- Panchang R, Nigam R, Riedel F, Janssen AW, Hla U (2007) A review of the studies on pteropods from the northern Indian Ocean region with a report on the pteropods of Irrawaddy continental shelf off Myanmar (Burma). *Indian J Mar Sci* 36:384–398.
- Pearson PN (2012) Oxygen isotopes in foraminifera: Overview and historical review. *The Paleontolog Soc Papers* 18:1-38. <https://doi.org/10.1017/s1089332600002539>
- Pfleger, F. B. (1948). Foraminifera of a submarine core from the Caribbean Sea.14:1-9.
- Phillips SC, Johnson JE, Underwood MB, Guo J, Giosan L, Rose K (2014) Long-timescale variation in bulk and clay mineral composition of Indian continental margin sediments in the Bay of Bengal, Arabian Sea, and Andaman Sea. *Mar Pet Geol* 58:117-138. <https://doi.org/10.1016/j.marpetgeo.2014.06.018>
- Potemra JT, Luther ME, O'Brien JJ (1991) The seasonal circulation of the upper ocean in the Bay of Bengal. *J Geophys Res: Oceans* 96:12667-12683. <https://doi.org/10.1029/91jc01045>
- Prell WL, Murray DW, Clemens SC, Anderson DM (1992) Evolution and variability of the Indian Ocean summer monsoon: evidence from the western Arabian Sea drilling program. Washington DC American Geophysical Union Geophysical Monograph Series 70:447-469. <https://doi.org/10.1029/gm070p0447>
- Prell WL, Kutzbach JE (1997) The impact of Tibet-Himalayan elevation on the sensitivity of the monsoon climate system to changes in solar radiation. Tectonic uplift and climate change 171-201. [https://doi.org/10.1007/978-1-4615-5935-1\\_8](https://doi.org/10.1007/978-1-4615-5935-1_8)

- Railsback LB, Gibbard PL, Head MJ, Voarintsoa NRG, Toucanne S (2015) An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. *Quat Sci Rev* 111:94-106. <https://doi.org/10.1016/j.quascirev.2015.01.012>
- Ramaswamy V, Nair RR (1994). Fluxes of material in the Arabian Sea and Bay of Bengal - sediment trap studies. *J Earth Syst Sci* 103:189–210. <https://doi.org/10.1007/bf02839536>
- Rao LG, Jayaraman R (1968) Hydrographical features of the southern and central Bay of Bengal during the transition period between winter and summer. *B Natl Inst Sci India*.
- Rao PS, Ramaswamy V, Thwin S, Rao NS, Raiker V (2005) Sediment texture, distribution and transport on the Ayeyarwady continental shelf, Andaman Sea. *Mar Geol* 216:239-247. <https://doi.org/10.1016/j.margeo.2005.02.016>
- Raju DV, Gouveia AD, Murty CS (1981) Some physical characteristics of Andaman Sea waters during winter. *Indian J Mar Sci*, 211-218.
- Raju KK, Ramprasad T, Rao PS, Rao PR, Varghese J (2004) New insights into the tectonic evolution of the Andaman basin, northeast Indian Ocean. *Earth Planet Sci Lett* 221:145-162. [https://doi.org/10.1016/s0012-821x\(04\)00075-5](https://doi.org/10.1016/s0012-821x(04)00075-5)
- Ramage CS (1971) *Monsoon Meteorology*. Academic Press, New York
- Ramaswamy V, Rao PS, Rao KH, Thwin S, Rao NS, Raiker V (2004) Tidal influence on suspended sediment distribution and dispersal in the northern Andaman Sea and Gulf of Martaban. *Mar Geol* 208:33-42. <https://doi.org/10.1016/j.margeo.2004.04.019>
- Rashid H, Flower BP, Poore RZ, Quinn TM (2007) A ~25 ka Indian Ocean monsoon variability record from the Andaman Sea. *Quat Sci Rev* 26:2586-25897. <https://doi.org/10.1016/j.quascirev.2007.07.002>
- Rashid H, Gurlan AT, Marche B, Sheppard K, Khelifi N (2019) Changes in Indian summer monsoon using neodymium (Nd) isotopes in the Andaman Sea during the last 24,000 years. *Earth Syst Environ* 3:241-253. <https://doi.org/10.1007/s41748-019-00105-0>
- Rashid H, Wang Y, Gurlan AT (2021) Impact of climate change on past Indian monsoon and circulation: A perspective based on radiogenic and trace metal geochemistry. *Atmos* 12:330. <https://doi.org/10.3390/atmos12030330>.
- Rasmussen SO, Andersen KK, Svensson AM et al (2006) A new Greenland ice core chronology for the last glacial termination. *J Geophys Res* 111. <https://doi.org/10.1029/2005jd006079>
- Ravelo AC, Shackleton NJ (1995) Evidence for Surface-Water Circulation Changes at Site 851 in the Eastern Tropical Pacific Ocean. *Proceedings of the Ocean Drilling Program, Scientific Results*. <https://doi.org/10.2973/odp.proc.sr.138.126.1995>
- Rixen T, Ramachandran P, Lehnhoff L, Dasbach D, Gaye B, Urban B, Ramachandran R, Ittekkot V (2011) Impact of monsoon-driven surface ocean processes on a coral off Port Blair on the Andaman Islands and their link to North Atlantic climate variations. *Glob Planet Chang* 75:1-3. <https://doi.org/10.1016/j.gloplacha.2010.09.005>

- Rizal S, Damm P, Wahid MA, Sündermann J, Ilhamsyah Y, Iskandar T (2012) General circulation in the Malacca Strait and Andaman Sea: A numerical model study. *Am J Environ Sci* 8:479-488. <https://doi.org/10.3844/ajessp.2012.479.488>
- Robinson RA, Bird MI, Oo NW, Hoey TB, Aye MM, Higgitt DL, Swe A, Tun T, Win SL (2007) The Irrawaddy River sediment flux to the Indian Ocean: the original nineteenth-century data revisited. *J Geol* 115:629-640. <https://doi.org/10.1086/521607>
- Rodolfo KS (1969a) Sediments of the Andaman basin, northeastern Indian Ocean. *Mar Geol* 7:371-402. [https://doi.org/10.1016/0025-3227\(69\)90014-0](https://doi.org/10.1016/0025-3227(69)90014-0)
- Rodolfo KS (1969b) Bathymetry and marine geology of the Andaman Basin, and tectonic implications for Southeast Asia. *Geol Soc Am Bull* 80:1203-1230. [https://doi.org/10.1130/0016-7606\(1969\)80\[1203:bamgot\]2.0.co;2](https://doi.org/10.1130/0016-7606(1969)80[1203:bamgot]2.0.co;2)
- Roy SK, Sharma S (1993) Evolution of Andaman forearc basin and its hydrocarbon potential. In *Proceedings of the Second Seminar on Petroliferous Basins of India*, KDM Institute of Petroleum Exploration, ONGC, Dehra Dun
- Roy SK, Chaudhuri A, Banerjee S (2020) Spatial Variation in the Composition of Andaman Flysch Across the Andaman Islands in Relation to Source of Sediments and Tectonics. *The Andaman Islands and Adjoining Offshore: Geology, Tectonics and Palaeoclimate*. 65-91. [https://doi.org/10.1007/978-3-030-39843-9\\_4](https://doi.org/10.1007/978-3-030-39843-9_4)
- Ruddiman WF (2001) *Earth's climate: past and future*. Macmillan.
- Ruddiman WF (2006) What is the timing of orbital-scale monsoon changes? *Quat Sci Rev* 25:657-658. <https://doi.org/10.1016/j.quascirev.2006.02.004>
- Saha BK, Rakshit S, Mazumdar S, Deb Roy DK, Bhattacharjee D (1997) Morphology and sediment characters of sea mounts and undersea ridges in Andaman Sea. *Ind Minerals* 50:339-360.
- Saidova KM (2008) Benthic foraminifera communities of the Andaman Sea (Indian Ocean). *Oceanology* 48:517-523. <https://doi.org/10.1134/s0001437008040073>
- Saraswat R (2015) Non – destructive foraminiferal paleoclimatic proxies: A brief insight *Proceedings of the Natl Sci Acad* 81. <https://doi.org/10.16943/ptinsa/2015/v81i2/48094>
- Sarkar A, Ramesh R, Bhattacharya S K, Rajagopalan G (1990). Oxygen isotope evidence for a stronger winter monsoon current during the last glaciation. *Nat*, 343:549-551. <https://doi.org/10.1038/343549a0>
- Sarma VV, Narvekar PV (2001) A study on inorganic carbon components in the Andaman Sea during the post monsoon season. *Oceanologica Acta* 24:125-134. [https://doi.org/10.1016/s0399-1784\(00\)01133-6](https://doi.org/10.1016/s0399-1784(00)01133-6)
- Schiebel R, Smart SM, Jentzen A, Jonkers L, Morard R, Meilland J, Michel E, Coxall HK, Hull PM, de Garidel-Thoron T, Aze T (2018) Advances in planktonic foraminifer research: new perspectives for paleoceanography. *Rev Micropaléontol* 61:113-138. <https://doi.org/10.1016/j.revmic.2018.10.001>



- Sebastian T, Nath BN, Venkateshwarlu M, Miriyala P, Prakash A, Linsy P, Kocherla M, Kazip A, Sijinkumar AV (2019) Impact of the Indian Summer Monsoon variability on the source area weathering in the Indo-Burman ranges during the last 21 kyr—A sediment record from the Andaman Sea. *Palaeogeogr Palaeoclimatol Palaeoecolog* 516:22-34. <https://doi.org/10.1016/j.palaeo.2018.11.035>
- Sengupta R, Moraes C, George M, Kureishy T, Noronha R, Fondekar S (1981) Chemistry and hydrography of the Andaman Sea. *Indian J Mar Sci* 10:228–233.
- Shi X, Liu S, Zhang X, Sun Y, Cao P, Zhang H, Li X, Xu S, Qiao S, Khokiattiwong S, Kornkanitnan N (2022). Millennial-scale hydroclimate changes in Indian monsoon realm during the last deglaciation. *Quat Sci Rev* 292:107702. <https://doi.org/10.1016/j.quascirev.2022.107702>
- Sijinkumar AV, Nath BN, Guptha MVS (2010). Late Quaternary record of pteropod preservation from the Andaman Sea. *Mar Geol* 275:221-229. <https://doi.org/10.1016/j.margeo.2010.06.003>
- Sijinkumar AV, Nath BN, Possnert G, Aldahan A (2011). *Pulleniatina* minimum events in the Andaman Sea (NE Indian Ocean): implications for winter monsoon and thermocline changes. *Mar Micropaleontol* 81:88-94. <https://doi.org/10.1016/j.marmicro.2011.09.001>
- Sijinkumar AV, Nath BN, Guptha MV, Ahmad SM, Rao BR (2015). Timing and preservation mechanism of deglacial pteropod spike from the Andaman Sea, northeastern Indian Ocean. *Boreas* 44:432-444. <https://doi.org/10.1111/bor.12099>
- Sijinkumar AV, Clemens S, Nath BN, Prell W, Benschila R, Lengaigne M (2016a).  $\delta^{18}\text{O}$  and salinity variability from the Last Glacial Maximum to Recent in the Bay of Bengal and Andaman Sea. *Quat Sci Rev* 135:79-91. <https://doi.org/10.1016/j.quascirev.2016.01.022>
- Sijinkumar AV, Nath BN, Clemens S (2016b). North Atlantic climatic changes reflected in the Late Quaternary foraminiferal abundance record of the Andaman Sea, north-eastern Indian Ocean. *Palaeogeogr Palaeoclimatol Palaeoecolog* 446:11-18. <https://doi.org/10.1016/j.palaeo.2016.01.009>
- Sijinkumar AV, Nath BN, Miriyala P (2020a). Late Quaternary Chronostratigraphy, Carbonate Mass Accumulation Rates and Palaeoceanography of the Andaman Sea. *The Andaman Islands and Adjoining Offshore: Geology, Tectonics and Palaeoclimate 2020*: 289-313. [https://doi.org/10.1007/978-3-030-39843-9\\_14](https://doi.org/10.1007/978-3-030-39843-9_14)
- Sijinkumar AV, NATH BN, Vinodkumar KB (2020b). Scanning electron microscopic studies of fossil pteropods from the Andaman Sea: Inferences on carbonate dissolution. *Proc Indian Natl Sci Acad* 86:1107-1120. <https://doi.org/10.16943/ptinsa/2019/49714>
- Sijinkumar AV, Nath BN, Clemens S, Gayathri NM, Miriyala P (2021). Late Quaternary record of Indian summer monsoon-induced stratification and productivity collapse in the Andaman Sea. *J Quat Sci* 36:298-310. <https://doi.org/10.1002/jqs.3278>
- Sijinkumar AV, Nath BN, & Prabhakar S (2022). Late Quaternary carbonate preservation in the Andaman Sea versus the Central Indian Basin: A test of dissolution under diverse oceanographic settings in the Indian Ocean. *Quat Int* 642:103-115. <https://doi.org/10.1016/j.quaint.2021.06.014>

- Singh AK, Tiwari M, Srivastava A (2016) Wind strength variability in the western Arabian Sea since the last glacial maximum: southwest vs. northeast monsoon modes. *J Clim Change* 2:57–70. <https://doi.org/10.3233/jcc-160017>
- Singh SC, Moeremans R, McArdle J, Johansen K (2013) Seismic images of the silver strike-slip fault and back thrust in the Andaman-Nicobar region. *J Geophys Res* 118:5208–5224. <https://doi.org/10.1002/jgrb.50378>
- Socquet A, Pubellier M (2005) Cenozoic deformation in western Yunnan (China-Myanmar border). *J. Asian Earth Sci.* 24:495–515. <https://doi.org/10.1016/j.jseaes.2004.03.006>
- Sreevidya E, Sijinkumar AV, Nath BN (2022). Palaeoceanographic significance of aragonitic pteropods in the Indian Ocean—a review. *Boreas* 51:1-19. <https://doi.org/10.1111/bor.12540>
- Steinke S, Mohtadi M, Groeneveld J, Lin LC, Löwemark L, Chen MT, Rendle-Bühning R (2010) Reconstructing the southern South China Sea upper water column structure since the Last Glacial Maximum: Implications for the East Asian winter monsoon development. *Paleoceanogr.* <https://doi.org/10.1029/2009pa001850>.
- Steph S, Regenber M, Tiedemann R, Mulitza S, Nürnberg D (2009). Stable isotopes of planktonic foraminifera from tropical Atlantic/Caribbean core-tops: Implications for reconstructing upper ocean stratification. *Mar Micropaleontol* 71:1-19. <https://doi.org/10.1016/j.marmicro.2008.12.004>
- Stoll HM, Arevalos A, Burke A, Ziveri P, Mortyn G, Shimizu N, Unger D (2007) Seasonal cycles in biogenic production and export in northern Bay of Bengal sediment traps. *Deep Sea Res Part II: Topical Stud Oceanogra* 54:558–580. <https://doi.org/10.1016/j.dsr2.2007.01.002>
- Trenberth KE, Stepaniak DP, Caron JM (2000). The global monsoon as seen through the divergent atmospheric circulation. *J Climate* 13:3969-3993. [https://doi.org/10.1175/1520-0442\(2000\)013<3969:tgmast>2.0.co;2](https://doi.org/10.1175/1520-0442(2000)013<3969:tgmast>2.0.co;2)
- Tripathi S, Tiwari M, Lee J, Khim BK (2017). First evidence of denitrification vis-à-vis monsoon in the Arabian Sea since Late Miocene. *Sci Rep* 7:43056. <https://doi.org/10.1038/srep43056>
- Unger D, Ittekkot V, Schäfer P, Tiemann J, Reschke S. (2003). Seasonality and interannual variability of particle fluxes to the deep Bay of Bengal: Influence of riverine input and oceanographic processes. *Deep Sea Res Part II: Topical Stud Oceanogra* 50:897–923. [https://doi.org/10.1016/s0967-0645\(02\)00612-4](https://doi.org/10.1016/s0967-0645(02)00612-4)
- Unger D, Ittekkot V, Schäfer P, Tiemann J (2005) Biogeochemistry of particulate organic matter from the Bay of Bengal as discernible from hydrolysable neutral carbohydrates and amino acids. *Mar Chem* 96:155–184. <https://doi.org/10.1016/j.marchem.2004.12.005>
- Urey HC, Lowenstam HA, Epstein S and McKinney CR (1951) Measurement of paleotemperatures and temperatures of the Upper Cretaceous of England, Denmark, and the southern United States. *Bull Geol Soc Am* 62:399-416. [https://doi.org/10.1130/0016-7606\(1951\)62\[399:mopato\]2.0.co;2](https://doi.org/10.1130/0016-7606(1951)62[399:mopato]2.0.co;2)
- Varkey MJ, Murty VSN, Suryanarayana A (1996). Physical oceanography of the Bay of Bengal and Andaman Sea. *Oceanogr Mar Biol Annu Rev* 34:1–70.

- Wall M, Schmidt GM, Janjang P, Khokiattiwong S, Richter C (2012). Differential Impact of Monsoon and Large Amplitude Internal Waves on Coral Reef Development in the Andaman Sea. *PLoS ONE* 7: e50207.
- Wang YJ, Cheng H, Edwards RL, An ZS, Wu JY, Shen CC, Dorale JA (2001). A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China. *Science* 294:2345-2348. <https://doi.org/10.1126/science.1064618>
- Wang B, Ding, Q (2008) Global monsoon: Dominant mode of annual variation in the tropics. *Dynamics of Atmospheres and Oceans* 44:165-183. <https://doi.org/10.1016/j.dynatmoce.2007.05.002>
- Wang PX, Wang B, Cheng H, Fasullo J, Guo Z, Kiefer T, Liu Z (2017). The global monsoon across time scales: Mechanisms and outstanding issues. *Earth Sci Rev* 174: 84-121. <https://doi.org/10.1016/j.earscirev.2017.07.006>
- Wanner H, Mercolli L, Grosjean M, Ritz SP (2015). Holocene climate variability and change; a data-based review. *J Geol Soc* 172:254-263. <https://doi.org/10.1144/jgs2013-101>.
- Webster PJ, Magana VO, Palmer TN, Shukla J, Tomas RA, Yanai MU, Yasunari T (1999) Monsoons: processes, predictability, and the prospects for prediction. *J Geophys Res* 103, 14451–14510. <https://doi.org/10.1029/97jc02719>
- Wei G, Sun M, Li X, Nie B (2000). Mg/Ca, Sr/Ca and U/Ca ratios of a porites coral from Sanya Bay, Hainan Island, South China Sea and their relationships to sea surface temperature. *Palaeogeogr Palaeoclimatol Palaeoecolog* 162:59-74. [https://doi.org/10.1016/s0031-0182\(00\)00105-x](https://doi.org/10.1016/s0031-0182(00)00105-x)
- Wyrtki K (1961) Physical oceanography of the Southeast Asian waters. *Naga Rep.* 2: 1–195.
- Wyrtki K, Bennet EB, Rochford DJ (1971) Oceanographic Atlas of the International Indian Ocean Expedition 531.
- Wyrtki KL (1973) Physical oceanography of the Indian Ocean. *Ecol Stud* 18-36 [https://doi.org/10.1007/978-3-642-65468-8\\_3](https://doi.org/10.1007/978-3-642-65468-8_3)
- Xu X, Liu J, Huang Y, Zhang L, Yi L, Liu S, Yang Y, Cao L, Tan L (2022). An Intertropical Convergence Zone shift controlled the terrestrial material supply on the Ninetyeast Ridge. *Clim Past* 18;1369-1384 <https://doi.org/10.5194/cp-18-1369-2022>
- Yadava MG, Ramesh R (2001) Past rainfall and trace element variations in a tropical speleothem from India. *Mausam* 52:307-316. <https://doi.org/10.54302/mausam.v52i1.1697>
- Yadava MG, Ramesh R (2005) Monsoon reconstruction from radiocarbon dated tropical Indian speleothems. *Holocene* 15:48-59. <https://doi.org/10.1191/0959683605h1783rp>
- Yang YP, Xiang R, Huang Y, Liu SF, Liu JG, Khokiattiwong S, Kornkanitnan N (2021) Meridional migration of Indian Ocean monsoon precipitation during the Early Holocene: Evidence from the Andaman Sea. *Geophys. Res. Lett.* <https://doi.org/10.1002/essoar.10506717.1>

- Yang Z, Luo C, Ariful Islam GM, Dong X, Su X, Xiang R, Du S, Yang Y, Liu S (2023) Northward migration of the maximum Indian summer monsoon precipitation during the early–mid-Holocene: Evidence from sporopollen in the Andaman Sea. *Mar Micropaleontol* 181:102230. <https://doi.org/10.1016/j.marmicro.2023.10223>
- Zhisheng A, Kutzbach JE, Prell WL, Porter SC (2001). Evolution of Asian monsoons and phased uplift of the Himalaya–Tibetan plateau since Late Miocene times. *Nature* 411:62-66. <https://doi.org/10.1038/35075035>
- Zhou X, Duchamp-Alphonse S, Kageyama M, Bassinot F, Beaufort L, Colin C (2020) Dynamics of primary productivity in the northeastern Bay of Bengal over the last 26000 years. *Clim Past* 16:1969-1986. <https://doi.org/10.5194/cp-16-1969-2020>

## Legend to Figures and Table

- Figure 1 (a) The geological map of the eastern Himalayan region, south-eastern Tibet, Myanmar, parts of western lithological units and major rivers systems in the Andaman region. The source rocks with various  $\epsilon_{Nd}$  in and around the Andaman Sea and Bay of Bengal are also marked (modified after Rashid et al. 2019). The grey rectangle marks the Andaman Sea. (b) The bathymetry of the Andaman Sea. The direction of surface currents during summer monsoon are shown by arrows (Rizal et al. 2012).
- Figure 2 The wind pattern in the Andaman Sea during summer (a) and winter (b) monsoon obtained by taking average of the wind speed and sea surface temperature during the period of 1999-2021 from ERA5-ECMWF analysis.
- Figure 3 The cores used for paleoclimatic studies from the Andaman Sea. (U1447 Lee et al. 2020; NGHP 17A Ali et al. 2015; MD77-169 Duplessey 1982; SN SC-03 2008 Achyuthan et al. 2014; SK234 GC60 Awasthi et al. 2014; MD77-176 Duplessey 1982; StMY6 Ota et al. 2017; ADM-159 Liu et al. 2021; ADM-9 Cao et al. 2015; ADM-C1 Huang et al. 2020; RC12-344 Duplessey 1982; SSK50 GC03A Sebastian et al. 2019; U1448 Johnck et al. 2020; RVS 2 Sijinkumar et al. 2015; SK168 GC01 Sijinkumar et al. 2010; SSD 18 Sijinkumar et al. 2021; AAS11 GC01 Ahmad et al. 2000; MD77 167, 168, 170, 172, 173, 174, 175 Fontugne and Duplessey 1986; MD77-171 Duplessey 1982).
- Figure 4 The variation in the oxygen isotopic ratio of *Trilobatus sacculifer* during the last 1 Ma (Gebregiorgis et al. 2018) and Miocene - Pliocene transition (Johnck et al. 2020) in the Andaman Sea.
- Figure 5 The variation in the stable oxygen isotopic ratio of *Globigerinoides ruber* and *Neogloboquadrina dutertrei* during MIS5 in the Andaman Sea (Nilsson-Kerr et al. 2020; 2022).
- Figure 6 A compilation of the oxygen isotopic variation in mixed layer dwelling planktic foraminifera *Globigerinoides ruber* in cores collected from the Andaman Sea. a) RVS 2 (Sijinkumar et al. 2015), b) AAS 11 (Ahmad et al. 2000), c) ADM 159 (Liu et al. 2021), d) SK168 GC01 (Sijinkumar et al. 2010), e) SK234 GC60 (Awasthi et al. 2014), f) RC12-344 (Rashid et al. 2007).
- Figure 7 Mg/Ca based temperature variation during the Late Quaternary, in cores a) SK168 GC01 (Gebregiorgis et al. 2016), and b) ADM-159 (Liu et al. 2021) collected from the Andaman Sea.
- Table 1 Details of the core samples discussed in the present review and mentioned in Figure 3. The serial numbers correspond to the site in Figure 3.

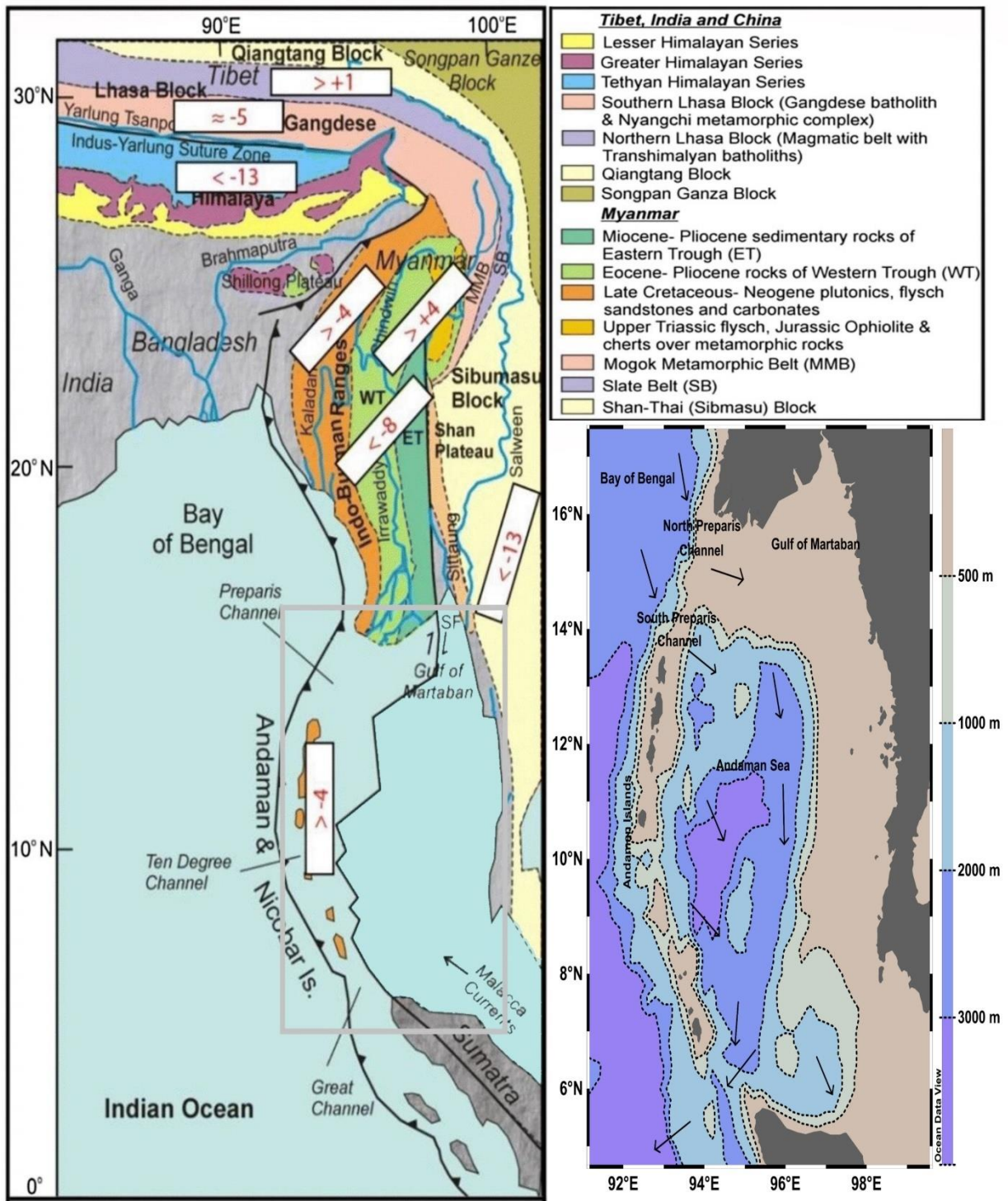


Figure 1

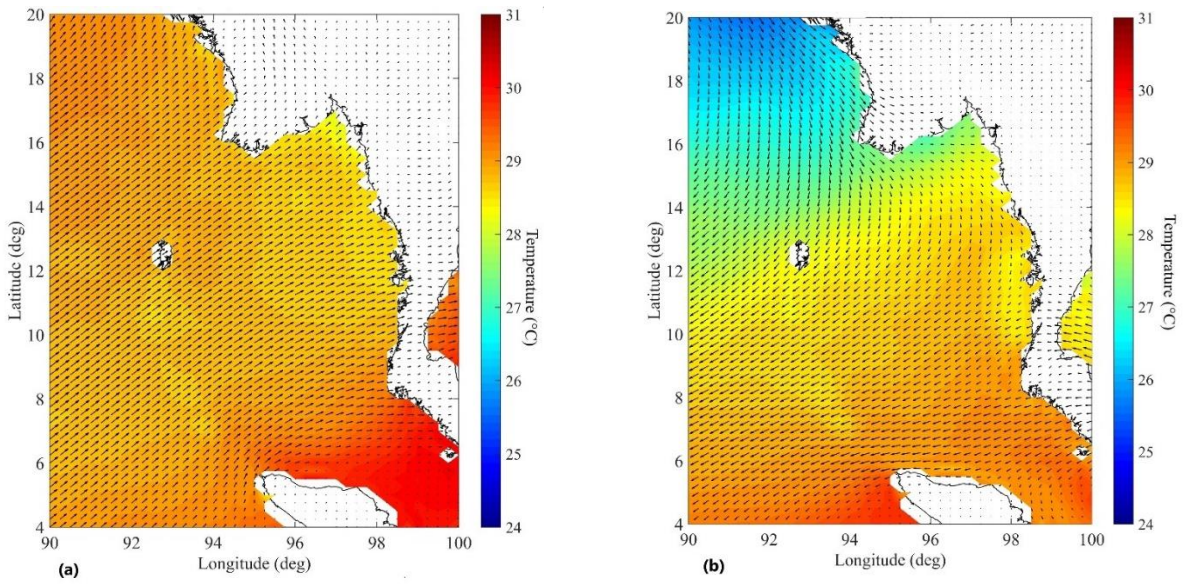


Figure 2



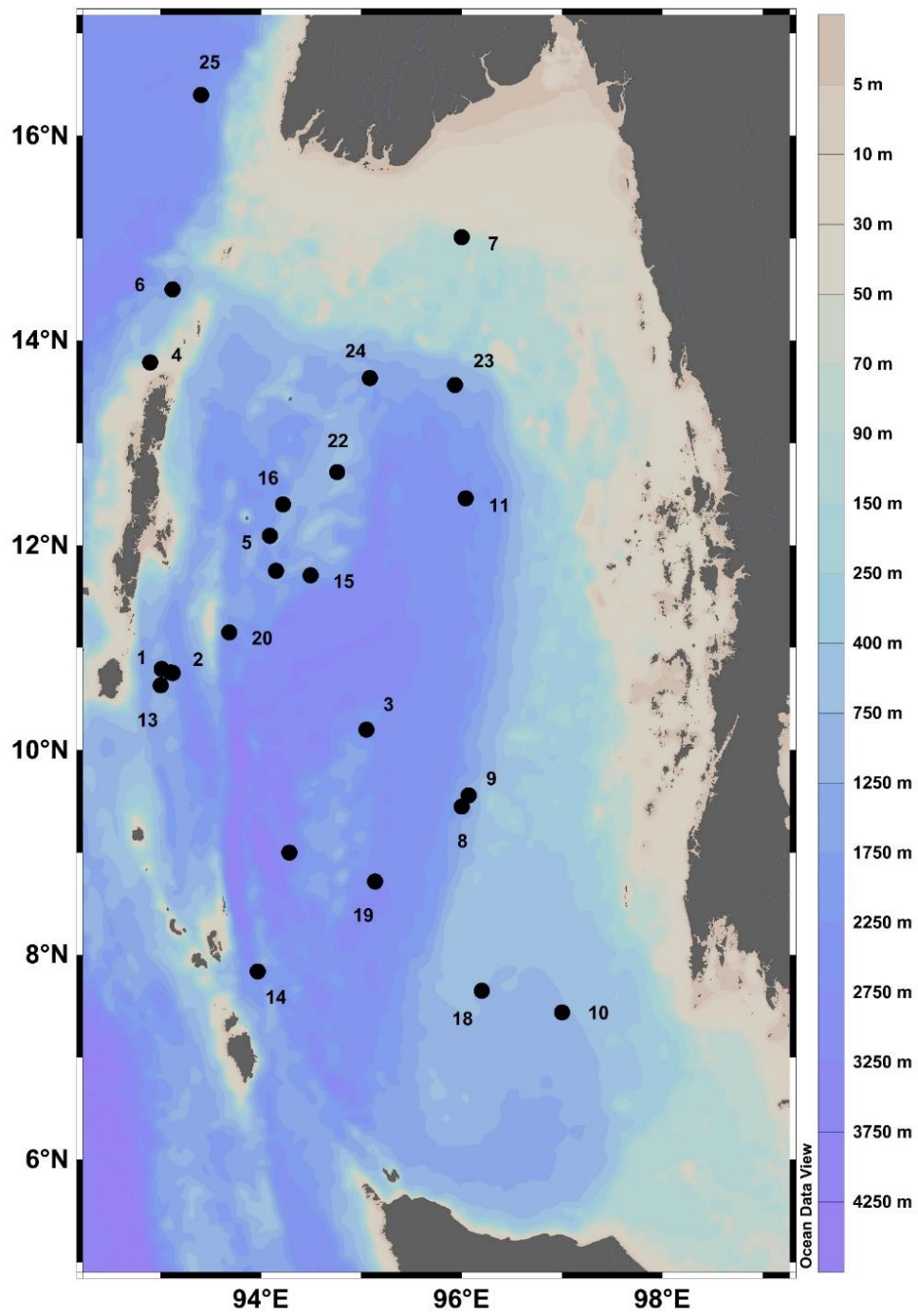


Figure 3



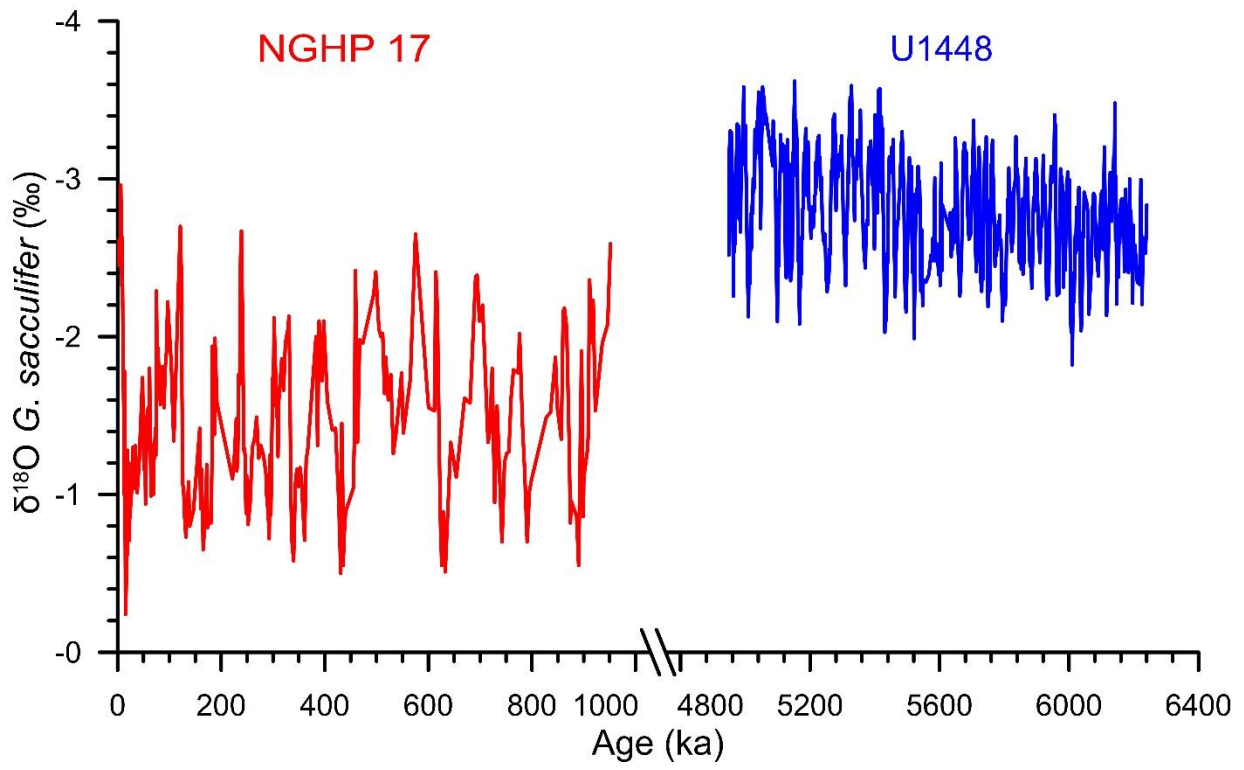


Figure 4

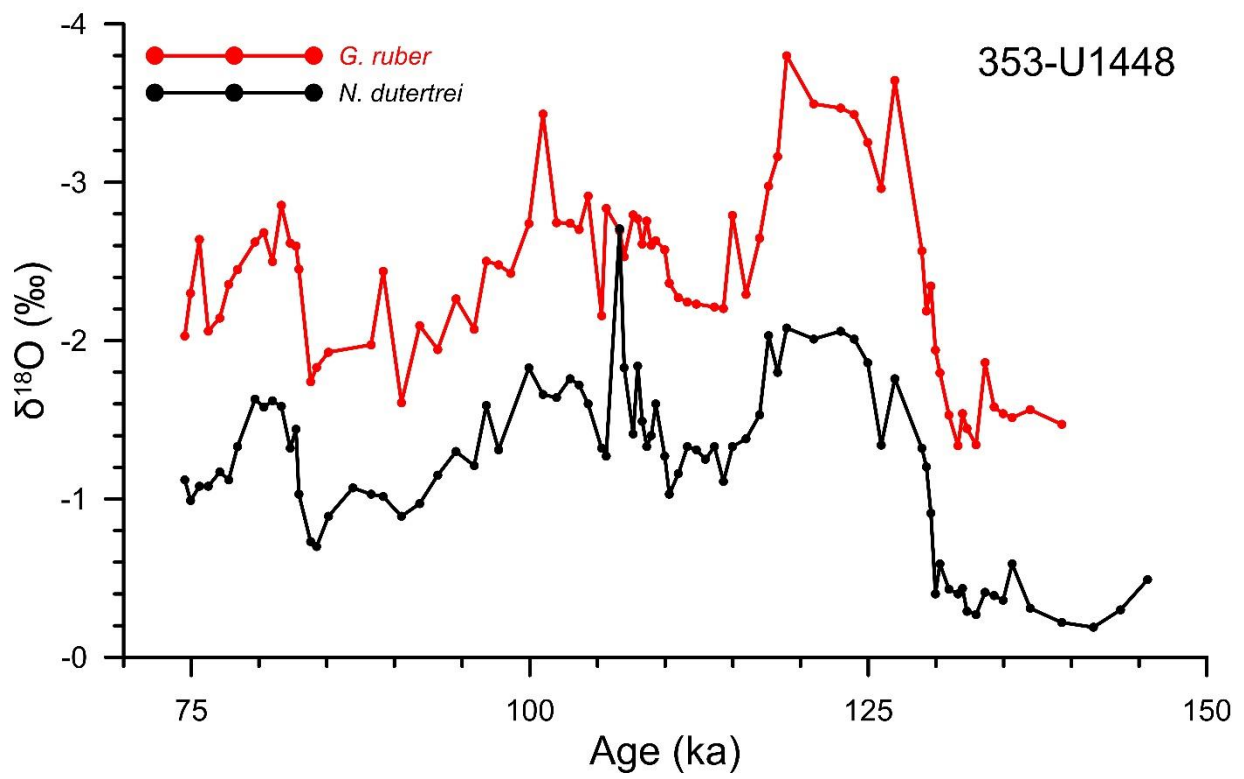


Figure 5

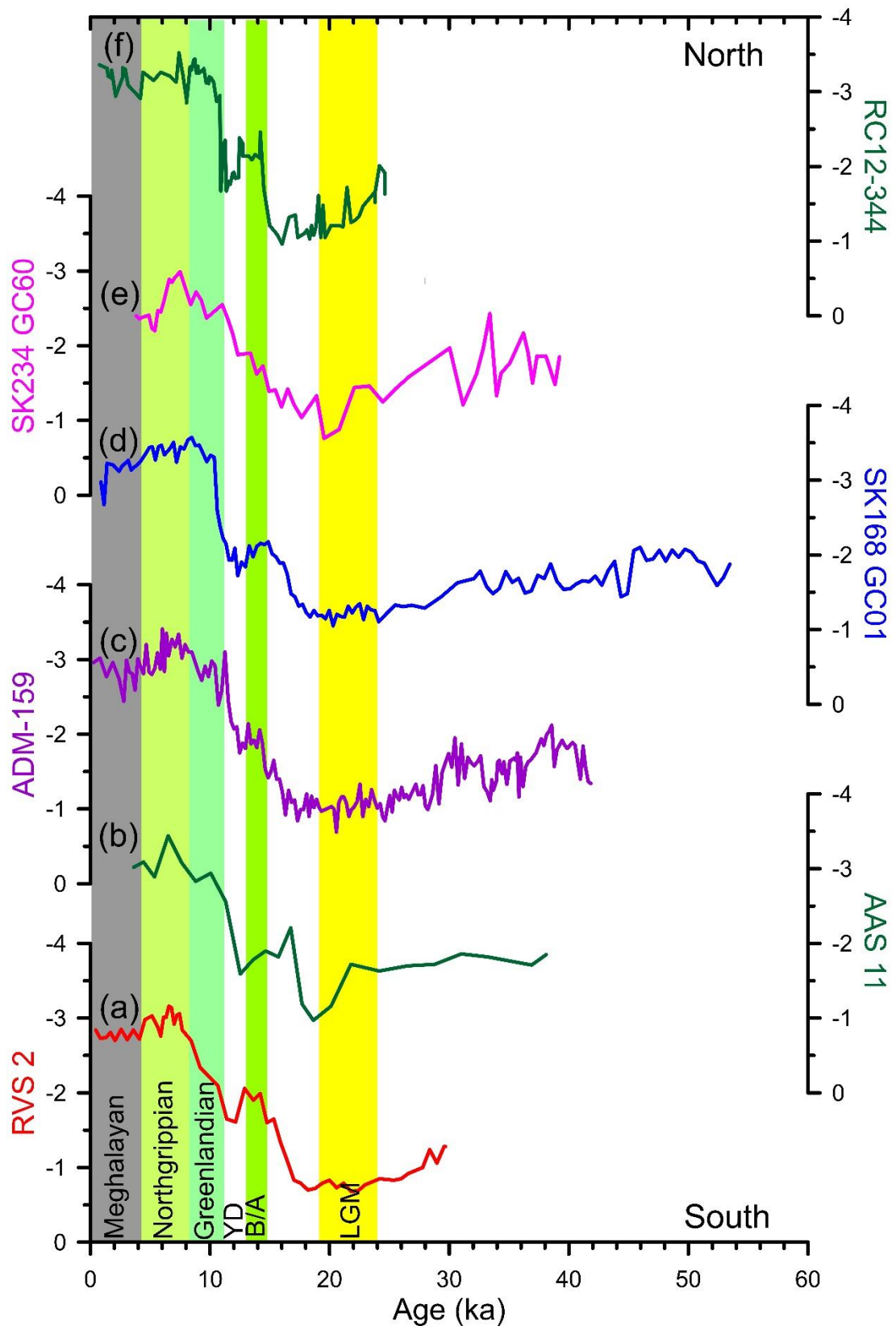


Figure 6

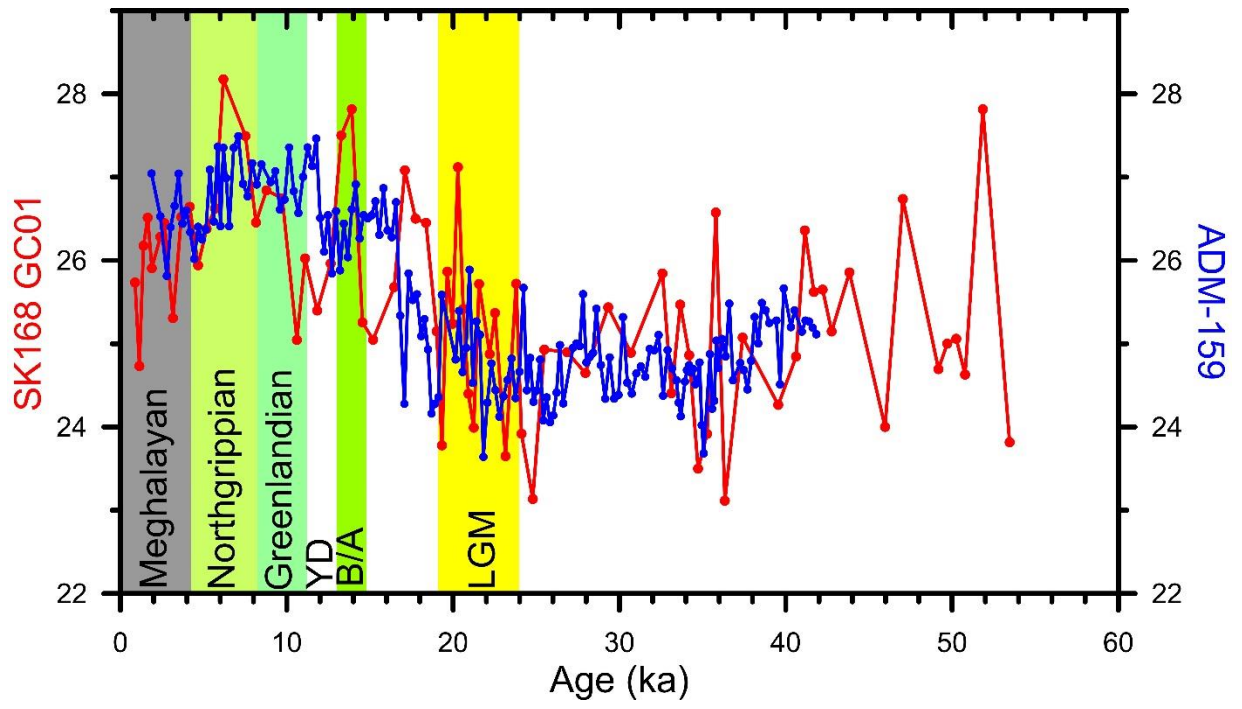


Figure 7

Table 1

Sl. No.	Core/Site	Lat. (°N)	Long. (°E)	Dating Technique	No of Radiocarbon Dates	References
1	U1447	10.79	93.00	Biostratigraphic, Paleomagnetic, Sedimentation rate and Lithounits		Lee et al. 2020
2	NGHP 17A	10.75	93.11	<sup>14</sup> C AMS, $\delta^{18}\text{O}$ stratigraphy	5	Ali et al. 2015; Gebregiorgis et al. 2018
3	MD77-169	10.20	95.05	<sup>14</sup> C AMS, $\delta^{18}\text{O}$ stratigraphy	10	Duplessey 1982; Fontugne and Duplessey 1986; Colin et al. 1998; 1999; 2006
4	SNSC-03 2008	13.79	92.90	<sup>14</sup> C dating	5	Achyuthan et al. 2014; Nagasundaram et al. 2014
5	SK234 GC60	12.10	94.09	<sup>14</sup> C AMS, $\delta^{18}\text{O}$ stratigraphy	10	Awasthi et al. 2014; Kumar et al. 2018
6	MD77-176	14.51	93.13	<sup>14</sup> C AMS, $\delta^{18}\text{O}$ stratigraphy	31	Duplessey 1982; Colin et al. 2006; Marzin et al. 2013; Zhou et al. 2020
7	StMY6	15.00	96.00	<sup>14</sup> C AMS	7	Ota et al. 2017
8	ADM-159	9.27	95.61	<sup>14</sup> C AMS	112	Liu et al. 2021
9	ADM-9	9.56	96.07	<sup>14</sup> C AMS	10	Cao et al. 2015; Shii et al. 2022
10	ADM-C1	7.44	97.00	<sup>14</sup> C AMS	5	Huang et al. 2020
11	RC12-344	12.46	96.04	<sup>14</sup> C AMS, $\delta^{18}\text{O}$ stratigraphy	9	Duplessey 1982; Fontugne and Duplessey 1986; Rashid et al. 2017; 2019
12	SSK50 GC03A	10.76	93.10	<sup>14</sup> C AMS	5	Sebastian et al. 2019
13	U1448	10.63	93.00	$\delta^{18}\text{O}$ stratigraphy		Johnck et al. 2020; Kuhnt et al. 2020; Nilsson-Kerr et al. 2021; 2022
14	RVS2	7.70	93.96	<sup>14</sup> C AMS	7	Sijinkumar et al. 2015; 2016a; 2016b; 2020a; 2021b; Gayathri et al. 2022; Lal et al. 2022
15	SK168 GC01	11.71	94.49	<sup>14</sup> C AMS, $\delta^{18}\text{O}$ stratigraphy	5	Sijinkumar et al. 2010; 2011; 2015; 2016a; 2016b; 2020a; 2020b; 2021b; Lal et al. 2022; Gebregiorgis et al. 2016; Miriyala et al. 2017; Jayan et al. 2021
16	SSD 18	12.40	94.22	<sup>14</sup> C AMS	3	Sijinkumar et al. 2021
17	AAS11 GC01	9.00	94.28	<sup>14</sup> C AMS	10	Ahmad et al. 2000; Sijinkumar et al. 2011; 2015; 2016a; 2016b; 2020a; 2021b; Jayan et al. 2021
18	MD77-167	7.65	96.20	$\delta^{18}\text{O}$ stratigraphy		Fontugne and Duplessey 1986
19	MD77-168	8.72	95.14	$\delta^{18}\text{O}$ stratigraphy		Fontugne and Duplessey 1986
20	MD77-170	11.15	93.68	$\delta^{18}\text{O}$ stratigraphy		Fontugne and Duplessey 1986
21	MD77-171	11.75	94.15	$\delta^{18}\text{O}$ stratigraphy		Duplessey 1982; Fontugne and Duplessey 1986
22	MD77-172	12.72	94.77	$\delta^{18}\text{O}$ stratigraphy		Fontugne and Duplessey 1986
23	MD77-173	12.77	96.06	$\delta^{18}\text{O}$ stratigraphy		Fontugne and Duplessey 1986
24	MD77-174	13.57	95.93	$\delta^{18}\text{O}$ stratigraphy		Fontugne and Duplessey 1986
25	MD77-175	13.64	95.08	$\delta^{18}\text{O}$ stratigraphy		Fontugne and Duplessey 1986