Two decades of progress: A comprehensive review of paleoclimatic and paleoceanographic research in the northwestern Bay of Bengal (2000–2024)

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ABSTRACT

Microfossils preserved in marine sediments serve as valuable archives for the paleoceanographic and paleoclimatological processes. Various biotic and abiotic factors, including nutrient availability, oxygen conditions, light penetration, temperature, and salinity, control the distribution of these microfossils. Additionally, post-depositional processes such as burial, decomposition, and preservation influence the integrity of microfossil records. As a result, these microscopic remains provide crucial insights into Earth's geological past, helping reconstruct paleoclimate and oceanographic history. Marine sediments contain a diverse array of microfossils, primarily comprising foraminifera, pteropods, ostracods, radiolarians, diatoms, and calcareous nannoplankton. Among these, foraminifera have gained special attention due to their high abundance, widespread distribution, ecological sensitivity, and relative ease of study. These protists serve as indicators of oceanic conditions, providing information on ocean chemistry, water mass characteristics, stratification, circulation, and productivity. Their tests also serve as environmental recorders, making them helpful in monitoring pollution and detecting anthropogenic impacts. The foraminiferal assemblages and morphogroups are widely used as proxies for reconstructing paleomonsoon intensity, variations in terrigenous flux, and associated hydrographic changes in the marine environment. The stable oxygen and carbon isotopes, as well as the elemental composition, of foraminiferal tests have been widely used in paleoceanographic reconstructions. Oxygen isotope ratios ($^{18}O/^{16}O$) provide insights into past seawater temperatures and ice volume changes, while carbon isotopes ($^{13}C/^{12}C$) help to infer ocean productivity and circulation patterns. Similarly, radiolarians, which are abundant in deep-sea sediments below the Calcium Carbonate Compensation Depth (CCD), are essential for biostratigraphic correlation where calcareous microfossils undergo dissolution. Their distribution helps trace paleogeographic shifts and tectonic evolution in ocean basins.

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1. Introduction

The Bay of Bengal (BoB), located in the northeastern part of the Indian Ocean, spans approximately 2.2 million square kilometers and measures about 2,090 km in length and 1,610 km in width (Lafond, 1966). The Bay is a semi-enclosed basin bounded on the west and northwest by India, on the north by Bangladesh, and on the east by Myanmar and the Andaman and Nicobar Islands. The Bengal fan, the largest submarine fan in the world, is located in the BoB, covers an area of approximately 3×10^6 km^2, and reaches a depth of 5000 m (Curray et al., 2002). The BoB is a region of positive water balance with excess precipitation over evaporation and is influenced mainly by the seasonally reversing Indian Monsoonal wind system, This system is a product of differential heating and cooling of the Asian continent and the Indian Ocean, which drives the seasonal circulation and alternating wind patterns (Naidu et al., 2015; Roxy et al., 2015; Gadgil, 2018; Joseph et al., 2024). Due to the resulting pressure differences, the northeasterly and southwesterly winds converge in a zone of low pressure, known as the Inter Tropical Convergence Zone (ITCZ) (Gadgil, 2003). The southwest monsoon (SWM), also known as the summer monsoon, develops as the ITCZ migrates northward, with the Indian landmass heating up, resulting in low pressure over this region. Thus, moisture-laden winds blow from the Indian Ocean (a high-pressure region) towards the Indian subcontinent, generating heavy precipitation and river runoff over the Indian landmass, which flows through the peninsular rivers into the BoB. The Northeast monsoon (NEM), also known as the winter monsoon, develops during the southward migration of the ITCZ, which blows from the Indian subcontinent (the high-pressure region) towards the comparatively moisture-laden Indian Ocean.

2. Climatic and oceanographic setting

The Indian monsoon system, driven by the differential migration of the ITCZ, influences oceanographic processes in the BoB. The northward migration of ITCZ results in a wet summer monsoon with higher precipitation, while the southward migration of ITCZ results in a drier winter monsoon with comparatively lesser precipitation (Shankar et al., 2002; Rashid et al., 2011; Haridas et al., 2022). The intense rainfall during the summer monsoon over the Indian subcontinent leads to a massive discharge of freshwater and sediment into the Bay (Mohanty et al., 2008; Bretschneider et al., 2021; Ota et al., 2022; Liu et al., 2023). The northern and western BoB are primarily affected by fluvial discharge from both the Himalayan and the peninsular rivers. Major rivers draining into the Bay are the Ganges and Brahmaputra (1003 x 10^6 m^3yr^{-1}, 926 x 10^6 tonnes yr^{-1}), Irrawaddy (422 x 10^6 m^3yr^{-1}, 265 x 10^6 tonnes yr^{-1}), Godavari (92.2 x 10^6 m^3yr^{-1}, 170 x 10^6 tonnes yr^{-1}), Mahanadi (54.5 x 10^6 m^3yr^{-1}, 15.7 x 10^6 tonnes yr^{-1}), Krishna (32.4 x 10^6 m^3yr^{-1}, 4 x 10^6 tonnes yr^{-1}), and Cauvery (21.5 x 10^6 m^3yr^{-1}, 1.5 x 10^6 tonnes yr^{-1}). Together, these rivers supply about 1350 million tonnes of sediment annually, accounting for about eight percent of the total global riverine sediment supply to the ocean. Additionally, they deliver around 1,300 km^3 of freshwater per year, significantly influencing coastal and marine ecosystems (Milliman and Syvitski, 1992; Milliman, 2001). As a result, the Bay of Bengal (BoB) is one of the largest recipients of freshwater and sediment input in the global ocean. Since the majority of precipitation eventually drains into the BoB, it is often referred to as the 'sink of the Indian summer monsoon' (Rashid et al., 2011). The huge amount of freshwater discharge followed by the southwest monsoon results in a strong salinity gradient in the BoB, ranging from 26 psu in the north to 34 psu in the south (Vinayachandran et al., 2013; Sengupta et al., 2016; Sijinkumar et al., 2016; Da Silva et al., 2017; Naik and Naidu, 2019). Thus, salinity in northern BoB is reduced by ~7psu and results in a Low Salinity Plume (LSP), especially along the northern BoB during the southwest monsoon period, but shifts towards the south during the late southwest monsoon period (Chaitanya et al., 2014; Loganathan et al., 2021; Li et al., 2023). During the mid-Holocene, the BoB exhibited a north-to-south salinity gradient, indicating enhanced precipitation and runoff. In contrast, the reduced salinity gradient observed during the glacial age suggests a decline in precipitation and runoff (Sijinkumar et al., 2016). Freshwater influx also results in maximum freshening of the top 10–40 m, especially in the northern BoB, and creates strong near-surface haline stratification (Vinayachandran et al., 2002). The intensified stratification significantly contributes to regulating Sea Surface Temperature (SST) and restricting vertical nutrient mixing in the BoB (Narvekar and Kumar, 2014; Krishnamohan et al., 2019). Thus, during high discharge

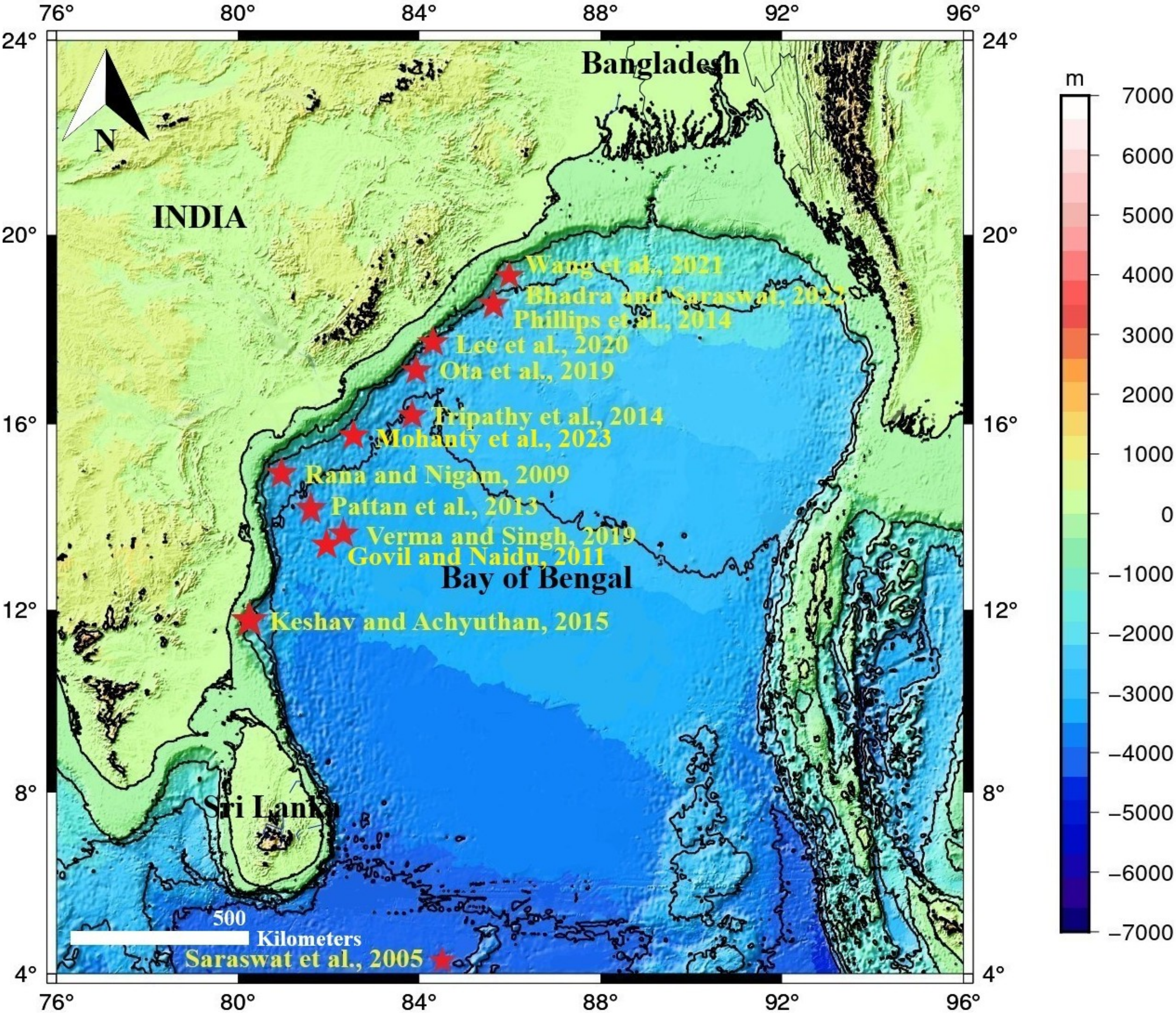

Fig. 1. Map showing the key downcore records of the Bay of Bengal.

periods, the northern BoB witnessed low total biogenic production (Phillips et al., 2014; Ota et al., 2019). Stratification also inhibits vertical oxygen exchange, triggering the development of an intense Oxygen Minimum Zone (OMZ) along the northern Bay (Sarma et al., 2016; Sridevi and Sarma, 2020; Rixen et al., 2020; Udaya Bhaskar et al., 2021). Studies on biogeochemical cycling along the west coast of BoB during the summer monsoon period also suggest that river discharge significantly impacts stratification and primary production, thereby intensifying the OMZ (Sarma et al., 2012). In addition to this, intense oxygen depletion is also associated with high productivity, nutrient enrichment, and decomposition of sinking organic matter, which removes dissolved oxygen from intermediate water depths (Sarma, 2002; Sardessai et al., 2007; Sarma et al., 2013, 2016; Bristow et al., 2017; Sarma and Udaya Bhaskar, 2018; Suokhrie et al., 2020). The intensity and thickness of the OMZ layer are more pronounced in the northwestern region, where increased stratification and biological productivity result from enhanced riverine discharge (Sarma et al., 2014; Udaya Bhaskar et al., 2021). Oxygen concentrations were below the detection limits in the northwestern coastal BoB between 100 and 500 m associated with strong stratification and high phytoplankton biomass (Sarma et al., 2013). The Oxygen Deficient Zone (ODZ) of the BoB differs from that of the Arabian Sea due to a lower bacterial respiration rate and the faster sinking of organic matter in the BoB. As a result, the associated oxygen uptake does not lead to denitrification in the BoB, unlike in the Arabian Sea (Naqvi et al., 2000; Sarma, 2002; Suokhrie et al., 2020). This difference is also visible in the benthic foraminiferal assemblages recorded from the two basins (Suokhrie et al., 2020; Kaithwar et al., 2020; Aravind et al., 2024). Riverine discharge plays a significant role in plankton biomass and productivity along the BoB, as it delivers substantial nutrients to coastal regions (Sarma et al., 2013; Venkataramana et al., 2017; Bharathi et al., 2018). Although rivers pour a huge amount of nutrients into the BoB, the limitation of solar radiation due to persistent cloud cover and nitrate depletion in the surface restricts the phytoplankton growth (Gomes et al., 2000; Prasanna Kumar et al., 2002; Madhupratap et al., 2003; Madhu et al., 2006). Phytoplankton in the BoB are mainly influenced by the concentration of nutrients such as silicate, nitrate, and phosphate (Paul et al., 2008). Muraleedharan et al. (2007) reported that BoB is enriched in silicate and phosphate, while being depleted in nitrate. However, nitrate availability increases near the coast due to upwelling, thereby increasing productivity. Sarma et al. (2016) also noted that the northern BoB features low-salinity waters with higher silicate concentrations than nitrate or phosphate, suggesting that freshwater is the primary source of silicate. Thus, riverine discharge significantly influences siliceous phytoplankton production in the BoB (Lee et al., 2020). Whereas biogenic calcareous production in the northwestern BoB is largely controlled by coastal upwelling, rivers supply only insufficient nitrate relative to silicate (Sarma et al., 2016). The marine plankton assemblage in the northwestern BoB is mainly influenced by the intensity of riverine discharge (Ota et al., 2019). During periods of higher discharge (interglacial), biogenous siliceous production increased, whereas lower discharge (glacial) periods favored calcareous production. Venkataramana et al. (2017) observed high nutrient concentrations in the southern coastal BoB, with elevated suspended matter that limits phytoplankton biomass. In contrast, low nutrient concentration and suspended matter were observed at the northern coastal BoB, coupled with higher phytoplankton biomass and zooplankton abundance. Hence, it is concluded that in the coastal BoB, primary production is predominantly driven by light availability rather than nutrient supply. Sarma et al. (2012) reported that along the western continental shelf of the BoB, freshwater discharge largely controls the inorganic carbon components in the surface waters. The pCO_2 levels were higher in peninsular rivers and were reported in the southwest coast of the BoB, while higher pCO_2 levels in the glacial river Ganges were noticed from the northwest coast. Compared to the Arabian Sea, primary productivity in the BoB is lower (Madhupratap et al., 2003), but higher rates were observed near the river mouth and along certain parts of the northern and the western BoB due to the eddies that brings up nutrients in the stratified waters (Prasanna Kumar et al., 2004, 2010; Madhu et al., 2006). Even though the riverine flux brings nutrients, they are thought to be lost to the deep because of the narrow shelf (Qasim, 1977; Madhupratap et al., 2003; Sengupta et al., 2016; Radhakrishna et al., 1978; Prasanna Kumar et al., 2010; Nishath et al., 2017). Primary production is higher during winter (0.2–0.56 gC m-2 day-1) than during the summer monsoon (0.1 - 0.2 gC m-2 day-1) due to thick cloud cover over the BoB during the latter season (Gomes et al., 2000). Bristow et al. (2017) hypothesized that the BoB may become a dead zone, as nutrients from riverine sources will increase primary production and sinking carbon fluxes.

Thus, the Bay of Bengal (BoB) represents a unique oceanographic setting and is one of the most climatically vulnerable regions in the world. Consequently, it has become a key hotspot for climatic and oceanographic research (Fig. 1). Although paleoclimatic records for the western Bay of Bengal are limited, there has been a notable lack of effort to investigate provenance, hydrographic changes, and variations in productivity. This review synthesizes significant studies conducted on paleoclimatic and paleoceanographic reconstructions in the northern and western BoB. The research, spanning from 2000 to 2024, employs various proxies, including microfaunal abundance and distribution patterns, microfaunal geochemistry, sediment geochemistry, and hydrological and climatological parameters.

3. Microfaunal proxy

The study of global warming and its related climatic changes has gained significant international attention in recent times. As the Indian economy is primarily dependent on agriculture, it is crucial to study the monsoon and its relationship to global climatic variability. For paleoclimatic studies, it is essential to obtain climatic data from the geological past, extending far beyond the available instrumental records. These studies are crucial for understanding the factors that influence monsoon variability and long-term climate change, thereby aiding the development of future climate projections. Given the intrinsic connection between the ocean and climate, oceanic sediments are among the most valuable archives for reconstructing past climatic and oceanographic conditions (Rana et al., 2007). Marine microfossils, particularly foraminifera, have been widely utilized to reconstruct past monsoon fluctuations. Both planktonic and benthic foraminifera were used to reconstruct paleoclimatic, paleoenvironmental, and paleoceanographic conditions as the chances of diagenetic alterations are limited for them (Panchang and Nigam et al., 2007; Saraswat et al., 2015; Ma et al., 2019; Anbuselvan and Senthil Nathan, 2021; Bhadra and Saraswat, 2021; Jayan et al., 2021; Maeda et al., 2022; Mohanty et al., 2023; Aravind et al., 2024). The benthic foraminiferal abundance and distribution patterns are mainly controlled by changes in nutrient flux (organic carbon) to the sea floor and bottom water oxygenation conditions. Benthic foraminifera, the extremely sensitive bottom water indicators, are affected by pore water oxygen levels, hence are used as paleo-oxygenation and paleoceanographic tracers (Saraswat et al., 2005; Nigam et al., 2007; Ahmad et al., 2012; Raza et al., 2014; Manasa et al., 2016; Chowdhury and Bhaumik, 2019; Suokhrie et al., 2020, 2021; Verma et al., 2021; Saalim et al., 2022; Aravind et al., 2024). The abundance and distribution patterns of benthic foraminifera were also used as tracers of past monsoonal variations (Chauhan, 2003; Saraswat et al., 2005; Tiwari et al., 2005; Govil and Naidu, 2011; Saraswat et al., 2012, 2013; Mahesh and Banakar, 2014; Sijinkumar et al., 2016; Suokhrie et al., 2018; Verma et al., 2021). Saraswat et al. (2005) studied paleo-monsoonal history in the distal BoB from the abundance and mean proloculus size of *Epistominella exigua*. Suokhrie et al. (2017) in their study along the central-western BoB observed a peak in the relative abundance of Angular Asymmetrical Benthic Foraminifera (AABF). They suggested a lesser terrigenous influx and periods of reduced monsoonal precipitation. Rana and Nigam (2009) attempted to infer cyclicity in late Holocene monsoonal changes in the western BoB from benthic foraminiferal abundance, and the study documented an inverse relationship between AABF abundance and monsoonal precipitation. The study also used the abundance of *Uvigerina* sp. and *Bulimina marginata* to deduce the monsoonal changes. Absence of AABF had been noticed along the river mouth, where low saline and turbid conditions prevail. Lower salinity conditions reduced the abundance of *Uvigerina* sp. and *Bulimina marginata*. Saraswat et al. (2017) conducted a study in the western BoB, using *Asterorotalia trispinosa* as a paleomonsoonal proxy. Their findings revealed a positive correlation between the species' relative abundance and temperature. In contrast, its abundance showed a negative correlation with salinity and the percentage of organic carbon (Corg) in the weight. Similarly, Panchang and Nigam (2014) documented a significant presence of *Asterorotalia trispinosa* in the shallow waters of the Ayeyarwady Delta shelf off Myanmar. They proposed that fluctuations in its abundance could serve as a reliable proxy for monsoonal variability.

Several studies highlighted species assemblages and water-mass characteristics (Anbuselvan and Senthil Nathan, 2019; Verma et al., 2021; Harikrishnan and Senthil Nathan, 2023; Mohanty et al., 2023). Solai et al. (2013) found that diverse parameters, including coastal morphology, wave dynamics, bathymetry, and environmental conditions, primarily control the distribution of benthic foraminifera along the east coast of India. Nearshore regions exhibited significantly lower species diversity compared to the offshore area, with a corresponding increase in foraminiferal distribution at greater depths. Anbuselvan and Senthil Nathan (2019) reported that the distribution of benthic foraminiferal biofacies is primarily controlled by the nature of sediments and bathymetry, coupled with hydrodynamic conditions, salinity, and dissolved oxygen. An abundance of *Brizalina spathulata, Bolivina ordinaria, Uvigerina parvula,* and *Bulimina aculeata* characterizes a low-energy and oxygen-depleted muddy environment (Anbuselvan and Senthil Nathan, 2019). Rao et al. (2013) demonstrated that the BoB is relatively well-ventilated, as indicated by higher absolute benthic foraminiferal abundance and species diversity. Extremely low planktonic-to-benthic (PF/BF) ratios suggest water depths below the lysocline, where the dominance of benthic foraminiferal species over planktonic forms is attributed to the fragmentation and dissolution of planktonic tests. A decreased benthic foraminiferal diversity and richness is documented by Suokhrie et al. (2021) along the western BoB due to the turbulent conditions caused by the riverine influx. Saalim et al. (2019) conducted a paleoecological study along the west of the BoB to assess the ecological preferences of agglutinated benthic foraminiferal morphogroups. The study observed a relative increase in the abundance of agglutinated benthic foraminifera with depth, while the abundance of calcareous benthic foraminifera decreased. The high abundance of agglutinated benthic foraminifera in the western BoB is attributed to carbon dioxide sequestration and the resulting decrease in deep-sea pH (Bernhard et al., 2009). This lowering in pH of surface waters in the western BoB is due to the increased nitrate and sulfate aerosol loading (Sarma et al., 2015).

Verma et al. (2021) and Aravind et al. (2024) utilized benthic foraminiferal abundance and distribution patterns as proxies for reconstructing past bottom-water oxygen characteristics in response to monsoonal variations. Verma and Singh (2019) documented the *abundance of Cibicides* (oxic, low organic carbon) and observed significant changes in bottom-water oxygenation and nutrient levels along the western BoB. The study reported an abrupt increase in the total abundance of the genus at the Pleistocene-Holocene boundary, suggesting a reduction in organic matter flux to the seafloor associated with increased summer monsoonal precipitation and strong stratification. The study also noticed the abundance of *Cibicides robertsonianus, C. wuellerstorfi, C. labatulus, C. dorsopostulosus,* and *C. kullenbergi* in an oligotrophic high-oxygen bottom environment during the late Pleistocene. Panchang and Nigam (2012) utilized the low-saline, shallow-water habitat of *Asterorotalia trispinosa* as a paleomonsoon proxy. Previous researchers (Devi and Patil, 2009; Rao et al., 2013) also reported that *Asterorotalia trispinosa* is common in riverine flux regions of the northern BoB. Anbuselvan and Senthil Nathan (2019) and Harikrishnan and Senthil Nathan (2023) also reported diverse benthic foraminiferal assemblages and their associations with distinct bathymetry, sediment type, and hydrodynamic conditions along the central eastern and southwestern coasts of the BoB.

Quaternary researchers widely use benthic foraminifera as tracers of past sea-level variations. Reconstruction of paleo sea-level changes has garnered global attention over the past two decades, mainly due to the impact of global warming and climate change. Unnikrishnan and Shankar (2007) reported sea-level rise at an average rate of 1.29 mm/year along the north Indian Ocean coasts. Few attempts have been made along the eastern shore of India to reconstruct paleo-sea-level changes (Banerjee, 2000; Vaz, 2000; Rana et al., 2007). Foraminifera, which remain exposed for more extended geologic periods on the seafloor due to a lack of burial, become dull and earthy in appearance (relict foraminifera). Such relict foraminifera have been widely used as indicators in paleo-sea-level studies. Rana et al. (2007) attempted to reconstruct paleo-sea-level variations using relict forams along the east coast of India during the late Pleistocene and early Holocene periods. The study examined the potential of the foraminiferal genera *Amphistegina*, *Operculina*, *Calcarina*, and *Alveolinella*, typically associated with coral reef environments, as proxies for paleo low sea levels. The study also demonstrated three different sea stands (episodic sea level rise) at various depths (110–80 m, 80–60 m, and 30 m) along the east coast of India, and a tentative sea-level curve for the period between ~14,000 and ~9,000 years BP was prepared.

Planktonic foraminifera are also considered as proxies for paleo monsoonal, paleoceanographic, and paleoproductivity reconstructions (Kudrass et al., 2001; Chowdhury et al., 2003; Rashid et al., 2007, 2011; Sijinkumar et al., 2010, 2011, 2016; Govil and Naidu, 2011; Ahmad et al., 2012; Raza et al., 2014; Da Silva et al., 2017; Kumar et al., 2018; Anbuselvan and Senthil Nathan, 2021). Since they thrive in the surface ocean, they offer valuable insights into surface oceanographic variations, particularly the past sea surface salinity, productivity, and sea surface temperature conditions. The global distribution through ocean currents and rapid evolution over short geologic intervals make the planktonic foraminifera sensitive paleoclimatic and paleoceanographic indicators. Chowdhury et al. (2003) analyzed the distribution of planktonic foraminifera in the northern BoB and found that most species are tropical to subtropical in nature. However, the presence of the subpolar species *Globigerina bulloides* in the shelf area suggests localized upwelling activity. They also reported the dominance of *Globigerinoides ruber* (white) and *Neogloboquadrina dutertrei* in the northern BoB. Ramaswamy and Gaye (2006) observed a decline in planktonic foraminiferal carbonate flux in the north and central BoB, likely due to significant salinity variations.

In contrast, the flux of diatom opal and coccolithophorid carbonate showed a slight increase. Even

Table 1. Summary of key microfaunal investigations from the Bay of Bengal and their significance in reconstructing late Quaternary paleoceanographic and climatic variability.

Author & Year	Sample location	Proxy used	Principal findings
Anbuselvan and Senthil Nathan (2019)	Central shelf BoB	Benthic foraminifera	Principal component analysis of the dominant species, along with grain size and bottom-water physicochemical parameters, indicates that benthic foraminiferal distribution is primarily governed by sediment characteristics, bathymetry, salinity, dissolved oxygen, and prevailing hydrodynamic conditions
Anbuselvan and Senthil Nathan (2021)	Southwestern BoB	Planktonic foraminifera	The species distribution and abundance within the continental shelf are primarily controlled by depth associated with the distance of coastline, hydrodynamic and sedimentary dynamic processes, and stability of physicochemical parameters
Aravind et al. (2024)	Southern BoB	Benthic foraminifera	The Holocene was characterized by well-oxygenated waters, with dominance of epifaunal and plano-convex/trochispiral taxa, reflecting warm, oxygen-rich conditions. In contrast, the last glacial period exhibited low to moderate oxygenation with higher abundances of infaunal, tapered/cylindrical, and dysoxic species, highlighting the link between foraminiferal assemblages and glacial–interglacial oxygenation changes
Bhadra and Saraswat (2021)	Western BoB	Planktonic foraminifera	Noticed that planktic foraminiferal abundance is primarily governed by the terrigenous input and hydrographic conditions of the BoB, where a very low population of planktonic foraminifera is recorded in the immediate vicinity of river mouths
Bhadra and Saraswat (2022)	Western BoB	Planktonic foraminifera	An abundance of summer monsoon assemblages revealed that the Indian summer monsoon (ISM) was more vigorous during the warm interstadials and weaker during the stadials. In contrast, the winter monsoon assemblage suggested a weak winter monsoon during the interstadials
Bhattacharjee et al. (2013)	Northwestern BoB	Planktonic foraminifera	Reported the first time presence of the pink chromotype of *Globigerinoides ruber* and suggested that the reappearance of *G. ruber* is due to the increasing water temperature and new food resources in the area
Chowdhury et al. (2003)	Northern BoB	Planktonic foraminifera	The planktonic foraminiferal assemblages revealed distinct biofacies patterns, strongly influenced by surface productivity, upwelling activity, and regional hydrography. Downcore and isotopic evidence further indicate marked temporal variation, with Recent sediments dominating the shallow eastern shelf and Pleistocene sediments characterising the upper continental slope
Harikrishnan and Senthil Nathan (2023)	Southwestern BoB	Benthic foraminifera	The study identified the relationships among benthic foraminiferal assemblages, bathymetry, and sediment and bottom-water characteristics using statistical methods. Observed four assemblages with attributes of different environmental conditions
Jayan et al. (2021)	Andaman Sea	Planktonic foraminifera	The Last Glacial Maximum (LGM), the deglacial interval, the Younger Dryas (YD), and the late Holocene periods, all of which were associated with a weakened Indian Summer Monsoon (ISM), exhibited high abundances of G. ruber s.l. In contrast, the abundance of this morphotype declined between 30 and 23 ka, during the Bølling/Allerød (B/A), and throughout the early to mid-Holocene, coinciding with strengthened ISM conditions.

Table 1. *Continued.*

Ma et al. (2019)	Northeastern BoB	Benthic foraminiferal assemblages and geochemical tracers	The LGM period was characterised by Southern sourced water masses and dominated by intermediate and deep infaunal species reflecting low oxygen concentration and/or meso- to eutrophic deep water conditions; whereas the Holocene is characterised by an oligo– to mesotrophic environment with well-ventilated bottom water conditions
Mohanty et al. (2023)	Western BoB	Benthic foraminifera	Variations in benthic foraminiferal assemblages record changes in the Indian Summer Monsoon over the last 1690 years, reflecting warm, humid intervals during intensified ISM phases and cooler, weaker monsoon phases. Spectral analysis further reveals that these monsoonal fluctuations are linked to solar activity, which in turn influenced socio-economic developments and the rise and fall of dynasties across the Indian subcontinent during the late Holocene
Nigam et al. (2007)	Central west coast of India	Benthic foraminifera	The enhanced abundance of Rounded Benthic Foraminifera serves as a reliable indicator of oxygen-depleted conditions, particularly in shallow waters. This benthic foraminiferal response provides a valuable tool for reconstructing the spatial and temporal extent of hypoxia linked to increased anthropogenic activity along coastal regions
Panchang and Nigam (2012)	Ayeyarwaddy Delta Shelf	*Asterorotalia trispinosa*	Downcore fluctuations in abundance reflected the climatic variability of the past 489 years and established the reliability of using the proxy
Panchang and Nigam (2014)	Ayeyarwady Delta shelf	*Asterorotalia trispinosa*	Based on benthic foraminiferal assemblages, three distinct ecological zones—coral reef, nearshore low-salinity, and outer shelf–slope —reflecting the prevailing salinity gradient across the region, have been identified.
Ramaswamy and Gaye (2006)	Northern Indian Ocean	Planktonic foraminifera	Study inferred that elevated riverine freshwater flux enhanced the oceanic CO_2 uptake and increased silicate supply, thus favoured diatom production, whereas the associated reduction in salinity resulted in a decline of planktonic foraminiferal species
Rana and Nigam (2009)	Western BoB	Benthic foraminifera	Documented an inverse relationship between angular asymmetrical benthic foraminifera (AABF) abundance and monsoonal precipitation; Also inferred six prominent events (652, 624, 566, 548, 536, and 227 yr BP) of dry periods during the last ~700 years
Rana et al. (2007)	East coast India	Relict foraminifera	Demonstrated three different sea stands (episodic sea level rise) at different depths (110–80 m, 80–60 m, and 30 m), suggesting episodic sea level rise during the Late Pleistocene and early Holocene
Rao et al. (2013)	Off Chennai	Benthic and planktonic foraminifera	Noticed dominance of benthic foraminiferal species over planktonics, attributed to the fragmentation and dissolution of planktonics; Extremely low planktonic-to-benthic (PF/BF) ratios suggest water depths below the lysocline.
Saalim et al. (2019)	Western BoB	Benthic foraminifera	The higher abundance of agglutinated benthic foraminifera with depth was observed, accompanied by a decrease in calcareous taxa. This elevated abundance is likely linked to enhanced carbon dioxide sequestration and the consequent lowering of pH in the deep-sea environment
Saraswat et al. (2005)	Distal Bay of Bengal fan	*Epistominella exigua*	Documented the paleo monsoonal history from the distal BoB from the abundance and mean proloculus size

Table 1. *Continued.*

Saraswat et al. (2015)	General study	Benthic and planktonic foraminifera	Classified foraminiferal paleoclimatic proxies into two: destructive and non-destructive, where non-destructive proxies are more robust in paleoclimatic reconstruction
Saraswat et al. (2017)	Western BoB	*Asterorotalia trispinosa*	Revealed a positive correlation between the species' relative abundance and temperature, while its abundance showed a negative correlation with salinity
Solai et al. (2013)	Gulf of Mannar	Benthic foraminifera	Coastal morphology, wave dynamics, bathymetry, and environmental parameters largely control fluctuations in the distribution of foraminifera
Suokhrie et al. (2021)	Western BoB	Benthic foraminifera	Observed that riverine flux affects the living benthic foraminiferal abundance, among which the dissolved oxygen and organic carbon mostly control benthic foraminiferal distribution
Suokhrie et al. (2020)	Central-western BoB	Benthic foraminifera	The Bay of Bengal oxygen-deficient zone (ODZ) hosts a distinct benthic foraminiferal community compared to the Arabian Sea, with only four species shared between the two regions. This difference is attributed to the absence of denitrification and related biogeochemical processes in the Bay of Bengal, which shapes its unique benthic fauna.
Suokhrie et al. (2017)	Western BoB	Benthic foraminifera	Observed peak in relative abundance of Angular Asymmetrical Benthic Foraminifera (AABF) during periods of reduced monsoonal precipitation; Increasing monsoonal discharge is noticed during the Medieval Warm Period (MWP:~734–1251 AD) and decreasing discharge during the Little Ice Age (LIA: peaks at ~1431, 1524, and 1630 AD)
Verma et al. (2021)	Western BoB	Benthic foraminifera	Bottom-water oxygenation over the last 45 ka was controlled by productivity, organic matter flux, and deep-water circulation, with well-ventilated conditions during warm periods and oxygen-poor conditions during cold stadials and the LGM. Shifts from oxygenated to depleted waters, such as from the Bølling–Allerød to the Younger Dryas, reflect the influence of North Atlantic Deep Water inflow and climate variability
Verma and Singh (2019)	Western BoB	*Cibicides*	Distinct fluctuations in the abundance of the *cibicidid* group indicate substantial variation in bottom-water oxygenation and variations in organic carbon flux associated with surface-water productivity
Wang et al. (2021)	Northwestern BoB	Benthic and planktonic foraminifera	Inferred a glacial-interglacial contrast in foraminiferal dissolution, with more substantial dissolution noticed during the interglacial (Marine Isotope Stage MIS 1 and MIS 5) periods than the glacial (Marine Isotope Stage MIS 2–4 and MIS 6) periods

though several researchers reported the sporadic presence of planktonic foraminifera in the northern BoB, high-resolution subcentennial-to-decadal records are limited in this region (Kudrass et al., 2001; Chauhan, 2003; Rana and Nigam, 2009; Rashid et al., 2011; Panchang and Nigam, 2012). Recently, Bhadra and Saraswat (2021) reported a very low population of planktonic foraminifera in the immediate vicinity of river mouths, where the terrigenous input and hydrographic conditions of the BoB mainly control the abundance.

Bhattacharjee et al. (2013) studied the surface sediments of the northwestern BoB and reported, for the first time, the presence of the pink chromotype of *Globigerinoides ruber*. It was suggested that the reappearance of *G. ruber* is due to rising water temperatures and the availability of new food resources in the area. Recently, Wang et al. (2021) reconstructed a glacial-interglacial contrast in foraminiferal dissolution above the lysocline from the northwestern BoB. The study documented that the dissolution of planktonic foraminiferal species was more substantial during the interglacial (Marine Isotope Stages: MIS 1 and MIS 5) periods than the glacial (Marine Isotope Stages: MIS 2–4 and MIS 6) periods, even though the location lies above modern lysocline in the BoB (2000–2800 m). Bhadra and Saraswat (2022) reported low absolute abundance of planktonic foraminifera in the western BoB, attributed to increased terrestrial influx, high productivity, the ballast effect, methane seepage, anthropogenic CO_2 flux, and shallowing of the lysocline. The significant contributions of microfaunal proxies are summarized in Table 1.

4. Isotope geochemistry

The stable oxygen and carbon isotopic composition of foraminiferal shells is a reliable proxy for reconstructing paleoclimatic and paleoceanographic fluctuations of the geologic past. Oxygen isotope values primarily reflect sea-surface temperature conditions, fluctuations in global ice volume, paleomonsoonal variations, and paleoclimatic oscillations. At the same time, carbon isotopes reflect paleoproductivity and the age of water masses. Rashid et al. (2007) in their study reconstructed the Sea Surface Temperature (SST) and paleo monsoon variability with the aid of oxygen isotopes of planktonic foraminifera and suggested that the BoB experienced a more vigorous SW monsoon during the Bølling-Ållerød and the early Holocene, whereas a weaker monsoon during the Younger Dryas and the late Holocene periods. Similarly, Kessarkar et al. (2013) studied variations in Indian summer monsoon intensity during the Bølling-Ållerød and Holocene periods, reporting an intensification of the Indian summer monsoon that began at the onset of the Bølling-Ållerød. Fritz-Endres et al. (2019) suggested that Mg/Ca and δ^{18}O records of foraminifera are proxies to reconstruct the SST in a complex depositional environment.

Govil and Naidu (2011) reconstructed $\delta^{18}O_{sw}$ sea surface salinity and SST changes in the BoB using paired planktonic foraminiferal measurements of δ^{18}O and Mg/Ca, and suggested that the BoB was approximately 3.2 °C cooler during the Last Glacial Maximum (LGM). A ~3.5 °C rise in SST was reported from 17 to 10 ka BP. The study also reported the onset of the southwest monsoon during the Bølling-Ållerød, as evidenced by low $\delta^{18}O_{sw}$ values at ~14.7 ka BP. Enrichment of δ^{18}O during ~11–13 ka BP has been reported, suggesting the Younger Dryas cooling event in the BoB. Ahmad et al. (2013) reported that the BoB exhibited more depleted $\delta^{18}O_{sw}$ values on the western side than in the central and southern regions during the early Holocene. This depleted planktonic δ^{18}O of the west of the BoB and the Andaman Sea is caused by the influx of low salinity surface water due to heavy precipitation compared to the central and southern BoB. However, δ^{18}O values showed a marked depletion at 8–6 ka BP across the entire BoB, indicating the influx of low-salinity water driven by intense Indian monsoon precipitation, which influenced the salinity structure throughout the BoB. According to Rashid et al. (2011), the most enriched seawater δ^{18}O values were reported in the BoB during 18.2 to 14.8 ka BP, which suggests less precipitation and/ or less rainfall. The most depleted $\delta^{18}O_{sw}$ values in the early Holocene indicate that the Indian Summer Monsoon was vigorous, resulting in significant rainfall. The study also reported that the monsoon was stronger during the Bølling/Allerød and weaker during the Younger Dryas periods. The global climate shifts were characterized by sudden δ^{18}O depletion (LGM to Bølling-Ållerød) and enrichment (Bølling-Ållerød to LGM). Gautam et al. (2021) and Achyuthan et al. (2013) conducted a study on stable isotopes and salinity in the surface waters of the BoB. They inferred that both δ^{18}O and salinity are low in the northern and northeastern BoB during the southwest monsoon, whereas they increase towards the southern BoB. This is caused by the southward-moving East India Coastal Current, which carries the freshwater discharge from both the Peninsular and Himalayan Rivers. The study also reported that δ^{18}O of fresh water discharge from the Himalayan and Peninsular Rivers during the northeast monsoon is significantly lower than that of the peninsular rivers during the southwest monsoon. Fritz-Endres (2016) reported that the SST and SSS seasonal range is larger in the northern part of the Bay, while smaller in the southern part of the Bay.

Benthic foraminiferal stable carbon-isotopic composition has been used as an effective proxy to investigate deep-ocean circulation, water-mass characteristics, and their sources. Deep water masses in the southern BoB are significantly influenced by the external Circumpolar Deep Water (CDW), which is a mixture of the North Atlantic Deep Water (NADW) and the Southern Ocean Deep Water (Singh et al., 2016). During the Holocene, the NADW had a greater influence on the BoB, whereas during the LGM the Southern Ocean Deep Water contributed to the BoB (Ahmad et al., 2012; Raza et al., 2014). According to Raza et al. (2014), a significant decrease in benthic δ^{13}C values during the Last Glacial Maximum and between 50–65 ka BP suggests a drastic reduction in North Atlantic Deep Water inflow into the BoB. Additionally, a gradual increase in ben-

Table 2. Summary of significant stable isotope geochemical studies of the Bay of Bengal and their implications for paleoceanographic and climatic reconstruction.

Author	Sample location	Proxy used	Principal findings
Achyuthan et al. (2013)	Western BoB	$\delta^{18}O$ and δD records of water samples	Seasonal variations in $\delta^{18}O$ and salinity across the Bay of Bengal are primarily controlled by precipitation, river runoff, and evaporation balance (P + R − |E|), with the strongest $\delta^{18}O$–salinity relationship observed during the southwest monsoon when Himalayan river discharge peaks.
Ahmad et al. (2013)	Central, southern, and western BoB	$\delta^{18}O$ records of planktonic foraminifera	The early Holocene showed lower $\delta^{18}O$ values in its western sector than in the central and southern BoB, attributed to enhanced freshwater input from intense precipitation. A pronounced $\delta^{18}O$ depletion between 8 and 6 ka BP across the entire basin indicates widespread low-salinity conditions driven by strengthened Indian monsoon rainfall
Fritz-Endres et al. (2019)	Northern BoB	Mg/Ca and $\delta^{18}O$ records of planktonic foraminifera	Mg/Ca and $\delta^{18}O$ signatures of foraminiferal tests serve as reliable proxies for reconstructing sea surface temperatures in complex depositional settings
Gautam et al. (2021)	Western BoB	$\delta^{18}O$ and $\delta^{13}C$ records of planktonic foraminifera	The $\delta^{18}O$ and $\delta^{13}C$ records of *Globigerina bulloides* and *Orbulina universa* reveal pronounced monsoonal variability over the past 46 kyr, with a dominant northeast monsoon during the Last Glacial Maximum.
Govil and Naidu (2011)	Western BoB	$\delta^{18}O$ records of planktonic foraminifera	Documented that the BoB was approximately 3.2°C cooler during the Last Glacial Maximum (LGM), followed by a ~3.5 °C increase in SST between 17 and 10 ka BP. The study also identified the onset of the southwest monsoon during the Bølling–Allerød (~14.7 ka BP), indicated by depleted $\delta^{18}O$ values, while the subsequent $\delta^{18}O$ enrichment between ~11–13 ka BP reflects the Younger Dryas cooling event in the region
Ma et al. (2019)	Northeastern BoB	$\delta^{18}O$ and $\delta^{13}C$ records of benthic foraminifera	During the LGM, deep waters were predominantly influenced by Southern Ocean waters with lower $\delta^{13}C$ values, whereas in the late Holocene, North Atlantic Deep Water (NADW) with higher $\delta^{13}C$ values and notable B-P age offsets became increasingly dominant.
Rashid et al. (2007)	Northern BoB	$\delta^{18}O$ records of planktonic foraminifera	Reconstruction of Sea Surface Temperature (SST) and past monsoon variability suggested intensified southwest monsoon during the Bølling–Allerød and early Holocene, while reduced monsoon conditions prevailed during the Younger Dryas and late Holocene
Rashid et al., 2011	Northern BoB	$\delta^{18}O$ records of planktonic foraminifera	Enriched seawater $\delta^{18}O$ values recorded between 18.2 and 14.8 ka BP indicate reduced precipitation and weaker monsoonal influence, whereas the markedly depleted $\delta^{18}O$ values in the early Holocene reflect an intensified Indian Summer Monsoon
Raza et al. (2014)	Southern BoB	$\delta^{13}C$ records of benthic foraminifera	Significant decline in benthic $\delta^{13}C$ values during the LGM and between 50–65 ka BP indicates a substantial weakening of North Atlantic Deep Water inflow into the Bay of Bengal. The subsequent gradual rise in benthic foraminiferal $\delta^{13}C$ values since the LGM reflects the incursion of better-ventilated deep waters characterized by higher $\delta^{13}C$ signatures
Singh et al. (2016)	Southern BoB	$\delta^{13}C$ records of benthic foraminifera	Deep-water masses in the southern Bay of Bengal are primarily influenced by the incursion of Circumpolar Deep Water (CDW), formed by the mixing of North Atlantic Deep Water (NADW) and Southern Ocean Deep Water.
Tripathy et al. (2011)	Northern BoB	Sr-Nd isotopic composition	Observed a decrease in sediment supply during the LGM, attributed to a weakened southwest monsoon that led to diminished fluvial discharge.

thic foraminiferal δ^{13}C values since the LGM indicates the introduction of better-ventilated deep water with higher δ^{13}C values. Ma et al. (2019) analyzed changes in benthic foraminiferal assemblages, oxygen- and carbon-stable isotope values, and radiocarbon dates to reconstruct the evolution of intermediate water masses in the northeastern BoB from the LGM to the Holocene. Their study demonstrated that during the LGM, Southern Ocean Waters with lower δ^{13}C values dominated.

In contrast, in the late Holocene, NADW with higher δ^{13}C values and significant B-P age offsets became more prominent. Similarly, Tripathy et al. (2011) used Sr-Nd isotope ratios to trace sediment provenance in the western BoB and observed a reduction in sediment supply during the LGM. This decline was attributed to a weakening southwest monsoon, which reduced fluvial input. The most significant stable isotope geochemistry research of the BoB is summarised in Table 2.

5. Sedimentological and elemental geochemical proxies

Sediment geochemistry is also a robust tool in paleoclimatic and paleoceanographic reconstructions. The various sedimentological and geochemical proxies include grain size, major and trace elemental compositions, clay mineralogy, dissolved oxygen concentration, and elemental chemistry of marine sediments. Datta and Subramanian (2000) studied grain-size characteristics and found that sediments delivered by the Peninsular Rivers in the BoB are coarser than those from the Himalayan Rivers. Tripathy et al. (2014) attempted to record temporal changes in sediment provenance of the western BoB using major and trace element geochemistry. They noticed a reduction in sediment supply from the Himalayas during the LGM, due to the weakening of the southwest monsoon and the extensive glacial cover over the Higher Himalayas. The study also documented an intense Holocene monsoon, as evidenced by the severe chemical weathering. Bejugam and Nayak (2017) conducted a survey of sediment transport direction along the western margin of the BoB and observed that the net direction is from west to east and from north to south.

The study also reported two different clay mineral distributions, with illite as the dominant clay mineral off the northern BoB. At the same time, smectite is the dominant type in the southern part, indicating that granitic and basaltic sources are present. Bejugam and Nayak (2019) investigated the provenance of sediments and the role of monsoons and dissolved oxygen in the preservation of organic elements and metals in recent times. Phillips et al. (2014) conducted a geochemical study of monsoon-influenced variation in productivity and lithogenic sediment flux in the Mahanadi Basin, suggesting that the Mahanadi Basin is a supply-dominated margin where monsoonal intensity plays a dominant role in terrigenous sedimentation, and that variations in monsoon-driven stratification limit productivity. The study also suggested that during the LGM, the southwest monsoon was weak, leading to reduced stratification, enhanced mixing, higher productivity, and lower sediment accumulation rates. At the same time, the Holocene witnessed a strong southwest monsoon, strong stratification, limited mixing, lower productivity, and higher sediment accumulation rates. Keshav and Achyuthan (2015) found, in their study on trace and major elemental geochemistry, that the intensification of the northeast and southwest monsoons led to higher precipitation, thereby increasing sediment flux and freshwater runoff into the BoB. Ota et al. (2019) demonstrated that TiO_2 content varies on glacial-interglacial timescales, with higher values during MIS 1, MIS 3, and MIS 5 and lower values during MIS 2 and MIS 4. They also reported that the influx of detrital material was greater during MIS 1, 3, and 5a, when sea level was relatively high, and a decrease in Indian monsoonal precipitation caused low detrital input during MIS 2 and 4. A detailed study by Kangane et al. (2021) on grain-size fractions, clay minerals, and primary and trace elements of the western BoB identified six depositional environments with varying hydrodynamic conditions, dating back to ~2300 cal yr BP. Da Silva et al. (2017) studied organic carbon and stable carbon isotopes in the western BoB off the Mahanadi basin. They reported significant variations in productivity at marine isotope substages and millennial timescales. Panmei et al. (2018) attempted to understand the variation in calcium carbonate deposition and magnetic susceptibility associated with the Indian monsoon system, inferring that variations are mainly controlled by terrigenous dilution related to river discharge. The interglacial period was characterized by lower $CaCO_3$ content, and MS values suggest a more vigorous southwest monsoon, diluting the supply of terrigenous material.

Table 3. Summary of major sedimentological and geochemical proxy studies of the BoB.

Author & Year	Sample location	Proxy used	Principal findings
Bejugam and Nayak (2019)	Western BoB	Sediment geochemistry	Identified two different sediment sources in western BoB, with acidic igneous rocks characteristic of the Mahandi river, and a fundamental igneous source characteristic of the Godavari and Krishna rivers. The study also reported illite as the dominant clay mineral off Mahanadi, while smectite was the dominant one off Godavari and Krishna
Bejugam and Nayak (2019)	Western BoB	Trace metals	Recorded noticed dominance of Ba and Pb associated with felsic source for northern (Mahanadi and Vamsadhara) transects, and lower Ba and Pb associated with mafic source for southern (Godavari, Krishna, and Pennar) transects
Da Silva et al. (2017)	Off the Mahanadi basin	Organic carbon and stable carbon isotopes	Reported significant increase in productivity during the colder sub-stages and stadials (Dansgaard-Oeschger cycle) associated with wind-driven processes, convective mixing, and cold-core eddies
Datta and Subramanian (2000)	Bengal basin	Grain size characteristics	Documented that sediments delivered by the Himalayan Rivers to the BoB are fine-grained compared to those of the sediments transported by the Peninsular Rivers
Kangane et al. (2021)	Western BoB	Grain size fractions, clay minerals, and major and trace element geochemistry	Indicated six distinct zones of depositional environments of varying hydrodynamic conditions from ~2300 cal yr BP to present
Keshav and Achyuthan (2015)	Off Cuddalore	Major and trace elemental geochemistry	Late Holocene documented intensified northeast as well as southwest monsoon and the associated high sediment and freshwater flux to the BoB
Ota et al., 2019	Western BoB	Major and trace element geochemistry; clay mineralogy	Marine Isotope Stages (MIS) 1, 3, and 5a witnessed increased Indian summer monsoonal precipitation and riverine discharge. Whereas MIS 2 and 4 noticed decreased Indian monsoonal rainfall and associated higher $\delta^{18}O$, lower TiO_2 contents, and weaker weathering in the sediment source area
Panmei et al. (2018)	Northern BoB	Sediment geochemistry	Interglacial periods (Marine Isotope Stage (MIS) 5a & 1, except MIS 3) were characterised by lower CaCO3 and lower magnetic susceptibility (MS), corresponding to a strong southwest monsoon (SWM) and a weak northeast monsoon (NEM). In contrast, Glacial periods (MIS 4 & 2) documented higher $CaCO_3$, high MS, enhanced sediment supply associated with weak SWM and strong NEM
Pattan et al. (2013)	Western BoB	Redox-sensitive elements	The study reported that oxic conditions occurred during the Late Holocene (the last 4.5 ka BP), the Last Glacial Maximum (20–15 ka BP), and from 45 ka BP to 21 ka BP. Between 15.2 and 4.5 ka BP, characterised by the suboxic condition peaking at 9.5 ka BP, associated with intensified SW monsoon
Phillips et al. (2014)	Off the Mahanadi basin	Sediment geochemistry	Noticed that the Mahanadi basin is a supply-dominated margin where monsoonal intensity largely controls the terrigenous sedimentation, and the monsoon-driven stratification limits the productivity fluctuations
Tripathy et al. (2014)	Western BoB	Major and trace element geochemistry	Documented a strong monsoon with associated intense chemical weathering during the Holocene period, whereas weakening of the Southwest monsoon and lowering of sediment supply during the LGM

In contrast, the glacial period exhibited higher $CaCO_3$ and MS values, attributed to higher primary productivity and carbonaceous terrigenous input from continental shelf areas, as well as less river discharge from the Himalayan rivers due to a weakened southwest monsoon and a more vigorous northeast monsoon. A geochemical study by Pattan et al. (2013) examined redox-sensitive elements along the western BoB to reconstruct past depositional conditions. The study reported that suboxic conditions prevailed from 15.2 to 4.5 ka BP, peaking at 9.5 ka BP, while oxic conditions occurred during the Late Holocene (the last 4.5 ka BP), the Last Glacial Maximum (20–15 ka BP), and from 45 ka BP to 21 ka BP. Suboxic conditions at 9.5 ka BP are associated with higher concentrations of terrestrially derived elements in the Ganges-Brahmaputra River system. A summary of major sedimentological and geochemical proxy studies from the Bay of Bengal is presented in Table 3.

6. Hydrographic proxies

Estimation of multiple hydrographic parameters in the BoB, such as Chlorophyll concentration, oxygen fluxes, wind stress, altimeter data, nutrient concentration, phytoplankton distribution, and pCO_2 levels, provides information on past oceanographic variability. The Chlorophyll a (Chl-a) concentration has been used to understand the paleoproductivity fluctuations in the BoB (Gomes et al., 2000). The study documented that the seasonality of phytoplankton biomass and productivity is caused by changes in surface salinity associated with freshwater discharge. Prasanna Kumar et al. (2002) observed lower productivity in the BoB by measuring the Chlorophyll a (Chl-a) concentration, which is primarily due to the lower availability of nitrate. By analyzing Chl-a concentrations and primary productivity values, Madhupratap et al. (2003) suggested reduced biological productivity during the summer monsoon season due to strong cloud cover. Still, the episodic occurrence of cyclones enhanced the surface productivity. Similarly, Sarma et al. (2016) based on Chl-a concentrations and nutrient analysis, observed higher silicate concentrations, whereas lower salinity, nitrogen, and phosphate concentrations in the northwestern BoB. A species-specific response of phytoplankton to nutrient concentrations of the BoB has been reported primarily by Paul et al. (2008). Venkataramana et al. (2017) studied Chl-a and nutrient concentrations and reported that primary production in the coastal BoB is controlled by light availability in the water column during peak river discharge. Shankar et al. (2002) analyzed hydrographic wind stress and altimeter data, revealing that monsoon currents in the BoB are driven by Ekman pumping and winds in the equatorial Indian Ocean. Muraleedharan et al. (2007) studied the hydrographic and biological parameters and inferred that the plankton populations of the BoB are primarily influenced by upwelling, cyclonic eddies, and warm gyres. Narvekar and Kumar (2014) analyzed hydrographic and atmospheric data. They noted an increase in stratification and a shallowing of the mixed layer in the northern BoB during the summer monsoon, driven by substantial water flux in the region.

Li et al. (2017) elucidated the seasonal variability of mixed-layer depth and barrier-layer thickness. Shah et al. (2018) observed a high dissolved oxygen concentration in surface and subsurface waters of the northern BoB due to the enhanced terrestrial flux. Loganathan et al. (2021) documented that during the southwest monsoon season, a Low Salinity Plume (LSP) forms along the northern BoB, which moves southward during the late southwest monsoon season. Lee et al. (2020) adopted a multiproxy approach. They documented a shift in biogenic marine productivity across the Mid-Pliocene Transition (MPT), closely linked to riverine discharge, which is regulated by the intensity of the Indian Monsoon. Unnikrishnan and Shankar (2007) utilized tide gauge data to illustrate the average rate of sea-level rise along the Indian coast at 1.29 mm/year. The climate model by Krishnamohan et al. (2019) showed a significant amount of strong saline stratification, which controls SST in the BoB and thereby stabilizes the water column.

Fluvial input is considered to be the primary source of nutrients in the BoB (Saraswat et al., 2017). The discharge also promotes primary productivity through nutrient influx via rivers (Ramaswamy and Nair, 1994) in the surface ocean of the BoB, but to a significantly lesser extent than in the Arabian Sea, due to strong stratification that prevents wind-driven vertical mixing, except during cyclonic periods. Whereas maximum productivity in the open ocean BoB is associated with subsurface chlorophyll maxima (SCM~40–90 mbsl) (Prasanna Kumar et al., 2007) in both the central and the western Bay

Table 4. Summary of major hydrographic proxy-based studies from the Bay of Bengal.

Author & Year	Sample location	Proxy used	Principal findings
Bristow et al., 2017	Northern BoB	STOX (switchable trace oxygen) oxygen data	Observed that nitrogen has not been lost, although oxygen concentration remains below the detection level (1 to 2 M), and found that the BoB sustains denitrifier and anammox populations, resulting in limited yet notable nitrogen removal
Gomes et al. (2000)	Western and northern BoB	Chlorophyll a (Chl-a) concentration	Seasonal hydrographic variations strongly regulated the nutrient availability, light conditions, and phytoplankton biomass and productivity. While stratification and cloud cover generally suppress productivity, episodic physical processes such as eddy activity, coastal upwelling, and riverine inputs intermittently enhance phytoplankton growth across different seasons
Krishnamohan et al. (2019)	Northern BoB	Hydrographic parameters	Freshwater-induced strong salinity stratification inhibits vertical heat mixing, thereby maintaining warm sea surface temperatures and high climatological rainfall over the BoB.
Lee et al. (2020)	Northwestern BoB	Multiproxy approach	Documented a shift in biogenic marine productivity across the Mid-Pliocene Transition (MPT), closely linked to riverine discharge regulated by the intensity of the Indian Monsoon. Inferred a decline in riverine flux across the Mid-Pliocene Transition (MPT), caused by the weakened Indian summer monsoon (and/or strengthened Indian winter monsoon).
Li et al. (2017)	Northern BoB	Oceanographic parameters	Observed that Intraseasonal variability of mixed-layer depth (MLD), isothermal layer depth (ILD), and barrier layer thickness (BLT) is mainly governed by internal oceanic instabilities, while the influence of intraseasonal oscillations of the monsoon (MISOs) is comparatively weaker. During MISOs, wind stress primarily drives MLD deepening, surface cooling controls ILD deepening, and the limited BLT variability results from the compensating effects of multiple forcing mechanisms.
Loganathan et al. (2021)	Northwestern BoB	Hydrographic and Chlorophyll a concentration	Freshwater input via rivers generated low saline plumes (LSP), which move towards the southward in association with the East India Coastal Current (EICC)
Madhupratap et al. (2003)	Western BoB	Chlorophyll a (Chl-a) concentrations	The study inferred that biological productivity was low during the summer monsoon, owing to the strong cloud cover, whereas episodic cyclone events contributed to short-term enhancements in surface productivity.
Muraleedharan et al. (2007)	Western BoB	Hydrographic and biologic parameters	Suggested that basin-scale and mesoscale processes largely influence the plankton populations of the BoB. Within the upper 300 m, three distinct spatially varying physical processes were identified: (i) an anticyclonic warm gyre in the southern offshore of the southern Bay, (ii) a cyclonic eddy in the northern Bay, and (iii) an upwelling region adjacent to the southern coast.
Narvekar and Kumar (2014)	Northern BoB	Hydrographic, Nitrate, and chlorophyll a, River runoff, Atmospheric, and Remote sensing data	Noticed temperature-dominated stratification and associated shallow mixed layer during the spring intermonsoon, which makes the upper waters nutrient-depleted and oligotrophic. Whereas in the summer, the nutrient riverine flux enhances the surface chlorophyll
Paul et al. (2008)	Central and western BoB	Nutrient ratios and phytoplankton cell abundance	The study found higher nutrient concentrations in the western BoB than in the central BoB, which contributed to higher phytoplankton abundance. The study provides the first detailed species-specific response of phytoplankton to nutrient concentrations of the BoB.

Table 4. *Continued.*

Prasanna Kumar et al., 2002	Central BoB	Chlorophyll a (Chl-a) concentrations	BoB is characterised by lower biological productivity due to limited nitrate availability, associated with strong stratification and weak vertical mixing.
Prasanna Kumar et al. (2007)	Central and western BoB	Hydrographic data	Noticed that eddy pumping is responsible for the enhanced biological productivity associated with enhanced nutrient concentrations, and also enhanced the chlorophyll concentration
Ramaswamy and Nair (1994)	Northern Indian Ocean	Particle flux data	Observed higher biogenic and lithogenic particulate matter in the BoB despite the Arabian Sea being more productive. Studies also suggest that interannual variability in organic carbon flux across the northern Indian Ocean is strongly linked to the southwest monsoon, and lithogenic inputs from surrounding landmasses partly modulate its transfer to deeper waters
Sarma and Udaya Bhaskar (2018)	Northwestern BoB	Hydrographic data	Documented that the supply of dissolved oxygen-rich water might have resulted in the weakening of OMZ in the BoB, whereas the supply of high-nutrient, organic-rich, and oxygen-poor waters led to the strengthening of OMZ in the offshore of the Arabian Sea and the Eastern Tropical Pacific
Sarma et al. (2012)	Western BoB	pCO_2 levels	Lower pCO_2 levels were observed in the Northwestern Bay of Bengal (NW BoB) compared to the Southwestern Bay of Bengal (SW BoB). The study also noticed that the peninsular rivers strongly influence the SW region, whereas the Ganges river influences the NW region.
Sarma et al. (2013)	Northwestern BoB	Hydrographic parameters	Reported below detection limits of oxygen concentrations along the Northwestern (NW) coastal Bay of Bengal between 100 and 500 m caused by the strong stratification and high phytoplankton biomass
Sarma et al. (2015)	Western BoB	pCO_2 levels	Noticed more basic and lower pCO_2 in coastal BoB with notably higher rates of pH decline and DIC increase in the Northwestern Bay of Bengal (NW BoB) compared to the southwest BoB. The increased acidity is associated with an increase in sulphate and nitrogen aerosol loadings over the NW BoB
Sarma et al. (2016)	Northern BoB	Chlorophyll a (Chl-a) concentrations	Observed that the water column stratification strongly controls the nutrient supply and thereby regulates the biomass and size structure of phytoplankton. The study also highlights that near-surface water in the northern BoB was relatively nutrient-poor.
Sarma (2002)	Western BoB	oxygen flux data	Noticed that oxygen levels within the Bay of Bengal Oxygen Minimum Zone are primarily controlled by the physical and biological processes, resulting in persistently low concentrations with no seasonal variations
Shah et al. (2018)	Northern BoB	Dissolved oxygen concentration (DOC)	Observed high concentrations of dissolved organic carbon in surface and subsurface waters, attributed to high flux of terrestrially derived fresh water and remineralisation of biogenic sinking particles
Shankar et al. (2002)	Northern Indian Ocean	Hydrographic wind stress and altimeter data	Noticed that monsoonal circulation is primarily governed by Ekman pumping and wind forcing from the equatorial Indian Ocean
Sridevi and Sarma (2020)	Western BoB	Hydrographic data	Suggested cyclonic regions are characterised by intense salinity stratification and intensified oxygen minimum zones, associated with inhibited vertical mixing and increased primary and export production. In contrast, anticyclonic areas are characterised by increased dissolved oxygen due to vertical pumping and lateral advection.
Unnikrishnan and Shankar (2007)	Indian Ocean coasts	Sea-level data	Reported sea-level rise between 1.06–1.75 mm yr−1, at an average rate of 1.29 mm/year along the north Indian Ocean coasts
Venkataramana et al. (2017)	Western coastal BoB	Chlorophyll a (Chl-a) and nutrient concentrations	Observed high nutrient concentration associated with high suspended matter, which limits the phytoplankton biomass in the southern coastal BoB. In contrast, northern coastal BoB exhibited lower nutrient and suspended particulate matter concentrations, yet supported elevated phytoplankton biomass and higher zooplankton abundance.

throughout the year (Da Silva et al., 2017). A relatively less intense influx of freshwater during the winter monsoon weakens stratification, thereby enhancing mixing, nutrient availability, and productivity. Many studies have also reported improved productivity during the weaker monsoon periods (Phillips et al., 2014; Da Silva et al., 2017; Panmei et al., 2018) and during the winter season (Verma et al., 2021). The coastal and northern BoB have also been reported to have depleted oxygen levels due to nutrient enrichment and stratification through river discharge (Sarma et al., 2013, 2016). High productivity depletes dissolved oxygen, forming an Oxygen Minimum Zone (OMZ) at intermediate depths of 600–800 m, but no anoxic zone (Bristow et al., 2017). The northwestern BoB is characterized by a lower dissolved oxygen concentrations than the eastern BoB and the Andaman Sea, due to lower primary production and more vigorous mixing in these latter regions (Sarma and Udaya Bhaskar, 2018). Another significant characteristic of the BoB is the occurrence of both cyclonic and anticyclonic eddies, which form at approximately 100 km² per year and play a crucial role in maintaining dissolved oxygen levels in the OMZ (Sridevi and Sarma, 2020). Sarma et al. (2013) found that the northwestern coastal BoB experienced depleted oxygen concentrations between 100 and 500 m due to strong river discharge during the summer monsoon. In 2002, Sarma conducted a study using oxygen flux data from the BoB across different months and observed that physical and biological processes in the BoB essentially drive the development of the Oxygen Minimum Zone. Sridevi and Sarma (2020) reported that the OMZ in the Bay of Bengal is intensifying to a critical state due to the periodic generation of anticyclonic eddies. Sarma et al. (2015) noted a high pCO_2, increased sulfate and nitrogen aerosol loading in the northwestern coastal BoB. Sarma et al. (2012) estimated pCO_2 levels in the BoB using CO_2 flux data and noted higher pCO_2 levels in the peninsular rivers of the southwest coast.

In contrast, lower values were observed in the Ganges River, a glacial river on the northwest coast of India. Shah et al. (2018) reported a high concentration of Dissolved Organic Carbon in the northern BoB, caused by the considerable terrestrial freshwater input through various rivers, which decreases towards the southern BoB. A summary of major hydrographic proxy-based studies from the Bay of Bengal and their implications for physical, biogeochemical, and monsoonal variability is presented in Table 4.

7. Research gaps and future directions

Despite significant advances in understanding the climatic and oceanographic variability of the Bay of Bengal (BoB), particularly along its northern and western sectors, several key gaps persist in paleoceanographic and paleoclimatic research from the northwestern BoB. Over the past two decades, studies in this region have primarily focused on broad-scale trends, yet high-resolution, multiproxy reconstructions from deep-sea sediment cores remain scarce. The available sediment cores generally exhibit low temporal resolution, limiting the ability to resolve millennial- to centennial-scale climate fluctuations and rapid monsoon-driven events. Moreover, the integration of microfaunal (foraminiferal and radiolarian), geochemical (stable isotopes and elemental ratios), and sedimentological (grain size and texture) proxies remains limited, constraining comprehensive reconstructions of past monsoonal variability and bottom-water conditions. In addition, the massive sedimentation and turbidity associated with enhanced riverine input within the western BoB constrain the retrieval of undisturbed sediment cores for high-resolution reconstruction studies. Furthermore, post-depositional processes such as slumping, reworking, and bioturbation disrupt high-resolution paleoclimatic reconstruction. The complex hydrodynamic regime, marked by variable monsoon intensity, mesoscale eddies, and strong boundary currents, adds additional uncertainty in interpreting spatial and temporal paleoceanographic patterns.

To address these challenges, future research should prioritize high-resolution, multiproxy approaches that integrate microfossil (including radiolarians, which remain underutilized), geochemical ($\delta^{18}O$, $\delta^{13}C$, trace and rare earth elements), and sedimentological (granulometric and mineralogical) analyses. Enhanced spatial coverage through coordinated core collection from both shallow shelf and deeper offshore regions is essential to capture the full gradient of monsoon and hydrographic variability. Establishing chronologically well-constrained, high-quality datasets from these archives will significantly improve the reconstruction of past climate dynamics and strengthen our understanding of the paleoceanographic evolution and monsoon variability of the northwestern Bay of Bengal.

8. Conclusion

The growing interest among Quaternary researchers in global warming and associated climatic changes has boosted the study of paleoclimatology and paleoceanography worldwide. Although the Bay of Bengal is recognized as a unique oceanographic setting, reconstruction studies from the region are relatively scarce compared to those from the Arabian Sea, owing to the region's high sediment load from major rivers, which creates a high-energy, turbid condition. Paleoclimatic and paleoceanographic reconstruction studies help understand the factors that influence the monsoon and the patterns of climatic variation, thereby aiding in planning for the future impacts of these changes. The comprehensive information on paleoclimatic and paleoceanographic reconstructions of the northern and western Bay of Bengal presented here will offer deeper insights into the geological aspects of the study area and provide a long-term context for understanding climatic variability and its associated impacts on the biosphere. Future progress in understanding the paleoclimatic and hydrographic evolution of the northwestern Bay of Bengal depends on the development of chronologically robust, high-resolution multiproxy datasets that integrate microfaunal, geochemical, and sedimentological evidence.

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Conflict of interest

The authors declare that they have no conflict of interest associated with this publication.

CRediT statement

VGV: Conceptualization, Resources, Data collection and design, Writing – review & editing. NRN: Writing – Original Draft Preparation, Supervision, review & editing.

Declaration of competing interest

The authors have no competing interests to declare.

Data availability

The data are available and can be requested from the corresponding author.

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