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REVIEW ARTICLE

Recent advancements in marine micropaleontological and paleoceanographic research from India

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Abstract

The article presents an overview of the research contributions in the field of Marine Micropaleontology and Paleoceanography, made by the Indian scientists during the last five years. Keeping pace with recent development in analytical techniques, significant contributions have been made in diversified research aspects: paleoceanographic proxy development, Asian monsoon variability and dynamics, Neogene-Quaternary evolution of the Indian Ocean in relation to the global climate change, carbonate cycle and ocean acidification, development of oxygen minimum zone and its variability through time. Although, the major emphasis is given to the Indian Ocean paleoceanographic studies, a few Indian research groups are also actively engaged in understanding ocean-climate evolution of the Atlantic and Pacific Oceans, inter-basinal connections and their implications on global ocean deep circulation and climate on tectonic to millennial time scales.

Keywords Micropaleontology · Paleoceanography · Indian Ocean · Proxy records

Introduction

The 'Marine Micropaleontology', deals with the remains of micro fauna and flora preserved in sea-floor sediments, and has been playing a crucial role in unravelling the history of ocean-climate changes through time on various (Millennial to Centennial) time scales. In recent years, there has been rapid development in marine micropaleontological research across the globe, which contributed to a better understanding of the paleoceanographic evolution of the ocean basins and climatic development of the surrounding regions. Although the interest in 'Paleoceanography' using microfossil assemblages continued, over the last few decades the interest shifted to geochemical measurements. The foraminiferal isotope and trace metal ratios are used to reconstruct temperature, salinity, productivity, pH and associated hydrographic changes in the oceans on different timescales (e.g., Anand et al. 2003, 2008; Jung et al. 2009; Govil and Naidu 2011; Mahesh and Banakar 2014; Tiwari et al. 2015; Naik and Naidu 2015; Ma et al. 2020; Singh et al. 2023a, b). The sediment archives retrieved from the different areas of the world oceans are utilised to gain better insights into the dynamics of the global ocean and climate change on various time scales. Nevertheless, a large number of studies have been undertaken on short sediment cores. It mainly focused on the northern Indian Ocean, in order to accomplish enhanced comprehension of Indian monsoon variability and surface to deep circulation changes on glacial/interglacial to millennial and centennial time scales (e.g., Singh et al. 2006, 2011, 2018; Singh, 2021; Sijinkumar et al. 2010; Naik et al. 2011; Naidu et al. 2014; Verma et al. 2018).

The participation of Indian researchers in various International Ocean Discovery/Integrated Ocean Drilling Program (IODP) Expeditions carried out in the Indian (IODP 353 354, 355, 356, 359), Pacific (IODP 346, 363, 378), and Atlantic Oceans (IODP 339, 390/393, 397, 401), provided an opportunity to gain insights into the long-term paleoceanographic and climatic variability and associated forcing factors and feedback mechanisms (e.g., Kennett and Barker 1990; Zachos et al. 2001; Clift et al. 2022). We review the important contributions made by the Indian geoscientist between 2019 and 2023 in the field of Micropaleontology

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and Paleoceanography. If a published work is not included in this paper, it is purely unintentional. Articles which do not fall within the scope of this paper are excluded.

Micropaleontological proxy development and refinements

A thorough understanding of a relationship between microfaunal distribution and modern ecological conditions is essential for a better reconstruction of past climatic and oceanographic changes using fossil records. Recently, a detailed study has been made on microhabitat preferences of recent benthic foraminifera in different regions of the northern Indian Ocean (northwest Bay of Bengal, Gulf of Munnar), characterized by varying dissolved oxygen, temperature, organic matter flux, and substrate (e.g., Saalim et al. 2019, 2022; Suokhrie et al. 2020, 2021; Kaithwar et al. 2020; Singh et al. 2021; Singh et al. 2022a, b). These results show that the variations of bottom water oxygen levels and organic matter strongly modulate morphological characteristics and composition of benthic foraminiferal assemblages. Kurtarkar et al. (2019) through the culture experiments, suggested adverse effect of global warming on benthic foraminiferal productivity. Another study on the distribution of two solution-susceptible species *Globigerina bulloides* and *G. glutinata* in from the Bay of Bengal (BoB), reported exceptionally high shell dissolution at shallow depths (~ 1000 m), which they attributed to the excessive biogenic respiration inducing carbonate undersaturation (Bhadra and Saraswat 2021, 2022).

Saraswat et al. (2023) developed empirical relation between the salinity, and temperature with the $\delta^{18}O$ in the northern Indian Ocean. They used measured values of $\delta^{18}O_{G.\ ruber}$ in surficial sediment of the northern Indian Ocean (including published records) to assess the effect of fluvial influx-induced surface seawater salinity and temperature on $\delta^{18}O$. The large basin wide salinity gradient in the northern Indian Ocean leads to high variability in $\delta^{18}O_{ruber}$, however, the temperature showed minimal effect on the variability of $\delta^{18}O_{ruber}$ (Saraswat et al. 2023).

A significant progress has been made in recent years to understand the various factors governing the preservation potential of pteropods in sediment and its application in the late Quaternary oceanographic changes in the northern Indian Ocean (Singh et al. 2021). Based on Scanning Electron Microscopic study of pteropod shells recovered from the Andaman Sea, Sijinkumar et al. (2020) noticed dissolution features on the shell surfaces of pteropods during warm periods (interstadials). Ambokar et al. (2022) reported cold water species *Peraclis* from a shallow core off Saurashtra coast. The authors interpreted abundance maxima of *Peraclis* to demarcate cold events. Besides pteropods, the shells of certain planktic foraminifera species in the various oceanographic settings are known to show selective dissolution, therefore it may serve as a proxy for reconstruction of surface ocean conditions. Sijinkumar et al. (2022) studied the relationship between *Goloborotalia menardii* (a solution-resistant species) abundance and its fragments to evaluate the efficacy of its abundance/fragment ratio in interpreting the paleoceanographic changes.

Earlier studies including model simulations point towards increase in atmospheric pCO_2 in near future. The increase in atmospheric pCO_2 will lead to decline of surface ocean pH, this will impact the calcifying marine biota because of a drop in carbonate saturation. Therefore, it is essential to understand the effect of ocean acidification on marine life including aragonite coral reefs, which are biodiversity hotspots of oceans. Guillermic et al. (2020), used boron isotopes in surface-dwelling multiple planktic foraminifera species from surficial sediment. The study demonstrates that the boron isotope measurements of multiple planktic foraminiferal species calcifying at different water depths have potential to constrain vertical profile of pH and pCO_2.

Paleomonsoon reconstructions

Several paleoceanographic and paleoclimatic reconstructions from the South Asian monsoon dominated regions show that the changes in Earth's orbital parameters significantly influence the monsoon intensity (e.g., Clemens et al. 1991; Clemens and Prell 2003; Wang et al. 2010, 2014, 2017). The surface ocean circulation and hydrography of the northern Indian Ocean including the two semi-enclosed basins; Arabian Sea (AS) and BoB, are primarily driven by the seasonal reversals of the Indian monsoon. Majority of the previous paleoclimatic and paleoceanographic records come from the areas influenced primarily by the Indian summer monsoon-associated upwelling or precipitation (e.g., Clemens et al. 1991; Naidu and Malmgren 1996; Vénec-Peyré and Caulet 2000; Gupta et al. 2003). The surface hydrographic changes in western Arabian Sea (WAS) in response to seasonal monsoon circulation changes over the last 170 kyr BP at glacial/interglacial scales were investigated by Khan et al. (2022), based on the oxygen and carbon isotope records of planktic foraminifera. They found increased productivity during MIS5e and 5a and MIS3, mid-MIS4, and MIS1 due to intensified South West Monsoon (SWM) or coupled effect of North East Monsoon (NEM) and SWM. Over the years, there has been growing interest in paleomonsoon reconstructions on high-resolution time scales utilizing multiple faunal, geochemical, and isotope proxy records from the western Indian margin, a region of high sedimentation rates. These studies have provided valuable insights into the knowledge of the seasonal Indian monsoon dynamics, apart from the teleconnection between monsoon variability and high and low-latitude climatic components. Recently, foraminiferal assemblages (planktic and benthic) based proxy and isotope records from the sediment cores of northwestern Indian margin were used to evaluate past changes in the seasonal monsoon and its influence on the surface hydrography and productivity since the late glacial period (e.g., Saravanan et al. 2019; Ravichandran et al. 2021). The study by Saravanan et al. (2019) suggests intensification of Indian summer monsoon (ISM) during 3–2.5 ka and 4.6–5.4 ka and weakening between 3.4 and 4.6 ka. Earlier studies have also reported a dominant solar control over the short-term changes in Indian summer monsoon during the Holocene. Azharuddin et al. (2019), based on their high-resolution multiple proxy records from offshore Saurashtra (northeastern Arabian Sea: NEAS) recorded periodicities in SWM and productivity changes that correspond to solar cycles.

Although, some of the previous studies provide valuable information on sea surface temperature (SST) variations across the AS basin through time (e.g., Rostek et al. 1993; Dahl and Oppo 2006; Rashid et al. 2007), the seasonal changes in sea surface salinity (SSS) are not yet fully understood. Conventionally, the stable isotope measurements of foraminiferal shells are conducted on an assemblage of individuals of a species which provide an average of environmental information (e.g., Metcalfe et al. 2019). The isotope values of single shell hold the ability of short-lived changes, thus ideal to record seasonal changes. Naidu et al. (2019), using this novel approach carried out stable isotope measurements of individual test of *G. sacculifer* from the ODP Site 723A. The results provided insights into SSS and SST seasonality in the WAS since the last glacial maximum. The authors suggested large seasonal SST and SSS contrasts during the deglaciation compared to the Holocene, which they explained by increase of evaporation during winter and reduced summer precipitation.

Our understanding of the past dynamics of seasonal monsoon (summer vs. winter) variability still remains incomplete as proxy data of the winter monsoon are scarce, except for a few coming from the eastern Arabian Sea (EAS) (e.g., Singh et al. 2011, 2018; Satpathy et al. 2020). Besides, a few studies from the NEAS have shown a strong coupling between winter cooling and winter monsoon wind strength (e.g., Madhupratap et al. 1996). Godad et al. (2022) reconstructed winter sea surface temperature in the NEAS through the last 37 kyr, applying Artificial Neural Network (ANN) technique to planktic foraminifera species abundance data. They used the SST anomaly as a proxy to infer past changes in winter monsoon strength. The study reports low winter SST anomalies during cold stadials (Heinrich and Younger Dryas events) indicating strengthening of the winter monsoon winds. These studies further suggest a synchrony between the winter and summer monsoon variability, which they suggested to be due to southward shift of the Inter-Tropical Convergence Zone (ITCZ) during the northern Hemisphere cold events.

Despite striking similarities in the surface circulation, the hydrography in BoB is different from AS, as the BoB receives large fluvial flux during the SWM. High freshwater influx has profound influences on the biological productivity of BoB. Therefore, summer monsoon related signals are highly amplified in the bay compared to AS. Consequently, swings in SWM are likely to produce large-scale changes in surface salinity and biological productivity. Majority of the previous paleoceanographic studies from BoB, based on sedimentological, geochemical and isotope proxy records aimed to reconstruct ISM driven changes in precipitation, fluvial runoff, surface salinity stratification, sediment provenance and erosional history of the source region. However, the evolution of productivity in BoB and its relation to the past changes in upper water column structure in response to the seasonal monsoon variation is not yet fully understood. Verma et al. (2022), using planktic foraminiferal proxy records from a sediment core of the western BoB (off Krishna-Godavari Basin) reconstructed upper ocean structure and productivity changes over the last 45 kyr BP at millennial time scale. They inferred year-round high productivity in the northern Hemisphere cold events, which they related to the intensified NEM winds and less stratified surface waters. On the contrary, the study also shows low productivity during warm phases, due to stratified surface mixed layer associated with the enhanced fluvial discharge when summer monsoon-related precipitation was high. Interestingly, the paleoproductivity record of BoB was opposite to those from the NAS and WAS, where temporal changes in productivity are primarily driven by the SWM wind-induced upwelling. Foraminiferal census data combined with stable oxygen isotope record of a surface planktic foraminifera from a sediment core recovered from ~ 600 m water depth, offshore eastern Indian margin were used by Govil et al. (2022), to trace millennial-scale changes in surface hydrography of western BoB since 6 kyr BP. Authors inferred a reduction in the SWM related freshwater flux to the basin during 3.9 to 3.7 ka, followed by its intensification since 3.7 ka. Naik and Naidu (2019), used difference between oxygen isotope ratios of surface and thermocline depth dwelling planktic foraminifera species from the BoB and inferred a strong coupling between monsoon precipitation related stratification and thermocline shoaling in BoB. Suokhrie et al. (2022) generated muti-decadal paleomonsoon proxy record from the western BoB. They attributed the short-term changes in monsoon changes in the Holocene to the solar cycles, similar to previous reports from the Arabian Sea (e.g., Agnihotri et al. 2002; Gupta et al. 2005; Azharuddin et al. 2019).

In other study from BoB, Sijinkumar et al. (2021) developed ISM record for the past 55 ka, which shows broad ~ 10 ka periodicity, with the intensity maxima occurring at 37.7, 24.7, 13.5 and 5.4 ka. The land-locked Andaman Sea with its isolated nature of the deep regions receives high riverine influx during summer monsoon season, hence sediment archives of this basin are ideal to reconstruct past monsoon variability and deep-water circulation changes in relation to the climatic-tectonic interaction, on various time scales. Gayathri et al. (2022) based on the high resolution planktic foraminiferal and geochemical proxy records from the northern Andaman Sea demonstrated a similarity in millennial-scale oscillations in AS and BoB and suggested a common forcing processes modulating the changes in surface hydrography and productivity in both the BoB and AS basins. Furthermore, these authors identified two significant events of surface stratification during early and the mid-Holocene, which they suggested to have affected the upwelling and productivity in the Andaman Sea.

The central equatorial Indian Ocean is a unique area of interest for the investigation of monsoon-induced productivity and surface hydrographic changes, because the SWM and NEM winds are relatively weaker close to the equator, and stronger winds are more prevalent during monsoon transition periods (e.g., Shaji and Ruma 2020). Hence, the productivity variation in this region is primarily driven by the reversing monsoon surface circulation patterns. Yadav et al. (2022), used planktic foraminiferal assemblage records to study upper water column structure and productivity. They inferred high productivity (eutrophic) during the glacial and oligotrophic condition during the deglaciation and the Holocene attributed to the stratified-warm fresh water inflow to BoB. Besides planktic foraminifera, diatoms are also used in paleomonsoon reconstructions. Thacker et al. (2023) reviewed the Asian monsoon dynamics and underlying causes based on the earlier findings of diatom studies in the tropical monsoon regions. They concluded that the past changes in monsoon intensity and hydrological conditions during specific climatic events throughout the Quaternary were coherent on a regional scale.

Indian Ocean Paleoceanography

The tropical ocean acts as a major source of heat and vapour transport to the high latitude regions. In this context, the equatorial Indo-Pacific region, particularly the western equatorial Pacific (WEP) where the western Pacific Warm Pool (WPWP) develops is crucial component of the global climate system. The modelling and multi-proxy-based studies have revealed the significant role of SST changes across the low-latitude Indo-Pacific is regulating the global climate since the Pliocene. In recent years, there has been a growing interest amongst the paleoceanographers to investigate surface ocean dynamics in the tropical Indian Ocean and monsoon circulation changes through time.

Podder et al. (2021) using planktic foraminiferal assemblage and stable $\delta^{18}O$ and $\delta^{13}C$ isotope records from the ODP Hole 758A, reconstructed the surface–subsurface hydrographic variability (sea surface temperature, thermocline depth) in the tropical eastern Indian Ocean in response to global climate change since 6 Ma. They inferred shoaling of the thermocline depth from 6 to 3.4 Ma and ISM intensification during early Pliocene followed by the thermocline deepening and the weakening of ISM at 2.7 Ma. This major shift in Ocean–atmosphere circulation was attributed to the intensification of a walker circulation.

Earth witnessed both a gradual change and abrupt shifts in climate state in response to astronomical forcing and perturbations in global ocean circulations. Although a close link between high frequency climate variations and Atlantic meridional overturning circulation (AMOC) during the Quaternary is well known, hemispheric climatic response to astronomical forcing during long time intervals are not well understood. The Pliocene is considered as a potential analog of the future climate as high CO_2 concentration (~ 370 ppm) and higher temperature than pre-industrial time prevailed during this geological epoch (e.g., Ravelo et al. 2004). It is generally believed that the major shift from warm Pliocene climate to the cooler Pleistocene occurred due to waxing and waning of Polar ice sheets (e.g., Lisiecki and Raymo 2005). Several sea-land-ice based paleoclimatic studies have shown that the Pleistocene glaciation that began at ~ 2.7 Ma was followed by glacial/interglacial oscillations after the middle Pleistocene, when high frequency low amplitude climate oscillation (41 ka periodicity of obliquity) shifted to the low frequency and high amplitude oscillation (100 ka periodicity of eccentricity).

Singh et al. (2021) investigated the paleoceanographic evolution of the southeastern Indian Ocean (SEIO) during the Plio-Pleistocene period and its linkages to the Northern Hemisphere Glaciation (NHG) and Indian monsoon variability, using the benthic foraminiferal assemblages from ODP Site 752 and 757 combined with planktic foraminiferal abundances and stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) records from Site 757. The foraminiferal isotope proxy records indicate an increased influence of Antarctic intermediate water (AAIW) since 4.5 Ma, which was further enhanced after ~ 1.8 Ma. The study also suggests a switch in the Indonesian Throughflow (ITF) water source between ~ 4 and 3 Ma. The ITF a crucial component of the global thermohaline circulation influences significantly the surface and subsurface hydrography of the eastern equatorial Indian ocean (EEIO) and Australian-Asian monsoon (e.g., Kuhnt et al. 2004). The progressive constriction of Indonesian gateway and reduced ITF resulted changes in Indo-Pacific circulation, consequently continental humidity decreased at the beginning of Pliocene–Pleistocene transition. Bali et al. (2020) compared the Pliocene–Pleistocene planktic foraminiferal assemblage records of the eastern tropical Indian Ocean DSDP Site 214 with the western Pacific OPD Site 807 and inferred that the oligotrophic conditions in the western Pacific were developed at ~ 3.15 Ma, which they related to the gradual constriction of the Indonesian gateway. Saraswat et al. (2020) analysed 350 kyr record of planktic foraminiferal assemblages from IODP 355 and reconstructed changes in surface hydrography on glacial-interglacial. They inferred strengthened SW monsoon-induced upwelling during interglacials. A strong re-organization of the Indian monsoon circulation after mid-Pleistocene Transition (MPT) leading to the precessional control on SWM and eccentricity control on NEM was suggested by Bhadra et al. (2023). A 184 kyr record of SST and SSS changes in SEAS was established based on the coupled Mg/Ca and δ^{18}O measurements of *G. ruber* (e.g., Saraswat et al. 2019). The authors reported a shift in the effect and intensity of Indo-Pacific Warm Pool (IPWP) with reduced thermal gradient during the interglacial and large regional surface seawater temperature difference during the glacial periods.

The deep overturing circulation of global oceans is the major drivers of heat and nutrient transfer, hence modulating the oceans carbon storage and global climate (e.g., Broecker et al. 1985; Boyle and Keigwin 1987; Lynch-Stieglitz 2017). Several previous studies have shown that the global overturing circulation in the past varied on glacial/interglacial and millennial time scales (e.g., Boyle et al. 1995; Shackleton 2000; Jung et al. 2001; Pahnke and Zahn 2005), but exact mechanism and process responsible for such changes remain elusive. Particularly, studies pertaining to such crucial issues are very limited from the Indian Ocean. Singh et al. (2022a, b) using the proxy records of elemental and isotopic ratio of planktic foraminifera in a core from the southeast Arabian Sea, suggested the influence of tropical Indian Ocean in modulating AMOC. It is still not clear, whether past atmospheric CO_2 variability is related to changes in deep circulation and biological productivity. Many of earlier studies attempted in AS and BoB were based on the nutrient-based proxy records e.g. δ^{13}C of benthic foraminifera, sedimentary δ^{15}N and also a few benthic foraminifera assemblages. Lathika et al. (2021), for the first-time developed record of deep-water mass circulation changes in AS based on authigenic εNd record (from the bulk sediment and planktic foraminifera tests) for the last 136 ka. The study provides strong evidence of a reduction in the north Atlantic deep water (NADW) inflow to the Indian Ocean during the glacial and its enhancement during the interglacial by 20–40%.

In recent years, Nd isotopes in carbonate shells and bulk sediment have been increasingly used to trace deep ocean circulation (e.g., Burton and Vance 2000; Lathika et al. 2021; Prabhat et al. 2022). The AS and BoB, receives fluvial discharges from the surrounding continents mainly during SWM. Previous studies have shown that the fluvial input in these basins strongly influence the Nd variations (e.g., Burton and Vance 2000). More specifically, the effect of fluvial flux on seawater Nd isotope is confined to the surface layers with a little impact on deep water values. The conventional stable isotopes are the ideal proxy to distinguish between monsoonal and ocean circulation changes. Naik et al. (2019) generated Nd isotope records from the central BoB for the last 16 ka. The results showed that the deep water εNd signature for the major part of the deglaciation until ~ 8 ka was controlled by global overturning circulation. However, the εNd signal since ~ 8–7 ka was greatly influenced by the intensified SW monsoon related reverine particulates. The deep-water circulation plays a crucial role in global climate changes as it influences the carbon exchange between the atmosphere and the marine carbon pool. Hence, the paleoceanographic records of deepwater ventilation changes provide crucial information of past ocean circulation change. There have been limited studies on the past deepwater circulation changes in the northern Indian Ocean, and those were mainly based on the stable isotopes, radiocarbon changes, and geochemical proxy records (e.g., Piotrowski et al. 2009; Ahmad et al. 2012; Singh et al. 2012; Lathika et al. 2021; Naik and Nisha 2020; Bharti et al. 2022). These studies in general, show reduced ventilation during the LGM and beginning of the deglaciation and enhanced ventilation since ~ 14 kyr. Nisha et al. (2023) using paired benthic-planktic radiocarbon and benthic foraminifera carbon and oxygen isotopes from a sediment core of central Indian Ocean, studied deep water ventilation changes. Their study indicates the presence of poorly-ventilated CO_2-rich glacial water during the LGM and Heinrich event 1. These authors also noticed an abrupt decline in benthic-planktic ventilation ages during warm B/A interval in concurrence with the sharp increase in well-ventilated high δ^{13}C benthics NADW flow into the Indian Ocean.

The Agulhas leakage (AL) interlinks the upper water layers of the Indian Ocean and the Atlantic Ocean, therefore plays an important role in transferring heat between the two oceans and modulating AMOC. The ITF and Tasman leakage are the major contributors to AL. The paleoceanographic reconstructions of AL show enhanced AL and water mass transport during the glacial-interglacial transitions of the Pleistocene, which promoted the AMOC strength, and global heat transfer (e.g., Caley et al. (2012). Nirmal et al. (2023)) in their recent study based on the planktic foraminifera abundance records from ODP Hole 1088B and Hole 1090B evaluated the extension of AL for the last 1.2 Ma. This study further suggests the influence of AL at the subtropical convergence and subantarctic zone with strong AL fauna variations over the frontal zone at glacial-interglacial transitions of MIS 12, 12, 8, and 6. The faunal record agrees well with the notion of the southward expansion of AL during the transitions.

Carbonate cycle and the oxygen minimum zone

Extensive studies have been carried out in recent years to understand seasonal monsoon induced basin wide changes in the AS hydrography, oxygen minima zone (OMZ) variability and denitrification on millennial to glacial-interglacial scales, using isotope, geochemical and foraminiferal census records. The OMZ intensity in the western AS in spite of high surface primary productivity, relatively weaker compared to northeastern region. In the WAS, the biological consumption of the oxygen is counter balanced by the oxygen supply by the southern waters, as well as the vertical advection of oxygenated water (Resplandy et al. 2012). Pathak et al. (2021) studied ventilation history of OMZ intensification in the western Arabian Sea during the last glacial cycle using diversity indices and records of benthic foraminifera from the ODP Site 723. The study suggests a weakening of the OMZ intensity during MIS 5, which the authors attributed to increased lateral advection of oxygenated water and oxygen replenishment. The intensification of the OMZ during 114–108 ka and 102–92 ka was suggested to be related to the enhanced monsoon-induced export flux of organic matter and poor ventilation conditions. The authors further suggested high inflow of southern sourced oxygen-rich water during the early Holocene which compensated the oxygen demand because of high surface productivity, and ultimately resulted into a weak OMZ. The OMZ intensification during the late Holocene was explained by the increased outflow of low oxygenated Rea Sea water and shutting down of oxygen-rich southern sourced water (Pichevin et al. 2007).

In the current scenario of increasing CO_2 in the atmosphere, it is crucial to understand the marine carbonate cycles and changes in the carbonate ion concentrations (CO_3^{--}), which has significant potential to influence the atmospheric CO_2 level and climate (e.g., Caldeira and Wickett 2003; Yu et al. 2008; Takahashi et al. 2009). Ocean's alkalinity response to changes in atmospheric CO_2 expected to faster, because of supra lysoclinal carbonate dissolution. Yadav et al. (2022) made an attempt to record supra lysoclinal calcite dissolution in the equatorial Indian Ocean using multiple dissolution indices and noticed interval of calcite dissolution through MIS 3 and LGM, which they attributed to the pore-water undersaturation with respect to CO_3^{--} due to organic matter degradation. In order to assess the preservation patterns of pteropods and their relationship with the climatic and oceanographic history in the Laccadive Sea, temporal variation in pteropod abundance was carried out by Sreevidya et al. (2023). The study shows that the past changes in pteropod abundance at millennial scale (stadials/interstadials) are related to a combination of monsoon-associated changes in water column properties, aragonite saturation depth, and intermediate water ventilation. The variation in production and burial of marine carbonate in the past has influenced the atmospheric CO_2 (e.g., Opdyke and Walker 1992). Various investigations have undertaken to understand biogeochemical processes in water column pertaining to surface productivity, dissolved oxygen and CO_2 concentrations, carbonate ion concentrations, that impacted the preservation/dissolution of calcium carbonate in the northern Indian ocean at the millennial and glacial/interglacial time scales (However, changes of carbonate preservation/burial in shallow pelagic region of the equatorial Indian Ocean through time are less investigated. Yadav and Naik (2022) inferred the carbonate burial history at the Maldives carbonate platform at millennial time scale utilizing multiproxy records ($CaCO_3$, OC%, planktic foraminiferal shell weight). The study suggests that the carbonate dissolution occurred during LGM and the Holocene, and better preservation during the deglaciation, which was in line with earlier studies for other areas of AS.

Numerous studies including model simulations point towards a future scenario of atmospheric pCO_2 increases, and decline in surface ocean pH, which will have major impact on the calcifying marine biota because of a drop in carbonate saturation. Sreevidya et al. (2019) developed a 1.2 Myr record of pteropod preservation at Maldives, equatorial Indian Ocean and found a good correlation of reduced atmospheric CO_2 concentration and dissolution of a common pteropod species *Limacina inflata*. Tarique et al. (2021), based on the coralline $\delta^{11}B$ based proxy reconstructed pH changes in the western Indian Ocean during 1990–2013, which reflect large inter-annual variability at ENSO band. The study demonstrates high amplitude pH variations, modulated dominantly by the ENSO-related oceanographic process. Azharuddin et al. (2022) also developed foraminifera-based boron isotope proxy record from a core from the shelf off Saurashtra for deciphering past changes in pH and pCO_2 in NEAS during the Holocene. The study suggests intensified upwelling at ~ 4.4 and 2.7 ka resulting in CO_2 outgassing and ocean acidification, and a non-upwelling condition during 2.5–1.4 ka leading this region to become a CO_2 sink. The ocean acidification combined with the thermal stress, affect the coral calcification, but the underlying mechanism is not well understood, which is essential to predict the impact of rising greenhouse gases and global warming on corals. It is well established by now that different coral species calcify their tests in a range of environmental conditions, attributing to the physio-chemical characteristics of calcifying fluids. By their novel studies, Guillermic et al. (2021) using two independent techniques (microelectrode and boron geochemistry) measured calcifying fluid pH and carbonate chemistry of the two coral species grown under different temperatures and pCO_2 conditions. The new results provide insights into the impact of future global climate change on the calcifying fluid dynamics of tropical corals.

Southern ocean (Indian sector)

It is being increasingly realised that Antarctica ice play a vital role in modulating global climate, as it significantly impacts ocean circulation, biological productivity of Southern Ocean (SO) and partitioning of carbon between the ocean and atmosphere. The diatom assemblages and biogenic silica in a sediment core coming from the Indian sector of SO were analysed by Ghadi et al. (2020) to reconstruct SST and winter sea-ice temperature variability over the 150 ka. A comparison of SST and winter sea-ice (WSI) of Indian sector, with the Pacific and Atlantic sectors indicates high amplitude changes in sea ice in the Atlantic, and that was suggested to be related to the influence of the Weddell gyre. Shukla et al. (2021) reconstructed SST record in the SO for the last four interglacials, each showing two warm phases interrupted by a cold interval. They attributed these millennial-scale SST changes to the variations in northern summer insolation with feedback from both the hemispheric ice sheets coupled with the global ocean circulation and the carbon cycle. The long record of diatom productivity from SO developed by Shukla et al. (2023), suggests heterogeneity in the frontal migration in the Southern Ocean on glacial/interglacial timescale. In another diatom assemblage-based study from the sediment cores of SO, Nair et al. (2019) provide insights into the interactions between Southern Hemisphere high latitude (Southern Ocean), subtropics (Agulhas leakage) and Asian summer monsoon (ASM) during the glacial/interglacial periods. The authors concluded that the meridional shifts of SO associated with the low latitude insolation gradient and Antarctic climate change are the forcing factors of ASM variability as well as changes in the Agulhas leakage intensity. Nair et al. (2019) also studied changes in the size and flux of diatom species in response to the climatic variations during glacial/interglacial periods and terminations, and also the influence of iron, silica, and SST of sea ice on diatom size variations. Choudhari et al. (2023) investigated past changes in the coccolith production and deep ocean carbonate saturation in SO. Low coccolith concentration during the glacial period was explained by a combination of possible factors such as low production of coccolithophores, dilution by biogenic silica, and low carbonate saturation of the deep water.

Paleoceanographic studies in the Atlantic and Pacific Oceans

Das et al. (2021) studied the changes in sea-ice extent and carbonate compensation depth (CCD) in the northeastern Japan Sea through mid-Pleistocene and Holocene, using ice-rafted debris (IRD), foraminifera census counts and detrital fragments in core samples of IODP Site U1423. Based on the multiproxy records, they inferred and enhanced cooling at the beginning of the middle Pleistocene and the shallowing of the CCD between 880 and 450 ka. A significant decrease in the permanent and seasonal ice sheet and deepening of CCD was observed during the last 150 ka. Based on the benthic foraminiferal assemblage combined with geochemical proxy records, Das et al. (2021) reported a notable reduction in primary productivity between 2150 and 1700 ka and attributed it to the restricted supply of nutrients from the northern Pacific Ocean through the northern connecting strait. They further observed a marked shift in productivity patterns during the Middle Pleistocene Transition (MPT), evidenced by the dominance of low-oxygen tolerant species and higher flux of total organic carbon. It was inferred that the productivity changes in Japan Sea were modulated by 23 kyr precessional forcing at low latitude and superimposed on 41 and 100 kyr variability, linked to the high-latitude climate fluctuations.

The hydrography of East China Sea (ECS) is greatly influenced by the east Asian summer monsoon (EASM) induced precipitation. The warm, saline Kuroshio Current (KC) flowing from the subtropical North Pacific significantly influences the SST and SSS of East China Sea. Vats et al. (2020) developed 400 kyr record of planktic and benthic foraminiferal assemblages at the IODP Site U1429 and inferred glacial/interglacial changes in SST, EASM intensity, productivity and bottom water oxygenation in ECS, modulated mainly by the Kuroshio Current intensity. The authors recorded high inflow of KC to ECS during the interglacials, period of stronger EASM. Their study further suggests four phases of bottom oxygenation of ECS during the last 400 kyr.

Singh et al. (2023c) reconstructed high-resolution planktic foraminiferal proxies and Artificial Neural Network based SST records across the last three terminations (TI, TII and TIII) and the subsequent interglacials (Holocene, MIS 5e and MIS 7e) from IODP Site U1385, Northeastern Atlantic Ocean. These highly resolved proxy records revealed the uniqueness of the last three terminations in terms of abrupt climatic events (stadials and interstadials) interrupting these terminations. In terms of duration and rate of SST change, TI and TII were analogous, whereas TIII was relatively longer with a slower rate of SST change. Additionally, stadials interrupting these terminations revealed a complex anatomy ('W' shaped) with two or three cold phases sandwiching (a) brief warm phase(s). A major reorganization of the surface current system, oceanographic fronts and productivity conditions was also documented across these terminations. The study further reveals broad similarities in the climatic evolution of Holocene, MIS 5e and 7e interglacials in terms of surface hydrography and productivity. Superimposing these long-term trends were multiple brief cold events interrupting the Holocene (~ 11.3, 9.9, 8.2, 7.1, 5.5, 2.5 ka), MIS 5e (C28, C27, C27', C27a, C27b, C26, C26', C25), and MIS 7e (~ 238, 234, 231, 230 ka). The authors believe that these brief cold events were possibly induced by fluctuations in the deep water convection process.

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Declarations

Competing interests On behalf of all authors, the corresponding author states that there is no conflict of interest.

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