



Intrusion of Arabian Sea high salinity water and monsoon-associated processes modulate planktic foraminiferal abundance and carbon burial in the southwestern Bay of Bengal

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Abstract

The unicellular calcareous planktic foraminifera sequester a significant portion of the carbon dioxide dissolved in the ocean, thus burying the carbon in sediments for millions of years. The global warming and associated processes are likely to affect the planktic foraminiferal abundance and diversity. Therefore, their baseline distribution has to be documented and correlated with ambient parameters to assess its fate under different climate change scenarios. Here, we report an exceptionally high abundance of planktic foraminifera and thus large carbon burial in the southwestern Bay of Bengal. The very high absolute abundance of planktic foraminifera in the Cauvery River basin is attributed to biannual productivity, warmer and saline waters. *Globigerinita glutinata* is the highest abundant species followed by *Globigerinoides ruber* and *Globigerina bulloides*. *Globigerina bulloides* is abundant on the shelf, where the upwelling is more frequent. The relative abundance of *Globorotalia menardii* is positively correlated with thermocline salinity and negatively correlated with thermocline temperature. Similarly, *Neogloboquadrina dutertrei* and *Globoquadrina conglomerata* are negatively correlated with mixed layer as well as thermocline temperature and mixed layer salinity. Both these species are positively correlated with thermocline salinity. *Globigerina falconensis* is more abundant in the southernmost transect influenced by intense winter monsoon precipitation. We report that *G. ruber* prefers high saline and warmer waters with the highest abundance in the southernmost transect. From the foraminiferal distribution, it is evident that the temperature and salinity of the mixed layer as well as thermocline, food availability, and monsoon-associated processes affect the planktic foraminiferal abundance and thus carbon burial in the southwestern Bay of Bengal. The changes in influx of southeastern Arabian Sea water will affect the planktic foraminiferal population and subsequent carbon burial in the southwestern Bay of Bengal.

Keywords Planktic foraminifera · Calcium carbonate · Flux · Ecology · Monsoon · Bay of Bengal

Introduction

Oceans absorb a large fraction of anthropogenic carbon dioxide (CO₂), thus restricting its build up in the atmosphere. Once dissolved, CO₂ either reacts with water molecules to

form carbonate ions and hydrogen ions or is sequestered by the phytoplankton to form the organic matter. The marine organisms use these carbonate ions to precipitate calcareous shells. The single celled free-floating planktic foraminifera are amongst the major marine calcareous organisms inhabiting the upper ocean waters (Hemleben et al. 1989; Bé, 1977). They sequester a large amount of CO₂ and bury it in the ocean sediments for millions of years (Saraswat and Nigam 2013). Around 0.36–0.88 Gt/yr CaCO₃ is the total contribution of planktic foraminifera to the surface sediments of the world ocean, which is ~32–80% of the total deep-ocean calcite budget (Schiebel 2002). The ambient surface ocean conditions including temperature, salinity, pH, productivity, and currents strongly affect planktic foraminifera and their diversity (Lombard et al. 2011; Fraile et al. 2008; Zaric et al. 2005; Watkins et al. 1996). The sea surface

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temperature is considered the most important factor that controls the abundance and diversity of planktic foraminifera (Rutherford et al. 1999), shell size (Schmidt et al. 2004a), and composition (Morey et al. 2005). Therefore, changes in the seawater properties due to the global warming will affect planktic foraminifera and in turn carbon burial capacity of the oceans.

Additionally, being extremely sensitive to minor changes in the ambient environment, planktic foraminifera are extensively used in paleoclimatic reconstruction (Nigam 2005; Katz et al. 2010; Saraswat 2015). The past environmental conditions and the composition of ambient seawater can be reconstructed by using faunal abundance as well as through the chemical composition of their hard shells and changes in the stable isotopic and elemental ratio (Schiebel and Hemleben 2017). The comparison of surface distribution of recent planktic foraminifera with the ambient parameters provides information about the ecological preferences of the species and the factors controlling the geochemical signatures of the tests. The knowledge of the environmental control on the distribution, morphology, species abundance, and geochemical composition of the foraminiferal shells is used to reconstruct the paleoceanographic conditions (Kucera 2007).

The factors affecting planktic foraminiferal diversity and abundance, as well as the chemical characteristics of their shells, can be studied by using living specimen collected in plankton net (Iwasaki et al. 2017). However, one-time snapshot sampling does not address the resultant planktic foraminiferal abundance in marine sediments representing annual conditions. The sediment traps are deployed to understand the year round abundance and diversity of planktic foraminifera as well as their contribution to the carbon burial (Maeda et al. 2022; Kiss et al. 2021). However, such studies are mainly from the open ocean and are very limited (Bhadra and Saraswat 2021). Although the foraminiferal assemblage in the surface sediments is partially modulated by factors other than the ambient conditions prevailing at the time of living population, the ambient conditions still strongly modulate the resultant foraminiferal population in the sediments. That is why this sedimentary foraminiferal assemblage is the basis of all the paleoclimatic and paleoceanographic reconstruction. Therefore, an improved paleoclimatic reconstruction by using foraminiferal characteristics requires a comparison of the foraminiferal assemblages in the sediments with the ambient conditions (Saraswat et al. 2023a; Bhadra and Saraswat 2022; Wang et al. 2021; de Villiers 2005; Schiebel 2002; Peterson and Prell 1985).

The northern Indian Ocean is strongly influenced by the seasonal reversal of monsoon and thus provides a unique environmental setting for planktic foraminiferal studies. Therefore, multiple efforts were made to understand the factors affecting the planktic foraminiferal distribution in the northern Indian Ocean (Stainbank et al. 2019;

Munir and Sun 2018; Darling et al. 2017; Symphonia and Nathan 2014; Bhonsale and Saraswat 2012; Saraswat 2010; Chowdhury et al. 2003; Schulz et al. 2002; Naidu 1993; Duplessy et al. 1981; Cullen and Prell 1984; Bé and Hutson 1977; Bé and Tolderlund 1971; Zobel 1971). Both the eastern Arabian Sea (eAS) and Bay of Bengal (BoB) receive a large amount of monsoonal influx and direct precipitation (Behara et al. 2019; Vinayachandran et al. 2013; Rao and Sivakumar 2003). The huge freshwater influx, seasonal reversal of monsoon, surface water stratification, and mesoscale eddies create distinct environmental conditions in the Bay of Bengal (Jana et al. 2018; Li et al. 2017) to understand the response of planktic foraminifera to monsoon and associated processes. Therefore, a few attempts were made to document the planktic foraminiferal distribution from the Bay of Bengal (Maeda et al. 2022; Bhadra and Saraswat 2021; Anbuselvan and Senthil Nathan 2021; Symphonia and Nathan 2014; Chowdhury et al. 2003; Guptha et al. 1997; Cullen and Prell 1984). Guptha et al. (1997) and Maeda et al. (2022) reported an increase in the planktic foraminiferal flux in the central Bay of Bengal during both the summer and winter monsoon and the lowest flux from March to May, by using the sediment trap data. Recently, Bhadra and Saraswat (2021) studied foraminiferal distribution in the western Bay of Bengal (wBoB) to understand the response of planktic foraminifera to the huge fresh water influx. However, such information is missing from the southwestern Bay of Bengal (swBoB) as highlighted by Anbuselvan and Senthil Nathan (2021) and Symphonia and Nathan (2014). Anbuselvan and Senthil Nathan (2021) investigated a small part of the swBoB, but their work was limited to the continental shelf. Therefore, it is necessary to understand the distribution and ecology of planktic foraminifera from the swBoB as the region is influenced by both the summer as well as winter monsoon.

The regional physical processes like mesoscale eddies, cross-basin water exchange, seasonal surface circulation pattern, and the monsoonal flux directly affect the hydrology of the swBoB (Jayalakshmi et al. 2015; Vinayachandran 2009; Vinayachandran et al. 1999). The effect of these processes on the planktic foraminiferal population in the swBoB is still not clear. The region also has very high productivity resulting in a large organic matter flux. The organic matter availability not only strongly affects living foraminiferal population but also the preservation of the shells in the sediments. The utility of the organic matter as food for marine organisms depends on its origin and quality. The organic matter can be of marine or terrestrial origin. The rivers transport terrestrial organic matter to the sea (Gao et al. 2022). The C_{org}/N ratio can be used to differentiate the sources of organic matter. The low C_{org}/N ratio (< 7) indicates nitrogen rich marine produced

organic matter (Saraswat et al. 2023b; Ramaswamy et al. 2008; Suokhrie et al. 2022). However, post-depositional diagenetic changes modulate the C_{org}/N ratio (Waples and Sloan 1980; Freudenthal et al. 2001).

The correlation of the surface distribution of recent planktic foraminifera with the ambient parameters will help to understand the factors affecting the planktic foraminiferal population in this region. The objective of this study was to understand the planktic foraminiferal contribution to the carbon burial in the swBoB. Additionally, the factors affecting the planktic foraminiferal abundance and diversity in this region have also been studied to understand the fate of planktic foraminifera in the present climate change scenario.

Oceanographic setting

The Bay of Bengal is a tropical basin nestled in the eastern expanse of the northern Indian Ocean. Its hydrography is marked by the dynamic interplay of semi-annually reversing monsoon winds and currents (Schott and McCreary 2001). During the summer monsoon (June–September), a strong southwestern breeze graces the air, while the winter monsoon (November–February) ushers in the northeastern gust, accentuating the ever-changing character of this remarkable basin. The seasonal winds force the reversal of circulation in the upper ocean (Shankar et al. 2002). The summer monsoon current transports high salinity water

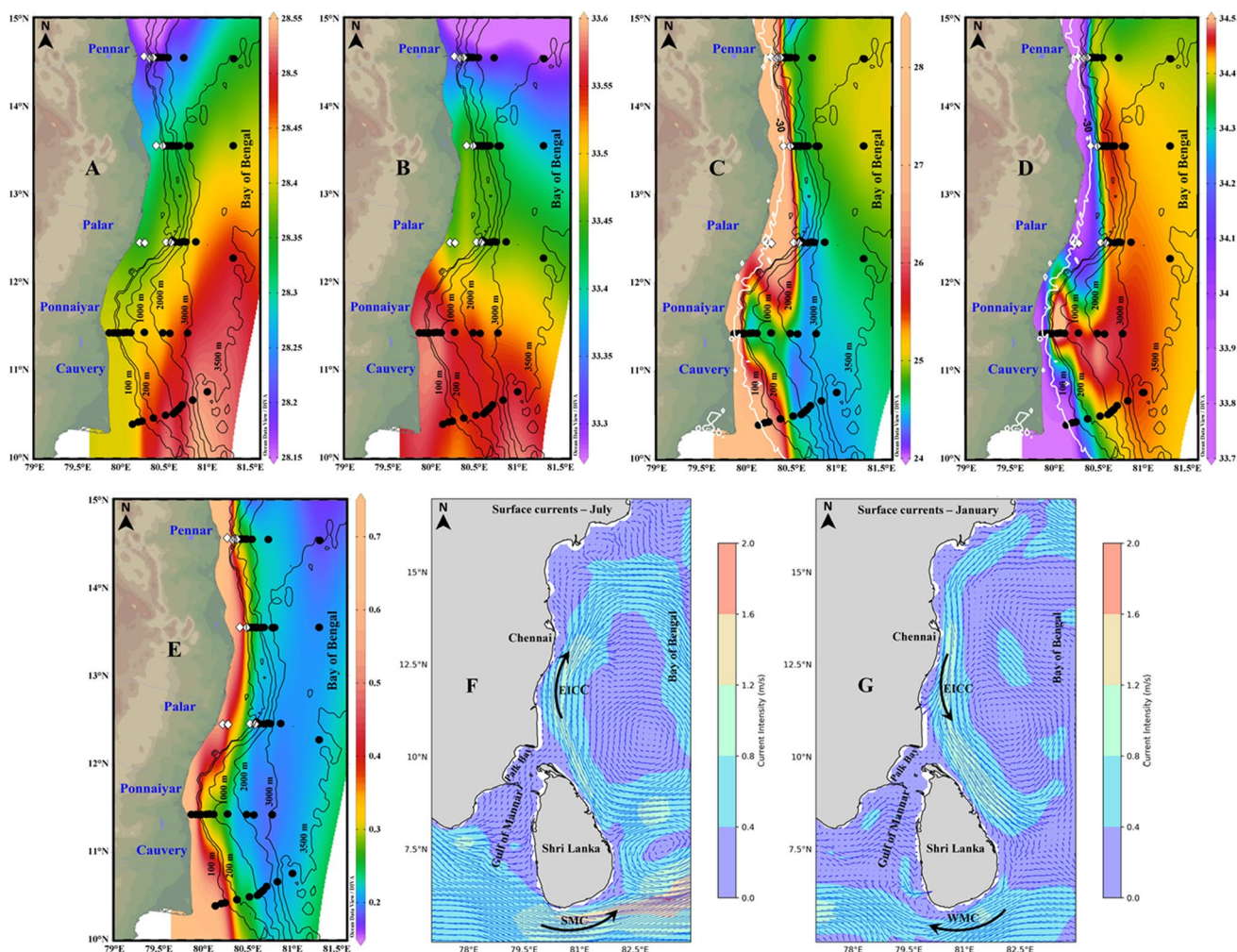


Fig. 1 The annual average mixed layer temperature (A), mixed layer salinity (B), thermocline temperature (C), thermocline salinity (D), surface chlorophyll-a (E), and seasonal (July representing southwest monsoon, and January representing northeast monsoon) surface currents (F & G), in the southwestern Bay of Bengal (Locarnini et al. 2019; Zweng et al. 2019). The background colour and length of the arrows indicate the intensity of the currents. The major currents in

the region are marked as East India Coastal Current (EICC), Summer Monsoon Current (SMC), and Winter Monsoon Current (WMC). The water depth between mixed layer and thermocline is marked by white contour line at 30 m. The black dots and white diamonds are the sample locations and major rivers are marked by blue lines. The black contour lines are bathymetry

from the southeastern Arabian Sea (seAS) into the swBoB (Fig. 1). At the onset of the summer monsoon, this influx from the Arabian Sea becomes a part of the East India Coastal Current (EICC) and flows as a broad and shallow current, extending predominantly towards the north, confined to the upper 200 m of the water column. The current steadily gains intensity as it ventures westward, acquiring a narrower profile as the summer season progresses. Notably, during the period of June to September, the summer monsoon current imparts a remarkable mean seasonal transport of approximately 10 Sv (Sverdrups) into the BoB (Vinayachandran et al. 1999). The winter monsoon current flows westward, south of Sri Lanka where it flows into the seAS (Fig. 1).

Brahmaputra, Ganga, Mahanadi, Godavari, Krishna, and Cauvery are the major rivers discharging a large quantity of fresh water into the BoB. Amongst these, Krishna, Pennar, and Cauvery rivers discharge a large amount of freshwater into the western BoB during both the summer as well as winter monsoon (Krishnamurthy and Shukla 2000). The dispersal of the freshwater across the basin imparts distinctive characteristic to the upper water column, wherein a low-salinity environment prevails. This phenomenon creates a robust stratification that remains pronounced throughout the year limiting the productivity. The bay experiences relatively lower primary productivity compared to the Arabian Sea. The extensive cloud cover, stratification, sediment load, and narrow shelf are the main cause of the low productivity in the BoB (Sarma et al. 2016; Prasanna Kumar et al. 2010, 2004, 2002; Madhupratap et al. 2003; Gomes et al. 2000; Radhakrishna et al. 1978; Qasim 1977). The physical processes such as the coastal upwelling and winter convective mixing are not very active in the BoB (Prasanna Kumar et al. 2002; Shetye et al. 1991). But the region can still experience episodic events such as eddies and gyres. These localized phenomena have the potential to enhance the productivity in the area (Jayalakshmi et al. 2015). The eddies and gyres govern the biological production in oligotrophic bay and influence the vertical transport of nutrients to the photic zone (Sabu et al. 2015; Fernandes and Ramaiah 2013; 2014; Ramaiah et al. 2010; Prasanna Kumar et al. 2010; 2004; 2002; Fernandes 2008; Muraleedharan et al. 2007; Vinayachandran et al. 2005). In swBoB, the intensity of cyclonic eddies is maximum during the winter season, but in summer season, the anticyclonic eddies are more common. However, the overall net primary production is less in the BoB as compared to the Arabian Sea (Jayalakshmi et al. 2015; Chen et al. 2013).

The strong stratification inhibits vertical mixing, causing intense evaporation and thus creating conditions favourable for cyclogenesis. The conditions reverse in winter, and the decrease in surface temperature creates an

“inversion layer” unlike the “barrier layer” in the summer. The mixed layer depth remains shallow (~30 m) in the Bay of Bengal as compared to the Arabian Sea because of the weak winds and strong stratification (Prasanna Kumar et al. 2002).

Material and methodology

During the 67th cruise of RV *Sindhu Sadhana* (SSD067) in November 2019, surface sediment samples were collected from the swBoB. A total of 67 surface samples (56 multicores and 11 grabs) were collected along coast perpendicular transects, at depths varying from shallow (24 m) to deep (3505 m) (Fig. 2). The sandy substrate hindered the operation of multicorer on the inner shelf. During the expedition, the multicores were carefully

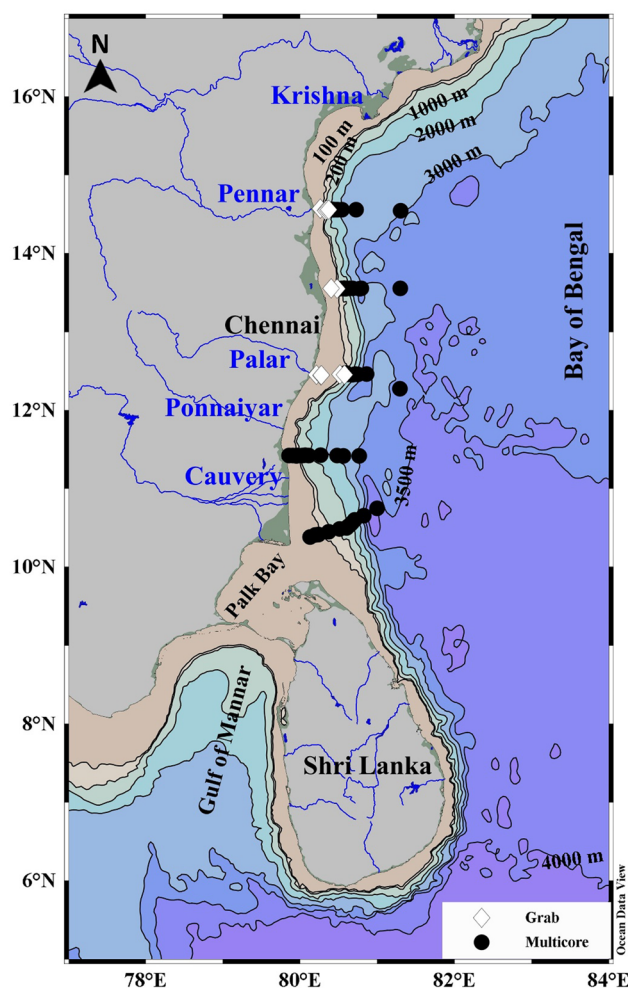


Fig. 2 The sample locations in the southwestern Bay of Bengal. The black dots are the multicore stations, and the white diamonds are grab samples. The rivers draining into the region are marked by blue lines. The background colour and contours are bathymetry

subsampling onboard at regular 1-cm intervals. Half of the sediments from each section were stored in zip-lock plastic bags and subsequently used for this work.

The sediments from the top 0–1 cm section were processed by following the established standard procedure (Naik et al. 2017). An appropriate amount (15–20 g) of freeze-dried and weighed sediment was wet sieved using a 63 µm mesh. The fraction > 63 µm, retained on the sieve, was then transferred to a glass beaker and dried overnight. The dried coarse fraction was subsequently weighed and stored in plastic vials for further analysis. A portion of the freeze-dried sediment was finely powdered and utilized for the total carbon (TC), total nitrogen (TN), and total inorganic carbon (TIC) analysis. The Elemental Analyzer (Flash2000NC Thermo) was used for TC and TN analysis. The CO₂ Coulometer (CM50170 UIC) was used for TIC analysis. The organic carbon content (C_{org}) was estimated by subtracting the TIC from the TC. The CaCO₃ was calculated from TIC and atomic weight of carbon in CaCO₃ by using the following equation:

$$\text{CaCO}_3(\%) = \text{TIC}(\%) \times \frac{100}{12}$$

An aliquot of the dried > 63 µm fraction was dry sieved at 125 µm, and the resulting fractions were weighed. A representative weighed aliquot of fraction > 125 µm was used to pick the planktic foraminifera. A minimum of 300 intact planktic foraminifera shells were picked from each sample by using the Olympus stereozoom microscope (SZX16) and mounted on a micropaleontological slide. In the case of sandy coarse fraction, if sufficient number of planktic foraminifera were not available, minimum 1 g of coarse fraction was used. The planktic foraminifera species were identified by following Schiebel and Hemleben (2017), Ovechkina et al. (2010), Hemleben et al. (1989), Bé (1967), and Parker (1962). *Globigerinoides ruber* (white) and its morphotypes (sensu stricto and sensu lato) live throughout the year and thrive in the upper part of the mixed layer. Both morphotypes represent annual surface water conditions (Thirumalai et al. 2014). Therefore, sensu stricto and sensu lato were together counted as *G. ruber*. The subspecies *Globorotalia menardii neoflexuosa* was also considered under *G. menardii* (Siccha and Kucera 2017; Cullen and Prell 1984). Spezzaferri et al. (2015) suggested *Trilobatus* as a new genus to distinguish the *trilobus* and *ruber* clades. They further suggested to use the term *Trilobatus trilobus* for specimens without sac and *Trilobatus sacculifer* for specimens with sac, in view of their different ecological preferences. Recently, a similar approach was also used by Bhadra and Saraswat (2021) and Anbuselvan and Senthil Nathan (2021). The absolute abundance of planktic foraminiferal shells was estimated from the following equation:

$$\begin{aligned} \text{Absolute Abundance} = & \frac{\text{Number of Planktic Foraminifera}}{\text{Wt. CF}(> 125 \mu\text{m}) \text{ used for picking}} \\ & \times \frac{\text{Wt. CF}(> 125 \mu\text{m}) \text{ after dry sieving}}{\text{Wt. CF}(> 63 \mu\text{m}) \text{ taken for dry sieving}} \\ & \times \frac{\text{Wt. CF}(> 63 \mu\text{m})}{\text{Wt. Dry Sediment}} \end{aligned}$$

The number of specimens of different planktic foraminiferal species was counted to calculate the relative abundance. Before processing, the volume of wet sediment was measured to calculate the flux of planktic foraminifera and calcium carbonate. The total planktic foraminiferal number per gram sediment (TPN/g sediment) and the relative abundance (%) of different species were plotted by using Ocean Data View software (Schlitzer 2021). For canonical correspondence analysis (CCA) and Pearson correlation coefficients (R^2), all the species, except those with relative abundance < 0.2% were correlated with different environmental parameters. The relative abundance of all species was used to calculate the Dominance, Simpson (1-D), and Shannon (H) diversity indices by using the Paleontological Statistics software, 'PAST' version 4.14 (Hammer et al. 2001).

The annual average temperature and salinity data for all the stations were sourced from the World Ocean Atlas 2018 (Locarnini et al. 2019; Zweng et al. 2019) via the Live Access Server of CSIR-National Institute of Oceanography Goa. Both the average temperature and salinity profiles of the mixed layer and thermocline were acquired. The mixed layer was considered as 30 m, while the thermocline depth was set from 30 to 150 m, as previously established by Muraleedharan et al. (2007). The annual average Chlorophyll-a data was obtained from the "Chlorophyll-a, NASA VIIRS Ocean color (2012 onward)" database through Live Access Server of CSIR-National Institute of Oceanography, Goa, and used as a productivity indicator at each station. The ocean currents data with u and v vectors (GOFS 3.1: 41-layer HYCOM + NCODA Global 1/12° Reanalysis) were obtained from HYCOM data server. The average surface currents data, for July and January of 2015, was taken with temporal resolution of 3 h.

Results

Ambient parameters

Both, the mixed layer temperature and salinity were highest in the southernmost region and decreased from south to north (Fig. 1). However, the thermocline temperature increased and salinity decreased from south to north. The thermocline temperature decreased and salinity increased towards the open ocean (Fig. 1). The lowest mixed layer temperature and salinity were 28.18 °C and 33.28 psu, and the

highest were 28.53 °C and 33.58 psu, respectively. For thermocline, the lowest temperature and salinity were 24.42 °C and 33.73 psu, and the highest were 28.20 °C and 34.50 psu. The annual average chlorophyll-a concentration was high only in the shelf region throughout the swBoB (Fig. 1).

The organic carbon varied from the lowest of 0.01% to the highest of 3.61%. The highest C_{org} was on the continental slope, all throughout the swBoB. Incidentally, C_{org} was low along the southernmost transect, but the total carbon (TC) was high (Fig. 3). The rest of the transects had high TC and $CaCO_3$

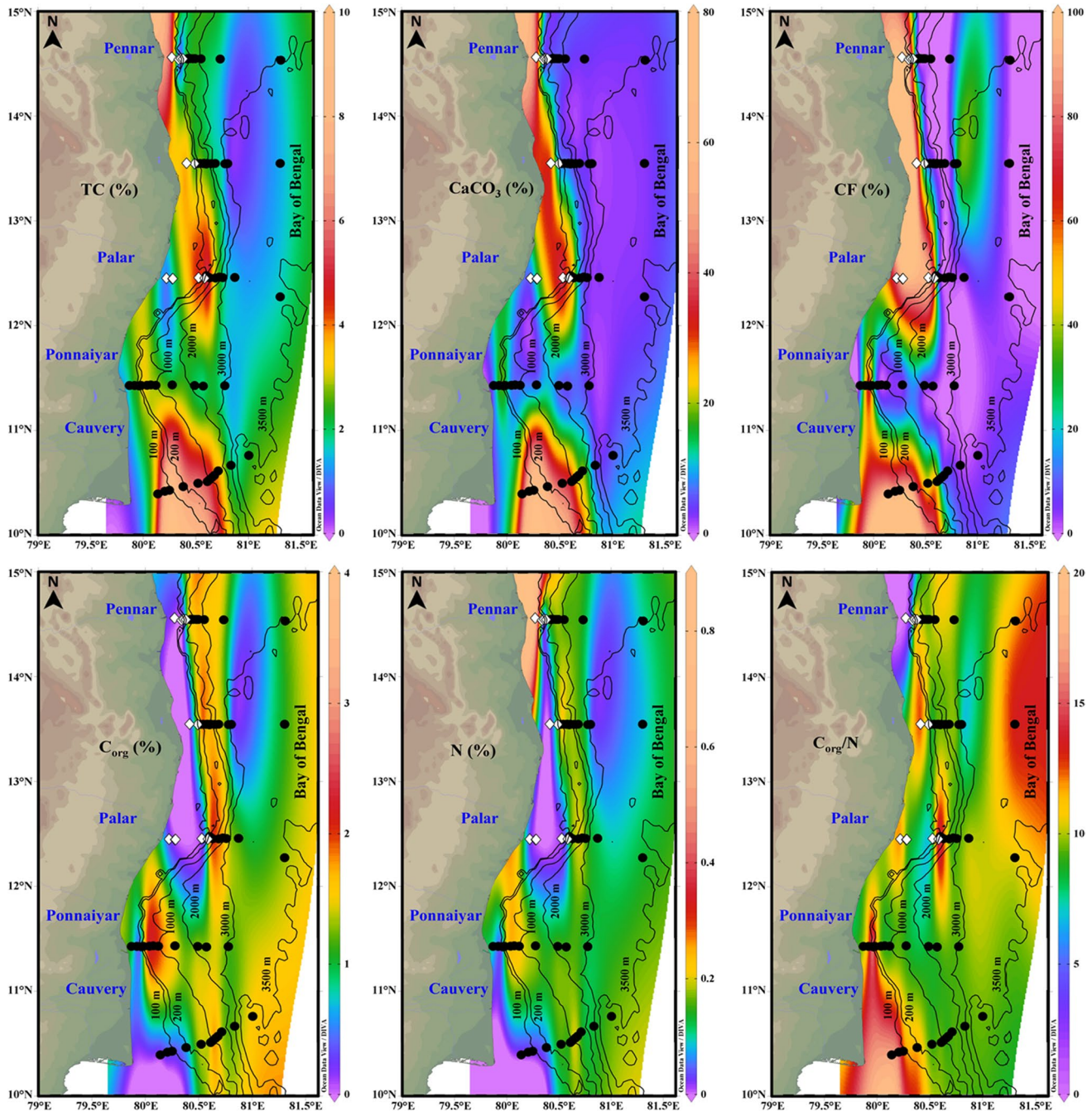


Fig. 3 The total carbon (TC), calcium carbonate ($CaCO_3$), coarse fraction (CF), organic carbon (C_{org}), nitrogen (N) percentage, and the ratio of organic carbon to nitrogen (C_{org}/N) in the surface sediments

of the southwestern Bay of Bengal. The black dots and white diamonds are the sample locations, and major rivers are marked by blue lines. The labelled contour lines are bathymetry

Table 1 Sample details with latitude, longitude, depth, absolute abundance (TPN, #/g sediment), shell flux (PF, shells/cm³) of planktic foraminifera, and CaCO₃ flux (mg/cm³) in the southwestern Bay of Bengal

Station	Latitude (°N)	Longitude (°E)	Depth (m)	TPN (#/g sediment)	PF flux (shells/cm ³)	CaCO ₃ flux (mg/cm ³)
MC01	14.5556	80.4010	318	342	98	14.59
MC02	14.5538	80.4159	598	296	64	12.49
MC03	14.5569	80.4214	721	332	68	11.08
MC04	14.5560	80.4385	1117	81	27	16.95
MC05	14.5401	81.3057	2994	132	45	6.25
MC06	14.5553	80.4418	1249	147	26	10.20
MC07	14.5557	80.4695	1556	229	35	10.04
MC08	14.5555	80.4913	1762	379	81	13.69
MC09	14.5532	80.5462	2018	427	70	12.93
MC10	14.5520	80.7283	2526	137	46	6.93
MC11	13.5501	81.3001	3289	147	11	4.17
MC12	13.5486	80.7996	2964	64	48	7.79
MC13	13.5462	80.7742	2735	299	55	9.16
MC14	13.5505	80.6819	2225	141	31	5.62
MC15	13.5486	80.6429	1725	46	11	5.53
MC16	12.4500	80.6833	1106	440	118	16.56
MC17	12.4524	80.6270	731	536	91	
MC18	13.5493	80.6075	1522	83	18	9.01
MC19	13.5449	80.5945	1124	196	59	12.51
MC20	13.5502	80.5784	895	107	54	12.10
MC21	13.5507	80.5708	620	490	153	18.66
MC22	13.5488	80.5687	480	5769	130	19.09
MC23	13.5500	80.5390	256	428	172	14.54
MC24	13.5498	80.5779	878	140	43	12.68
MC25	13.5483	80.5080	154	689	495	30.80
MC26	12.4643	80.5957	168	2237	2428	670.19
MC27	12.4626	80.5952	286	1030	179	36.19
MC28	12.4726	80.5980	470	557	144	32.63
MC29	12.4594	80.7205	1437	282	51	10.34
MC30	12.2700	81.3000	3429	107	36	6.23
MC31	12.4560	80.8670	3254	79	17	5.75
MC32	12.4534	80.7527	2760	81	21	6.99
MC33	11.4244	80.0682	738	231	69	11.04
MC34	11.4202	80.0323	509	323	78	12.28
MC35	11.4193	79.9768	277	430	89	12.22
MC36	11.4189	79.9658	128	227	270	450.14
MC37	11.4143	79.9572	91	55	58	51.60
MC38	11.4178	79.9135	52	281	318	127.83
MC39	11.4188	79.8634	28	10	2	9.10
MC40	11.4203	80.1159	1036	393	114	13.87
MC41	11.4236	80.2714	1480	217	59	9.08
MC42	11.4193	80.4839	2007	450	83	9.42
MC43	11.4132	80.5663	2570	258	81	6.49
MC44	11.4162	80.7722	3112	248	51	6.77
MC45	10.7480	81.0000	3505	426	56	8.77
MC46	10.6535	80.8314	2982	296	54	9.01
MC47	10.5996	80.7096	1695	2170	652	44.17
MC48	10.5567	80.6732	1240	32	129	22.04
MC49	10.5376	80.6521	1009	6193	2509	72.84
MC50	10.5122	80.6229	760	7034	1845	55.25

Table 1 (continued)

Station	Latitude (°N)	Longitude (°E)	Depth (m)	TPN (#/g sediment)	PF flux (shells/cm ³)	CaCO ₃ flux (mg/cm ³)
MC51	10.4979	80.6060	510	12060	6329	172.21
MC52	10.3785	80.1340	24	7	10	470.66
MC53	10.4048	80.2012	52	900	862	540.35
MC54	10.4125	80.2445	73	1111	1134	774.53
MC55	10.4489	80.3770	157	4260	3354	397.48
MC56	10.4812	80.5168	249	5374	4069	181.86
GR01	14.5688	80.2672	26	4	6	668.68
GR02	14.5473	80.3332	52	27	36	45.30
GR03	14.5562	80.3539	66	90	70	24.70
GR04	14.5537	80.3737	104	549	322	35.84
GR05	13.5479	80.4845	78	231	81	13.84
GR06	13.5523	80.4081	29	7	10	421.07
GR07	12.4480	80.2168	29	3	3	54.68
GR08	12.4425	80.2735	78	10	12	154.84
GR09	12.4434	80.2775	46	34	44	183.43
GR10	12.4538	80.5223	76	315	342	429.16
GR11	12.4479	80.5794	129	916	978	229.12

content only at shallow stations (shelf). CaCO₃ abundance varied from 4.17 to 774.53 mg/cm³ (Table 1), with an average of 102.90 mg/cm³. Interestingly, the highest C_{org}/N ratio was also in the southernmost transect, and it decreased with depth. However, an opposite trend was observed in the northern part of the study area. Here, C_{org}/N increased with depth (Fig. 3). The coarse fraction (> 63 μm) percentage was also high along the southern most transect, and for the rest of the transects, it was high only at shallow stations (Fig. 3).

Absolute abundance of planktic foraminifera

The total number of planktic foraminifera varied from 3 to 12,060 specimen/g dry sediment. The highest absolute abundance was in the southernmost transect, but the rest of the transects had a very low abundance of planktic foraminifera (Fig. 4). The total planktic foraminifera number was > 2000 to 12,060 specimen/g dry sediment in the southernmost transect. However, in other transects, the maximum absolute abundance of planktic foraminifera was < 2000 specimen/g dry sediment. A majority of the stations had < 500 planktic foraminifera/g dry sediment. Additionally, planktic foraminifera were abundant throughout the slope, only along the southernmost transect. In case of all other transects, planktic foraminifera abundance was slightly high only on the upper slope region. The absolute abundance of planktic foraminifera increased up to a depth of 1000 m and decreased after 1000 m. The range of planktic foraminifera flux values varied between 2 and 6329 shells/cm³ (Table 1), with a mean value of 434 shells/cm³. The highest planktic foraminifera shell flux was along the southernmost transect (Fig. 5).

Species abundance

A total of thirty-one planktic foraminifera species belonging to fifteen genera were found in the surface sediments of the swBoB (Fig. 6). The dominant species (relative abundance > 5%) include *Globigerinita glutinata*, *Globigerina bulloides*, *Globigerinoides ruber*, *Neogloboquadrina dutertrei*, *Trilobatus trilobus*, and *Trilobatus sacculifer* (Fig. 7). The dominant species constitute ~76% of the total planktic foraminiferal population (Fig. 6). The moderately abundant species (with average relative abundance > 1% and < 5%) were *Neogloboquadrina incompta*, *Globorotalia menardii*, *Globigerina falconensis*, *Globigerinella siphonifera*, *Globoturborotalita rube-scens*, *Globoquadrina conglomerata*, *Globigerinoides tenellus*, and *Pulleniatina obliquiloculata* (Fig. 6 and 8). The rare species with average relative abundance < 1% include *Globorotaloides hexagonus*, *Globigerinella calida*, *Globorotalia unguata*, *Globigerinella radians*, *Turborotalita quinqueloba*, *Orbulina universa*, *Globigerinoides conglobatus*, *Hastigerina pelagica*, and *Neogloboquadrina pachyderma* (Fig. 6 and 9). The relative abundance of *Turborotalita humilis*, *Sphaeroidinella dehiscens*, *Beella digitata*, *Globorotalia eastropacia*, *Globorotalia tumida*, *Globigerinella adamsi*, *Neogallitellia vivans*, and *Globigerinita uvula* was < 0.2% (Fig. 6).

Dominant species

Globigerinita glutinata was predominant in the swBoB (Fig. 6). The relative abundance of *G. glutinata* increased with depth except for a few stations. *Globigerinita glutinata* was abundant at the deepest (> 3000 m) stations of the two

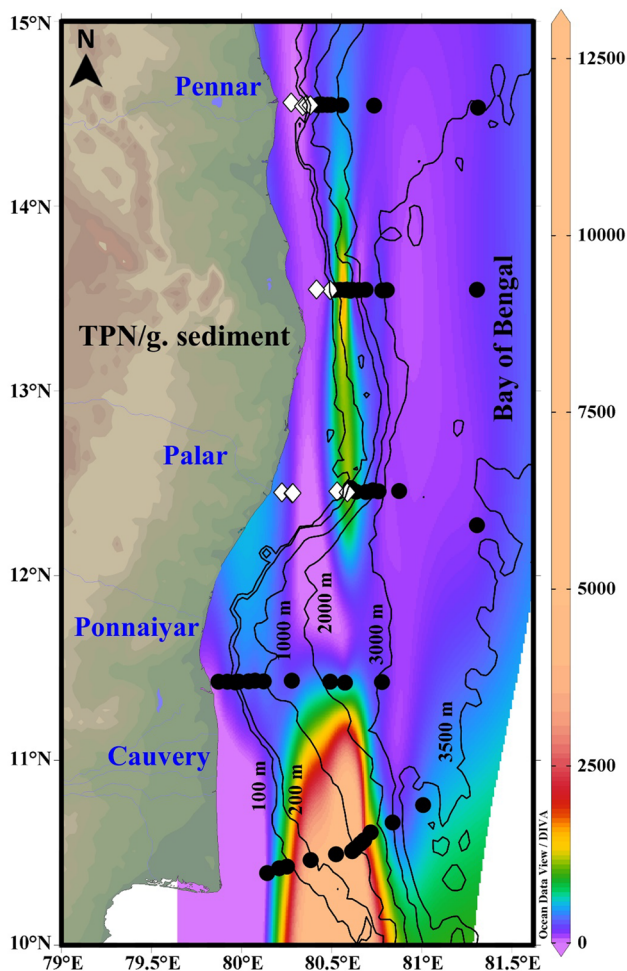


Fig. 4 The absolute abundance of planktic foraminifera (TPN/g sediment) in the swBoB. The black dots and white diamonds are the sample locations, and major rivers are marked by blue lines. The labelled contour lines are bathymetry

southern transects. However, the deepest (> 3000 m) stations along the upper 3 transects had a relatively low abundance of *G. glutinata*. In general, *G. glutinata* was relatively more abundant in the southern part of the study area (Fig. 7). The second most abundant species was *G. bulloides* (Fig. 7). The percentage of *G. bulloides* was high on the outer shelf and upper slope region except very shallow stations and decreased with increasing depth. The relative abundance of *G. bulloides* was low off Cauvery River, but it was high off Chennai and in the northern part of swBoB (Fig. 7). The highest relative abundance of *G. ruber* was in the southernmost transect and decreased towards north. Its abundance was high at very shallow stations off Pennar River, while in the southernmost transect, *G. ruber* was abundant on the slope (Fig. 7). *Neogloboquadrina dutertrei* was more abundant along the uppermost two transects and its abundance increased with depth. The percentage of *N. dutertrei* was low in the southern part of the study area, except the upper

slope region (Fig. 7). *Trilobatus trilobus* was abundant on the northern side of the Cauvery Basin. In the northern part of the study area, its relative abundance was high on the slope. Interestingly, the deepest stations of all the transects also had abundant *T. trilobus*. The relative abundance of *T. sacculifer* was higher than that of *T. trilobus*. The relative abundance of *T. sacculifer* increased with depth, except in the northernmost transect. The highest abundance of *Trilobatus sacculifer* was at the deepest station (MC45) of the southernmost transect (Fig. 7).

Moderately abundant species

Neogloboquadrina incompta was moderately abundant on the shelf in front of the Pennar and Cauvery rivers. However, it was more abundant on the upper slope in the middle part of the swBoB. The percentage of *G. menardii* increased with increasing water depth in all the transects (Fig. 8). It was rarely present on the entire continental shelf. *Globigerina falconensis* was more abundant only on the shallow shelf region especially near Cauvery River (Fig. 8). It was rarely present at all other stations on the outer shelf and further deeper regions. The abundance of *G. bulloides* was low in front of the Cauvery River, whereas *G. falconensis* had a high relative abundance in this region (Fig. 8). *Globigerinella siphonifera* was less abundant on the shelf and highly abundant at deeper stations except the southern part (Fig. 8). The abundance of *G. rubescens* was similar to that of *G. falconensis*. It was abundant at only a very few shallow water stations on the continental shelf. The highest abundance of *G. rubescens* was in the southernmost transect (Fig. 8). The relative abundance of *G. conglomerata* increased with increasing depth, and it was relatively more abundant in the northern part of the study area (Fig. 8). The surface distribution of *G. conglomerata* was similar to that of *G. menardii* (Fig. 8). The relative abundance of *G. tenellus* was similar to that of *G. falconensis*, with the zones of high relative abundance confined to the continental shelf, especially in the southern part of the study area. However, it was also abundant at a few stations on the upper slope, unlike *G. falconensis*. The relative abundance of *P. obliquiloculata* was high in the southern part as compared to the northern part of the study area. *Pulleniatina obliquiloculata* did not have any systematic distribution pattern with depth (Fig. 8).

Rare species

The average relative abundance of *G. hexagonus* was 0.97 (%) in the swBoB. Only one shallowest station in front of the Pennar River had a high relative abundance of *G. hexagonus*. The abundance of *G. calida* was comparatively high on the slope, and it was rare on the shelf, except in the northern Cauvery Basin (Fig. 9). The surface distribution of *T. quinqueloba* was

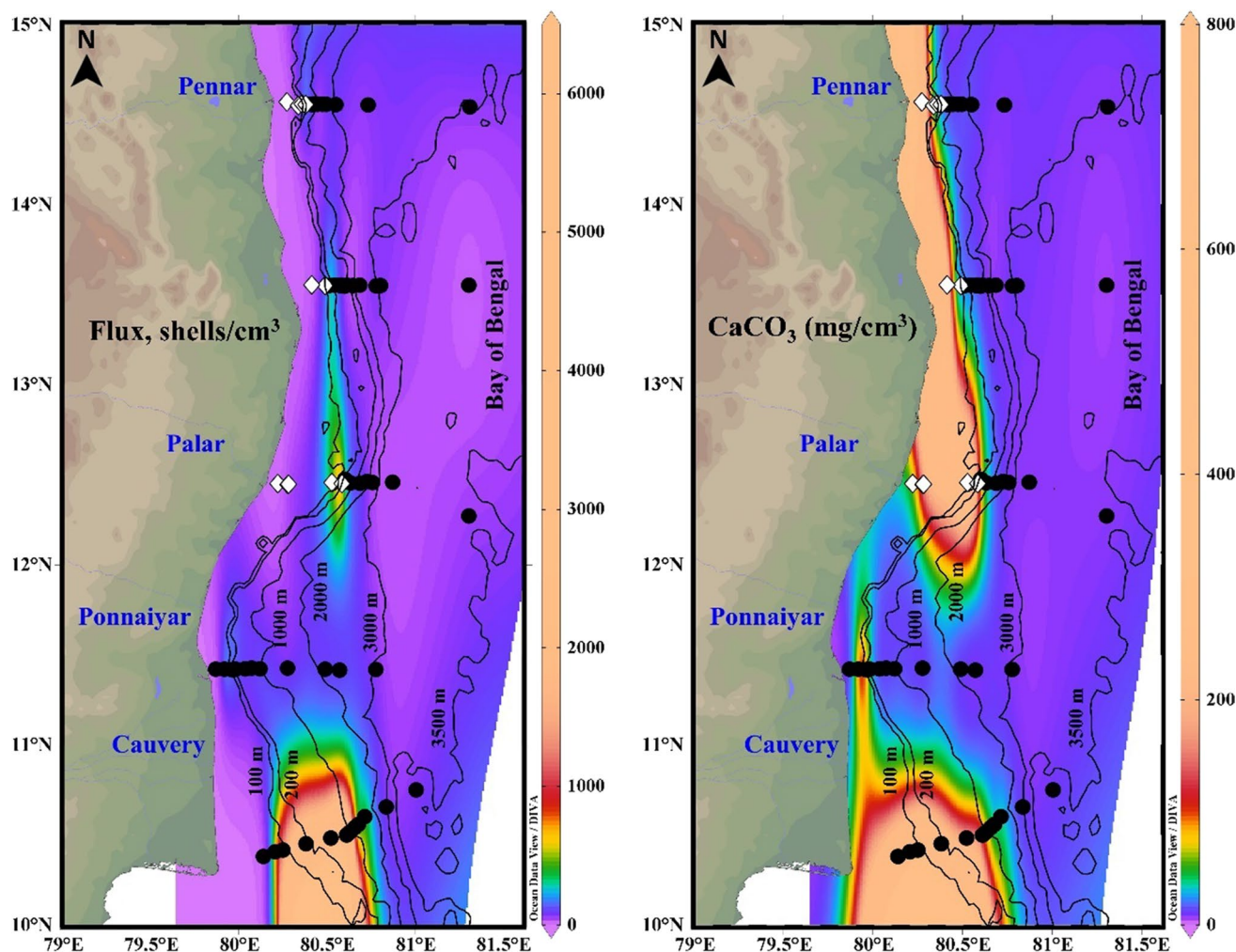


Fig. 5 The flux rate of total planktic foraminifera ($\text{shells}/\text{cm}^3$) and calcium carbonate (mg/cm^3) in the southwestern Bay of Bengal

similar to that of *G. calida*. *Globorotalia ungulata* was relatively more abundant on the shelf as well as upper slope and was almost absent at deeper stations. Thus, the relative abundance of *G. ungulata* decreased with increasing depth (Fig. 9). *Orbulina universa* was absent at most of the stations on the continental shelf. It was more abundant in the southern part as compared to northern part of study area. The relative abundance of *G. conglobatus* was high at a few stations on the shelf, and it was absent at the slope except the southern transect. Here, it was more abundant on the slope (Fig. 9). *Hastigerina pelagica* was found only at a few stations on the shelf. Interestingly, the relative abundance of *H. pelagica* was very high ($\sim 10\%$) at station GR08. *Neogloboquadrina pachyderma* was abundant on the upper slope in the northern part of the study area.

Canonical correspondence analysis

The canonical correspondence analysis helped to understand the relation between environmental parameters and planktic

foraminiferal species. Axis 1 and Axis 2 represent 69.89% and 23.13% of the variance for the selected species explained with CCA (Fig. 10). The permutation (p) values for both axes were the same as < 0.01 , and the Eigen values were 0.0481 and 0.0159, respectively. The relative abundance of *G. ruber* was positively correlated with the temperature and salinity of the mixed layer (Fig. 10). A similar preference for warmer temperature and high salinity in the mixed layer was also observed for *G. conglobatus*. The abundance of *G. menardii* was positively correlated with thermocline salinity and negatively correlated with thermocline temperature. However, *G. ungulata* showed an opposite preference, suggesting that *G. menardii* is a deep water and dissolution resistance species, and *G. ungulata* is shallow warm water and dissolution susceptible species (Fig. 10). The apparent calcification depth for *G. ungulata* is 81 ± 6 m positioned in the upper thermocline, whereas for *G. menardii*, it is 109 ± 8 m situated in the lower thermocline (Stainbank et al. 2019). *Globorotalia ungulata* has a lighter and thinner shell as compared to *G.*

AVERAGE RELATIVE ABUNDANCE (%)

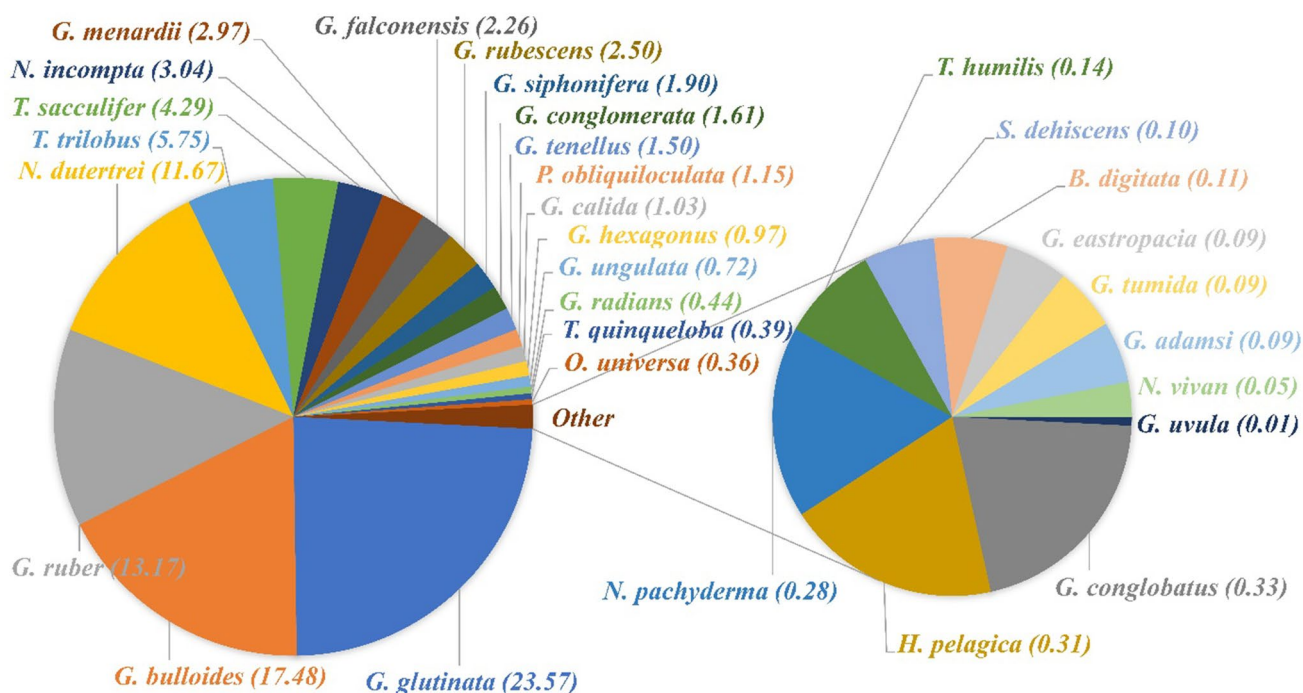


Fig. 6 Pie diagram showing the average relative abundance of planktic foraminifera species at all the stations in the southwestern Bay of Bengal. The numbers with species names are their average relative abundance

menardii (Lamb and Beard 1972). Therefore, *G. ungulata* is comparatively more prone to dissolution, unlike *G. menardii*. Similarly, *N. dutertrei* and *G. conglomerata* were negatively correlated with mixed layer temperature and salinity, as well as thermocline temperature and positively correlated with thermocline salinity. *Neogloboquadrina pachyderma* was also positively correlated with thermocline salinity. Several species (*G. falconensis*, *G. incompta*, *H. pelagica*, *G. bulloides*, and *T. quinqueloba*) were positively correlated with chlorophyll-a, clearly indicating that food availability controls their abundance (Fig. 10). However, *O. universa*, *G. menardii*, and *T. sacculifer* were negatively correlated with chlorophyll-a, suggesting their preference for low productivity oligotrophic waters.

Diversity indices

The stations on the continental shelf and lower slope had low Shannon and Simpson diversity index, but dominance was high (Fig. 11), while on the upper slope, it was opposite. The deepest stations of the three northern transects had a relatively higher planktic foraminiferal diversity. Overall, the planktic diversity was more in the southern part except at the deepest stations of the three northern transects. A relatively high diversity was also observed on the slope (Fig. 11).

Pearson correlation coefficient

The Pearson correlation values were used to understand the positive and negative correlation between the relative abundance of planktic foraminiferal species and different environmental parameters (Table 2). The probability values were calculated to test the null hypothesis and to know the significance of the correlation (Table 2). Only those correlation values that had *p* values 0.01, 0.05, and 0.1 were considered statistically very significant, significant, and insignificant, respectively. Surprisingly, *Globigerinita glutinata* was not strongly correlated with any environmental parameter. However, *G. bulloides* exhibited a robust negative correlation ($R^2 = -0.5064$; $p < 0.01$) with the temperature of mixed layer (Table 2). On the contrary, *G. ruber* had a strong positive correlation with both the temperature ($R^2 = 0.4469$; $p < 0.01$) and salinity ($R^2 = 0.4055$; $p < 0.01$) of the mixed layer (Table 2). *Neogloboquadrina dutertrei* was negatively correlated with temperature ($R^2 = -0.4146$; $p < 0.01$) and salinity ($R^2 = -0.5136$; $p < 0.01$) of the mixed layer and thermocline temperature ($R^2 = -0.2868$; $p < 0.05$) and positively correlated ($R^2 = 0.2799$; $p < 0.05$) with thermocline salinity. *Globorotalia menardii* exhibited a negative correlation ($R^2 = -0.3649$; $p < 0.01$) with thermocline temperature and a positive correlation

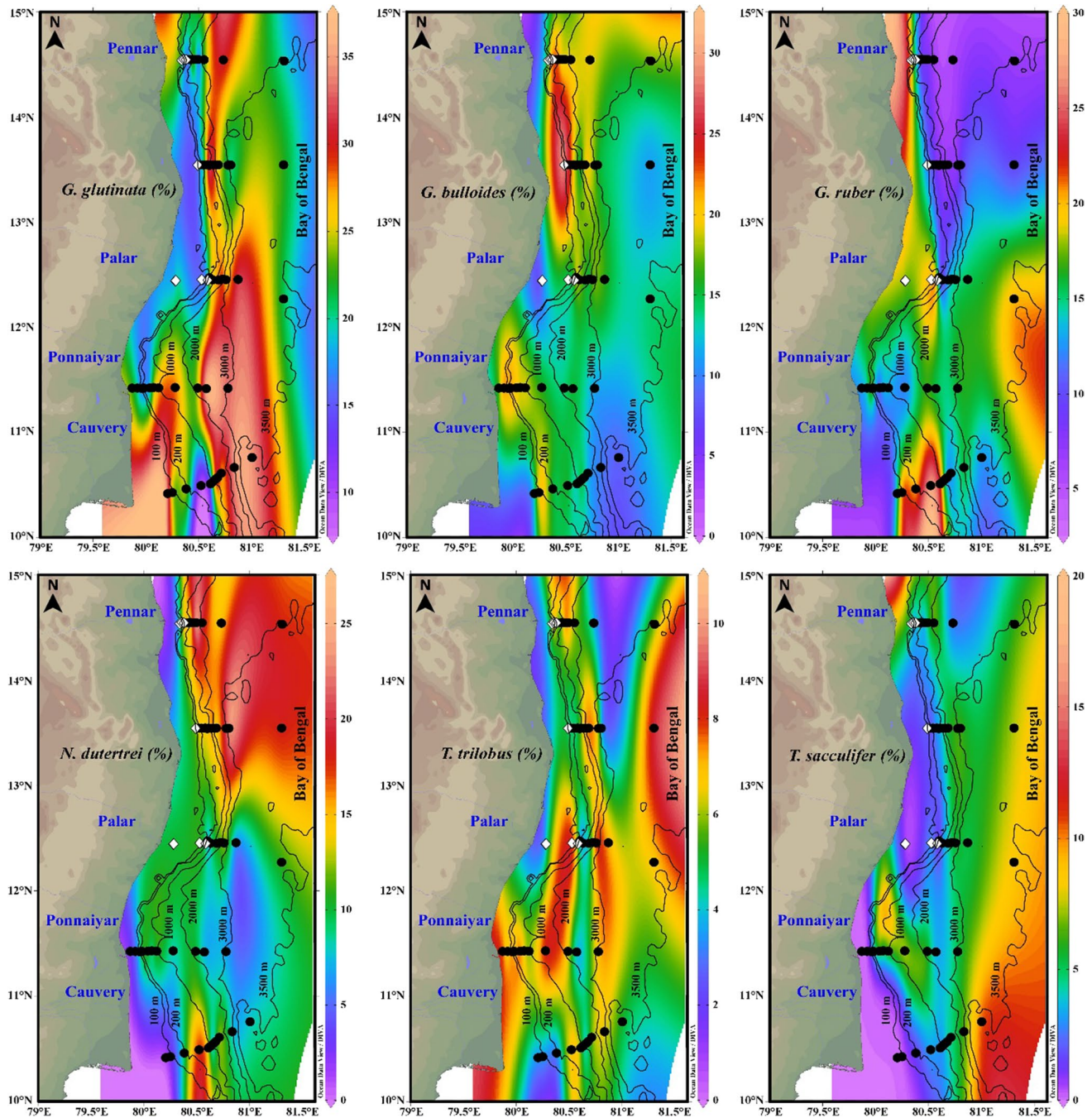


Fig. 7 The relative abundance (%) of dominant planktic foraminifera species in the southwestern Bay of Bengal. The black dots and white diamonds are the sample locations, and major rivers are marked by blue lines. The labelled contour lines are bathymetry

($R^2 = 0.3285$; $p < 0.05$) with thermocline salinity (Table 2). *Globorotalia unguolata* was positively correlated with thermocline temperature ($R^2 = 0.2959$; $p < 0.05$) and negatively with thermocline salinity ($R^2 = -0.3250$; $p < 0.05$). *Globigerinoides conglobatus* was positively correlated with mixed layer salinity ($R^2 = 0.2479$; $p > 0.05$). *Neogloboquadrina incompta* ($R^2 = 0.2610$; $p < 0.05$), *G. falconensis* ($R^2 = 0.7021$; $p < 0.01$), *G. rubescens* ($R^2 = 0.4840$;

$p < 0.01$), and *G. tenellus* ($R^2 = 0.4235$; $p < 0.01$) were positively correlated with chlorophyll-a, while *N. dutertrei* ($R^2 = -0.3621$; $p < 0.01$), *T. trilobus* ($R^2 = -0.3046$; $p < 0.05$), *T. sacculifer* ($R^2 = -0.4824$; $p < 0.01$), *G. menardii* ($R^2 = -0.5498$; $p < 0.01$), *G. siphonifera* ($R^2 = -0.3411$; $p < 0.01$), *G. conglomerata* ($R^2 = -0.4059$; $p < 0.01$), and *O. universa* ($R^2 = -0.3070$; $p < 0.05$) were negatively correlated with chlorophyll-a (Table 2).

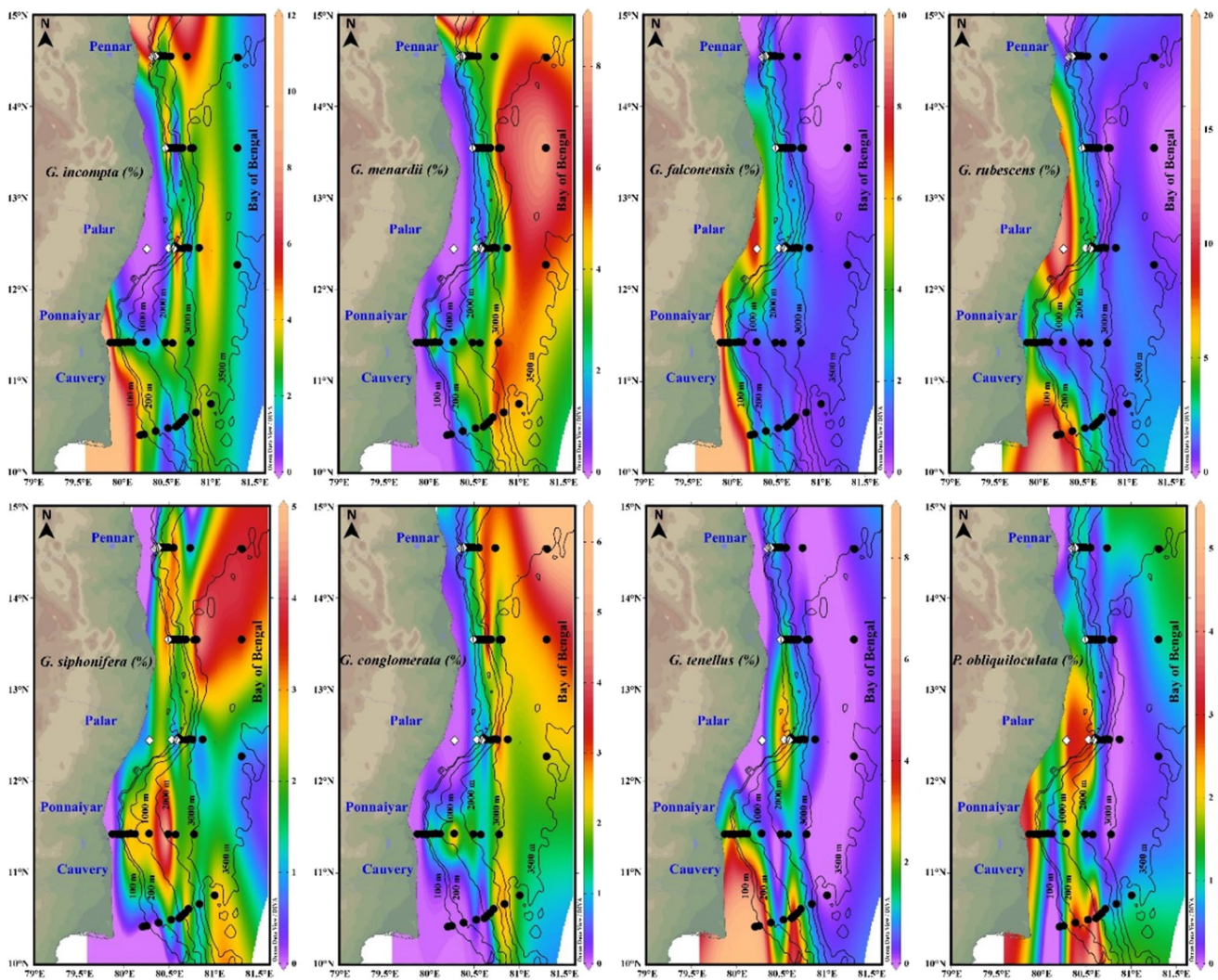


Fig. 8 The relative abundance (%) of moderately abundant planktic foraminifera species in the southwestern Bay of Bengal. The black dots and white diamonds are the sample locations, and major rivers are marked by blue lines. The labelled contour lines are bathymetry

Discussion

Carbon burial in the southwestern Bay of Bengal

The mean CaCO_3 (14.19%) was much higher in the swBoB than the north-western and west-central BoB. It was 7.60% in the west-central BoB (Suokhrie et al. 2021), and for the entire north-western and west-central BoB, it was 5.69% including a few data points from swBoB (Saraswat et al. 2017). These values suggest the trend of increasing CaCO_3 content in the surface sediments towards the south in western BoB. The maximum carbon burial was along the southernmost transect (Fig. 3) suggesting the influence of Gulf of Mannar water during the summer monsoon season. The carbon burial in marine realm occurs by two different pathways (Cartapanis et al. 2018), namely, transformation of dissolved inorganic carbon (DIC) into C_{org} through the utilization of

DIC by photosynthetic organisms, and extraction of DIC from the surrounding water by calcareous organisms to produce carbonate minerals (CaCO_3) and their burial at the seafloor. The C_{org} burial in marine sediments is modulated by the primary productivity in the surface water (Middelburg 2019; Thunell et al. 2000; Calvert and Pedersen 1992; Pedersen et al. 1992; Calvert et al. 1991), oxygen level in subsurface water (Middelburg 2019; Paropkari et al. 1993), sedimentation rate/mineral ballast (Hedges and Keil 1995; Ittekkot et al. 1991), texture of sediments (Calvert et al. 1995), and dilution by terrigenous material (Kandasamy and Nath 2016; Rullkotter 2006). However, the CaCO_3 content of the sediments is substantially modified by biological productivity in the overlying water column, dissolution in the water column as well as in sediments (Bhadra and Saraswat 2022) and dilution by terrigenous matter (Yadav et al. 2022; Govil et al. 2004).

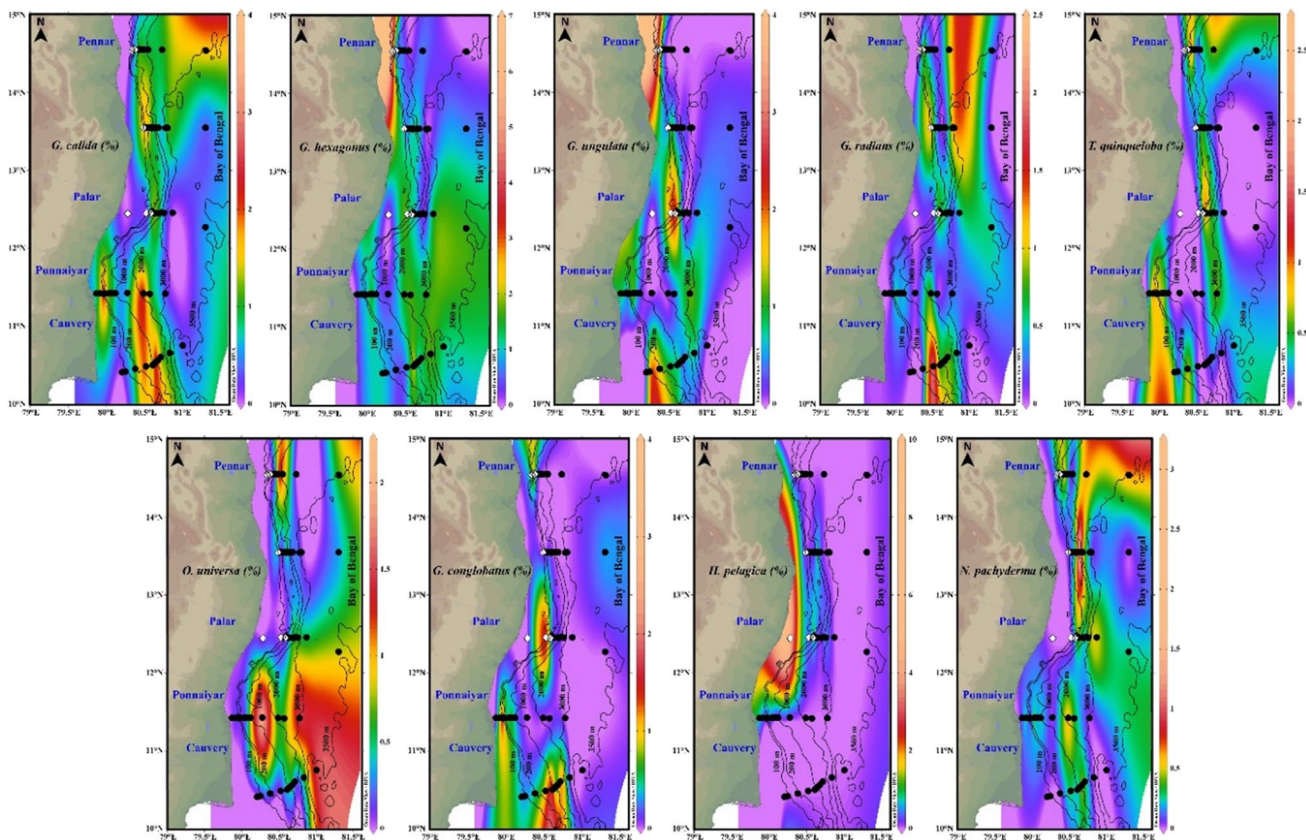


Fig. 9 The relative abundance (%) of rare planktic foraminifera species in the southwestern Bay of Bengal. The black dots and white diamonds are the sample locations, and major rivers are marked by blue lines. The labelled contour lines are bathymetry

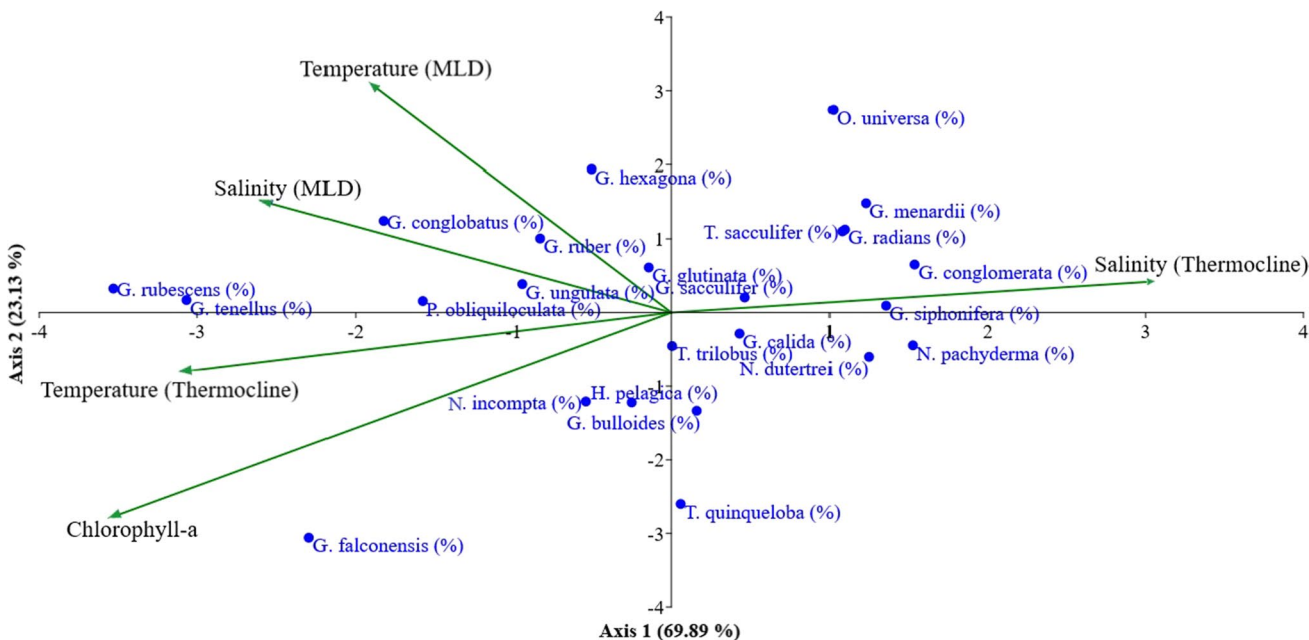


Fig. 10 Canonical correspondence analysis (CCA) plot between ambient parameters and the relative abundance of planktic foraminifera species. The ambient parameters are marked by solid green lines

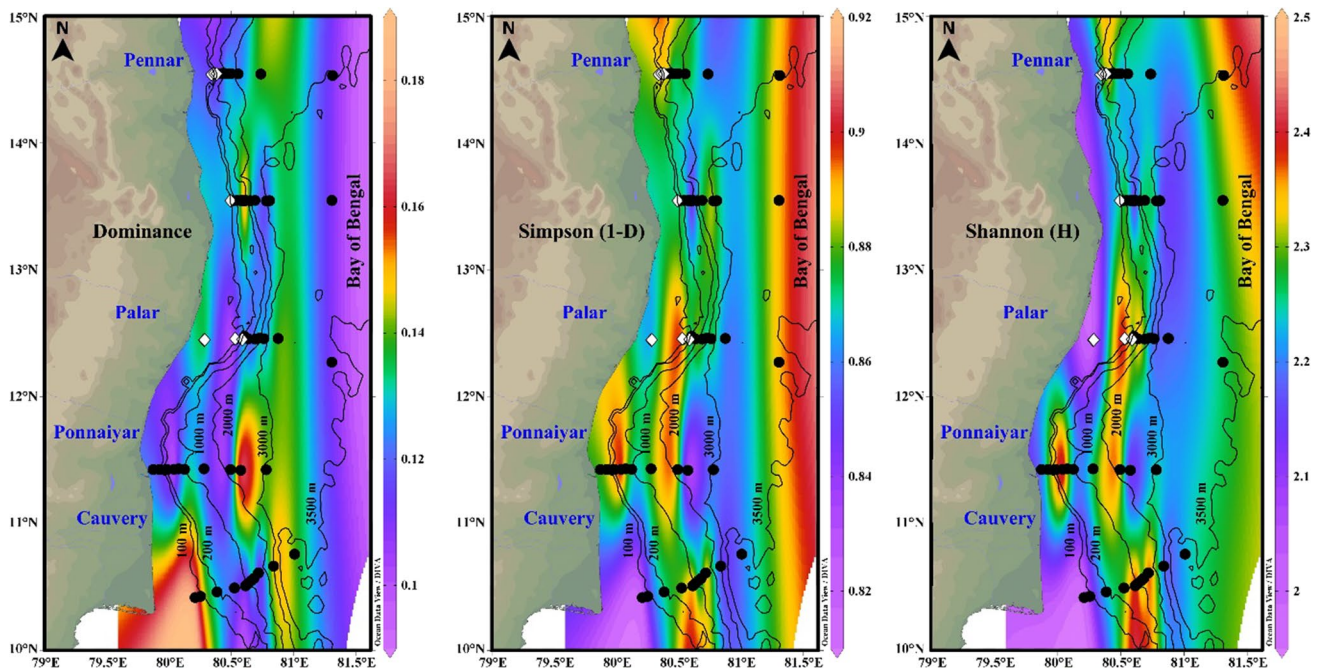


Fig. 11 The Dominance, Simpson (1-D) and Shannon (H) diversity indices of planktic foraminifera species from the southwestern Bay of Bengal. The black dots and white diamonds are the sample locations, and major rivers are marked by blue lines. The labelled contour lines are bathymetry

Table 2 The positive and negative Pearson correlation (R^2) values are given in green and blue colours, respectively. The significant probability (p) values are highlighted in orange colour

Species	Temperature (MLD) R^2	Temperature (MLD) p	Salinity (MLD) R^2	Salinity (MLD) p	Temperature (Thermocline) R^2	Temperature (Thermocline) p	Salinity (Thermocline) R^2	Salinity (Thermocline) p	Chl-a R^2	Chl-a p
<i>G. glutinata</i> (%)	0.2210	0.0844	0.1638	0.2069	-0.0965	0.4544	0.0169	0.9003	-0.1273	0.3307
<i>G. bulloides</i> (%)	-0.5064	0.0001	-0.2964	0.0233	0.1149	0.3761	-0.0052	0.9672	0.2383	0.0657
<i>G. ruber</i> (%)	0.4469	0.0005	0.4055	0.0009	0.2109	0.1038	-0.1945	0.1351	0.1037	0.4200
<i>N. dutertrei</i> (%)	-0.4146	0.0010	-0.5136	0.0001	-0.2868	0.0267	0.2799	0.0280	-0.3621	0.0035
<i>G. sacculifer</i> (%)	-0.0231	0.8597	-0.1109	0.3929	-0.2238	0.0832	0.2480	0.0549	-0.3046	0.0149
<i>T. trilobus</i> (%)	-0.0618	0.6356	-0.0061	0.9623	0.0532	0.6927	0.0303	0.8261	0.0611	0.6446
<i>T. sacculifer</i> (%)	0.0344	0.7874	-0.1215	0.3535	-0.3735	0.0028	0.3490	0.0054	-0.4824	0.0001
<i>N. incompta</i> (%)	-0.1188	0.3646	-0.0591	0.6519	0.0375	0.7793	-0.1145	0.3582	0.2610	0.0447
<i>G. menardii</i> (%)	0.0347	0.7906	-0.2268	0.0796	-0.3649	0.0043	0.3285	0.0122	-0.5498	0.0001
<i>G. falconensis</i> (%)	-0.0307	0.8206	0.2078	0.1110	0.3888	0.0018	-0.3725	0.0045	0.7021	0.0001
<i>G. siphonifera</i> (%)	-0.1061	0.4134	-0.1509	0.2466	-0.2836	0.0268	0.3309	0.0076	-0.3411	0.0069
<i>G. rubescens</i> (%)	0.2115	0.1049	0.2895	0.0237	0.5500	0.0002	-0.5607	0.0005	0.4840	0.0020
<i>G. conglomerata</i> (%)	-0.1375	0.2895	-0.3176	0.0116	-0.2246	0.0814	0.2249	0.0800	-0.4059	0.0026
<i>G. tenellus</i> (%)	0.2897	0.0204	0.4032	0.0009	0.3366	0.0117	-0.3319	0.0146	0.4235	0.0035
<i>P. obliquiloculata</i> (%)	0.2059	0.1138	0.2363	0.0640	0.2380	0.0626	-0.1774	0.1570	0.2249	0.0795
<i>G. hexagona</i> (%)	0.0655	0.6227	0.0622	0.6535	0.1850	0.1451	-0.2636	0.0501	-0.1145	0.3251
<i>G. calida</i> (%)	0.1112	0.3963	0.1810	0.1677	-0.2866	0.0279	0.3383	0.0085	-0.0890	0.5017
<i>G. ungulata</i> (%)	-0.0659	0.6127	-0.0418	0.7484	0.2959	0.0203	-0.3250	0.0145	0.0925	0.4864
<i>G. radians</i> (%)	0.0501	0.7036	-0.0350	0.7932	-0.2903	0.0254	0.2419	0.0568	-0.2407	0.0634
<i>T. quinqueloba</i> (%)	-0.2277	0.0762	-0.1113	0.4047	0.0464	0.7322	-0.0618	0.6371	0.1272	0.3173
<i>O. universa</i> (%)	0.2133	0.1021	0.1053	0.4207	-0.2892	0.0225	0.2719	0.0359	-0.3070	0.0218
<i>G. conglobatus</i> (%)	0.1848	0.1499	0.2479	0.0509	0.2154	0.0815	-0.1331	0.2820	0.0879	0.4761
<i>H. pelagica</i> (%)	0.0563	0.6664	0.1088	0.4060	-0.1437	0.2585	0.1323	0.2833	0.0482	0.7018
<i>N. pachyderma</i> (%)	-0.1665	0.2141	-0.1812	0.1645	-0.1291	0.2744	0.0884	0.4175	-0.1503	0.1754

The C_{org} content in the sediments was low on the shelf, while the surface water chlorophyll-a was high. The low sedimentary organic matter despite high water column

productivity means poor organic matter preservation in the sediments. The poor C_{org} preservation was because of the coarse-grained texture of the sediments and the influence

of oxygenated water (Hedges and Keil 1995). The C_{org} was also likely to be transported to the deeper depth with finer fraction of sediment due to the influence of riverine influx. The C_{org} content was maximum at intermediate depth (slope) suggesting the high C_{org} burial rate on the slope (Fig. 3). But the TC and $CaCO_3$ percentage were high on the shelf (Fig. 3), suggesting that a large part of the TC on the shelf was contributed by the calcareous organisms (foraminifers, pteropods, ostracods, gastropods, and others) on the shelf. The strong positive correlation ($R^2 = 0.8675$; $p < 0.01$)

between TC and $CaCO_3$ (Fig. 12a) confirms that a major part of TC was contributed by calcareous shells in the form of calcite mineral ($CaCO_3$) throughout the swBoB. Incidentally, there was no correlation ($R^2 = 0.0002$; $p > 0.1$) between TC and C_{org} (Fig. 12b). The low C_{org} and N content along the southernmost transect and high C_{org}/N ratio suggests a high burial rate of terrestrially derived C_{org} . The high TC, $CaCO_3$, and CF percentages along this transect suggest the maximum burial and sequestration of carbon through calcareous shell flux (Fig. 5). The quick burial due to higher sedimentation

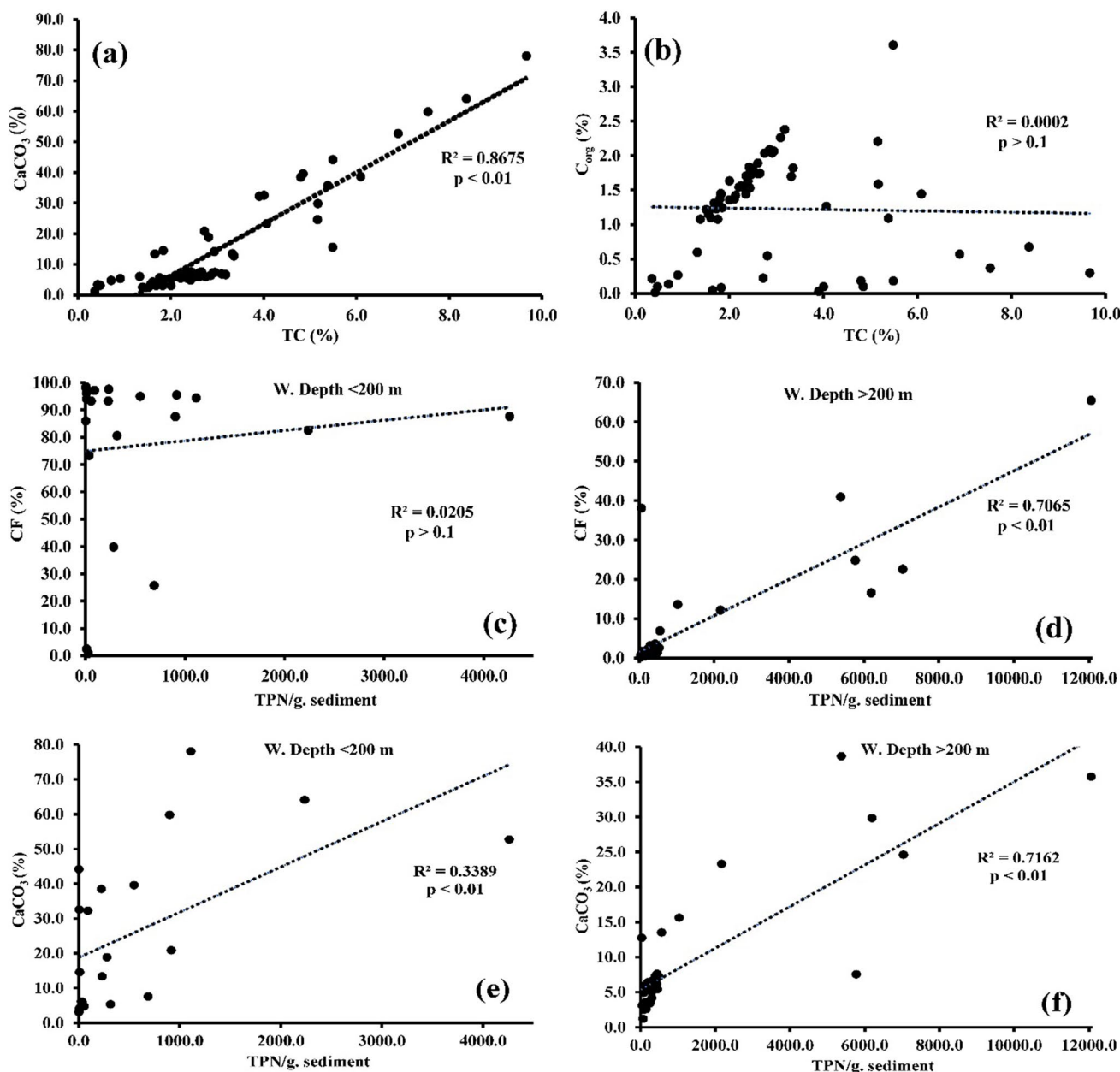


Fig. 12 The correlation between TC and $CaCO_3$ (a), TC and C_{org} (b), TPN/g sediment and CF at <200 m water depth (c), TPN/g sediment and CF at >200 m water depth (d), TPN/g sediment and

$CaCO_3$ at <200 m water depth (e), and TPN/g sediment and $CaCO_3$ at >200 m water depth (f) from the southwestern Bay of Bengal

rate decreases the remineralization during the downward flux of the planktic foraminiferal shells in the water column as well as after its settlement in the sediments. The higher burial rates, therefore, are mainly responsible for the better carbonate preservation in this part. Additionally, the higher overall planktic population is also attributed to the influx of more saline and carbonate enriched water from the Arabian Sea. However, the high C_{org} and N in front of the Pennar River and the low C_{org}/N ratio (Fig. 3) suggest relatively, higher marine produced C_{org} burial.

The mean C_{org} content and C_{org}/N ratio of sediments were 1.23% and 10.29, respectively, at a mean water depth of 1080 m in the swBoB. The mean C_{org} and C_{org}/N , in the entire western BoB, were 1.19% and 11.16 at a mean water depth of 564 m (Saalim et al. 2021; Suokhrie et al. 2020; Saraswat et al. 2017). The high C_{org} and low C_{org}/N suggests slightly higher C_{org} burial in the swBoB and less influence of terrigenous input. Nevertheless, the C_{org} content in the sediments was relatively higher in the west-central BoB (Saraswat et al. 2017). The high C_{org} in the west-central BoB was attributed to the upwelling in this region (Shetye et al. 1991). The low C_{org} and high C_{org}/N in the extreme north-west BoB (Saraswat et al. 2017) and in front of the Cauvery River suggests high terrigenous input and less C_{org} burial. A similar mean C_{org} (1.2%), but much higher mean C_{org}/N (17.43), were reported at a mean depth of 281 m in the western BoB from the Krishna River mouth to the Mahanadi River mouth (Krishna et al. 2013). However, here, the sampling was limited to a maximum water depth of 1209 m. Therefore, the dominance of terrestrially derived organic matter at the shallow depth stations results in higher C_{org}/N . The mean C_{org} (2.43%) at a mean water depth of 984 m in the eastern Arabian Sea along the western margin of India (Paropkari et al. 1993) suggests almost two fold C_{org} burial as compared to the western BoB. The highest carbon burial was in the Gulf of Mannar where the mean C_{org} and C_{org}/N at a mean water depth of 1059 m were 4.2% and 9.47, respectively (Singh et al. 2022).

Absolute abundance of planktic foraminifera

We observed the highest planktic foraminiferal abundance reported so far from the entire western Bay of Bengal (wBoB). In wBoB, the highest abundance, previously reported by Bhadra and Saraswat (2021), was 5086 specimens/g dry sediment. But in swBoB, the highest planktic foraminiferal abundance was an order of magnitude higher (12,000 specimens/g dry sediment) than so far reported from the wBoB (Fig. 4). The swBoB is a unique basin and is influenced by seasonally reversing monsoon circulation (Shankar et al. 2002; Schott and McCreary 2001). During the southwest monsoon, summer monsoon current transports 10 Sv of high salinity (0.9 psu higher) water from

the seAS into the BoB (Vinayachandran et al. 1999). At the same time, the influx of carbonate-enriched water from the Gulf of Mannar to the Palk Bay is $\sim 16.301 \text{ m}^3/\text{s}$ (Jagadeesan et al. 2013). This high salinity carbonate-enriched water further moves into the swBoB (Fig. 1F) and facilitates the abundance of planktic foraminifera in the southern part of the Cauvery Basin. The temperature, salinity, food availability (Lombard et al. 2011; Fraile et al. 2008; Zaric et al. 2005; Watkins et al. 1996), and dissolution (Wang et al. 2021; de Villiers 2005; Schiebel 2002; Peterson and Prell 1985) are the key parameters affecting planktic foraminiferal abundance. The warmer, saline, and carbonate-saturated waters sustain abundant presence of planktic foraminifera in the swBoB. Additionally, planktic foraminifera have been reported to secrete thicker and heavier shells at high salinity (Zarkogiannis et al. 2022). As the thicker and heavier shells sink faster, the exposure time to dissolution is less. Ultimately, the flux of calcareous shells increases.

The absolute abundance of planktic foraminifera increased with increasing water depth up to the upper slope. The highest planktic foraminiferal abundance was observed on the upper slope, but it decreased below 1000 m water depth (Fig. 4). The decrease in planktic foraminiferal abundance at deeper stations suggests the dissolution below the foraminiferal lysocline (Bhadra and Saraswat 2021). As we move from south to north, the foraminiferal lysocline shoals from 2600 to 2000 m in the BoB (Cullen and Prell 1984). The absolute abundance of planktic foraminifera also shows a similar shallowing trend of foraminiferal lysocline from south to north in the swBoB (Fig. 4).

The planktic foraminiferal population was low throughout the continental shelf as compared to the slope. Additionally, the abundance of planktic foraminifera was very low on the inner shelf (Fig. 4). The low planktic foraminiferal abundance on the shallow shelf is attributed to several factors. The planktic foraminifera require sufficient water column depth to thrive. A large number of planktic species migrate to deeper depths for reproduction (Schiebel and Hemleben 2017). The lack of sufficient water column depth on the shelf restricts the migration of several species and results in low planktic foraminifera abundance. The terrigenous flux is also high on the continental shelf. The low salinity and high turbidity due to terrigenous influx is detrimental to planktic foraminifera (Kucera 2007). Additionally, the dilution due to terrigenous influx also lowers the planktic foraminiferal abundance on the shelf (Bhadra and Saraswat 2021; Cullen and Prell 1984).

The low C_{org} content and high C_{org}/N ratio in surface sediments suggest low productivity along the southernmost transect. The high C_{org}/N ratio in front of the Cauvery River mouth (Fig. 3) suggests high terrestrial organic matter input. Therefore, the high abundance of planktic foraminifera in the southern part was attributed to the influx of seAS's high salinity and carbonate-saturated

water (Trask 1936). The high terrestrial input means a high energy condition that results in the deposition of coarse-grained sediments (Bejugam and Nayak 2017). The coarse-grained sediments and the influence of oxygenated water led to the poor preservation of organic matter (Suokhrie et al. 2022; Saalim et al. 2021; Bejugam and Nayak 2017; Calvert et al. 1995; Calvert and Pedersen 1992). Despite the riverine influx, salinity was high in this region because the high salinity seAS water mixes with less saline BoB water and thus maintains the high salinity in the southern part during the summer monsoon (Fig. 1B and F). However, the C_{org}/N was low in front of the Pennar River mouth and increased with depth (Fig. 3). This trend in C_{org}/N is because most of the riverine influx is from the northern side.

Planktic foraminifera contribution to the carbon burial

The high $CaCO_3$ content and relatively low absolute abundance of planktic foraminifera (TPN/g sediment) on the shelf (< 150 m) suggests that the planktic foraminifera are not a major contributor of $CaCO_3$ to the surface sediments on the continental shelf of swBoB (Fig. 3 and 4). The very weak positive correlation ($R^2 = 0.0205$; $p > 0.1$) between CF and TPN/g sediment (Fig. 12c) also confirms that the large part of CF on shallow shelf was contributed either by sand fraction or other meio and macro fauna. However, planktic foraminifera mainly contributed to the $CaCO_3$ content in the surface sediment at depths > 200 m (Fig. 12f), all throughout the swBoB, as evident by the strong positive correlation ($R^2 = 0.7162$; $p < 0.01$). The strong positive correlation ($R^2 = 0.7065$; $p < 0.01$) between CF and TPN/g sediment (Fig. 12d) also confirms that the large part of CF is planktic foraminifera shells. Along the southernmost transect, the high TC, $CaCO_3$, TPN/g sediment, and low C_{org} (Fig. 3, 4) as well as the strong positive correlation between $CaCO_3$ and TPN/g sediment (Fig. 12f), suggests that the substantial part of TC is of planktic foraminiferal origin in this region.

The average absolute abundance of planktic foraminifera was 257 specimens/g sediment in the north-west and west-central BoB (Bhadra and Saraswat 2021). However, the average absolute abundance was around four times higher (920 specimen/g sediment) in the swBoB. Similarly, the $CaCO_3$ content was also high in the swBoB relative to other parts of western BoB. The absolute abundance of planktic foraminifera also was relatively higher off Mahanadi River (Bhadra and Saraswat 2021) where the TIC ($CaCO_3$) percentage was also high (Saraswat et al. 2017). Therefore, planktic foraminiferal shells constituted a large fraction of the $CaCO_3$ on the slope and deeper regions of the wBoB.

Ecological preferences of the dominant planktic foraminiferal species

Globigerinita glutinata was the most abundant within the swBoB region, with an average relative abundance of 23.55% (Fig. 6 and 7). This species dominated the planktic foraminiferal assemblages, indicating its ecological success and adaptability within the local marine environment. Earlier, the dominant presence of *G. glutinata* was also reported from the wBoB (Bhadra and Saraswat 2021). Interestingly, *G. glutinata* was not the most abundant species in the sediment traps deployed in the Bay of Bengal (Maeda et al. 2022; Gupta et al. 1997). The difference was because the sediment trap studies used > 150 μm fraction to pick planktic foraminifera, but we have used a relatively finer fraction (> 125 μm). Therefore, the size variation of the CF used for picking may create a difference in its relative abundance. The maximum abundance of *G. glutinata* is commonly reported in subtropical to temperate waters (Schmuker and Schiebel 2002; Schiebel and Hemleben 2000). But in nutrient-rich conditions, it is more prominent in tropical waters as well (Mazumder et al. 2009; Schiebel et al. 2001). *Globigerinita glutinata* is a cosmopolitan species with a wide geographical distribution and can tolerate a large range of temperature and salinity (Mazumder et al. 2009; Hemleben et al. 1989). In the swBoB, *G. glutinata* displayed only a subtle positive correlation with R^2 of 0.2210 ($p > 0.05$) for mixed layer temperature and 0.1638 ($p > 0.1$) for mixed layer salinity, not suggesting its strong preference for warmer and saline waters (Fig. 10, Table 2). The higher relative abundance of *G. glutinata* was observed in the southern part as compared to the northern part of swBoB (Fig. 7), which might suggest the influence of high salinity and nutrient rich water influx from the seAS and Palk Bay. However, in wBoB, the relative abundance of *G. glutinata* was negatively correlated with mixed layer temperature and suggested to prefer relatively cooler water (Bhadra and Saraswat 2021). In the northeast Atlantic, food and nutrient availability control the relative abundance of *G. glutinata* (Schiebel et al. 2017, 2001; Chapman 2010; Schiebel and Hemleben 2000). In the Gulf of Aden, *G. glutinata* was associated with the entrainment of nutrients into the surface waters during the winter monsoon (Ivanova et al. 2003). However, in the Caribbean Sea, *G. glutinata* was associated with eddy-induced productivity (Schmuker and Schiebel 2002). In the swBoB also, productivity is controlled by the entrainment of eddy-driven nutrients into the surface water during the winter monsoon (Jayalakshmi et al. 2015). Therefore, we conclude that the presence of eddies controls the distribution of *G. glutinata*, rather than any specific change in temperature and salinity in the swBoB.

Globigerina bulloides was the second most abundant species in the swBoB (Fig. 7). *Globigerina bulloides* is

considered a non-symbiotic species usually found within the upper 60 m of the water column and prominently associated with temperate to sub-polar water masses, as well as upwelling settings in the low latitudes (Schiebel and Hemleben 2017; Peterson et al. 1991). *Globigerina bulloides* prefers cold and nutrient rich water (Reynolds and Thunell 1985; Thompson 1981). The relative abundance of *G. bulloides* was high on the shelf and upper slope (Fig. 7) where the concentration of chlorophyll-a was also high (Fig. 1E). A positive correlation with chlorophyll-a and a negative correlation with mixed layer temperature in the CCA plot as well as a significant negative correlation coefficient with mixed layer temperature ($R^2 = -0.5064$; $p < 0.01$) further confirms its preference for relatively cooler and nutrient rich waters (Table 2). During the southwest monsoon, coastal upwelling brings the deeper cold and nutrient-rich water to the surface and results in increased phytoplankton production on the shelf. Although, the upwelling in the swBoB is not as strong as in the northwestern and central western Bay of Bengal, prominent upwelling is reported until the Chennai coast (Shetye et al. 1991). Therefore, the high relative abundance of *G. bulloides* in the northern part of the swBoB along the Chennai coast was ascribed to upwelling during the summer season.

The high relative abundance of *G. ruber* was observed in the southern part of swBoB (Fig. 7) where the temperature and salinity both were high. *Globigerinoides ruber* is a symbiont-bearing species that resides within the mixed layer, most frequently found in the tropical to subtropical waters of the global ocean (Bijma et al. 1990a; Hemleben et al. 1989; Bé, 1977). *Globigerinoides ruber* and *G. bulloides* show an opposite trend which means *G. ruber* prefers high salinity and warm water, but *G. bulloides* prefers relatively cooler water. Both the CCA plot (Fig. 10) and Pearson correlation values (Table 2) also confirm that *G. ruber* prefers high salinity and warm water as compared to *G. bulloides*. A similar ecological preference of these species was also reported from the wBoB (Bhadra and Saraswat 2021). *Globigerinoides ruber* does not show any significant correlation with chlorophyll-a (Table 2), implying that the food availability is not a major controlling factor for *G. ruber*. It has been reported that *G. ruber* prefers oligotrophic conditions (Ravelo and Andreasen 1999; Ravelo et al. 1990). The relative abundance of *G. ruber* was high only on the continental shelf. According to Berger (1968), *G. ruber* is a dissolution susceptible species. The low abundance of *G. ruber* at deeper depths suggests higher dissolution in the northern part as compared to the southern part of swBoB. The high relative abundance of *G. ruber* at deeper depth along the southernmost transect (Fig. 7) suggests better preservation of planktic foraminifera in the southern part of swBoB.

The relative abundance of *N. dutertrei* was negatively correlated with thermocline temperature and positively

correlated with thermocline salinity suggesting its cold-water preference (Fig. 10, Table 2). *Neogloboquadrina dutertrei* is frequently found in the tropical to subtropical waters (Schiebel and Hemleben 2000; Bé, 1977). It was previously reported as a thermocline dweller species (Bilups and Spero 1996; Thunell and Reynolds 1984; Fairbanks et al. 1982). But, as the thermocline salinity decreased towards the north in the swBoB (Fig. 1D), the relative abundance of *N. dutertrei* increased (Fig. 7). A similar high relative abundance of *N. dutertrei* was also reported in the low salinity waters of the northern and western BoB (Bhadra and Saraswat 2021; Cullen and Prell 1984; Cullen and Duplessy 1979). Therefore, *N. dutertrei* can be used as a proxy for paleosalinity reconstruction in the BoB. As the relative abundance of *N. dutertrei* increased with increasing water depth, the high percentage of *N. dutertrei* at deeper depths is ascribed to its dissolution resistant nature (Bhadra and Saraswat 2022).

Trilobatus sacculifer was negatively correlated with chlorophyll-a suggesting its preference for oligotrophic waters (Fig. 10). Previously, several authors have reported its preference for oligotrophic surface waters, like *G. ruber* (Schiebel et al. 2004; Conan and Brummer 2000; Naidu and Malmgren 1996a). *Trilobatus sacculifer* is a symbiont-bearing mixed layer species and reproduces at ~80 m water depth, during the full moon, probably within the chlorophyll maxima (Bijma and Hemleben 1994; Bijma et al. 1990a; Hemleben et al. 1989). It was considered a euryhaline species and can tolerate the salinity range from 24 to 47 psu, and temperatures from 14 to 32 °C (Bijma et al. 1990b). Recently, *T. sacculifer* was assigned to two separate species, namely, *Trilobatus trilobus* (without sac) and *T. sacculifer* (with sac). Interestingly, *Trilobatus trilobus* and *T. sacculifer* show an opposite trend. The relative abundance of *T. trilobus* was more in the shallow regions, except a few stations, as compared to *T. sacculifer* and negatively correlated with temperature and salinity of the mixed layer. The relative abundance of *T. sacculifer* was also negatively correlated with temperature and salinity of the mixed layer but positively correlated with thermocline salinity (Fig. 10). The positive correlation ($R^2 = 0.3490$; $p < 0.01$) with thermocline salinity and negative correlation ($R^2 = -0.3735$; $p < 0.01$) with thermocline temperature suggests that *T. sacculifer* is a deep-cold water preferring species that migrates to deeper and cold water during reproduction. The high abundance at deeper depth also indicates that *T. sacculifer* is less prone to dissolution as compared to *T. trilobus*.

Factors affecting moderately abundant species

Neogloboquadrina incompta was more abundant in the swBoB as compared to wBoB (Fig. 8). The highest relative abundance of *N. incompta* in the wBoB was only 1.38%

(Bhadra and Saraswat 2021). However, in the swBoB, its highest relative abundance was 25%. The average abundance of *N. incompta* was also ~3% in the swBoB (Fig. 6). Additionally, *N. incompta* showed a weak positive correlation with annual average chlorophyll-a concentration (Table 2). In the northeastern Atlantic Ocean also, *N. incompta* was abundant during the low productive summer season (Schiebel and Hemleben 2000). It has also been reported that at the time of highest food availability, *N. incompta* is replaced by *G. bulloides* and *T. quinqueloba* (Schiebel et al. 2001). Therefore, *N. incompta* prefers oligotrophic conditions in swBoB as compared to wBoB, during the summer.

The average relative abundance of *G. menardii* in swBoB was 2.79%, but in wBoB, it was 1.15% (Bhadra and Saraswat 2021). It was also reported that as the temperature and salinity increased from north to south in BoB, the relative abundance of *G. menardii* also increased (Bhonsale and Saraswat 2012; Cullen and Prell 1984). However, in swBoB, the relative abundance of *G. menardii* decreased towards the south and was higher at the deeper stations of the northern part of the study area (Fig. 9). In swBoB, both the temperature and salinity of the mixed layer increased towards the south, but the thermocline temperature decreased and salinity increased (Fig. 1). From the CCA, we report a positive correlation of *G. menardii* with thermocline salinity and a negative correlation with thermocline temperature. The thermocline water was less saline and warmer at shallow stations (< 150 m, water depth). The thermocline salinity increased and temperature decreased with depth creating a large gradient. This gradient does not vary significantly from south to north (Fig. 1). Therefore, from both the CCA and correlation analysis, it is evident that *Globorotalia menardii* exhibits a positive correlation with thermocline salinity and a negative correlation with temperature (Fig. 10, Table 2). The high abundance of *G. menardii* at deeper stations also suggests that *G. menardii* is a dissolution resistant species. The decreasing abundance of *G. unguata* with depth was attributed to its dissolution susceptible nature and preference for less saline and warm water of thermocline. A similar dissolution ranking of these species was also reported by Bhadra and Saraswat (2022) from the north-west Bay of Bengal.

Globigerina falconensis was more abundant on the inner shelf and its abundance decreased towards the open ocean. The distribution pattern of *G. falconensis* is similar to that of *G. bulloides*. The relative presence of *G. falconensis* was high near the Cauvery River mouth (Fig. 8) where the upwelling was not as prominent as above the Chennai coast (Shetye et al. 1991). However, the winter monsoon influx is high in the southern part of the swBoB, indicating that *G. falconensis* can be used as a winter monsoon species. In the Arabian Sea also, *G. falconensis* was more abundant during the winter monsoon in the zone of vertical mixing, and *G.*

bulloides was more abundant during the summer season in the regions of strong upwelling (Schulz et al. 2002). Therefore, the change in the occurrence of these two species may be a good proxy to reconstruct the monsoon seasonality. *Globigerina falconensis* showed a very strong positive correlation ($R^2 = 0.7021$; $p < 0.01$) with chlorophyll-a (Fig. 10, Table 2) suggesting food availability as a major factor controlling its abundance.

The relative abundance of *G. siphonifera* increased towards the north as the salinity decreased (Fig. 1, 8). It means that *G. siphonifera* prefers low salinity waters. *Globigerinella siphonifera* was the most abundant species in the tropical to subtropical region (Bé, 1977). Experimentally, it is determined that the temperature and salinity tolerance range for *G. siphonifera* is 10–30 °C and 27–45 psu, respectively (Bijma et al. 1990b). However, *G. siphonifera* abundance was negatively correlated with thermocline temperature and positively with thermocline salinity in the swBoB (Table 2). Bhadra and Saraswat (2021) considered it a dominant species in the wBoB where the freshwater influx was more as compared to the swBoB. Here, *G. siphonifera* was moderately abundant. Therefore, its low abundance in swBoB was attributed to the low freshwater influx. Another moderately abundant species, *Globoturborotalita rubescens*, was more abundant on the shallow inner shelf particularly close to Cauvery River mouth (Fig. 8). The surface distribution of *G. rubescens* was similar to that of *G. falconensis*. Interestingly, the C_{org}/N ratio was also high in the regions having higher abundance of these species (Fig. 3), suggesting their preference for riverine influx derived terrestrial organic matter. The high abundance of *G. rubescens* along the continental margin was also observed by Bhadra and Saraswat (2021) and Bé and Hutson (1977).

The maximum relative abundance of *Globoquadrina conglomera* was ~6% with an average abundance of 1.53%. *Globoquadrina conglomera* was negatively correlated with mixed layer salinity ($R^2 = 0.3176$; $p < 0.05$), as well as thermocline temperature and positively correlated with thermocline salinity (Fig. 10 and Table 2). Its abundance increased from south to north (Fig. 8), like *N. dutertrei*, *G. menardii*, and *G. siphonifera* (Fig. 7) as the thermocline temperature increased and salinity decreased (Fig. 1C and D). Its relative abundance also increased with increasing water depth (Fig. 8). *Globoquadrina conglomera* is absent in the Atlantic Ocean and rare in the oligotrophic regions of the Indian and Pacific Oceans (Schiebel et al. 2004; Bé, 1977; Parker 1962). But in swBoB, *G. conglomera* was moderately abundant. The higher abundance of *G. conglomera* at deeper depth also suggests its dissolution resistant nature like *N. dutertrei*, *G. menardii*, and *G. siphonifera*. The relative abundance of *G. tenellus* was comparatively high on the outer shelf and upper slope, and it was almost absent at lower slope and at further deeper depths. But in the Arabian

Sea, a relatively high number of *G. tenellus* was observed at the lower slope (Naidu 1993). *Globigerinoides tenellus* was positively correlated with the mixed layer salinity as compared to mixed layer temperature, suggesting its high salinity preference. Pearson coefficient also indicates its relatively strong positive correlation with mixed layer salinity and chlorophyll-a (Table 2).

Pulleniatina obliquiloculata was abundant on the shelf and upper slope of the southern part of the study area. It is a cosmopolitan species (Li et al. 1997; Bé, 1977) reproducing at a monthly cycle and undergoing gametogenic (Hemleben et al. 1989). *Pulleniatina obliquiloculata* showed a weak positive correlation with mixed layer salinity and temperature as well as thermocline temperature (Fig. 8). The warm water on the shallow shelf and southern part of the study area facilitates relatively high abundance of *P. obliquiloculata*. Bhadra and Saraswat (2021) also reported that the higher abundance of *P. obliquiloculata* in the wBoB is sustained by the warm water conditions on the inner shelf.

Planktic foraminiferal diversity

The planktic foraminifera were less diverse on the shelf and the diversity increased with depth (Fig. 11). The low diversity on the continental shelf may be because of the shallow water depth and associated small range of seawater temperature but large salinity fluctuations not being favourable for several species. Additionally, many species migrate to deeper depths to reproduce. The shallow depth restricts the migration (Schiebel and Hemleben 2017). The turbulence on the shelf is also high, resulting in low diversity. Beyond the shelf, the diversity was high until 2000 m water depth (Fig. 11). However, planktic foraminifera were more diverse on the shelf in wBoB (Bhadra and Saraswat 2021). It may be because of the shallow lysocline in northwestern BoB, restricting the diversity on the upper slope. The high diversity on the upper slope region in the present study suggests a deeper lysocline in swBoB. The low species diversity at > 2000 m was due to lysoclinical dissolution (Fig. 11). The surface mixed layer dwelling species like *G. ruber*, *G. bulloides*, *G. falconensis*, *G. rubescens*, and *T. trilobus* are more prone to dissolution (Bhadra and Saraswat 2022). As the tests of dissolution prone species dissolve preferentially, the diversity decreases. The obvious question is why are these surface dwelling species more prone to dissolution? The surface dwelling species live in a warm and less dense water of the euphotic zone and form relatively light, porous, and open-structured shells. The dissolution resistant species such as *G. menardii*, *P. obliquiloculata*, and *N. dutertrei* live below the photic zone where the growth rate is also slow and thus they form relatively thicker and dense shells (Berger and Parker 1970). The high diversity at the deepest stations of the three northern transects may be due to the

presence of more thermocline species. The high salinity and carbonate enriched waters of the Gulf of Mannar and Palk Bay (Fig. 1F), coupled with the terrestrial influx, strongly dominate in the southern part of the swBoB. Such waters support a large diversity of planktic foraminiferal species in this part of the Bay of Bengal.

Conclusions

The highest carbon burial was observed in the southernmost part of the western BoB. We did not find large variation in C_{org} burial throughout the western BoB. However, the $CaCO_3$ burial was much higher in the southern part of swBoB where the planktic foraminiferal flux was also very high. Therefore, it is evident that the planktic foraminifera contribute significantly to the total carbon burial in the surface sediments of the swBoB. The very high planktic foraminiferal number in the swBoB suggests the biannual influence of the Palk Bay and Gulf of Mannar waters during the summer monsoon season as well as the higher productivity during winter season. Therefore, we conclude that planktic foraminifera can be effectively used to understand the change in the influence of the southeastern AS water in the swBoB. *Globigerinoides ruber* showed a preference for high salinity and warm waters. We infer that the relative abundance of *G. bulloides* and *G. falconensis* responds to the upwelling during summer and favorable conditions during the winter monsoon, respectively. The chaotic distribution pattern of *G. glutinata* may be the result of cyclonic eddies during the winter season. *Neogloboquadrina dutertrei*, *G. menardii*, *G. siphonifera*, and *G. conglomerata* were negatively correlated with mixed layer temperature and mixed layer salinity, as well as thermocline temperature and positively correlated with thermocline salinity. However, their spatial distribution from south to north suggests a preference for warm and less saline thermocline water. *Globorotalia menardii*, *P. obliquiloculata*, *N. dutertrei*, *G. conglomerata*, *G. glutinata*, and *T. sacculifer* were considered dissolution resistant species due to their high abundance at deeper depths, while the surface dwelling species like *G. ruber*, *G. bulloides*, *G. falconensis*, *G. rubescens*, and *T. trilobus* were more prone to dissolution. The high abundance of *T. sacculifer* at deeper depths suggests that *T. sacculifer* was less prone to dissolution as compared to *T. trilobus*. The positive correlation of *G. falconensis*, *G. incompta*, *G. bulloides*, *H. pelagica*, and *T. quinqueloba* with Chlorophyll-a suggests that the food availability also strongly controlled the planktic foraminiferal abundance. These findings will help to document the factors affecting the chemical composition of planktic foraminifera test and will also help to reconstruct the paleoclimatic and paleoceanographic conditions from the Bay of Bengal.

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Author contribution RS conceptualized and designed the project. Material preparation, data collection, and analysis were performed by MS and RS. The first draft of the manuscript was written by MS, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Ethical approval The manuscript has not been submitted to any journal other than Environmental Science and Pollution Research. We also promise that the submitted work is original and have not used any data or figures from any published articles. Here, we have used our own generated data and figures.

Consent to participate All the authors consent to participate in the research article and do not have any financial or proprietary interests in any material discussed in this article.

Consent for publication I assured that all authors agreed to publish this manuscript in Environmental Science and Pollution Research. The authors also obtained the consent, before submitting the manuscript, from CSIR-National Institute of Oceanography, Goa, where the work has been carried out.

Competing interests The authors declare no competing interests.

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