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ORIGINAL ARTICLE

Copepods of a creek and an inter-tidal beach: perspectives from Sagar Island of Ganges estuary, India

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Abstract

Copepods of an inter-tidal beach (ITB) and a creek of a single estuary are less compared. Copepods of the Chemaguri Creek (CC) and an ITB of Sagar Island, Ganges estuary (GE) were sampled seasonally from February 2021 to October 2022. It was hypothesized that the community structures (i.e., diversity, abundance and dominance) were different between habitats, and the CC hosted higher diversity and abundance of copepods than the ITB. Seasonal variabilities of the salinity (range CC: 7.0 to 20.40; ITB: 9.50 to 22.90) and water temperature (range CC: 21.40 to 32.60 °C; ITB: 19.70 to 31.90 °C) were significant for both the habitats. Total Nitrogen levels (range: 71.86 to 87.26 µmol.L^{-1}) varied significant among seasons only in the ITB. Calanoid copepods of the Paracalanidae and Acartiidae families dominated both the habitats. Species richness and cumulative abundances of the copepods were higher in the CC than ITB possibly because the latter is exposed to wave dashing whereas the CC provides a sheltered environment. Dissimilarity of the copepod community of the CC and ITB was 30.54%, majorly contributed by the Cyclopoids and Harpacticoids. The ITB had more Harpacticoids than the CC which had more Cyclopoids than the previous. *Acartiella tortaniformis* and *Acartia spinicauda* dominated the CC and the ITB, respectively. Small to medium size copepods were more frequent in both the habitats than large copepods. Micro-habitats within a habitat did limit the ecology of the copepods in the Sagar Island, GE; therefore, seasonality and habitat specificity shall be considered if copepods are used for water quality monitoring of a river-estuary.

Keywords Seasonal change · Diversity and distribution · Micro-habitat · Cyclopoid · Harpacticoid. Aquatic ecosystem

Introduction

Estuarine ecological literatures are generally focused to one habitat of an ecosystem at a time and their ecological communities; therefore, comparative studies between contrasting habitats of a single ecosystem are less studied. Diversity and distribution of both phyto- and zoo-plankton are well studied in theestuaries, creeks, inter-tidal beaches (ITBs), nearshore, offshore and open ocean because plankton form the base of the food web and play fundamental roles in energy transfer to the higher trophic levels (Paul et al. 2016; McQuatters-Gollop et al. 2019). Zooplankton (including copepods) diversity and distribution of the estuaries and intertidal waters are often corelated with the variability of salinity, water temperature, pH and nutrients those ecosystems (Bhattacharya et al. 2015; Paul et al. 2017, 2024; Basu et al. 2022; Gogoi et al. 2021). Studies separately conducted on the zooplankton community of the creeks and the ITBs suggested that zooplankton of the coastal waters are more neritic in origin and stenohaline in nature whereas those of the creeks are brackish in origin and often euryhaline in nature (Wooldridge and Bailey 1982; Dexter et al. 2020). The copepods of the ITBs are often influenced by the wave dashing, currents and winds rather than salinity (Baleani et al. 2024) but those inhabit in the creeks suffer less from mechanical forces and more sensitive to variable

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physical-chemical properties of the water masses of the river-estuaries which feed the creeks (Emmanuel and Onyema 2007).

The ecology of copepods within the contrasting habitats (such as creeks and ITBs) of a river-estuary is possibly different but drawing conclusions would be a premature exercise as the literature is scanty (Suthers et al. 2009). In the surf-zone of the Tramandaí–Armazém estuary channel, Brazil zooplankton community was affected by the salinity and current direction related to the river plume and its seasonal variations (Rodrigues et al. 2019). Some river-estuaries such as the Ganges, Amazon, Godavari form islands/sea facing beaches before they meet the sea (Da Costa et al. 2011; Rakhesh et al. 2013; Basu et al. 2022). Those islands are generally crisscrossed by several small to large creeks which get daily inundated by the incoming and outgoing tides of those large river-estuaries which are often meso- to marco-tidal in nature (Da Costa et al. 2011; Basu et al. 2022). In case of the river-estuaries of India which form islands before they meet the sea, it is observed that the Calanoid and Cyclopoid species populations form the majority of the copepod community in the inner channels of an estuary, and the outer section (i.e., the sea facing) hosts more Harpacticoids and Calanoid and less Cyclopoid copepods (Rakhesh et al. 2013; Tiwari and Nair 2002). The Indian Sundarbans region through which the Ganges estuary (GE) runs has islands which are Bay of Bengal facing (Mukhopadhyay et al. 2006). Zooplankton are exposed to the varying physical-chemical properties of the water masses of the creeks and ITBs of the GE (Sarkar et al. 1986; Bhattacharya et al. 2015; Nandy et al. 2018; Gogoi et al. 2021; Basu et al. 2022; Paul et al. 2024). The water quality and the ecology of the copepods of the creeks of Sagar Island of the GE had received attention in the estuarine literature (Sarkar et al. 1986; Basu et al. 2022; Gogoi et al. 2021) as early as 1980s when Professor Amalesh Choudhury along with his students did study the diversity and ecology of the zooplankton (including copepods) in the Chemaguri Creek (CC) of Sagar Island, and found that the seasonal changes in the salinity regimes of the creek limited the diversity of the copepod community structure which otherwise was dominated by the calanoid copepods (Bhunia and Choudhury 1983; Sarkar et al. 1986).

Professor Amalesh Choudhury is among the father figures of the estuarine science in India whose works were instrumental behind securing the UNESCO World Heritage Status for Indian Sundarbans in 1989 (Chakraborty and Nath 2021). The author met Prof. Choudhury on 28 November 2020 (between 4.00 and 6.25 P.M.) at his residence (i.e., Sodepur, West Bengal, India) and exchanged opinions on the recent status of the zooplankton diversity and distribution in the Sagar Island of the GE where Prof. Choudhury did many of his research. That discussion inspired the author to carry out *'Professor Amalesh Choudhury Memorial Field Work'* after the death (30.12.2020) of Prof. Choudhury as a tribute to one of the legendary estuarine biologists of India. The aims of the fields were to understand and compare the ecology of the copepod community of a creek and an ITB of a single river-estuary. Therefore the diversity, dominance, and distribution of the copepod community was studied in the CC and ITB of Sagar Island which is near the mouth of the GE. The hypothesis was that the structure of the copepod community of the CC was different than that of the ITB of Sagar Island and the previous had the higher diversity and abundance of the copepods than the latter.

Methods and materials

Study site

Indian Sundarbans region including the Sagar Island, the GE has a warm and humid climate and the seasons could broadly be classified as Premonsoon (PRM) (originally February to May but off late extended even to June), Monsoon (MON) (i.e. June to September but at times delayed and extend to middle of October) and Postmonsoon (POM) (i.e. originally October to January but recently shifting towards November to February) (Paul et al. 2024). In the Indian Sundarbans air temperature generally ranges 15 °C to 40 °C and the annual average rainfall is about 1600 mm out of which 75% to 80% rainfall occurs in the MON (Mukhopadhyay et al. 2006). Sagar Island is the largest island on the GE located between 21^{o} 37′21” N to 21^{o} 52′28” N and 88^{o} 01′46″ E to 88^{o} 9′25″ E (Mondal et al. 2020). The Sagar Island is about 12 km wide and 30 km in length with an average elevation of 6.5 m above mean sea level (Kumar et al. 2001). The island's northern and the western sides are surrounded by the main flow of the GE in India (Basu et al. 2022). On the eastern side of the Sagar Island there are several creeks which are influenced by the Muriganga estuary (which is a bifurcation of the GE) which has similarity in its physical-chemical characteristics with the mainstream of the GE (Basu et al. 2022; Paul et al. 2024). Southern section of the Sagar Island has an extended beach which faces the Bay of Bengal (Gogoi et al. 2021). The island hosts many sub-estuaries out of them the CC is the major one (Sarkar et al. 1986; Chowdhury et al. 2015; Basu et al. 2022). The banks of the CC are studded with semi-intense mangrove vegetation with salt marsh patches from the mid to low water mark (Saha and Choudhury 1995).

Field sampling

The copepod assemblages (size class > 200 µm) were sampled three times during each season (i.e., PRM, MON and POM) from February 2021 to October 2022. Copepod assemblages and water samples were collected from the three sampling sites of the CC which were about 1 KM apart from each other (i.e., Chemaguri Bazar (CB) (21° 40′ 50.969″ N, 88° 08′ 21.937″), Chemaguri Jetty (CJ) (21° 40′ 40.189″ N, 88° 08′ 54.179″), and Chemaguri Mouth (CM) (21° 41′ 0.009″ N, 88° 09′ 15.339″)) (see Fig. 1). Samples were also collected from the three sites of the ITB at the south of Sagar Island (i.e., Gangasagar (GS) (21° 37′ 58.228″ N, 88° 04′ 28.991″), Dhoblat (DL) (21° 38′ 4.598″ N, 88° 07′ 19.302″) and Light house (LH) (21° 39′ 30.079″ N, 88° 02′ 36.700″)) (see Fig. 1). On all the occasions, copepod assemblages were collected after dark during the high tide of a single tidal cycle from a dinghy boat. On each occasion of the copepod sampling, 100 L surface water (collected 5 times by a bucket of 20 L) was filtered through a 200 µ mesh (derived from the protocol adopted by Prof. Choudhury and his co-authors while they studied copepods of the CC in 1980s (Sarkar et al. 1986) and later modified by Paul et al. (2019, 2024) for studying the copepod community of the Muriganga stretch (adjacent to Sagar Island) of the GE. The filtrate was collected in a sampling bottle (1 L) then the copepod assemblages were preserved in 5 ml of 4% buffered formalin on site. On each sampling occasion, salinity (in practical salinity unit) and water temperature (°C) levels of the sampling sites were measured with a hand-held multi-parameter probe (YSI-1030, U.S.A.) from the surface water. Further, 2 L of surface water of the sampling site was filtered on spot using a GF/F filter paper (pore size 0.47 µm) by a hand pump for analysing nutrients at the laboratory. The filtered water was immediately put inside an ice box and along with the copepod samples brought back to the laboratory within 12 h of the collection of a given sampling occasion.

Laboratory analysis

In the laboratory, multiple aliquot samples (1 ml each aliquot, at least 1% of all the samples were analysed) of the copepod assemblages were taken from the filtrate and each aliquot was placed on a Sedgwick Rafter counting cell and examined under a stereo-microscope for quantitative enumeration (Bestscope-BS30T, China) and some extra samples were collected qualitatively which were intended for

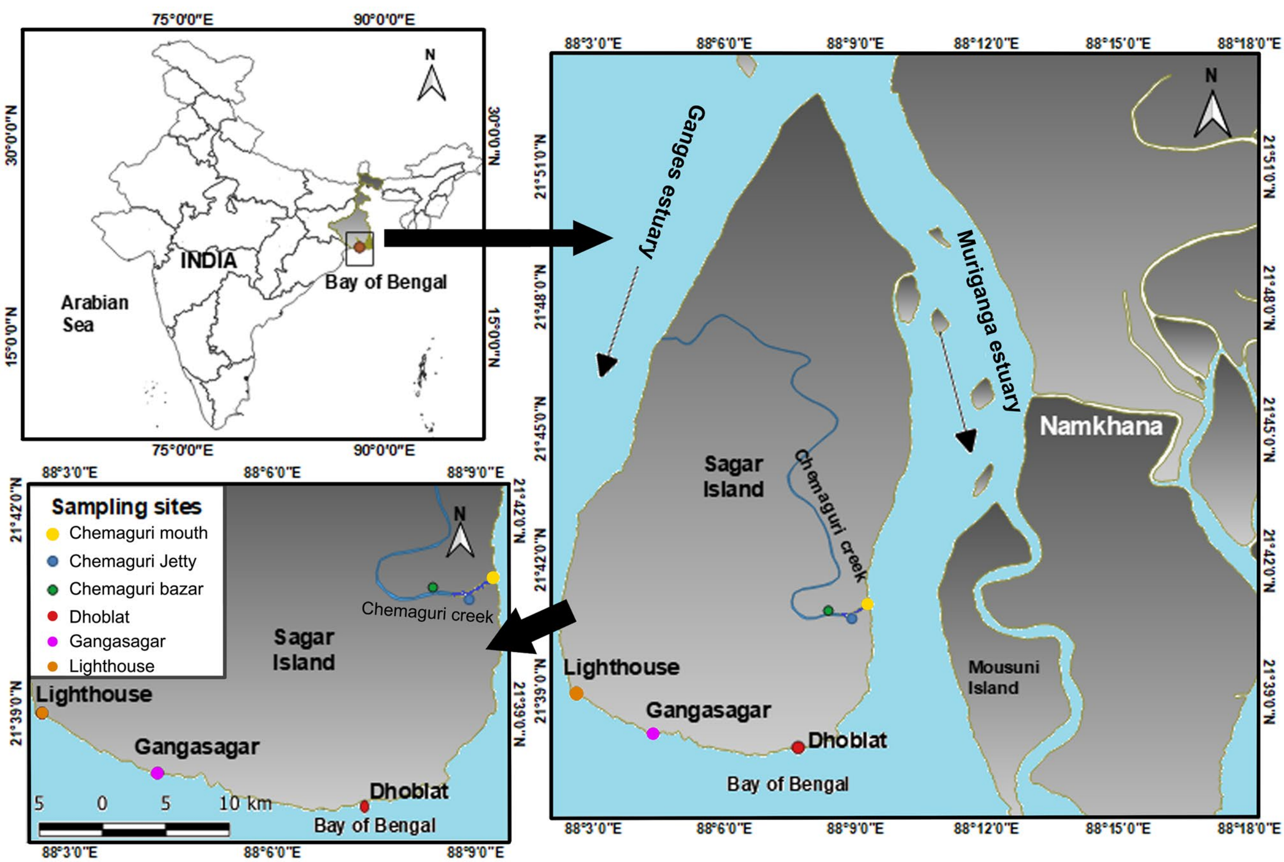

Fig. 1 Study area map and sampling sites on the Chemaguri Creek and the inter-tidal beach of Sagar Island of the Ganges estuary, India

identification purpose only. All the cooped samples were identified under a compound microscope (B1, Motic, Hongkong). Copepods (adults only not sexed) were identified to species level following the taxonomic literature (Kasturirangan 1963) and their abundances were expressed as individuals per cubic metre (ind.m^{-3}).The filtered water was first thawed then used for analysing the concentrations (µmol.L^{-1}) of Total Nitrogen (TN) (i.e., dissolved organic and inorganic fractions) and Total Phosphate (TP) (i.e., dissolved organic and inorganic fractions) following the protocol described by Grasshoff et al. (2009) using a UV-Vis spectrophotometer (Systronics, India, Model: 119).

Data analysis

The dataset was small so all the analysis followed non-parametric path. For comparing the seasonal and spatial variability of salinity, temperature, TN and TP Kruskal-Wallis tests were conducted followed by apost-hoc (Nemenyi) test if required. Further, within a given season environmental data of the CC vs. the ITB were compared following multiple Mann-Whitney U tests. All those tests were conducted by using PMCMRplus package (version: 1.9.12) in CRAN R 4.5.0. Multivariate analysis was conducted separately on the data collected from the CC and the ITB in PRIMER v7 software (Clarke and Gorley 2015). For each set of analysis at first the copepod abundance data was square-root transformed (after transformation ranged for CC: 0 to 10.46; for ITB : 0 to 8.90) for reducing the data dispersion (original scale for CC: 0 to 12000, for ITB: 0 to 6280). Then to explore the temporal and spatial variations of the copepod assemblages Non-metric Multidimensional Scaling (NMDS) were conducted (dimensionality i.e., K = 2) considering the Bray–Curtis measure of dissimilarity and the biplots were drawn. For testing the statistical significance of such variations permutational multivariate analysis of variance (PERMANOVA) were conducted. Similarity percentage analysis (SIMPER) was carried out to evaluate the major component species that contributed to the similarity and dissimilarity within the copepod assemblages among seasons, sampling sites as well as between the CC and the ITB. The hypothesis currently under consideration never intends to corelate the environmental variability of a specific habitat as well as the microhabitats with their respective copepod communities so any such correlation analysis is consciously avoided. Level of statistical significance was set at 95% (i.e., $\alpha = 0.05$). Values of U, K-W chi-square, Pseudo-F, F, Degrees of Freedom (df) and p were reported.

Results

Environmental variability of creek vs. beach

Variabilities of the salinity, water temperature, TN and TP levels of the CC and the ITB are summarized in the Table 1. For the CC, seasonal variability of the salinity was significant (K-W chi-squared = 11.39, df = 2, $p = 0.003$); salinity of the PRM was significantly higher than the MON but salinity of the POM not significantly different from the MON (Table 1). Water temperature varied significantly among the seasons (K-W chi-squared = 19.24, df = 2, $p < 0.001$); the PRM and the POM were less warm than the MON (Table 1). The TN (K-W chi-squared = 0.1, df = 2, $p = 0.61$) and the P (K-W chi-squared = 3.56, df = 2, $p = 0.168$) levels did not vary significantly among seasons (Table 1). For any given season, the spatial variability of salinity, water temperature, the TN and the TP levels of the CC were not significant. Salinity of the ITB significant varied among seasons (K-W chi-squared = 16.32, df = 2, $p = 0.0002$); salinity of PRM was significantly higher than the MON but the POM salinity was not significantly different from the MON salinity (Table 1). Water temperature too varied significantly among seasons (K-W chi-squared = 17.57, df = 2, $p < 0.001$); the POM was less warm than the MON but no such difference was found between the MON and the PRM (Table 1). The

Table 1 Variability (median, standard error and range) of salinity (P.S.U), water temperature (°C), Total Nitrogen (µmol.L^{-1}) and Total Phosphorus (µmol.L^{-1}) measured between February 2021 and October 2022 from the Chemaguri Creek and inter-tidal beach of Sagar Island of the Ganges estuary, India

Season	Chemaguri Creek				Inter-tidal Beach			
	Salinity (*P*.S.U)	Water Temperature (°C)	Total Nitrogen (µmol.L^{-1})	Total Phosphorus (µmol.L^{-1})	Salinity (*P*.S.U)	Water Temperature (°C)	Total Nitrogen (µmol.L^{-1})	Total Phosphorus (µmol.L^{-1})
Premonsoon	18.30 ± 0.62 (15.00–20.40.00.40)	29.00 ± 0.83 (24.20–29.90.20.90)	79.32 ± 0.77 (75.11–82.33.11.33)	2.11 ± 0.04 (1.87–2.32.87.32)	20.40 ± 0.46 (18.40–22.90.40.90)	30.20 ± 0.63 (26.00–31.50.00.50)	82.36 ± 0.74 (80.22–87.26.22.26)	2.14 ± 0.06 (2.11–2.65.11.65)
Monsoon	10.50 ± 1.47 (7.70–17.50.70.50)	31.40 ± 0.18 (31.20 −32.60)	77.23 ± 1.13 (72.87–83.28.87.28)	1.82 ± 0.13 (1.06–2.62.06.62)	12.60 ± 1.20 (9.50–19.20.50.20)	31.00 ± 0.26 (29.40–31.90.40.90)	78.66 ± 1.16 (71.86–82.32.86.32)	2.03 ± 0.18 (1.09–2.76.09.76)
Postmonsoon	11.90 ± 0.88 (9.60–16.70.60.70)	25.10 ± 0.61 (21.40–25.20.40.20)	80.25 ± 1.05 (75.45–84.23.45.23)	2.14 ± 0.12 (1.24–2.45.24.45)	15.10 ± 0.73 11.70–18.90.70.90	25.90 ± 1.01 (19.70–26.70.70.70)	83.15 ± 0.54 (80.36–85.65.36.65)	2.31 ± 0.06 (1.99–2.65.99.65)

TN varied significantly (K-W chi-squared = 12.55, df = 2, $p < 0.001$) among seasons. Compared to the TN level of the MON the TN of the PRM and the POM were significantly higher (Table 1). The TP level (K-W chi-squared = 4.54, df = 2, $p = 0.1$) did not vary significantly among seasons. For any given season, spatial variability of the salinity, water temperature, TN and TP levels were not significant different in the ITB. During the PRM salinity (W = 9.5, $p = 0.007$) and TN (W = 8.5, $p = 0.005$) levels of the ITB were significantly higher than those levels of the CC. During the MON, the water temperature level of the CC was significantly (W = 67.5, $p = 0.02$) higher than the ITB. In the POM, the TN levels of the ITB were significantly (W = 14, $p = 0.018$) higher than the CC. Seasonal variability of all other environmental parameters studied was not significant between the CC and the ITB.

Copepods of a creek

Calanoid copepods and its Paracalanidae and Acartiidae families dominated the CC followed by Cyclopoids, and the Harpacticoids were few only (Table 2). Irrespective of the seasons *Acartiella tortaniformis* was the most abundant copepod species in the CC (Table 2). Species such as *Oithona brevicornis*, *Bestiolina similis*, *Paracalanus parvus*, *Acartia spinicauda*, *Pseudodiaptamus serricaudatus* were highly abundant (Table 2). Among the least abundant species *Acrocalanus monachus* and *Euterpina acutifrons* were notable (Table 2). The copepod abundance was the highest in the POM (cumulative abundance: 769620 ind.m^{-3}) followed by the MON (717869 ind.m^{-3}) and the PRM (cumulative abundance: 303685 ind.m^{-3}). Seasonal variations (Fig. 2A) of the copepod assemblages were not statistically significant (PERMANOVA: DF = 2, Sum of Square = 1.83, Pseudo-F = 1.18, $P = 0.386$). The SIMPER analysis showed that the average similarity within the copepod communities

Table 2 Relative abundances (%) of the copepods sampled between February 2021 and October 2022 from the Chemaguri Creek (CC) and the inter-tidal beach (ITB) of Sagar Island of the Ganges estuary, India

Order	Family	Species	Premonsoon		Monsoon		Postmonsoon	
Calanoida	Paracalanidae		CC	ITB	CC	ITB	CC	ITB
		Paracalanus parvus	9.31	6.95	8.00	5.98	7.96	6.53
		Paracalanus aculeatus	4.31	3.02	4.50	3.38	4.44	3.34
		Paracalanus indicus	2.10	3.68	2.96	3.99	3.00	3.77
		Acrocalanus gracilis	2.58	2.23	2.41	2.36	2.47	2.37
		Acrocalanus longicornis	2.16	0.63	3.07	0.79	3.01	0.71
		Acroclanus monachus	0.16	0.00	0.00	0.00	0.00	0.00
		Bestiolina similis	10.12	8.31	7.93	9.65	8.02	8.77
		Paracalanus dubia	0.96	0.00	1.52	0.00	1.57	0.00
		Parvocalanus crassirostris	2.35	2.23	1.58	2.58	1.69	2.37
	Acartiidae	*Acartia spinicauda*	5.97	9.13	6.02	9.20	6.00	9.46
		Acartia tonsa	2.68	1.42	2.52	1.81	2.48	1.68
		Acatia tropica	1.93	0.00	1.14	0.00	0.98	0.00
		Acartiella tortaniformis	10.33	8.37	8.95	7.50	9.12	8.21
		Acatia swewlli	2.21	0.00	2.06	0.00	2.02	0.00
	Pseudodiaptomidae	*Pseudodiaptamus serricaudatus*	5.09	6.79	5.48	6.13	5.48	6.27
		Pseudodiaptamus binghami	2.07	2.45	2.41	1.65	2.47	2.07
	Calanidae	*Canthocalanus pauper*	3.70	6.70	4.54	6.07	4.50	7.11
	Eucalanidae	*Subeucalanus subcrassus*	2.58	6.26	2.48	6.05	2.41	6.38
		Subeucalanus crassus	1.13	0.00	1.04	0.00	0.98	0.00
		Eucalanus elongatus	1.02	0.00	1.63	0.00	1.57	0.00
	Pontellidae	*Labidocera euchaeta*	2.04	6.26	2.09	6.05	1.96	5.25
		Labidocera acuta	0.59	0.82	0.50	0.55	0.46	0.69
	Temoridae	*Temora turbinata*	3.29	2.07	4.50	2.13	4.44	2.11
	Euchaetidae	*Euchaeta marina*	2.71	0.00	3.41	0.00	3.59	0.00
Cyclopoida	Oithonidae	*Oithona similis*	2.83	2.23	2.52	4.29	2.48	2.37
		Oithona brevicornis	8.41	2.45	8.64	1.65	9.01	2.07
		Oithona nana	3.36	0.82	4.00	0.92	3.98	0.69
	Oncaeidae	*Oncea venusta*	0.67	0.00	0.00	0.00	0.00	0.00
	Corycaeidae	*Corycaeus crassiusculus*	3.16	2.23	4.07	2.36	3.92	2.37
Harpacticoida	Tachidiidae	*Euterpina acutifrons*	0.16	7.68	0.00	8.11	0.00	8.11
	Ectinosomatidae	*Microstella rosea*	0.00	7.24	0.00	6.82	0.00	6.82

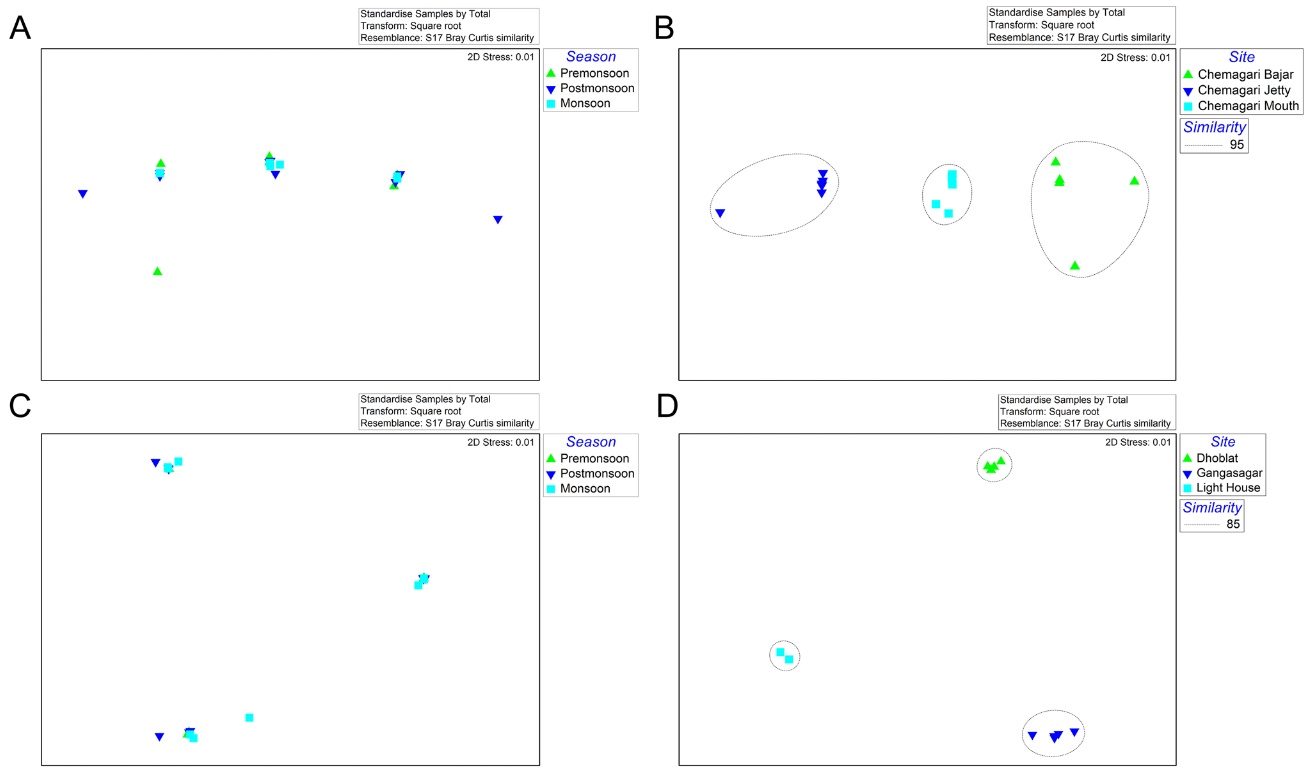

Fig. 2 Variability of the copepod assemblages sampled from the Chemaguri Creek (**A** and **B**) and the inter-tidal beach (C and D) of Sagar Island of the Ganges estuary, India

of the PRM, MON and POM were 81.07%, 99.83% and 98.74%, respectively. In all the seasons species such as *A. tortaniformis*, *B. similis*, *P. parvus and O. brevicornis* and *A. spinicauda* contributed chiefly behind such similarities. The average dissimilarity within the copepod communities of the PRM and the POM was 10.12%, between the PRM and the MON was 9.63%, and in both cases species such as *Temora turbinata*, *P. indicus* and *Acrocalanus longicornis* contributed chiefly to such dissimilarities. The dissimilarity between the POM and the MON was 0.67% chiefly contributed by species such as *O. brevicornis*, *Euchaeta marina* and *Parvocalanus crassirostris*.

Among sampling sites, in the PRM the species richness varied from 17 to 26. During the MON and the POM seasons species richness varied from 22 to 26. Spatially the cumulative abundance of the copepods was the highest at the CM (cumulative abundance: 764650 ind.m^{-3}) followed by the CB (cumulative abundance: 618590 ind.m^{-3}) and the CJ (cumulative abundance: 407434 ind.m^{-3}). Site-specific variations (Fig. 2B) of the copepod assemblages were statistically significant (PERMANOVA: DF = 2, Sum of Square = 1538.4, Pseudo-F = 991.77, P = 0.001). The SIMPER analysis showed that the average similarity within the copepod communities of the CB, CJ and CM were 93.34%, 92.82% and 93.48%, respectively. Such similarities were chiefly constituted by the *A. tortaniformis*, *B. similis*, *P. parvus and O. brevicornis* and *A. spinicauda* contributed. The average dissimilarity within the copepod communities of the CB and the CJ was 17.73% contributed chiefly by *Labidocera euchaeta*, *Parvocalanus dubia*, *Subeucalanus crassus*, *A. tropica*. Dissimilarity between the CB and CM was 15.23% and that was contributed chiefly by *Eucalanus elongatus*, *P. dubia*, *Euchaeta marina*, *Labidocera acuta*. The dissimilarity between the CJ and the CM was 16.12% contributed chiefly by *E. elongatus*, *L. euchaeta*, *S. crassus*, *A. tropica*, respectively.

Copepods of an inter-tidal beach

Calanoid (16 species) copepods dominated the habitat followed by 4 species of Cyclopoida and 3 species of Harpacticoida (Table 2). *Acartia spinicauda* was the most abundant species throughout all the seasons followed by notable others *B. similis*, *E. acutifrons*, *A. tortaniformis*, *Microsetella rosea*, *Canthocalanus pauper*, *L. acuta* and *A. longicornis* (Table 2). Species such as *M. rosea* were only found in the ITB. Copepods were more abundant during the MON (cumulative abundance: 440250 ind.m^{-3}) followed by their abundances in the POM (329130 ind.m^{-3}) and the PRM (cumulative abundance: 119169 ind.m^{-3}). Seasonal variability (Fig. 2C) of the copepod the assemblage was not significant (PERMANOVA: DF = 2, Sum of Square = 47.96, Pseudo-F = 3.225, *P* = 0.077). The SIMPER analysis showed that the average similarity within the copepod communities of the PRM, MON and POM were 99.99%, 95.50% and 98.03%, respectively. In all the seasons species such as *A. tortaniformis*, *B. similis*, *A. spinicauda* and *E. acutiforns* contributed chiefly behind such similarities. The average dissimilarity within the copepod communities of the PRM and POM was 0.99% (chiefly contributed by *L. euchaeta*, *A. spinicauda*, *B. similis* and *E. acutifrons*), between the PRM and MON that was 2.77% (chiefly contributed by *P. serricaudatus*, *O. similis*, *C. pauper* and *B. similis*). The dissimilarity between the POM and MON communities was 3.68% chiefly contributed by species such as *L. euchaeta*, *P. serricaudatus*, *O. similis* and *C. pauper*.

The cumulative abundance of the copepods was the highest at the LH (cumulative abundance: 327963 ind. m^{-3}) followed by the GS (cumulative abundance: 291184 ind.m^{-3}) and the DL (cumulative abundance: 197866 ind. m^{-3}). Among the sampling sites, the species richness varied between 16 and 21 in the PRM, 15 to 21 in the MON and 16 to 21 in the POM. Site-specific variations (Fig. 2D) of the copepod assemblages were statistically significant (PERMANOVA: DF = 2, Sum of Square = 4841, Pseudo-F = 325.49, *P* = 0.001). The SIMPER analysis showed that the average similarity within the copepod communities of the DL, GS and LH were 97.41% (chiefly contributed by *B. similis*, *A. spinicauda*, *A. tortaniformis* and *P. serricaudatus*), 95.24% (chiefly contributed by *B. similis*, *A. spinicauda*, *E. acutifrons* and *Microstella rosea*) and 99.02% (chiefly contributed by *P. parvus*, *A. tortaniformis*, *P. serricaudatus* and *A. spinicauda*), respectively. The average dissimilarity within the copepod communities of the DL and the GS was 23.16% contributed chiefly by *M. rosea*, *P. serricaudatus*, *T. turbinata* and *A. longicornis*, between the DL and the LH was 25.95% contributed chiefly by *M. rosea*, *P. binghami*, *O. brevicornis* and *A. longicornis*, and between the GS and the LH was 26.50% contributed chiefly by *P. serricaudatus*, *P. binghami*, *O. brevicornis* and *A. tonsa*, respectively.

Copepods of the CC vs. ITB

Table 2 showed that the maximum species richness of the CC was 30 which was 25 for the ITB. Species such as *P. dubia*, *A. tropica*, *A. monachus*, *S. crassus*, *E. elongatus*, *Oncea venusta* were not found among the samples collected from the ITB in any season but they were present in the CC. Relative abundance of the Harpacticoids in the ITB was higher than those of the CC (Table 2) and the latter had relatively higher abundance of the Cyclopoid copepods than the previous (Table 2). The SIMPER analysis showed the copepod assemblages of the CC are 86.03% similar chiefly contributed by species such as *A. tortaniformis* (7.05%), *P. parvus* (7.03%), *B . similis* (6.98%), *O. brevicornis* (6.88%) and *A. spinicauda* (6%). For the ITB that similarity was 80.21% chiefly contributed by *A. spinicauda* (8.93%), *B. similis* (8.56%), *A. tortaniformis* (7.95%), *E. acutifrons* (7.8%) and *C. pauper* (7.24%). The dissimilarity of the copepod assemblages of the CC and the ITB was 32.54%, chiefly contributed by species such as *E. acutifrons* (9.69%), *O. brevicornis* (7.72%), *M. rosea* (7.2%), *E. marina* (5.9%) *and O. nana* (5.12%).

Discussion

Habitat variability

Environmental data of the Sagar Island showed seasonal variability is pronounced for both the CC and the ITB; however, the spatial variability within a given habitat was not-significant. Every year Sagar Island experiences heavy rainfall during the MON months and significant seasonal variations of air and water temperatures (Mukhopadhyay et al. 2006; Chowdhury et al. 2015). Further, Sagar Island receives a mixed semidiurnal tidal regime with high tide zone ranges from 5 to 6 m (Paul and Bandyopadhyay 1987). Absence of significant seasonal variations in the TN and TP levels of the CC contradict Mukhopadhyay et al. (2006) and Choudhury et al. (2015) who found seasonality of those parameters mostly driven by the monsoon rains. The water masses of the ITB are highly influenced by the regular incoming tides of the adjacent the Bay of Bengal and the outgoing tides of the GE which receives huge volumes of freshwater from the upstream so the salinity of the intertidal-beach oscillates between mesohaline and polyhaline regimes (Mukhopadhyay et al. 2006; Chowdhury et al. 2015). Salinity and water-temperature of the ITB as well as the creek of Sagar Island followed a typical tropical pattern observed along the West Bengal coast by previous authors (Das 2010; Paul et al. 2024). The TN levels of the ITB was higher in the MON than the other seasons possibly related to the nutrient runoffs during late-monsoon (Mukhopadhyay et al. 2006; Choudhury et al. 2015). Seasonal variability of the TP of the ITB was significant but that too was in limited form. Seasonal variations of salinity, water temperature and the TN were significant when water masses of the CC and the ITB were compared. The ITB receives more salt, shallow in nature and gets direct sun exposure and nutrients from its surroundings whereas the CC is 8 to 10 m deep and has mangrove vegetation along the banks (Saha and Choudhury 1995).

Copepods of creeks vs. beach

Calanoids are the majority within the copepod community in the creeks of Sagar Island of the GE and they are mostly limited by the seasonal changes; Present results support the findings of the previous authors (Sarkar et al. 1986; Basu et al. 2022). Sarkar et al. (1986) conducted on the CC between March 1979 and February 1981, where the authors suggested the maximum density of the copepods (73 to 96.4% of the overall zooplankton density) was during the warm PRM and the lowest in the late MON. Their findings contradict the present results. The current study found cumulative abundance of the copepods peaked in the POM and dipped to the lowest in the PRM. Sarkar et al. (1986) observed 32 genera and 54 species among them Calanoids: 17 genera and 37 species, Cyclopoids: 7 genera and 9 species, and Harpacticoid: 8 genera each having single species. Basu et al. (2022) in their survey on the creeks of the Sagar Island found a total of 63 zooplankton taxa mostly represented by the copepods. Further the copepods constitute 59.55 to 73.13% of the total zooplankton density and among the zooplankton Calanoida contributed 46%, Cyclopoida (15%) and Harpacticoida (6%). The present results found lesser species richness of the copepods compared to the previous studies, a reason could be the copepod community had gone through the decadal changes as suggested by the Bhattacharya et al. (2015) who compared the species composition of the copepods of the Indian Sundarbans including those of the GE. Results showed site-specificity of the copepod assemblages despite there was no such variability in the environmental gradients of the CC. Sarkar et al. (1986) observed that in the CC there were three distinct categories of copepods such as eurihaline copepods which inhabits the creeks throughout the year which inhabits towards the CB, stenohaline copepods which migrate occasionally into the island and influence the copepod community of the CM, and some freshwater forms that inhabit the creeks for a limited period (e.g., during monsoon). *Acartiella tortaniformis* dominated the copepod community of the CC. That species is generally found in high numbers in the mangrove estuaries of the Indian Sundarbans (Bhattacharya et al. 2015; Nandy et al. 2018; Chakraborty et al. 2022). The semi-intense mangrove vegetation of the CC may be acting as one of its most suitable habitats. Stephen et al. (2013) studied the Bhayander creek (an annual average salinity of 24.9) and Thane creek (annual average 29.3) of Mumbai, India and suggested *Acartia southwelli*, *A. tropica* and *O. brevicornis* were highly abundant in the Bhayander creek and in the Thane creek *O. similis*, *Acartia kerolensis*, *Mesochra* sp. and *O. brevicornis* were abundant along with the presence of *B. similis*. Species such as *O. brevicornis* was highly abundant in the CC irrespective of the season and salinity regimes of the creek. The copepod community which belongs to the mesozooplankton stock of the Godavari estuarine-coastal waters had small copepods represented by the Paracalanidae, Acartiidae, Oithonidae, Corycaeidae, Oncaeidae, and Euterpinidae families which made up about 92% of the total copepod community of the estuary and 87% of the community in the neritic waters (Rakhesh et al. 2013). Further the abundance of the small copepods was almost 12 times than that of the large-sized copepods in the estuary and up to 7 times in the coastal waters (Rakhesh et al. 2013). Those results are similar to the findings of the present study as the copepod community of the CC was made mostly of the small- to medium-size copepods of the Paracalanidae, Acartiidae, Oithonidae families of the GE (Paul et al. 2019). In the Gopalpur Creek (annual average salinity > 28) of Odisha, India 45 species of zooplankton were observed dominated by the copepods (almost 80% of the biomass of the community) but their biomass did not vary significantly among seasons (Sahu et al. 2013); similar results were obtained in the present study. In a south-western tropical creek of Nigeria zooplankton community was dominated by calanoid copepods of *Acartia clausii*, *A. discaudata*, *P. parvus*, *Cyclopina* spp. were highly abundant among the Cyclopoid copepods and *E. acutifrons* was the most abundant Harpacticoid copepod, further Cyclopoids dominated the fresh/low brackish waters of the creek and the calanoids dominated the higher brackish waters (Emmanuel and Onyema 2007), which have limited similarities with the present results.

In the ITB the copepod abundance peaked in the MON and the majority of the community was small (< 1 mm) and medium (1 to 1.5 mm) size copepods as classified by Paul et al. (2019) who worked with the copepod community of the adjacent Muriganga estuary. Study of Kavitha et al. (2018) along the coasts of the Gulf of Manner, India found 56 species of copepods mostly Calanoida followed by Cyclopoida, Harpacticoida and Poecilostomatoida. Harpacticoida with 8 representative species made a significant biomass composition i.e., 32.56% followed by the Calanoids (38.99% with 35 representative species) and Cyclopoida (15.22% with 4 representative species), respectively (Kavitha et al. 2018). Further, *E. acutifrons* was the most abundant species (Kavitha et al. 2018). In the current study, *E. acutifrons* emerged as one of the co-dominant species of the copepod community which was dominated by *A. spinicauda*. Numeric contribution of the Harpacticoids in the copepod community of the ITB of Sagar Island, GE was significant. In the Chennai coast, Harpacticoid copepods contributed significantly in-terms of the diversity and abundance of the local meiofauna (Mantha et al. 2012). In the Marina beach of India, seasonal change affects the size class of the Calanoid copepods with smaller size copepods were more abundant in summer, and larger size copepods were more abundant during the

MON associated with high rainfall and nutrient availability (Nawaz et al. 2024). Nawaz et al. (2023) while studying the Calanoid copepods of the Paracalanidae family suggested the density of Paracalanidae was the highest in winter and the lowest in early monsoon and strong relationships exist between the Paracalanidae copepod abundance and the water salinity, pH, and nitrate content of the water masses. Relative contribution of the Paracalanidae family within the copepod community of the ITB of the Sagar Island hardly varied among seasons. Spatial variation of the copepod community was significant in the ITB, which could be a reflection of the variable freshwater influence of the GE on the eastern vs. western sides of the Sagar Island. The western side (i.e., LH site) of the island receives the main flow of the GE (i.e., namely Hooghly River); therefore, the volume of freshwater it receives is far more than the eastern site (i.e., DL), which receives the flow of Muriganga an off-shot of the GE that remains mostly mesohaline and in the summer months becomes polyhaline at times (Mukhopadhyay et al. 2006). The GS site being in between the LH and the DL as well as directly sea facing receives maximum influence of salt (Mukhopadhyay et al. 2006). Those environmental variability of the water masses possibly give rise to specialize micro-habitats inhabited preferred by specific species of the copepod community that have adapted the local conditions better than the others (Gogoi et al. 2021). A study conducted on the macro-tidal beaches of the estuaries of the Amazon region of Brazil suggested that the highest densities of the copepods were caught in the ebb tides of the rainy season and concluded that the lowering of the salinity due to the precipitation contributed to the proliferation of the copepod diversity and density near the estuary mouth which support the present results (Pinheiro et al. 2011). That study further observed *E. acutifrons* and *Paracalanus quasimodo* dominated the community in-terms of their abundances (Pinheiro et al. 2011). Species such as *E. acutifrons* was also highly abundant in the ITB of the Sagar Island. While reviewing the coastal copepod communities of the various islands and coastal waters of the Australia and Indonesia, McKinnon and Duggan (2014) suggested *Oithona* spp., *E. acutifrons*, *Microsetella* spp. and *Parvocalanus crassirostris* contributed largely towards the diversity and density of the local copepod communities which was found to some extent in the current study.

Both the CC and the ITB are highly influenced by the water masses of the GE. The ITB is more saline, nutrient rich and shallower than the CC, and the in the beach throughout the year wind causes suspension of solids which may be among the reasons behind finding less Cyclopoid and more Harpacticoid copepods. Such results were also observed in the coasts of the Iberian Peninsula, Portugal (Guerreiro et al. 2021). Both the habitats being close to the sea receive marine-intrusions throughout the year and host many neritic copepods (Gogoi et al. 2021; Basu et al. 2022; Paul et al. 2024). In the Sagar Island most of the copepods are brackish origin so eurihaline in nature and few are high salt tolerant species consequently they are less affected by the seasonal changes of water masses (Morgan et al. 2018; Paul et al. 2024). It is noticeable that the cumulative abundance of the copepod community in the ITB peaks in the MON. The large volume of freshwater which the GE receives during the MON often causes flood forcing many copepods to wash out towards the estuary mouth (Nandy et al. 2018). The ITB of the southern section of the Sagar Island is where the GE meets the sea (Chowdhury et al. 2015); therefore, it is possible that during the MON the ITB hosts both its resident copepod community and some migrants coming down from the upstream of the estuary. Species such as the *A. tortaniformis* dominated the creek but the *A. spinicauda* dominated the beach, both the species thrive better under brackish to marine environments of the estuaries of Indian Sundarbans including that of the Muriganga section of the GE which is adjacent to the Sagar Island (Chakaborty et al. 2022; Paul et al. 2024). The ITB had less species richness as well as abundance of copepods compared to the CC of the Sagar Island of the GE. A study conducted on the Dharamtar creek adjoining the Mumbai harbour of India found a distinct increase in the zooplankton (majority was copepods) biomass and various copepod populations from the harbour side towards the inside of the creek environment and copepod *A. spinicauda* was the dominant in the outer-section of the estuary (Tiwari and Nair 2002). It is possible that the high energy environment of an ITB causes more mechanical disruption to a plankton community then a sheltered habitat such as a creek; therefore, the latter supports more diversity and density of copepods. Such was also found along the coasts of the Argentina by Baleani et al. (2024). The current results have the similarity with the findings of the Morgan et al. (2018) and Guerreiro et al. (2021) as the dissimilarity of the copepod assemblages between the CC and the ITB was mainly driven by the Harpacticoids and some other neritic species which are specialized to reside near estuary mouth. It could be concluded that Sagar Island is under the variable influence of the water masses of the GE but its copepod community maintains microhabitat specificity rather being affected by the seasonal variability of the water masses. In India, copepods of any estuarine beaches are less studied; therefore; hardly compared with those of a creek where both the habitats are under the influence of a single river-estuary. The current work is a pioneering attempt towards establishing such a research line in the country for a better understanding of the estuarine zooplankton communities.

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Data availability Data would be provided after reasonable request.

Declarations

Competing interests Author declares that he has no competing interest.

Ethical approval No ethical standards were required to execute the study.

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