Cyclone Amphan effects on the copepods of Ganges estuary

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Abstract

Tropical cyclones are increasingly affecting the estuarine communities. Impacts of category-5 tropical cyclone Amphan (landfall on 20 May 2020 near Ganges estuary mouth) on the copepod community of Muriganga section of Ganges estuary was studied by sampling the copepod assemblages before (February to December 2019), shortly after (31 May to 12 June 2020) and post (September to November 2020) cyclone. Hypothesis was shortly after Amphan a relatively homogenous community consists of a few estuarine specialist copepods would succeed but within months that community would be replaced by a heterogenous one but those estuarine specialists would continue their dominance. Shortly after Amphan, species richness declined but the recovery process completed within months led by herbivorous *Paracalanus parvus*, omnivorous *Bestiolina similis*, *Acartia spinicauda*, *Acartiella tortaniformis*, and carnivorous *Oithona brevicornis*. Spatial homogeneity of the community that prevailed in Muriganga in pre-Amphan and shorty after Amphan was lost in post-Amphan. Community composition changed from pre- to shortly after to post-Amphan. Unilateral dominance of *B. similis* observed in pre-Amphan was challenged by *P. parvus*, *A. spinicauda*, *A. tortaniformis* and *O. brevicornis* shortly after Amphan and in post-Amphan. *Acartia spinicauda* proliferated shortly after Amphan and co-dominated the estuary along with *A. tortaniformis* but the latter replaced the former in post-Amphan. Copepods did rebuild their community within a few months from Amphan but experienced rearrangements of species composition, abundance, dominance hierarchy and feeding guilds, which may strain benthic-pelagic linkages of Ganges estuary so shall be monitored regularly by coastal institutions following uniform methods and best practises.

Introduction

Stochastic disruption of coastal-marine ecosystems is often the result of a discrete event that is extreme in nature (Sasaki et al. 2015). Tropical cyclones (TCs) also known as hurricanes and typhoons are increasingly affecting the lives and livelihoods of biological communities that inhibit inside and besides coastal-marine ecosystems (Pearl et al. 2001; Paul et al. 2020a, b; Phlips et al. 2020). Estuaries exhibit extreme variability of their morphology and environment, which affects the ecology of estuarine biota (Whitfield 1992). Extent of an ecological disruption of an estuary that follows a TC may vary depending on many factors including the morphology of an estuary, distance to landfall site, intensity of storm surge, severity of rainfall and/or flood that proceeds a TC, residence time of flood water (Beyrend-Dur et al. 2013; Kumar et al. 2017; Liu et al. 2021).

With the advancement of weather forecasting, tracking TCs before their land fall have become more predictable than 20th Century (Madsen and Jakobsen 2004; Mohanti et al. 2019); therefore, the estuarine scientific community is able to conduct before-after assessment of disruptions caused by a TC or successive TCs (Steinke and Ward 1989; Pearl et al. 2001; Mukherjee et al. 2012; Beyrend-Dur et al. 2013; Bhattacharya et al. 2014; Kumar et al. 2017; Paul et al. 2020a). Impacts of hurricanes that hit eastern coasts of North America have received attention in estuarine literatures because biogeochemical cycles and ecological communities a few estuaries are regularly monitored so assessments of before-after cyclonic disruptions are possible (Gong et al. 2007; Wetz and Pearl 2008; Pearl et al. 2018; Phlips et al. 2020; Wachnicka et al. 2020). For estuaries of developing countries such assessments are difficult because estuaries are hardly monitored in regular intervals (Kumar et al. 2017; Paul et al. 2020a). Even after that studies from India, South Africa, Taiwan and China have provided perspectives of ecological changes of lagoons and river-estuaries following TCs (Forbes and Cyrus 1992; Mukherjee et al. 2012; Beyrend-Dur et al. 2013; Bhattacharya et al. 2014; Kumar et al. 2017; Paul et al. 2020a,b). Those studies suggest that mechanical disruption brings structural and functional changes of an estuary after it is hit by a TC or successive TCs (Mukherjee et al. 2012; Bhattacharya et al. 2014; Kumar et al. 2017; Paul et al. 2020b).

The coasts of Bay of Bengal (BoB) are TC prone and an average of three to four TCs annually hit the region often in late premonsoon (April and May) and in early postmonsoon (October and November) (Alam et al. 2003). Tropical cyclone formation rates of BoB are lower than Atlantic and Pacific basins; however, shallow bathymetry of BoB, low-lying and flat coastal terrain, and high-population density cause devastating consequences when TCs make landfall (Balaguru et al. 2014). Analysis of TC data from 1877 to 2005 of BoB suggest increase (26% per hundred years) in the intensity of TCs specially in postmonsoon (Singh 2007). According to Balaguru et al. (2014) 'Increases in sea surface temperature and upper ocean heat

content made the ocean more conducive to TC intensification, while enhanced convective instability made the atmosphere more favorable for the growth of TCs. The largest changes in the atmosphere and ocean occurred in the eastern BoB, where nearly all major TCs form'. Many of those TCs generate in BoB hit Sundarbans that sprawled over India and Bangladesh; therefore, ecological communities of river-estuaries of Sundarbans are periodically affected by TCs (Mukherjee et al. 2012; Bhattacharya et al. 2014). Ecological resources of mangrove river-estuaries provide livelihood for many in the region; therefore, post-TC vulnerability of mesozooplankton (e.g. copepods) may harm local economy because they are prey for many fish and shell fish species (Sarkar and Bhattacharya 2003; Bhattacharya et al. 2014).

Ganges River of India is a macro-tidal river-estuary penetrates about 200 K.M. inside from its mouth but the salinity front seldom penetrates beyond 90 K.M (Mukhopadhyay et al. 2006). Near Namkhana of West Bengal, Ganges estuary bifurcates and the offshoot known as Muriganga takes a curved route before it meets BoB (Mukhopadhyay et al. 2006). Muriganga being close to coast faces brunt of storm surges, depressions and TCs (Paul et al. 2020a,b). Many plankton and fish resources of Muriganga are commercially exploited (Sinha et al. 1996; Sarkar and Bhattacharya 2003; Paul et al. 2019). Unless disrupted by any TC mesozooplankton of Muriganga shows two peaks per year firstly in late premonsoon and secondly in middle of postmonsoon (Sarkar et al. 1986), which is linked to phytoplankton bloom that precedes the peaks of zooplankton diversity and density (Biswas et al. 2010). About 36 species of copepods are reported from Muriganga and other river-estuaries of Indian Sundarban (Bhattacharya et al. 2015; Paul et al. 2019). Abundance of copepods is generally higher in dry seasons than wet season (i.e. monsoon); therefore, salinity possibly limits the copepod community of Indian Sundarban (Bhattacharya et al. 2015). Copepods *Bestiolina similis*, *Acartiella tortaniformis*, *Pseudodiaptomus serricaudatus*, *Paracalanus parvus*, *Acartia spinicauda* persist throughout the year in Muriganga and are considered as estuarine specialists who adapt quickly to the extreme changes of the estuary (Bhattacharya et al. 2015; Paul et al. 2019; Paul et al. 2020a,b). Competition among those species is intense because their spatial niches are segregated only by a few hundred meter stretch of Muriganga (Paul et al. 2019). Shortly after TC Aila, Fani and Bulbul, the copepod community of Muriganga lost many of its component populations as well as individuals of each population (Bhattacharya et al. 2014; Paul et al. 2020a,b).

Intensity of cyclones is increasing in Indian Sundarbans; therefore, prolong disruptions of estuarine food web is likely in future (Bhattacharya et al. 2014; Mandal and Hosaka 2020; Paul et al. 2020b). 'Cyclone Ecology (CE)' research program for Indian estuaries was established by the authors in May 2019. The CE program takes Ganges estuary (GE) as a model ecosystem for studying ecological changes of plankton resources after a TC and/or successive TCs. The program applies a before-after sampling design to monitor abiotic parameters and plankton communities of Muriganga section of GE. Previous studies conducted under the CE program after TC Fani and TC Bulbul suggested that distance to the landfall site has a close relation to time which copepods take to rebuild their community structure that used to prevail before the cyclonic disruption of Muriganga (Paul et al. 2020a,b). It was also suggested that shortly after a TC small size omnivore copepods lead in the recovery process of the community (Paul et al. 2020b). Muriganga is facing periodic TCs only in space of a few months (Paul et al. 2020a); however, all the cyclone studies conducted on Muriganga so far are essentially short-term (i.e. within few weeks of cyclonic disruption). First-time, an attempt is made to assess short- (i.e. a few weeks after a TC) as well as medium-term (i.e. a few months after a TC) impacts of a TC on the copepod community of Muriganga.

Amphan was a category-5 TC which had a 1-minute sustained windspeed of 270 K.M./hour and a 3-minute windspeed of 240 K.M./hour (Khan et al. 2021). On 20 May 2019 Amphan landfall near Bakkhali region, which is about a few kilometer from the CE program sites on Muriganga. At the time of land fall it had a speed of 150-160 K.M./hour and gust up to 185-190 K.M./hour. Sagar Island which is less than 10 K.M from the CE program sites experienced wind speed of 111 K.M./hour. The storm surge (4.6 m at Sagar Island) and torrential rainfall (~ 250 mm in Indian Sundarbans within few hours before-after landfall) associated with TC Amphan flooded most of Sagar Island (154.254 km^2) and Namkhana (198.485 km^2) of Indian Sundarbans which are besides Muriganga and are close to the CE program sites (Das et al. 2020; Halder et al. 2021; Kumar et al. 2021). The study assessed the impacts of TC Amphan on the copepod community of Muriganga with a hypothesis that within a few weeks of TC Amphan a relatively homogenous community made up primarily by a few estuarine specialist copepod species would succeed but within a few months that community would be replaced by a more heterogenous community but the dominance of those estuarine specialists would continue. The study aimed to understand short- to

medium-term vulnerability and/or resilience of the copepod community following a category-5 tropical cyclone in a river-estuary.

Materials And Methods

Study site

Sundarbans (21°32′, 22°40′N; 88°05′, 89°00′E), a UNESCO World Heritage site, is the largest deltaic mangrove forest of the world, dominated by estuaries on the land-ocean boundary of Ganges-Brahmaputra delta (Mukhopadhyay et al. 2006). It covers about 10200 km^2 reserved forest out of which 41% is under India territory (Mukhopadhyay et al. 2006). Indian Sundarbans has three distinct seasons i) a hot and humid pre-monsoon (PRM) season from March to June (of late, it is extended by several weeks); ii) a warm and humid monsoon (MON) between July and October but its arrival has often been delayed in recent years. Most (> 70% of annual average rainfall between 150 and 200 cm) of the rainfall occurs during MON and iii) a mild winter (November to February) known as post-monsoon (POM) (Ganguly et al. 2014; Bhattacharya et al. 2015; Nandi et al. 2018). Ganges estuary runs through the western most boundary of Indian Sundarbans. Muriganga is an offshoot of GE that has similar physical-chemical properties of Hooghly channel of the estuary (Mukhopadhyay et al. 2006). Muriganga has moderately developed mangrove vegetation and an intensely cultivated hinterland on the sides of the channel. Under the CE program, plankton resources of S1, S2 and S3 sites which are about 500 m from each other in north-south direction on Muriganga are regularly monitored in stable and/or perturbed state of the estuary (Paul et al. 2019, 2020a,b). Site S1 (21°44'53.8"N, 88°12'46.2" E) is towards the upstream of Muriganga and near to a mudflat that mostly remains sub-merged and emerges during the lowest low tide (Fig.1). Site S3 (21°44'55.4"N, 88°12'36.8"E) is towards the downstream and near Taitan Island which has a semi-intense mangrove patch (Fig.1). Site S2 (21°44'55.7"N, 88°12'40.0"E) is equal distant from S1 and S3 (Fig.1) and close to a dense mangrove patch of Half-Fish Island, which is recently declared as reserve by Forest Department of West Bengal, India.

Before-after sampling design

Amphan landfall on 20 May 2020 and caused massive damage to infrastructure including roads to Indian Sundarbans so Muriganga remained inaccessible for a week so sampling begun on 31 May 2020. At first, samplings (details in section 2.3.) were conducted weekly basis from 31 May to 12 June 2020, which were assumed as shortly after Amphan samples. After a pause of three months, samplings were conducted on monthly interval from September to November 2020, which were assumed as post-Amphan samples. Seasonal samplings conducted from S1, S2, and S3 sites of Muriganga in 2019 when estuary was not perturbed by any TC. Those were assumed as pre-Amphan samples.

Measurement of abiotic parameters and copepod sampling

All the samples were collected on high tide at dark from a motor boat and on each occasion of sampling from S1, S2 and S3; salinity, water-temperature (°C) and pH levels of Muriganga were measured (in triplicate) by a hand held multi-parameter probe (YSI-1030, USA) from subsurface water and also copepod assemblages (> 200 mm) were collected. For collection of copepod assemblages, at each sampling site, 100 L of estuarine water was collected through a 10 L plastic bucket and sieved through a 200 mm plankton mesh after minor modification of the protocol adopted by Paul et al. (2019, 2020a,b). Copepod assemblages were collected in triplicate. 5 ml of 4% buffered formalin was added to copepod samples for preservation. Samples were then transported to laboratory where multiple aliquot samples each of 1 ml were drawn. Each aliquot was placed on a Sedgwick Rafter counting cell and examined under a stereo-microscope (Bestscope-BS30T, China). Copepod individuals were identified to species level following the taxonomic literature of Kasturirangan (1963). Abundance (all life stages are pooled) of each species was expressed as individual(s) per cubic metre (i.e. ind.m^{-3}).

Study of feeding guilds of copepods

Feeding guild of each sampled copepod species was reviewed from Turner (2004), Islam et al. (2006), Bhattacharya et al. (2015), and Paul et al. (2019). In terms of feeding guilds they were classified either as herbivorous or carnivorous or omnivorous species.

Data structure, presentation and analysis

Analyses were performed using CRAN-R 4.1.1 (R Core Team 2021) and PRIMER- 7.0 (Clarke and Gorley 2015). Results of statistical tests were presented with corresponding t, W, F, K-W chi-square and p values and degrees of freedom (DF).

Abiotic variability

After a TC abiotic variability of an estuary generally exaggerates so frequent monitoring is required (Pearl et al. 2018; Paul et al. 2020a) which was not feasible because Muriganga was less accessible after TC Amphan and amid COVID-19 lockdown of India. Further detailed analysis of the abiotic variability was beyond the scope of the conceived hypothesis; therefore, statistical comparisons of abiotic data among pre-, shortly after- and post-Amphan periods were not conducted rather abiotic variability of Muriganga was summarized in Table 1 and discussed accordingly.

Relative abundance and dominant copepods

Site-specific relative abundance of copepods were calculated for the pre-, shortly after- and post-Amphan periods (see Table 2). For analysing dominant and or co-dominant status of a few frequently caught species, index of dominance was calculated following the formula adopted by Bhattacharya et al. (2014) i.e. $Y_i = (N_i/N) * F_i$ where Y_i is the dominance of species i, N_i is the number of individuals of species i at all sites (i.e. S1, S2 and S3), N is the number of all species at all sites, and F_i is the frequency of sites at which species i occurs. Species with a Y_i value greater than 0.02 were considered dominant species of the habitat (Bhattacharya et al. 2014). Such was calculated for the pre-, shortly after- and post-Amphan periods (Table 3).

Spatial and temporal variability of the copepod assemblages

Species abundance dataset was square root transformed so that abundances of a few rare species remained in consideration of the multivariate analysis. Then ordination analysis (on species abundance dataset) was conducted through Non-metric Multidimensional Scaling (NMDS) using the Bray–Curtis measure of dissimilarity ('Vegan' package version 2.5.6). Inference on dimensionality of NMDS (K = 2 were considered) was taken only after examining the stress scores, Shepard diagrams, non-metric and linear fit R^2 scores (see details in Annexure 1). Then NMDS biplots were drawn (Fig.2).

To evaluate spatial (among S1, S2 and S3) variability of the copepod assemblages of pre-, shortly after- and post-Amphan periods multiple Permutational Multivariate Analysis of Variance (PERMANOVA) were conducted (i.e. Adonis test, permutations = 999, method = Bray-Curtis, package: 'Vegan' version: 2.5.6). A PERMANOVA was then conducted on the entire species abundance dataset to evaluate the temporal variability of the copepod community. Whenever a PERMANOVA analysis was conducted assumption of homogeneity of multi-variate dispersion was tested by conducting Analysis of variance (ANOVA). Similarity percentage analysis (i.e. SIMPER) was conducted for the assessment of similarity and dissimilarity of the copepod assemblages. Such was done separately for pre-, shortly after- and post-Amphan periods (Table 4, 5).

Results

Abiotic variability of Muriganga before-after Amphan

In 2019, the highest salinity (i.e. 19.30) was measured in May and the lowest (i.e. 8.60) was measured in August (Table 1). The highest water-temperature (i.e. 31.20 °C) was measured in May 2019 and it dropped to the lowest (i.e. 20.40°C) in December 2019 (Table 1). The highest pH (i.e. 8.64) was measured in December and the lowest pH (i.e. 7.10) was measured in May 2019 (Table 1). Shortly after Amphan, meso- to poly-haline (16.20 to 19.30) salinity, warm water-temperature and alkaline pH

conditions of Muriganga were evident but in post-Amphan salinity (i.e. 4.80 to 7.70) of Muriganga dropped; however, warm water-temperature and alkaline pH conditions persisted (Table 1).

Community structure before-after Amphan

Species richness in pre-, shortly after- and post-Amphan were up to 26, 22 and 25, respectively (Table 2). *Bestiolina similis*, *Paracalanus parvus*, *Acartia spinicauda*, *Acartiella tortaniformis* and *Oithona brevicornis* were highly abundant whereas *Euchaeta marina*, *Eucalanus crassus*, *Labidocera euchaeta,* and *Oithona similis* were among the rare species (Table 2). Compared to pre-Amphan relative abundances of *B. similis* were less at S2 and S3 shortly after Amphan and post-Amphan (Table 2). *Acartia spinicauda* was more frequent shortly after Amphan than pre- and post-Amphan so were *Acrocalanus gracilis* and *Acartia sewelli* (Table 2). Primary feeding guilds of *B. similis*, *A. spinicauda*, *A. tortaniformis* were omnivorous and their abundances did rise shortly after Amphan. Exception was *Acartia tonsa* which has a primarily omnivorous feeding guild but the species was absent from S1 and S2 shortly after Amphan (Table 2). Among carnivorous species *O. brevicornis*, *O. similis* and *E. marina* were noted. Shortly after Amphan, abundance of *O. brevicornis* did rise but *O. similis* was absent from all the sites (Table 2). All other copepods were herbivorous (Table 2). Shortly after Amphan, herbivorous *Pseudodiaptamus binghami* was absent (Table 2). Relative abundance of herbivorous *Acrocalanus gibber* was higher shortly after Amphan than pre- and post-Amphan (Table 2). Relative abundance of herbivorous *Pseudodiaptamus serricaudatus* was considerably less (was even absent at S1 and S2) shortly after Amphan compared to its relative abundances in pre- and post-Amphan (Table 2). *Bestiolina similis* maintained its dominant status throughout pre-Amphan (Table 3). Shortly after Amphan *A. spinicauda* and *P. parvus* dominated Muriganga but *B. similis* soon regained its dominant position (Table 3). Species such as *A. tortaniformis*, *A. spinicauda* and *O. brevicornis* co-dominated Muriganga along with *B. similis* shortly after and post-Amphan periods.

Spatial-temporal variability of community before-after Amphan

Spatial variability of the copepod community in pre-Amphan (Fig.2) (PERMANOVA: DF = 2, Sum of Square = 0.12, Pseudo-F = 0.74, R^2 = 0.05, P = 0.69; the assumption of homogeneity of multivariate dispersion was not violated (ANOVA: DF = 2, F = 0.12, P = 0.88)) and shortly after-Amphan (Fig.3) (PERMANOVA: DF = 2, Sum of Square = 0.16, Pseudo-F = 0.58, R^2 = 0.16, P = 0.79; the assumption of homogeneity of multivariate dispersion was not violated (ANOVA: DF = 2, F = 0.48, P = 0.63)) was not significant. In post-Amphan (Fig.4), the copepod community exhibited significant spatial variability (PERMANOVA: DF = 2, Sum of Square = 0.14, Pseudo-F = 4.73, R^2 = 0.61, P = 0.004; the assumption of homogeneity of multivariate dispersion was not violated (ANOVA: DF = 2, F = 0.09, P = 0.91)).

Temporally the composition of the copepod community varied significantly among pre-, shortly after- and post-Amphan (PERMANOVA: DF = 2, Sum of Square = 0.81, Pseudo-F = 4.89, R^2 = 0.24, P = 0.001; the assumption of homogeneity of multivariate dispersion was not violated (ANOVA: DF = 2, F = 0.08, P = 0.87)) (Fig.5). During pre-Amphan, the average similarities of the community sampled from S1, S2 and S3 sites were 52.55%, 53.98% and 57.13%, respectively and were primarily driven by *B. similis*, *P. parvus*, *A. spinicauda* (Table 4) whereas the dissimilarities between S1 and S2 was 43.26%, S1 and S3 was 43.88%, S2 and S3 was 39.46%. Dissimilarities were chiefly contributed by *A. tortaniformis*, *A. tropica*, *O. brevicornis* (Table 5). Shortly after Amphan similarities of the community among S1, S2 and S3 were 34.55%, 50.13% and 60.68%, respectively (Table 4) and primarily driven by *B. similis*, *A. spinicauda*, *A. tortaniformis* and a few other species (Table 4). The dissimilarities of the copepod community between S1 and S2 was 50.20%, S1 and S3 was 48.65%, S2 and S3 was 37.62% and were driven mainly by *A. spinicauda*, *A. tortaniformis*, *O. brevicornis* (Table 5). Post-Amphan similarities of the community of S1, S2 and S3 were 80.34%, 78.02% and 81.54%, respectively and *B. similis*, *P. parvus*, *A. spinicauda*, *A. tortaniformis* were among the primary contributors (Table 4). The dissimilarities between S1 and S2 was 29.83%, S1 and S3 was 29.87%, S2 and S3 was 23.09% (Table 4) and were largely contributed by *Paracalanus dubia*, *A. tropica*, *Acrocalanus longicornis*, *Oncea venusta*, *Labidocera acuta* (Table 5).

Discussion

Abiotic variability of Muriganga

Results demonstrate that in short- to medium-term (i.e. within a few weeks to a few months from the landfall of TC Amphan) the copepod community of Muriganga had rebuild their community and a few estuarine specialist species dominated throughout the period. The pelagic communities of river-estuaries generally recover soon after TCs because disruptions are often mechanical and are forced by floods which proceed TCs (Cheal et al. 2002; Peierls et al. 2003; Mukherjee et al. 2012; Paul et al. 2020a; Liu et al. 2021). If the abiotic conditions of the habitat change drastically after a TC and remained so for a considerable period then that poses a challenge for populations to recolonize the habitat, which happened after TC Aila (May 2009) in Indian Sundarbans (Mukherjee et al. 2012; Bhattacharya et al. 2014). Shortly after Amphan, Muriganga turned to a warm, polyhaline and alkaline (pH > 8) habitat and such a condition lasted for a few weeks; however, that is not unusual for Muriganga specially in late PRM to early MON because evaporation rates remain high in that period due to high ambient temperature (Mukhopadhyay et al. 2006). Muriganga may remain saline even after receiving post-TC rains for a few days because salinity of Muriganga is dependent more on tidal inflow of marine waters of adjacent BoB than on precipitation (Choudhury et al. 2015; Das et al. 2016; Paul et al. 2020b). During and even after a few days of a TC, strong onshore winds enhance the landward saltwater intrusion (Michener et al. 1997). For Muriganga such was observed shortly after TC Phailin in October 2013 (Das et al. 2016), TC Fani in May 2019 (Paul et al. 2020b) and a similar condition persisted even after TC Amphan in May 2020. Shortly after TC Amphan, alkalinity of Muriganga was high possibly for the intrusion and dominance of sea water over riverine flow (Das et al. 2016). Post-Amphan, a considerable decline in salinity of Muriganga was evident because the system received a lot of rain in 2020 as there was a delay in the onset of monsoon and the rainy days carried on well into November. Muriganga usually remains alkaline and its pH profile has a negative correlation with seasonal rainfall and positive correlation with salinity (Mukhopadhyay et al. 2006; Choudhury et al. 2015; Das et al. 2016). Post-Amphan, a drop in the pH level of Muriganga was also observed than shortly after Amphan. Overall, the abiotic changes of Muriganga that occurred shortly after- and post-Amphan might not be that drastic for the copepod community which is face considerable tidal and seasonal variability of abiotic conditions (Sarkar et al. 1986; Paul et al. 2019).

Copepod community before-after TC Amphan

Shortly after Amphan there was a decline in the species richness and in the abundance of a few species of copepods which lasted a few weeks. Such a temporary decline in the species richness was also observed in the river-estuaries of Indian Sundarbans after TC Aila, Fani and BulBul, and in the Chilika lagoon of Orissa, India after TC Hudhud (Bhattacharya et al. 2014; Paul et al. 2020a; Srichandan et al. 2021). Copepods *B. similis*, *P. parvus*, *A. spinicauda*, *A. tortaniformis* and *O. brevicornis* were often abundant, which was also observed after TC Aila, Fani and BulBul (Bhattacharya et al. 2014; Paul et al. 2020a,b). After TC Hudhud, a major shift in the zooplankton community of Chilika lagoon was seen, which was primarily caused by copepods of genus *Acartia*, *Acrocalanus*, *Euterpina*, *Oithona* and *Pseudodiaptomus* under the influence of exaggerated variability of salinity, turbidity and phytoplankton density (Srichandan et al. 2021). *Bestiolina similis* is an estuarine specialist that could survive even under extreme and abrupt changes of estuarine environment (Paul et al. 2020b). In Indian Sundarbans *B. similis* maintained its dominant status in the copepod community after cyclone Aila, Fani, Bulbul (Bhattacharya et al. 2014; Paul et al. 2020a,b) and even in the pre-Amphan period but shortly after Amphan and later in the post-Amphan it lost its dominant position in the community on various occasions to *P. parvus*, *A. spinicauda*, *A. tortaniformis* and *O. brevicornis*. Bhattacharya et al. (2014) observed proliferation of *A. spinicauda* in Indian Sundarbans after cyclone Aila in 2009. The calanoid copepods of Taiwan's Danshuei River estuary declined considerably after successive typhoons during 2008–2009, which led to a sudden proliferation of *A. spinicauda* followed by a temporary replacement of *Pseudodiaptomus annandalei* which otherwise dominates the estuary (Beyrend-Dur et al. 2013). Sudden proliferation of *A. spinicauda* was also observed shortly after Amphan and it temporarily replaced the dominant *B. similis*. After cyclone Aila, *O. brevicornis* population was highly abundant in Indian Sundarban (Bhattacharya et al. 2014) but that was not observed shortly after Amphan rather it was months after Amphan when *O. brevicornis* population proliferated in Muriganga and co-dominated the estuary along with *A. tortaniformis* and *P. parvus*. When Muriganga remains unperturbed by any cyclone for months *P. parvus* and *B. similis* competes with each other for spatial niche (Paul et al. 2019). Shortly after Amphan, *P. parvus* population

proliferated in Muriganga and co-dominated the estuary along with *A. tortaniformis*; however, such proliferation of *P. parvus* was also observed shortly after TC Fani and Bulbul (Paul et al. 2020a).

After TC Fani disrupted Muriganga omnivorous copepods started the recolonization process within a few days and were later joined by herbivorous and finally by carnivorous copepods (Paul et al. 2020b). In the Chilika lagoon After TC Hudhud, nauplii and copepodites stages were dominant as the phytoplankton density of the lagoon increased in response to the upsurge in the nutrient level of the habitat (Srichandan et al. 2021). The majority of copepod species which succeeded in Muriganga after Amphan was herbivore consistent with the previous work conducted by Paul et al. (2020a) in Muriganga. Except *Acartia tonsa* abundances of all other omnivorous copepods did rise shortly after Amphan. Results have similarity with Bhattacharya et al. (2014) who found similar situations after TC Aila ravaged Indian Sundarbans. After Amphan, carnivorous *O. brevicornis* population slowly proliferated; however, its proliferation did not resemble the overwhelming proliferation of the species observed by Bhattacharya et al. (2014) in Indian Sundarbans after TC Aila. A delayed recolonization of *O. brevicornis* was also observed after TC Fani and Bulbul (Paul et al. 2020a). Overall, the results demonstrate many rearrangements which had occurred in the composition, abundance, dominance, and feeding guilds of the copepod community after Muriganga was disrupted by Amphan. A few of those changes had occurred previously after Muriganga was hit by TCs and had lasted only temporarily without any far reaching consequences for the benthic-pelagic coupling of the estuary (Paul et al. 2020a,b). A few changes that have happened exclusively after Amphan need to be closely monitored.

Studies conducted by Paul et al. (2020a,b) after TC Fani and Bulbul on the same stretch of Muriganga suggested that after a TC abiotic and biological gradients of Muriganga are temporarily washed away because of heavy rainfall that generally follows a TC so the estuary becomes a homogenous habitat for a few weeks. The copepod community of Muriganga exhibited a significant spatial variability in post-Amphan, which was absent shortly after Amphan and in pre-Amphan. The community composition also varied significantly among pre-, shortly after- and post-Amphan periods similar to the conditions observed in Chilika lagoon of India by Kumar et al. (2017) and Srichandan et al. (2021) after TC Hudhud. The post-Amphan similarities of the community were higher than those of pre-Amphan and shortly after Amphan but irrespectively of time *B. similis*, *A. spinicauda* were among the chief contributors of those similarities. Dissimilarities of the copepod community were less in the post-Amphan compared to the pre- and shortly after- Amphan periods. Shortly after Amphan, dissimilarities of the community at S1 and S2 sites were higher than the pre-Amphan period but the dissimilarities at S3 site was less than the pre-Amphan period. Hurricane Ike in 2008 and Hurricane Harvey in 2017 struck the Gulf of Mexico of USA and on both the occasions the pelagic communities including zooplankton were severely perturbed but zooplankton recovered fast and their recovery time was related more with the severity of the flood that followed a TC rather than the storm surge (Liu et al. 2021). Liu et al. (2021) further suggested that 'aftermaths of the two hurricanes exhibited distinct spatial arrangements of zooplankton assemblages associated with hydrographic factors largely signifying the relative impact of floodwater discharge and storm surge on pelagic communities'. The aftermath of TCs may cause decreases in the abundance, biomass and species composition of zooplankton (including) in estuaries but most changes are temporary due to the short life cycle and potential replenishment from adjacent coastal waters, particularly for the study area with a short residence and sheared residual circulation driving coastal ocean water upstream near the sea-floor (Rayson et al. 2015; Paul et al. 2020a,b). That is highly plausible for the copepod community of the inter-connected river-estuaries of Indian Sundarbans including Muriganga which receives coastal water from the adjacent BoB (Bhattacharya et al. 2014; Paul et al. 2020a,b). Liu et al. (2021) suggested the differences in the short- and long-term comparisons of zooplankton abundance after TCs reveal the intense effect of physical removals (i.e. scouring) by TCs on estuarine pelagic communities. Studies conducted on open systems suggested that tidal advection of sea water carrying coastal and oceanic species replenish zooplankton communities sooner than estuarine lakes (Forbes and Cyrus 1992; Beyrend-Dur et al. 2013; Kumar et al. 2017; Liu et al. 2017); therefore copepods of river-estuaries generally recover fast after being disrupted by a TC or successive TC (Paul et al. 2020a). If the number of TCs increases or TCs become more intense than ever or both, then the vulnerability of copepod community cannot be ruled out because the recovery time may not be available between two successive TCs (Paul et al. 2020a).

A roadmap of cyclone ecology for Indian estuaries

Intensity of TCs is increasing in BoB region which is a global hotspot of TCs (Golder et al. 2021). Till 2050 annual incidences of cyclonic disturbances may vary from 5 to 13 and on average there may be one severe cyclonic storm per year and that is most likely in the post-monsoon (Sen et al. 2021); therefore, estuarine communities are likely to be stressed for longer time than they used to be from cyclone-mediated disruptions (Kumar et al. 2017; Paul et al. 2020a). That may lead to unforeseen consequences for estuarine plankton including enhanced flexibility to adapt stressful conditions, shift in ecological distribution and a few species may even perish (Cheal et al. 2002; Peierls et al. 2003; Liu et al. 2021). Regular TCs may strain benthic-pelagic couples of Indian estuaries (Joseph et al. 2011; Mukherjee et al. 2012; Mangesh et al. 2016; Paul et al. 2020a; Mishra et al. 2021; Srichandan et al. 2021) so natural nurseries of many species may be compromised which in consequence would impact the livelihood options of many in the coastal communities (Mohan et al. 1997; Sarkar and Bhattacharya 2003; Sreekanth et al. 2021). Considering that a threat to ecology and economic potentials of Indian estuaries, Paul et al. (2020a) suggested regular monitoring of estuaries before-after cyclonic disruptions considering United Nations Decade of Ocean (2020–2030) as a baseline. A pragmatic way of implementing that is, by adopting uniform sampling design, methods, best practises, and by establishing collaborations among the coastal institutions (public and/or private) of India where each institution focuses at least on a single estuary that is ecologically and economically serving the local and/or regional communities.

Declarations

Acknowledgements

Conflicts of interest

All authors declare that they have no conflict of interest on connection with this study.

Ethical approval

Biological samples were collected in accordance with the ethical standards of University of Calcutta, India.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Dr. Sourav Paul, Mr. Samya Karan and Dr. Bhaskar Bhattacharya. The first draft of the manuscript was written by Dr. Sourav Paul and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability

The datasets generated during and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

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Tables

Table 1. Salinity, water-temperature (°C) and pH of Muriganga section of Ganges estuary, India in pre- (February to December 2019), shortly after- (31 May to 12 June 2020) and post- (September to November 2020) tropical cyclone Amphan.

Period	Sampling Date	Salinity			Water-temperature			pH		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
Pre-Amphan	25.02.2019	13.27	13.93	14.03	23.40	23.30	23.00	7.90	7.80	7.60
	14.05.2019	19.30	19.20	19.20	31.20	31.20	31.30	7.10	7.10	7.20
	24.08.2019	8.90	8.85	8.60	27.10	27.32	27.27	8.10	8.11	8.14
	18.11.2019	9.80	10.10	10.20	23.20	23.20	23.30	8.40	8.60	8.60
	28.12.2019	10.00	10.90	10.90	20.40	20.70	20.70	8.64	8.42	8.53
Shortly after-Amphan	31.05.2020	17.80	17.50	18.50	30.10	30.80	29.90	8.31	8.22	8.25
	05.06.2020	18.30	18.20	19.30	29.60	29.90	29.90	8.41	8.56	8.39
	12.06.2020	16.20	16.20	16.30	28.30	28.30	28.40	8.33	8.34	8.51
Post-Amphan	09.09.2020	5.10	5.30	5.10	29.70	29.60	29.70	7.81	7.80	7.76
	03.10.2020	5.10	5.10	4.80	30.20	30.20	30.25	7.00	7.66	7.88
	21.11.2020	7.50	7.65	7.70	26.90	26.80	26.80	7.50	7.48	7.54

Table 2. Relative abundance (%) of copepod species on Muriganga section of Ganges estuary, India in pre- (February to December 2019), shortly after- (31 May to 12 June 2020) and post- (September to November 2020) tropical cyclone Amphan.

Copepod species	S1			S2			S3		
	PRA	SAA	POA	PRA	SAA	POA	PRA	SAA	POA
Paracalanus parvas	12.86	10.98	10.16	10.60	07.55	10.68	09.53	08.90	10.16
Paracalanus aculeatus	04.77	01.87	04.06	04.79	04.73	01.37	04.14	04.52	02.56
Paracalanus indicus	00.47	03.75	03.20	01.18	04.91	02.90	01.02	04.52	02.56
Paracalanus dubia	02.03	01.87	00.00	02.13	01.32	05.60	04.40	01.26	04.35
Acrocalanus gibber	00.00	05.27	01.87	00.00	03.12	00.75	00.00	02.12	00.00
Acrocalanus gracilis	01.69	05.36	03.36	02.75	07.76	02.90	00.86	04.38	03.64
Acrocalanus longicornis	01.86	03.61	00.00	00.74	01.32	02.90	00.90	02.32	02.53
Bestiolina simils	21.30	21.86	20.24	21.73	22.50	17.43	19.45	19.60	14.90
Parvocalanus crassirostris	03.26	01.87	04.97	02.47	01.32	01.37	01.53	03.79	03.28
Acartia spinicauda	08.70	14.33	12.82	09.83	17.68	09.87	10.31	16.28	10.55
Acartia sewelli	00.00	05.53	01.44	00.00	03.78	00.75	00.00	02.26	01.82
Acartia tonsa	02.33	00.00	00.00	01.40	00.00	01.37	01.17	01.26	01.82
Acatia tropica	04.59	00.00	00.00	04.56	00.00	03.82	06.63	00.00	05.45
Acartiella tortaniformis	16.65	16.33	17.63	11.31	12.28	14.69	13.13	13.28	12.01
Pseudodiaptamus serricaudatus	02.94	00.00	05.39	06.84	00.00	02.74	08.87	01.26	05.84
Pseudodiaptamus binghami	02.50	00.00	02.19	02.49	00.00	00.75	02.90	00.00	00.72
Canthocalanus pauper	00.00	00.00	02.19	02.10	00.00	03.66	02.55	02.06	01.82
Eucalanus subcrassus	00.47	00.00	01.44	03.03	00.00	02.90	01.15	00.00	02.18
Eucalanus crassus	01.55	00.00	00.00	01.41	00.00	00.00	00.86	00.00	01.10
Euchaeta marina	00.00	00.00	00.00	00.00	02.08	00.00	00.00	00.00	00.00
Labidocera euchaeta	01.08	00.00	00.00	01.40	00.00	00.00	00.86	00.00	00.00
Labidocera acuta	01.55	01.74	00.00	01.76	00.00	02.90	01.17	02.12	00.74
Temora turbinata	00.00	00.00	02.19	01.24	00.00	01.37	00.76	01.26	01.82
Corycaeus danae	01.08	00.00	01.44	01.03	02.28	02.88	00.86	01.00	01.10
Oncea venusta	03.16	00.00	00.00	00.00	00.00	00.00	00.00	01.26	02.53
Oithona similis	00.47	00.00	00.00	00.36	00.00	01.37	00.61	00.00	00.00
Oithona brevicornis	04.68	05.62	05.39	04.85	07.37	05.00	06.35	06.52	06.53

PRA = Pre-Amphan; SAA = Shortly after-Amphan; POA = Post-Amphan

Table 3. Index of dominance of a few abundant species of copepods on Muriganga section of Ganges estuary, India in pre- (February to December 2019), shortly after- (31 May to 12 June 2020) and post- (September to November 2020) tropical cyclone Amphan.

Sampling Period	Sampling Date	*Bestiolina similis*	*Acartiella tortaniformis*	*Acartia spinicauda*	*Paracalanus parvas*	*Oithona brevicornis*
Pre-Amphan	25.02.2019	0.12	0.01	0.06	0.08	0.06
	14.05.2019	0.23	0.18	0.13	0.11	0.04
	24.08.2019	0.13	0.06	0.04	0.11	0.02
	18.11.2019	0.22	0.15	0.09	0.11	0.08
	28.12.2019	0.29	0.28	0.11	0.07	0.02
Shortly after Amphan	31.05.2020	0.03	0.03	0.12	0.17	0.00
	05.06.2020	0.22	0.14	0.21	0.07	0.08
	12.06.2020	0.19	0.14	0.12	0.11	0.08
Post-Amphan	09.09.2020	0.17	0.14	0.10	0.08	0.07
	03.10.2020	0.16	0.13	0.11	0.07	0.05
	21.11.2020	0.03	0.37	0.01	0.26	0.16

Table 4. Similarities of the copepod community of S1, S2 and S3 sites on **Muriganga** section of Ganges estuary, India in pre- (February to December 2019), shortly after- (31 May to 12 June 2020) and post- (September to November 2020) tropical cyclone **Amphan**.

Pre-Amphan (February to December 2019)						
S1		**S2**		**S3**	
Species	Average similarity: 52.55%	Species	Average similarity: 53.98%	Species	Average similarity: 57.13%
B. simils	20.54	*B. simils*	19.14	*B. simils*	18.77
A. tortaniformis	18.27	*P. parvas*	13.11	*P. parvas*	14.37
P. parvas	14.93	*A. spinicauda*	12.98	*A. spinicauda*	11.87
A. spinicauda	12.28	*P. serricaudatus*	11.67	*P. serricaudatus*	11.40
Acatia tropica	06.38	*P. aculeatus*	08.29	*O. brevicornis*	09.41
Shortly after- Amphan (31 May to 12 June 2020)						
S1		**S2**		**S3**	
Species	Average similarity: 34.55%	Species	Average similarity: 50.13%	Species	Average similarity: 60.68%
B. similis	33.84	*B. similis*	28.47	*B. similis*	20.78
A. gibber	12.59	*A. spinicauda*	24.51	*A. spinicauda*	18.59
A. tortaniformis	12.32	*A. gracilis*	15.92	*A. tortaniformis*	17.74
A. spinicauda	11.06	*A. tortaniformis*	07.84	*P. parvas*	13.51
Acartia sewelli	08.93	-	-	-	-
Post-Amphan (September to November 2020)						
S1		**S2**		**S3**	
Species	Average similarity: 80.34%	Species	Average similarity: 78.02%	Species	Average similarity: 81.54%
B. similis	14.15	*B. similis*	13.02	*B. similis*	10.07
A. tortaniformis	13.02	*A. tortaniformis*	12.05	*A. tortaniformis*	09.30
A. spinicauda	10.93	*A. spinicauda*	09.60	*P. parvus*	08.98
P. parvus	09.98	*P. parvus*	08.91	*A. spinicauda*	08.55
P. serricaudatus	06.20	*P. dubia*	07.11	*O. brevicornis*	06.56

Table 5. Dissimilarities of the copepod community of S1, S2 and S3 sites on **Muriganga** section of Ganges estuary, India in pre- (February to December 2019), shortly after- (31 May to 12 June 2020) and post- (September to November 2020) tropical cyclone **Amphan**.

| Pre-Amphan (February to December 2019)							
S1 & S2		**S1 & S3**		**S2 & S3**			
Species	Average dissimilarity: 43.26%	Species	Average dissimilarity: 43.88%	Species	Average dissimilarity: 39.46%		
A. tortaniformis	7.38	A. tortaniformis	7.23	A. tortaniformis	8.66		
B. simils	6.42	A. tropica	6.52	A. tropica	6.75		
O. brevicornis	5.74	P. serricaudatus	6.41	P. aculeatus	5.91		
P. serricaudatus	5.33	O. brevicornis	6.23	P. dubia	5.55		
P. parvas	5.15	B. simils	5.93	B. simils	5.49		
Shortly after- Amphan (31 May to 12 June 2020)							
S1 & S2		**S1 & S3**		**S2 & S3**			
Species	Average dissimilarity: 50.20%	Species	Average dissimilarity: 48.65%	Species	Average dissimilarity: 37.62%		
A. spinicauda	10.61	A. spinicauda	9.54	A. tortaniformis	7.88		
A. tortaniformis	9.50	A. tortaniformis	7.66	O. brevicornis	7.45		
A. gracilis	8.40	O. brevicornis	7.54	P. parvas	7.31		
B. similis	8.22	B. similis	7.36	P. aculeatus	6.45		
O. brevicornis	7.86	P. parvas	6.85	A. gibber	6.11		
Post-Amphan (September to November 2020)							
S1 & S2		**S1 & S3**		**S2 & S3**			
Species	Average dissimilarity: 29.83%	Species	Average dissimilarity: 29.87%	Species	Average dissimilarity: 23.09%		
P. dubia	11.27	A. tropica	11.06	O. venusta	8.47		
A. longicornis	7.86	P. dubia	9.76	P. serricaudatus	7.00		
L. acuta	7.86	A. longicornis	7.34	L. acuta	6.31		
A. tropica	7.45	O. venusta	7.34	A. tropica	5.83		
P. crassirostris	4.92	A. tonsa	6.39	P. crassirostris	5.25		

Figures
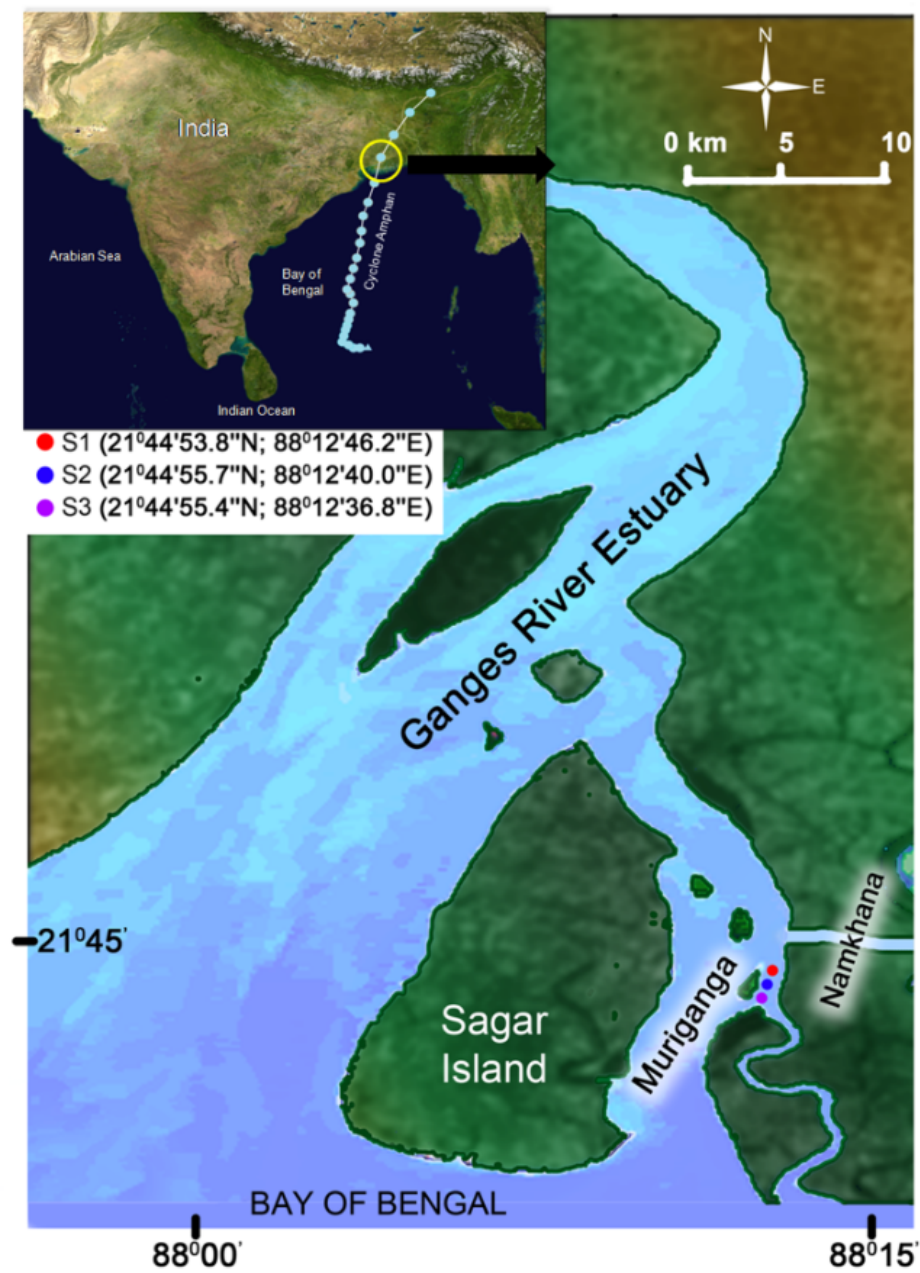
Figure 1

Map of the study area, track of tropical cyclone Amphan and sampling stations (S1, S2 and S3) on Muriganga section of Ganges estuary, India (modified after Paul et al. 2020b).
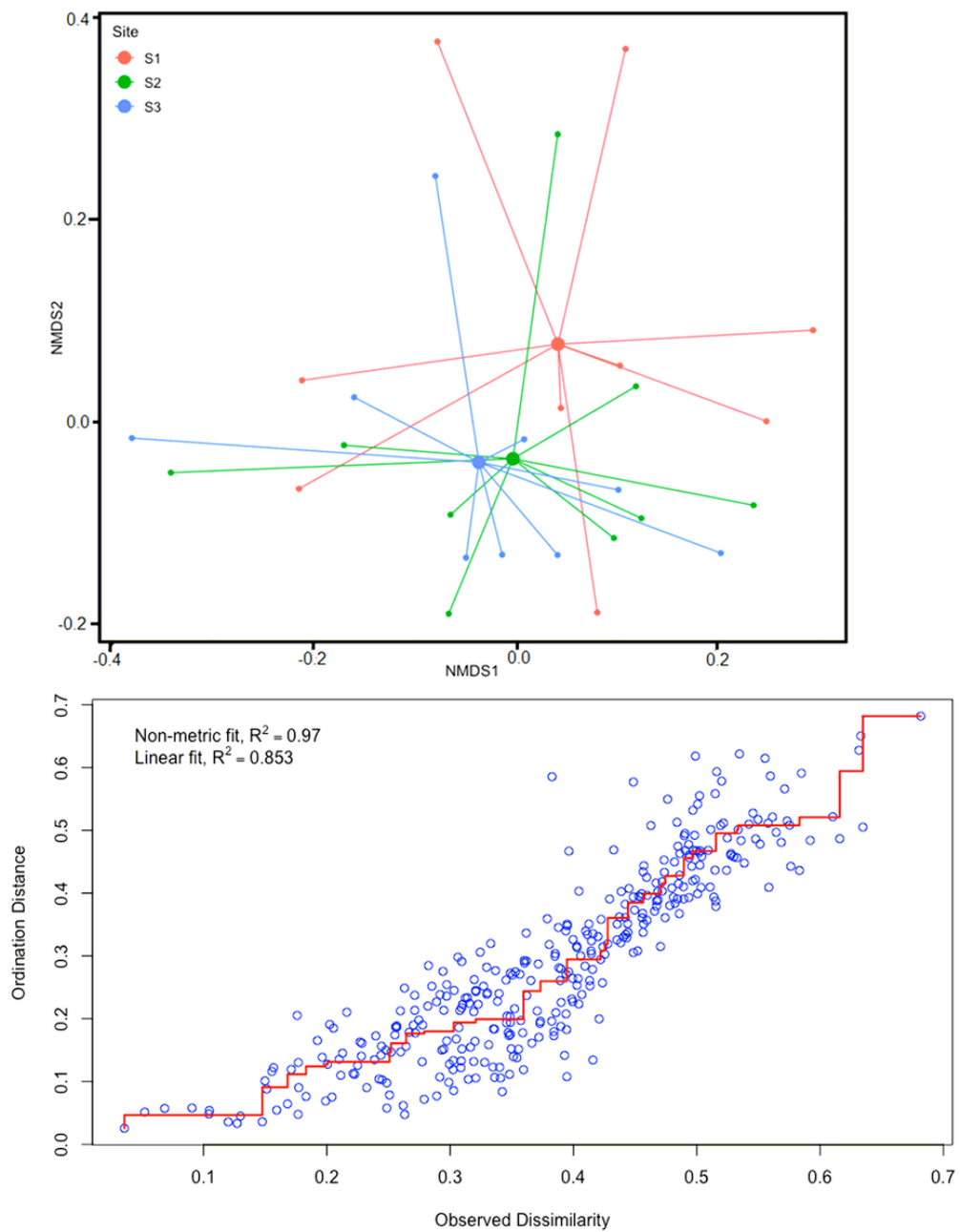
Figure 2

Spatial variability of the copepod community sampled before (February to December 2019) tropical cyclone Amphan from S1, S2 and S3 sites on Muriganga section of Ganges estuary, India.
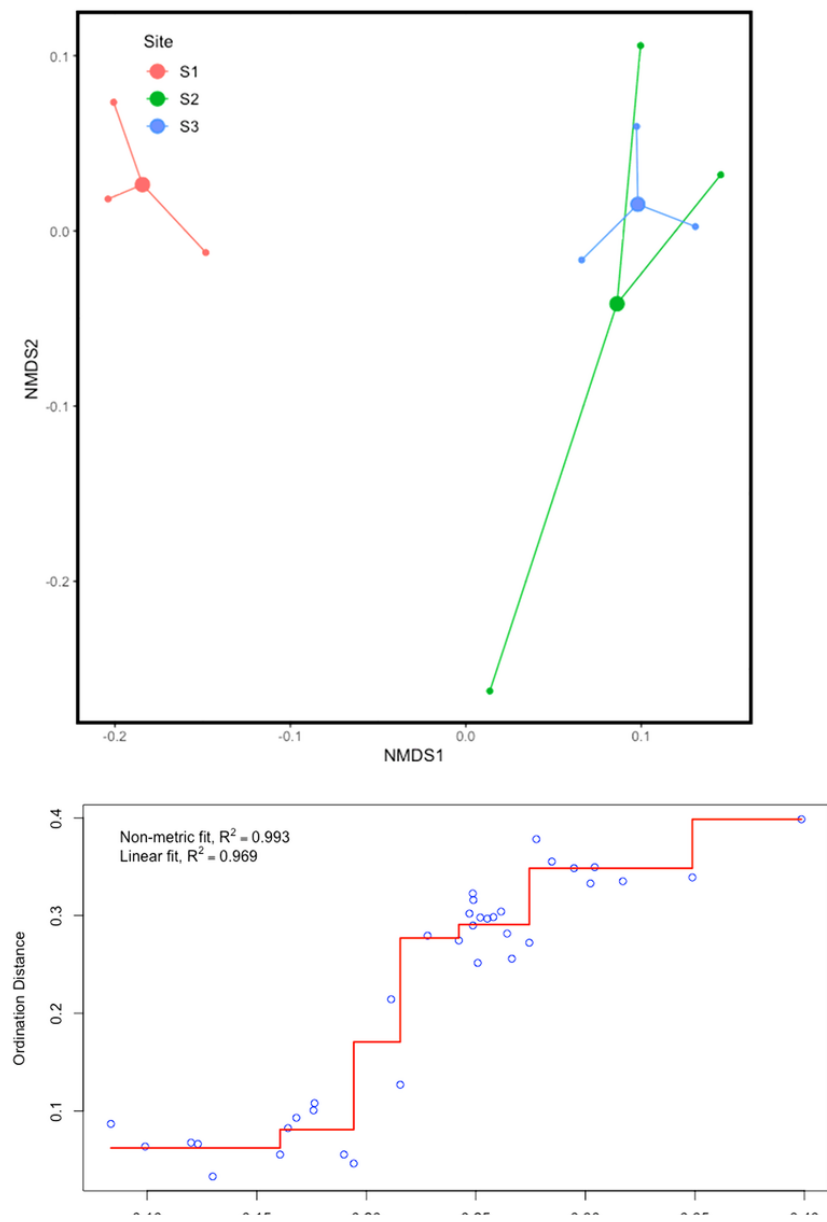
Figure 3

Spatial variability of the copepod community sampled shortly after (31 May to 12 June 2020) tropical cyclone Amphan from S1, S2 and S3 sites on Muriganga section of Ganges estuary, India.
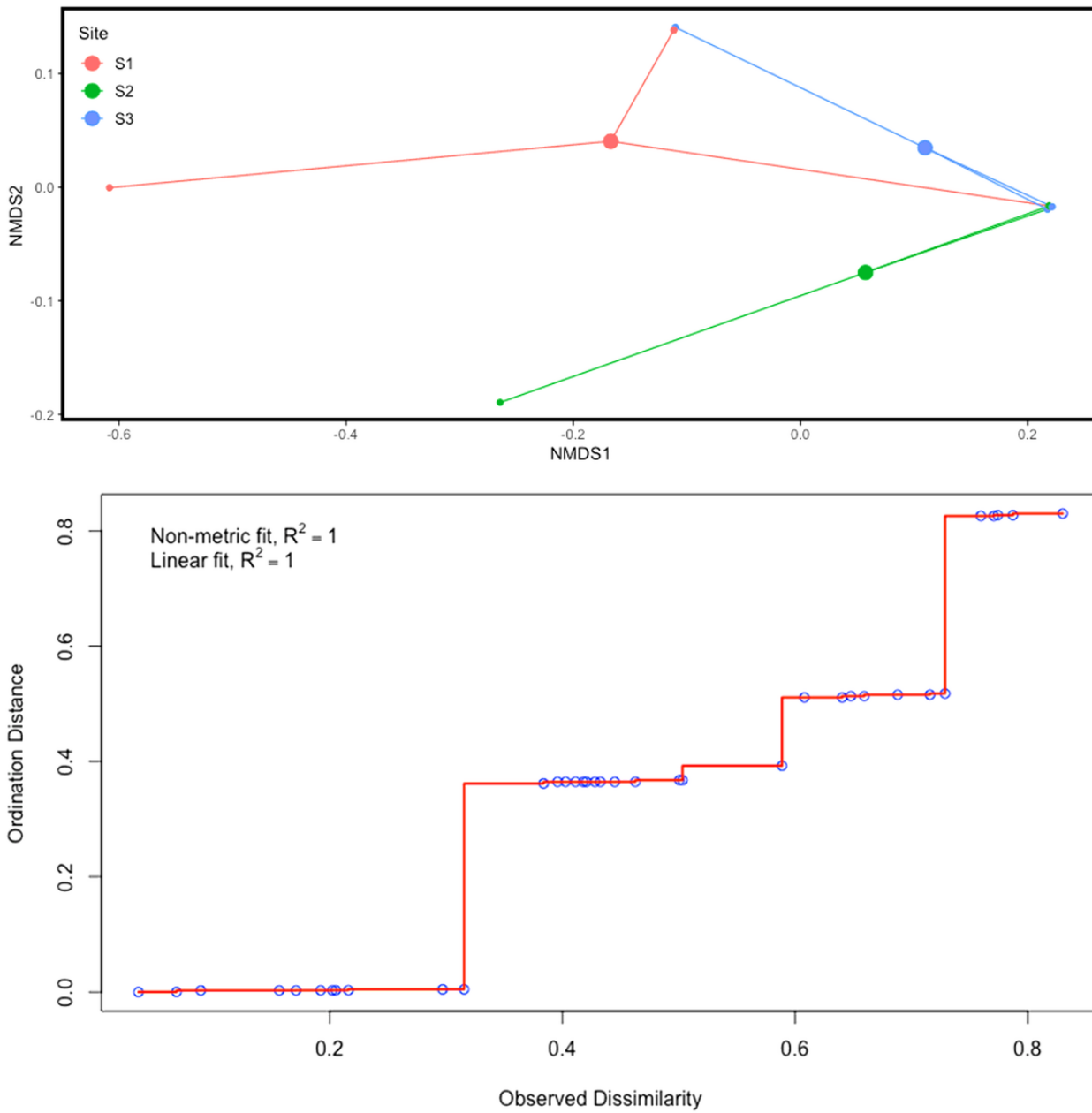
Figure 4

Spatial variability of the copepod community sampled post (September to November 2020) tropical cyclone Amphan from S1, S2 and S3 sites on Muriganga section of Ganges estuary, India.
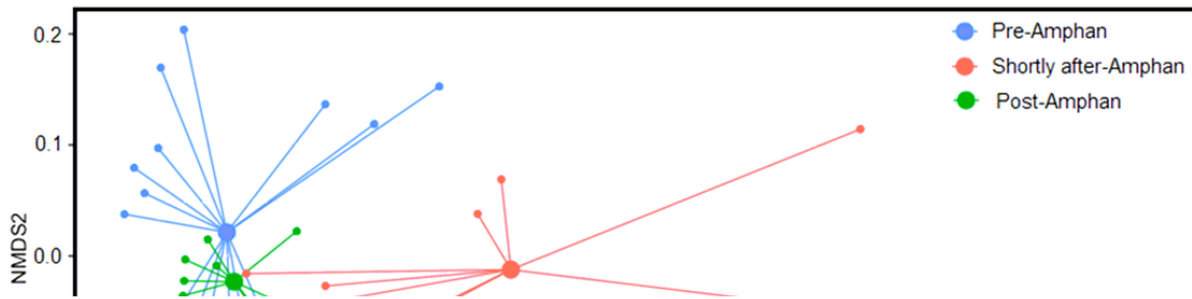
Figure 5

Temporal variability of the copepod community sampled from Muriganga section of Ganges estuary, India in pre- (February to December 2019), shortly after- (31 May to 12 June 2020) and post- (September to November 2020) tropical cyclone Amphan.