

## Distributional characteristics of surface-layer mesozooplankton in the Bay of Bengal during the 2005 winter monsoon

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Present study consists spatial patterns in biomass, abundance and composition of mesozooplankton in Bay of Bengal. Surface samples were collected from a central open ocean transect along 88°E and western coastal transect during the 2005 winter monsoon. During the sampling period, both sea level- and sea surface temperature anomalies inferred from satellite imagery were the lowest at the southern stations of the western Bay transect. These anomalies coincided with the highest biomass and abundance of zooplankton, of copepods in particular. Western region was richer in biomass and abundance compared to the central waters. Zooplankton community comprised 28 taxonomic groups. Predominant copepod community exhibited low species richness with just 46 identified species. They were evenly distributed over stations and their diversity did not vary much between oceanic and coastal transects. Copepod *Undinula vulgaris* was common in the oceanic waters and *Temora stylifera* in the coastal. This study highlights the occurrence of pockets of dense zooplankton biomass in the moderately productive (primary) bay.

**[Keywords:** Mesozooplankton, Copepods, Spatial distribution, Bay of Bengal]

### Introduction

Bay of Bengal, a semi-enclosed basin in the northeastern Indian Ocean, experiences seasonally reversing monsoons<sup>1</sup>. With some of the major rivers of the subcontinent draining into it and precipitation exceeding evaporation, the surface waters particularly in its northern extent are typically low in salinity. During the winter monsoon, the cool dry northeasterlies of  $\sim 5\text{-}6\text{ m s}^{-1}$  predominate over the Bay and the equatorward flowing East India Coastal Current weakens and decays<sup>2</sup>.

Observations on epipelagic zooplankton in the Bay began mostly during the International Indian Ocean Expedition (IIOE). While the biomass and taxonomic details of mesozooplankton are reported in earlier studies<sup>3-8</sup>, detailed analyses on surface dwelling community composition are sparse. As a part of the Bay of Bengal Process Studies (BoBPS) programme, mesozooplankton samples were collected from the surface with the aim of understanding spatial differences in biomass and composition of surface dwelling zooplankton.

Copepods form an important bulk of the zooplankton, transferring energy from the primary

producers (phytoplankton) to tertiary producers. Information on their abundance and species compositional would improve our understanding of how assemblages vary across the salinity and productivity gradients of this Bay. One hypothesis tested during this study is that the freshwater lens in the surface maintains zooplankton assemblages unique to a low-saline/estuarine environment. In order to elucidate this aspect, sampling was carried out as a part of the Bay of Bengal process Studies programme during 2001-2006<sup>7-9</sup>. Since copepods comprised over 90% of total zooplankton abundance at most locations, their species composition was investigated in greater detail to explore differences between oceanic and coastal communities.

### Materials and Methods

Zooplankton samples were collected during December 3-31, 2005 on the cruise 240 of "FORV Sagar Sampada" along two transects shown in Fig. 1. Four stations (WB1-WB4) were sampled in the Western Bay (WB) which is along the east coast of India and five stations (CB1-CB5) along an oceanic transect in the Central Bay (CB). Due to the narrow steep continental shelf, the depth at some coastal stations exceeded 1000 m. A Bongo net (Hydrobios;

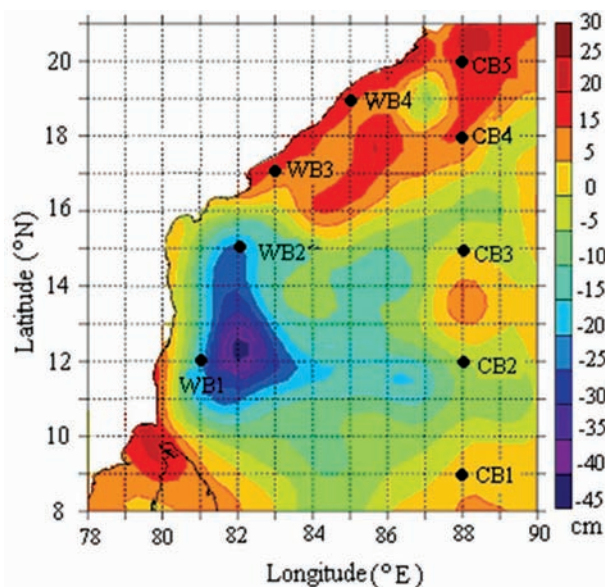


Fig. 1—Location of sampling stations (●) in the Bay of Bengal. Stations WB1-WB4 are along the western Bay/ east coast of India. CB1-CB5 are along 88°E in the central Bay, Topex/Poseidon ERS1/2 merged sea-level anomalies during the time of sampling are also shown.

mouth area 0.28 m<sup>2</sup>, mesh size 300 μm) was towed horizontally at dusk for a duration of 10 min (ship speed 2 knots) to collect zooplankton. The net was fitted with a calibrated digital flow meter (Hydrobios, Model 438 110) to quantify the volume of water filtered.

Biomass was measured volumetrically<sup>10</sup> (ICES 2000) after removing large detrital particles. For this, samples from each station were filtered onto a 200-μm mesh net-piece; excess water was blotted out using absorbent paper and transferred to a measuring cylinder with a known volume of water to determine the volume displaced. Thereafter, the samples were fixed with 4% buffered formaldehyde-seawater solution and brought to the laboratory for enumeration and identification.

For conversion of zooplankton volume to carbon biomass, dry weight was considered to be 7.5% of displacement volume and, 34.2% of the dry wt as carbon<sup>11</sup>.

Simultaneous measurements of sea surface temperatures (SST, °C) and salinity (PSU) were made using a CTD (conductivity, temperature, depth; *Sea Bird Electronics*) attached to a rosette sampler fitted with Go Flo bottles. Dissolved oxygen concentration

from water samples collected was measured by Winkler's method<sup>12</sup>. In addition to in situ measurements of hydrographic data, satellite data was also used. Merged sea-level anomalies and geostrophic velocities obtained from Topex-Poseidon/ERS1/2 satellites (<http://las.avisio.oceanobs.com>) were examined during the study period. Surface chlorophyll concentration was derived from the monthly mean SeaWiFS (<http://reason.gsfc.nasa.gov/OPS/Giovanni/ocean.seawifs.shtm>) global 9-km imagery.

Depending on the volume, the samples were subsampled by Folsom splitter and aliquots used for enumeration of zooplankton taxa under a 70X stereo-zoom microscope (Olympus SZH 10). All zooplankton were identified to the taxonomic group level<sup>13</sup>. Only copepods, the most abundant taxon were identified to species level by following<sup>14,15</sup>.

Using the data on species abundance, Shannon diversity ( $H_2$ ), species richness ( $d$ ), and species evenness ( $J_2$ ) indices were calculated<sup>16-18</sup>. In order to explore the spatial distribution of copepod species, the copepod species abundance data were first tested for normality by the Kolmogorov–Smirnov and Lilliefors tests (STATISTICA 6). Data was then transformed logarithmically ( $\log [x+1]$ ) in order to reduce the relative differences between the abundant and rare species. Cluster analysis was done using the log-transformed species data and group average method of linking Bray-Curtis similarity (PRIMER 5). The non parametric Spearman correlation (STATISTICA 6) was computed to test the effect of environmental variables on the biotic components studied in this investigation.

## Results

Sea surface temperature in the Western Bay (WB) was <27°C with the coolest temperatures at WB1 and WB2. Surface salinity which varied from 32.02 to 33.24 psu was lower at WB4. Dissolved oxygen concentration that ranged from 216 to 224 μm was greatest at WB2 (Table 1). Sea Level Anomaly (SLA) was strongly positive at the two northern stations while around the southern stations WB1 and WB2, it was highly negative. Geostrophic velocity maps (Fig. 2) during the sampling period also showed large-scale cyclonic circulation around the southern stations.

Table 1

Station	Temperature (°C)	Salinity	DO (µm)
<i>Western Bay</i>			
WB1	26.49	33.24	220
WB2	26.48	33.09	224
WB3	26.88	33.00	216
WB4	26.84	32.02	220
<i>Central Bay</i>			
CB1	28.64	33.25	209
CB2	28.66	32.93	211
CB3	28.57	32.20	213
CB4	27.86	32.40	221
CB5	26.79	32.63	220

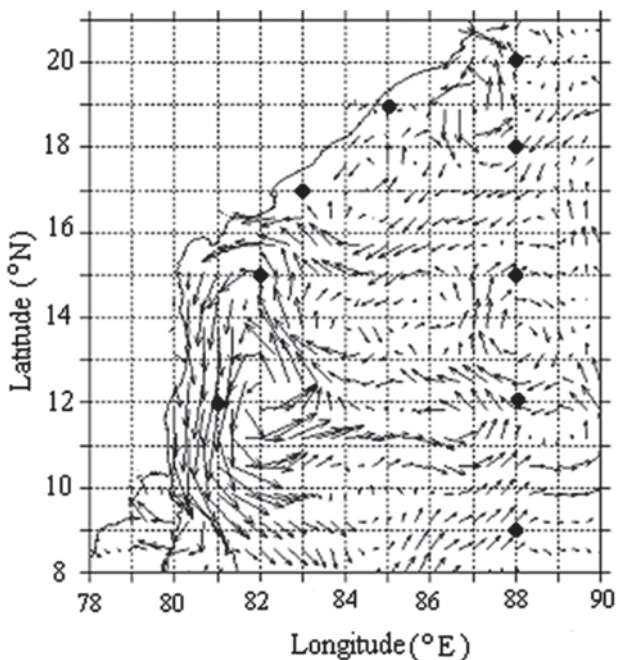


Fig. 2–Geostrophic velocities ( $cm s^{-1}$ ) in the Bay of Bengal derived from Topex/Poseidon ERS1/2 during the time of sampling. Dark circles (•) indicate sampling stations.

Higher chlorophyll (chl) *a* concentration in the range of 0.3-1.0  $mg m^{-3}$  was recorded in the entire western Bay (Fig. 3). Satellite imagery depicted a large zone of high chl *a* associated with the cyclonic eddy between 10° and 15°N and 81° and 86°E, covering the stations WB1 and WB2.

Sea surface temperature was warmer than 28°C in the southern stations of the Central Bay (CB) and

decreased northwards to a minimum of 26.8°C at CB5 (Table 1). Sea surface salinity was lower in the northern locations and ranged from 32.20 to 33.25 psu. The dissolved oxygen content ranged from 209-220 µm and was more in the northern stations.

Sea level anomalies (SLA) were positive near stations CB1 and CB5 (Fig. 1). Chl *a* concentration was low along this entire oceanic transect (Fig. 3), ranging from ~0.1  $mg m^{-3}$  at CB1 to 0.2  $mg m^{-3}$  at stations north of it.

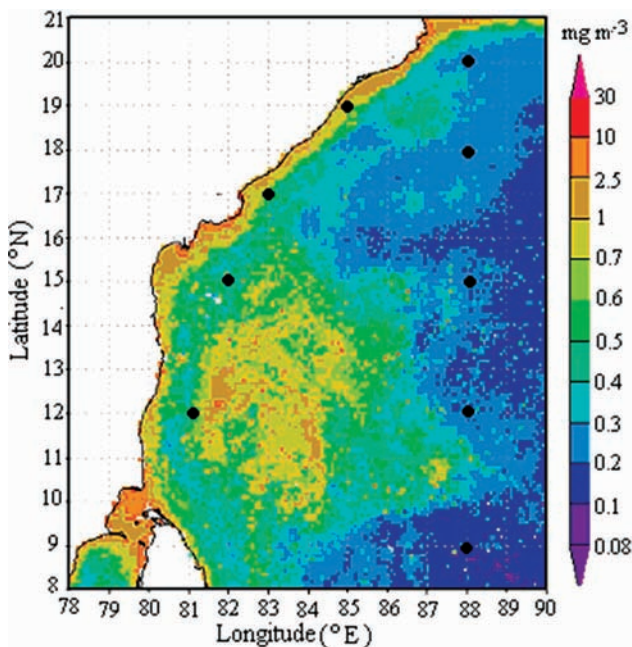


Fig. 3–Distribution of SeaWiFS sea surface chlorophyll concentration in the Bay of Bengal. Dark circles (•) indicate sampling stations.

Biovolume of zooplankton in the WB ranged from 0.5 to 6.2 (average  $2.5 \pm 2.7$ )  $mL m^{-3}$  (Fig. 4). This is equivalent to carbon biomass of 12.4-159.8 ( $63.1 \pm 68.8$ )  $mg C m^{-3}$ . The numerical abundance varied from 759 to 9769 ( $3471 \pm 4262$ ) individuals  $m^{-3}$  with low numbers in the northern location. The correlation between biomass and abundance was highly significant ( $R=0.98, p<0.05$ ).

In the CB, biovolume varied from 0.1 to 0.7 ( $0.4 \pm 0.3$ )  $mL m^{-3}$  (Fig. 4). It was quite low at the southernmost and the northernmost stations and was higher between CB2 and CB4. Zooplankton carbon biomass in this transect was 1.3-17.9 ( $9.8 \pm 7.9$ )  $mg C m^{-3}$ . The numerical abundance ranged from 53 to 632 ( $279 \pm 236$ )  $ind.m^{-3}$  and was higher at CB2 and CB5.

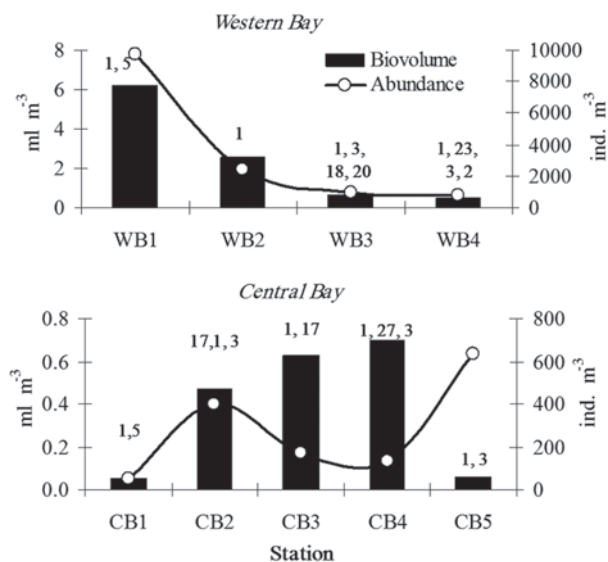


Fig. 4—Variation of zooplankton biovolume and abundance at different stations in the western and central Bay of Bengal. Figures on each histogram denote the taxonomic groups contributing >5% to the total abundance (Refer to Table 2 for the per cent contribution of each group).

Biomass and abundance was six and 12 times lower than in the western transect.

During this study, 28 diverse groups of zooplankton were found, the composition of which varied widely between stations (Table 2). In the WB, the predominant copepods ranged from 50 to 93% with the highest proportion at WB2 (Table 2). At WB1, decapod larvae were the second most in abundance. At WB3, chaetognaths (8.3%), euphausiids (4.5%) and siphonophores (4.5%) were other important groups. At WB4, invertebrate eggs accounted for a considerable percentage (26%), followed by chaetognaths (11%) and appendicularians (4.8%).

In the CB too, copepods constituted the single largest taxon comprising 50->80% except at CB2 where echinoderm larvae made up to 61% of the total zooplankton abundance. Apart from the copepods, the relatively large sized decapod larvae and appendicularia were the only taxa that were found at CB1. The second most important taxa at CB2, CB3

Table 2

Gr. No	Groups	% abundance at different stations									
		WB1	WB2	WB3	WB4	CB1	CB2	CB3	CB4	CB5	
1	Copepoda	<b>87.76</b>	<b>92.61</b>	<b>75.08</b>	<b>49.71</b>	<b>89.66</b>	<b>30.90</b>	<b>83.26</b>	<b>50.40</b>	<b>84.39</b>	
2	Appendicularia	0.31	1.34	0.50	<b>4.79</b>	3.45	0.10	-	-	0.42	
3	Chaetognatha	3.37	1.62	<b>8.29</b>	<b>11.18</b>	-	<b>4.84</b>	2.90	<b>18.95</b>	<b>8.72</b>	
4	Polychaeta	0.10	1.97	0.69	0.13	-	-	1.34	0.40	-	
5	Decapoda	<b>4.49</b>	0.42	3.01	0.00	<b>6.90</b>	1.24	2.68	2.82	0.14	
6	Lucifer	1.43	0.07	2.39	-	-	1.03	2.46	0.81	0.14	
7	Acetes	-	0.25	0.25	-	-	-	-	-	-	
8	Thalassocaris	2.65	-	0.13	-	-	0.21	-	2.02	-	
9	Sergestes	0.20	0.04	0.06	-	-	-	-	-	-	
10	Unidentified decapod	0.10	-	-	-	6.90	-	-	-	-	
11	Brachyuran zoea	-	0.04	0.19	-	-	-	-	-	-	
12	Megalopa	0.10	0.04	-	-	-	-	0.22	-	-	
13	Mysida	0.51	-	0.06	0.32	-	-	-	0.81	0.14	
14	Stomatopoda	-	-	0.13	-	-	-	-	-	-	
15	Amphipoda	0.20	0.18	0.06	0.13	-	0.51	2.01	1.21	0.14	
16	Isopoda	-	-	-	-	-	-	-	0.81	-	
17	Ostracoda	0.92	-	0.19	0.06	-	-	-	1.21	-	
18	Pteropoda	0.10	0.07	0.13	0.19	-	0.21	0.22	1.21	0.14	



19	Cephalopoda	-	-	0.00	-	-	0.10	-	-	-
20	Gastropoda	-	-	0.06	-	-	-	1.12	-	-
21	Bivalvia	-	-	0.06	-	-	-	0.22	-	-
22	Pterotrachea	-	-	-	-	-	-	-	0.40	-
23	Cladocera	0.20	-	-	-	-	-	-	-	-
24	Echinodermata	-	-	0.06	0.45	-	<b>60.76</b>	<b>4.46</b>	2.82	-
25	Euphausiacea	0.61	0.07	<b>4.46</b>	0.26	-	-	-	1.61	-
26	Medusae	0.10	-	0.94	0.70	-	-	-	-	0.42
27	Siphonophora	0.61	0.04	<b>4.52</b>	2.43	-	-	0.22	2.02	3.80
28	Salpida	0.20	0.21	0.44	1.53	-	-	0.22	1.61	0.28
29	Doliolida	0.31	0.04	0.13	0.51	-	-	0.45	0.81	0.28
30	Invertebrate eggs	-	1.09	0.38	<b>25.56</b>	-	0.72	-	1.61	0.56
31	Fish egg	-	-	-	-	-	-	-	-	0.56
32	Fish larva	-	-	0.38	0.13	-	-	-	0.81	-
33	<i>Amphioxus</i>	0.10	0.35	0.25	0.19	-	-	-	0.40	-
34	Foraminifera	0.10	-	0.19	1.60	-	0.62	0.89	<b>10.08</b>	-
35	Radiolaria	-	-	-	0.13	-	-	-	-	-
	Individuals 100 m <sup>-3</sup>	976947	239159	96254	75879	5259	40290	17348	13387	63235

\*dominant groups (e<sup>5</sup>% of total zooplankton abundance) at stations are highlighted in bold

and CB5 were the copepods (31%), echinoderm larvae and chaetognaths respectively. At CB4, chaetognaths and foraminifera accounted for 19% and 10% respectively.

In the WB, Calanoida was the most abundant, contributing 75% to the total copepod abundance. Under this order, 29 species in 18 genera within 12 families were identified. *Temora* spp. was the dominant calanoid and contributed 10-26% (Table 3). The other dominant calanoids were *Acrocalanus longicornis* and *Eucalanus crassus* at WB1 and WB2. At WB3, *Centropages furcatus*, *Cosmocalanus darwinii*, *Euchaeta marina* and *Calocalanus pavo*

were more in numbers. Nine species of Poecilostomatoida from 3 genera in 3 families contributed 16% to the total copepod abundance. Among these, *Oncaea* spp. and *Sapphirina* sp. were preponderant. *Oithona* spp. (3-24%), the only genus from a single family identified under Cyclopoida was found in higher abundance in this transect. No harpacticoids were found in the WB.

In the CB, 25 calanoid species belonging to 18 genera and 11 families were identified. These comprised 71% of the total copepod individuals. *Undinula vulgaris* was the predominant calanoid at four of the five stations (Table 3). Its abundance

**Table 3**

Species	% abundance at different stations								
	WB1	WB2	WB3	WB4	CB1	CB2	CB3	CB4	CB5
<i>Canthocalanus pauper</i>	-	-	-	-	3.85	7.81	1.85	-	-
<i>Cosmocalanus darwinii</i>	1.61	-	9.09	4.35	-	-	1.85	-	-
<i>Undinula vulgaris</i>	-	-	-	-	19.23	10.94	31.48	22.73	-
<i>Candacia bradyi</i>	1.61	-	-	-	-	<b>6.25</b>	<b>9.26</b>	<b>13.64</b>	-
<i>Candacia pachydactyla</i>	-	-	-	-	<b>7.69</b>	3.12	-	-	-
<i>Candacia</i> spp.	3.23	<b>4.65</b>	-	-	-	1.56	-	-	<b>13.21</b>

<i>Centropages calaninus</i>	1.61	2.33	-	-	3.85	-	1.85	-	-
<i>C. furcatus</i>	-	-	<b>12.12</b>	4.35	-	3.12	1.85	-	-
<i>Clausocalanus</i> spp.	-	1.16	-	4.35	-	1.56	-	-	3.77
<i>Eucalanus crassus</i>	<b>8.06</b>	<b>6.98</b>	3.03	-	-	-	-	-	-
<i>E. elongates</i>	1.61	1.16	-	-	-	-	1.85	-	-
<i>E. mucronatus</i>	1.61	-	-	-	-	-	-	-	-
<i>E. pseudoattenuatus</i>	1.61	-	-	-	-	-	-	-	-
<i>Pareucalanus attenuatus</i>	1.61	-	3.03	4.35	3.85	1.56	1.85	-	-
<i>Euchaeta indica</i>	1.61	1.16	-	-	-	1.56	1.85	-	1.89
<i>E. marina</i>	-	-	<b>6.06</b>	4.35	-	1.56	1.85	-	-
<i>Euchaeta</i> spp.	1.61	-	-	-	-	<b>4.69</b>	1.85	-	1.89
<i>Pleuromamma indica</i>	1.61	2.33	-	4.35	-	-	-	<b>22.73</b>	1.89
<i>Pleuromamma</i> sp.	1.61	-	-	-	-	-	-	-	-
<i>Acrocalanus longicornis</i>	<b>17.74</b>	<b>16.28</b>	-	-	<b>7.69</b>	-	-	-	<b>7.55</b>
<i>Acrocalanus</i> spp.	-	-	3.03	4.35	-	<b>9.37</b>	3.7	-	1.89
<i>Calocalanus pavo</i>	-	1.16	<b>6.06</b>	4.35	-	-	-	4.55	1.89
<i>Paracalanus indicus</i>	-	2.33	3.03	-	-	-	-	-	-
<i>P. parvus</i>	-	-	-	4.35	3.85	-	-	-	-
<i>Paracalanus</i> spp.	<b>4.84</b>	-	3.03	-	3.85	3.12	-	-	-
<i>Calanopia elliptica</i>	1.61	-	-	-	-	-	-	-	-
<i>Labidocera pavo</i>	-	-	-	4.35	-	1.56	-	-	1.89
<i>Pontellina plumata</i>	1.61	1.16	-	4.35	-	1.56	1.85	<b>4.55</b>	-
<i>Rhincalanus cornutus</i>	1.61	-	-	-	-	-	-	-	-
<i>Scolecithrix danae</i>	-	-	-	-	-	1.56	<b>5.56</b>	<b>4.55</b>	-
<i>Scottocalanus helenae</i>	1.61	3.49	3.03	-	-	1.56	-	-	<b>9.43</b>
<i>Temora discaudata</i>	<b>11.29</b>	4.65	-	-	-	-	-	-	-
<i>T. stylifera</i>	<b>9.68</b>	<b>16.28</b>	<b>12.12</b>	<b>26.09</b>	-	3.12	-	<b>4.55</b>	<b>28.3</b>
<i>Oithona</i> spp.	3.23	<b>24.42</b>	<b>15.15</b>	-	-	-	1.85	<b>4.55</b>	-
<i>Macrosetella gracilis</i>	-	-	-	-	-	-	1.85	-	-
<i>Oncaea venusta</i>	1.61	-	3.03	<b>8.7</b>	<b>7.69</b>	<b>4.69</b>	<b>7.41</b>	-	3.77
<i>Oncaea</i> sp.	<b>6.45</b>	3.49	<b>9.09</b>	<b>8.7</b>	3.85	-	-	-	<b>16.98</b>
<i>Corycaeus catus</i>	-	-	-	4.35	3.85	-	-	-	-
<i>C. danae</i>	1.61	-	-	-	-	<b>4.69</b>	-	<b>4.55</b>	-
<i>C. longistylis</i>	1.61	-	-	-	-	<b>11.54</b>	<b>4.69</b>	3.7	1.89
<i>C. speciosus</i>	-	-	3.03	-	-	<b>11.54</b>	-	-	-
<i>Corycaeus</i> spp.	1.61	2.33	-	4.35	-	-	1.85	<b>4.55</b>	1.89
<i>Farranula carinata</i>	-	-	-	-	-	-	1.85	-	-
<i>Copilia quadrata</i>	-	-	-	-	-	-	-	<b>4.55</b>	-
<i>Copilia</i> sp.	3.23	3.49	-	-	-	1.56	1.85	-	1.89
<i>Sapphirina</i> sp.	-	-	<b>6.06</b>	-	3.85	<b>18.75</b>	<b>11.11</b>	<b>4.55</b>	-
Total individuals 100 m <sup>-3</sup>	857320	221493	72266	37721	4715	12448	14443	6748	53363
Number of species	28	18	16	16	14	23	22	12	16

\*dominant species (e"5% of total copepod abundance) at stations are highlighted in bold

ranged from 11% to 31%. At CB4, *Pleuromamma indica* was also predominant. At the northern most station CB5, abundance of *Temora stylifera* (28%) was notable. The other numerically important calanoid species were mostly from families Candaciidae, Paracalanidae and Scolecitrichidae and, rarely from Euchaetidae and Pontellidae. 11 species of Poecilostomatoida from 5 genera within 3 families constituted 28% of the total copepods. The poecilostomatoid *Oncaea* spp. occurred in the same abundances as in the WB, however species of *Corycaeus*, *Copilia* and *Sapphirina* were highly abundant mostly at the southern stations of the CB. Copepods from Cyclopoida were represented by a single species *Oithona* (none-4.55%). The lone harpacticoid species *Macrosetella gracilis* was found at just one station in the CB accounting for <1% in abundance.

Though a total of 46 copepod species was recorded, the number of species found in each transect was about the same with 39 species in WB and 38 in CB.

The total number of species (S) found at each station ranged from 16 to 28 in the WB and 12 to 23 in the CB (Fig. 5). While the number of species progressively decreased northwards i.e. from WB1 to WB4 in the western transect, they were found to be higher at CB2 and CB3 in the central transect. Species richness (d) ranged from 1.34 to 2.05 in the WB and 1.38 to 2.19 in the CB. Species evenness (J') was >0.8 at all stations in both transects. Shannon

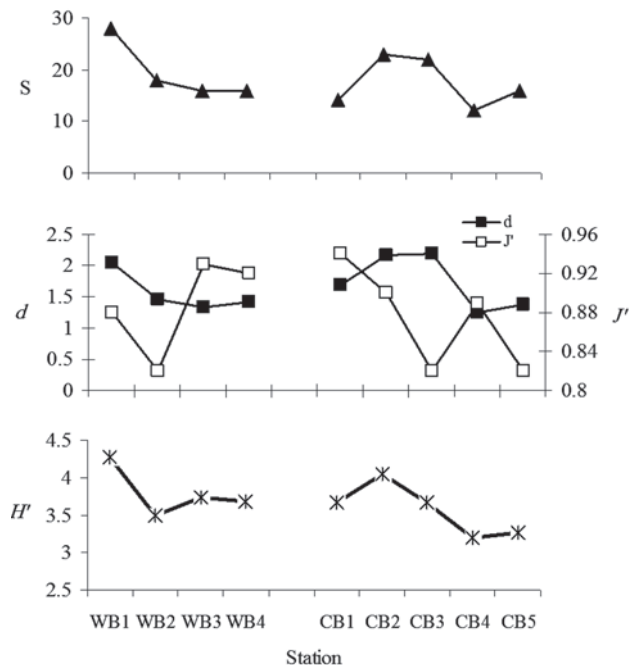


Fig. 5–Variation of total number of copepod species (S), species richness (d), species evenness (J') and Shannon and diversity (H') in surface waters of the western (WB1-WB4) and central (CB1-CB5) Bay during the 2005 winter monsoon.

diversity (H') ranged from 3.43 to 4.23 in the WB and 3.19 to 4.05 in the CB. It appeared to decrease towards northern stations.

Total zooplankton and copepod abundance correlated significantly negatively with temperature, and positively with chl a (Table 4). Temperature

Table 4

Parameters	N	Spearman R	t (N-2)	p-level
Biovolume & Temperature	9	-0.5500	-1.7424	0.1250
Biovolume & Salinity	9	-0.0167	-0.0441	0.9661
Biovolume & DO	9	0.5500	1.7424	0.1250
Biovolume & S	9	0.3899	1.1202	0.2996
Biovolume & d	9	0.0167	0.0441	0.9661
Biovolume & J'	9	-0.4577	-1.3620	0.2154
Biovolume & H'	9	0.0921	0.2446	0.8138
Biovolume chl a	9	0.5509	1.7463	0.1243
Biovolume SLA	9	-0.5022	-1.5367	0.1683
Abundance & Temperature	9	-0.8000	-3.5277	<b>0.0096</b>
Abundance & Salinity	9	0.2667	0.7320	0.4879
Abundance & DO	9	0.2833	0.7817	0.4600

Abundance & S	9	0.6950	2.5575	<b>0.0377</b>
Abundance & d	9	0.1167	0.3108	0.7650
Abundance & J'	9	-0.2204	-0.5977	0.5688
Abundance & H'	9	0.5858	1.9123	0.0974
Abundance chl <i>a</i>	9	0.8481	4.2357	<b>0.0039</b>
Abundance SLA	9	-0.4597	-1.3695	0.2132
Copepod abundance & Temperature	9	-0.8500	-4.2691	<b>0.0037</b>
copepod abundance & Salinity	9	0.2333	0.6349	0.5457
copepod abundance & DO	9	0.4167	1.2127	0.2646
copepod abundance & S	9	0.5594	1.7856	0.1173
copepod abundance & d	9	-0.0500	-0.1325	0.8984
copepod abundance & J'	9	-0.3560	-1.0079	0.3471
copepod abundance & H'	9	0.3849	1.1035	0.3063
copepod abundance chl <i>a</i>	9	0.7520	3.0180	<b>0.0194</b>
copepod abundance SLA	9	-0.4001	-1.1550	0.2860
S & Temperature	9	-0.1695	-0.4551	0.6628
S & Salinity	9	0.1017	0.2705	0.7946
S & DO	9	-0.1865	-0.5022	0.6310
S & SLA	9	-0.6667	-2.3665	<b>0.0499</b>
d & Temperature	9	0.3000	0.8321	0.4328
d & Salinity	9	0.1000	0.2659	0.7980
d & DO	9	-0.5667	-1.8196	0.1116
d & SLA	9	-0.5533	-1.7575	0.1222
J' & Temperature	9	0.4916	1.4936	0.1789
J' & Salinity	9	0.3390	0.9535	0.3721
J' & DO	9	-0.4577	-1.3620	0.2154
J' & SLA	9	0.1039	0.2764	0.7902
Temperature & DO	9	-0.7500	-3.0000	<b>0.0199</b>
DO and chl <i>a</i>	9	0.7311	2.8353	<b>0.0252</b>
Temperature & chl <i>a</i>	9	-0.6733	-2.4091	<b>0.0468</b>

**Bold r-values** significant at  $p < 0.05$

correlated significantly negatively with dissolved oxygen and chl *a*. Dissolved oxygen too showed good positive relation with chl *a*. Total number of species (S) correlated significantly positively with total zooplankton abundance and significantly negatively with sea level anomaly.

Cluster analysis is presented in Fig. 6. At <20% similarity level, the four open ocean stations CB1, CB2, CB3 and CB4 formed one cluster I and all four

stations from western Bay and CB5 from central Bay formed cluster II.

### Discussion

The western Bay of Bengal supports much higher zooplankton biovolume and abundance compared to the offshore areas during the 2005 winter. In contrast, during the summer monsoon of 2002, zooplankton biomass from the mixed layer was lower in the western Bay compared to the oceanic transect<sup>8</sup>.



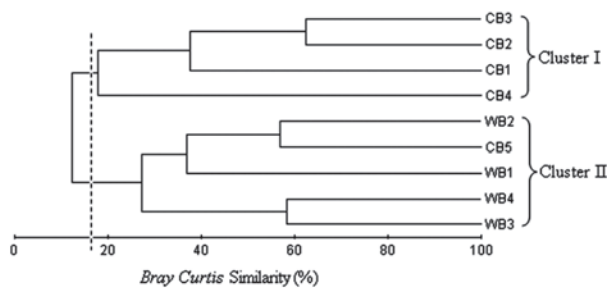


Fig. 6—Dendrogram showing site similarity of copepod species composition in the Bay of Bengal, based on Bray-Curtis Similarity Index (stations WB1-WB4 are from the western Bay, CB1-CB5 are from the central Bay; Refer to Fig. 1 for their locations).

During the present study, the biomass that ranged from 12.4 to 159.8 mg C m<sup>-3</sup>. However the biomass in the CB is about similar to that reported by Jyothisbabu *et al.* (2004) and is higher than that of<sup>19</sup> for the Indian Ocean along 110°E during winter.

Though the Bay experiences a perennial warm pool, the temperatures along the WB and in the northern CB were lower by ~2°C during this study. Since freshwater remains capped in the upper few meters of the Bay for most part of the year<sup>20</sup>, as Jyothisbabu *et al.* (2004) suggest, the winter cooling does not lead to convective mixing as a result of intense low-salinity-induced stratification. La Fond and Varadachari<sup>21,22</sup> have reported upwelling in the WB during the winter monsoon. High zooplankton biomass in particular at WB1 and WB2 coincided with lower temperature and increased dissolved oxygen concentration. Negative sea level anomaly, anticlockwise circulation and dense chlorophyll patch at these two locations are indicative of upwelling-like features around the time of sampling. This is supported by the observation that zooplankton/copepod abundance correlated significantly negatively with temperature and significantly positively with chlorophyll.

Enhanced chl *a* concentrations were earlier ascribed to circular cyclonic features near WB1 and WB2 and, CB5<sup>23</sup>. As seen from the SeaWiFS monthly mean chl *a* map, the central transect with chl *a* concentration between 0.1 and 0.3 mg m<sup>-3</sup> was the most oligotrophic around the southernmost station CB1, where both biomass and abundance of zooplankton were the lowest. The northernmost station, CB5 where the numerical abundance of

zooplankton was high was closer to a circular cyclonic water movement, where a denser chl *a* patch was seen. In addition to this, silica mainly from rivers fuel diatom production towards the north of the Bay<sup>24</sup>. Aggregations of grazers associated with enhanced chlorophyll concentrations following the phytoplankton bloom have been normally found in coastal and oceanic waters<sup>25,26</sup>. Increased zooplankton biomass in cold-core eddies has been reported in the western- and central Bay of Bengal<sup>7</sup>.

Copepods comprising 31-93% of the total zooplankton abundance were generally the most abundant taxon similar to many earlier studies in the Bay<sup>27, 6-9</sup>, Arabian Sea<sup>28, 29, 30</sup> as well as in other oceans<sup>31,32,33</sup>. It is interesting to note that echinoderm larvae which never appeared in significant numbers during any other season in the Bay<sup>8</sup> comprised 60% of the total zooplankton abundance at the oceanic station CB2. These meroplanktic larvae are mostly restricted to coastal areas<sup>34</sup>. Due to slower swimming rates<sup>35</sup>, they are mostly dispersed by surface currents<sup>36</sup> as observed in this study. Some echinoids, as<sup>37</sup> suggest, time their spawning period to phytoplankton blooms in winter so that their larvae benefit from a nutrient rich environment. Also as observed in Northwest Mediterranean, stratification is known to keep the larval abundance in surface waters<sup>34</sup>.

Similar to the observations of Nair *et al.*<sup>27</sup>, higher proportion of decapod larvae were found at the 12°N latitude in the coastal as well as oceanic waters. The presence of carnivores/omnivores chaetognaths, euphausiids, decapods and siphonophores that constituted an important bulk of the biomass at many locations would result in a significant removal of the surface phytoplankton through trophic cascading.

With species evenness >0.8 at all stations, apparently, the copepod species are relatively uniformly distributed at all stations. As Woodd-Walker *et al.*<sup>38</sup> suggest, this is a common feature in the tropics. High species evenness signifies community stability, which is dependent on the environment<sup>26</sup>. Thermohaline stratification of the surface waters is observed during most of the time of the year in the Bay<sup>20,23,27</sup>. In these studies, it was confirmed that freshwater exists as a surface lens throughout seasons in the area sampled. From our observations, we presume that this layer is not conducive for a large variety of copepod species

(species richness < 2.5). This statement is made in view of the relatively higher species richness that was observed when the mixed layer was vertically sampled<sup>7,9</sup>. As the zooplankton diversity increases with depth, comparatively more number of species were reported in the earlier studies carried out along the same transects. It must be also noted that diversity indices may be biased within the present data set due to the characteristic of the net mesh used (300 µm). Therefore, some smaller copepod species are likely to be poorly sampled and underestimated. Coupled closely with primary production, the secondary production in the tropics is also known to cause higher diversity in surface living copepods<sup>39,40</sup>. Further, the higher diversity at stations away from the coast along both transects can be ascribed to relatively stable environmental conditions.

Herbivorous calanoid species such as *Canthocalanus pauper* and *Undinula vulgaris* belonging to family Calanidae are common in the coastal waters of India (Nair *et al.*, 1981). However, their preponderance in CB points towards their advection by the EICC, which is equator-ward at this time of the year. As Lawson<sup>41</sup> suggest, the surface currents in the Bay allow the epipelagic species to extend their distribution throughout the basin. *U. vulgaris* has a widespread occurrence ranging from neritic tropical waters to open oceans<sup>42</sup>. Its ability to feed on wide array of phytoplankton and switch between several modes of feeding<sup>43</sup> (Turner 2008) allows a wide distribution of this species in this moderately oligotrophic Bay. Various feeding strategies of species such as coarse filter-feeding of calanoids/eucalanoids and fine particle feeding of *Acrocalanus* spp. and *Paracalanus* spp. helps them to coexist non-competitively in the surface layers of WB and CB.

The relatively higher abundance of Centropagiidae (*Centropages furcatus*) in WB and Pontellidae in the north is indicative of their ability to thrive in waters of low salinity<sup>44</sup> (Stephen 1992). Carnivorous copepods like candaciids were generally common in the CB though members of Euchetiidae were distributed along both transects. *Temora stylifera* which was dominant in the WB is a tropical-subtropical neritic copepod that was found to increase in abundance during winter in the Northeastern Atlantic<sup>45</sup>. This surface-living omnivorous copepod

that ingests a variety of phytoplankton is primarily an opportunistic herbivore<sup>46</sup>. It is also thought to be predatory<sup>47</sup>. It was thought to be endemic to the Atlantic Ocean<sup>48</sup> but has been recorded earlier in the Indian Ocean<sup>14,49,27</sup>.

The warm water fauna such as *Corycaeus* spp., *Copilia* spp. and *Sapphirina* spp.<sup>50</sup> were found in higher proportion in the CB between CB1 and CB4 where the temperature was between 27.8 and 28.6°C. However, the species of *Oncaea* with an ability to exploit the lower size spectrum of food<sup>51</sup> showed a more or less ubiquitous occurrence in spite of the bias in their abundance due to larger net mesh size used in this study. Peak depth of occurrence of *Pleuromamma indica*, a strong vertical migrator in the Bay is in the upper 200 m<sup>52</sup>. Fernandes<sup>7</sup> reported its higher abundance in the mixed layer at night at CB4 where the minimum dissolved oxygen concentration occurred at depths as shallow as 80 m. Higher abundance of this low-oxygen tolerant, oceanic species at this station indicates that it surfaces at dusk for feeding.

As indicated from cluster analysis, offshore stations CB1 to CB4 are similar in the distribution of the dominant species *Undinula vulgaris* (11-31%). All the coastal stations from the WB and the northernmost station (CB5) from central Bay had a predominance of low-salinity species *Temora stylifera* (10-28%). From this study it is understood that these two copepods are the key species at the sea surface in contrast to *Oncaea venusta* from the relatively thicker mixed layer<sup>8,9</sup>. It is also evident that copepod abundance and their species distribution pattern differ among the coastal and oceanic stations. The stations in proximity to the coast and those away from the coast harbor different key species. Similar trend is observed in the surface-zooplankton biomass and abundance between the central and western regions of the Bay during winter. It is apparent from this study that zooplankton biomass, abundance as well as the predominant copepod species are directly linked to the hydrographic features such as temperature, salinity, currents and food availability in the Bay of Bengal.

## Conclusion

From the information available, it seems that good fishery grounds occur in regions of high plankton

production. In Indian waters, a close relationship between the zooplankton biomass and the pelagic fishes<sup>53</sup>. However in stable tropical waters where constant replenishment of nutrients does not occur, the high fisheries potential is more localized<sup>54</sup>. For e.g. Pelagic fisheries of Tuna and other predatory fishes are observed in local enrichments at the high seas and, shoaling clupeoids are principally located in the coastal upwellings<sup>55</sup>. This study gives an indication of potential fishery grounds in the coastal and open ocean of the Bay of Bengal that contributes 33% to the two million tons annual fish catch of India<sup>56</sup> (CMFRI 2006). However for a more precise assessment of tertiary production and potential fishery zones, monitoring of zooplankton biomass and abundance must be carried out frequently on a seasonal and annual basis in order to ascertain whether the observed high biomass of zooplankton is short lived or is persistent in the particular region.

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