

## Trace metal dynamics in zooplankton from the Bay of Bengal during summer monsoon

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**ABSTRACT:** Trace metal (Fe, Co, Ni, Cu, Zn, Cd and Pb) concentrations in zooplankton from the mixed layer were investigated at 8 coastal and 20 offshore stations in the western Bay of Bengal during the summer monsoon of 2003. The ecotoxicological importance of trace metal uptake was apparent within the Bay of Bengal zooplankton. There was a distinct spatial heterogeneity of metals, with highest concentrations in the upwelling zones of the southeast coast, moderate concentrations in the cyclonic eddy of the northeast coast, and lowest concentrations in the open ocean warm gyre regions. The average trace metal concentrations ( $\mu\text{g g}^{-1}$ ) in coastal zooplankton (Fe,  $44,894.1 \pm 12,198.2$ ; Co,  $46.2 \pm 4.6$ ; Ni,  $62.8 \pm 6.5$ ; Cu,  $84.9 \pm 6.7$ ; Zn,  $7,546.8 \pm 1,051.7$ ; Cd,  $46.2 \pm 5.6$ ; Pb,  $19.2 \pm 2.6$ ) were higher than in offshore zooplankton (Fe,  $3,423.4 \pm 681.6$ ; Co,  $19.5 \pm 3.81$ ; Ni,  $25.3 \pm 7.3$ ; Cu,  $29.4 \pm 4.2$ ; Zn,  $502.3 \pm 124.3$ ; Cd,  $14.3 \pm 2.9$ ; Pb,  $3.2 \pm 2.0$ ). A comparison of average trace metal concentrations in zooplankton from the Bay of Bengal showed enrichment of Fe, Co, Ni, Cu, Zn, Cd and Pb in coastal zooplankton may be related to metal absorption from primary producers, and differences in metal concentrations in phytoplankton from coastal waters (upwelling zone and cyclonic eddy) compared with offshore waters (warm gyre). Zooplankton showed a great capacity for accumulations of trace metals, with average concentration factors of  $4,867,929 \pm 569,971$ ,  $246,757 \pm 51,321$ ,  $337,180 \pm 125,725$ ,  $43,480 \pm 11,212$ ,  $1,046,371 \pm 110,286$ ,  $601,679 \pm 213,949$  &  $15,420 \pm 9,201$  for Fe, Co, Ni, Cu, Zn, Cd and Pb with respect to dissolved concentrations in coastal and offshore waters of the Bay of Bengal.

**Key words:** Bay of Bengal; zooplankton; trace metals; bioavailability; bioaccumulation

# 1. INTRODUCTION

The toxicity of trace metals in the oceans is largely dependent on their concentration in seawater and in marine sources of food. However, both sources are integrated into accumulated concentrations in higher trophic level marine organisms (e.g. Zooplankton). This bioaccumulated fraction cannot be detected directly by measuring metal concentrations in the soluble phase; it can only be assessed by determining the amount of metal incorporated into whole organisms.

Zooplankton are ubiquitous in seawater, living throughout the water column, with a limited swimming capacity relative to large marine predators. They are the most abundant animals in the sea, and thus play an important role in the marine food chain. Zooplankton feed on phytoplankton and in turn form food for animals at higher trophic levels (Kleppel, 1993). Thus, zooplankton may contribute to the transfer of trace metals to higher trophic levels due to their significant capacity to bioaccumulate metals from their food, as well as from seawater. Due to these factors, zooplankton have been chosen as one of the recommended groups for base line studies of trace metals in the marine environment (Prosi, 1981; Stemberger and Chen, 1988; Wang and Fisher, 1998).

The North Indian Ocean is subjected to seasonally reversing monsoonal winds and wide-scale upper ocean circulation (Shankar et al., 2002). Thus the background concentration of metals in zooplankton are expected to show a minimum of anthropogenic influence from waters in the coastal belt, making the Bay of Bengal an interesting place for trace metal investigation. However natural events like algal blooms often contribute to metal availability and these phenomena are likely to influence the ecological system of the East and West Coast of India (Anoop et al., 2007; Jyothibabu et al., 2003, 2008; Madhu et al., 2006). Spatial studies of metal concentrations in surface zooplankton from the Indian Exclusive Economic Zone (EEZ) of the Arabian Sea and Bay of Bengal have revealed particularly high metal concentrations at river mouths, upwelling zones, and eddy mixing zones, in comparison to other areas (Rejomon, 2005; Rejomon et al., 2008). These areas were referred to as metal-anomalies within the zooplankton populations (Rejomon, 2005; Rejomon et al., 2008), and two mechanisms were hypothesized to have caused these observations: (1) increased metal bioavailability may have caused more effective uptake mechanisms to have evolved due to either specific accumulation strategies of organisms; or (2) a spatial heterogeneity of metal absorption from food items due to different feeding

strategies between zooplankton populations from river mouths, upwelling zones, and eddy mixing zones.

Along the East Coast of India, several large rivers (Brahmaputra, Ganges, Mahanadi, Godavari, Krishna and Kaveri) drain into the coastal waters and contribute to the terrestrially derived trace metal loads. These rivers deliver large quantities of sediment that are constantly moved north or south, depending on the direction and angle of wave approach with respect to the coast (Alagarsamy and Zhang, 2005; Kumar, 2006). In addition, the Bay of Bengal (Fig. 1) is also frequently influenced by upwelling and eddy mixing of metal-rich subsurface waters (50 to 75m) with surface waters. Both of these mechanisms increase metal availability in surface waters, without a large export of metals to deeper waters, and hence may increase metal availability for zooplankton (Rejomon, 2005). Earlier studies noted a high enrichment of trace metals in zooplankton from offshore waters compared with coastal waters, and suggested the possibility that metal accumulation in the Bay of Bengal zooplankton was due to the Bay's peculiar gyral circulation pattern (George and Kureishy, 1979). So far, little information about spatial fluctuations of background concentrations of trace metals in zooplankton from the Bay of Bengal is available. To fill this gap, trace metal concentrations in seawater and zooplankton from the upper mixed layer (ML) of the Bay of Bengal were investigated. Moreover, soluble metal concentrations from the ML gives a broader picture of both the environmental conditions of the area under investigation, to assess possible bioaccumulation patterns, and in turn, further helps determine whether or not zooplankton ecology is influenced by the source.

## 2. MATERIALS AND METHODS

As part of Marine Research-Living Resource Program (MRLR), trace metal distribution in seawater and zooplankton from the ML were studied in the Indian EEZ of the Bay of Bengal, during cruise 215 of the Fishery and Oceanographic Research Vessel (FORV) Sagar Sampada in July - August 2003. The investigation in the western Bay of Bengal, is based on samples (Fig. 1) along four transects perpendicular to the coast at 11.5°N, 13.5°N, 15.5°N and 17.5°N. Trace metal studies were performed on all transects at coastal (50m depth, inner shelf and 150m depth, outer shelf) and offshore stations (> 1000m depth). Seawater and zooplankton samples were collected from the ML on each transect in the case of inner shelf, outer shelf and offshore stations. The depth of the ML was determined as the depth where the density difference from the surface was  $> 0.2 \text{ kg m}^{-3}$  (Shetye et al., 1996). Water samples

were collected from standard depths (surface, 10m, 20m, 30m, 50m and 75m) within the ML only, with the number of sampling depths dependent on the depth of the ML.

Zooplankton samples were collected over the ML using a Hydrobios multiple plankton net (mouth area 0.25 m<sup>2</sup>, mesh width 200µm). Zooplankton samples were sorted under a binocular microscope and visually observed to ensure the absence of any foreign particles. Copepods were the most abundant taxa in the zooplankton samples, with chaetognaths, ostracods, and euphausiids the second most abundant taxa. Due to different potentials for bioaccumulation of trace metals in copepods, ostracods and euphausiids, the samples were sorted and only copepods (zooplankton) were used for the measurement of trace metals. The copepod samples were placed in a small nylon sieve and thoroughly rinsed with Milli-Q water to remove salts. Water adhering to the samples was removed by placing the sieve on laboratory filter paper, which introduced no contamination. Subsequently, the samples were dried in an oven at 65°C and stored in a vacuum dessicator.

Water samples were collected using a new PVC-coated stainless steel CTD-rosette sampler with pre-cleaned 5-litre Teflon coated Go-Flo bottles (General Oceanics Ltd). Upon recovery, samples were filtered directly from the Go-Flo samplers, under nitrogen pressure, through pre-weighed and acid washed 0.45µm membrane (Millipore) filters mounted on Teflon filter blocks to separate them into dissolved and particulate fractions. The filtered water samples were stored after acidifying with pure HCl to a pH of 2-3. Trace metals (Fe, Co, Ni, Cu, Zn, Cd and Pb) in seawater were extracted using Ammonium Pyrrolidene Dithio Carbamate-Methyl Isobutyl Ketone (APDC-MIBK; Brooks et al., 1967), and were analysed using a Graphite Furnace Atomic Absorption Spectrophotometer (GFAAS, ZL-4110). The detection limit is defined as the smallest amount of an analyte which would produce a signal equal to three times the value of the standard deviation of at least ten determinations from a blank solution. The detection limit of elements in the Graphite Furnace AAS (µg l<sup>-1</sup>) were found to be 0.098, 0.006, 0.004, 0.009, 0.095, 0.007 and 0.008 for Fe, Co, Ni, Cu, Zn, Cd and Pb, respectively.

Zooplankton samples were first powdered and aliquots of about 300mg were digested for 3 hours at 80°C with 300µl HNO<sub>3</sub> (65%, suprapure, Merck) in tightly closed 2 ml Eppendorf reaction tubes (Zauke et al. 1996a). These digests were diluted to 25ml with HCl (0.1N) and subjected to Flame Atomic Absorption Spectrophotometer (FAAS, *PE A Analyst100*). The signals of blanks, standards and samples were measured by aspirating the solutions into the atomizer using the optimized instrumental

conditions given in Table 1. The detection limit of elements in Flame AAS ( $\mu\text{g g}^{-1}$ ) were found to be 0.004, 0.010, 0.009, 0.002, 0.002, 0.001 and 0.030 for Fe, Co, Ni, Cu, Zn, Cd and Pb, respectively.

Bioaccumulation factors (concentration factors) were calculated for each metal and copepod as the ratio of the metal concentration in the organism's body relative to its concentration in the ambient seawater. All metal concentrations in seawater samples are reported in ppb, whereas in zooplankton the values are reported in ppm of dry weight.

Pearson's correlation coefficients were used to examine relationships between the different trace metals in the zooplankton.

Due to the limited number of independent replicates (represented by one MPN net haul for zooplankton sampling and one CTD cast at each depth for water sampling from each station), statistical evaluation of the data, is not applicable. Thus, comparisons between metal concentrations in seawater and zooplankton have to be done on a heuristic basis. Further, the reported metal concentration in water is done as mean dissolved metal concentrations from the ML of each station.

### 3. RESULTS

#### 3.1. Trace metal concentrations in water and zooplankton from coastal and offshore waters

The heuristic comparison of the metal concentrations detected in seawater and zooplankton from the ML of coastal and offshore sites relies on the concentration ranges, which are compiled in Tables 2 and 3. The metal concentrations in seawater and zooplankton of the coastal area vary depending upon the sampling sites [Station positions: B1, B2, B7, B8, B14, B15, B23 & B24 respectively]. Iron, cobalt, nickel, copper, zinc, cadmium and lead concentrations ( $\mu\text{g l}^{-1}$ ) in seawater ranged from 2.96 to 3.58, 0.134 to 0.188, 1.28 to 1.98, 1.27 to 1.98, 2.45 to 2.89, 0.041 to 0.058 and 0.511 to 0.785, respectively (with averages of  $3.32 \pm 0.25$ ,  $0.173 \pm 0.023$ ,  $1.74 \pm 0.29$ ,  $1.78 \pm 0.31$ ,  $2.74 \pm 0.18$ ,  $0.052 \pm 0.006$  and  $0.694 \pm 0.111$ ). In zooplankton ( $\mu\text{g g}^{-1}$ ), concentrations of iron, cobalt, nickel, copper, zinc, cadmium and lead ranged from 25137.1 to 52962.1, 38.2 to 49.8, 52.1 to 67.1, 73.1 to 89.5, 5800.3 to 8162.2, 36.2 to 49.8 & 14.8 to 21.8, respectively (with averages of  $44894.1 \pm 12198.2$ ,  $46.2 \pm 4.6$ ,  $62.8 \pm 6.5$ ,  $84.9 \pm 6.7$ ,  $7546.8 \pm 1051.7$ ,  $46.2 \pm 5.6$  and  $19.2 \pm 2.6$ ). Similar to the coastal areas, metal concentrations in

seawater and in zooplankton from the offshore area varied depending upon the sampling sites [Station positions: B<sub>3</sub>, B<sub>4</sub>, B<sub>5</sub>, B<sub>6</sub>, B<sub>9</sub>, B<sub>10</sub>, B<sub>11</sub>, B<sub>12</sub>, B<sub>13</sub>, B<sub>16</sub>, B<sub>17</sub>, B<sub>18</sub>, B<sub>19</sub>, B<sub>20</sub>, B<sub>21</sub>, B<sub>22</sub>, B<sub>25</sub>, B<sub>26</sub>, B<sub>27</sub> & B<sub>28</sub> respectively]. Iron, cobalt, nickel, copper, zinc, cadmium and lead concentrations ( $\mu\text{g l}^{-1}$ ) in seawater, ranged from 1.24 to 2.79, 0.045 to 0.124, 0.034 to 0.088, 0.48 to 1.68, 0.88 to 1.92, 0.018 to 0.042 & 0.114 to 0.496, respectively (with averages of  $2.36 \pm 0.44$ ,  $0.086 \pm 0.022$ ,  $0.057 \pm 0.018$ ,  $0.76 \pm 0.26$ ,  $1.44 \pm 0.38$ ,  $0.031 \pm 0.007$  and  $0.318 \pm 0.127$ ). In contrast, in zooplankton ( $\mu\text{g g}^{-1}$ ) the concentrations of iron, cobalt, nickel, copper, zinc, cadmium and lead ranged from 1135.2 to 4556.2, 13.8 to 24.8, 14.8 to 34.4, 22.8 to 35.3, 356.8 to 785.3, 9.3 to 18.8 & 1.5 to 7.7, respectively (with averages of  $3423.4 \pm 681.6$ ,  $19.5 \pm 3.81$ ,  $25.3 \pm 7.3$ ,  $29.4 \pm 4.2$ ,  $502.3 \pm 124.3$ ,  $14.3 \pm 2.9$  and  $3.2 \pm 2.0$ ).

Trace metal concentrations in seawater and zooplankton along the southeast transects (southeast coast), of the coastal stations off Nagapattanam, Madras, and Kakinada were found to be considerably higher than at the coastal stations off Vishakapatnam or at offshore stations on the southeast and northeast coasts. For instance, the average iron content ( $51470 \mu\text{g g}^{-1}$ ) in zooplankton off the southeast coast, ( $11.5^{\circ}$ - $15.5^{\circ}\text{N}/79.94^{\circ}$ - $80.59^{\circ}\text{E}$ ) showed a fifteen-fold and two-fold increase relative to the average iron content ( $3423$  &  $25164 \mu\text{g g}^{-1}$ ) in zooplankton from the offshore stations ( $11.5^{\circ}$ - $17.5^{\circ}\text{N}/82^{\circ}$ - $88^{\circ}\text{E}$ ) and northeast coast ( $17.5^{\circ}\text{N}/83.3^{\circ}$ - $84^{\circ}\text{E}$ ) of the Bay of Bengal. Similarly, the average cobalt and nickel content ( $48.7$  &  $66.1 \mu\text{g g}^{-1}$ ) in zooplankton off the southeast coast showed an enrichment of 1.25 and 2.5 relative to the average concentrations in zooplankton from the offshore stations ( $19.5$  &  $38.8 \mu\text{g g}^{-1}$ ) and northeast coast stations ( $25.3$  &  $52.6 \mu\text{g g}^{-1}$ ). Likewise, the average copper and cadmium content ( $88.5$  &  $49.3 \mu\text{g g}^{-1}$ ) in zooplankton off the southeast coast showed an enrichment of 1.2 and 3.0 when compared to the average concentrations in zooplankton from the offshore stations ( $29.2$  &  $74.2 \mu\text{g g}^{-1}$ ) and northeast coast stations ( $14.3$  &  $37.2 \mu\text{g g}^{-1}$ ). The average zinc content ( $8114.2 \mu\text{g g}^{-1}$ ) in zooplankton off the southeast coast showed an enrichment of 16.2 and 1.4 when compared to the average for zooplankton from the offshore stations ( $502.3 \mu\text{g g}^{-1}$ ) and northeast coast stations ( $5844.9 \mu\text{g g}^{-1}$ ). The average lead content ( $20.6 \mu\text{g g}^{-1}$ ) in zooplankton off the southeast coast also showed an enrichment of 1.4 and 6.7 when compared to the average content ( $3.1$  &  $15.2 \mu\text{g g}^{-1}$ ) in zooplankton from the offshore stations and northeast coast.

In general, metal concentrations in seawater and zooplankton from stations in the southeast coast region were found to be higher than those in the northeast coast or the offshore waters. Within the southeast coast region metal concentrations were quite homogeneous among stations. Similar to the

coastal waters, at offshore stations metal concentrations in seawater and zooplankton increased from the offshore end of the transects to an offshore belt in the middle of the southeast coast. The high concentrations of trace metals in zooplankton collected at coastal as well as offshore stations often coincided with high concentrations of dissolved metals, and hence their higher concentrations might be attributed to their higher concentrations existing in seawater.

### 3.2. Bioaccumulation of trace metals in zooplankton from the coastal and offshore waters

High metal bioavailability results in high concentrations of the corresponding metals in the biota through the bioaccumulation process. Bioaccumulation is referred to as the process by which a chemical compound or an element is accumulated into biota from its surrounding environment. Hence, bioaccumulation factors can provide knowledge of how enriched organisms are in particular elements, with respect to the surrounding environment.

The average concentration of trace metals in zooplankton ( $\mu\text{g g}^{-1}$ ), from the coastal as well as offshore waters of the Bay of Bengal (Table 4 & 5), showed the sequence  $\text{Fe} > \text{Zn} > \text{Cu} > \text{Ni} > \text{Co} > \text{Cd} > \text{Pb}$ . In coastal and offshore zooplankton, the essential element iron was the most enriched, while the non-essential elements Cd and Pb were the least enriched. However all the elements showed a relative enrichment in zooplankton from coastal waters compared with offshore waters. Thus, iron and zinc ( $44894$  &  $7546 \mu\text{g g}^{-1}$ ) showed a 13 and 15-fold increase in zooplankton from coastal waters when compared to zooplankton from offshore waters ( $3423$  &  $502 \mu\text{g g}^{-1}$ ). Similarly, lead was 6 times higher in zooplankton from coastal waters compared with those in offshore waters ( $19.2$  and  $3.2 \mu\text{g g}^{-1}$ , respectively). Likewise, cobalt, nickel, copper, and cadmium ( $46.2$ ,  $62.8$ ,  $84.9$  &  $42.2 \mu\text{g g}^{-1}$ ) were also enriched (2.4 to 2.9 times) in zooplankton from coastal waters compared to offshore zooplankton ( $19.5$ ,  $25.3$ ,  $29.4$  &  $14.3 \mu\text{g g}^{-1}$ ).

Since bioaccumulation factors represent the potential of organisms to bioaccumulate trace metals, a comparative ranking of bioaccumulation factors was also done. The bioaccumulation factor is evaluated in relation to the concentration of the soluble metal in the environment. The data shown in Table 4 & 5 confirm the high capacity of the zooplankton as bioaccumulators of trace metals. The average bioaccumulation factor of elements in zooplankton from the coastal waters (Table 4), followed the order  $\text{Fe} > \text{Zn} > \text{Cd} > \text{Co} > \text{Cu} > \text{Ni} > \text{Pb}$ , whereas in offshore waters (Table 5), it followed the order  $\text{Fe} > \text{Cd}$

> Ni > Zn > Co > Cu > Pb. The bioaccumulation factor for all metals, except nickel, is higher in coastal zooplankton. Although the order of bioaccumulation factors varies between environments, Fe is always the highest and Pb is always the lowest.

### 3.3. Inter-metal relationships in zooplankton from the coastal and offshore waters

Possible associations among the trace metals (inter-metal correlations) found in the zooplankton were assessed by means of Pearson's correlation coefficients (Tables 6 & 7). The correlations between the different metals in the zooplankton may result from similar accumulation behavior of trace metals and metabolic interactions. Thus, significant correlations were found among most of the metals present and this may reflect a common source of occurrence and subsequent accumulation into the zooplankton. These inter-metal relationships for essential and non-essential metals have been regarded as indicative of similar biogeochemical pathways for metal accumulation in zooplankton. In coastal zooplankton, the correlation matrix showed more significant inter-metal relationships and the essential metal Fe showed a high correlation with Co, Ni, Cu, Zn, Cd and Pb. A high inter-metal correlation between the toxic metals Cd and Pb is also noteworthy. However in the offshore zooplankton, the essential metal Fe showed a weak correlation between Co, Ni, Cu, Zn, Cd and Pb. Pempkowiak et al. (2006) also noted similar inter-metal correlations between the essential and non-essential metals in zooplankton from the Southern Baltic.

## 4. DISCUSSION

### 4.1. Spatial variations of trace metals in water and zooplankton from the coastal and offshore areas of the Bay of Bengal

Trace metal concentrations in seawater and zooplankton peaked in the northeast coastal region (17.5°N/83.3°-84°E), then receded within a coastal belt (11.5°-15.5°N/79.94°-80.59°E) in the southeast coastal region. Similar to coastal areas, concentration of metals in seawater and zooplankton in offshore areas decreased offshore of 11.5°N, 13.5°N, 15.5°N and 17.5°N, and slowly increased again at the end of the transects. Metal concentration peaked in a middle offshore belt (13.5°-15.5°N/82°-88°E) of the southern Bay.



Trace metals in the Bay of Bengal are likely enriched during summer monsoons due to high riverine influxes, and mixing of subsurface with surface waters through upwelling and cyclonic eddies. These trace metals may ultimately become available to the biota. Nevertheless, the riverine waters enriched with trace metals draining in the coastal belt are replaced by subsurface waters of high salinity (Table 8), penetrating towards the coastal zone of shelf waters by Ekman drift on the southeast coast and cyclonic eddy pumping on the northeast coast during the summer monsoon (Shetye et al., 1991; Muraleedharan et al., 2007). Further, the low salinity waters that drift offshore and are considered to be the predominant carriers of trace metals, are further upwelled by a warm gyre in the southern Bay of Bengal, potentially making trace metals available for offshore zooplankton (Muraleedharan et al., 2007). Thus, the predominant inputs of trace metals to the coastal zone of the Bay of Bengal are long-range transport by deep oceanic water mass exchanges and locally from river discharges as the summer cooling proceeds; zooplankton inhabiting the coastal belt eventually become more enriched in dissolved metals than offshore zooplankton.

The peak of metal concentrations in zooplankton from the coastal waters is found to coincide with an upwelling system along the southeast coast and a cyclonic eddy along the northwest coast. Offshore, the peak in trace metal concentrations is found to be consistent with an anti-cyclonic warm gyre in the southern Bay of Bengal, as described by Muraleedharan et al. (2007). They described the hydrodynamics of the Bay of Bengal during the summer monsoon of 2003, which supports the hypothesis regarding metal-anomalies in zooplankton. Thus, the distinct spatial variations of metals in zooplankton we observed in the Bay of Bengal ML was likely caused by differences in metal bioavailability. This may have been due to different (bio-) accumulation strategies of the zooplankton, or to spatial heterogeneity of metal absorption by the food (phytoplankton) for zooplankton. Differences in trace metal absorption in phytoplankton may have arisen due to variations in salinity, temperature, nutrient regime and/or taxonomy between the various ecological regimes. These regimes are determined by hydrographic processes in the water column (Brown and Depledge, 1991).

In order to further assess the observed enrichment patterns of trace metals in zooplankton from the Bay of Bengal, spatial variability in hydrobiological properties and zooplankton ecology must also be assessed. Average values for the depth range of the mixed layer (ML), ML temperature, ML salinity, mesozooplankton biovolume and copepod abundance (as reported by Muraleedharan et al., 2007) at the three different hydrographical regimes are presented in Table 8. In the upwelling zone (11.5°-

15.5°N/79.94°-80.59°E) the base of the ML is found at ~ 27 m, whereas in the cyclonic eddy region (17.5°N/83.3°-84°E) it is ~ 38 m and in the warm gyre (13.5°-15.5°N/82-88°E) it is deeper and ~74 m. The ML temperature in the upwelling zone ranged from 26.82 to 27.37°C, whereas in the cyclonic eddy it was cooler than either than the upwelling zone or warm gyre and ranged from 26.39 to 26.82°C. In the warm gyre the temperature is considerably warmer than either the cyclonic eddy or the upwelling zone and ranged from 28.70 to 28.86°C. Salinity ranged from 34.30 to 34.41 psu in the upwelling zone and was more saline than either the cyclonic eddy or the warm gyre. The warm gyre was characterized by low saline waters of 33.56 to 33.76 psu, whereas the cyclonic eddy was characterized by moderately saline waters of 34.10 to 34.18 psu. Mesozooplankton biovolume was highest (1.12 ml m<sup>-3</sup>) in the upwelling zone with an abundance of 1697 ind. m<sup>-3</sup> of copepods, with moderate biovolume ( 0.67 ml m<sup>-3</sup>) in the cyclonic eddy and an abundance of 1036 ind. m<sup>-3</sup> of copepods. The lowest biovolume (0.14 ml m<sup>-3</sup>) was found in the warm gyre, with an abundance of 310 ind. m<sup>-3</sup> of copepods. These patterns in mesozooplankton biovolume closely followed a shallowing of the ML towards the coast from the open ocean regions of the Bay of Bengal.

Information regarding water masses in the three hydrographic regimes suggest that the reported salinity differences are too low (upwelling zone 34.30 to 34.41 psu; cyclonic eddy 34.10 to 34.18 psu; and warm gyre 33.56 to 33.76 psu) to cause different metal speciation for the dissolved metals. Moreover, the different patterns of enrichment of dissolved metal concentrations in the ecological regimes of the Bay of Bengal did not support the hypothesis that the observed spatial differences of metal concentration in zooplankton might be related to metal bioavailability and different accumulation strategies in organisms. However, the spatial trend in the metal content of zooplankton closely follows the abundance patterns of copepods noted in the ML of the various ecological regimes (upwelling zone 1697 ind. m<sup>-3</sup>; cyclonic eddy 1036 ind. m<sup>-3</sup>; and warm gyre 310 ind. m<sup>-3</sup>). These regimes are in turn delineated by contrasting hydrographic processes, causing spatial heterogeneity of metals in zooplankton populations in the Bay of Bengal. This view is also further supported by the fact that diurnal variations of mesozooplankton standing stocks was highly insignificant in the ML of the upwelling zone, due to a high availability of (prey) food as a consequence of higher phytoplankton biomass occurring there compared to the cyclonic eddy or warm gyre regions of the Bay of Bengal (Muraleedharan et al., 2007).

The concentration of trace metals in zooplankton have rarely been reported in the literature, and is especially scarce from the north Indian Ocean. Here we consider the Bay of Bengal background

concentrations of metals observed in biota as natural, and compare the data regionally (see 3.1 section) and to reported values from other regions of the world. However, the expression “background levels” must be used with some caution, as its meaning differs according to the local geochemical or hydrodynamic conditions of the body of water under examination (Conti, 2002). Petri and Zauke (1993) reported trace metal concentrations ( $\mu\text{g g}^{-1}$ ) of 3.8-9.5 for Cd, 53-107 for Cu, 49-63 for Zn, and 0.4-1.4 for Pb in zooplankton from the Antarctic Peninsula. They also reported trace metal concentrations ( $\mu\text{g g}^{-1}$ ) of 12-13 for Cd, 67-93 for Cu, 44-46 for Zn, and 0.8-1.6 for Pb in zooplankton from the Weddell Sea. Ritterhoff and Zauke (1997) determined trace metal concentrations ( $\mu\text{g g}^{-1}$ ) in zooplankton from the Greenland Sea, and their reported values were 0.3-0.6 for Cd, 4-6 for Cu, 0.3-0.5 for Pb, and 86-389 for Zn. Kahle and Zauke (2003) also determined trace metal concentrations ( $\mu\text{g g}^{-1}$ ) in zooplankton from the Weddell Sea, and their reported values were 0.02-0.08 for Co, 4.3-11.4 for Ni, 11-26 for Cu, 183-518 for Zn, 3.7-10.2 for Cd, and 0.2-0.7 for Pb. Similar concentrations of Zn ( $320 \mu\text{g g}^{-1}$ ) but with relatively higher concentrations of Cd ( $7.5 \mu\text{g g}^{-1}$ ), Pb ( $33 \mu\text{g g}^{-1}$ ) and Cu ( $55 \mu\text{g g}^{-1}$ ) were also reported for mixed copepods off Mauretania (Everaarts et al., 1993).

The average trace metal concentrations in zooplankton (Table 9) in the Bay of Bengal were higher than those reported from the Arctic and Antarctic Oceans. This is probably because the environment of the Bay of Bengal is more enriched in trace metals (see the second paragraph of the section 4.1, about the sources for enriching metals in the upper ocean), than the presumably pristine environments found in the Arctic and the Antarctic Oceans.

Bioaccumulation factors for metals represent the outcome of many processes involved in the bioaccumulation of metals in zooplankton. Hence, the bioaccumulation of metals in zooplankton depends upon bioavailability, the amount of dissolved metal uptake, the physiological efficiency of the organism to excrete excess metals, as well as on the feeding rate and prey availability (Rainbow, 1997). The ranking of bioaccumulation factors for all elements except Fe and Pb, also varied between coastal and offshore zooplankton. Differences in the bioaccumulation factors for elements like Co, Ni, Cu, Zn and Cd compared with the essential element Fe and non-essential element Pb, might be related to different physiology of copepods feeding in coastal and offshore waters. This hypothesis can be supported by the fact that copepods from the ML of coastal waters were influenced by summer cooling due to upwelling and eddy mixing of subsurface waters, and appeared to have different feeding

behaviours, whereas copepods from the ML of the offshore waters were influenced by warming due to a freshwater induced warm gyre.

Further, the bioaccumulation factors for all the elements (except nickel) are higher in coastal waters, and the bioaccumulation factors followed the same order for Fe and Pb only in the coastal and offshore zooplankton. All other elements showed variations that were likely due to variations in the passage of these metals through the trophic food chain, which may be more important than dissolved metal uptake in coastal and offshore waters (Wang, 2002). The concentration of a metal in herbivores is attributable to uptake from food and has shown to be dependent on the concentration of the metal in the phytoplankton food and the assimilation efficiency of ingested metal in the herbivore (Wang and Fisher, 1999). Thus, the high bioaccumulation factors for the metals like Fe, Co, Cu, Zn, Cd & Pb in coastal zooplankton, compared to offshore zooplankton can be attributed to variation in the concentration factor of metals in the algal food chain in coastal and offshore waters. The high bioaccumulation factor of Ni in offshore zooplankton is attributed to the assimilation efficiency of this ingested element in copepods from the highly enriched Ni in coastal waters and slightly enriched Ni in offshore waters (Hook and Fisher, 2002).

#### 4.2. Hypothesis for metal anomalies in zooplankton

Metal anomalies in zooplankton refer to: (1) the occurrence of individual copepods, of the same species, with both low and high metal concentrations within the same water mass; and (2) comparatively higher metal concentrations in zooplankton in the Bay of Bengal compared with zooplankton from other oceans, such as the Arctic and Antarctic (Rejomon, 2005). The results presented in this paper supports such metal anomalies in the copepods from the coastal and offshore waters of the western Bay of Bengal. This view is further supported by the pronounced increase of metal concentrations in zooplankton from warm gyre to cyclonic eddy, and further increases in the upwelling zone. Substantial differences were also reported on more local scales, with an order of magnitude higher trace metal concentrations in copepods from coastal waters than offshore waters. Coastal zooplankton are under direct anthropogenic influence from the coast, with heavier riverine influence than offshore waters. Offshore waters are influenced by basin-scale physical mixing processes, including cyclonic eddies during winter monsoon in the western Bay of Bengal (Rejomon et al., 2008).

### 4.3. Further spatial and seasonal assessment of detected metal concentrations in water and zooplankton

The high metal concentrations in zooplankton found in this study are broadly in agreement with data from other regions of the world. Studies on the taxonomic composition and behaviour of mesozooplankton in the ML of the Bay of Bengal by Muraleedharan et al. (2007) showed that despite significant differences in the abundance of various taxa of zooplankton, diurnal variations in standing stocks are found to be less significant as one moves from the warm gyre to cyclonic eddy and to the upwelling zone. However, the differences in trace metal enrichment in zooplankton observed from the upwelling zone, cyclonic eddy and warm gyre are significant. There are a number of possible explanations for these differences: (1) changing bioavailability of trace metals due to different (bio-)accumulation strategies of the copepods present; (2) spatially enhanced metal availability in coastal waters caused by river runoff and deeper water (50- 75m) outcropping to surface layers, as a result of upwelling and eddy mixing (Everaarts et al. 1993; Rejomon, 2005); and (3) changing metal absorption in copepods from food items during upwelling while they are intensively feeding on phytoplankton, although the food uptake path is less relevant in the cyclonic eddy and irrelevant in the warm gyre (Muraleedharan et al., 2007). The reduced water temperature and complex effects of upwelling plays a prominent role in structuring of phytoplankton communities in the upper ocean. In turn, this affects zooplankton communities, which have longer life cycles as shown by higher biomass due to higher food availability in the mixed layer (Madhupratap et al. 1990; Muraleedharan et al. 2007). The longer life cycles of zooplankton promote higher accumulation of trace metals from the high food chain bioavailability of metals due to intensive feeding on the high phytoplankton biomass at the upwelling zone, compared with the cyclonic eddy and warm gyre regions (Muraleedharan et al. 2007). Such long life cycles are also evident for copepods in the upwelling zone in response to reduced water temperatures and longer feeding periods, which promote a higher accumulation of trace metals in zooplankton from the North Sea (Fransz et al. 1991).

To explore seasonal variations in the trace metal concentration of seawater and zooplankton in the Bay of Bengal, we compared the average metal concentration in seawater and zooplankton during summer monsoon from the Bay of Bengal (Table 9), to the reported average metal concentrations in seawater ( $\mu\text{g l}^{-1}$ ) [Fe-2.34, Co-0.076, Ni-0.046, Cu-0.895, Zn-1.38, Cd-0.026 & Pb-0.306] and zooplankton ( $\mu\text{g g}^{-1}$ ) [ Fe-14073, Co-24.2, Ni-29.5, Cu-46.2, Zn-2000, Cd-18.7 & Pb-6.55] during

winter monsoon from the Bay of Bengal (Rejomon et al., 2008). The average metal concentrations in the seawater and zooplankton during the summer monsoon (present study) are considerably higher than those found during the winter monsoon. Nevertheless, consistent seasonal and spatial variations in the heterogeneity of trace metals in the upwelling zone, cyclonic eddy and warm gyre, suggests that trace metal absorption into zooplankton from their food. A decrease in the enrichment of trace metals in zooplankton from the upwelling zone to cyclonic eddy, and further into the warm gyre. This is coincident with a decrease in abundance of zooplankton across the same regions, due to varying food availability in these ecological regimes. An increase in feeding rate by zooplankton from winter monsoon to summer monsoon are also likely to cause enrichment in trace metal concentrations in zooplankton from the Bay of Bengal during the summer monsoon. Further evidence for spatial and seasonal variations in metal concentration of zooplankton in relation to the life cycle has been provided for copepods from Mumbai waters, and experimentally derived for other oceanic regions (Zauke et al., 1996b; Nair et al., 1999).

Dissolved metals available to zooplankton in the Bay of Bengal can be taken up by zooplankton from more than one route, depending on the habitat and ultimately the physiology of the species concerned (Rainbow, 1995; Kahle and Zauke, 2002). For example, zooplankton metal uptake may be related to the response of a species to events like upwelling, or passage between the cyclonic eddy and warm gyre. The relative importance of these different routes varies between trace metals and zooplankton species, and is related to the ecology of the species concerned (Rainbow et al., 1990; Ritterhoff and Zauke, 1997). The physico-chemistry of trace metal speciation in solution is also important in releasing the free metal ion, typically the bio-available form, but the physiological responses of zooplankton species may also affect uptake rates (Rainbow, 1995). However such a pathway is quite implausible in the Bay of Bengal (see fifth paragraph of the 3.1 section). This view is further supported by the fact that metals are not only taken up from the soluble phase but also from absorption from the food (Wang and Fisher, 1998), where adsorption of metals to the surfaces of zooplankton cannot occur in the water column (Kahle and Zauke, 2003). Indeed, the ecophysiological adaptations required by zooplankton living in the upwelling zone, cyclonic eddy or warm gyre regions, each with varying physico-chemical environments, as well as the the pre-adaptations of zooplankton to coping with changes in metal bioavailability from the food chain, are significant, and likely to be important in the food chain of the Bay of Bengal (Rainbow, 1997; Wang, 2002; Muraleedharan et al., 2007). Future studies must determine how metal bioavailability is influenced by such factors.

This study found significant variability in trace metal concentrations in zooplankton, which were induced by: (1) spatial differences in the bioavailability of trace metals from primary producers in the food web in different ecological regimes; and (2) seasonal variations in metal concentrations in zooplankton. Specific accumulation strategies of zooplankton did not explain the differences observed. Moreover, this study found that the enrichment of dissolved metals was related to the relative abundance of zooplankton in the upwelling zone and cyclonic eddy. The zooplankton distribution at coastal and offshore stations showed that copepods constituted > 80 % of the population. High zooplankton biomass dominated by a single group (copepods) may be the result of enrichment of organic matter (e.g. iron), in the Bay of Bengal waters. Further, virtually all the dissolved metals are related to the ecology of the zooplankton community of the area, and hence can recirculate quickly from dead animals back into new, living individuals by the action of physically forced chemical changes in the water column.

## 5. CONCLUSION

Trends of increasing metal concentrations in zooplankton from the north to south (cyclonic eddy to upwelling zone), at shelf areas as well as southeast open ocean regions (warm gyre), of the Bay of Bengal give rise to the hypothesis that increasing metal bioavailability occurs because of complex hydrological processes occurring in the various ecological regimes found, and are not dominated by anthropogenic impacts. Metal concentrations within seawater and zooplankton populations of the various hydrographic regimes change in response to the differing ecological regimes. These regimes are determined by hydrographic processes like upwelling, cyclonic eddies and warm gyres, and future studies should focus on metal concentrations in phytoplankton and the primary food web of the Bay of Bengal.

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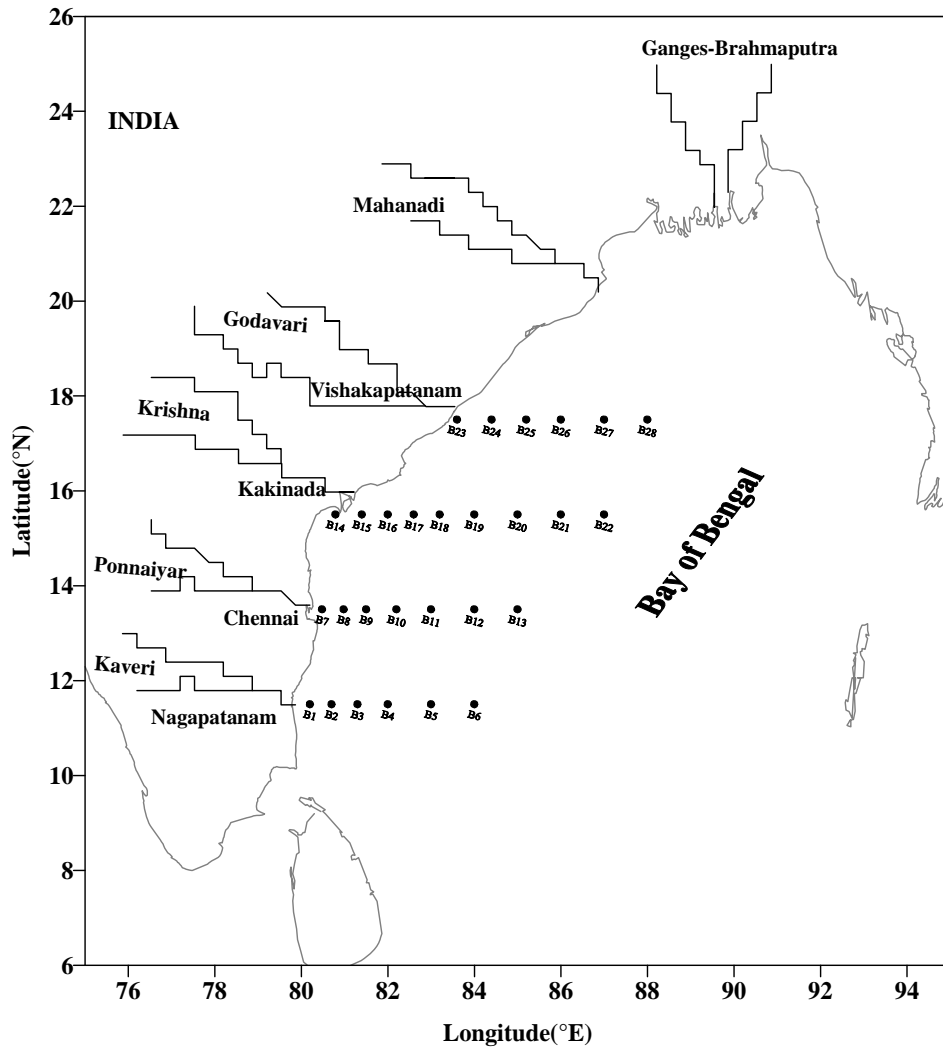
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**Fig. 1.** Map of the study area with station locations.

**Table 1.** Optimum instrumental conditions for metal analysis by Flame Atomic Absorption Spectrophotometer

Element	Wavelength (nm)	Slit width (nm)	Flame
Fe	248.3	0.2	Air-acetylene
Co	240.7	0.2	Air-acetylene
Ni	232.0	0.2	Air-acetylene
Cu	324.8	0.7	Air-acetylene
Zn	213.9	0.7	Air-acetylene
Cd	228.8	0.7	Air-acetylene
Pb	283.3	0.7	Air-acetylene

**Table 2.** Dissolved trace metals ( $\mu\text{g l}^{-1}$ ) from the coastal and offshore stations of the western Bay of Bengal.

Latitude ( $^{\circ}\text{N}$ )	Longitude ( $^{\circ}\text{E}$ )	Station Number	Fe ( $\mu\text{g l}^{-1}$ )	Co ( $\mu\text{g l}^{-1}$ )	Ni ( $\mu\text{g l}^{-1}$ )	Cu ( $\mu\text{g l}^{-1}$ )	Zn ( $\mu\text{g l}^{-1}$ )	Cd ( $\mu\text{g l}^{-1}$ )	Pb ( $\mu\text{g l}^{-1}$ )
11.5	79.94	B1	3.58	0.185	1.95	1.95	2.89	0.058	0.785
11.5	79.98	B2	3.56	0.188	1.98	1.98	2.86	0.056	0.723
11.5	81	B3	1.24	0.045	0.034	0.48	0.88	0.018	0.115
11.5	82	B4	1.29	0.048	0.036	0.52	0.88	0.018	0.114
11.5	83	B5	2.21	0.062	0.038	0.52	0.98	0.021	0.118
11.5	84	B6	2.24	0.074	0.042	0.54	0.98	0.022	0.121
13.5	80.48	B7	3.47	0.184	1.88	1.94	2.86	0.052	0.741
13.5	80.55	B8	3.45	0.186	1.84	1.92	2.84	0.054	0.751
13.5	81	B9	2.52	0.084	0.042	0.76	1.66	0.035	0.386
13.5	82	B10	2.51	0.086	0.048	0.74	1.68	0.034	0.385
13.5	83	B11	2.59	0.084	0.062	0.76	1.72	0.032	0.422
13.5	84	B12	2.61	0.086	0.064	0.88	1.61	0.033	0.424
13.5	85	B13	2.68	0.084	0.066	0.88	1.74	0.034	0.332
15.5	80.59	B14	3.26	0.182	1.86	1.96	2.78	0.056	0.764
15.5	80.71	B15	3.28	0.184	1.87	1.94	2.76	0.054	0.756
15.5	81	B16	2.64	0.082	0.058	0.88	1.72	0.035	0.424
15.5	82	B17	2.66	0.108	0.062	0.89	1.74	0.034	0.422
15.5	83	B18	2.68	0.114	0.064	1.61	1.72	0.036	0.496
15.5	84	B19	2.64	0.112	0.084	1.68	1.74	0.038	0.468
15.5	85	B20	2.62	0.124	0.082	0.74	1.76	0.038	0.348
15.5	86	B21	2.79	0.124	0.088	0.78	1.88	0.042	0.346
15.5	87	B22	2.71	0.108	0.086	0.68	1.92	0.044	0.344
17.5	83.33	B23	2.97	0.138	1.28	1.27	2.48	0.041	0.511
17.5	84.01	B24	2.96	0.134	1.29	1.29	2.45	0.044	0.521
17.5	85	B25	2.21	0.078	0.044	0.66	1.06	0.028	0.324
17.5	86	B26	2.21	0.076	0.046	0.58	1.08	0.026	0.328
17.5	87	B27	2.06	0.074	0.044	0.56	1.06	0.026	0.326
17.5	88	B28	2.08	0.074	0.044	0.54	1.05	0.026	0.122

**Table 3.** Zooplankton trace metals ( $\mu\text{g g}^{-1}$ ) from the coastal and offshore stations of the western Bay of Bengal.

Latitude ( $^{\circ}\text{N}$ )	Longitude ( $^{\circ}\text{E}$ )	Station number	Fe ( $\mu\text{g g}^{-1}$ )	Co ( $\mu\text{g g}^{-1}$ )	Ni ( $\mu\text{g g}^{-1}$ )	Cu ( $\mu\text{g g}^{-1}$ )	Zn ( $\mu\text{g g}^{-1}$ )	Cd ( $\mu\text{g g}^{-1}$ )	Pb ( $\mu\text{g g}^{-1}$ )
11.5	79.94	B1	51999.3	49.8	68.1	89.5	8162.2	49.8	21.1
11.5	79.98	B2	52962.1	47.8	66.5	88.8	8066.1	49.4	20.1
11.5	81	B3	1135.2	13.8	14.8	22.8	356.8	9.3	1.5
11.5	82	B4	3175.3	13.9	14.8	23.8	365.4	9.4	1.5
11.5	83	B5	3185.4	14.1	15.6	24.6	375.4	9.6	1.6
11.5	84	B6	3278.3	17.5	15.1	24.2	372.4	9.8	1.6
13.5	80.48	B7	50989.3	47.8	67.1	89.5	8162.2	48.8	21.8
13.5	80.55	B8	50962.1	48.8	66.5	87.2	8066.1	49.4	20.1
13.5	81	B9	3274.2	16.3	20.3	29.8	458.9	14.8	1.6
13.5	82	B10	3655.4	19.8	22.4	29.6	458.2	14.6	1.9
13.5	83	B11	3645.4	23.3	30.2	31.4	484.2	15.1	3.5
13.5	84	B12	3544.2	22.3	31.2	34.4	478.5	15.8	3.7
13.5	85	B13	3538.2	20.2	32.5	27.5	475.8	16.5	3.7
15.5	80.59	B14	50949.3	48.8	62.1	89.5	8162.2	48.8	21.1
15.5	80.71	B15	50962.1	48.9	66.5	86.2	8066.1	49.4	20.1
15.5	81	B16	3275.3	21.4	33.4	27.2	476.6	17.6	2.8
15.5	82	B17	3543.4	22.1	32.2	32.1	488.4	16.7	2.2
15.5	83	B18	3654.6	22.4	31.4	33.1	584.6	15.2	3.5
15.5	84	B19	3856.5	23.8	30.5	33.5	588.7	15.4	3.8
15.5	85	B20	4156.2	24.8	32.4	35.3	684.3	16.3	6.7
15.5	86	B21	4556.2	24.2	34.4	32.8	783.3	18.3	7.7
15.5	87	B22	4356.2	24.3	32.4	33.7	785.3	18.8	7.2
17.5	83.33	B23	25137.1	38.2	52.1	75.3	5800.3	38.1	15.5
17.5	84.01	B24	25191.3	39.3	53.1	73.1	5889.4	36.2	14.8
17.5	85	B25	3222.7	19.4	20.4	25.8	456.2	12.2	1.7
17.5	86	B26	3204.1	18.8	21.5	24.9	458.6	13.7	1.8
17.5	87	B27	3114.1	18.5	19.8	25.4	456.2	13.2	1.7
17.5	88	B28	3106.1	17.3	19.9	26.4	457.6	13.7	1.8

**Table 4.** Average concentration of trace metals in different compartments and average bioaccumulation (baf) factors for trace metals in zooplankton from the coastal stations of the western Bay of Bengal.

Metal	Fe	Co	Ni	Cu	Zn	Cd	Pb
Dissolved ( $\mu\text{g l}^{-1}$ )	$3.32 \pm 0.25$	$0.173 \pm 0.023$	$1.74 \pm 0.29$	$1.78 \pm 0.31$	$2.74 \pm 0.18$	$0.052 \pm 0.006$	$0.694 \pm 0.111$
Zooplankton ( $\mu\text{g g}^{-1}$ )	$44894.1 \pm 12198.2$	$46.2 \pm 4.6$	$62.8 \pm 6.5$	$84.9 \pm 6.7$	$7546.8 \pm 1051.7$	$46.2 \pm 5.6$	$19.2 \pm 2.6$
Bioaccumulation factors (baf)	$13375996 \pm 3042727$	$268697 \pm 11997$	$36394 \pm 2967$	$48543 \pm 5891$	$2742488 \pm 233666$	$891534 \pm 39677$	$27858 \pm 1232$

**Table 5.** Average concentration of trace metals in different compartments and average bioaccumulation (baf) factors for trace metals in zooplankton from the offshore stations of the western Bay of Bengal.

Metal	Fe	Co	Ni	Cu	Zn	Cd	Pb
Dissolved ( $\mu\text{g l}^{-1}$ )	$2.36 \pm 0.44$	$0.086 \pm 0.022$	$0.057 \pm 0.018$	$0.76 \pm 0.26$	$1.44 \pm 0.38$	$0.031 \pm 0.007$	$0.318 \pm 0.127$
Zooplankton ( $\mu\text{g g}^{-1}$ )	$3423.4 \pm 681.6$	$19.5 \pm 3.81$	$25.3 \pm 7.3$	$29.4 \pm 4.2$	$502.3 \pm 124.3$	$14.3 \pm 2.9$	$3.2 \pm 2.0$
Bioaccumulation factors (baf)	$1464702 \pm 289995$	$237981 \pm 58360$	$457495 \pm 113127$	$41454 \pm 12277$	$367923 \pm 111921$	$485737 \pm 122240$	$10445 \pm 5344$

**Table 6.** Pearson product-moment correlation coefficients between trace metals in the coastal zooplankton

Metal	Fe	Co	Ni	Cu	Zn	Cd	Pb
Fe	1.00						
Co	0.98**	1.00					
Ni	0.96**	0.95**	1.00				
Cu	0.98**	0.96**	0.93**	1.00			
Zn	0.98**	0.98**	0.96**	0.98**	1.00		
Cd	0.98**	0.98**	0.96**	0.97**	0.98**	1.00	
Pb	0.97**	0.97**	0.93**	0.98**	0.97**	0.98**	1.00

Significant correlations are indicated by \*\* at  $p < 0.001$

**Table 7.** Pearson product-moment correlation coefficients between trace metals in the offshore zooplankton

Metal	Fe	Co	Ni	Cu	Zn	Cd	Pb
Fe	1.00						
Co	0.69*	1.00					
Ni	0.73*	0.95**	1.00				
Cu	0.72*	0.95**	0.95**	1.00			
Zn	0.77*	0.66*	0.74*	0.69*	1.00		
Cd	0.74*	0.95**	0.92**	0.90**	0.78*	1.00	
Pb	0.70*	0.73*	0.75*	0.78*	0.88*	0.74*	1.00

Significant correlations are indicated by \* at  $p < 0.05$  and \*\* at  $p < 0.001$



**Table 8.** Characteristics of various parameters (range of mixed layer, temperature, salinity, mean values of meso zooplankton biovolume and mean values of copepods abundance) in the three different hydrographic regimes (Muraleedharan et al., 2007).

Physical processes	Station locations [Latitude. (°N)/Longitude. (°E)]	Mixed Layer Depth (m)	Temperature (°C)	Salinity (psu)	Zooplankton biovolume (ml m <sup>-3</sup> )	Copepods abundance (ind. m <sup>-3</sup> )
Upwelling	11.5-15.5/ 79.8-80.8	0-27	27.37- 26.82	34.30- 34.41	1.12	1697
Cyclonic eddy	17.5/83.3-84	0-38	26.82- 26.39	34.10- 34.18	0.67	1036
Warm gyre	13.5-15.5 / 82-88	0-74	28.86- 28.70	33.56- 33.76	0.14	310

**Table 9.** Average concentration of trace metals in different compartments and average bioaccumulation (baf) factors for trace metals in zooplankton from the coastal and offshore stations of the western Bay of Bengal during summer monsoon.

Metal	Fe	Co	Ni	Cu	Zn	Cd	Pb
Dissolved (µg l <sup>-1</sup> )	2.63 ± 0.59	0.111 ± 0.045	0.539 ± 0.195	1.05 ± 0.54	1.81 ± 0.68	0.037 ± 0.012	0.425 ± 0.211
Zooplankton (µg g <sup>-1</sup> )	15272.1 ± 2072.5	27.1 ± 12.9	36.2 ± 18.6	48.4 ± 26.2	2515.6 ± 586.5	23.4 ± 15.2	7.7 ± 3.6
Bioaccumulation factors (baf)	4867929 ± 569971	246757 ± 51321	337180 ± 125725	43480 ± 11212	1046371 ± 110286	601679 ± 213949	15420 ± 9201