

## **Interplay of Diverse Environmental Settings and Their Influence on the Plankton Community off Myanmar during the Spring Intermonsoon**

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### **Abstract**

The northern Andaman Sea including the Myanmar waters is one of the least studied regions of the northern Indian Ocean. The freshwater and suspended sediments carried by Ayeyawady/ Irrawaddy, the peculiar surface circulation, coastline morphology and shallow bathymetry in the Gulf of Mottama facilitate several diverse environmental settings in the study region. In order to understand the environmental settings and their linkages to the plankton community in the study region, this paper combined *in-situ* data of 'First India - Myanmar Joint Oceanographic Expedition' with satellite oceanography observations. The study period was the Spring Inter-monsoon (March - May), which was characterized by high tidal activity in the Gulf of Mottama region (tidal height 6 - 8m) causing strong tidal currents and re-suspension of sediments. The tidal currents and eastward advection of Ayeyawady influx caused the lowest salinity, highest concentration of nutrients, suspended sediments and chlorophyll *a* in the Gulf of Mottama region. Conversely, high salinity, highest temperature, lowest nutrients and suspended sediments prevalent in the offshore waters of the northern Andaman Sea induced a massive bloom of *Trichodesmium erythreum*, which was mostly in the declining phase during the observation. The *in-situ* and satellite remote sensing data clearly showed that the *Trichodesmium erythreum* bloom observed in the offshore waters was closely linked to a warm core eddy. The decomposition of the bloom favored swarms of siphonophores and hydromedusae through a trophic link involving copepods and appendicularians. Aided by satellite remote sensing data and multivariate statistical tools, five diverse environmental settings have been identified in the study domain. The analysis showed a close coupling between phytoplankton biomass and nutrients with their higher values in the Gulf of Mottama, off Rakhine, Ayeyawady and Tanintharyi region as compared to the offshore waters in the northern Andaman Sea. The zooplankton community dominated by copepods and chaetognaths preferred regions with high salinity, chlorophyll, deep mixed layer and low suspended sediments as existed off Rakhine, Ayeyawady and Thanintharyi regions. The study evidences, for the first time, the spatial segregation of environmental settings and its linkages to the plankton community off Myanmar during the Spring Intermonsoon.

**Key words** – Chlorophyll, Zooplankton, Copepods, Multivariate statistics, Tidal currents, Turbidity, Ayeyawady, Andaman Sea, Bay of Bengal

## **1. Introduction**

The Bay of Bengal including the Andaman Sea is bordered in the north, east and west by the Asian continent. All major rivers of India (Krishna, Cauvery, Godavari, Mahanadi, Brahmaputra and Ganges), Bangladesh (Meghna) and Myanmar (Ayeyawady, Thalwin & Sittaung) drain into the Bay of Bengal. During the monsoon (June to September –Southwest Monsoon and November to February - Northeast Monsoon), these rivers bring enormous quantities of freshwater and suspended sediment into the Bay of Bengal. This marks the Bay of Bengal oceanographically unique where fresh water inflow through rainfall and river influx exceeds evaporation (Ittekkot et al., 1991; Prasannakumar et al., 2002). The resulting low saline upper layer in the Bay of Bengal plays a crucial role in various exchange processes between the atmosphere and the ocean, thereby influencing the biological and biochemical processes taking place in the region (Ittekkot et al., 1991; Prasannakumar et al., 2002).

In recent years, significant success has been achieved in integrating *in-situ* and satellite remote sensing data to understand the oceanographic settings and their linkages to the plankton productivity in the eastern Arabian Sea and the western Bay of Bengal (Jyothibabu et al., 2008; 2010). However, such cohesive studies integrating the environmental setting and plankton community are absent from the eastern Bay of Bengal; this is especially true for the northern Andaman Sea and Myanmar waters (Desai et al., 1987). In this paper, we demarcated the spatial organization of different environmental settings off Myanmar during the Spring Intermonsoon, caused primarily by the difference in land-ocean-atmosphere interaction, and show how plankton communities respond to these environmental settings.

## **2. Materials and Methods**

### **2.1. Study area and sampling**

The Union of Myanmar (10° - 28°N and 90° - 108°E) is the largest Southeast Asian country with a long coastline of about 3000 km. The coastline of Myanmar is broadly divided into three regions (a) Rakhine coast (b) Ayeyawady delta – Gulf of Mottama (Gulf of Martaban) region and (c) Tanintharyi coast (Figure 1). The rainfall in Myanmar is highly seasonal - the major part occurs during the Southwest Monsoon (June- September) causing heavy freshwater transport through Ayeyawady, Sittaung and Thanlwin (Rodolfo, 1969; Varkey et al., 1996). Among these rivers, Ayeyawady is the largest with an annual mean runoff of  $13018 \text{ m}^3 \text{ s}^{-1}$  that enters the northern Andaman Sea through nine principal distributaries. Together with Sittaung and Thanlwin,

Ayeyawady transport enormous quantities of suspended materials during the Southwest Monsoon (Varkey et al., 1996). Conversely, the present study period (Spring Intermonsoon/Pre-monsoon), is a dry/least discharge period and, therefore, the amount of freshwater influx through Ayeyawady is the seasonal lowest during the study period (Ramaswamy et al., 2004; 2008).

During the study period (Spring Intermonsoon), the northern Andaman Sea is characterized by a large, turbid zone in the Gulf of Mottama region where suspended sediment concentration exceeds  $500 \text{ mg l}^{-1}$  (Ramaswamy et al., 2004, Figure 2). As the rainfall and river discharge in the study region are mostly restricted to the Southwest Monsoon period, the highly turbid Zone in the Gulf of Mottama region during the present study period is not significantly contributed by the rainfall and river influx. The recent research showed that this high turbidity zone in the Gulf of Mottama region is mainly caused by the re-suspension of sediments by strong tidal currents (Ramaswamy et al., 2004).

The field data presented in this paper is the result of the 'First India - Myanmar Joint Oceanographic Expedition in the Andaman Sea'. The field sampling was carried out onboard ORV Sagar *Kanya* during April – May 2002. The main activity during the field sampling was to execute the close-grid sampling of geological parameters, and the results of these measurements significantly improved our understanding of the suspended sediment concentration and dispersal, source of organic carbon in the bottom sediment, seafloor and seismic activity and particulate organic carbon (Ramaswamy et al., 2004, 2008; Rao et al., 2005).

In the present study, the data of environmental (physicochemical) parameters and chlorophyll *a* collected from 60 locations are used to segregate the environmental settings in the study region. The biological response of these spatially segregated diverse environmental settings has been explained in terms of various plankton components in the representative clusters (Figure 3).

## **2.2. Methods**

### **2.2.1. Environmental (physicochemical) parameters**

A Conductivity Temperature Depth (CTD) profiler (Model - Seabird, USA) was used to record the vertical distribution of temperature ( $^{\circ}\text{C}$ ) and salinity in various locations in the study area. The spatial distribution of surface water temperature and salinity presented is based on the CTD data from a uniform depth in the surface waters (2m). The CTD data was also used to derive the mixed layer depth (MLD) in different environmental setting, and it was calculated as the depth at which

sigma – t value increased by  $0.2\text{kg m}^{-3}$  as compared to the value at the surface. Water samples for dissolved oxygen (DO) and nutrients (nitrate -  $\text{NO}_3$ , silicate -  $\text{SiO}_4$  and phosphate –  $\text{PO}_4$ ) were collected from surface waters using Go Flow samplers attached to a CTD rosette. Concentration of  $\text{NO}_3$ ,  $\text{SiO}_4$  and  $\text{PO}_4$  was measured using an autoanalyser (Skalar San Plus) as per the standard procedure (Grasshoff, 1983). Water samples for dissolved oxygen (DO) were analyzed following the Winkler's titration method.

### **2.2.2. Satellite Remote Sensing data**

The satellite remote sensing data of relevant parameters detailed below representing the cruise period were retrieved from online databases. The SeaWiFS chlorophyll *a* concentration and satellite remote sensing reflectance at 555 nm (measure of suspended sediments) were downloaded from Giovanni (Goddard Earth Sciences, Data and Information Services Center, NASA). The weekly mean SST of AVHRR and 3 day mean ocean surface winds (QuikSCAT) were downloaded from NOAA Ocean Watch. The Sea Surface Height Anomaly (SSHA) and surface currents data were retrieved from Merged Altimetry data products of JASON-1 (<http://www.aviso.oceanobs.com/en/>).

### **2.2.3 Biological parameters**

#### **2.2.3.1 Chlorophyll *a* and primary production**

1 litre of water sample was collected from discrete depths (surface, 10, 20m) using Go Flo bottles. These samples were passed through GF/F filters to concentrate the phytoplankton cells. The chlorophyll *a* concentrated on the filters was extracted in 10 ml 90% acetone (Qualigens AR, Mumbai). The measurement of chlorophyll *a* was carried out using a Turner fluorometer following the standard procedure (UNESCO, 1994). The primary production in the surface waters was estimated based on  $^{14}\text{C}$  – technique with simulated *in - situ* incubation for six hours (UNESCO, 1994). Prior to the incubation of water samples, 1 ml of  $\text{NaH}^{14}\text{CO}_3$  was added to each incubation bottle and after six-hours of incubation (06.00 -12.00 hours), samples were filtered through 47 mm GF/F filters with gentle suction. These filters were then exposed to concentrated HCl fumes to remove excess inorganic carbon and then stored in scintillation vials. Liquid scintillation cocktail was added to the vials, a day before the radioactivity measurements in a Wallac Liquid Scintillation counter (Model 1409). The disintegrations per minute (DPMs) were converted to daily production rates ( $\text{mgC m}^{-3} \text{d}^{-1}$ ) following standard protocols (UNESCO 1994).

During the cruise, when an extensive bloom of *Trichodesmium* was observed in the offshore waters of the northern Andaman Sea, six surface water samples (10 liters each) were collected from different zones in the bloom region, using a clean bucket, and preserved in 2% formalin for microscopic analyses. In the laboratory, the main algal biomass, which was in a decomposed stage, was separated from the rest of the samples and allowed to settle under gravity. The subsamples of the settled materials were examined for live bundles of *Trichodesmium* and photomicrographs were taken using a CK30 Olympus inverted microscope. The total abundance of *Trichodesmium* was not counted during the present study, as most of the bloom biomass was in a partially decomposed state.

### **2.2.3.2. Zooplankton**

Zooplankton samples were collected using a Bongo net with a mouth area of 1.8 m<sup>2</sup> and a mesh size of 200 µm. The Bongo net was operated horizontally (at ~2 m depth) with a flow meter (Hydro-bios) attached to the mouth. The speed of the ship was regulated at 2 – 3 knots and all the collections were made during daytime to minimize the effect of diel vertical migration of zooplankton. After the retrieval of Bongo, zooplankton samples were filtered through a 200µm nylon sieve and the excess water in the samples were removed using blotting paper. The biomass of the samples were measured based on the displacement volume method (Postel et al., 2000). The samples were then preserved in 4% formalin in seawater for further analysis. Sub samples (50%) were taken using Folsom splitter and were sorted to the group level, and abundance of each group was calculated following the standard procedure (Postel et al., 2000).

### **2.2.4. Statistical Analyses**

Multivariate statistics is a powerful tool to analyze and interpret the inter-relationships in environmental and biological parameters (Clarke and Warwick, 2001; Rakhesh et al., 2006; Jagadeesan et al., 2013). In the present study, we used (a) cluster/Similarity Profile (SIMPROF) analyses to segregate several locations into groups (clusters) with close and statistically significant similarity (b) Non-Metric Multidimensional Scaling (NMDS) performed on standardized, and square root transformed data sets of physicochemical variables (salinity, temperature, remote sensing reflectance at 555nm, nitrate and silicate) to make spatial grouping of locations based on the quantitative difference in their spatial distribution, and (c) Redundancy Analysis (RDA) to find the linear relationships among a set of physicochemical and biological variables (Jagadeesan et al., 2013).

### 3. Results

#### 3.1. Oceanographic features and segregation of locations

The predicted tidal data at Elephant Point (in the Gulf of Mottama) during the cruise period is presented in Figure 2a, which shows exceptionally high tidal activity (6-8m). This high tidal activity generates strong tidal currents and re-suspension of sediments in the Gulf of Mottama causing the waters to appear brownish. This is in sharp contrast with the clear bluish waters in the offshore regions of the northern Andaman Sea (Figure 2b). The sea surface salinity distribution showed high salinity waters distributed off Rakhine, Ayeyawady delta and Tanintharyi coasts. On the other hand, a drop in salinity was evident in the Gulf of Mottama due to the eastward movement of the Ayeyawady influx (Figure 2c). In general, relatively cool water was found off the Rakhine, Ayeyawady and Tanintharyi coast whereas warmer waters ( $>31^{\circ}\text{C}$ ) were encountered in the Gulf of Mottama and the offshore regions of the northern Andaman Sea (Figure 2d). The mixed layer depth (MLD) in different parts of the study area is presented in Table 1, which shows relatively shallow mixed layer in the Gulf of Mottama region and offshore waters of the Andaman Sea. The spatial distribution of DO,  $\text{NO}_3$ ,  $\text{SiO}_4$  and  $\text{PO}_4$  are shown in Table 1. The concentration of DO was generally high in the study area ( $>200\mu\text{M}$ ) except in the Gulf of Mottama where the concentration was low ( $<190\mu\text{M}$ ). The nutrients concentrations were highest in the Gulf of Mottama and the lowest in the offshore waters of the Andaman Sea (Table 1).

The results of Cluster/SIMPROF analysis are presented in Figure 3, which shows five statistically significant clusters of locations in the study region. Similarly, NMDS plots showing the distribution of different environmental parameters in segregated clusters are presented in Figure 4. Each of these clusters indicates a specific environmental setting, which is different from the rest of the clusters. In other words, locations grouped in one cluster have statistically significant similarity in their environmental characteristics. The general environmental characteristics of these clusters and their approximate geographical locations are presented in Table 2. Cluster 1 represents locations off the Rakhine coast having the highest salinity, lowest temperature, low nutrients and suspended sediments. Cluster 2 was formed of relatively fewer locations situated between the inshore and offshore waters of the Gulf of Mottama with low salinity, high temperature, high nutrients and suspended sediments. The cluster 3 was formed of the largest number of locations situated in the offshore waters of the northern Andaman Sea having high salinity, highest temperature, lowest nutrients and suspended sediments. The environmental setting grouped under cluster 4 was

characteristic of some locations off Ayeyawady delta and Tanintharyi region having high salinity, low temperature, low nutrients and suspended sediments. The cluster 5 represented locations in the Gulf of Mottama characterized by the lowest salinity, high temperature, highest nutrients and suspended sediments. Here after, cluster 1 represents Rakhine coast, cluster 2 represents Off Gulf of Mottama, cluster 3 represents offshore waters of the northern Andaman Sea, cluster 4 represents Off Ayeyawady delta and south off Thanintharyi coast and cluster 5 represents Gulf of Mottama. (Table 2)

### **3.2. Chlorophyll *a*, primary production and *Trichodesmium* bloom**

The spatial distribution of chlorophyll *a* in the study area based on *in-situ* data is shown in Figure 5a & b. The chlorophyll *a* concentration was the highest in cluster 5 characterized by low salinity, low dissolved oxygen and high nutrient concentration. On the other hand, the lowest concentration of chlorophyll *a* was found in cluster 3 where surface water was the warmest with the lowest nutrients concentration (Figure 5a & b). The supplementary evidence for the distribution of chlorophyll *a* in the study region is presented by the satellite imagery for the study period (Figure 5c). It corroborates the chlorophyll *a* distribution pattern evident in the *in-situ* measurements presented in Figure 5a & b. However, a significant increase in chlorophyll *a* concentration in cluster 5 is evident in satellite imagery ( $1.5 - 3\text{mg m}^{-3}$ ) when compared to the *in-situ* data ( $0.6 - 1\text{mg m}^{-3}$ ). This overestimation of chlorophyll *a* in satellite imagery is caused by the interference of high suspended sediment concentration in cluster 5 (Figure 5d).

The spatial segregation of sampling locations in the study area based on statistically significant differences in the environmental setting is presented in Figure 3 and 4. The representative location of each of these environmental setting is indicated in Figure 3b and their general characteristics in Table 2. The chlorophyll *a* concentration was the highest in cluster 5 followed by cluster 1 & 4. The primary production was the highest in cluster 4 followed by clusters 1 & 5. During the field sampling, an extensive bloom of *Trichodesmium erythreum* ( $>10000\text{ km}^2$ ) was observed in cluster 3 (Figure 6a –c). The location of the bloom is marked in Figure 5a & b. During the sampling, the bloom was mostly in the declining/decomposition phase (Figure 6a & b) and appeared as bands of partially decomposed bundles floating on the sea surface (Figure 6a & b). The long whitish bands of *Trichodesmium* bloom evident in Figure 6, differed from the routine thick yellowish band reported earlier (Jyothibabu et al., 2003; Mohanty et al., 2010; Martin et al., 2013), indicated the late stage of the bloom decomposition.

### 3.3. Zooplankton and their response to the environmental settings

The zooplankton community in the study area was composed of 15 taxonomic groups (Table 2). Copepods formed the most numerically dominant group (av. 77%) followed by chaetognaths (av. 23%) (Table 3). The distribution of the total zooplankton biomass and abundance in various environmental settings are presented in Figure 7c & d. The biomass and abundance showed a similar trend in distribution with higher values in cluster 1 (av. 99.4 ml 100 m<sup>-3</sup> and av. 274685 ind. 100 m<sup>-3</sup>, respectively) followed by cluster 4 (av. 51.5 ml 100m<sup>-3</sup> and av. 86217 ind. 100 m<sup>-3</sup>, respectively). The zooplankton biomass and abundance was noticeably low in cluster 2 (av. 9.2 ml 100 m<sup>-3</sup> and av. 10605 ind. 100 m<sup>-3</sup>, respectively) and clusters 5 (av. 5.8 ml 100 m<sup>-3</sup> and av. 945 ind. 100 m<sup>-3</sup>, respectively). The distribution of dominant as well as carnivorous zooplankton groups in different environmental settings is presented in Figure 7 e - h.

The distribution of copepods and chaetognaths showed the highest abundance in cluster 1 (av. 234213 ind.100 m<sup>-3</sup> and av. 28931 ind. 100 m<sup>-3</sup>, respectively) followed by cluster 4 (av.72244 ind.100 m<sup>-3</sup> and av. 12379 ind. 100 m<sup>-3</sup>, respectively). The distribution of siphonophores and medusa in different environmental settings are presented Figure 7 g & h, which shows significantly high abundance in cluster 3 (av. 1260 ind.100 m<sup>-3</sup> and av. 15146 ind. 100 m<sup>-3</sup>, respectively) followed by cluster 1 (av. 158 ind.100 m<sup>-3</sup> and av. 306 ind.100 m<sup>-3</sup>, respectively). These carnivores were almost absent in cluster 5, characterized by low salinity, low DO, high nutrients and suspended sediments. The bloom was also associated with conspicuous swarms of planktonic carnivores (medusa and siphonophores) in regions where bloom decomposition was in the final stage (Figure 6b).

### 3.4. Ecological Interrelationships

The result of the RDA analysis is presented as a Triplot (Figure 8), in which samples are displayed by points; quantitative environmental and biological variables are shown by arrows. The direction of a parameter arrow indicates the direction of increase of that variable and the angle between two parameters represent how significantly they are correlated. In the present analyses, the first two axis of the Triplot explained 94% of the interactions of physicochemical and biological parameters (Monte Carlo test, P<0.05). The hydrographical variables (salinity, temperature, mixed layer depth, nitrate and silicate) varied between spatially assembled locations representative of different environmental clusters. The hydrographical parameters together explained 95.6% of the distributional variation in biological parameters. The nitrate and silicate showed significant positive correlation with one another and an inverse relationship with salinity. Clusters 2 & 5 were oriented in



the right hand side of the Triplot. These locations were characterized by the lowest salinity and the highest nutrients. Clusters 1 & 4 were oriented in the left hand side bottom of the Triplot characterized by high salinity, low nutrient and deep MLD. Cluster 3 was oriented in the top left hand side of the Triplot characterized by the highest temperature, shallow MLD and lowest nutrients.

Like physicochemical parameters, biological variables also displayed a clear spatial segregation in the study area (Figure 8). The high concentration of chlorophyll *a* was oriented towards clusters 2 & 5, whereas the increasing values of mesozooplankton biomass, mesozooplankton density, copepod density and chaetognaths density were oriented towards clusters 1 & 4. In RDA Triplot, the representative locations of cluster 1 (green colour inverted triangle) and cluster 4 (pink colour squares) were characterized by high salinity, deep MLD, high mesozooplankton (MSP) biomass and high abundances of copepods. The representative locations of cluster 2 (blue colour triangle) and cluster 5 (light green colour diamond) were characterized by low salinity, high concentration of nutrients and chlorophyll, but had low mesozooplankton and abundance of copepods. The representative locations of cluster 3 (red colour circle) have the highest temperature, high salinity and high abundance of siphonophores and medusae. In these locations MSP biomass and copepods abundance were found to be low. The overall result showed a positive relationship between the zooplankton biomass/density, and the abundance of copepods and chaetognaths. The high abundance of medusae and siphonophores were oriented towards cluster 3. Chlorophyll *a* showed a strong positive relationship with nitrate and silicate whereas mesozooplankton biomass, mesozooplankton density, chaetognaths density and copepod density showed a strong positive relationship with high salinity, low temperature and deep mixed layer.

#### **4. Discussion**

The present study period (Spring Intermonsoon) is the primary heating period in the northern Indian Ocean, which is the reason for the high sea surface temperature (>28°C) observed in the study area. The surface salinity was generally high in the study area due to reduced rainfall and river influx. An exception to this was cluster 5 (Gulf of Mottama), which was relatively low saline (28.4) due to eastward advection of Ayeyawady river influx during the study period (Ramaswamy et al., 2004). The high freshwater influx and suspended sediment input into the Myanmar waters are mostly associated with the heavy rainfall during the Southwest Monsoon (Ramaswamy et al., 2004). Strong tidal activity during the present study period generates tidal currents and re-suspension of sediments in the Gulf of Mottama region (see Ramaswamy et al., 2004 for a detailed description).

During the study period, Ayeyawady influx was the seasonal lowest, which gets advected eastward along the coastline into the Gulf of Mottama. This limits the offshore spread of the freshwater in the Ayeyawady Delta region causing relatively high salinity off the coast. Low salinity and warm waters in cluster 5 caused MLD to be relatively shallow. The re - suspension of sediments by tidal currents caused high concentrations of nitrate and silicate in the mixed layer in cluster 5 (Figure 4). Alternatively, the sediment re-suspension in the region caused depletion of dissolved oxygen (Table 1).

#### **4.1. Chlorophyll *a* and primary production**

Nutrients and solar radiation are decisive factors that influence the phytoplankton community in the marine environment (Gomes et al., 2000). The transformation of nutrients into algal biomass requires sufficient solar radiation to support photosynthesis. Any physical factor that strongly inhibits the solar energy can hinder the photosynthesis and nutrient uptake (Cloern 1987, 1999). However, in spite of high suspended sediments, cluster 5 showed high amounts of chlorophyll *a*, which is strange in the context of the scientific facts previously discussed. One possible reason for this strange observation in cluster 5 could be the mixing/churning of water column by tidal currents. As a result, phytoplankton cells in the mixed layer intermittently get solar radiation enabling photosynthesis and transformation of nutrients into biomass. Another possible mechanism could be the increased chlorophyll *a* content in phytoplankton cells exposed to low light conditions (Anning et al., 2000). Comparable environmental setting of cluster 5 do exist in the Gulf of Kutch and Gulf of Kambhat, along the northwestern coast of India. These regions have a tidal range of 7-11m with high amount of suspended sediments (Rao and Rao, 1995). However, recent high resolution satellite imageries (Indian Remote Sensing Satellite P4) corrected for suspended sediments show exceptionally high concentrations of chlorophyll *a* in the Gulf of Kutch and Gulf of Kambhat during non rainy periods (Dwivedi et al., 2006). Therefore, it will be worthwhile to carry out focused research to understand the mechanism behind high amount of chlorophyll *a* in such regions of the northern Indian Ocean characterized by strong tidal currents and re-suspension of sediments.

The overall trend in the primary production was similar to the chlorophyll distribution with the lowest primary production in cluster 3 as compared to the rest of the region. However, the primary production in clusters 2 & 5 was lower than clusters 1& 4, which was in contrast to the trend in chlorophyll *a* distribution. This anomaly is the result of high turbidity in clusters 2 & 5, which probably decreased the primary production in the region.

## 4.2. *Trichodesmium* bloom and warm core eddy

The occurrence of *Trichodesmium erythraeum* bloom in the northern Indian Ocean is believed to be a biological indication of the surface layer stratification and nitrogen limitation (Carpenter and Capone 1992; Jyothibabu et al. 2003). In the entire stretch of the cruise track extending from Chennai (India) to Yangon (Myanmar), we observed the *Trichodesmium* bloom only in the northern Andaman Sea. Moreover, a recent literature suggests that the high abundance of *Trichodesmium* filaments has a linkage with the mesoscale processes in the ocean (Davis and McGillicuddy Jr., 2006). Therefore, we investigated the role of any mesoscale processes behind the formation of the *Trichodesmium* bloom in the offshore waters of the northern Andaman Sea. The analyses of the mesoscale physical processes that existed in the northern Andaman Sea during the study period, using satellite Sea Surface Height Anomaly (SSHA) and surface currents, brought to light some intriguing observations. For corroborating the observed features in the satellite imageries, the vertical structure of the water column across the *Trichodesmium* bloom region is also considered.

In recent years, experimental studies confirmed that *Trichodesmium* requires two to three weeks for completing their growth phase to form thick blooms (Chen et al., 1996; Ohki and Fujita, 1988; Bell et al., 2005). Similarly, field observation along the northwestern African coast showed that weak winds and warm sea surface favour the formation of *Trichodesmium* bloom (Ramos et al., 2005). Therefore, we analyzed the sea surface temperature, winds, currents, and height anomaly existing in the northern Andaman Sea a fortnight period before and during the field sampling. The fascinating results of the analyses are presented in Figures 9 & 10, which clearly shows that the bloom of *Trichodesmium* observed in the northern Andaman Sea was closely linked to a warm core eddy consistent in the region for more than a fortnight period (Figure 10). The bloom region was characterized by weak winds and the warmest sea surface as compared to the adjacent areas.

The vertical structures of the water column in the region presented in Figures 9c & 10d corroborates the warm core eddy signatures in the satellite imageries. Warm core eddy elicits convergence of surface water leading to an increase in the ambient temperature and nitrogen scarcity in the subsurface waters. This probably favoured the blooming of *Trichodesmium* in the study region. This view has a scientific basis as recent studies proved that *Trichodesmium* prefers medium to low levels of Photosynthetically Active Radiation (PAR) to form blooms, and such low level of PAR normally occurs in the subsurface waters (Ohki et al., 1986; Capone et al., 1997; Bell et al., 1999, 2005). It is our future interest to have a thorough understanding of the linkages between *Trichodesmium* blooms and warm core eddy in the northern Indian Ocean.

It is experimentally proved that *Trichodesmium* can assimilate nutrients such as  $\text{NO}_3$ ,  $\text{NH}_4$  and  $\text{PO}_4$  (Lin et al. 1998; Ohki et al., 1986; Stihl et al., 2001; Holl and Montoya, 2005; Martin et al., 2013). Paradoxically, when the nutrients exist in high concentrations, they inhibit the growth of *Trichodesmium* (Lin et al. 1998; Ohki et al., 1986; Stihl et al., 2001; Holl and Montoya, 2005; Martin et al., 2013). However, a few field studies observed an increase in  $\text{PO}_4$  concentration linked with *Trichodesmium* blooms and this has been attributed to the exudates from bloom biomass (Chang et al., 2000; Mohanty et al., 2006). In the present data, however, such an enhanced phosphate level ( $>1 \mu\text{M}$  of  $\text{PO}_4$  - Mohanty et al., 2010) was not found in the bloom region (Table 1). This could be the result of the late phase of the bloom decomposition in the study region.

### **4.3. Response of plankton in diverse environmental settings**

The response of various plankton components to diverse environmental settings is explained in Figure 7 while the results of the RDA analyses have been presented in Figure 8. The distribution of phytoplankton biomass (chlorophyll *a*) was positively correlated with nutrient concentration with higher values in clusters 2 & 5, cluster 1, and cluster 4 as compared with cluster 3. Zooplankton is the chief consumer of phytoplankton, but is rare to observe a significant positive relationship between them because these components are influenced differently by the environmental factors (Madhupratap and Parulekar 1993; Madhupratap et al. 2001). In the present study, the Gulf of Mottama showed high chlorophyll and primary production, but the zooplankton total biomass and abundance was significantly low in the region. This low mesozooplankton community in cluster 5 is due to the high suspended sediment concentration and low dissolved oxygen concentration, which might have limited the growth of planktonic crustaceans (Suzanne 2005). Similarly, chaetognaths, which is considered to be a primary carnivore, prefers high saline environments with abundant copepods for their nutrition (Jagadeesan et al., 2013). On the other hand, as expected, the offshore waters of the Andaman Sea characterized by low chlorophyll *a* and primary production had significantly low zooplankton biomass and abundance. In general, the zooplankton community in the study region dominated by copepods and chaetognaths preferred regions with high salinity, high chlorophyll, deep MLD and low suspended sediments as existed in clusters 1 and 4.

The top planktonic carnivores (medusae and siphonophores) formed swarms in cluster 3 where *Trichodesmium* bloom decomposition was in the final stage (Figure 6). The top planktonic carnivores were also found in cluster 1 as compared to the rest of the region, which can be explained as the region had salinity with high abundance of their preferred food, copepods and appendicularians (Mills, 1995; D'Ambra et al., 2013). Mills, (1995) reviewed studies on carnivorous plankton and

concluded that low productive regions of the oceans are characterized by small flagellate phytoplankton, small copepods and numerous planktonic carnivores. Our earlier observation in the Bay of Bengal corroborates the above conclusion and found increased abundance of jelly fishes in oligotrophic waters inhabited by *Trichodesmium* bloom (Jyothibabu et al., 2003). However, it is still not fully understood why these top carnivores form swarms where *Trichodesmium* bloom decomposition takes place. One possible reason is the trophic link through smaller copepods and appendicularians, which are reported as favourable food source of planktonic carnivores (Mills., 1995; D'Ambra et al., 2013). In the present study, the high abundance of appendicularians coincided with the high abundance of top planktonic carnivores but the abundance of copepods was lower than that off the Rakhine coast probably due to the high degree of top down control.

## 5. Conclusion

This paper presents the diverse environmental settings in the northern Andaman Sea including the Myanmar waters and shows how they influence the plankton components during the spring intermonsoon period. Turbid waters containing a high concentration of nutrients were characteristic of cluster 5 (Gulf of Mottama region) due to the re-suspension of sediments by strong tidal currents. On the other hand, cluster 3 (offshore region of the northern Andaman Sea) was characterized by the highest temperature, low MLD, lowest nutrients and chlorophyll a, which favoured the blooming of *Trichodesmium erythraeum* (~10000 km<sup>2</sup>). The satellite remote sensing and *in-situ* data clearly showed that the extensive bloom of *Trichodesmium erythraeum* was closely linked to a warm core eddy. Aided by satellite remote sensing data and multivariate statistical tools, five diverse environmental settings have been identified in the study region and the response of the plankton community to these environmental settings were found to be different. In general, the phytoplankton biomass was positively correlated with nutrient concentration with higher values in cluster 5 (Gulf of Mottama), cluster 1 (off Rakhine), cluster 4 (off Ayeyawady and Thanintharyi regions) as compared to cluster 3 (offshore waters of the northern Andaman Sea). The zooplankton community dominated by copepods and chaetognaths preferred regions with high salinity, high chlorophyll, deep MLD and low suspended sediments as existed in clusters 1 and 4.

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## Figure Captions

**Figure 1** – Study area with sampling locations. Rivers including several tributaries of Ayeyawady are shown.

**Figure 2** – (a) The predicted tidal cycle at Elephant point in the Gulf of Mottama during the study period showing the macro-tidal activity in the region. The location of Elephant Point is marked in Figure 1. Panel (b) shows the suspended sediments in the Gulf of Mottama region (brown waters) in contrast to the blue waters in the offshore waters of the northern Andaman Sea. The distribution of surface salinity and temperature showing clear spatial signatures is given in panel (c) and (d), respectively.

**Figure 3** – (a) Euclidian distance matrix based cluster / SIMPROF presenting the spatial assemblage (clustering) of locations based on relevant physico-chemical parameters and (b) The five clusters of locations with contrasting environmental features (SIMPROF,  $P < 0.05$ ) are overlaid on the study area map for the clear visualization of the segregated of locations into clusters. The environmental features of the study area presented are based on the data collected from all locations presented in Figure 1. Conversely, the response of plankton components in different environmental settings are described based on representative locations from each cluster presented as black and white solid circles in Figure 2b. Abbreviations: PP – Primary productivity, MSP – Mesozooplankton

**Figure 4** – (a) NMDS segregation of locations based on physicochemical parameters. Panels (b-f) represent overlaid data of relevant parameters showing their differences among five clusters of locations segregated. The size of the bubbles indicates the proportionate quantity of the physico-chemical parameters.

**Figure 5** - (a & b) Mean concentration of chlorophyll *a* in the surface ( $\text{mg m}^{-3}$ ) and upper 20m integrated ( $\text{mg m}^{-2}$ ). SeaWIFS imagery of chlorophyll *a* ( $\text{mg m}^{-3}$ ) and remote sensing reflectance at 555nm (an index of suspended sediments) are presented in panels (c) and (d), respectively.

**Figure 6** - Snapshots of extensive *Trichodesmium erythraeum* bloom in (a) partially decomposed and (b) almost completely decomposed stages. Panel (b) indicates abundant carnivorous plankton (jelly fishes and siphonophores) in regions where the *Trichodesmium* bloom was in the late stage of decomposition. Prominent white circles shown by red pointers are jelly fishes and less prominent white chain-like forms shown by yellow pointers are siphonophores. Panel (c) shows a live bundle of *Trichodesmium erythraeum* in 10X to show the morphology.

**Figure 7** – The response of plankton in representative locations of spatially assembled clusters overlaid on salinity distribution in the study area. Panels (a) chlorophyll *a* ( $\text{mg m}^{-3}$ ), (b) primary production ( $\text{mgC m}^{-3} \text{d}^{-1}$ ), (c) mesozooplankton biomass ( $\text{ml } 100^{-3}$ ) and (d) mesozooplankton total abundance ( $\text{ind. } 100^{-3}$ ). Subsequent panels (e - h) represent the density of copepods ( $\text{ind. } 100 \text{ m}^{-3}$ ),

chaetognaths (ind.  $100 \text{ m}^{-3}$ ), medusa (ind.  $100\text{m}^{-3}$ ) and siphonophores (ind.  $100\text{m}^{-3}$ ), respectively. The bubble position represents the clusters showed in Figure 3b and the bubble size indicates the proportionate value of the parameters.

**Figure 8** - Temperature overlaid attribution Triplot showing the distribution and relationship of physico-chemical and biological parameters in biological locations representing the clusters. The physico-chemical variables are represented by solid red lines and biological variables by dotted blue lines. The numbers in the Triplot along with representative symbols are same as in Figure 3. The pink contour lines represent temperature gradient attribution on spatially arranged parameters.

**Figure 9** – Surface wind ( $\text{ms}^{-1}$ ) and SST ( $^{\circ}\text{C}$ ) in the study region (a) a fortnight before as well as (b) during the time the field sampling along the zonal transect crossing the *Trichodesmium* bloom. The bloom regions are marked with white dotted circle. Panels (a) and (b) represent the wind, whereas, (c) and (d) are SST.

**Figure 10** - Sea Surface Height Anomaly (SSHA) merged with surface currents (a) a fortnight before as well as (b) during the field sampling. Panels (c) and (d) respectively represent the vertical distribution of salinity and temperature along the zonal transect marked in panel (a) and (b). The signatures of the warm core eddy are highlighted with white dotted circles and rectangles.

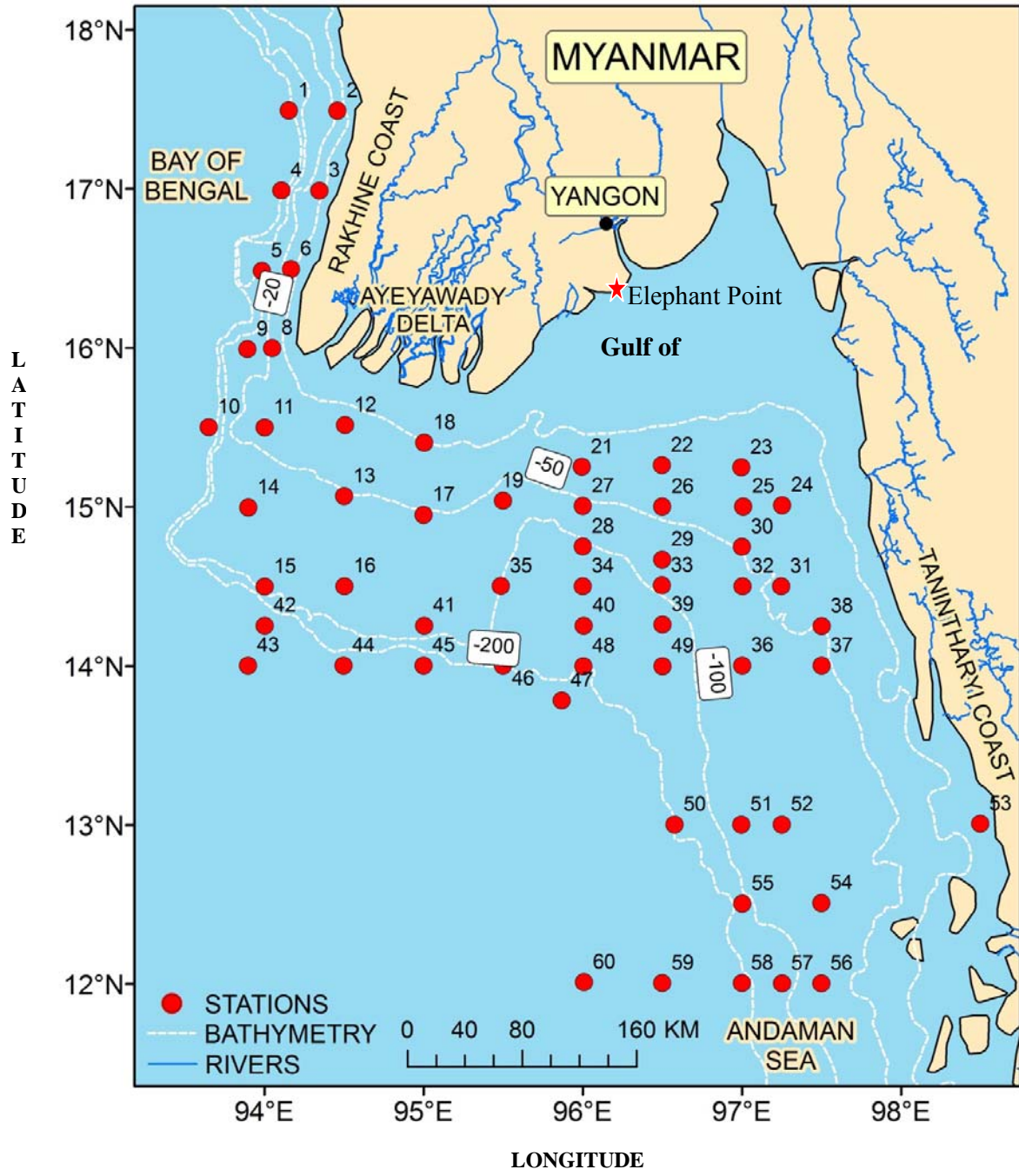


Figure 1

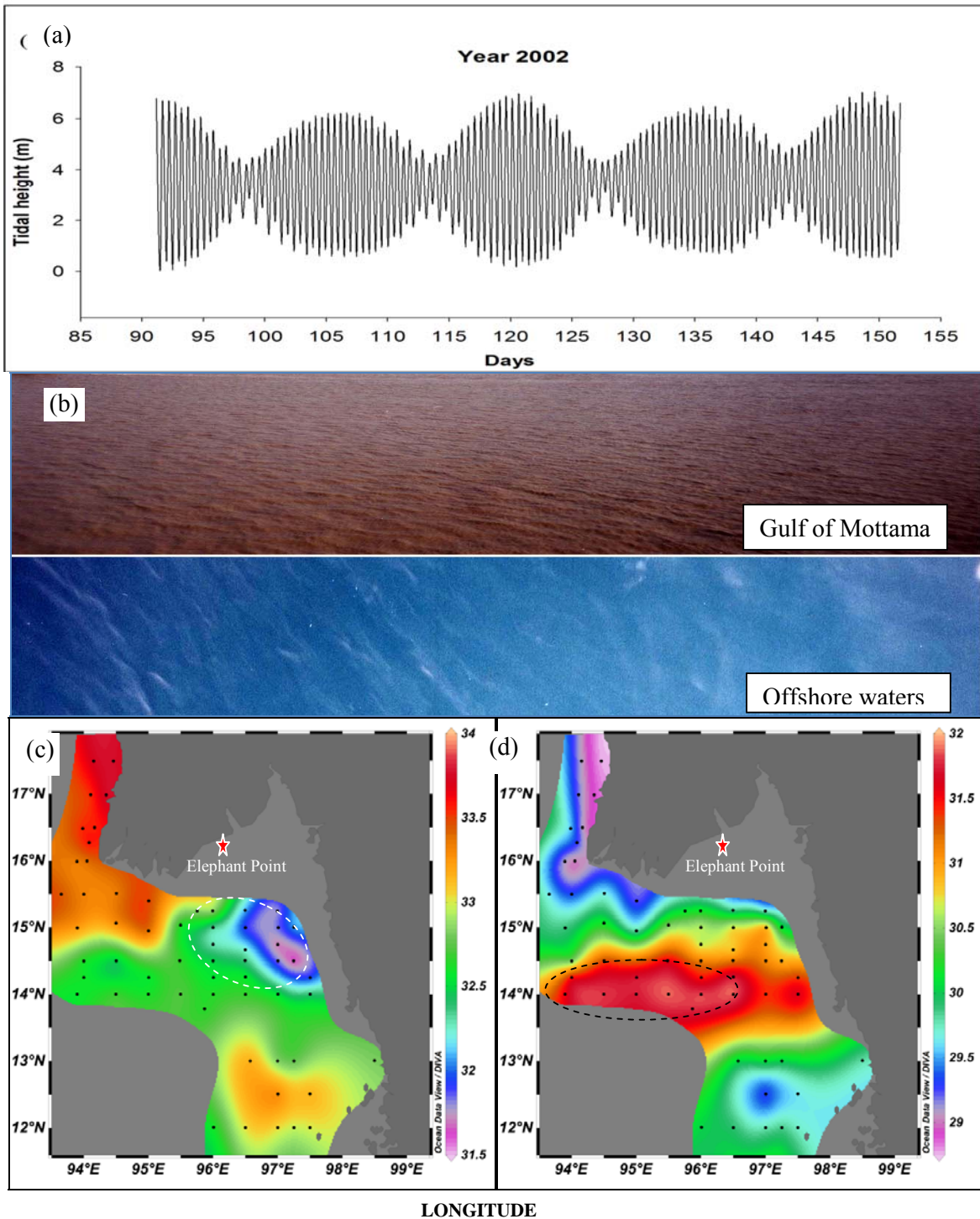


Figure 2

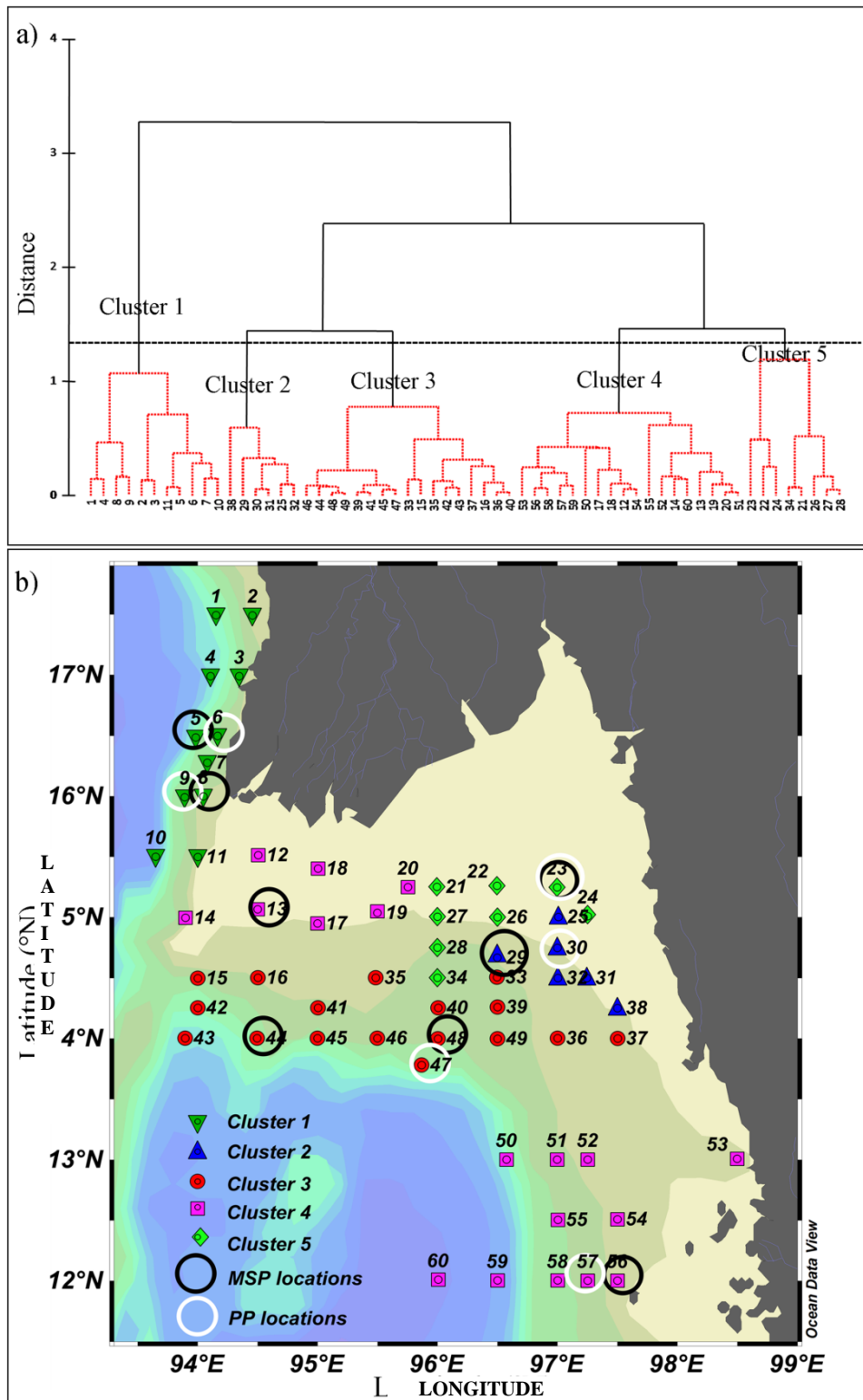


Figure 3

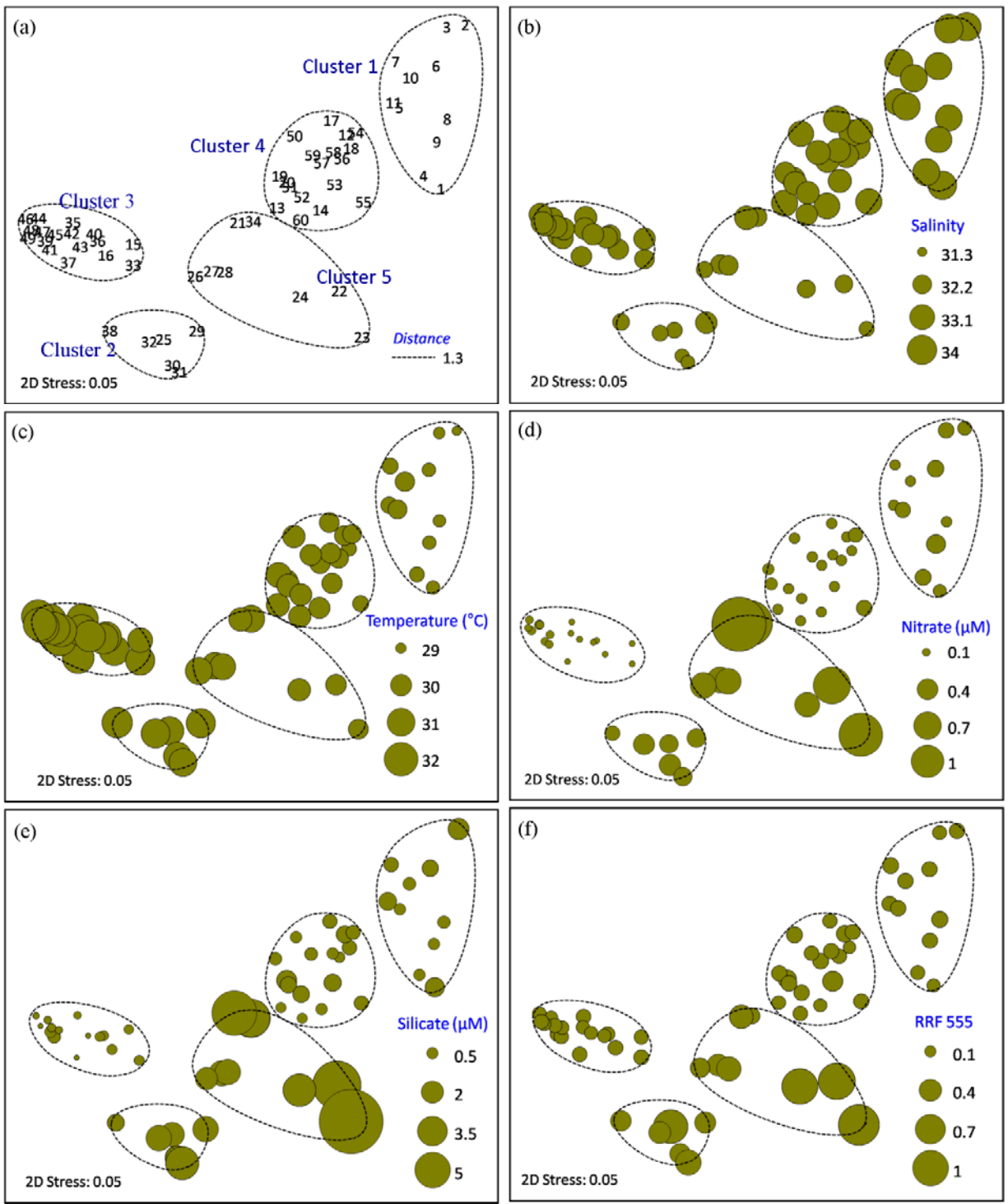


Figure 4

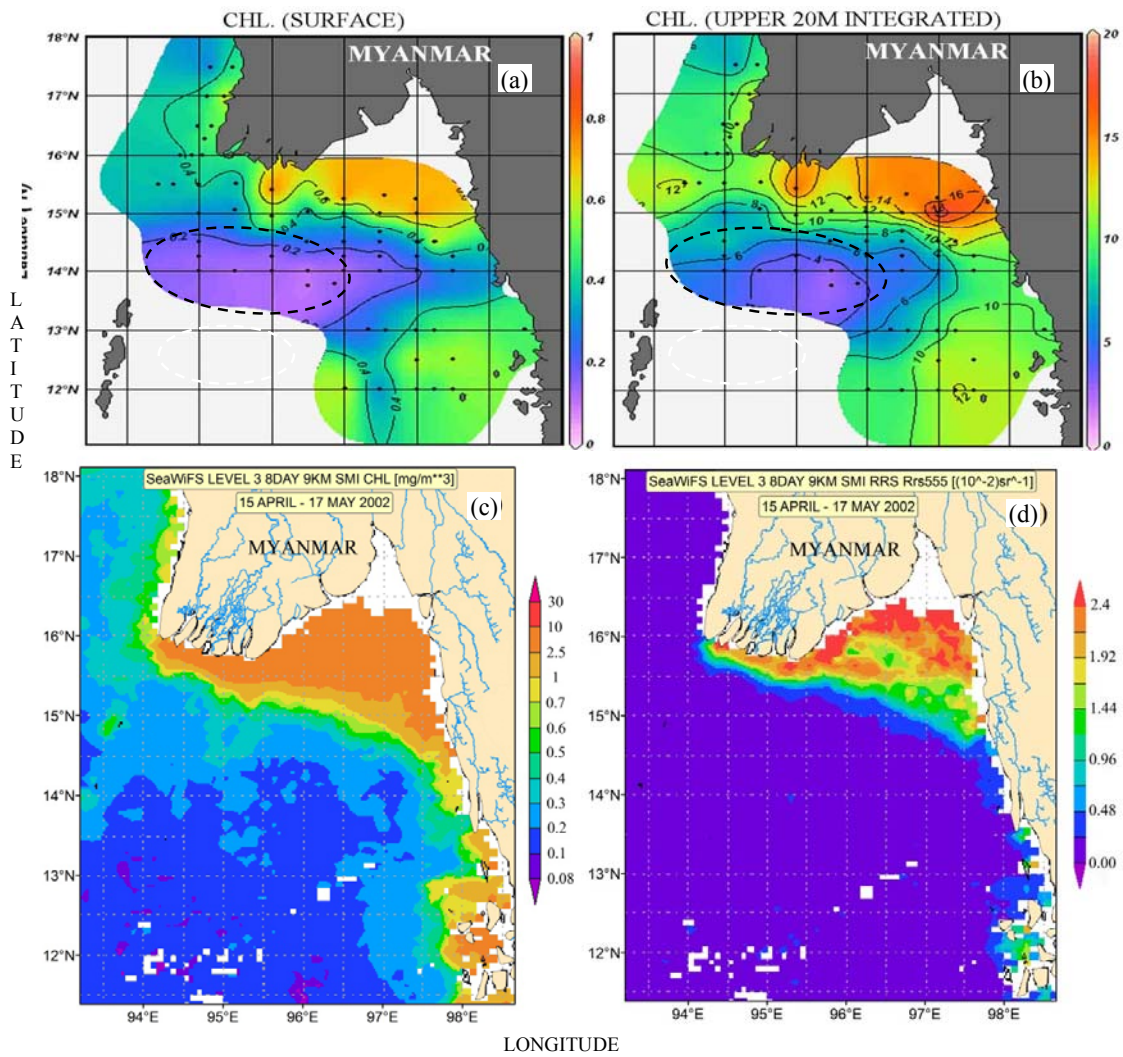
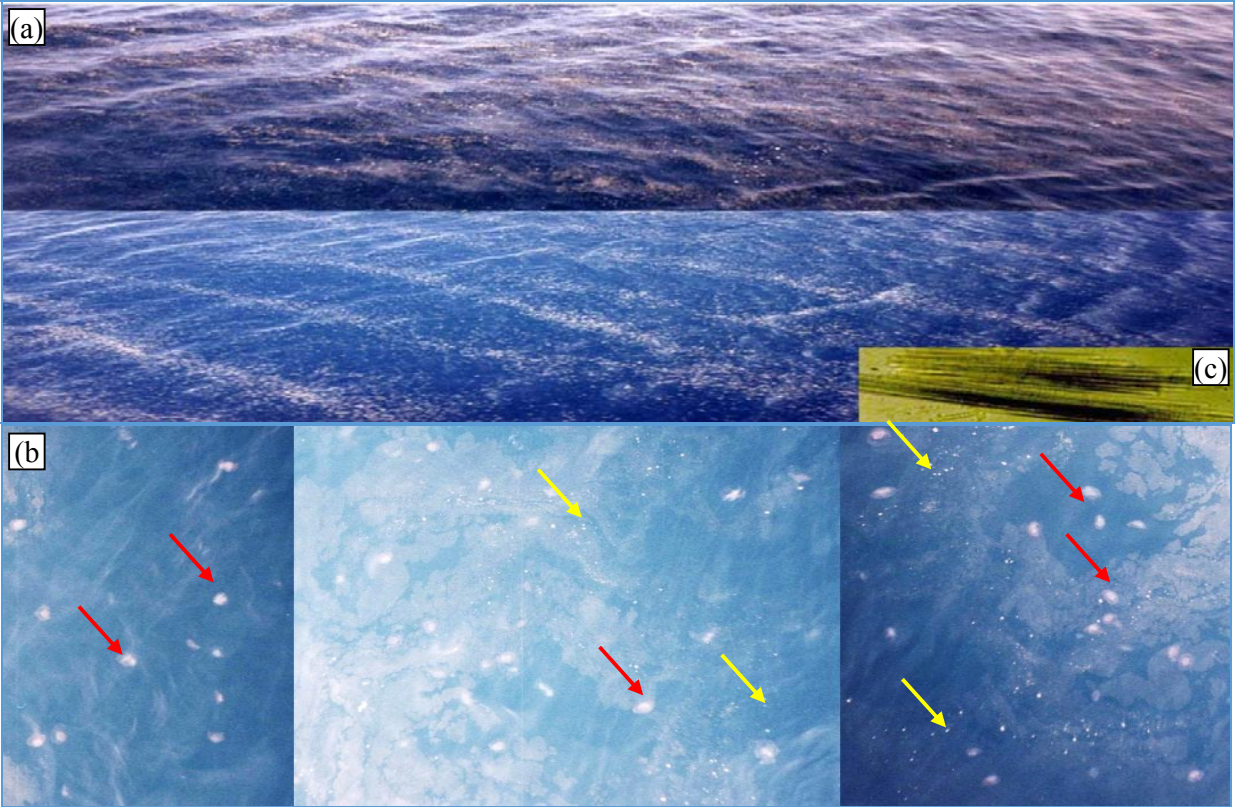


Figure 5





**Figure 6**

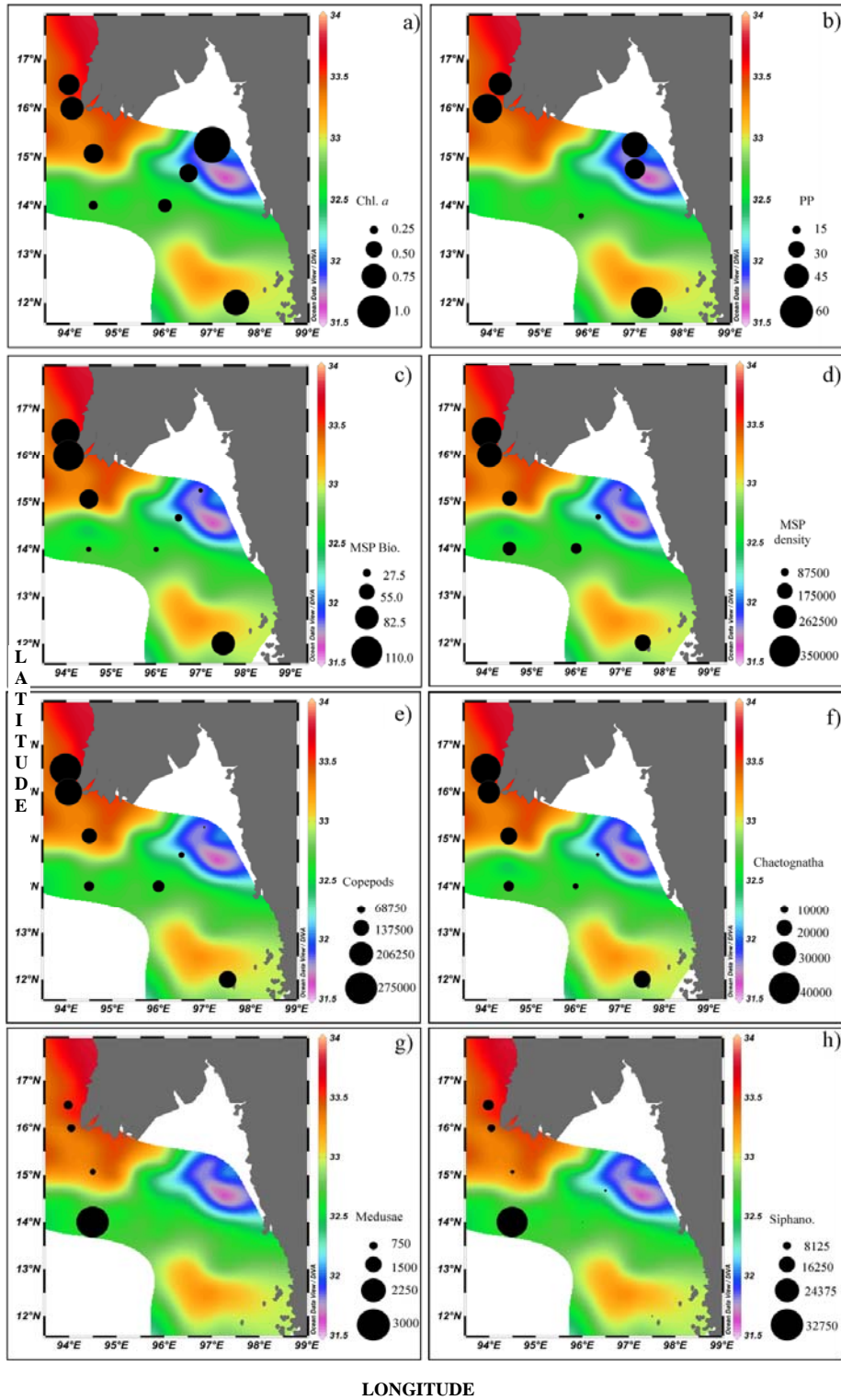


Figure 7

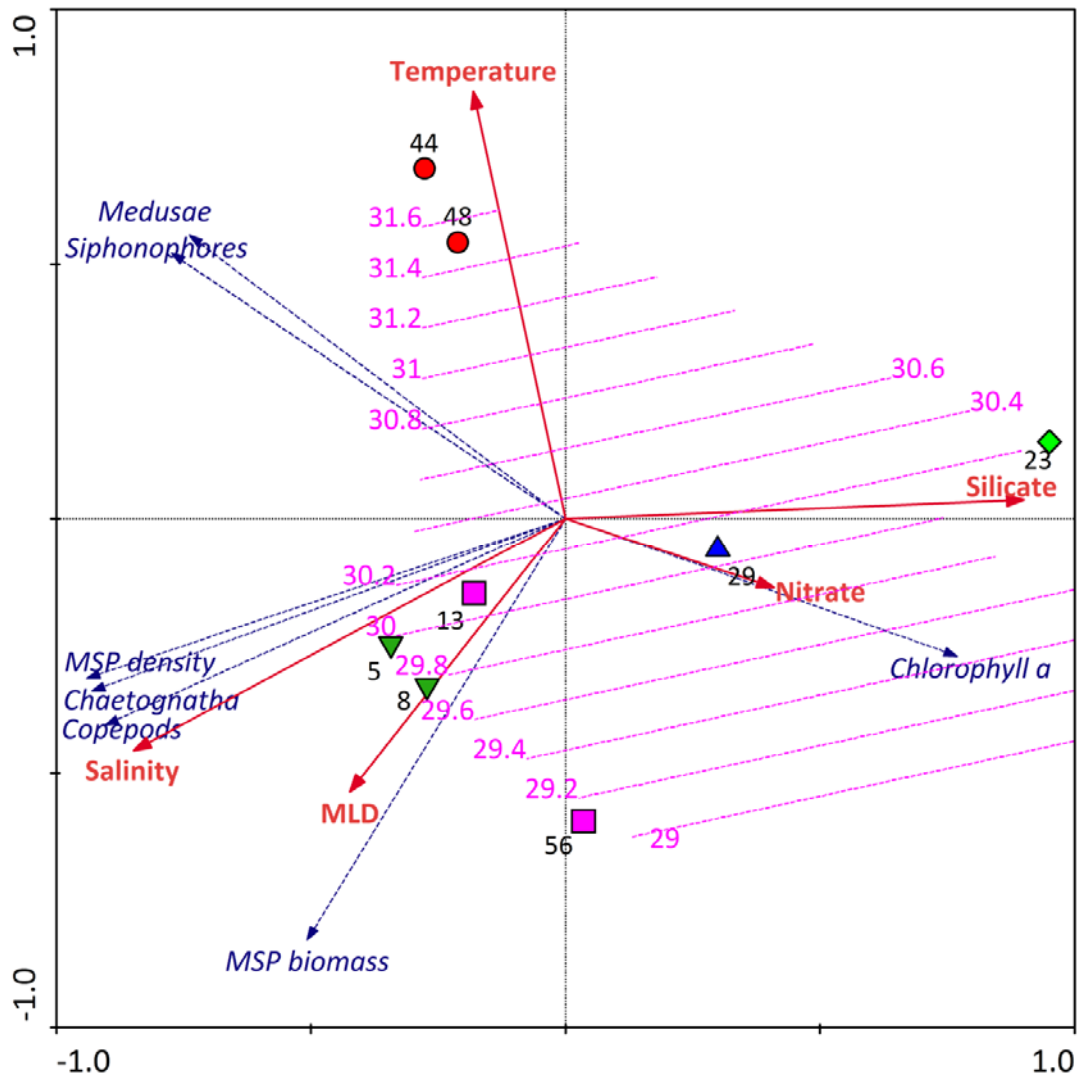


Figure 8

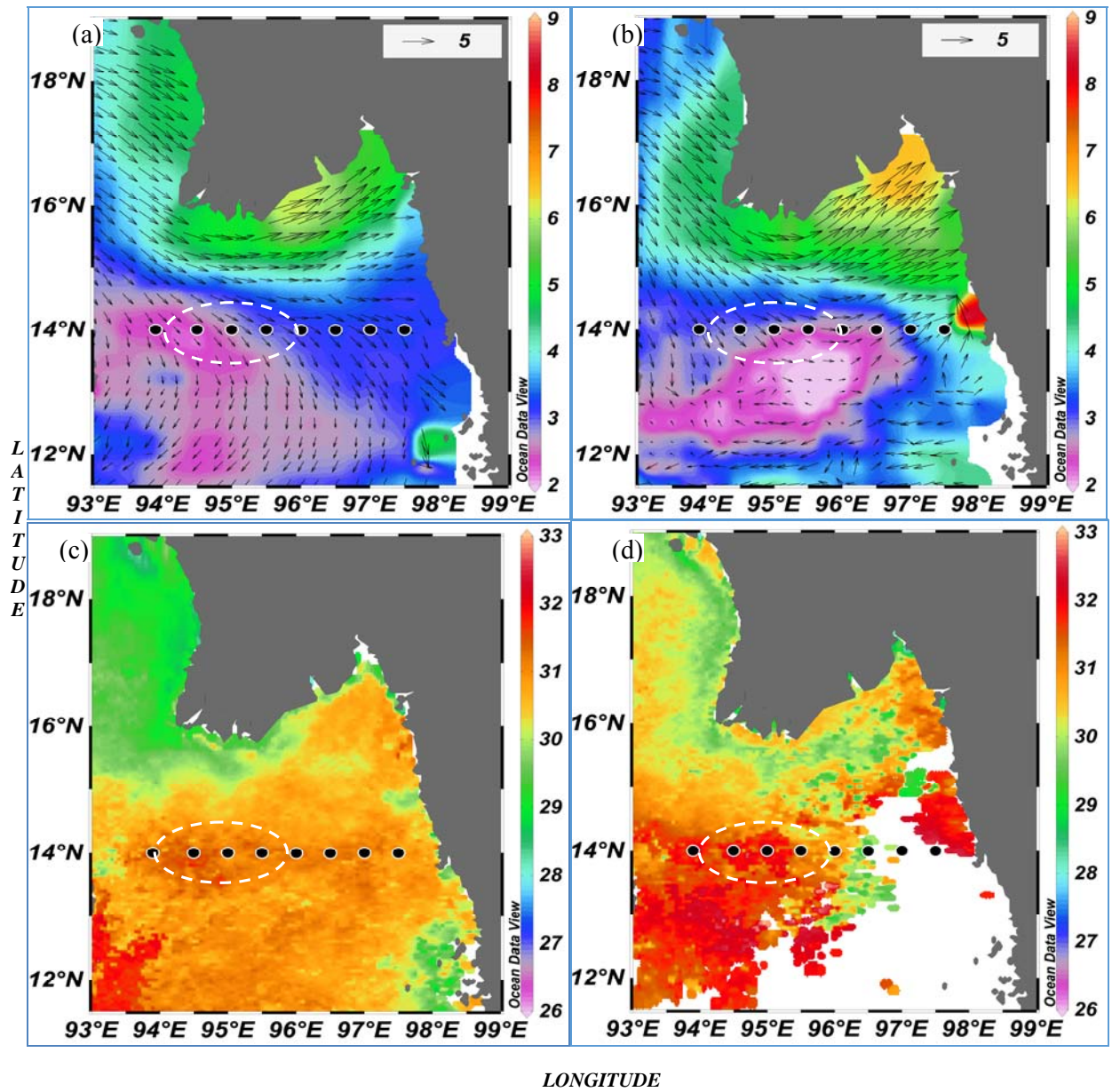


Figure 9

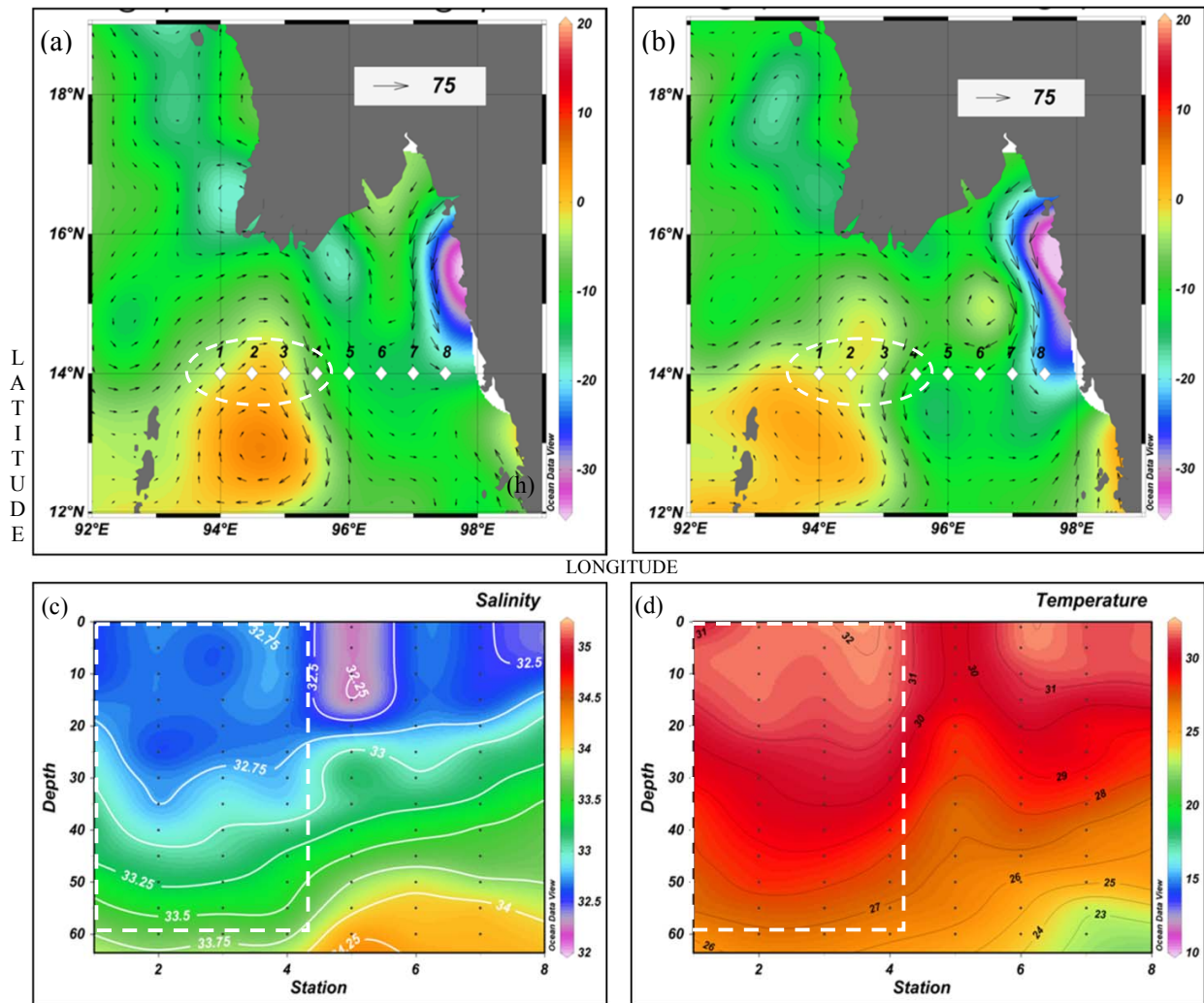


Figure 10

Locations	5	8	13	23	29	44	48	56
Salinity	33.55	33.37	33.28	31.78	32.26	32.68	32.34	32.99
Temperature (°C)	29.59	28.98	30.18	29.68	30.77	31.78	31.84	29.72
Nitrate (µM)	0.22	0.10	0.05	1.89	0.36	0.059	0.059	0.189
Silicate (µM)	0.33	0.025	0.44	5.96	5.62	0.223	0.114	0.45
MLD (meters)	21	25	26	8	16	18	24	48
Chl a (mg.m <sup>-3</sup> )	0.26	0.41	0.29	0.78	0.23	0.14	0.34	0.49

**Table 1** - Environmental parameters in representative locations of spatially segregated diverse environmental settings. Stations selected are same as in Figure 2.

Segregation	Locations	General characteristics	Region
Cluster 1	1-11	Highest salinity, lowest temperature, low nutrients and suspended sediments	Rakhine coast
Cluster 2	25, 29, 30- 32, 38	Low salinity, high temperature, high nutrients and suspended sediments	Off Gulf of Mottama
Cluster 3	15, 16, 33, 35, 36, 37, 39, 40 - 49	High salinity, highest temperature, lowest nutrients and suspended sediments	Offshore waters of the northern Andaman Sea
Cluster 4	12- 14, 17- 20, 50-60	High salinity, low temperature, low nutrients and suspended sediments	Off Ayeyawady delta and south off Thanintharyi coast
Cluster 5	21-24, 26- 28, 34	Lowest salinity, high temperature, highest nutrient and suspended sediments	Gulf of Mottama

**Table 2** – General characteristics of the environmental settings in segregated clusters with their sampling locations in different regions of the study domain.

Locations	Cluster 1		Cluster 2	Cluster 3		Cluster 4		Cluster 5
	5	8	29	44	48	13	56	23
Foraminifera	1050	553	-	-	1583	266	329	-
Medusae	156	160	-	2436	84	-	-	-
Siphonophora	508	104	140	30264	28	360	49	-
Polychaeta	-	-	-	-	44	-	-	-
Ostracoda	2303	1351	-	182	83	574	-	-
Copepods	269906	198520	9394	27048	37861	63624	80864	924
Amphipods	-	-	-	-	28	-	-	-
Euphausida	1288	616	126	-	-	-	-	-
<b>Decapoda</b>	1946	1022	196	427	505	511	203	-
Pteropoda	42	28	-	126	67	-	-	-
Heteropoda	6048	3185	175	441	39	784	28	-
Gastropoda	336	161	98	105	22	56	-	-
Chaetognatha	37198	20664	476	4438	1361	12971	11788	-
Copelata	1372	651	-	1372	-	-	-	-
Fish Eggs and larvae	140	63	-	-	6	-	28	21
<b>Total</b>	<b>322293</b>	<b>227078</b>	<b>10605</b>	<b>66839</b>	<b>41711</b>	<b>79146</b>	<b>93289</b>	<b>945</b>
Values (mean) in clusters	(274685)		10605	(54275)		(86217)		945

**Table 3** - Various zooplankton groups and their abundance (ind.100 m<sup>-3</sup>) in different environmental settings/clusters. The representative locations in various clusters are same as in figure 2.