Chapter 4
Phytoplankton species composition, Community Structure, bio-diversity

This chapter compiles work done on phytoplankton species identification and enumeration; spatial and temporal distribution for open and coastal waters. Standard keys were used for microscopic identification and chlorophyll-a concentration was measured using spectrophotometric method. To study vertical distribution of phytoplankton, percent light intensities in the water column were measured using Satlantic® hyper-spectral underwater radiometer. Various diversity indices were calculated and compared to analyze their performance for bloom conditions. Outcomes of this work very clearly showed that diatoms were most dominant in the regions and seasons studied. Among the diversity indices, shannon’s index best represented the bloom conditions. Near shore regions of the coast had highest diversity. Vertical distribution of phytoplankton was greatly influenced by light and its correlation with chlorophyll-a concentrations did not stand good for surface with Noctiluca blooms during winter monsoon season.
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Communities can be defined as recurrent organized systems of organisms responding in a related way to changes in the environment (Legendre and Legendre, 1978). Disturbance in the environment produces changes in the growth variables of an individual, which causes reorganization of the community (Smayda, 1963). As a result of these changes, the organisms undergo physiological, morphological and cytological changes, to adapt and survive in the changed environmental conditions. This leads to succession of the species/organism/group of organisms. Apart from these changes, regional circulation patterns of the aquatic ecosystems also affect the distribution and abundance of individual species (Smayda, 1978).

Phytoplankton community structure undergoes changes in response to changes in the environmental conditions. Thus they act as indicators of water quality. The major factors governing the community structure of phytoplankton are nutrient availability, mixing of water masses, light, temperature, turbulence and salinity. To establish a quantitative relation between phytoplankton and their response to water quality, a long term monitoring or their simultaneous analysis of sites that reflects differences in water quality variables due to human activity is required (Harding, 1994; Marcela, 2003; Kelly-Gerreyn et al., 2004).

Global warming causes the taxonomic shift in the phytoplankton community structure where a diatom dominated waters are replaced by the dinoflagellates one (Leterme et al., 2008). This taxonomic shift may also lead towards non-endemic species, including toxic species that may be potentially harmful algal blooms (Penna et al., 2005). Such taxonomic shifts can induce changes in functional properties of the communities (Beaugrand, 2005).

Apart from being affected by the environmental conditions, phytoplankton itself has important impacts on water quality and therefore plays an important role in many ecosystem processes (Domingues et al., 2008). Phytoplankton is usually employed to
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assess the nutrient load, eutrophication and responses to many other environmental stressors, due to its fast population responses to changes in water quality, hydrology or climate (Domingues et al., 2008; Devlin et al., 2009; Spatharis and Tsirtsis, 2010). Phytoplankton assessment has been required by different legislations (e.g. Clean Water Act (PL 92-500, 1972 (Bricker et al., 2008), in USA; Marine Strategy Framework Directive-MSFD, 2008/56/EC (Ferreira et al., 2011), in Europe) and conventions (e.g. Oslo–Paris Convention (OSPAR, 2009); and Helsinki Convention (HELCOM, 2009) that explicitly address eutrophication. Water Framework Directive (WFD, 2000/60/EC) has mentioned phytoplankton as one of the biological quality elements, for assessing the ecological status of water bodies.

Our knowledge of biodiversity patterns in marine phytoplankton is very limited in comparison to that of the biodiversity of plants on the land (Irigoien et al., 2004) despite of the fact that oceans are crucial for life on earth. It is well established that diversity enhances productivity and stability in communities of higher organisms; however, knowledge of such relationships between unicellular organisms like phytoplankton, which contribute to about 50% to the global primary productivity, is still lacking (Ptacnik et al., 2008).

A diversity index is a measure of species diversity within a community that consists of co-occurring populations of several (two or more) different species. It includes two components: richness and evenness. Richness is the measure of the number of different species within a sample showing that more the types of species in a community, the higher is the diversity or greater is the richness. Evenness is the measure of relative abundance of the different species within a community.

In this study we have tried to analyze phytoplankton species composition, community structure and diversity (evenness and richness) using various diversity indices like Shannon Diversity Index, Simpsons Diversity Index, Marglef Diversity Index, McIntosh Diversity Index, Pielou Evenness Index and dominance index. For the study phytoplankton community was classified into three categories such as Diatoms (Bacillariophyceae), Dinoflagellates (Dinophyceae) and other algae that included Chlorophytes, Coccolithophorids and Cyanophytes. The use of these indices is well
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established in ecological literature however choice of a suitable index depends on how well the richness and evenness is represented by each index.

4.1 Methods:

4.1(a) Phytoplankton identification, enumeration and distribution:

Water samples were collected from various sampling depths, which were decided on the basis of percent light intensity/penetration with reference to the surface irradiance in the water column. Satlantic® under water hyper-spectral radiometer was used to measure the light levels at the sampling sites. For identification and enumeration of phytoplankton species, 500 ml of sea water was fixed with 1% lugol’s Iodine and preserved in 3% buffered formaldehyde solution. The preserved samples were stored under dark and cool conditions until analyzed under microscope. Samples were concentrated approximately to 5-10 ml by siphoning the top layer of the sample carefully with a tube. 1ml of the concentrated sample was transferred to a Sedgwick-Rafter slide and identified and counted using an Olympus® Inverted Microscope (Model IX 50) at 200 % magnification. Standard taxonomic keys (Tomas, 1997) were used for identification. With an aim of studying seasonal variation in phytoplankton species composition, community structure and diversity, sampling cruises were categorized into fall inter monsoon (October-November), winter-monsoon (December-March) and inter-monsoon (April-May) seasons.

To study the spatial distribution of phytoplankton Arabian Sea was categorized as Coastal (< 50m depth), shelf (50-200m depth), slope (200-500m depth) and Open Ocean (>500m depth). Phytoplankton cell count was mapped using surfer (version 8.01), surface mapping system, Golden software; Inc. Data sets obtained for sampling points represented the values of only a point of the large water body. Thus to have information of phytoplankton distribution over a larger spatial extent of the region under study krigging extrapolation was used as a gridding method, assuming that phytoplankton distribution should be same for a region with similar physical forcing. Krigging extrapolation was chosen as method of gridding as it is one of the more flexible methods, is useful for gridding almost any type of data sets and generates a good map for most data sets.
4.1(b) Calculation of diversity indices:

To analyze the bio-diversity of phytoplankton species and communities identified through microscopy various diversity indices such as Shannon Diversity Index, Simpson Diversity Index, Margalef Diversity Index, McIntosh Diversity Index, Pielou Evenness Index and dominance index were computed (Motwani et al., in press). For analyzing the community structure of phytoplankton in the North-Eastern Arabian Sea these indices were calculated as follows:

- **Shannon Diversity Index**:

This index is applied to biological systems very commonly for calculating diversity. It was derived from a mathematical formula by Shannon in 1948 (Mandaville, 2002).

\[
H' = -\sum (\frac{n_i}{N} \times \ln (\frac{n_i}{N}))
\]

- **Simpson Diversity Index**:

This diversity index is derived by Simpson in 1949 (Simpson, 1949 and Mandaville, 2002). Simpson index values (\(\Delta\)) are between 0 – 1. But while calculating, final result is subtracted from 1 to correct the inverse proportion.

\[
1 - \Delta = \frac{\sum n_i (n_i -1)}{N (N-1)}
\]
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- **Margalef Diversity Index:**

  It has no limit value and shows a variation depending upon the number of species. Thus, it is used for comparison between various sites (Turkmen et al., 2010).

  \[
  d = (S-1) / \ln N
  \]

  - d: Margalef Diversity Index
  - S: Total number of species
  - N: Total number of individuals

- **McIntosh Diversity Index:**

  It was suggested by McIntosh in 1967. The value ranges between 0–1. The closer is the value to 1; the more homogeneous is the distribution of phytoplankton (McIntosh, 1967).

  \[
  Mc = [N - \sqrt{\sum n_i^2}] / [N - \sqrt{N}]
  \]

  - Mc: McIntosh Diversity Index
  - ni: Number of individuals belonging to i species
  - N: Total number of individuals

- **Pielou Evenness Index:**

  It was derived from Shannon index by Pielou in 1966. The ratio of Shannon index to the maximum value gives the Pielou Evenness Index result. The values range between 0 – 1. The closer is the value to 1; the more even is the distribution of phytoplankton (Pielou, 1966).

  \[
  J' = H' / H'_{\text{max}}
  \]

  - J’: Pielou evenness index
  - H’: The observed value of Shannon index
  - H’max: lnS
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S: Total number of species

- **Dominance Index:**

Dominance index ranges from 0 to 1. 0 represents that all taxa are equally distributed and 1 means one taxon dominates the community completely (Simpson, 1949).

\[
D = \sum \left(\frac{n_i}{n}\right)^2
\]

\[n_i: \text{Number of individuals of taxon } i\]

4.1(c) *Estimation of Chlorophyll-a Concentration*:

Depending on the density of phytoplankton, 50ml to 300ml of water samples from each sampling site and depth were filtered. Whatman® GF/F filters with pore size of 0.7 µm and diameter 25 mm were used for filtration of the water samples. The filters were then preserved in liquid nitrogen until further analyzed.

The filter papers containing phytoplankton cells were placed in test tube filled with 90% aqueous acetone. For extraction of pigments from the cells, the filtrates were gently ground using a glass rod and incubated in cool and dark conditions for 24 hours. After the incubation period, the extracts were transferred to a graduated centrifugation tube and the volume was made up to 10 ml by adding 90% acetone in all the tubes. The solution was then centrifuged for about 15 minutes at 5000rpm. The supernatant solution was transferred to a cuvette of 1 cm path length. The optical densities of the solutions were determined using Shimadzu® UV-VIS spectrophotometer (UV-1800) at wavelengths 664nm, 647nm and 630nm, corresponding to the maximum absorption wavelengths of chlorophyll-a, b and c respectively and at 750nm corresponding to absorption by sediments. Coastal waters are expected to have significant proportion of sediments along with phytoplankton cells in the particulate form. The absorption values of the wavelengths corresponding to pigments were corrected by subtracting the values of blank (absorption by acetone) and then by absorption values at 750 nm for small turbidity corrections from those of
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the pigment values. The individual concentration of chlorophyll-a in the extracts was determined using the equation of Jeffrey and Humphrey (1975):

\[ Chl_a = 11.85 (OD)_{664} - 1.54 (OD)_{647} - 0.08 (OD)_{630} \]

Where: Chl\textsubscript{a} is the concentration of chlorophyll-a (mg/L)

(OD\textsubscript{664}, (OD\textsubscript{647} and (OD\textsubscript{630} are the corrected optical densities at the respective wavelengths

Finally the amount of pigment per unit volume of sample was determined as follows:

\[ \text{Chlorophyll-a (mg/m}^3\text{)} = \text{Chl}_a \times \text{volume of extract (L)} / \text{volume of sample (m}^3\text{)} \]

4.2 Results and discussions:

4.2(a) Taxonomic positions and descriptions of major phytoplankton genus recorded:

**Diatoms**

1. *Asterionellopsis*

   Order: Bacillariales

   Sub-order: Fragilariineae

   Family: Fragilariaceae

   Genus: *Asterionellopsis*

   Cells have dissimilar ends in valve as well as in girdle views. Cells joined by valve faces of expanded foot pole in star-like, spiral chains. Foot poles angular in girdle view and more or less rounded in valve view *(Tomas et al., 1997).*

   Major species recorded: *A. glacialis*
2. *Bacteriastrum*
   Order: Biddulphiales
   Sub-order: Buddulphiineae
   Family: Chaetoceraceae
   Genus: *Bacteriastrum*
   Cells have dissimilar ends in valve as well as in girdle views. Cells joined by valve faces of expanded foot pole in star-like, spiral chains. Foot poles angular in girdle view and more or less rounded in valve view (Tomas et al., 1997).
   Major species recorded: *B. delicatulum, B. elongatum, B. hyalinum*

3. *Biddulphia/Odontella*
   Order: Biddulphiales
   Sub-order: Buddulphiineae
   Family: Euphodiscaceae
   Genus: *Biddulphia/Odontella*
   Cells form straight or zigzag chains. Valves are elliptical or lanceolate with an elevation and an ocellus at each pole. Two or more labiate processes per valve with usually long external tubes (Tomas et al., 1997).
   Major species recorded: *B. mobiliensis, B. sinensis, B. rhombus*

4. *Chaetoceros*
   Order: Biddulphiales
   Sub-order: Buddulphiineae
   Family: Chaetoceraceae
   Genus: *Chaetoceros*
   Cells in long chains and are inseparable due to fusion of silica between setae. Each valve has two setae, one at each end of the apical axis (Tomas et al., 1997).
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5. Coscinodiscus
Order: Biddulphiales
   Sub-order: Coscinodiscineae
   Family: Coscinodiscaceae
   Genus: Coscinodiscus
Cells are solitary with circular valves, usually presence of radial arrangement of areolae. Frustules discoid to cylindrical, coin shaped, with stepped elevated valve face or of wedge shape (Tomas et al., 1997).
Major species recorded: C. centralis, C. ecentricus, C. granii, C. marginatus, C. nitidus, C. wailesii, C. radiatus

6. Ditylum
Order: Biddulphiales
   Sub-order: Buddulphiineae
   Family: Lithodesmiaceae
   Genus: Ditylum
Marginal ridge conspicuous, often fringed, no defined elevations at valve corners (Tomas et al., 1997).
Major species recorded: D. brightwelli
7. **Eucampia**

Order: Biddulphiales  
Sub-order: Buddulphiineae  
Family: Hemiaulaceae  
Genus: *Eucampia*

Pervalvar axis is long. Cell form chains that are often helically curved, Valve wall characterized by elevations with ribbed top plate (*Tomas et al., 1997*).  
Major species recorded: *E. zodiacus*

8. **Guinardia**

Order: Biddulphiales  
Sub-order: Rhizosoleniineae  
Family: Rhizosoleniaceae  
Genus: *Guinardia*

Cells cylindrical and form chains. Girdle composed of open/spilt bands with ligulae and ant-ligulae (*Tomas et al., 1997*).  
Major species recorded: *G. delicatula, G. flaccid, G. striata*

9. **Hemialus**

Order: Biddulphiales  
Sub-order: Buddulphiineae  
Family: Hemiaulaceae  
Genus: *Hemialus*

Valve wall characterized by elevations that are usually long and slender with pointed ends and no ribbed top plate, apertures between cells in chains mostly wide (*Tomas et al., 1997*).  
Major species recorded: *H. haukii, H. sinensis, H. indicus*
10. **Lauderia**

Order: Biddulphiales  
Sub-order: Coscinodiscineae  
Family: Thalassiosiraceae  
Genus: *Lauderia*

Cells form chain. Valve structure mainly consists of long occluded process and radial ribs whereas central processes rudimentary or missing (*Tomas et al.*, 1997).

Major species recorded: *L. borealis*

12. **Melosira**

Order: Biddulphiales  
Sub-order: Coscinodiscineae  
Family: Melosiraceae  
Genus: *Melosira*

Cells in chain united by mucilage pads, sometimes also by a corona consisting of large irregular spins, value mantle high and strongly curved (*Tomas et al.*, 1997).

Major species recorded: *M. moniliformis*

13. **Navicula**

Order: Bacillariales  
Sub-order: Bacillariineae  
Family: Naviculaceae  
Genus: *Navicula*

Cells solitary and rectangular in girdle view. Valves lanceolate and sometimes with produced ends. Transapical striae are lineate which may be crossed by ginner longitudinal striations (*Tomas et al.*, 1997).

Major species recorded: *N. didyma, N. directa, N. distans*
14. **Nitzschia**

Order: Bacillariales

Sub-order: Bacillariineae

Family: Bacillariaceae

Genus: *Nitzschia*

Cells rectangular or spindle shaped in girdle view. Frustules untwisted. Valves elongate and raphe with bridge of silica cross linking the valve beneath the raphe (*Tomas et al.*, 1997).

Major species recorded: *N. closterium, N. longissima, N. rectilonga, N. sigma*

15. **Planktoniella**

Order: Biddulphiales

Sub-order: Coscinodiscineae

Family: Thalassiosiraceae

Genus: *Planktoniella*

Cells are discoid with organic extrusions from the girdle (*Tomas et al.*, 1997).

Major species recorded: *P. blanda, P. Sol*

16. **Pleurosigma**

Order: Bacillariales

Sub-order: Bacillariineae

Family: Naviculaceae

Genus: *Pleurosigma*

Valves more or less flattened, gently sigmoid. Outline of the valves lanceolate. Central raphe may be straight or sigmoidal. Three striae system: one transverse and two oblique (*Tomas et al.*, 1997).

Major species recorded: *P. aestuarii, P. angulatum, P. elongatum, P. normanii*
17. *Pseudonitzschia*

Order: Bacillariales

Sub-order: Bacillariineae

Family: Bacillariaceae

Genus: *Pseudonitzschia*

Cells spindle shaped in girdle view. Cells united by overlap of valve ends into stepped chains. Valves elongate and raphe with bridge of silica cross linking the valve beneath the raphe (Tomas et al., 1997).

Major species recorded: *P. australis, P. delicatissima, P. pungens, P. seriata*

18. *Rhizosolenia*

Order: Biddulphiales

Sub-order: Rhizosoleniineae

Family: Rhizosoleniaceae

Genus: *Rhizosolenia*

Cells cylindrical and form chains. Valves are regular conical, processes straight and generally with otaria (Tomas et al., 1997).

Major species recorded: *R. alata, R. bergonii, R. fragilissima, R. hebetate, R. imbricate, R. indica, R. robusta, R. setigera*

19. *Skeletonema*

Order: Biddulphiales

Sub-order: Coscinodiscineae

Family: Thalassiosiraceae

Genus: *Skeletonema*

Cells form chains, linked by threads of organic matter from strutted processes. Such Strutted processes are absent in central process. Outline of the valve circular (Tomas et al., 1997).

Major species recorded: *S. costatum*
20. **Thalassionema**

Order: Bacillariales  
Sub-order: Fragilariaceae  
Family: Fragilariaceae  
Genus: *Thalassionema*

Straight cells (not twisted) in stellate, zigzag, or fan shaped colonies (Tomas et al., 1997).

Major species recorded: *T. frauenfeldii, T. nitzschoidis*

21. **Thalassiosira**

Order: Biddulphiales  
Sub-order: Coscinodiscineae  
Family: Thalassiosiraceae  
Genus: *Thalassiosira*

Cells are usually discoid and in chains (sometimes solitary and embedded in mucilage), valve mantle with loculate areolae in various patterns. Connecting threads (strutted process) extrude from the margins of the valve face (Tomas et al., 1997).

Major species recorded: *T. angulata, T. condensate, T. decipiens, T. poroseriata, T. anguste-lineata*

22. **Thalassiothrix/Lioloma**

Order: Bacillariales  
Sub-order: Fragilarineae  
Family: Thalassionemataceae  
Genus: *Thalassiothrix/Lioloma*

Cells solitary or in stellate, zigzag, or fan shaped colonies. Cells are not twisted (Tomas et al., 1997).

Major species recorded: *T. delicatulum, T. elongatum, T. pacificum*
**Dinoflagellates**

23. *Alexandrium*

   Order: Gonyaulacales
   
   Family: Goniodomataceae
   
   Genus: *Alexandrium*
   
   Cells armored with typically spherical to hemispherical to oval to slightly bi-conical shape that may or may not have horns or spines *(Tomas et al., 1997)*.
   
   Major species recorded: *A. catenella, A. ostenfeldii, A. tamarense*

24. *Ceratium*

   Order: Gonyaulacales
   
   Family: Ceratiaceae
   
   Genus: *Ceratium*
   
   Cells armored with two to four hollow horns. Central body somewhat dorsoventrally compressed *(Tomas et al., 1997)*.
   
   Major species recorded: *C. furca, C. fusus, C. incisum, C. teres, C. trichoceros*

26. *Heterocapsa*

   Order: Peridinales
   
   Family: Calciodinellaceae
   
   Genus: *Heterocapsa*
   
   Cells are small (<20µm), armored dinokonts. Epitheca rounded to conical and hypotheca rounded to attenuated. Cingulum slightly displaced and descending *(Tomas et al., 1997)*.
   
   Major species recorded: *H. triquetra*
27. *Noctiluca*

Order: Noctilucales

Family: Noctilucaceae

Genus: *Noctiluca*

Large sub-spherical, inflated vegetative cells with two flagella and striated tentacle. The cytoplasm is vacuolate and can contain photosynthetic symbionts (Tomas et al., 1997).

Major species recorded: *N. scintillans*

28. *Prorocentrum*

Order: Prorocentrales

Family: Prorocentraceae

Genus: *Prorocentrum*

Cells armored whose shape varies from spheroid to pyriform in valve view. Cells have two anterior dissimilar flagella (Tomas et al., 1997).

Major species recorded: *P. arcuatum, P.balticum, P. belizeanum, P. compressum, P. dentatum, P. lima, P. micans, P. minimum, P. scutellum*

30. *Pyrocystis*

Order: Gonyaulacales

Family: Pyrocystaceae

Genus: *Pyrocystis*

Non-flagellated bladder cells can be spherical, fusiform, and lanceolate or crescent shaped (Tomas et al., 1997).

Major species recorded: *P. fusiformis, P. noctiluca*

31. *Scrippsiella*

Order: Peridinales

Family: calciodinellaceae

Genus: *Scrippsiella*

Cells are small (<50µm), armored dinokonts occurring
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in planktonic and benthic habitats (Tomas et al., 1997).
Major species recorded: *S. trochoidea*

**Other Algae**

32. *Clamydomonas*
Division: Chlorophyta
Class: Chlorophyceae
Order: Volvocales
Family: Chlamydomonadaceae
Genus: *Clamydomonas*
The marine species is small (4.5-5µm), two flagellate, cell wall relatively thick, papilla and contractile vacuoles are absent (Tomas et al., 1997).

33. *Coelosphaerium*
Class: Cyanophyceae
Order: Chroococcales
Family: Gomphosphaeriaceae
Genus: *Coelosphaerium*
Spherical to oval colonies of cells held in a single outer layer of the mucilage. Usually colorless or black in the presence of gas vesicles (http://www.algaebase.org/search/genus/detail/?genus_id=43586).
Major species recorded: *C. minutissimum*

34. *Dictyocha*
Division: Chromophyta
Class: Dictyochoiphyceae
Order: Dictyochales
Family: Dictyochoaceae
Genus: *Dictyocha*
Cell skeleton usually have quadrangular or hexagonal shape (Tomas et al., 1997).
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Major species recorded: *D. fibula, D. octonaria, D. speculum*

35. *Meringosphaera*
   
   Class: Xanthophyceae
   
   Order: Mischococcales
   
   Family: Pleurochloridaceae
   
   Genus: *Meringosphaera*
   
   Spines long, undulating and tapering toward the distal end, radiating in all directions (Tomas et al., 1997).
   
   Major species recorded: *M. mediterranea*

37. *Trichodesmium*
   
   Class: Cyanophyceae
   
   Order: Oscillatoriales
   
   Family: Phormidiaceae
   
   Genus: *Trichodesmium*
   
   Long filaments form of tufts of colonies with 20-200 cells.
   
   (http://www.algaebase.org/search/species/detail/?species_id=24714)
   
   Major species recorded: *T. erythrium*

4.2(b) Phytoplankton species composition and community structure for north-eastern Arabian Sea (case 1 water):

The phytoplankton community structure of the Arabian Sea was highly diverse with 287 species identified. In terms of number of species (richness), dinoflagellates exhibited the greatest diversity with 142 species followed by diatoms with 137 species, other algae with 7 species. Diatoms and dinoflagellates were the most diverse groups. Out of 142 species of dinoflagellates 37% was contributed by three genera: *Ceratium* (22 species; 16%), *Protoperidinium* (19 species; 13.38%) and *Prorocentrum* (11 species; 8%). Of the 137 species of diatoms, 32.5 % was represented by three genera: *Chaetoceros* (20 species; 15%), *Navicula* (13 species; 9.5%) and *Rhizosolenia* (11 species; 8%). Among other algae, *Trichodesmium* and
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*Dictyocha* both contributed to 29% of total species of other algae. As a whole, a pronounced prevalence of dinoflagellates and diatoms were typical for the phytoplankton community in the Arabian Sea during the period of analysis.

Total phytoplankton cells observed in samples collected from north-eastern Arabian Sea ranged from (1 cell/lit to 26388 cells/lit) during 2003 to 2007. In terms of total number of cells per liter volume of water (evenness), diatoms were the most dominant group, followed by dinoflagellates and other algae. Out of 217391 cells of diatoms per liter of water sample, which contributed to 65% of total phytoplankton diversity, *Navicula sp.* (26388 cells/lit), *Thalassiothrix frauenfeldii* (14902 cells/lit), *Skeletonema costatum* (12689 cells/lit) were the major contributors. Of the 79408 cells of dinoflagellates per liter of water sample which contributed to 24% of total phytoplankton diversity *Noctiluca scintillans* (17861 cells/lit), *Scrispiella trachoidea* (8966 cells/lit) and *Prorocentrum minimus* (7372 cells/lit) were the major contributors. Among other algae that contributed to 13% of the total diversity, *Trichodesmium thibautii* (21195 cells/lit) and *Trichodesmium erythraeum* (19332 cells/lit) were the major contributors. As shown in figure 4.2 (b-1), a pronounced prevalence of diatoms was typical for the phytoplankton community in the Arabian Sea during the period of analysis.

![Figure 4.2 (b-1): Richness of various Phytoplankton groups](image)

Studies by *Escaravage et al.,* (1996) showed that high N/P ratio favours the growth of diatoms in the phytoplankton community. *Yung et al.,* (1997) found that the dominance shifts towards dinoflagellates if the N/P ratio decreases significantly whereas experiments by *Egge* (1998) showed that diatoms decreased as N/P ratio increased. Studies by *Huang et al.,* (2012) showed that N/P ratio has a significant effect on the cell abundance, chlorophyll-α concentration, specific growth rate, diversity indices, species composition, and succession of the phytoplankton community.
**4.2(c) Temporal variations in phytoplankton concentration for case 1 waters:**

The prevalence of diatoms was at a maximum (68%) during the inter-monsoon period (April to May) and reduced to 52% during the winter-monsoon period (February and March). Dinoflagellates contributed only 24% to the total species diversity, with 32% during the winter-monsoon period, and reduced to 22% during the Inter-monsoon period. Other algae contributed to 11% during spring inter monsoon whereas there percentage increased to 18% during winter monsoon period. Their concentrations in winter monsoon and inter monsoon periods are summarized in table 4.2 (c-1) and figures 4.2 (c-1) illustrates their group wise concentration in the two periods.

As represented in figure 4.2 (c-2) and 4.2 (c-3), major contributors to the diatoms during winter monsoon season were *Rhizosolenia shrubsolei* (7164 cells/lit; 22%), *Rhizosolenia hebetata* (4555 cells/lit; 14%), *Navicula* sp. (4500 cells/lit; 14%) and *Podosira stelliger* (3789 cells/lit; 12%) whereas during spring inter monsoon period *Navicula* sp. (24300 cells/lit; 14%), *Thalassiothrix frauenfeldii* (14366 cells/lit; 8%) and *Skeletonema costatum* (12676 cells/lit; 7%) were the most dominant species among diatoms. *Noctiluca scintillans* (16501 cells/lit) alone contributed to 82% of the total dinoflagellates in the winter monsoon period while during spring inter monsoon period 16% was constituted by *Scripsiella trachoides* (8966 cells/lit) and 13% was contributed by *Prorocentrum minimus* (7372 cells/lit). *Trichodesmium thibautii* (9427 cells/lit) dominated with 85% among other algae during winter monsoon season while during spring inter monsoon period *Trichodesmium erythraeum* (17674 cells/lit; 59%) and *Trichodesmium thibautii* (11768 cells/lit; 40%) were the greatest contributors among other algae. Annexure 4.2 provides a detailed list of Phytoplankton types studied and annexure 4.3 shows detailed values for percent contribution of various groups from open ocean (case I) waters of north-eastern Arabian sea (case I) for various seasons.
Table 4.2(c-1): Phytoplankton cell concentration and percent contribution, in winter monsoon and inter monsoon periods and their group wise concentration and percent contribution in the two periods

<table>
<thead>
<tr>
<th></th>
<th>Winter monsoon period</th>
<th>Inter monsoon period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(60867 cells/lit)</td>
<td>(55658 cells/lit)</td>
</tr>
<tr>
<td>Total cell Concentration</td>
<td>52%</td>
<td>48%</td>
</tr>
<tr>
<td>Diatoms</td>
<td>42568 cells/lit</td>
<td>42568 cells/lit</td>
</tr>
<tr>
<td>Dinoflagellates</td>
<td>15407 cells/lit</td>
<td>15407 cells/lit</td>
</tr>
<tr>
<td>Other Algae</td>
<td>2892 cells/lit</td>
<td>2892 cells/lit</td>
</tr>
<tr>
<td>Diatoms</td>
<td>36170 cells/lit</td>
<td>36170 cells/lit</td>
</tr>
<tr>
<td>Dinoflagellates</td>
<td>10714 cells/lit</td>
<td>10714 cells/lit</td>
</tr>
<tr>
<td>Other Algae</td>
<td>8774 cells/lit</td>
<td>8774 cells/lit</td>
</tr>
</tbody>
</table>

Figure 4.2(c-1): Percent contribution of diatoms, dinoflagellates and other algae in winter and inter monsoon periods

Figure 4.2(c-2): Major phytoplankton species contributing to various groups in Open Ocean waters during winter monsoon periods
Figure 4.2(c-3): Major phytoplankton species contributing to various groups in Open Ocean waters during spring inter monsoon periods

4.2(d) Spatial variations in phytoplankton concentration for case I waters:

*Noctiluca scintillans* formed massive blooms in the open ocean of northern Arabian Sea (figure 4.2 (d-2)) covering a large area from 17°19.40'N and 70°11.95'E to 20°28.72’N and 67°30.51’E during winter monsoon period as shown in figure 4.2 (d-1) whereas *Trichodesmium erythraeum* formed bloom in the coastal waters at 20°31.87’N and 70°34.77’E during inter monsoon period as shown in figure 4.2 (d-1).

Figure 4.2(d-1): Spatial distribution of phytoplankton cells over the Arabian Sea during winter and inter monsoon periods. The colour bar shows cell concentration (cells/lit); green to red colour in the map shows the region covered by the bloom (Maps prepared using Surfer (version8.01), surface mapping system, Golden software, Inc.)
Figure 4.2 (d-2): Massive Noctiluca bloom observed in the North-eastern Arabian Sea

Variation in phytoplankton community structure is mainly governed by physical factors such as light, temperature and availability of nutrients. Open oceans can be considered as stable systems with respect to physical disturbances and environmental heterogeneity as compared to the coastal systems. Thus there is always an opportunity for greater diversity according to stability-time hypothesis proposed by Sanders (1968). His hypothesis, in general, stands true for the open ocean region of the Arabian Sea but north-eastern Arabian Sea undergoes convective mixing due to winter cooling. This mixings brings up nutrients from the deep ocean bottoms and is probably the cause of occurrence of Noctiluca bloom in the region during winter monsoon every year.

4.2(e) phytoplankton bio-diversity and its seasonal variations for case I waters:

The diversity indices were calculated using the cell counts obtained from the samples collected during the open ocean cruises. All the diversity indices represent the phytoplankton diversity over the Arabian Sea. The results showed a good range of values as shown in table 4.2 (e-1). To compare seasonal variations in diversity indices, coinciding sampling sites for winter and inter monsoon periods were selected and plotted together, as shown in figure 4.2 (e-1). This comparison showed that diversity was higher during inter monsoon period than the diversity during winter
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Monsoon. Values of diversity indices were higher in the inter monsoon period than in winter monsoon season due the *Noctiluca* bloom during winter monsoon which greatly reduced the diversity during this period. The results of dominance index showed that dominance was higher during winter monsoon than during inter monsoon period. Higher values of dominance index clearly indicate presence of a bloom condition and that the distribution of the species is uneven. Annexure 4.4 provides detailed values of diversity indices for various open ocean cruises.

Table 4.2(e-1): Range of diversity indices in winter and inter monsoon cruises

<table>
<thead>
<tr>
<th></th>
<th>Winter Monsoon</th>
<th>Inter Monsoon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum value</td>
<td>Maximum value</td>
</tr>
<tr>
<td><strong>Shannon Index</strong> $H'$</td>
<td>0.79 FORV-253</td>
<td>2.59 FORV-253</td>
</tr>
<tr>
<td><strong>Simpson's Index</strong> $\Delta$</td>
<td>1.36 FORV-222</td>
<td>10.27 FORV-253</td>
</tr>
<tr>
<td><strong>Margalef Index</strong> $d$</td>
<td>0.44 FORV-222</td>
<td>3.02 FORV-253</td>
</tr>
<tr>
<td><strong>McIntosh Index</strong> $M_c$</td>
<td>0.17 FORV-222</td>
<td>0.71 FORV-253</td>
</tr>
<tr>
<td><strong>Pielou Evenness Index</strong> $J'$</td>
<td>0.09 FORV-253</td>
<td>0.40 FORV-253</td>
</tr>
<tr>
<td><strong>Dominance Index</strong> $D$</td>
<td>0.01 FORV-222</td>
<td>0.69 FORV-253</td>
</tr>
</tbody>
</table>

Figure 4.2 (e-1): Comparison between various diversity indices of coinciding sampling sites of winter monsoon and inter monsoon seasons
Table 4.2 (e-2): diversity indices for selected common sampling points of winter monsoon season

<table>
<thead>
<tr>
<th>Station</th>
<th>H’</th>
<th>Δ</th>
<th>d</th>
<th>Mc</th>
<th>J’</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stn2</td>
<td>2.14946</td>
<td>8.242653</td>
<td>1.142061</td>
<td>0.670752</td>
<td>0.30737</td>
<td>0.122118</td>
</tr>
<tr>
<td>Stn5</td>
<td>2.589652</td>
<td>9.160251</td>
<td>2.935168</td>
<td>0.687767</td>
<td>0.286316</td>
<td>0.109863</td>
</tr>
<tr>
<td>Stn7</td>
<td>1.65</td>
<td>2.40</td>
<td>3.02</td>
<td>0.36</td>
<td>0.22</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Table 4.2 (e-3): diversity indices for selected common sampling points of inter monsoon period

<table>
<thead>
<tr>
<th>Station</th>
<th>H’</th>
<th>Δ</th>
<th>d</th>
<th>Mc</th>
<th>J’</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stn6</td>
<td>2.510828</td>
<td>9.930233</td>
<td>2.304056</td>
<td>0.707868</td>
<td>0.387387</td>
<td>0.102041</td>
</tr>
<tr>
<td>Stn8</td>
<td>2.62033</td>
<td>12.47826</td>
<td>2.335268</td>
<td>0.744273</td>
<td>0.40984</td>
<td>0.081633</td>
</tr>
<tr>
<td>Stn11</td>
<td>2.52</td>
<td>9.44</td>
<td>2.28</td>
<td>0.70</td>
<td>0.38</td>
<td>0.11</td>
</tr>
</tbody>
</table>

To determine which index best represents the diversity, the diversity indices (Shannon’s index, Simpson’s index, Margalef index and McIntosh index) were correlated with the phytoplankton cell counts. The results of this correlation, as shown in figure 4.2 (e-2), clearly indicated that Shannon’s index has better correlation with the cell counts. Thus it is a better representative of phytoplankton diversity as compared to other indices. Values of $r^2$ (shown in figure 4.2 (e-2)) were low for all the indices as none of these could formulate the richness component of diversity except Shannon’s index. On the other hand, Shannon’s index fails to express the evenness component of the diversity. Margalef index did not appear to be sensitive to low diversity conditions.

If one or two species dominate the phytoplankton community, the phytoplankton distribution will be uneven. Such an inverse relation between dominance and evenness was computed and their negative correlation has $r^2=0.73$ and RMSE=0.003 as shown in figure 4.2 (e-3).
Since Shannon’s index was found to better represent the diversity for bloom and non-bloom conditions, detailed analysis of diversity for both case I and case II waters was carried out using Shannon’s index only. The detailed station-wise variations in Shannon’s index for major phytoplankton communities computed for different open ocean cruises are shown in figures 4.2 (e-4), 4.2 (e-5), 4.2 (e-6), and 4.2 (e-7). Annexure 4.5 provides station-wise detailed values of various diversity indices and corresponding total phytoplankton cell count for Open Ocean waters of north eastern Arabian Sea.
Figure 4.2 (e-4), 4.2 (e-5), 4.2 (e-6) and 4.2 (e-7): Shannon’s index for various stations of FORV-244, FORV-253, FORV-212 AND FORV-222 respectively
4.2(f) Phytoplankton diversity in coastal waters of Veraval (case 2 waters):

Coastal waters off Veraval have good phytoplankton diversity. Total 282919 phytoplankton cells were studied among which 275623 cells were of diatoms which formed 97.4 percent of the total number of phytoplankton. Among 275623 cells of diatoms *Skeletonema costatum* occurred with highest cell count that contributed to 21.7 %, while *Asterionellopsis glacialis* contributed to 18.5 %. 4902 cells of dinoflagellates formed 1.7 % of the total phytoplankton whereas 2394 cells of other algae contributed to 0.8 %. The major contributors to total dinoflagellates were *Prorocentrum micans* and *Pyrocystis fusiformis* with 15.2 and 11.4 % respectively and *Coelosphaerium minutissimum* was the major other algae (cyanophyte) which contributed to 31.2 %.

As shown in figure 4.2 (f-1) diatoms dominated in all the seasons studied with very less variation in percentage from season to season. *Asterionellopsis glacialis* dominated the fall inter monsoon season with 39.81 %. Diatoms formed 97.689 % (114725 cells/lit) of total phytoplankton in fall inter monsoon season where *Asterionellopsis glacialis* was the major species contributing to 40.751 % of total diatoms of the season. They reduced to 96.127 (100075 cells/lit) in winter monsoon with *Pseudonitzschia delicatissima* as highest contributor (8.141 %) to total diatoms of the season. Diatoms attained their maxima in inter monsoon season with 99.099 % (60863 cells/lit) *Skeletonema costatum* dominated the diatom diversity with 84.849 %. Number of Dinoflagellates and other algae fluctuated greatly in varying seasons. Dinoflagellates and other algae contributed to 1.750 (2208 cells/lit) and 0.559 (733 cells/lit) % respectively in fall inter monsoon season. *Scrippsiella trochoidea* was the major species (0.186 percent) among the dinoflagellates whereas *Trichodesmium erythrium* dominated other algae with 66.362 %. They showed an increase to 2.232 (2324 cells/lit) and (1707 cells/lit) 1.639 % respectively in winter monsoon season and again decreased to 0.851 (523 cells/lit) and 0.488 (30 cells/lit) respectively in inter monsoon season. *Pyrocystis fusiformis* (0.518 %) was the major dinoflagellate species and *Coelosphaerium minutissimum* (0.718 %) was the major other algae in winter monsoon season. *Prorocentrum micans* (0.14 %) was the major dinoflagellate whereas *Eutreptiella marina* was the only other algae found during inter monsoon season. This is represented in figure 4.2 (f-2), 4.2 (f-3) and 4.2 (f-4). Annexure 4.6
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provides list of Phytoplankton types studied and their percent contribution to various groups for coastal waters of Veraval (case II) for various seasons.

Figure 4.2(f-1): Percent contributions of diatoms, dinoflagellates and other algae in fall inter, winter and inter monsoon seasons

Figure 4.2(f-2): Major phytoplankton species contributing to various groups in coastal waters during fall inter monsoon season
**Phytoplankton species composition, Community structure and bio-diversity**

**Winter Monsoon Season**
- **Diatoms** (100075 cells/lit) 96.127%
- **Pseudonitzschia delicatissima** 8.14%
- **Pyrocystis fusiformis** 0.51%
- **Ceolosphaerium minutissimum** 0.71%

**Spring Inter Monsoon Season**
- **Diatoms** (60863 cells/lit) 99.10%
- **Skeletonema costatum** 84.84%
- **Prorocentrum micans** 0.14%
- **Eutreptiella marina** 100%

Figure 4.2(f-3): Major phytoplankton species contributing to various groups in coastal waters during winter monsoon season

Figure 4.2(f-4): Major phytoplankton species contributing to various groups in coastal waters during spring inter monsoon season
Variation in phytoplankton community structure is mainly governed by light, temperature and availability of nutrients. Although, there is no influx of nutrients by riverine runoff in the coastal waters of Veraval, high doses of inorganic pollutants from fishing and shipping activities, carry large quantities of nitrogen and phosphorous to the marine system of this region. Inorganic nitrogen and phosphorous are the two most important macro-nutrients responsible for good phytoplankton growth; and also play an important role in determining the phytoplankton community and succession through resource competition and limitation (Kobayashi and church, 2003).

Sampling was carried out during tide time (http://tides.mobilegeographics.com/locations/6758.html?y=2011&m=12&d=24), the waters were well mixed and thus we assume that nutrients were not limiting. According to Wetzel, 2001, light and temperature are two inseparable components that affect the distribution of phytoplankton. Variations in temperature along the vertical profile of the water as well as seasonally, were not very significant (see annexure 4.1). Thus it can be inferred that variations in light is the major factor controlling the distribution of species along the depth and seasons. Marglef, (1963), introduced the term phytoplankton succession and Harris, 1986, state that phytoplankton succession is initiated and governed by turbulence in the water column; based on which, he classified aquatic systems as ‘stable’ and ‘unstable’. Phytoplankton communities can be preserved and perpetuated in the stable systems whereas in the unstable one, the nutrients are well mixed due to re-suspension of the particulate matter. Such unstable systems are turbid and can affect the penetration of light into the deeper layers thus influencing the translocation of the phytoplankton communities (Leland, 2003; Walks and cyr, 2004 and Rejas et al., 2005). It is also noteworthy that the dominating groups, diatoms and dinoflagellates, both belong to the red lineage of evolution in open as well as coastal waters. This shows that these groups are more adaptive, successful and established along the long period of evolution.
4.2(g) Spatial variations in phytoplankton concentration for near shore and off shore stations:

Phytoplankton composition was categorized spatially into near shore and off shore stations on the basis of the distance of sampling stations from the coast. The Shannon diversity index which represents species richness, reached over 1.5 for off shore stations in almost all the months (except spring inter monsoon). Diversity index was higher in near shore stations and was more than 2 at most for near coast stations. Figure 4.2 (g-1) illustrates the seasonal variations in shannon’s index which shows that diversity increased during winter monsoon in off shore stations whereas it decreases in fall inter monsoon and inter monsoon. Diversity indices are higher in near coast stations indicating that stratification is completely absent in near coast stations as these regions are constantly churned due to tidal influences and land drainage.

As also described in the study area, inter monsoons are less productive in terms of phytoplankton photosynthesis due to higher sea surface temperatures (\(~28^\circ\text{C}\)\), shallower mixed layer depths (around 20-30m) and strong stratification. In contrast, fall inter monsoon period (September and October; only October here) showed good diversity. Fall inter monsoon period is a transition period from summer monsoon to winter monsoon. Summer monsoons are characterized by lot of churning and terrestrial inputs of organic matter into marine waters. Thus concentration of nutrients is high during and immediately after the monsoon season. Higher diversity index during fall inter monsoon period (as compared to the spring inter monsoon period) can thus be correlated with sufficient availability of the nutrients.
During winter monsoon season (November–February) cold winds from north, also known as north easterlies, blow over the northern part of the Arabian Sea. During winter, the winter cooling effect also comes into action where the cold, dry continental air blowing into the northern Arabian Sea (Madhupratap et al., 1996) causes the sea surface temperatures to fall (~24°C), the cooler surface waters gain densities and start sinking. Due to this cooling effect, the mixed layer depth deepens and sometimes causes convective mixing of the waters. This convective mixing brings the lower nutrient rich waters to the surface that becomes available for enhanced growth of phytoplankton.

4.2(h) Phytoplankton concentrations and its relation with light and chlorophyll:

Based on the intensity of light in the vertical column of water, distribution of overall phytoplankton cell count (figure 4.2 (h-1)) and phytoplankton types (figure 4.2 (h-2)) was studied. Results showed that phytoplankton count was highest (maximum count observed was 23940 cells/ lit) in the upper highly lit layers of the water (100 to 80% light). Phytoplankton count suddenly dropped down at the depths with percent light intensities ranging from 70 to 10. Again a rise in cell count was observed at the depth with 5 % light intensity, with respect to that at the surface. This depth was identified as Deep Chlorophyll Maxima (DCM). For most station points studied, DCM ranged at depths with 5% to 1% light intensities. On classifying the overall cell count into phytoplankton types, it was found that the water surface (100% light intensity) was dominated by dinoflagellates while diatoms were most abundant at the DCM depth with 5% light intensity. This was again due to the presence of Noctiluca bloom at the surface. Light, in general, is known to affect the vertical distribution, photosynthetic rates and efficiencies, pigment composition, cellular nutrient contents and various metabolic pathways (Tomas, 1997). Diatoms are non-motile, as they lack flagellate for locomotion and are purely on the mercy of water currents. Dinoflagellates in contrast, show vertical migratory movements that have been related to positive geotaxis and also considered to be influenced by light (Levandowsky and Kaneta, 1987). Light can also affect the distribution of phytoplankton indirectly by influencing the distribution of bacterial populations. Changes in bacterial populations can change the ecological niche of the region inhabited by both, the bacteria and the
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phytoplankton, thus making the region either inhabitable or more favorable for the associated phytoplankton species.

Figure 4.2 (h-1): Phytoplankton distribution in the vertical column of water, varying at various percent light intensities

Figure 4.2 (h-2): Concentration of phytoplankton types at depths with 100 %, 5% and 1% light intensities
Phytoplankton concentration in cell/lit was found to be directly proportional/linearly related to the chlorophyll concentration. Vertical distribution of phytoplankton cells was related to chlorophyll concentrations at surface, Deep Chlorophyll Maxima (DCM) and 1% light level depth (euphotic depth). As shown in figure 4.2 (h-1), this correlation stands well in the inter monsoon period with $r^2=0.968$ at surface, $r^2=0.895$ at DCM and $r^2=0.807$ at 1% light level. Phytoplankton concentration does not show a very good correlation with chlorophyll, in the winter monsoon period. It has $r^2=0.195$ at surface, $r^2=0.82$ at DCM and $r^2=0.71$ at 1% light level. This is because *Noctiluca scintillans* formed bloom at the surface in the winter monsoon period. Though the number of cells/lit was found to be high in this period but chlorophyll concentration remained comparatively low. *Trichodesmium erythraeum* also formed bloom in the inter monsoon period, but this bloom was restricted to the coastal waters only and coastal waters have a well mixed vertical profile with respect to phytoplankton cells, chlorophyll and light. So the bloom condition did not influence the correlation between cells and chlorophyll very significantly. Annexure 4.8 provides detailed values for cell count and chlorophyll-$a$ concentrations for surface DCM and 1% light level measured for spring inter and winter monsoon season.

![Graph](image)

Figure 4.2(h-3): Correlation between phytoplankton cell counts and Chlorophyll-$a$ at surface, DCM and 1% during winter and inter monsoon periods. The dotted lines are the linear fits applied to the data.
4.3 Conclusions:

Diatoms formed the major group contributing to phytoplankton diversity in both winter and inter monsoon seasons for both Open Ocean as well as coastal waters. Although phytoplankton cell count was high, diversity for surface waters during winter monsoon season was very less due to *Noctiluca* bloom. Diatoms were most abundant and the diversity at Deep Chlorophyll Maxima (DCM) and 1% light level was considerably good in both winter and inter monsoon season. Although none of the six diversity indices studied, could rightly express the richness and evenness component of the diversity, Shannon’s index represented diversity better than other diversity indices, particularly during the bloom conditions. Correlation between phytoplankton cell count and chlorophyll concentration was not good during the bloom conditions, thus it can be concluded that chlorophyll-α concentration can serve as a substitute for phytoplankton biomass only in the non bloom conditions. Especially in case of *Noctiluca scintillans* bloom, where *Noctiluca* does not have its own pigments, chlorophyll-α concentration cannot be used as a proxy for phytoplankton biomass. Remote sensing techniques can also be used as an additional tool to infer diversity and phytoplankton composition. Again, as chlorophyll-α is not a good representative of phytoplankton diversity during bloom conditions, there is a need for specific algorithms for phytoplankton types that are bloom forming.