Chapter VII

Noctiluca scintillans Bloom and Zooplankton Relationship in the Northern Arabian Sea using in-situ and Remotely Sensed Data

7.1. Introduction
7.2. Materials and Methods
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7.1. Introduction

Phytoplankton play an important role as primary producers in the marine ecosystem forming the base of the marine food web. The organic matter so produced ultimately determines the secondary production and tertiary production among which are included species of fish, prawns, mussels etc. that we harvest. Although invisible to the naked eye, phytoplankton play an outstanding role in scavenging atmospheric carbon dioxide and the production of about 80% of the oxygen. When conditions are favorable (i.e. optimal light, favorable water temperature, plentiful nutrients), phytoplankton can grow and reproduce at such a high rate that they create dense, highly colored patches in the water, known as algal bloom and red tides in marine environment. These natural phenomena are termed as ‘algal blooms’ or ‘red tides’. Red tide blooms are not only red but can be brown, yellow, green or milky in color. These blooms can be the more toxic Harmful Algal Blooms (HAB) or non-toxic species of algae. In many cases the proliferation of planktonic algae is beneficial for aquaculture and wild fisheries operations especially in the case of ‘spring blooms’ of higher latitudes. However, algal blooms can have negative effects, causing severe economic loss to aquaculture, fisheries and tourism operations, and also cause major environmental disturbances and have significant human health impacts. The International Council for the Exploration of Seas (ICES, 1984) has defined the phytoplankton blooms as ‘those, which are noticeable,
particularly to the general public, directly or indirectly through their effects such as visible discoloration of the water, foam production, fish or invertebrate mortality or toxicity to humans’.

Among around 5000 species (the number is still rising with recent advances in technology) of extant marine phytoplankton (Sournia et al., 1991), approximately 300 species including diatoms, dinoflagellate, raphidophytes, prymnesiophytes, cyanophytes and silicoflagellates can at times cause algal blooms. Only a few dozen of these species have the ability to produce potent toxins which can find their way through fish and shellfish to humans. These toxins accumulate in shellfish while feeding on these algae, resulting in poisonous syndromes like paralytic shellfish poisoning, diarrhoeic shellfish poisoning, amnesic shellfish poisoning and neurotoxic shellfish poisoning in human consumers. Fish may be contaminated as well, causing ciguatera fish poisoning, which results in human illness or death followed by consumption of the contaminated fin fish (Richardson, 1997). Though HABs are natural phenomena and have occurred throughout the recorded history, recent studies around the world indicate that they have increased in frequency and geographic distribution over the past few decades (Daranas et al., 2001). According to Ho and Hodgkiss (1991) in a review on red tides in subtropical coastal waters from 1928 to 1989, the number of HABs increased from 1-2 every ten years at the beginning of the period to over 220 between 1980 to 1989. Increase in frequency of HABs have been reported along the South African coasts (Horstman, 1981), Dutch coastal waters (Cadee, 1986), Seto inland Sea, Japan (Imai and Itoh, 1987), Hong Kong (Lam and Ho, 1989), Black Sea (Turkoglu and Koray, 2002), in Chinese coastal waters
(Qi et al., 1995), in the coastal waters of North America (Horner et al., 1997) and in the Gulf of Oman (Anderson 2004; Thangaraja et al., 2007).

The transfer of toxins through marine food web is an important aspect of the dynamics of HABs. Toxins associated with marine phytoplankton can enter pelagic food webs through ingestion by phytoplanktivorous zooplankton and these organisms serve as vectors for toxin transfer to higher trophic levels, including humans (Lefebvre et al., 1999; Turner and Tester, 1997; Turner et al., 1998). In the case of paralytic shellfish poisoning in Massachusetts Bay (Turner et al., 2000) larger zooplankton of size fractions (200–500 mm, 4500 mm), dominated by Calanus finmarchicus and Centropages typicus, were found to accumulate large quantities of the relevant toxin. These copepods represent potential vectors for the direct transfer of PSP toxins to zooplanktivorous baleen whales, such as the north Atlantic right whale, as reported from the Bay of Fundy (Durbin et al., 2002; Doucette et al., 2005). This emphasizes the importance of spatiotemporal variations in zooplankton community structure and their potential influence on the routes of toxin transfer in the trophic chain. The toxins or metabolites produced by certain species of phytoplankton have a poisonous influence on the herbivorous zooplankton. The resulting break in the food chain upsets the balance between phytoplankton and zooplankton, which results in the spectacular growth of the phytoplankton. The success of a phytoplankton species is not only dependent on their specific growth rate, but also the difference between growth and loss. Mesozooplankton, one of the main grazers on phytoplankton, could play a key role in the control, structure and development of dinoflagellate blooms (Jansen et al., 2006). The effect of HABs on grazers is variable and
appears to be situation specific. Some grazers are adversely affected by phycotoxins, whereas there are no apparent effects on others.

Algal blooms occurring in the Arabian Sea are of immense trophic and ecological significance. Until the late 1990s *Noctiluca scintillans*, a large green heterotrophic dinoflagellate was a minor component of phytoplankton in the northern Arabian Sea, appearing in bloom form only sporadically during the southwest monsoon at the southwest coast of India and in association with low-oxygen upwelled waters (Naqvi *et al.*, 1998; Sahayak *et al.*, 2005). Since then however, *N. scintillans* blooms have increased in frequency, intensity and distribution, but with the majority of blooms being observed during northeast monsoon. Large blooms of these organisms have now become more pervasive and widespread throughout the Gulf of Oman and in the western and central Arabian Sea (Gomes *et al.*, 2008; Gomes *et al.*, 2009). *N. scintillans* is a cosmopolitan heterotrophic dinoflagellate, and forms distinct red tides in temperate waters (Elbrachter and Qi, 1998). However this species causes greenish discoloration of surface seawater in tropical Southeast Asian waters (Sweeney, 1978). Generally, there are two strains of *N. scintillans* that have been reported worldwide, the green and the red. The green *N. scintillans* contains photosynthetic green flagellate *Pedinomonas noctilucae* as an endosymbiont, whereas the *N. scintillans* without an endosymbiont is called red *Noctiluca*, which is heterotrophic and imparts pink or red color to the bloom (Elbrachter and Qi, 1998; Sweeney, 1978). Al-Azri *et al.* (2007, 2012) also reported *N. scintillans* blooms during the winter monsoon in the Gulf of Oman. In the Arabian Sea waters, blooms of *N. scintillans* appear in the form of a green tide. The Ocean Color Monitor (OCM) images retrieved from IRS-P4 could substantiate the increased chlorophyll *a* in
the northern Arabian Sea towards the end of March (Sarangi et al., 2005; Dwivedi et al., 2006). This bloom covered a large area of the Arabian Sea from the west coast of India to the coast of Oman.

In particular to this \emph{N. scintillans} bloom in the Arabian Sea, have been studied from cruises conducted in the Arabian Sea during March 2003, March 2007 and February and March 2009 and using satellite data. As well as zooplankton biomass during bloom period in the Arabian Sea to study effect of \emph{N. scintillans} on zooplankton.

7.2 Materials and Methods

Sequential \emph{in-situ} data collected in the Northeastern Arabian Sea on research vessels ORV \textit{Sagar Kanya} and FORV \textit{Sagar Sampada} from 2003-2009 were used to study \emph{N. scintillans} bloom and analyzed as described in Chapter III. Sea WiFS derived chlorophyll \emph{a} and NOAA-AVHRR derived SST were used to study bloom, as well as microzooplankton and mesozooplankton biomass were estimated using an \emph{in-house} developed algorithms as explained in chapter III. To study spatial and temporal distribution of SST, chlorophyll \emph{a}, microzooplankton and mesozooplankton in Arabian Sea during bloom period. For this study, Arabian Sea was divided into four areas [Area 1 (20°-24° N, 60°-64° E-Northwest Arabian Sea), Area 2 (20°-24° N, 64°-68° E - Northeast Arabian Sea), Area 3 (16°-20° N, 60°-64° E - Southwest Arabian Sea), Area 4 (16°-20° N, 64°-68° E - Southeast Arabian Sea)].
7.3. Results

7.3.1. March 2003

7.3.1.1. In-situ observation

*N. scintillans* tends to aggregate at the surface to form large, slimy green patches. During the cruise SS-212 (27 February to 5 March 2003), *N. scintillans* bloom was at its peak intensity. Surface chlorophyll *a* concentration varied between 0.17 and 1.63 mg.m\(^{-3}\). Euphotic column average chlorophyll *a* varied between 0.416 and 1.06 mg.m\(^{-3}\). Chlorophyll *a* concentration was also high, wherever *N. scintillans* cells were present in large amounts. It can be seen from the Figure 7.1 that chlorophyll *a* shows a positive trend with *N. scintillans* (\(r^2 = 0.533\)). SST varied between 24.62\(^\circ\)C and 28.17\(^\circ\)C and average euphotic column temperature varied between 23.96\(^\circ\)C and 28.06\(^\circ\)C. Surface number of *N. scintillans* correlated significantly with SST (\(r^2 = 0.624\)) (Figure 7.2).

7.3.1.2. Satellite observations

Figure 7.3 shows the spatial distribution of chlorophyll *a*, SST, microzooplankton and mesozooplankton during March 2003. In Table 7.1, data extracted from the four domains were shown. Chlorophyll *a* concentration was highest in domain 1 and lowest in domain 4. It means that in northwest Arabian Sea bloom was more dense than central eastern Arabian Sea. SST was also low in northern Arabian Sea compare to Central Arabian Sea during March 2003. Highest estimated microzooplankton and mesozooplankton biomass were observed in domain 1 (Table 7.1 and Figure 7.3). Figure 7.4 (a) and (b) allowed to follow the onset and evolution of phytoplankton blooms of 2003 both spatially and temporally.
7.3.2. March 2007

7.3.2.1. In-situ observations

During cruise, SS-253 (1-15 March 2007) an intense green color *N. scintillans* bloom in Northeastern Arabian Sea observed in the upper layer (Figure 7.5). The surface *N. scintillans* density was found 48-7200 cells/L. Surface chlorophyll *a* was found to increase with increase in *N. scintillans* cells ($r^2=0.53$) (Figure 7.6a). SST versus *N. scintillans* cell count did not show any significant correlation, however with increase in temperature *N. scintillans* cells count decreased (Figure 7.6b).

7.3.2.2. Satellite observations

Spatial distribution of chlorophyll *a*, SST, microzooplankton and mesozooplankton were shown in Figure 7.7. Table 7.2 shows the values obtained from the four different domains during March 2007. During March 2007, chlorophyll *a* value was comparatively lower than March 2003. In February 2007 chlorophyll *a* concentration was higher than March 2007 (Figure 7.8 (a)). From the SeaWiFS derived chlorophyll *a* data it appears that during 2007, bloom was at a peak in the Northeastern Arabian Sea during February and commenced declining during March. The estimated microzooplankton and mesozooplankton biomass were also high, where *N. scintillans* bloom was observed.

7.3.3. February and March 2009

7.3.3.1. In-situ observations

During the cruises SK-256 (9- 23 February 2009) and SS-263 (27 February to 14 March 2009) bloom of *N. scintillans* was observed. In February 2009, Surface temperature varied between 24.5 and 28.14°C. The highest *N. scintillans* cells (9600
cells/L) were observed at 66°10.20'E, 20°59.57'N. While the highest surface chlorophyll a concentration, which was 27.7 mg/m³, was observed at the same location. During March 2009, density of the *N. scintillans* cells was low in the range from 2-80 cells/L. Sea surface temperature (SST) ranged from 25.41°C to 28.48°C.

7.3.3.2. Satellite observations

Figure 7.9 and 7.10 shows spatial distribution of chlorophyll a, SST microzooplankton and mesozooplankton during February and March 2009 respectively. During 2009 chlorophyll a concentration was high during February and it declined in March (Figure 7.11 a). As well as highest concentration of chlorophyll a was observed in northern Arabian Sea, as compared to central Arabian Sea. During March, chlorophyll a concentration decreased due to weak convection resulting from low wind speeds (1-3 m/s) and beginning of warming due to end of winter season (Figure 7.11 b)). Microzooplankton and mesozooplankton biomass were high during February month as compared to March 2009 (Table 7.4).

7.4. Discussion

*N. scintillans* bloom is prominent in the surface layer as indicated by high Chlorophyll a. *N. scintillans* has been reported as a voracious feeder preying on different micro organic food species of the pelagic food web (Fond-Umani *et al.*, 2004; Escalera *et al.*, 2007; Padmakumar *et al.*, 2008; Padmakumar *et al.*, 2012). Green *N. scintillans* in nature primarily depends on the photosynthetic products of endosymbionts (Padmakumar *et al.*, 2010; Dwivedi *et al.*, 2012). Green *N. scintillans* contains a photosynthetic symbiont *Pedinomonas noctilucae* (a prasinophyte), but it also feeds on other plankton when the food supply is abundant (Harrison *et al.*, 2011). Gomes *et al.* (2009) have
suggested that *N. scintillans* might be a mixotroph. Sweeney (1971) was the first to grow the green *N. scintillans* under laboratory conditions, and demonstrated that the green *N. scintillans* survives in light without addition of food for at least four weeks and that in darkness the symbiotic flagellate disappeared and the green *N. scintillans* died within a few days without a food supply. However, the growth and proliferation of the red form of *N. scintillans* without endosymbionts depend largely on the size, quality and density of the prey (Buskey, 1995; Kiorboe and Titelman, 1998; Nakamura, 1998). It is particularly abundant in high productivity areas such as upwelling or eutrophic areas where diatoms dominate, since they are its preferred food source. Green *N. scintillans* is restricted to a temperature range of 25°C–30°C and mainly occurs in tropical waters of Southeast Asia, Bay of Bengal (east coast of India), in the eastern, western and northern Arabian Sea, the Red Sea, and recently it has become very abundant in the Gulf of Oman. Another recent study by Mohamed and Mesaad (2007) reported an intense bloom of *N. scintillans* for the first time in the Red Sea, off the southwestern coasts of Saudi Arabia with cell counts of $3.0 \times 10^6$ cells L$^{-1}$ in February–March of 2004 and 2005.

The time series images of chlorophyll $a$ derived from the IRS-P4/OCM have also shown a large scale increase in phytoplankton biomass (>1 mg m$^{-3}$) in the open waters of northeastern Arabian Sea during February-March 2000, due to the formation of *N. scintillans* blooms (Sarangi et al., 2005). Within the northern AS, blooms begin during the first week of February and last until the end of March. In the northeastern Arabian Sea the monthly images were generated from IRS-P4 data for three consecutive years of 2003 to 2005 during February-March months (Dwivedi *et al.*, 2006). Dwivedi *et al.* (2006) attributed the interannual differences in the winter blooms in the north Arabian
Sea to changes in annual wind speed. Relatively high value of chlorophyll $a$ in the bloom area compared to non-bloom area is due to the flagellates associated with *Noctiluca*. Relatively stable low temperature, high salinity, calm sea and muggy weather are known to favor proliferation and blooming of *Noctiluca*.

Gomes *et al.* (2008) used satellite altimetry data overlaid on satellite ocean color chlorophyll $a$ for the period 2003-2006 to show a strong coupling between chlorophyll $a$ and mesoscale eddy activity in the western Arabian Sea. Gomes *et al.* (2008) have also emphasized that *N. scintillans* favor colder (~ 22°C) waters that are nutrient rich and low in dissolved oxygen. It could be speculated that *N. scintillans* in the Gulf of Oman may arise from the shoaling of the western Arabian Sea, by their strength and longevity, could help transport a significant amount of water and dissolved constituents eastward into the central Arabian Sea, making it an extremely important component of the regional dynamics, biology and chemistry (Flagg and Kim, 1998).

Padmakumar *et al.* (2010) in an in-depth study on red *N. scintillans* bloom in southwest cost of India, reported that low zooplankton biomass could be found in the red *N. scintillans* bloom area as compared to the adjacent stations. Padmakumar *et al.* (2008) in their observation noted that zooplankton biomass was very high in the green *N. scintillans* bloom area in northern Arabian Sea as compared to non-bloom area; food vacuoles were not observed in the *N. scintillans* cells. Copepoda, Chaetognatha, Cladocera, Fish eggs, Amphipoda, Heteropoda, Jellyfish, Lucifer, Oikopleura, Salps, Doliolids and Siphonophores were abundant in the zooplankton. Matondkar *et al.* (2012) in their study noted that *N. scintillans* was grazed by zooplankton. Dwivedi *et al.* (2012) in their study noted that there is no circumstantial fish mortality or fall in their catch in *N.
scintillans bloom area and suggest that the boom is not harmful and eco friendly at least in northeastern Arabian Sea.
### Table 7.1. Area averaged values of chlorophyll $a$, SST, Microzooplankton and Mesozooplankton for March 2003 [Area 1 (20°-24° N, 60°-64° E), Area 2 (20°-24° N, 64°-68° E), Area 3 (16°-20° N, 60°-64° E), Area 4 (16°-20° N, 64°-68° E)]

<table>
<thead>
<tr>
<th>Area</th>
<th>Chlorophyll $a$ (mg/m³)</th>
<th>SST (°C)</th>
<th>Microzooplankton (mg C/m³)</th>
<th>Mesozooplankton (mg C/m²)</th>
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<td>6.766</td>
<td>70.154</td>
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<tr>
<td>4</td>
<td>0.458</td>
<td>26.96</td>
<td>6.091</td>
<td>69.25</td>
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### Table 7.2. Area averaged values of chlorophyll $a$, SST, Microzooplankton and mesozooplankton for March 2007 [Area 1 (20°-24° N, 60°-64° E), Area 2 (20°-24° N, 64°-68° E), Area 3 (16°-20° N, 60°-64° E), Area 4 (16°-20° N, 64°-68° E)].

<table>
<thead>
<tr>
<th>Area</th>
<th>Chlorophyll $a$ (mg/m³)</th>
<th>SST (°C)</th>
<th>Microzooplankton (mg C/m³)</th>
<th>Mesozooplankton (mg C/m²)</th>
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Table 7.3. Area averaged values of chlorophyll $a$, SST, Microzooplankton and Mesozooplankton for February 2009 [Area 1 (20°-24° N, 60°-64° E), Area 2 (20°-24° N, 64°-68° E), Area 3 (16°-20° N, 60°-64° E), Area 4 (16°-20° N, 64°-68° E)].

<table>
<thead>
<tr>
<th>Area</th>
<th>Chlorophyll (mg /m³)</th>
<th>SST (°C)</th>
<th>Microzooplankton (mg C/m³)</th>
<th>Mesozooplankton (mg C/m²)</th>
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Table 7.4. Area averaged values of chlorophyll $a$, SST, Microzooplankton and Mesozooplankton for March 2009 [Area 1 (20°-24° N, 60°-64° E), Area 2 (20°-24° N, 64°-68° E), Area 3 (16°-20° N, 60°-64° E), Area 4 (16°-20° N, 64°-68° E)].

<table>
<thead>
<tr>
<th>Area</th>
<th>Chlorophyll (mg /m³)</th>
<th>SST (°C)</th>
<th>Microzooplankton (mg C/m³)</th>
<th>Mesozooplankton (mg C/m²)</th>
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Figure 7.1. Scatter plots showing chlorophyll \( a \) versus \textit{N. scintillans} cells count (L1) for cruise SS-212 (Feb-Mar 2003)


Figure 7.2. Scatter plots showing SST versus \textit{N. scintillans} cells count (L1) for cruise SS-212 (Feb-Mar 2003)
Figure 7.3. Satellite derived images showing spatial distribution of SST in °C (a), chlorophyll $a$ concentration in mg/m$^3$ (b), Microzooplankton biomass image in mg C/m$^3$ (c) and mesozooplankton biomass in mmol C/m$^2$ (d) for the March 2003.
Figure 7.4 Monthly area averaged chlorophyll $a$ and SST for the November 2002 to May 2003
Figure 7.5. *Noctiluca scintillans* bloom during March 2007

Figure 7.6. Scatter plots showing chlorophyll $a$ versus *N. scintillans* cells counts and SST versus *N. scintillans* cells counts for cruise SS-253 (March 2007).
Figure 7.7. Satellite derived images showing spatial distribution of SST in °C (a), chlorophyll $a$ concentration in mg/m$^3$ (b), Microzooplankton biomass image in mg C/m$^3$ (c) and mesozooplankton biomass in mmol C/m$^2$ (d) for the March 2007.
Figure 7.8. Monthly area averaged chlorophyll $a$ and SST for the November 2006 to May 2007
Figure 7.9. Satellite derived images showing spatial distribution of SST in °C (a), chlorophyll \( a \) concentration in mg/m\(^3\) (b), Microzooplankton biomass image in mg C/m\(^3\) (c) and mesozooplankton biomass in mmol C/m\(^2\) (d) for the February 2009.
Figure 7.10. Satellite derived images showing spatial distribution of SST in °C (a), chlorophyll $a$ concentration in mg/m$^3$ (b), Microzooplankton biomass image in mg C/m$^3$ (c) and mesozooplankton biomass in mmol C/m$^2$ (d) for the March 2009.
Figure 7.11. Monthly area averaged chlorophyll $a$ and SST for the November 2008 to May 2009
Figure 7.12. Photo micrographs showing grazing activities during the *Noctiluca miliaris* bloom: (a) Diatoms shells located in *Noctiluca miliaris* cells (20X) (b) Amphipods ambushing *Noctiluca miliaris* cells (c & d) Ostracods grazing on *Noctiluca miliaris* (e & f) Jelly-fish and Salps feeding on *Noctiluca miliaris* cells. (Matondkar et al., 2012)