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Algal blooms: a perspective from the coasts of India

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Abstract Algal blooms have been documented along the west and east coasts of India. A review of bloom occurrences in Indian waters from 1908 to 2009 points out that a total of 101 cases have been reported. A comparison of the bloom cases reported before and after1950's reveals that there is an increase in the number of bloom occurrences. The reports of algal blooms indicate their predominance along the west coast of India especially the southern part. Majority of the blooms reported along the west coast of India are caused by dinoflagellates whereas diatom blooms prevail along the east coast. There have been 39 causative species responsible for blooms, of which *Noctiluca scintillans* and *Trichodesmium erythraeum* are the most common. Reporting of massive fish mortality in Indian waters has been associated with the blooming of *Cochlodinium polykrikoides*, *Karenia brevis*, *Karenia mikimotoi*, *Noctiluca scintillans*, *Trichodesmium erythraeum*, *Trichodesmium thiebautii* and *Chattonella marina*. Most of the blooms occurred during withdrawal of the south–west monsoon and pre–monsoon period. In Indian waters, this process is mainly influenced by seasonal upwelling and monsoonal forcing that causes high riverine discharge resulting in nutrient–enriched waters that provides a competitive edge for blooming of phytoplankton species.

Keywords algal bloom · causative species · coastal water · *Noctiluca* · *Trichodesmium* · India

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1 Introduction

Phytoplankton are important constituents of the marine food web and comprise 40 % of the total fixed global primary productivity (Falkowski 1984). Of about 5,000 species of marine phytoplankton that exist in the world, ~ 7 % are responsible for algal blooms (or red tides) which includes diatoms, dinoflagellates, raphidophytes, prymnesiophytes and silicoflagellates (Sournia 1995). Of this, ~ 2 % of phytoplankton species are harmful or toxic and ~ 75 % are contributed by dinoflagellates (Smayda 1997). The occurrence of blooms are spontaneous and remarkable; their growth and persistence are brought about by a combination of physical, chemical and biological factors interacting in ways that are often sudden and unpredictable (Glibert et al. 2005 and references therein).

Algal blooms that discolour the seawater are commonly referred to as 'red tide'. According to GEOHAB (2001), the term Harmful Algal Bloom (HAB) events include the proliferation of algae in marine or brackish waters, which can cause massive fish kills, contaminate seafood with toxins, and alter ecosystems in ways that humans perceive as harmful. HABs show high diversity with regard to causative organisms, bloom dynamics and type of impact (Zingone and Enevoldsen 2000). Broadly, bloom species can be classified into three different groups: (1) those which produce harmless water discolourations, but the dense bloom on decomposition can cause anoxia and lead to indiscriminate mortality of marine life, (2) species which produce potent toxins causing a variety of gastrointestinal and neurological illness to humans and (3) species which are not toxic to humans but harmful to fish and invertebrates by damaging or clogging their fish gills. The high–biomass producers are linked with production of scums and reduction of habitat for fish and shellfish. Interestingly, some HAB species do not attain high biomass; they can be harmful at low concentrations (GEOHAB 2001). In recent years, the incidences of HABs appear to be increasing in frequency and intensity worldwide (Anderson 1989; Smayda 1990; Hallegraeff 1993).

The suddenness with which the blooms appear and disappear is an interesting feature to probe. The problems arising from HABs are very diverse, the causes are many and they are on the increase. There are five possible reasons for increase in frequency and geographical extent of HAB events (Anderson 1989; Smayda 1990; Hallegraeff 1993): (1) improved methods for detection and monitoring methods of blooms that would previously have gone unreported, (2) species dispersal through currents, storms or other natural mechanisms, (3) introduction of new algal species into inshore areas through ship ballast water exchange or aquaculture, (4) long–term climatic changes and (5) cultural eutrophication. These reasons may vary from one bio–region to the other with regional environmental settings. With global increase in algal blooms, it becomes necessary for every maritime country to have an understanding about the algal bloom scenario in their territorial water bodies.

India, being one of the major maritime countries is endowed with a coastline of approximately 7,500 km and embraced by two important seas i.e. the Arabian Sea (AS) on the west and Bay of Bengal (BOB) on the east coast of India. This marine environment embodies diverse habitats such as estuaries, mangrove swamps, brackish water lakes, coral reefs, islands and offshore waters that support a great diversity of flora and fauna. The coastline is dotted with 12 major ports, six each on the west and east coasts of India. In addition, there are 163 minor and intermediate ports along the coastline and sea–islands. These serve as gateways for international and national trade. With increase in shipping traffic, this region is also susceptible to ship–mediated invasion (Anil et al. 2002). Bioinvasion is considered as one of the vectors for global expansion of HABs in other parts of the world (Hallegraeff 1998; Blackburn et al. 2001; Marangoni et al. 2001).

The present study summarizes the algal bloom scenario in Indian waters. Algal bloom data are collated from various sources such as research journals, articles, reports, conference proceedings and newspaper reportings. The aim of this study is to (1) provide algal bloom reportings and frequency of causative species responsible for bloom formation and (2) understand the causative factors for such blooms based on the environmental settings prevalent during the bloom period.

2 Characteristic features of the study area

The seas along the Indian coast – the AS and BOB, are land–locked in the north and forced by seasonally–reversing monsoon winds, making it unique among the world oceans. The monsoon winds reverse twice a year, blowing from south–west (SW) during May–September and from the north–east (NE) during November–January with the transition taking place during the months in between. The coastal currents along the west and east coasts of India provide a link between the AS and BOB. These reversing currents carry high salinity AS water into BOB and vice versa (Shenoi et al. 2005 and references therein).

Despite the striking similarities, the basins show differences in hydrological conditions. Differences between regions of AS and BOB arise because of the following reasons. Both, the AS and BOB show opposing trends in surface circulation during summer (SW) and winter (NE) monsoons. The BOB receives large quantities of fresh water from rivers 1.6 x 10^{12} m^3 yr^{-1} compared to 0.3 x 10^{12} m^3 yr^{-1} in the AS (Subramanian 1993). The suspended sediment discharge into the BOB is estimated to be 1.4 x 10^9 tonnes compared to about 195 x 10^6 tonnes in the AS (Subramanian 1993). The AS has salinity usually in the range 35–37 psu due to excess evaporation over rainfall. In contrast, the BOB has much lower salinity (30–33 psu) due to large influx of freshwater from river discharge and high amount of rainfall (Panikkar and Jayaraman 1966). In the BOB, the surface temperatures range between 27 and 29 ^{o}C; except for shallow areas near the coast. The fluctuations are much wider (23–29 ^{o}C) along the AS coast of India (Panikkar and Jayaraman 1966).

Due to the hydrographic differences between the AS and BOB detailed above, algal bloom reportings have been discussed in separate sections i.e. west and east coast of India. Based on their seasonal occurrence, blooms occurring on the west coast of India during February–May, June–September and October–January are categorized as pre–monsoon (PrM), south–west monsoon (SWM) and post–monsoon (PoM) periods. Whereas on the east coast of India, blooms occurring during February–May, June–September, October–November and December–January are categorized as PrM, SWM, PoM and north–east monsoon (NEM).

3 Algal bloom reportings

In Indian waters, first observations on algal blooms that caused massive fish mortality was reported by James Hornell in 1908 while cruising along the Malabar coast to Laccadive islands (Hornell 1908). A review of algal bloom occurrences in Indian waters from 1908 to 2009 showed a total of 101 bloom incidents (Tables 1, 2). Thirty nine causative species were responsible for bloom occurrence (Table 3). *Trichodesmium erythraeum* and *Noctiluca scintillans* were the common blooming species in coastal waters of India. With enhancement in observation and monitoring, there has been an increased reporting of algal blooms. However, in order to capture the information documented, the ten decadal algal bloom reporting periods (1908–2009) have been divided into two periods, the first five decadal period (1908–1950) and second five decadal period (1950–2009) (Fig. 1a, b). Based on these 2 time periods, it is evident that in the recent past there has been an exponential increase in algal bloom events along the Indian coasts (Fig. 1). These observations also indicate that during the period from 1908 to 1950, the number of blooms was less and it was restricted between the 8 to 12 ^{o}N latitudinal margins along the Indian coasts with majority of the blooms recorded from the SW coast of India (Fig. 1a). From 1950 to 2009, the distribution of bloom incidents has spread from 8 to 20 ^{o}N latitude i.e. from southern to northern part along both the coasts of India (Fig. 1b).

The occurrence of blooms in Indian waters is a matter of concern as most of the bloom cases reported so far have direct or indirect effects on these coastal waters and have affected fisheries, other marine organisms and humans (Tables 1, 2).

3.1 West coast

There are a total of 68 cases of algal bloom occurrences reported along the west coast of India (Table 1). These blooms were caused by diatoms, dinoflagellates, cyanobacteria, raphidophytes and haptophytes. Among these groups, dinoflagellates were the predominant group with maximum number of bloom cases being reported (Fig. 2a). Most of the bloom cases were reported to have direct and indirect effects on fisheries, and six cases had direct effects on human health, of which 3 Paralytic Shellfish Poisoning (PSP) cases were reported along the west coast of India (Table 1).

About 32 causative species were responsible for the 68 bloom occurrences reported (Table 3). *Noctiluca scintillans* (=*Noctiluca miliaris*) and *Trichodesmium erythraeum* were the most frequently occurring bloom species (Table 3). With respect to the spatial distribution of algal blooms along the western continental shelf from Gujarat to Kerala, highest prevalence of bloom incidents were reported from Kerala coast followed by Mangalore and Goa (Fig. 2b). There were 23 causative species of dinoflagellates responsible for bloom occurrences along the Kerala coast (Table 3). Most of the raphidophyte (*Chattonella marina*) blooms (Subrahmanyan 1954, Jugnu and Kripa 2009) have been reported from the Kerala coast (Fig. 2b). Cyanobacterial blooms of *Microcystis aeruginosa* (March 2008) have sprung up in the in–shore waters of Kerala (Padmakumar et al. 2008a).

Algal blooms are reported to occur throughout the year, with majority of the blooms occurring during March–May (PrM) and September–October (withdrawal of SWM and early PoM period) on the west coast (Fig. 3a). Owing to the rough weather, the number of expeditions taken during monsoon period is less. This could account for comparatively lower bloom reportings during monsoon. Based on the categorization of algal blooms during different seasonal periods, diatom blooms mainly occur during May and August–November whereas dinoflagellate blooms are more frequent during September–October period (Fig. 3b). *Trichodesmium erythraeum* blooms (cyanobacteria) are a seasonal, recurrent phenomenon occurring during February–May period (Fig. 3b) along the west coast of India with 12 bloom cases reported by this causative species (Table 1). Occurrence of raphidophyte blooms by *Chattonella marina* has been reported only during August–November period (Fig. 3b).

Consequences of blooms have been debated from the positive and negative points of view. The positive aspect of diatom blooms is that it may be beneficial to fisheries whereas blooms can negatively affect fisheries and human health. *Fragilariopsis oceanica* can be considered a good indicator for the abundance of oil sardine stocks in the coastal waters of India (Devassy 1974). Diatom blooms by *Fragilariopsis* (=*Fragilaria*) *oceanica* and *Skeletonema costatum* have been reported as a recurring annual feature (Gopinathan 1974; Devassy 1983; Devassy and Goes 1988; Tiwari and Nair 1998; Mitbavkar and Anil 2002; Patil and Anil 2008). High abundance of *Skeletonema costatum* has been reported in Mumbai port subsequent to monsoon events, following the input of nutrients and lowered salinity (D'Costa and Anil 2010).

Direct impact of HABs on human health has been reported from Mangalore (Karunasagar et al. 1984) and Kerala (Karunasagar et al. 1998) coasts. In most cases of *Noctiluca* and *Trichodesmium* blooms, discolouration of water occurs, along with the virtual exclusion of organisms and decreased fish catch (Table 1). In some instances, blooms of these species have also caused fish mortality due to oxygen deficiency (Table 1).

An open ocean bloom of the marine prymnesiophyte, *Phaeocystis globosa* was reported in central AS (along 64 ^{o}E) during the monsoon period between13–19 ^{o}N in open waters (Madhupratap et al. 2000, data not shown).

3.2 East coast

There are 33 cases of algal bloom occurrences reported along the east coast of India (Table 2). Blooms of diatoms, dinoflagellates and cyanobacteria have been reported from coastal waters along the east coast of India. Among these groups, diatoms were the most predominant with 12 bloom cases being reported (Table 2). Of the 12 causative species reported, *Asterionella japonica* (= *Asterionella glacialis*), *Noctiluca scintillans* and *Trichodesmium erythraeum* were the common bloom forming species on the east coast of India (Table 3). Spatial distribution of bloom occurrences indicates their prevalence more towards the Tamil Nadu and Orissa coast (Fig. 2c).

Along the east coast of India, algal blooms occur throughout the year with the exception of January and November. Overall, maximum number of bloom cases was reported during the PrM period from March to May (Fig. 3a). Most diatom blooms prevailed during the PrM period (March–May) whereas dinoflagellate blooms occurred during April–August and were less frequent in the other months (Fig. 3c). Cyanobacterial blooms were reported mostly during the PrM period (March).

The first bloom occurrence of *Asterionella japonica* (= *Asterionella glacialis*) was reported during 1967 in coastal waters off Visakhapatnam (Subba Rao 1969). Subsequently, these blooms were reported from Tamil Nadu and Orissa coasts (Table 2). Among dinoflagellate blooms, *Noctiluca scintillans* were mostly reported on the east coast of India (Tables 2, 3). On one occasion, bleaching of corals was reported in the Gulf of Mannar due to *Noctiluca* bloom that resulted in oxygen depletion. This in turn, affected fishes and marine animals (Gopakumar et al. 2009). There was also reporting of a PSP outbreak in 1981 from Tamil Nadu coast that resulted in hospitalization of 85 people and 3 deaths after consuming bloom–affected mussels (Silas et al. 1982). Some incidents of *Trichodesmium* blooms causing massive fish mortality were reported in the coastal waters of Tamil Nadu (Chacko 1942; Chidambaram and Unny 1944; Chellam and Alagarswami 1978; Satpathy et al. 2007; Anantharaman et al. 2010).

4 Possible causative factors responsible for algal blooms

As compared to other parts of the world, the occurrence of bloom events is comparatively less in Indian waters. Along both the coasts of India, algal blooms have been reported throughout the year (Fig. 3a) with species–specific blooms occurring during different time periods (Fig. 3b, c).

The formation of blooms are influenced by various factors that can be categorized into (a) physical processes such as upwelling, cyclones and eddies (GEOHAB 2005; McGillicuddy 2007; Vinaychandran and Mathew 2003), (b) chemical processes such as increased nutrient conditions (eutrophication) (Anderson et al. 2002; Smayda 2005) and (c) biological processes like competition, grazing and allelopathy (Smayda 1998; Granéli and Johansson 2003). Physical processes impact blooms during the onset stage, chemical processes play a role when nutrient–enriched waters are prevalent, while biological processes become predominant as the bloom progresses (Glibert et al. 2005 and references therein). These factors in combination with local meteorological conditions will have different impacts from one geographical region to the other, and will thus influence bloom dynamics differently (Naik et al. 2011b). Therefore, it becomes necessary to understand the causative factors and mechanisms that drive bloom formation in the region.

4.1 West coast

Algal bloom cases reported from the west coast of India points out the suitable period for their occurrence. Withdrawal of monsoon and commencement of PoM provides better season for bloom formation (Fig. 3a). The PrM period was also marked with several cases, among which cyanobacterial blooms (*Trichodesmium eryhraeum*) were the most common (Fig. 3b). These blooms have a well–defined periodicity and annual rhythm between February and May (Table 1, Fig. 3b); and can be described as a seasonal phenomenon (Devassy et al. 1978). The conditions during the PrM such as warm waters and low nutrient concentrations are known to favour *Trichodesmium* blooms (Devassy et al. 1978).

The AS is one of the most highly productive regions of the world ocean (Smith et al. 1991; Banse 1994). The west coast of India undergoes periods of strong upwelling during monsoon and delivers cold, nutrient–rich waters from bottom depths. As a result, upwelling coupled with monsoon leads to high nutrient conditions triggering high primary production (de Sousa et al. 1996). Due to high biological productivity, the intermediate water gets depleted of oxygen creating hypoxic conditions during September–October (Naqvi et al., 2000). Therefore, blooms occurring during monsoon can be the result of increased discharge of nutrients by land run–off, precipitation and upwelling (Raghukumar and Anil 2003; Patil and Anil 2008). The Indian summer monsoon has vigorous intra–seasonal oscillations in the form of active and weak (or broken) spells of rainfall within the monsoon season (Ramamurty 1969); resulting in sudden changes of salinity and water temperatures. This might act as a trigger mechanism to induce the blooming of certain species which prefer a particular range of salinity and temperature in the presence of sufficient nutrients in coastal waters. Blooming of *Skeletonema* spp. under low saline conditions has been reported along the west coast of India (Subrahmanyan 1959; Gopinathan 1974; Patil and Anil 2008). Lower temperature has been considered a major factor for raphidophyte blooms of *Chattonella marina* along the Kerala coast (Padmakumar et al. 2011).

It is evident that the monsoons can provide favourable conditions to trigger bloom formation of several phytoplankton species. Break in monsoon can also provide a window of opportunity for certain phytoplankton species to bloom. Patil (2003) reported high concentration of *Cochlodinium polykrikoides* and *Gymnodinium catenatum* during a monsoon break (July 2000) in coastal waters off Goa and their concentration decreased with restart of freshwater discharge. In the subsequent year (October 2001), blooms of *Cochlodinium polykrikoides* occurred that coincided with massive fish mortality (O'Herald 2001). During this bloom, it was found that large parts of the inner– and mid–shelf between Goa and Mangalore were covered by cold waters that had been brought up from deeper offshore layers and were devoid of dissolved oxygen (O'Herald 2001). The potential of monsoon to influence the diatom and dinoflagellate communities and shifts in species dominance has been observed in Mumbai port (D'Costa et al. 2008; D'Costa and Anil 2010).

Although, the conditions are favourable during monsoon, there are lesser occurrence of blooms during this period (Fig. 3). This can be also related to non–efficient utilization of nutrients by phytoplankton under low irradiance due to monsoonal cloud cover (Patil and Anil 2008), since, nutrient uptake is an energy–demanding process and is therefore, partly light–dependent (Kooistra et al. 2007). The PoM conditions provide favourable conditions such as bright sunlight, warmer waters and nutrient input from rainfall and upwelled waters for phytoplankton species to proliferate and result in bloom formation. This could be the probable reason for increased occurrence of blooms (diatoms, dinoflagellates and raphidophytes) during early PoM (Fig. 3b) which can be considered as a recovery period. The frequency of *Noctiluca* blooms is high during August to October (Fig. 3b), coinciding with the end of upwelling season, and usually preceded by a diatom bloom (Velappan and Subrahmanyan 1955; Padmakumar et al. 2010a). It has also been reported that *N. scintillans* blooms occurred commonly and were sustained along with multiseries diatom blooms that were generated by upwelling–induced eutrophic conditions during the SWM period in Kochi waters (Sahayak et al 2005; Padmakumar et al. 2010). Observation of *Noctiluca* cells collected from the bloom–affected area (Kochi) harboured diatoms (*Chaetoceros*, *Navicula*, *Thalassiosira*, *Coscinodiscus* and *Nitzschia*) in their food vacuoles, suggesting *Noctiluca* feeds on phytoplankton (Padmakumar et al. 2010a). Many times at bloom site of *Noctiluca*, there is virtual exclusion of zooplankton; fish larvae and shoaling fishes (mackerels, sardines and anchovies) also tend to avoid these waters.

The influence of BOB characteristics on the events occurring in AS along the west coast of India has been recognized (Shetye et al. 1991a; Shenoi et al. 1999). Shetye et al. (1991a) have observed a core of low saline water on the inner continental slope off the SW coast of India during early NEM. Shenoi et al. (1999) observed the penetration of low saline waters from BOB and the commencement of upwelling before the onset of monsoon. According to Shetye et al. (1991a) and Shenoi et al. (1999), the low saline waters could be coming from the SW corner of BOB. Prakash and Viswanatha Sarma (1964) suggested that during the blooming period, which coincides with the onset of the NEM, waters of lower salinity from BOB enters the coastal circulation of the SW coast of India and probably favours the development of blooms of certain species (Subrahmanyan 1960).

4.2 East coast

The BOB is known for its unique characteristic features: large volume of freshwater input from river discharge and rainfall, warmer sea surface temperatures, monsoonal clouds and reversal of currents. BOB is considered to have lower biological productivity than its western counterpart, the AS. The low biological productivity of BOB has been speculated to be due to various reasons such as narrow shelf, cloud cover during summer monsoon, turbidity resulting from sediment influx and fresh water–induced stratification (Qasim 1977; Radhakrishna 1978; Gomes et al. 2000). Along the east coast of India, upwelling does occur but the strongly stratified surface layer of the BOB restricts the transport of nutrients from deeper layers to the surface (Prasanna Kumar et al. 2002). The stratification is especially intense during the SWM period due to enormous influx of freshwater through precipitation and riverine discharges that leads to the formation of low salinity cap at the surface.

In BOB, the majority of bloom cases are reported during the PrM (Fig. 3a), mostly dominated by diatom and cyanobacterial blooms (Fig. 3c). Among diatom blooms, *Asterionella japonica* has been found as the most abundant bloom forming species on the east coast of India (Subba Rao 1969; Choudhury and Panigrahy 1989; Panigrahy and Gouda 1990). These reports indicated that blooming of *A. japonica* was common in north–western BOB during PrM months (i.e. March–May) (Table 2). Subba Rao (1969) reported the appearance of *A. japonica* bloom off Visakhapatnam, as a consequence of local upwelling that resulted in enrichment of nutrients and lowering of sea surface temperature. However studies have shown that wind–driven upwelling signatures can be eroded by local hydrographical features such as currents and eddies (Shetye et al. 1991b).

From reported bloom incidents, most of the cyanobacterial blooms (*Trichodesmium erythraeum*) are mainly observed during the PrM period (Fig. 3c). Observations from remotely sensed images by Hegde et al. (2008) indicated the prevalence of *Trichodesmium* along the coasts of India during summer months and throughout the year in south–eastern BOB. The prevalence of stratified conditions in the BOB almost throughout the year has been pointed out as an important factor facilitating the preponderance of *Trichodesmium* blooms (Hegde et al. 2008). These results also indicated the possibility of seed populations of *Trichodesmium* dispersing from the eastern part of the BOB towards the west.

Among the dinoflagellate blooms, *Noctiluca scintillans* was the most common and frequently occurring species in BOB that were reported from the month of April (PrM) to October (PoM) (Table 2, Fig. 3c). *Noctiluca* blooms occur in nutrient–enriched waters during plankton succession. In coastal waters of Palk Bay and Gulf of Mannar in Tamil Nadu, *N. scintillans* blooms were succeeded by diatom peaks of varying intensities (Raghu Prasad 1953; Raghu Prasad and Jayaraman 1954). Bloom formation in BOB can also be driven by physical mechanisms such as eddies (Gomes et al. 2000; Prasanna Kumar et al. 2004) and cyclones (Madhu et al. 2002; Vinayachandran and Mathew 2003; Rao et al. 2006) that can uplift or transport nutrients from bottom layers to the surface. Naik et al. (2011b) have highlighted the importance of these physical features that might trigger frequently occurring HAB species such as *N. scintillans* to form blooms during cyclone–prone seasons.

5. Impact of algal blooms on human health and sustainable fishery

The extent of threat on human health from HABs in India waters remains relatively meagre. Until 1980s, the phenomenon of Paralytic Shellfish Poisoning (PSP) was virtually unknown in Indian waters. So far, four PSP cases have been recorded from the coastal waters of Tamil Nadu (1 case), Mangalore (2 case) and Kerala (1 case). However, the dinoflagellates responsible for PSP outbreak could not be identified. The first PSP outbreak was recorded from Tamil Nadu in 1981 that resulted in hospitalization of 85 people and 3 deaths after consuming bloom affected clams *Meretrix casta* (Silas et al. 1982). In 1983, an outbreak of PSP resulted in death of a boy and hospitalization of several individuals following the consumption of clams (*Meretrix crasta*) harvested from Kumble estuary, Mangalore (Karunasagar et al. 1984). These clams were analysed with High Performance Liquid Chromatography (HPLC) and the toxin profile obtained corresponded to a strain of *Alexandrium tamiyavanichi* Balech isolated from Thailand (Karunasagar et al. 1990). Subsequently, low levels of PSP were recorded in shellfish from surrounding estuaries near Mangalore on two occasions during 1985 and 1986 (Segar et al.1989). Planktonic and cyst forms of *Gymnodinium catenatum,* a PSP–producing dinoflagellate were recorded during a study in Kumta River, Mangalore (Godhe et al. 1996) and there was no toxicity in shellfish. This study highlighted the importance of close monitoring of coastal waters, sediment and shell fish.

An outbreak of PSP was also reported from Kerala in 1997, where 7 people died and over 500 were hospitalised after consuming bloom affected mussels *Perna indica* (Karunasagar et al. 1998). Another bloom that hit Kerala in 17th September 2004 resulted in nauseating smell emanating from the coastal waters (The Hindu 2004; The Hindustan Times 2004). This bloom resulted in large–scale fish mortality and hospitalization of 200 people especially children who suffered from nausea and breathlessness caused by nauseating stench from the bloom and putrefying fish. The causative organism reported during the stench event included *Cochlodinium polykrikoides* (The Hindu 2004) and *Karenia brevis* (The Hindustan Times 2004); and subsequent to this event, an unidentified holococcolithophore (Ramaiah et al.2005) and *Noctiluca scintillans* (Sahayak et al. 2005) were reported.

The Indian fisheries economy depends heavily upon the coastal zone for marine products, so it is especially sensitive to constraints from red tides and toxic microalgae. HABs cause substantial impacts on the growth, recruitment and mortality of fish population, especially fish–killing algal blooms that cause direct and severe damage to coastal fishing industries. So far, there are 7 fish–killing species such as *Cochlodinium polykrikoides*, *Karenia brevis*, *Karenia mikimotoi*, *Noctiluca scintillans*, *Trichodesmium erythraeum*, *Trichodesmium thiebautii* and *Chattonella marina* that form algal blooms and are responsible for massive fish mortality in Indian waters (Tables 1, 2).

Although, studies are underway, efficient monitoring systems have to be established in order to minimize public health risks and damage to fisheries. This is critical as the people of the coastal areas in the region are highly dependent on fishery and are thus vulnerable to any incident that might affect seafood availability. The greatest problem for human society will be caused by being unprepared for significant range extensions of HAB species or the increase of algal biotoxin problems in poorly monitored areas (Hallegraeff 2010).Therefore, it is imperative that environmental challenges such as HABs are combated to maintain the sustainable productivity of the sea.

6 On–going monitoring programmes

The impact of HAB events have increased public awareness and demand for monitoring of HABs to reduce or eliminate bloom impacts on coastal resources, local economies, and threats to public health. As a result, there is an increasing focus on early detection of bloom species, environmental conditions supporting blooms, and toxins associated with some of the toxin–producing species. As a result, several HAB and phytoplankton monitoring programmes are now underway. A number of research groups focusing on phytoplankton ecology along the Indian coasts have been involved in these efforts. Interestingly, the locations of HABs reported from Indian waters are closely correlated with the location of these research groups that naturally tend to focus on coastal areas in their vicinity. Due to these ongoing programmes, the wide distribution and expansion of HABs in Indian waters is being recognized.

6.1 Monitoring of algal blooms in Indian Exclusive Economic Zone (EEZ)

For monitoring of HABs along the Indian coasts, a national coordinated multi–institutional research program on “HABs in the Indian EEZ” is being funded by Ministry of Earth Sciences (MOES) with Centre for Marine Living Resources and Ecology (CMLRE) as the project coordinator and participation of various institutions. This programme envisages extensive monitoring of HABs in the Indian EEZ, identification of causative toxic/ harmful microalgal species, dynamics of bloom formation, spread and crash and its ecological consequences on marine ecosystems. Regular oceanic cruises are being conducted for the surveillance, identification, enumeration and ecology of HABs in territorial waters and contiguous seas in the Indian EEZ.

6.2 Ballast Water Management programme

Ignoring problems caused by ballast water introductions could pose a threat to coastal water bodies. The introduction of harmful aquatic organisms and pathogens to new environments via ships’ ballast water has been considered as an important vector for global expansion of HABs. India, being one of the major maritime countries, is susceptible to ship–mediated bioinvasion (Anil et al., 2002). The CSIR–National Institute of Oceanography (NIO) is leading the Ballast Water Management

Programme–India (BAMPI) which is supported by Directorate General of Shipping and Ministry of Shipping, India. Under this programme, Port Baseline Biological Surveys (PBBS) are being carried out at major ports of India. One of the major components of PBBS is the exploration of the diversity of phytoplankton in water column and dinoflagellate cyst in the sediment. The research carried out under this BAMPI programme relevant to phytoplankton and dinoflagellate cysts are published (D'Costa et al. 2008; D'Costa and Anil 2010; Naik et al. 2010; D'Silva et al. 2011).

6.3 Other programmes

In addition to this, there are other programs sponsored by the government to explore the biodiversity of the seas around India and oceanographic studies that provide useful information pertaining to HAB dynamics. A phytoplankton–monitoring programme under the Indian Expendable Bathythermographic (XBT) programme funded by Ministry of Earth Sciences is in existence since early 2000. Regular oceanic cruises are undertaken with 'the ships of opportunity network' which utilizes passenger ships plying between Chennai–Port Blair and Port Blair–Kolkata transects in the BOB. The research work undertaken under XBT programme are published (Hegde et al. 2008; Kulkarni et al. 2010; Naik et al. 2011 a, b).

Remote sensing provides a synoptic tool for detection and monitoring of HABs on global scale. A new bio–optical algorithm has been developed to provide accurate assessments of chlorophyll *a* (Chl a) concentration for detection and mapping of algal blooms from satellite data in optically complex waters of the Arabian Sea (Shanmugam 2011). The algorithm is derived using Sea–viewing Wide Field–of–view Sensor (SeaWiFS) bands, and it is subsequently tuned to be applicable to Moderate Resolution Imaging Spectroradiometer (MODIS)/Aqua data. Indian National Centre for Ocean Information Services (INCOIS) has modified and adapted the Red Tide Indices (Ahn and Shanmugam 2006) as Bloom Index (BI) for Indian waters.

7 Conclusion

This study provides an overview of algal bloom history, causative species involved, frequency and seasonal occurrence of blooms from the continental margins of India. The occurrences of algal blooms in Indian waters indicate that the west coast is a more bloom–prone area compared to the east coast. Most blooms occurring in Indian waters are naturally driven due to physical forcing such as monsoonal influence, riverine discharge and seasonal upwelling. Eddies and cyclones can also be considered as a triggering factor for provoking bloom formation in BOB (east coast of India). Besides these factors, variations in temperature, salinity, irradiance, water stability, nutrient–enriched waters and prey availability are important conditions that influence bloom formation. The regular timing of some species–specific bloom followed a seasonal pattern, for e.g. *Asterionella japonica* (pre–monsoon), *Chattonella marina* (withdrawal of monsoon) and *Trichodesmium erythraeum* (pre–monsoon), whereas the non–seasonal dinoflagellate blooms responds to short term events such as sunny, calm weather. *Noctiluca* blooms occur in nutrient–enriched waters and are sustained along with diatom blooms that are generated by upwelling–induced conditions during the monsoon period. Since these algal bloom outbreaks are sporadic and unpredictable, regular monitoring of bloom–prone areas will provide significant insights into bloom dynamics and thus provide a modern tool for HAB monitoring as a step ahead.

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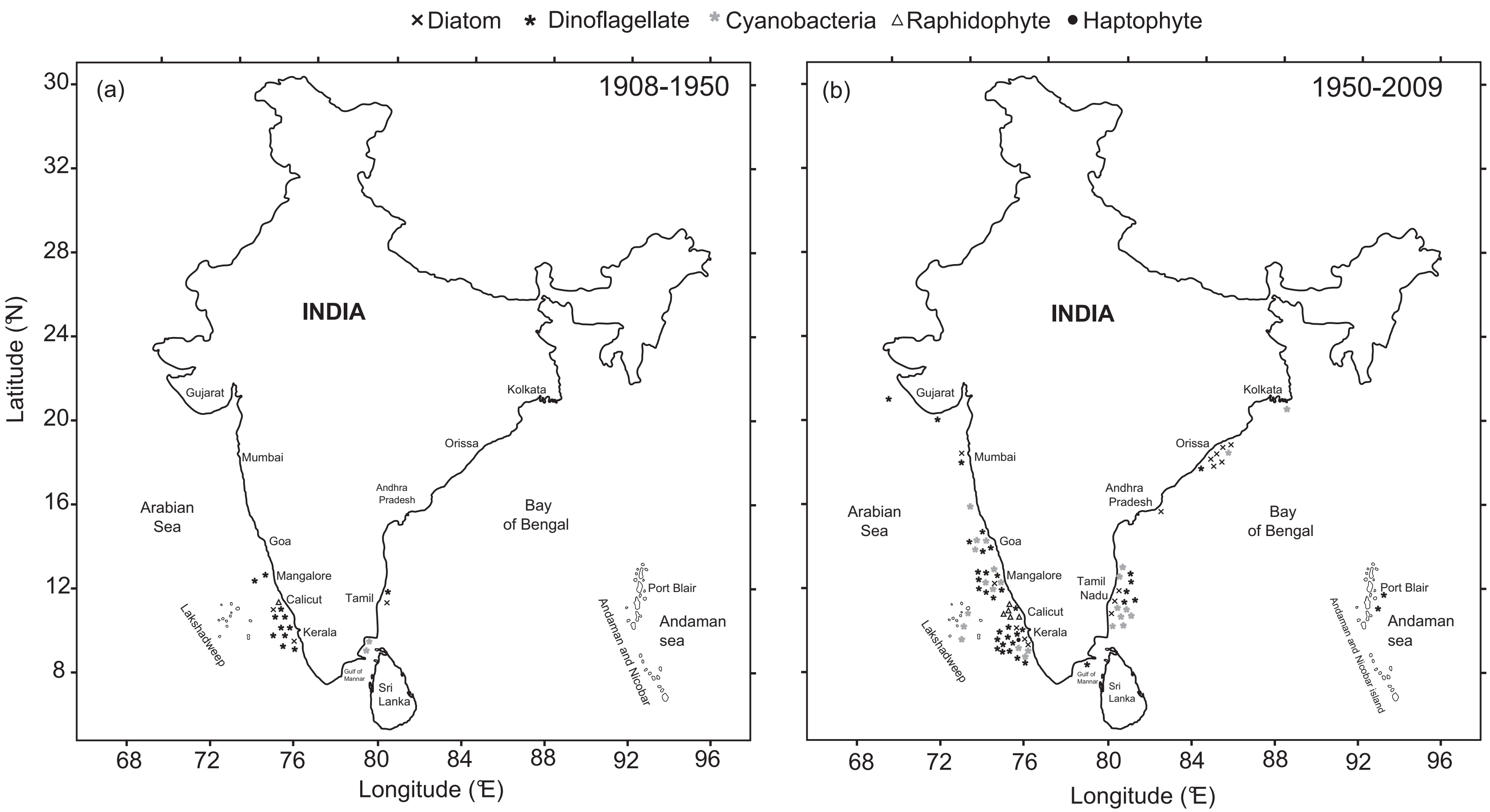
Legends to figures

Fig. 1 Occurrence of algal blooms along the Indian coasts from (a) 1908 to 1950 and (b) 1950 to 2009

Fig. 2 (a) Spatial variation of total algal bloom reportings along the west and east coast of India. In detail, region–wise distribution of diatom, dinoflagellate, cyanobacteria, raphidohyte and haptophyte blooms along the (b) west and (c) east coasts of India

Fig. 3 (a) Seasonal variation of algal bloom occurrences during different time periods of the year along the west and east coasts of India. Predominance of diatom, dinoflagellate, cyanobacteria, raphidohyte and haptophyte blooms during different time periods of the year along the (b) west and (c) east coasts of India



× Diatom * Dinoflagellate * Cyanobacteria △ Raphidophyte ● Haptophyte
(a)
1908-1950
(b)
1950-2009
INDIA
Gujarat
Mumbai
Goa
Mangalore
Calicut
Kerala
Tamil
Tamil Nadu
Andhra Pradesh
Orissa
Kolkata
Arabian Sea
Bay of Bengal
Lakshadweep
Gulf of Mannar
Sri Lanka
Port Blair
Andaman sea
Andaman and Nicobar
Andaman and Nicobar island
Latitude (°N)
Longitude (°E)
30
32
28
24
20
16
12
8
68
72
76
80
84
88
92
96

Fig. 1

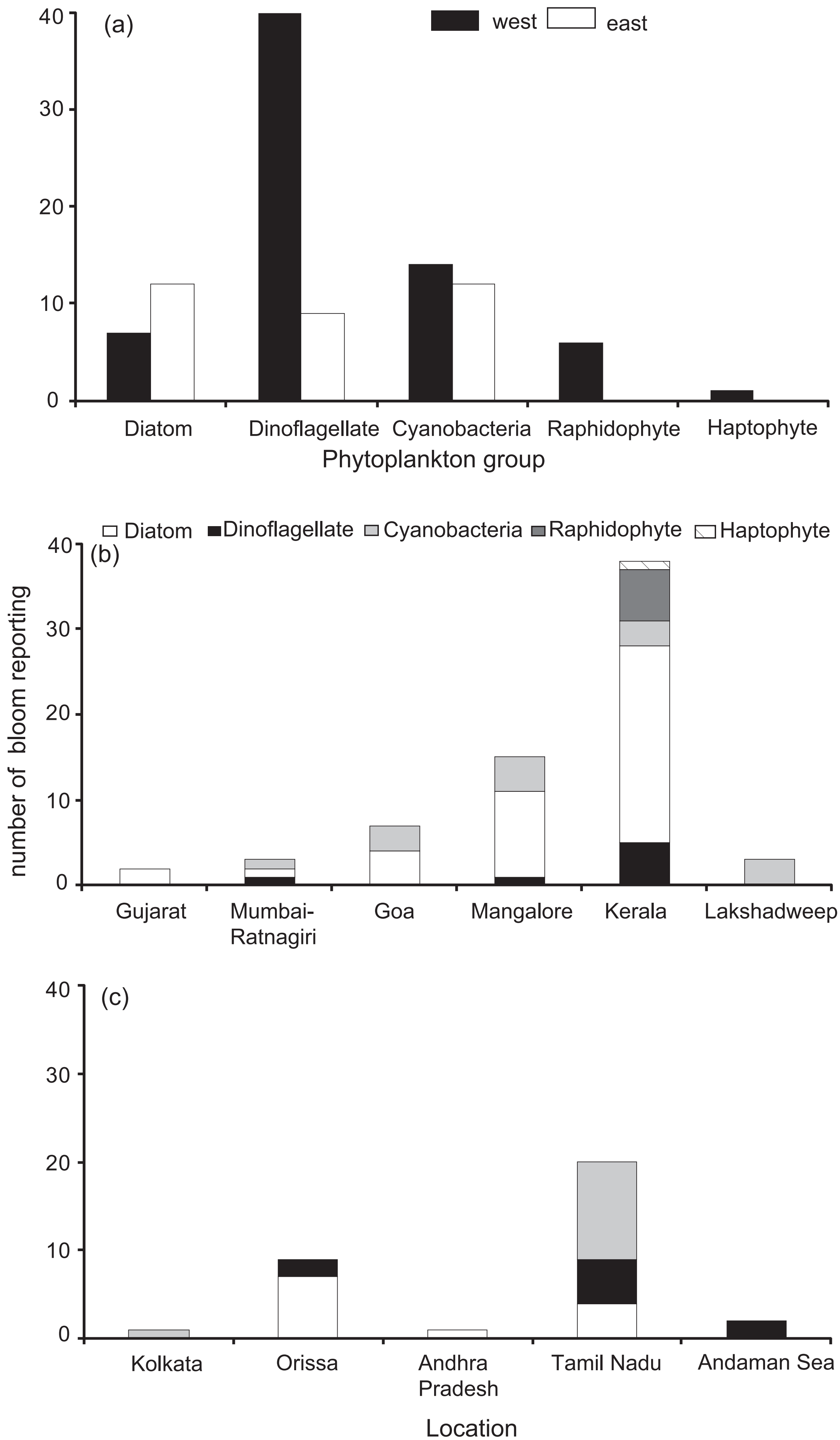

(a)
west
east
40
30
20
10
0
Diatom
Dinoflagellate
Cyanobacteria
Raphidophyte
Haptophyte
Phytoplankton group
Diatom
Dinoflagellate
Cyanobacteria
Raphidophyte
Haptophyte
(b)
number of bloom reporting
Gujarat
Mumbai-Ratnagiri
Goa
Mangalore
Kerala
Lakshadweep
(c)
Kolkata
Orissa
Andhra Pradesh
Tamil Nadu
Andaman Sea
Location

Fig. 2

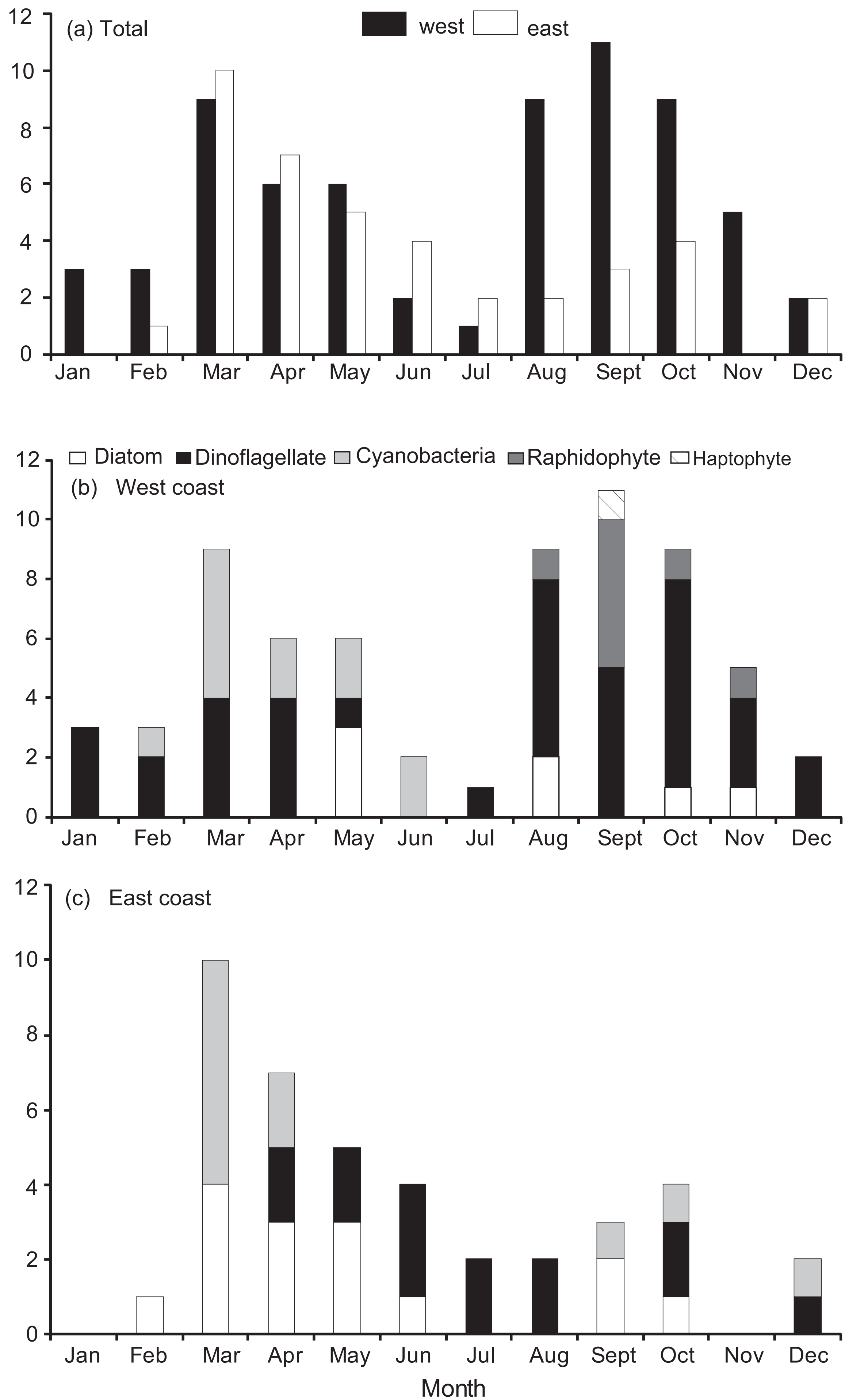

(a) Total
west
east
Diatom
Dinoflagellate
Cyanobacteria
Raphidophyte
Haptophyte
(b) West coast
(c) East coast
0
2
4
6
8
10
12
Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec
Month

Fig. 3

Table 1 Reportings of algal blooms along the west coast of India. PrM: Pre–monsoon, SWM: South–West Monsoon, PoM: Post–monsoon, CC: Cell count, Chl a: Chlorophyll *a*, PP: Primary Productivity

Sr. no.	Causative organism	Place of occurrence	Year	Season	Effect	CC, Chl a & PP	Reference
	Diatom						
1	a) *Ditylum* sp. b) *Thalassiosira* sp.	Malabar coast	1st May 1922 7th May 1922	PrM PrM	–	–	Hornell & Nayudu (1923)
2	*Fragilaria oceanica*	Off Kaikani, Mangalore	August 1972	SWM	–	CC: 36.8 x 10^6 cells L^{-1} Chl a: 123.5 µg L^{-1}	Devassy (1974)
3	a) *Nitzschia sigma* b) *Skeletonema costatum*	Cochin backwaters, Kerala	May 1970 November 1970	PrM PoM	–	CC: 1.4 x 10^6 cells L^{-1} CC: 0.9 x 10^6 cells L^{-1}	Devassy & Bhattathiri (1974)
4	*Skeletonema costatum*	Dharamtar Creek, Mumbai	October 1984–1985	PoM	–	CC: 9 x 10^5 cells L^{-1} Chl a: 6.4 mg m^{-3}	Tiwari & Nair (1998)
5	*Coscinodiscus asteromphalus* var. *centralis*	Off Kodikkal–Calicut, Kerala coast	August 2006	SWM	Brownish red discolouration of water	CC: 7 x 10^6 cells L^{-1} Chl a: 206.5 mg m^{-3} PP: 5.6 g C m^{-3} day^{-1}	Padmakumar et al. (2007)
	Dinoflagellate						
6	Unidentified flagellate (*Noctiluca* ?)	Malabar coast	November 1908	PoM	Massive fish mortality	–	Hornell (1908)
7	Unidentified Peridian (*Noctiluca* ?)	Malabar to south Kanara coasts	September–October 1916	SWM	Massive fish mortality	–	Hornell (1917)
8	a) *Glenodinium*, b) *Gymnodinium* sp.1, sp.2 & sp.3 c) *Prorocentrum micans* d) *Prorocentrum* sp. e) *Cochlodinium* sp.1 f) *Cochlodinium* sp.2	Malabar coast	November 1921 December 1921 January 1922 January 1922 August 1922 October 1922	PoM PoM PoM PoM SWM PoM	Discolouration of water	–	Hornell & Nayudu (1923)
9	*Noctiluca miliaris*, *Gymnodinium* sp.4 & *Dinophysis* sp.	Malabar & Kanara coasts	October 1948	PoM	No mortality; but fishes avoided the area. Abrupt setback in fisheries was observed	CC: 0.5 x 10^5 cells L^{-1}	Bhimachar & George (1950)

Table 1 continued

Sr. no.	Causative organism	Place of occurrence	Year	Season	Effect	CC, Chl a & PP	Reference
10	*Gonyaulax polygramma*	off Cochin, Kerala coast	November 1963	PoM	Non–toxic but virtual exclusion of zooplankton	CC: 10.8 x 10^6 cells L^{-1}	Prakash & Viswanatha Sarma (1964)
11	*Noctiluca miliaris*	a) off Quilon, Kerala	August 1976	SWM	Red colouration to water	CC: 2.4–4.1 x 10^5 m^{-3}	Venugopal et al. (1979)
		b) Cochin, Kerala	August 1977	SWM		CC: 3.0–7.7 x 10^5 m^{-3}	Devassy et al. (1979)
12	Species not identified (toxin profile corresponded to *Alexandrium tamiyavanichi*)	Kumble estuary, Mangalore coast	4th April 1983	PrM	Reports of PSP, one death reported & several hospitalized after consumption of clams *Meretrix casta*	–	Karunasagar et al. (1984)
13	*Noctiluca miliaris*	Mandovi & Zuari estuaries; coastal waters of Goa	February–April 1987	PrM	green colouration to water, fish catch decreased	CC: 0.2–5.1 x 10^4 cells L^{-1}, Chl a: 16.7 mg m^{-3}	Devassy & Nair (1987)
14	Unknown causative species	Mangalore	April 1985 & March–April 1986	PrM	low levels of PSP recorded in shellfish	–	Segar et al. (1989)
15	*Noctiluca miliaris*	Mangalore	January 1987	PoM	Intense green colouration of water	CC: 1.6 x 10^4 –7.6 x 10^9 m^{-3}	Katti et al. (1988)
16	*Gymnodinium nagasakiense*	Brackwish water fish farm at Kodi, Karnataka	11th–15th December 1989	PoM	Red colouration of water & fish mortality reported	CC: 4 x 10^8 cells L^{-1}	Karunasagar (1993)
17	*Noctiluca miliaris*	off Mangalore	May 1993	PrM	Increased proportion of *Moraxella* like bacteria with bloom	CC: 1.6 x 10^6 ells m^{-3}	Nayak et al. (2000)
18	Unknown causative species	Vizhinjam, Kerala coast	September 1997	SWM	Outbreak of PSP. 7 deaths reported, over 500 hospitalized after consuming bloom affected mussel	–	Karunasagar et al. (1998)

Table 1 continued

Sr. no.	Causative organism	Place of occurrence	Year	Season	Effect	CC, Chl a & PP	Reference
					Perna indica		
19	*Noctiluca* sp.	Cochin–Calicut, off Kerala coast	8–10th August 1998	SWM	oxygen depletion resulted in severe mortality of fish	–	Naqvi et al. (1998)
20	*Cochlodinium polykrikoides*	off Goa	October 2001	PoM	Fish mortality coincided with bloom occurrence	–	O'Herald (2001)
21	*Noctiluca scintillans*	off Goa to Porbandar (Gujarat) coast	26th February–15th March 2003	PrM	Green colouration to water	CC: 0.6– 25.42 x 10^2 cells L^{-1}	Prabhu Matondkar et al. (2004)
22	Causative species varied, a)*Cochlodinium polykrikoides* b) *Karenia brevis*	Kerala coast	17th September 2004	SWM	About 200 children hospitalized & fish mortality reported	–	The Hindu (2004), The Hindustan Times (2004)
23	*Noctiluca miliaris*	off south Thiruvananthapuram, Kerala coast	29th September 2004	SWM	Red discolouration of water	CC: 9 x 10^5 cells L^{-1}	Sahayak et al. (2005)
24	*Karenia mikimotoi*	Kerala coast	July–September 2004	SWM	Mass mortality of fish	CC: 9.0 x 10^4 cells L^{-1} Chl a: 8.8–721 mg m^{-3}	Iyer et al. (2008)
25	*Noctiluca miliaris*	off Gujarat	March 2007	PrM	Deep green colouration of water	CC: 4 x 10^6 cells m^{-3} Chl a: 21.9 mg m^{-3}	Padmakumar et al. (2008b)
26	*Protoperidinium* sp.	Mangalore coast	8th October 2008	PoM	No fish kills	CC: 8.1 x 10^8 cells L^{-1} Chl a: 12.3 µg L^{-1}	Sanilkumar et al. (2009)
27	*Noctiluca miliaris*	off Goa	8th October 2008	PoM	No fish kills	CC: 2 x 10^4 cells L^{-1}	Sanilkumar et al. (2009)
28	*Noctiluca scintillans*	off Kochi, Kerala	19th August 2008	SWM	Brick red discolouration of water, no fish mortality	CC: 5 x 10^8 cells L^{-1}	Padamakumar et al. (2010a)
29	*Karenia mikimotoi*	Cochin barmouth,	21st October 2009	POM	Intense brownish	CC: 7.0–15.5 x10^6	Madhu et al. (2011)

Table 1 continued

Sr. no.	Causative organism	Place of occurrence	Year	Season	Effect	CC, Chl a & PP	Reference
		Kerala			colouration to water	cellsL^{-1}, Chl a: 24–85.8 mg m^{-3}	
	Cyanobacteria						
30	*Trichodesmium erythraeum* & *Trichodesmium hildebrontii*	Ullal, off Mangalore coast	13th & 21st March 1964	PrM	–	–	Prabhu et al. (1965)
31	*Trichodesmium erythraeum*	Minicoy Island, Lakshadweep	May–June 1965	SWM	Adverse effects on Tuna fisheries	–	Nagabhushanam (1967)
32	*Trichodesmium erythraeum*	Laccadive island	April 1968	PrM	–	–	Qasim (1970)
33	*Trichodesmium erythraeum*	near–shore waters of Goa	March 1972	PrM	No fish mortality reported	CC: 3.4 x 10^5 cells ml^{-1} Chl a: 2.12 mg m^{-3}	Ramamurthy et al. (1972)
34	*Trichodesmium erythraeum*	coastal waters of Goa	February–April 1975	PrM	–	CC: 0.2 x 10^5 cells ml^{-1}	Devassy et al. (1978)
35	*Trichodesmium erythraeum*	Ratnagiri–Mangalore & Laccadive island	March 1977	PrM	Swarming of *Physalia* coincided with the bloom	CC: 0.4 x 10^5 filaments L^{-1}	Verlencar (1978)
36	*Trichodesmium erythraeum*	Mangalore–Quilon	6–20th May 2005	PrM	Discolouration of water, no mortality reported	CC: 0.5 x 10^5 filaments ml^{-1}	Anoop et al. (2007)
37	*Microcystis aeruginosa*	Chalakudy River in Central Kerala	March 2008	PrM	Discolouration of water. Itching, irritation of the skin among local people	CC: 4 x 10^8 cells m^{-3} Chl a: 23.4 mg m^{-3}	Padmakumar et al. (2008a)
38	*Trichodesmium erythraeum*	off Kollam, Kochi & Kannur, Kerala coast	29th May–11th June 2009	Onset of SWM	Brown discolouration of water	CC: 1.14 x 10^6, 1.97 x 10^6, 1.51 x 10^6 filaments L^{-1}	Padmakumar et al. (2010b)
	Raphidophyte						
39	*Hornellia marina*	Calicut, North Kerala	August & November 1949, September 1952,	SWM	Green discolouration, Fish & Faunal mortality	–	Subrahmanyan (1954)

Table 1 continued

Sr. no.	Causative organism	Place of occurrence	Year	Season	Effect	CC, Chl a & PP	Reference
40	*Chattonella marina*	Calicut to Tellicherry, Kerala	a) September 2002 b) September 2003	SWM SWM	Fishery was affected	CC: 28 x 10^7 cells L^{-1} CC: 1.4 x 10^7 cells L^{-1}	Jugnu & Kripa (2009)
41	*Chattonella marina*	off Kochi, Kerala	September 2009	SWM	Rusty brownish–red discolouration of water	CC: 1.59 x 10^7 cells L^{-1} Chl a: 8.3 µg L^{-1}	Padmakumar et al. (2011)
	Haptophyte						
42	Unidentified holococcolithophore	Kerala	September–October 2004	Withdrawal of SWM	–	CC: 1.9–57.7 cells L^{-1}	Ramaiah et al. (2005)

Table 2 Reportings of algal blooms along the east coast of India. PrM: Pre–monsoon, SWM: South–West Monsoon, PoM: Post–monsoon, NEM: North–East Monsoon, CC: Cell count, Chl a: Chlorophyll *a*, PP: Primary Productivity

Sr. no.	Causative organism	Place of occurrence	Year	Season	Effect	CC, Chl a & PP	Reference
	Diatom						
1	a) *Rhizosolenia alata* b) *Rhizosolenia imbricata*	inshore waters off Mandapam, Tamil Nadu	March 1950 February 1951	PrM PrM	–	–	Raghu Prasad (1956)
2	*Asterionella japonica*	off Vishakhapatnam, Andra Pradesh	April 1967	PrM	Greenish–brown discolouration of coastal waters	CC: 6.7–93.2 x 10^6 cells L^{-1}, Chl a: 11–36 $\mu g\ L^{-1}$	Subba Rao (1969)
3	*Asterionella glacialis*	Vellar estuary, Tamil Nadu	March & September/October 1983	PrM SWM	–	CC: 0.2 x 10^5 cells L^{-1}	Mani et al. (1986)
4	*Asterionella glacialis*	Gopalpur, Orissa coast	26th March 1988	PrM	Greenish–brown patch observed	CC: 0.4 x 10^5 cells L^{-1} Chl a : 70 mg m^{-3}	Choudhury & Panigrahy (1989)
5	*Asterionella glacialis*	Rushikulya estuary, Orissa coast	April–May 1988	PrM	–	CC: 0.4–0.9 x 10^5 cells L^{-1}	Panigrahy & Gouda (1990)
6	a) *Asterionella glacialis* b) *Thalassiothrix fraunfeldii* c) *Coscinodiscus centralis* & *Coscinodiscus excentricus*	Bahuda estuary, Orissa coast	May 1991 September 1991 June 1992	PrM SWM SWM	–	CC: 2.7 x 10^6 cells L^{-1} CC: 2.2 x 10^6 cells L^{-1} CC: 3.7 x 10^5 cells L^{-1}	Mishra & Panigrahy (1995)
7	*Asterionella glacialis*	off Kalpakam, Tamil Nadu	May 1993	PrM	No fish mortality reported	CC: 5.5 x 10^{10} cells m^{-3} Chl a: 22.7 $\mu g\ L^{-1}$	Satpathy & Nair (1996)
8	*Asterionella glacialis*	Gopalpur, Orissa	24th March–4th April 2004	PrM	Dark–brown discolouration of water	CC: 20.1–72.2 x 10^5 cells L^{-1}, Chl a: 63–7220 mg m^{-3}	Sasamal et al. (2005)
	Dinoflagellate						
9	*Noctiluca miliaris*	Madras, Tamil Nadu	June 1935	SWM	Pink colouration to water. Mortality of fish	–	Aiyar (1936)

Table 2 continued

Sr. no.	Causative organism	Place of occurrence	Year	Season	Effect	CC, Chl a & PP	Reference
10	*Noctiluca miliaris*	Palk Bay, Mandapam–Tamil Nadu	April–July 1952	PrM	–	–	Raghu Prasad (1953, 1958)
11	*Noctiluca miliaris*	Vellar Estuary, Tamil Nadu	August 1966, August 1967, May 1968	SWM SWM PrM	–	CC: 0.7–2.9 x 10^4 cells 10 ml^{-1}	Santha Joseph (1975)
12	Species not identified	Vayalar village, Tamil Nadu	1981		PSP outbreak resulted in the hospitalization of 85 people & 3 death reported after consuming bloom affected mussel *Meretrix casta*	–	Silas et al. (1982)
13	*Noctiluca scintillans*	Kalpakkam, Tamil Nadu	11–17th October 1988	PoM	–	CC: 0.4 x 10^5 cells L^{-1} Chl a: 28 mg m^{-3}	Sargunam & Rao (1989)
14	*Noctiluca scintillans*	Port Blair Bay, Andamans	June–July 2000	SWM	Green colouration to water	CC: 1.5–2.3 x10^4 cells L^{-1},Chl a: 17.6 mg m^{-3}	Eashwar et al. (2001)
15	*Noctiluca scintillans*	Minnie bay, Port Blair–Andamans	20th December 2002	NEM	Green colouration to water	CC: 0.2 x 10^5 cells L^{-1} Chl a: 32.7 mg m^{-3}	Dharani et al. (2004)
16	*Noctiluca scintillans*	Rushikulya river, South Orissa coast	5th April 2005	PrM	Red discolouration of water, oxygen depletion	CC: 2.83 x 10^5 cells L^{-1}	Mohanty et al. (2007)
17	*Noctiluca scintillans*	Gulf of Mannar, Orissa	2nd –12th October 2008	PoM	Deep-green colouration to water. Corals got bleached, due to lack of oxygen. Many fishes & sea animals died	CC: 13.5 x 10^5 cells L^{-1} Chl a: 116 mg m^{-3}	Gopakumar et al. (2009)
	Cyanobacteria						
18	*Trichodesmium erythraeum*	Krusadai island, Gulf of Mannar	May 1942	PrM	Mortality of marine fauna (*Holothuria atra*	–	Chacko (1942)

Table 2 continued

Sr. no.	Causative organism	Place of occurrence	Year	Season	Effect	CC, Chl a & PP	Reference
					& fishes)		
19	*Trichodesmium erythraeum*	Southern coast of Pamban, Gulf of Mannar	May 1942	PrM	Mortality of fishes & crabs	–	Chidambaram & Unny (1944)
20	*Trichodesmium erythraeum*	Porto Novo, Tamil Nadu	March 1964, 1965, 1969, 1972	PrM	–	–	Ramamurthy (1968), Ramamurthy (1970a, 1970b, 1973)
21	*Trichodesmium thiebautii*	Gulf of Mannar, Tamil Nadu	March–April & September 1973	PrM SWM	Fish mortality	–	Chellam & Alagarswami (1978)
22	*Trichodesmium erythraeum*	a) Tamil Nadu b) off Kolkata	11th April 2001 25th April 2001	PrM	Brownish–yellow colouration of water	PP: 2160 mg C m^{-2} d^{-1} PP: 1740 mg C m^{-2} d^{-1}	Jyothibabu et al. (2003)
23	*Trichodesmium erythraeum*	Kalpakkam, Tamil Nadu	16th March 2007	PrM	Yellowish–green colouration of water. No fish mortality reported	CC: 4.1 x 10^6 cells L^{-1}	Satpathy et al. (2007)
24	*Trichodesmium erythraeum*	Mandapam & Keelakarai, Tamil Nadu	October 2008	PoM	Mortality of several fishes and shellfishes	–	Anantharaman et al. (2010)
25	*Microcystis aeruginosa*	Vellar estuary, Tamil Nadu	December 2009	NEM	–	CC: 37.6 x 10^3 colony L^{-1}, Chl a: 18.61 µg L^{-1}	Santhosh Kumar et al. (2010)

Table 3 List of causative bloom species and number of bloom cases reported along the west and east coasts of India

Causative species	West coast						East coast				
	Gujarat	Mumbai–Ratnagiri	Goa	Mangalore	Kerala	Lakshadweep	Kolkata	Orissa	Andhra Pradesh	Tamil Nadu	Andaman Sea
Diatom											
Asterionella glacialis(=*Asterionella japonica*)								4	1	2	
Coscinodiscus asteromphalus var. *centralis*					1						
Coscinodiscus centralis								1			
Coscinodiscus excentricus								1			
Ditylum sp.					1						
Fragilaria oceanica				1							
Nitzschia sigma					1						
Rhizosolenia alata										1	
Rhizosolenia imbricata										1	
Skeletonema costatum		1									
Skeletonema sp.					1						
Thalassiosira sp.					1						
Thalassiothrix fraunfeldii								1			
Dinoflagellate											
Cochlodinium polykrikoides			1		1						
Cochlodinium sp.1					1						
Cochlodinium sp.2					1						
Dinophysis sp.					1						
Glenodinium					1						
Gonyaulax polygramma					1						
Gymnodinium sp.1					1						
Gymnodinium sp.2					1						
Gymnodinium sp.3					1						

Table 3 continued

Causative species	West coast						East coast				
	Gujarat	Mumbai–Ratnagiri	Goa	Mangalore	Kerala	Lakshadweep	Kolkata	Orissa	Andhra Pradesh	Tamil Nadu	Andaman Sea
Gymnodinium sp.4				1	1						
Karenia brevis					1						
Karenia mikimotoi (= *Gymnodinium nagasakiense*)				1	2						
Noctiluca miliaris (= *Noctulica scintillans*)	2	1	3	3	5			1		4	2
Noctiluca sp.					1			1			
Prorocentrum micans					1						
Prorocentrum sp.					1						
Protoperidinium sp.				1							
Unidentified flagellate (*Noctiluca*?)					1						
Unidentified Peridian (*Noctiluca*?)				1	1						
Unidentified PSP species				2	1					1	
Cyanobacteria											
Trichodesmium erythraeum		1	3	3	2	3	1			9	
Trichodesmium hildebrontii				1							
Trichodesmium thiebautii										1	
Microcystis aeruginosa					1					1	
Raphidophyte											
Chattonella marina (=*Hornellia marina*)					7						
Haptophyte											
Unidentified holococcolithophore					1						