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Understanding the dietary relationship between extensive *Noctiluca* bloom outbreaks and Jellyfish swarms along the eastern Arabian Sea (West coast of India)

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The paper attempts to understand the interrelationship between recurring blooms of dinoflagellate, *Noctiluca scintillans* as well as increasing jellyfish swarms along the coastal waters of eastern Arabian Sea. The grazing of *N. scintillans* on diatoms in the productive waters with reduced competition pressure due to the opportunistic feeding of jellyfishes on zooplankton are described here. With the development of *N. scintillans* in the favourable environmental conditions, jellyfishes utilize this dinoflagellate as their food source and thrive in the coastal waters. Hence, trophic interaction between *Noctiluca* and jellyfishes leading to their proliferation in the coastal waters are delineated.

Introduction

Marine ecosystems are experiencing serious threats that affect the diversity, sustainability and services they render to human beings. Eutrophication, expansion of hypoxia, increased ocean acidification, dwindling fisheries, algal blooms and increasing gelatinous zooplankton or jellyfish swarms are some among them. Harmful algal blooms (HABs) along the productive eastern Arabian Sea are increasing in the last few decades[1,2]. The bloom of *Noctiluca scintillans* that results in red tide during summer monsoon mainly along the southeastern Arabian Sea and green tide along the northeastern Arabian Sea during winter monsoon is a recurrent phenomenon[3-9]. These are opportunistic dinoflagellates exhibiting high growth and reproduction rate within a particular season[10].

Noctiluca is a heterotrophic dinoflagellate that feeds on small diatoms, dinoflagellates, eggs of copepods and microzooplankton[10,11]. They are a significant competitor for mesozooplankton that prey upon mixed diatom blooms during summer monsoon associated upwelling[7,12,13]. The bloom of *Noctiluca* generally appears in red causing a red tide. Green *Noctiluca* harbours green photosynthetic prasinophyte endosymbiont *Pedinomonas noctilucae* which is absent in red *Noctiluca* and provides nutrition to the dinoflagellate and imparts a green colour to its bloom[14,15]. However, green *Noctiluca* is also observed to depend on phagotrophy which is evident from the food vacuoles with diatoms inside these dinoflagellates from the northern Arabian Sea winter blooms[16]. Owing to its large size and high ammonia concentration *N. scintillans* are often avoided by smaller zooplankton and fishes, while the major predators of *N. scintillans* include gelatinous zooplankton and certain large fishes[16,17].

Gelatinous zooplankton mainly jellyfishes are characterised by broad diet spectrum, high reproduction as well as growth rates and experience less predation pressure[18]. Underpinned with these benefits they can form huge swarms in the pelagic water column under favourable environmental conditions. Climate change, alteration in aquatic habitats, eutrophication and unsustainable fisheries are the primary external factors contributing to their population outburst[19,20] and are referred to as synanthropic, benefitting from the environmental alterations caused by anthropogenic influences[21,22].

Materials and Methods

Frequent blooms of *N. scintillans* were observed and reported from the eastern Arabian Sea as a part of regular monitoring programs for harmful algal blooms and associated microalgal studies. Samples were collected on the incidence of bloom events along the west coast of India. Taking into account on these studies conducted as well as from various published reports on the blooms caused by *N. scintillans*[1,2,3-9] the

frequency of bloom events were tabulated for a period of seven years (2010-2016). An increase in the pelagic population of gelatinous zooplankton is identified along the west coast of India and a pooled data on the reports of mainly salps and jellyfish outbursts were obtained through various sources for the study period (2010-2016). Monitoring of coastal waters for such outbreaks was done along with various coastal biodiversity initiatives, algae monitoring programmes etc. Information was also gathered from local fisher folks as well as from newspapers and media. A feeding experiment was carried out using jellyfishes with live *Noctiluca* cells to identify the preference of this gelatinous zooplankton towards *Noctiluca* cells. For this, starved jellyfishes and salps were fed with a known number of *N. scintillans* cells collected from the bloom area in well aerated experimental tanks on-board research vessel. Those jellyfishes, as well as salps devoid of *Noctiluca* cells, were identified and selected through morphological examination were used for the feeding experiments.

Results and Discussion

In recent decades, there appears an increase in the pelagic populations of jellyfishes as well as their swarm outbreaks across the globe[23]. This macrozooplankton, with the lack of complex body structures, is adaptable to variations in the habitat and can thrive in a changing environment. The global increase in the gelatinous zooplankton community mainly jellyfishes have reflected in the productive Arabian Sea ecosystem also. The increase in the frequency and intensity of jellyfish swarms along the eastern Arabian Sea at times causes stink to beachgoers.

The present study attempts to delineate the interrelationship between the jellyfish swarms and frequent *N. scintillans* blooms along the eastern Arabian Sea ecosystem. Recently observation on red tides caused by *N. scintillans* shows a yearly increase along the south-eastern Arabian Sea mainly during the mid-late phase of summer monsoon season (Fig. 1a). Interestingly, moderate to intense swarms of jellyfishes occurs in this region along with or following red tides. Similarly, along the northeastern Arabian Sea, huge swarms of gelatinous zooplankton including salps and jellyfishes are observed along with or following green tide caused by *N. scintillans* (Fig. 1b). In both cases, a preponderance of *N. scintillans* abundance was observed before or during the initial stages of jellyfish swarms. This lead to a detailed analysis of *Noctiluca* blooms as well as jellyfish blooms in the eastern Arabian Sea along with their feeding habits.

The red tide caused by heterotrophic dinoflagellate, *N. scintillans* is commonly observed in the coastal waters of southeastern Arabian Sea, in the form of blooms usually during relaxation periods of upwelling. The frequency of red tide formation by *Noctiluca scintillans* were tabulated based on the present survey as well as from previously published reports[1,2,3-9] and the analysis showed an increasing trend in the frequency of occurrence in the last decade along the southeastern Arabian Sea (Fig. 2). The major hotspots of *N. scintillans* blooms along the

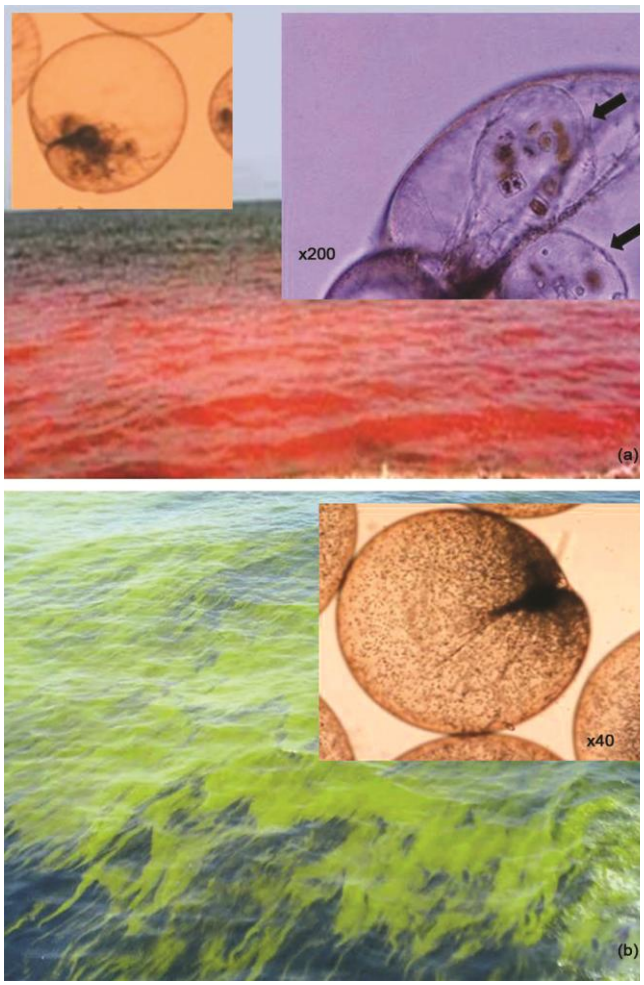

Fig. 1 — (a) Red tides by *Noctiluca scintillans* along the southeastern Arabian sea (Inset- microphotograph of red *Noctiluca* with diatom cells inside the food vacuoles, x 40) (b) Green tide by *N. scintillans* along the northeastern Arabian Sea (Inset- microphotograph of green *Noctiluca* with endosymbiont *Pedinomonas noctilucae*, x 40)

eastern Arabian Sea are shown in Figure 3. Along the Northern Arabian Sea, the blooms of green *Noctiluca* are also observed to be increasing during the later phases of winter monsoon season[16].

Attempts were also made to quantify the increasing gelatinous zooplankton blooms along the eastern Arabian Sea. An interpretation of these results clearly showed an increasing trend in the gelatinous zooplankton population as well as the frequency of swarms along the west coast of India (Fig. 2). Along the eastern Arabian Sea regular swarms of gelatinous zooplankton mainly salps and jellyfishes were observed as a part of routine monitoring programmes (Fig. 4). From the analysis, it is clear that both the blooms of *N. scintillans* and jellyfishes are increasing

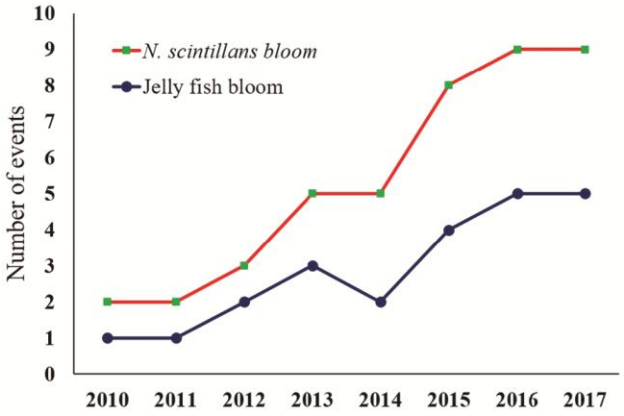

Fig. 2 — The frequency of bloom events of *N. scintillans* and gelatinous zooplankton along eastern Arabian Sea during the period 2010 to 2017

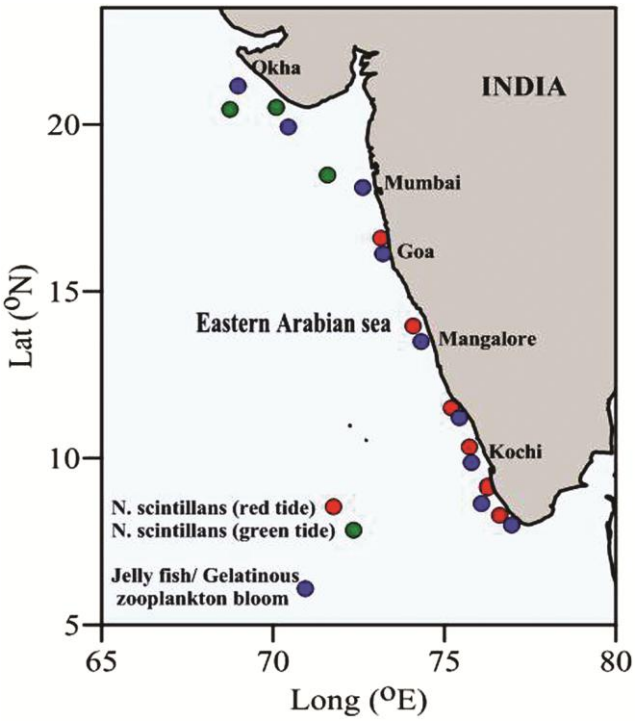

Fig. 3 — The major hot spots of red and green tides of *N. scintillans* and gelatinous zooplankton along the eastern Arabian Sea during the period of 2010 to 2017

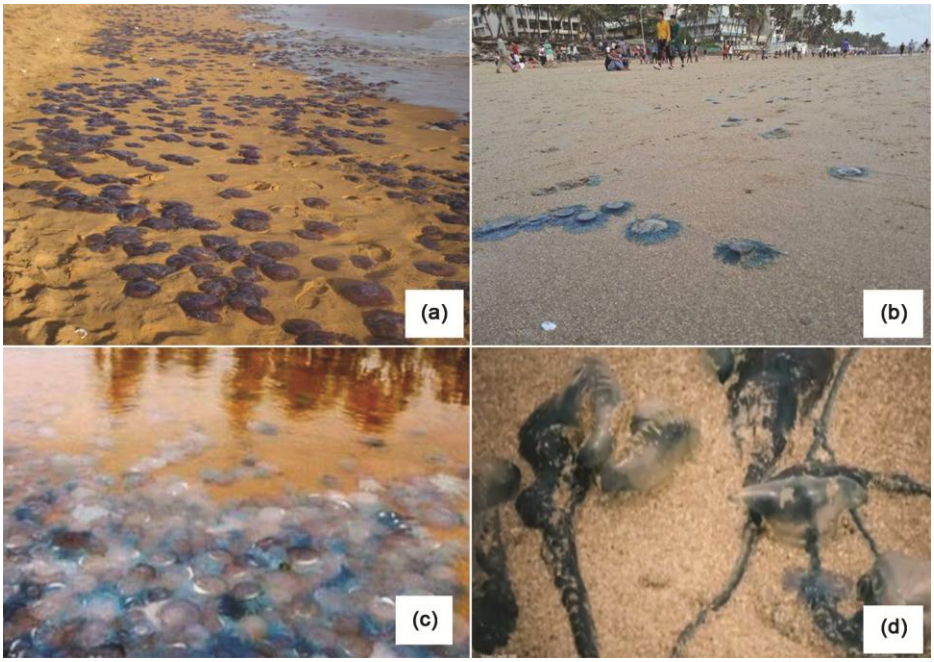

Fig. 4 — Various events of jellyfish swarms and beach stinks along the eastern Arabian Sea: (a) Thiruvananthapuram, (b) Juhu beach Mumbai, (c) Kappil beach Kollam, and (d) Blue bottle jellyfish washed ashore along various beaches of Mumbai. (*Photo courtesy*-(a) *The Hindu daily*, (b) *Times of India*, (c) *The Hindu daily*, and (d) *Indian express*)

concomitantly (Fig. 2) showing some distinct interrelationships. Moreover, the major areas of both red tides of *Noctiluca* and jellyfish swarms are observed to be overlapping (Fig. 3).

In a classic production pattern and trophic transfer along the west coast of India during the summer monsoon, the upwelling process and nutrient pulses trigger the mixed diatom bloom (MDB) along the southeastern Arabian sea[24]. The winter mixing along the north eastern Arabian sea also initiates diatom blooms. These mixed diatom blooms (MDB) are fed by mesozooplankton, the secondary producers. The jellyfishes prey upon mesozooplankton thereby reducing their grazing pressure on diatoms which in turn favours *N. scintillans* that devours on these diatoms as a source of their nutrition[25]. With the increased abundance of diatoms, *N. scintillans* multiply and with favourable environmental conditions, mainly relaxation phase of upwelling they develop as blooms. The preponderance of diatom blooms before *N. scintillans* blooms was previously reported from eastern Arabian Sea[7]. Hence, indirectly jellyfishes supported the blooming of *N. scintillans* by reducing the competitive pressure with mesozooplankton.

A feeding experiment carried out using jellyfishes with live *Noctiluca* cells showed the preference of this gelatinous zooplankton towards *Noctiluca* cells. The gelatinous zooplankton were observed to ingest *Noctiluca* cells and there was a considerable decrease in the number of *Noctiluca* cells in the experimental tank (Fig. 5). Feeding experiments carried out previously along the northeastern Arabian Sea also observed significant grazing of salps on *N. scintillans*[16].

The schematic representation of this relationship is shown in Figure 6. The illustration shows on one side (right) a healthy and sustainable tropical coastal marine ecosystem presenting classical marine food chain in which the nutrient input through monsoonal mixing is used up by the primary producers dominated by diatoms which in turn are consumed by primary consumers mainly zooplankton and passing the energy to higher trophic levels. The other side of the schematic representation (left) shows a disrupted food chain characterising an unsustainable and less diverse ecosystem. Both the jellyfishes as well as *N. scintillans* play an important role here. The increasing jellyfish population feeds on mesozooplankton and provides favourable conditions for *N. scintillans* to develop into blooms by feeding on diatoms with less competition. With the plentiful availability of *N. scintillans* cells, these jellyfishes utilize them as a food source and flourish that leading to jellyfish swarming. This can

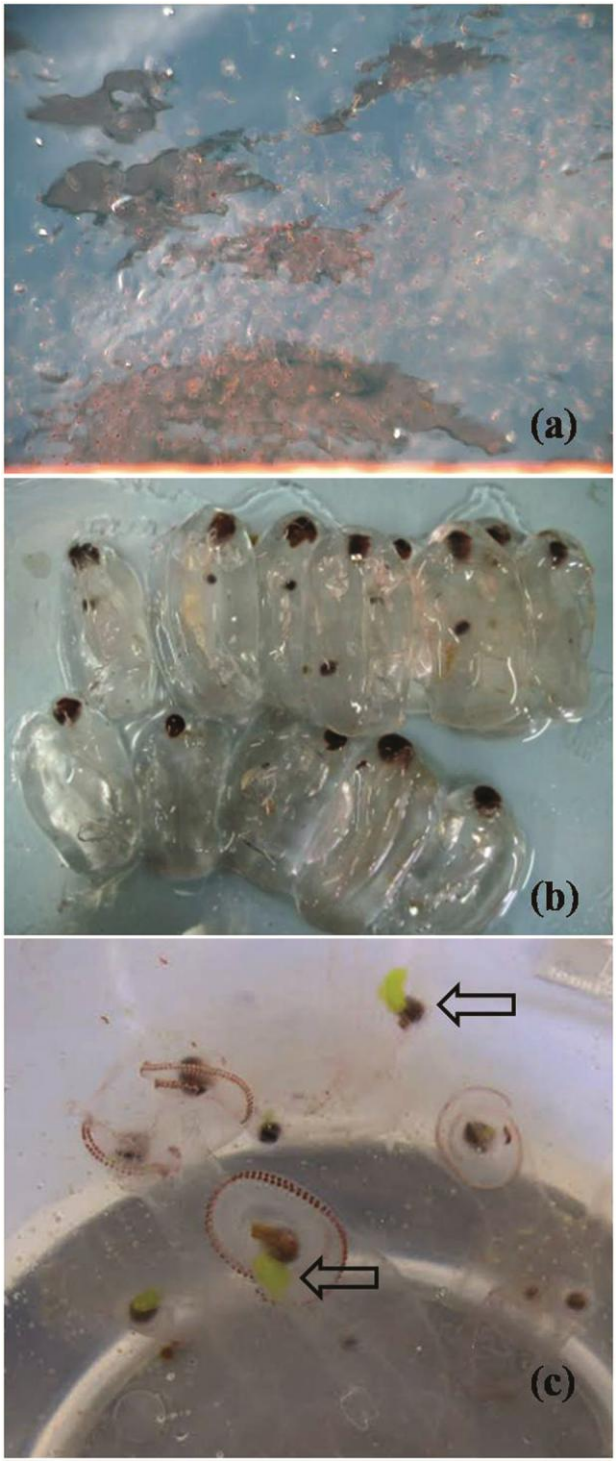

Fig. 5 — (a) Swarming of Salps along the eastern Arabian Sea, (b) Salp colony, and (c) Salps with ingested *N. scintillans* during feeding experiment

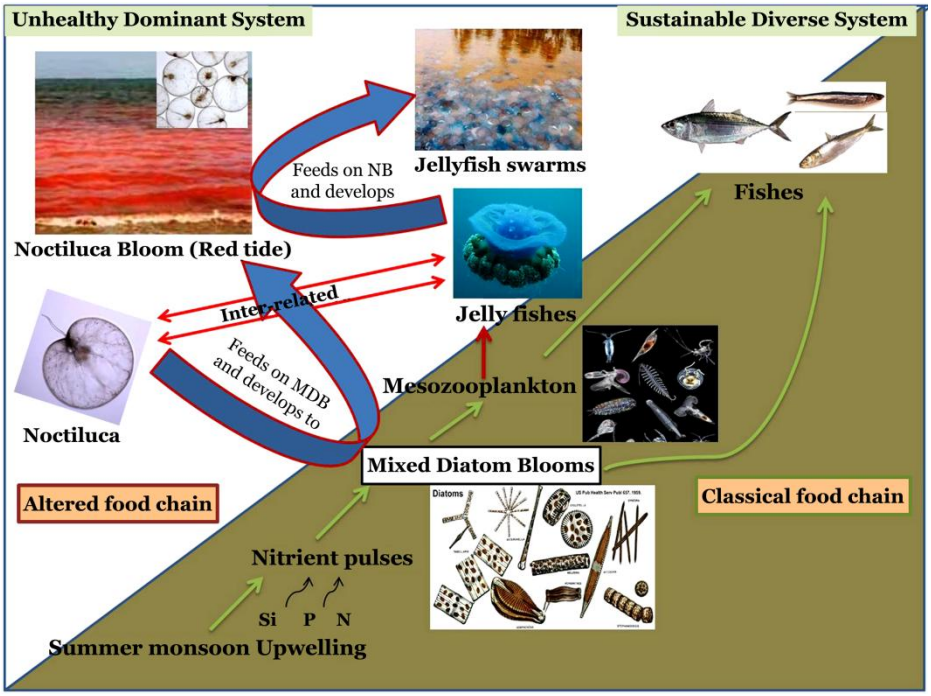

Fig. 6— The schematic representation of inter-relationship of *Noctiluca scintillans* and jellyfishes and its influence on the marine food chain

also lead to shortening and disruptions of the food chain in these marine ecosystems.

The increasing *N. scintillans* blooms thus give a decisive stroke towards the population outburst of gelatinous zooplankton in the Arabian Sea. On the other hand, their grazing on other mesozooplankton reduces the competitive pressure to the dinoflagellate *N. scintillans* for their major prey, diatoms. Hence, it can be assumed that there exists an interrelationship between the swarms of jellyfish and blooms of *N. scintillans* both supporting each other in their bloom formation and existence. However, this relation cannot be considered solely responsible for the out burst of jellyfish swarms and *Noctiluca* blooms but can be one among the robust features favouring these two events along the eastern Arabians Sea. Further studies attempting to understand the biology and ecology, trophic status and swarming behaviour of the jellyfishes as well as *in-situ* and laboratory-based grazing experiments by both *Noctiluca* as well jellyfishes can bring more insight into this interrelationship. Such findings can help in managing the threat of increasing red and green tides of *Noctiluca* as well as jellyfish swarms along the eastern Arabian Sea.

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Conflict of Interest

The authors declare that they have no conflict of interest.

Author Contributions

LCT wrote the manuscript with input from KBP. LCT and KBP conducted the field study. LCT conducted taxonomic identifications. KBP and SBN supervised this study and provided research materials.

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