Indian Journal of Geo Marine Sciences
Vol. 47 (02), February 2018, pp. 259-268

Review Article

Impact of climate change on marine plankton with special reference to Indian Seas

Biraja Kumar Sahu[1]*, Premalata Pati & R. C. Panigrahy

Department of Marine Sciences, Berhampur University, Berhampur-760 007, Odisha, India
[1]Environment and Sustainability Department, CSIR-IMMT, Bhubaneswar-751 013, Odisha, India

*[E-mail: birajkumar@gmail.com]

Received 13 November 2015 ; Revised 01 April 2016

The seas surrounding India, namely Arabian Sea (AS) and Bay of Bengal (BoB) with their associated coastal embayments form one of the highly productive areas and biodiversity hotspots in the tropics contributing profusely to the socio-economic front of the region. Therefore, acquiring knowledge on the climate change scenario of this region and its impacts on marine ecosystems in general and planktons, in particular, is considered crucial for better resilience. In fact, several attempts have been made of late to understand the climate change impacts on plankton, corals and mangroves of this region. In this article, we tried to update the climate change scenario of Indian seas and its impact on plankton communities based on the information gathered from the peer reviewed publications and scientific reports. Results of this review have shown that the global warming generated SST (Sea Surface Temperature) rise and sea water acidification related pH fall have affected the species composition, abundance, phenology and metabolic pathways of plankton populations in this region.

[Keywords: Global warming, Ocean acidification, Plankton, Arabian Sea, Bay of Bengal]

Introduction

Climate is defined as the average condition of the atmosphere and its underlying land and water on seasonal, decadal, centennial and even longer timescales[1]. Earth's climate is changing continuously since its origin under the influence of some intrinsic natural processes and extrinsic activities of anthropogenic origin. The change in the physical and chemical attributes of the ambiance controls the survival and continuity of life at individual, population and community levels. The earth had experienced many changes in the quality of its air, water and land which had extensively affected the living systems. The glaring example of the impact of climate change on biota on planet earth was the extinction of several species including dinosaurs as a result of the drastic changes about 65 million years ago[2]. Recently Hoegh-Guldberg and Bruno[3] had claimed that the distribution of organisms, functioning of ecosystems and sustenance of biological resources greatly depends upon the climate of the ambiance. Global warming, sea water acidification and ozone depletion in the stratosphere encountered in recent decades are due to GHGs emission. It imparts most noteworthy changes with far reaching consequences on ecological and socio-economic fronts. The Intergovernmental Panel on Climate Change (IPCC) has laid emphasis for the proper understanding of the current climate change scenario and their interaction and impacts on different ecosystems at local, regional and global scales[4].

We derive lots of goods in form of food, fodder, precious stones, ornaments, novel biomolecules used in diagnostic kits and medicines and services like transport & communication from marine ecosystems. It has been estimated that the ocean resources could account for about 21 trillion US$ y^{-1} [Ref.5]. Again, they play a fundamental role in shaping the world's climate, maintaining biogeochemical cycling of nutrients, gas regulation and water cycle. The primary producer of ocean, the phytoplankton, assimilates about 50% of CO_2 on earth[6] and thus stands as the main suppliers of oxygen we breathe. In recognition of such enormous socioeconomic and ecological implications, emphasis has been laid to understand the impact of climate change on marine environment with due emphasis on plankton.

Global warming increases the sea surface temperature (SST) that promotes ice melting, glacier retreat and thermal expansion resulting sea level rise. It also changes the direction of wind & current, precipitation: evaporation ratio, formation of *El-Nino* & *La-Nina*. It makes the water column more stratified that prevents mixing, upwelling & sinking. It alters the monsoons which trigger irregular rains, creation of floods and increase the frequency & intensity of storms and cyclones ultimately affecting the hydrographic properties and nutrient dynamics in Indian seas. Such change in thermal property of sea water and its consequential developments obviously impose catastrophic effects on marine biodiversity, more so the sensitive plankton community. Sea water acidification also has many negative impacts on marine life. It reduces pH of water that brings many visible alterations in chemical properties of the medium directly interfering with the carbonate bicarbonate equilibrium and metabolic functions of the organisms. The plankton populations are very much affected by both these climate change elements.

Although numerous studies have been undertaken on plankton dynamics of Indian seas beginning from the early parts of 20th century[7], our understanding about the response and interaction of plankton to climate change appears to be much less compared to other parts of the world. The reason could be difficulties in reaching to remote areas & abyssal depths, technological short falls and the cost they involve. Of late, however some stress has been given to quantify the climate change scenario and its impact on marine plankton at local and regional scales so as to evolve strategies to mitigate the future risks. In this review, we have elucidated the current climate change scenario of Indian Seas and their impact on plankton.

Marine plankton and their significance

The pelagic components in the sea are broadly divided into three categories namely plankton, nekton and pleuston. The plankton are free floating and drifting, mostly microscopic, organisms moving passively along with the water current. The plant, animal and bacterial fractions of plankton are commonly known as Phytoplankton, Zooplankton & Bacterioplankton respectively[8]. Phytoplankton are the autotrophic component of the plankton community which absorbs radiant energy and convert it to energy rich organic compounds through photosynthesis. They are normally distributed within the lighted surface layers down to a maximum depth of 200m. Most phytoplankton species are microscopic unicellular or colonial algae with size range between 0.4 and 200 µm (Table 1)[9]. Although they share only about 1% of the earth's photosynthetic biomass, they contribute more than 45% of our planet's annual net primary production[10,11]. Phytoplankton thus controls the

Table 1. Classification of plankton into different size-classes

1. Femtoplankton	: 0.02-0.2 µm
2. Picoplankton	: 0.2-2 µm
3. Nanoplankton	: 2-20 µm
4. Microplankton	: 20-200 µm
5. Mesoplankton	: 0.2-20 mm
6. Macroplankton	: 2-20 cm
7. Megaplankton	: 20-200 cm

(Source: Sieburth *et al.*[9], 1978)

trophic dynamics of marine ecosystems, determines the fishery potential of water masses and strongly influenced global biogeochemical cycles[12]. Further, owing to their small size, rapid nutrient uptake ability, faster growth, quick turnover rates, specific growth requirements, susceptibility to grazing and sensitive to environmental disturbances, many species are useful as the indicators of water quality changes[13-15]. Zooplankton comprises of diverse taxonomic groups, representing almost all the animal phyla, on the other hand are heterotrophic denizens with wide size range from a few microns (microzooplankton - ciliates & radiolarians) to some meters (the gigantic jelly fishes) constitute the intermediate steps in food chain. They feed on bacterioplankton, phytoplankton or other zooplankton, detritus matter and at times nektonic organisms too. Although, they are found mainly in surface layers where food is abundant, their distribution is ubiquitous. From ecological point of view, Zooplanktons are considered as the chief index of secondary production by virtue of their sheer abundance and intermediate position in the food chain. The species composition, density and distribution of zooplankton are usually taken as the good indicator of the trophic status of aquatic ecosystems[16]. Any short and long term changes in environmental conditions influence the species composition, diversity, population size, biomass and abundance of both phyto and zooplanktons, and thus are considered as useful tools in predicting the ecosystem.

The present climate change scenario and future predictions

Earth's climate has witnessed tremendous shifts during the past few decades. The changes have been primarily related to (i) global warming due to green house gas (GHG) accumulation in the atmosphere, (ii) ocean acidification caused by excess CO_2 sink in sea water and (iii) ozone depletion in the stratosphere. All these climate change events owe their origin to anthropogenic activities, which promotes the deposition of GHGs such as carbon dioxide, methane, nitrous oxide, carbon monoxide etc in the atmosphere. The GHG emission primarily comes from five sectors, such as energy production, agriculture, industry, vehicular emissions and other sources. Carbon dioxide, the key factor behind global warming and acidification is mainly derived from the burning of fossil fuels and forest fires. The second important GHG behind global warming, the methane, comes from rice fields, while other gases derived mainly from industrial sources. The addition of CO_2 to the atmosphere is on rise globally at an accelerated rate from industrial sector and vehicular emissions. Globally it has increased by about 6% during the last decade. India being a developing country giving importance to growth of industrial and agricultural sectors, the GHG emissions has shown an ascending swing. It has been estimated that the GHG emission in India which was at 1301.21 million tonnes in 2000 rose to 1727.71 million tonnes by 2007[17] and 2100 million tonnes of CO_2 equivalent by 2013 placing it at 4th position among the CO_2 emitting nations in the world[18].

Oceans play a pivotal role in shaping the world climate because they have the largest heat absorbing capacity on the earth. Levitus *et al.*[19] have opined that the net heat uptake by the oceans during the past 50 years was about 20 times higher than the atmosphere. Since marine phytoplankton contributes ~50% of the total global primary production, oceans act as the major sites of CO_2 sink[20]. Thus, it can balance the global warming. Additions of GHG to the atmosphere has increased the global average temperature by about 2°C in the past few decades and most of these added energy is absorbed by sea water resulting 0.6°C temperature rise in upper 600 m[21]. Indian seas also witnessed the impact of global warming. Based on the temperature data of 1904 to 1994, Rupakumar *et al.*[22] have reported that the Northern Indian Ocean has been warmed up by about 0.5°C. According to Vivekanandan[23] the 20th century was the warmest century during the past 1000 years. He further opined that 1990s was the warmest decade and the period between 1998 & 2004 were the warmest years accompanied with of several instances of *El Nino* & *La Nina*. It has been predicted that with the current rate of GHG emission, global warming and ocean acidification are likely to continue bringing more serious implications and risks to marine denizens.

India has experienced remarkable growth in its industrial and agriculture sectors and thereby accelerated the GHG emissions to atmosphere. Dash *et al.*[24] analyzed the meteorological data from 1901 - 2003 and found significant rise in air as well as sea surface temperature over the Indian peninsula. According to their findings the northern and southern sectors of the AS experienced SST rise of about 0.9 and 1.0°C respectively during the last 100 years (Figure 1), whereas the northern and southern sectors of BoB experienced SST rise of 0.8 and 1.0°C (Figure 2).

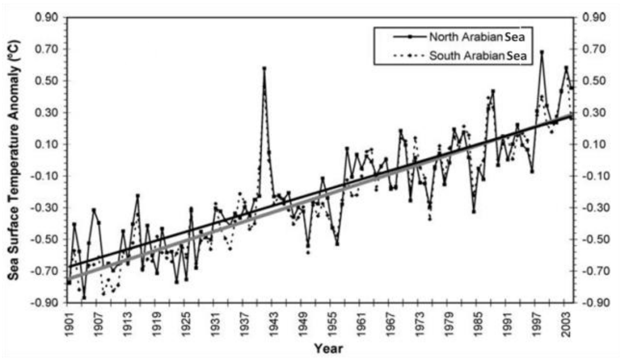

Figure 1. Time series of Sea Surface Temperature (°C) over Arabian Sea (Source: Dash *et al.*[24], 2007)

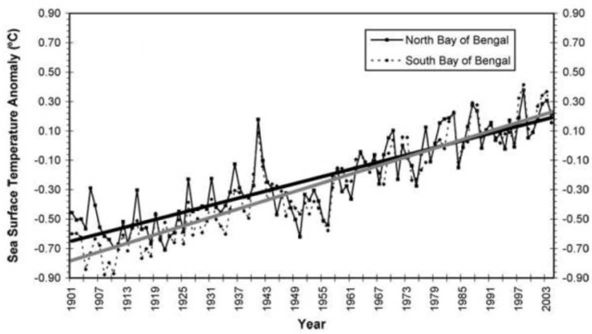

Figure 2. Time series of Sea Surface Temperature (°C) over Bay of Bengal (Source: Dash *et al.*[24] 2007)

The rise in SST was directly linked to the warming of atmosphere by about 1.0-1.1°C. The rise in SST of Indian Seas remained almost similar to the global SST increase reported by Webster *et al.*[25]. However Vivekanandan *et al.*[26] projected the SST rise in Indian seas by about 0.2°C along the northwest, southwest and northeast regions and 0.3°C along the southeast region during 1960-2005 (45 years). They have predicted an annual average SST rise of about 2.0-3.5°C towards the end of 2099[27].

Marine environments in India

India is a maritime country situated in the tropical belt of the Indian Ocean. It is surrounded by the two arms of the northern Indian Ocean, the Arabian Sea (AS) on the west coast and Bay of Bengal (BoB) on the east coast. The Bay of Bengal is a broad U-shaped semi-enclosed landlocked basin whose western margin borders the Indian subcontinent. The other countries of the region are Sri Lanka, Myanmar, Burma, Java, Indonesia, Thailand and Bangladesh. This is a shallow sea (average depth 2,600 m) that occupies an area of about 2.2 million km^2 [Ref.28,29]. From hydrographical view point, the Bay is vertically divided into three layers, the surface layer (0-100m), thermocline layer (100-1000m) and deep sea region (>1000m). The surface layer is characterized by relatively warm, low saline, oxygen and nutrient rich water mass, while the deep sea zone is characterized by more saline and low temperature waters that remain reasonably undisturbed[30]. It is influenced by the two reversible Asian monsoons of India, the southwest monsoon during June-September and northeast monsoon during November-January/February. The spatio-temporal variation of hydrographic features and nutrients in surface layer is more prominent during monsoon season due to massive influx of fresh water into the Bay via different rivers. The Indian segment of the BoB virtually behaves like an estuary during monsoon and post monsoon periods with minimum surface salinity of about 17 ppt[31] with distinct vertical gradient. It has been designated as one of the Large Marine Ecosystems (LME-34) of the world by National Oceanic and Atmospheric Administration (NOAA).

The Arabian Sea on the other hand is a hammerhead-shaped branch of the north-western Indian Ocean connected to a series of gulfs and straits. The countries bordering it other than India are Baharin, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, Somalia, United Arab Emirates and Yemen. It covers an area of about 3.8 million km^2 and its average depth is about 4,652 m. It forms one of the world's most productive regions from tropics. Only two major rivers namely *Tapti* & *Narmada* and some minor rivers pour fresh water into the Indian segment of the AS. Excessive evaporation to precipitation ratio leads to the formation of high surface salinity areas and this high salinity water sink and renew deep waters almost regularly[32]. The water quality and biological productivity of this sea is also affected by Indian monsoons. During summer (June-September) monsoon, the coastal upwelling along Somalia, Arabia and southern part of the Indian west coast, makes the coastal waters a zone of high productivity[33]. The offshore zone of the central AS remains highly productive under the influence of upwelling, wind-driven mixing and lateral advection[34,35]. This sea is also designated as one of the Large Marine Ecosystem (LME-32) of the World.

The coastal realm of India broadly consists of three major categories of ecosystems namely, the gulf ecosystems, coastal ecosystems and Island ecosystems. The prominent gulf ecosystems of BoB are the Gulf of Mannar and those of AS are the Gulf of Kachchh and Gulf of Khambhat. The prominent Island ecosystems in the BoB are Andaman & Nicobar Islands and those in AS are the Lakshadweep & Minicoy Islands. The Exclusive Economic Zone (EEZ) of India stands at 2.02 million km^2. Both the coasts are endowed with extensive areas of estuaries formed near the mouths of 14 major, 44 medium 144 minor rivers and many rivulets debauching huge quantities (~1.62 x 10^{12} m^3/y) of silt borne fresh water into them[36]. The quantum of fresh water input into the BoB is however much more (2950 km^3) compared to AS[37]. The physiography, climatic regime, hydrographic features, nutrient dynamics and biological productivity of these two seas remain quite different from each other[38-40].

The marine and coastal ecosystems associated with the Indian subcontinent are highly productive and constitute one of the richest fishing grounds in Asia. The marine fishery harvest from these two seas exhibited steady increase over the past 60 years. The total harvest has reached to about 3.18 million tonnes in 2009-2010, from about 1.5 lakh tonnes in 1950[41]. Of late, several coastal areas were also brought under brackish water farming and mariculture. Both the coasts are endowed with many diverse marine coastal ecosystems enriched with large varieties of flora and fauna providing ample socio-economic benefit to coastal populations. The environmental situations of these seas however have witnessed visible signs of environmental degradation as a result of anthropogenic interventions like addition of chemical pollutants, overfishing and reclamation of wetlands for urbanization, aquaculture and other activities. The recently known anthropogenic climate changes, especially global warming and surface water acidification had also affected them critically threatening the sustenance of their biodiversity, more so the plankton.

Climate change effect on plankton

Phytoplankton primary production accounts for about 95% of global marine primary productivity and therefore any change in composition and abundance of phytoplankton is bound to affect the overall functioning of ecosystems and their biogeochemical activities. Zooplankton as secondary and tertiary producers too play crucial role in transfer of food energy from producers to top level consumers. Both phytoplankton and zooplankton species respond quickly to the changes in the physical, chemical and biological attributes of their ambiance. Hence they are immediate victims of the climate change and therefore changes in composition and distribution of plankton is often used as a good marker of climate change. Gregg *et al.*[42] have opined that the annual primary production of world's oceans had decreased by about 6% since 1980s in which nearly 70% occurred at high latitudes within the Pacific and Indian Ocean gyres. The species composition of phytoplankton communities, their phenology and productivity had changed in response to warming, acidification and stratifications in oceans[43,44].

Hays *et al.*[45] have elaborately discussed the interactions between climate change and plankton with due emphasis to the changes in species diversity, abundance, distribution and phenology. They also examined the impacts of the changes in plankton on commercial fish stocks and roles of plankton in dictating the pace of climate change via feedback mechanisms of elevated CO_2 concentrations. They opined that both phyto and zooplankton could serve as good indicators and measures of climate change because: (i) unlike intertidal benthos and pelagic nektons, only a few species are commercially exploited and as such, any long term change in the community structure of plankton can safely be attributed to climate change; (ii) most of the plankton species are short lived with quick turnover rates and hence their population size remains less influenced by the persistence of individuals of previous years; (iii) they use to respond quickly to the changes in environmental parameters and (iv) exhibit spectacular changes in their distribution with ability to contract and expand geographically based on their affinity to temperature, salinity and oceanic current. The research findings of recent years have confirmed the occurrence of systematic changes in plankton abundance and community structure in several parts of world oceans, for example the shifts in the abundance of mesozooplankton in the productive upwelling areas of Benguela[46] and California coast[47] were linked to climate change. The shift in the timing of *Neocalanus plumuchrus* abundance in north subarctic Pacific was also endorsed to change in SST[48]. The 1000 km northward shift of the warm water calanoid copepods in North Atlantic Ocean was reported as the consequence of warm water assemblages replacing the cold water[49,50]. Atkinson *et al.*[51] had attributed the sharp decline in Antarctic Krill population of preceding 25 years to reduced phytoplankton blooms in summer and ice algae in winter. The reduction in plankton production followed by fall in fisheries catch in Humboldt Current was ascribed to ENSO (*El-Nino* Southern Oscillation), a phenomenon developed due to global warming[52]. The inter-annual variability of North Sea jellyfish during 1971-1986 was ascribed to the North Atlantic Oscillation linked to SST rise[53]. Barnard *et al.*[54] have reported the expansion of *Ceratium trichoceros* from the tropical and temperate waters to warmer waters justifying the impact of SST. They observed that *C. trichoceros* which was restricted to south of UK, had shown its presence to west coast of Scotland and the northern North Sea coupled with the global warming induced SST rise.

Experimental results with seven species of phytoplankton of Indian seas had shown: (i) faster rate of cell multiplication yielding high population density at higher temperature (29°C) as compared to lower temperature (24°C), (ii) decaying rate of cells on day 10 at 29°C as against on day 12, at 24°C and (iii) difference in dominance of species at different temperatures[55]. This denotes that change in temperature affects the growth rate, species composition, population size and longevity of marine phytoplankton in Indian seas.

The spring outbursts of some phytoplankton species in Indian Seas of the past few decades were mainly attributed to nutrient enrichment in surface layers that could occur either due to localised upwelling and/or exogenous supply of nutrients from land sources[56-59]. The *Red tide* incidents due to blooms of nitrogen fixing cyanobacteria *Trichodesmium sp* in the Arabian Sea were ascribed to surface layer warming and optimal light availability rather than nutrient enrichment[60,61]. Padmakumar *et al.*[62] had documented significant increase in the frequency, intensity and spatial coverage of phytoplankton blooms in Indian EEZ on decadal basis since 1900. The blooming incidents were less and steady during 1900-1950 and sharp increase was noticed between 1998 & 2015[62-65] (Figure 3).

As many 80 blooming cases viz. 31 dinoflagellates, 27 cyanobacteria, 18 diatoms, 3 raphidophyte and 1 haptophyte were recorded during 1998-2010. Of the various factors responsible for bloom formation SST rise (ca. 0.2°C) and thermal stratification considered more significant, probably favoured for blooming of *Trichodesmium erythraeum* in AS. *Trichodesmium erythraeum* bloom in AS usually occurs during premonsoon period when the surface water remains warm, brilliant sunlight is available and hydrographic condition is stable even nitrogenous nutrient is deficient[66,67] as reported from other parts of the world[68,69]. The rise in SST and its consequential events like stratifications under the influence of global warming is therefore believed to have triggered the blooming incidents of *Trichodesmium erythraeum* in these periods. Another major finding relating to impact of climate change on phytoplankton of the AS is massive outbreaks of *Noctiluca scintillans* bloom replacing some diatom species. Gomes *et al.*[70] found that a radical shift in the composition of winter phytoplankton blooms in the northern AS. Many trophically important diatom species in nutrient-rich waters during winter were replaced by the green dinoflagellate *Noctiluca scintillans*.

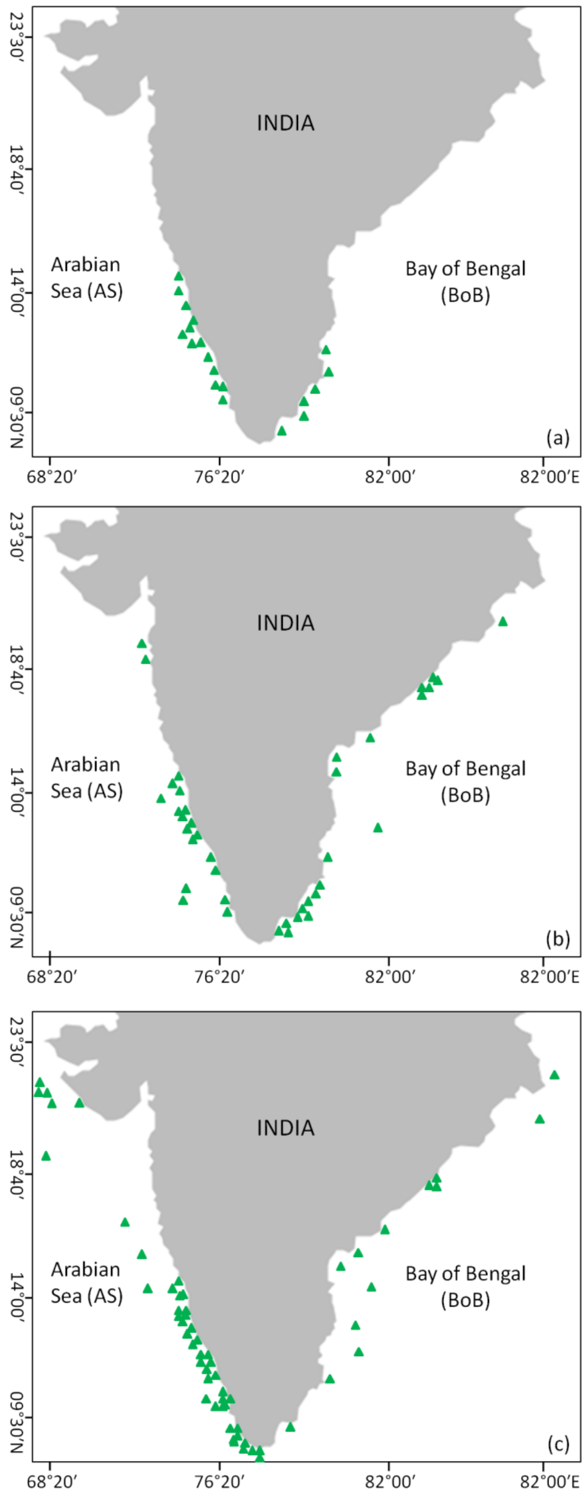

Figure 3. Phytoplankton blooms in Indian Seas (a) 1917-1957 (b) 1958-1997 (c) 1998-2015 (Source:Ref[62-65])

This change in bloom forming components had found to have visibly disrupted the diatom-sustained food chain causing damage to the regional fisheries. The shifts in bloom forming species were related to spread of oxygen minimum zones[70] that could be directly or indirectly related to global warming.

The shift in the phytoplankton community structure, especially changes in species diversity bound to influence on higher trophic levels because phytoplankton serve as direct food to many species and also there exists species specificity in predator-prey interrelations. Godhantaraman[71] have investigated the impacts of climate variability and changes on the diversity and trophic structure of plankton in an estuarine system of South India. This long-term study spanning over 20 years (1988-2008) showed discernible changes in species distribution, abundance and community shifts in coastal marine plankton in response to climate variability. A comparative analysis of phytoplankton composition and abundance in the Sundarban mangrove ecosystem was investigated by Biswas *et al.*[72] in relation to climate variability. They found strong correlation between phytoplankton abundance and rainfall patterns. The impact of climate change in the Sundarban aquatic ecosystems was assessed by taking phytoplankton as proxies by Bhattacharjee *et al.*[73], which delineated well defined succession of natural phytoplankton assemblages at short temporal gradients in relation to shifts in environmental parameters. The diatom communities are mostly influenced by change in temperature since 1980 onwards with frequent occurrence of some species which were rare in previous studies.

Role of dissolved CO_2 and its consequential events found to have far reaching consequences on plankton community of oceans. When CO_2 levels in atmosphere are increased, most part of it gets dissolved in sea water. The enhanced levels of dissolved CO_2 effects carbonate - bicarbonate equilibrium leading more amount of bicarbonate making the water acidic thereby reducing pH. The anthropogenic emissions of CO_2 have resulted significant changes in atmospheric CO_2 concentration during past few decades. It rose to about 398 ppm in 2014 from the pre-industrial level 280 ppm reducing the pH by about 0.12 units. Jacoboson[74] have reported the fall of pH in sea water from 8.25 to 8.14 due to CO_2 additions during 1751 to 1994. It has been predicted that the increase in CO_2 level shall continue in future and as such the sea water pH may fall further by about 0.3 pH units towards the end of this century[75]. The increased CO_2 concentration in the atmosphere followed by reduction in pH of sea water is likely to affect the marine plankton in many ways. The increased dissolved CO_2 in sea water found to enhance the rate of phytoplankton photosynthesis by about 40-200%[76] and thus can act as sink of CO_2. Again, the production of $CaCO_3$ through calcification by some Cocolithophores will leave CO_2 in sea water. It could be so because, in calcification process bicarbonate is normally preferred over CO_2. This will serve as source of CO_2 to the medium water through negative feedback. These ecological and biogeochemical interactions among the calcifying and non calcifying plankton will affect the CO_2 levels in the water there by the plankton primary production.

Biswas *et al.*[77] studied the response of phytoplankton to elevated CO_2 concentration in Godavari river estuary. They observed higher concentrations of total chlorophyll, phytoplankton growth rate, particulate organic matter, photosynthetic oxygen evolution and total bacterial count under elevated CO_2 treatments. This study had suggested that CO_2 concentration coupled with nutrient supply had significant effects on phytoplankton community. Subsequently, Biswas *et al.*[78] have studied the effect of elevated levels of CO_2 on microzooplankton. The tintinnids (microzooplankton) have responded positively to elevated CO_2 levels suggesting that increased abundance of tintinnids at high CO_2 levels could have significant influence in the nutrient biogeochemistry of the coastal waters of the BoB. Biswas *et al.*[79] had observed that the phytoplankton communities dominated by diatoms perform better as regards to CCMs (carbon concentration mechanisms) under low CO_2 conditions and the process could be suppressed with the increasing levels of CO_2. Thus plankton community derives benefit from the increasing CO_2 levels. Bhattacharya *et al.*[80] studied the long-term decadal change in copepod community in coastal waters of Sunderban mangrove wetland. They noticed pronounced decadal change in zooplankton community composition along with their feeding guilds. The other note worthy finding was that some copepod species reported in 1980s were totally absent in recent years, which they attributed to the sharp changes in environmental variables and changes in biological interactions like predation, competition and feeding habits. According to the studies of Sarkar[81] in mangrove wetland, climate change effect on microzooplankton would have adverse impacts on phytoplankton community and herbivorous copepods and thus affecting ecosystem services.

Conclusions

The oceans had experienced visible changes in their physical, chemical and biological properties under the influence of anthropogenic climate change such as global warming and sea water acidification. Prominent physical changes are marked by rise in SST, stratification, change in direction and pattern of wind driven currents. Prominent change in chemical properties included increase in CO_2 contents in sea water and fall in pH. The rise in SST and reduced pH severely interfered with many chemical and biochemical interaction affecting a range of marine life in which plankton and corals are the worst victims. Both the phytoplankton and zooplankton populations of Indian seas seems to be significantly influenced by the altered physico-chemical properties like SST rise, increase in CO_2 concentration, stratification and influx of fresh water as a result of floods & droughts. Marked changes in species composition, abundance and phenology of plankton populations, especially tremendous shifts in frequency and intensity of phytoplankton blooms encountered were attributable to global warming and sea water acidification.

Acknowledgements

Authors wish to place in record their thanks to the Head of the Department of Marine Sciences for encouragement. PP acknowledges the financial support in term of fellowship provided by DST, Govt. of India under INSPIRE Fellowship programme. BKS thanks DST, Government of India for the SERB-NPDF fellowship (PDF/2017/000522).

References

1. Le Treut, H., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson, T., Prather, M., Historical Overview of Climate Change. In: *Climate Change, The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Solomon et al., Cambridge University Press, 2007
2. Dudley, W., Biodiversity, Greenhaven Press, USA, 2002, pp.224
3. Hoegh-Guldberg, O., Bruno, J.F., The impact of climate change on the world’s marine ecosystems. *Science*, 328(2010) 1523–1528
4. Intergovernmental Panel on Climate Change. Impacts, Adaptation and Vulnerability summary for policy makers. IPCC Working Group II, In: *Fourth Assessment Report*, 2007, pp.16
5. Costanza, R., Folke, C., Valuing ecosystem services with efficiency, fairness and sustainability as goals. In: Daily G, editor. Nature’s services: societal dependence on natural ecosystems. Washington, DC: Island Press. 1997, pp.49–70
6. Field, J.G., Hempel, G., Summerhayes, C.P., (Ed.), In: *Oceans 2020: Science, Trends, and the Challenge of Sustainability*. Island Press, Washington D.C. 2002, pp.365
7. Sewell, R.B.S., Notes on Plankton from the Chilka Lake. *Rec. Ind. Mus.*, IX(1913), Miscellanea, p. 338
8. Parsons, T.R.K., Takahashi, M., Hargrave, B.T., Biological oceanographc processes, 2nd edn. Pergamon Press, Oxford, 1977
9. Sieburth, J.M., Smetacek, V., Lenz, J., Pelagic ecosystem structure: Heterotrophic compartments of the plankton and their relationship to plankton size fractions. *Limnol. Oceanogr.*, 23(1978) 1256-1263
10. Field, C.B., Behrenfeld, M.J., Randerson, J.T., Falkowski, P., Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components. *Science*, 281(1998) 237-240
11. Bowler, C., Karl, D.M., Colwell, R.R., Microbial oceanography in a sea of opportunity. *Nature*, 459(2009) 180-184
12. Katz, M.E., Finkel, Z.V., Grzebyk, D., Knoll, A.H., Falkowski, P.G., Evolutionary trajectories and biogeochemical impacts of marine eukaryotic phytoplankton. *Annu. Rev. Ecol. Evol. Syst.*, 35(2004) 523–556
13. Pearl, B.W., Nuisance phytoplankton blooms in coastal, estuarine and inland waters. *Limnol. Oceanogr.*, 33(1988) 823-847
14. Reynolds, C.S., Padisak, J., Sommer, U., Intermediate disturbance in the ecology of phytoplankton and the maintenance of species diversity: a synthesis. *Hydrobiologia*, 249(1993) 183-188
15. Stolte, W., Mccollin, T., Noordeloos, A., Riegman, R., Effect of nitrogen-source on the size distribution within marine-phytoplankton populations. *J. Exp. Mar. Biol. Ecol.*, 184(1994) 83–97
16. An, X.P., Du, Z.H., Zhang, J.H., Li, Y.P., Qi, J.W., Structure of the zooplankton community in Hulun Lake, China. *Procedia Environ. Sci.*, 13(2012) 1099–1109
17. MoEF Annual report, Government of India, New Delhi, 2010, pp.295
18. Olivier, J.G.J., Janssens-Maenhout, G., Muntean, M., Peters, J.A.H.W., Trends in global CO_2 emissions; 2014 Report, The Hague: PBL Netherlands Environmental Assessment Agency; Ispra: European Commission, Joint Research Centre, 2014
19. Levitus, S., Antonov, J., Boyer, T. Warming of the World Ocean, 1955-2003. Geophys. Res. Lett., 32(2005) L02604
20. Falkowski, P.G., Raven, J.A., Aquatic Photosynthesis. Princeton University Press, Princeton, 2007, pp.488
21. Pachauri, R.K., Reisinger, A., Climate Change: Synthesis Report, IPCC, Geneva, Switzerland, 2007, pp.104
22. Rupakumar, R., Krishnakumar, K., Ashrit, R.G., Patwardhan, S.K., Pant, G.B., Climate Change in India: observations and model projection. In: Shukla et al., (Eds) Climate Change and India: Issues, Concerns and Opportunities Tata McGraw Hill Publishing Company Limited, New Delhi, 2002
23. Vivekanandan, E., Oceanic and deep-sea fisheries of India. In: Handbook of Fisheries and Aquaculture Indian Council of Agricultural Research, New Delhi, 2006, pp.93-105
24. Dash, S.K., Jenamani, R.K., Kalsi, S.R., Panda, S.K., Some evidence of climate change in twentieth-century India. *Clim. Change.*, 85(2007) 299–321

25. Webster, P.J., Holland, G.J., Curry, J.A., Chan, H.R., Changes in tropical cyclones number, duration and intensity in a warming environment. *Science*, 309(2005) 1844–1846
26. Vivekanandan, E., Rajagopalan, M., Pillai, N.G.K., Recent trends in sea surface temperature and its impact on oil sardine. In: Aggarwal, P.K. (Ed) *Impact, Adaptation and Vulnerability of Indian Agriculture to Climate Change*, Indian Council of Agricultural Research, New Delhi, 2009a, pp 89-92
27. Vivekanandan, E., Ali, M.H., Jasper, B., Rajagopalan, M., Vulnerability of corals to warming of the Indian seas: a projection for the 21st century. *Curr. Sci.*, 97(2009b) 1654-1658
28. LaFond, E.C., Fairbridge, K.W., In: *Bay of Bengal, (Eci.), The Encyclopedia of Oceanography*, Van Nostrand Reinhold Co., New York, 1966, pp.110-118
29. Unger, D., Ittekkot, V., Schafer, P., Tiemann, J., Reschke, S., Seasonality and interannual variability of particle input and oceanographic processes. *Deep-Sea Res Pt II*, 50(2003) 897-923
30. Dwivedi, S.N., Choubey, A.K., Indian Ocean Large Marine Ecosystems: Need for National and Regional Framework for Conservation and Sustainable Development. In: *Large Marine Ecosystems of the Indian Ocean*, Blackwell Publishing Co., 1998, pp.361-368
31. Ganapati, P.N., Rao, T.S.S., Some remarks on hydrography and Biology of the Bay of Bengal. *J. Mar. biol. Ass. India*, 1(1959) 224-227
32. Dietrich, G., The unique situation in the environment of the Indian Ocean. In: Zeitzschel, B. (Eds.) *The Biology of the Indian Ocean*. Springer, Berlin, 1973, pp.1-6
33. Prasanna Kumar, S., Muraleedharan, P.M., Prasad, T.G., Gauns, M., Ramaiah, N., deSouza, S.N., Sardesai, S., Madhupratap, M., Why is the Bay of Bengal less productive during summer monsoon compared to the Arabian Sea?. *Geophys. Res. Lett.*, 29(2002) 2235
34. Lee, C.B., Jones, K.B., Fischer, A., The upper-ocean response to monsoonal forcing in the Arabian Sea: seasonal and spatial variability, *Deep-Sea Res Pt II*, 47(2000) 1177-1226
35. Prasanna Kumar, S., Madhupratap, M., Dileep Kumar, M., Muraleedharan, P.M., deSouza, S.N., Gauns, M., Sarma VVSS, High biological productivity in the central Arabian Sea during summer monsoon driven by Ekman pumping and lateral advection. *Curr. Sci.*, 81(2001) 1633 – 1638
36. UNESCO, River inputs to the ocean systems: status and recommendations for research. UNESCO Technical papers in Marine Science, No. 55, Final Report of the SCOR Working group 46, Paris, 1988, pp.25
37. Sooria, P.M., Reny, P.D., Jagadeesan, L., Nair, M., Influence of river influx on phytoplankton community during fall inter-monsoon in the coastal waters of Kakinada, east coast of India. *Indian J. Mar. Sci.*, 40(2011) 550-558
38. Qasim, S.Z., Biological productivity of the Indian Ocean. *Indian J. Mar. Sci.*, 6(1977) 122-137
39. Sengupta, R., Qasim, S.Z., The Indian Ocean - an environmental overview. In: The Oceans- Realities and Prospects, edited by Sharma, R.C., Rajesh Publications, New Delhi. 1985, pp.7-40
40. Gauns, M., Madhupratap, M., Ramaiah, N., Jyothibabu, R., Fernandes, V., Paul, J.T., Prasanna Kumar, S., Comparative accounts of biological productivity characteristics and estimates of carbon fluxes in the Arabian Sea and the Bay of Bengal. *Deep-Sea Res Pt II*, 52(2005) 2003-2017
41. SydaRao, G., CMFRI achieves maiden success in the finfish breeding of pompano. ICAR Reporter, July - September, 2011, pp.13
42. Gregg, W., Conkright, M., Ginoux, P., OReilly, J., Casey, N., Ocean primary production and climate: Global decadal changes. *Geophys. Res. Lett.*, 30(2003) 1809
43. Doney, S.C., Fabry, V.J., Feely, R.A., Kleypas, J.A., Ocean acidification: the other CO_2 problem. *Ann. Rev. Mar. Sci.*, 1(2009) 169–92
44. Polovina, J., Uchida, I., Balazs, G., Howell, E.A., Parker, D., Dutton, P., The Kuroshio Extension Bifurcation Region: a pelagic hotspot for juvenile loggerhead sea turtles. *Deep-Sea Res Pt II*, 53(2006) 326–339
45. Hays, G.C., Richardson, A.J., Robinson, C., Climate change and marine phytoplankton. *Trends Ecol. Evolut.*, 20(2005) 337-344
46. Verheye HM, Richardson AJ, Hutchings L, Marska G, Gianakouras D, 1998. Long-term trends in the abundance and community structure of coastal zooplankton in the southern Benguela system, 1951- present. *S. Afr. J. Mar. Sci.*, 19: 317–332.
47. Roemmich, D., McGowan, J., Climatic warming and the decline of zooplankton in the California. *Curr. Sci.* 268(1995) 352–353
48. Mackas, D.L., Goldblatt, R., Lewis, A.G., Inter decadal variation in developmental timing of *Neocalanus plumchrus* populations at Ocean Station in the subarctic North Pacific Ocean. *Can. J. Fish. Aquat. Sci.*, 55(1998) 1878–1893
49. Beaugrand, G., Reid, P.C., Ibañez, F., Lindley, J.A., Edwards, M., Reorganization of North Atlantic marine copepod biodiversity and climate. *Science*, 296(2002) 1692–1694
50. Beaugrand, G., Reid, P.C., Long-term changes in phytoplankton, zooplankton and salmon related to climate. *Global Change Biol.*, 9(2003) 801–817
51. Atkinson, A., Siegel, V., Pakhomov, E., Rothery, P., Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature*, 432(2004) 100–103
52. Alheit, J., Niquen, M., Regime shifts in the Humboldt Current ecosystem. *Prog. Oceanogr.*, 60(2004) 201–222
53. Lynam, C.P., Hay, S.J., Brierley, A.S., Inter annual variability in abundance of North Sea jellyfish and links to the North Atlantic Oscillation. *Limnol. Oceanogr.*, 49(2004) 637–643
54. Barnard, R., Batten, S.D., Beaugrand, G., et al., Continuous plankton records: plankton atlas of the North Atlantic Ocean (1958–1999). II. Biogeographical charts. *Mar. Ecol. Prog. Ser.* (Suppl.), 2004 11-75.
55. Vivekanandan, E., Marine Fisheries Policy Brief-3; Climate change and Indian Marine Fisheries, In: CMFRI Special Publication 105(2011) pp.1-97
56. Panigrahy, R.C., Gouda, R., Occurrence of bloom of the diatom *Asterionella glacialis* (Castracane) in the Rushikulya estuary, East Coast of India. *Mahasagar Bull. Natl. Inst. Oceanogr.*, 23(1990) 179-182
57. Mishra, S., Sahu, G., Mohanty, A.K., Singh, S.K., Panigrahy, R.C., Impact of the diatom *Asterionella glacialis* (Castracane) bloom on the water quality and phytoplankton community structure in coastal waters of Gopalpur Sea, Bay of Bengal. *Asian J. Water Environ. Pollut.*, 3(2006) 71-77
58. Mohanty, A.K., Satpathy, K.K., Sahu, G., Sasmal, S.K., Sahu, B.K., Panigrahy, R.C., Red tide of *Noctiluca scintillans* and its impact on the Coastal Water Quality of the Near-shore waters of the Rushikulya River, Bay of Bengal. Curr. Sci., 93(2007) 616-617

59. Padmakumar, K.B., Sanjeevan, V.N., Menon, N.R., Potentially harmful dinoflagellates of the Indian EEZ. In: *Marine Ecosystems Challenges and Opportunities*. Book of Abstracts, Marine Biological Association of India, 2009, pp.154-156
60. Devassy, V.P., Bhattathiri, P.M.A., Qasim, S.Z., *Trichodesmium* phenomenon. *Indian J. Mar. Sci.*, 7(1978) 168–186
61. Matondkar, S.G.P., Parab, S.G., Desa, E., Dwivedi, R.M., Basin scale distribution of *Trichodesmium* spp. in the Arabian Sea using Oceansat I/OCM. . In: Robert JF et al. (eds.) *Remote Sensing of the Marine Environment*. Proc SPIE Vol. 6406(2006) 64060V1-10.
62. Padmakumar, K.B., Menon, N.R., Sanjeevan, V.N., Is Occurrence of Harmful Algal Blooms in the Exclusive Economic Zone of India on the Rise?. *Int. J. Oceanogr.*, Article ID 263946, 2012, pp.1-7.
63. D'Silva, M.S., Anil, A.C., Naik, R.K., D'Costa, P.M., Algal blooms: a perspective from the coasts of India. Nat. Hazards, 63(2012) 1225–1253
64. Biswas, S.N., Godhantaraman, N., Sarangi, R. K., Bhattacharya, B. D., Sarkar, S. K. and Satpathy, K. K. (2013), Bloom of *Hemidiscus hardmannianus* (Bacillariophyceae) and Its Impact on Water Quality and Plankton Community Structure in a Mangrove Wetland. Clean Soil Air Water, 41: 333–339
65. Sulochanan, B., Dineshbabu, A.P., Saravanan, R., Bhat, G.S., Lavanya S., Occurrence of *Noctiluca scintillans* bloom off Mangalore in the Arabian Sea. *Indian J. Fish.*, 61(2014) 42-48
66. Qasim, S.Z., Some characteristics of a Trichodesmium bloom in the Laccadives. *Deep-Sea Res.*, 17(1970) 655-660
67. Padmakumar, K.B., Algal blooms and zooplankton standing crop along the South West coast of India, Ph.D. thesis, Cochin University of Science and Technology, Kerala, India. 2010, pp.260
68. Suvapepant, S., *Trichodesmium* blooms in Gulf of Thailand. In: E.J. Carpenter (Ed), *Marine Pelagic Cyanobacteria: Trichodesmium and other diazotrophs*. Kluwer Academic Press, 1992, pp.343-348
69. Sellner, K.G., Physiology, ecology and toxic properties of marine cyanobacteria blooms. *Limnol. Oceanogr.*, 42(1997) 1089-1104
70. Gomes, H.R., Goes, J.I., Matondkar, S.G.P., Buskey, E.J., Basu, S., Parab, S., Thoppil, P., Massive outbreaks of *Noctiluca scintillans* blooms in the Arabian Sea due to spread of hypoxia. *Nat. Commun.*, 5(2014) 4862
71. Godhantaraman, N., Impacts of climate variability and change on marine plankton communities in tropical coastal ecosystems, South India. Paper presented at the symposium on Climate change: Global risks, challenges and decisions. Copenhagen. 2009
72. Biswas, H., Dey, M., Ganguly, D., De, T.K., Ghosh, S. and Jana, T.K., Comparative analysis of phytoplankton composition and abundance over a two decade period at the land–ocean boundary of a tropical mangrove ecosystem. *Estuar. Coast.*, 33(2010) 384-394
73. Bhattacharjee, D., Samanta, B., Danda, A., Bhadury, P., 2013. Impact of Climate Change in the Sundarban Aquatic Ecosystems: Phytoplankton as Proxies. In: Sundaresan et al. (eds.), *Climate Change and Island and Coastal Vulnerability*, Springer Netherlands, 2013, pp.126-140
74. Jacobson, M.Z., Studying ocean acidification with conservative, stable numerical schemes for nonequilibrium air-ocean exchange and ocean equilibrium chemistry, *J. Geophys. Res.*, 110(2005) D07302
75. Riebesell, U., Effects of CO_2 enrichment on marine phytoplankton. *J. Oceanogr.*, 60(2004) 719–729
76. Schippers, P., Lurling, M., Scheffer, M., Increase of atmospheric CO_2 promotes phytoplankton productivity. *Ecol. Lett.*, 7(2004) 446–451
77. Biswas, H., Cros, A., Yadav, K., Ramana, V.V., Prasad, V.R., Acharyya, T., Babu, P.V., The response of a natural phytoplankton community from the Godavari River Estuary to increasing CO_2 concentrations during the pre-monsoon period. *J. Exp. Mar. Biol. Ecol.*, 407(2011) 284–293
78. Biswas, H., Gadi, S.D., Ramana, V.V., Bharathi, M.D., Priyan, R.K., Manjari, D.T., Dileep Kumar, M., Enhanced abundance of Tintinnids under elevated CO_2 level from coastal Bay of Bengal. *Biodiversity Conserv.*, 21(2012) 1309-1326
79. Biswas, H., Rahman Shaik, A., Bandyopadhyay, D., Preliminary evidences of CCM operation and its down regulation in relation to increasing CO_2 levels in natural phytoplankton assemblages from the coastal waters of Bay of Bengal. EGU General Assembly, held 27 April - 2 May, 2014 in Vienna, Austria, id. 336, 2014
80. Bhattacharya, B.D., Hwang, J.S., Sarkar, S.K., Rakhsit, D., Murugan, K., Tseng, L.C., Community structure of mesozooplankton in coastal waters of Sundarban mangrove wetland, India: A multivariate approach. *J. Mar. Syst.*, 141(2015) 112–121
81. Sarkar, S.K., Loricate ciliate tintinnids in a tropical mangrove wetland: diversity, distribution and impact of climate change. Springer International Publishing, 2015, pp.106