A DECADE OF PHYSICAL AND BIOGEOCHEMICAL MEASUREMENTS IN THE NORTHERN INDIAN OCEAN

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1. ABSTRACT

The northern Indian Ocean consists of two tropical basins (Arabian Sea and Bay of Bengal) and the equatorial region that comes under the influence of monsoonal wind reversal. We present the results from three Indian programmes since 1992 aimed at understanding the seasonal variability of physical and biogeochemical parameters. The results showed strongest seasonal cycle in the Arabian Sea with blooms during summer and winter. Upwelling, advection and wind-mixing drive the summer bloom, while the winter bloom was due to convective-mixing. In the Bay of Bengal mesoscale eddies enhanced the biological productivity. The data collected so far suggest very low chlorophyll biomass and productivity in the equatorial Indian Ocean. Though our understanding of the coupling between the physical and biogeochemical fields in the northern Indian Ocean over the seasonal scale have enhanced tremendously, a sustained regional observational network including repeat sections, moored arrays and drifters is needed for understanding the climate variability.

2. INTRODUCTION

The northern Indian Ocean consists of two tropical basins – the Arabian Sea and the Bay of Bengal – and the equatorial region, which comes under the influence of strong monsoonal wind reversal. In response to this forcing, the upper ocean circulation and hydrography show strong seasonality. Northern Indian Ocean is a very special region from the biogeochemical perspective as all the 3 regions have distinct biogeochemical characteristics. For example, the Arabian Sea (AS), in the western part of the north Indian Ocean houses one of the most productive regions of the world's ocean as well as intense oxygen minimum and denitrification zones [1,2]. In contrast, the Bay of Bengal (BoB), in the eastern part of the north Indian Ocean is biologically a low productive region having a comparatively thinner and less intense oxygen minimum zone with no evidence of denitrification [3,4]. However, the equatorial Indian Ocean (EIO), neither have intense oxygen minimum zone nor denitrification [5].

It was the International Indian Ocean Expedition (IIOE) during 1959 to 1965 that provided the first description of the physical, chemical [6] and biological [7] characteristics of this region. Since then there have been several observational campaigns, both by individual nations as well as through international collaborative efforts, which contributed towards furthering our understanding of the biogeochemistry of this region. The availability of satellite remote sensing data further enhanced our understanding of the basin-wide structure and its variability.

3. DATA

In this paper we present the results from 3 national programmes that India under took onboard its research ships ORV *Sagar Kanya* and FORV *Sagar Sampada* to address the seasonal variability of physical and biogeochemical parameters since 1992 – (1) the Joint Global Ocean Flux Studies (JGOFS) during 1992-1997 in the Arabian Sea, (2) the Bay of Bengal Process Study (BOBPS) during 2001-2006 and (3) the Equatorial Indian Ocean Process Study (EIOPS) which started in 2005 and will continue until 2012 (For cruise details see Tab. 1 and for location see Fig.1a). The uniqueness of these programmes was that co-located physical and biogeochemical parameters were/are being collected using clean techniques following JGOFS Protocol [8] including *in situ* incubation for primary productivity measurements. The data from the above programmes have revealed several new insights about the coupling between the physical forcing and biogeochemical response in the northern Indian Ocean (see for example [9] and the references therein; [10] and the references therein; [11] and the references there in).

4. RESUTLS

The basin-averaged remotely sensed chlorophyll pigment concentrations showed that the Arabian Sea was the most productive region in the northern Indian Ocean followed by the Bay of Bengal and the equatorial Indian Ocean (Fig.1b). The results from the *in situ* physical and biogeochemical measurements in the Arabian Sea showed strongest seasonal cycle with high chlorophyll biomass as well as productivity occurring during summer (June-September) followed by winter (November-February) (Fig.1c). The spring intermonsoon, however, showed the least chlorophyll biomass and productivity. During summer monsoon the upwelling along the coasts of Somalia, Arabia and the southern part of the west coast of India brings cool and nutrient rich waters to the surface which triggers phytoplankton blooms. In addition to this, the cyclonic wind stress curl north of the Findlater Jet which becomes active during summer drives an upward Ekman pumping and supplies subsurface nutrients to the euphotic zone (see the shoaling of thermocline and nitracline in Fig.1d). The advection of nutrient rich waters from the upwelling regions into the central Arabian Sea along with wind-driven mixing under the influence of strong monsoon winds are other physical processes that supply nutrients to the upper layers of the Arabian Sea during summer [12]. Thus, the summer blooms in the Arabian Sea are driven by a combination of processes such as upwelling along the coasts of Somalia, Arabia and southern part of the west coast of India, advection from the upwelling region to central Arabian Sea, Ekman pumping associated with the cyclonic wind stress curl north of the Findlater Jet and wind-driven mixing all of which supplies subsurface nutrients to the euphotic zone [11-12].

In winter, northern Arabian Sea is cooled due to reduced incoming solar radiation as well as evaporative cooling under the influence of the dry northeast trade winds from continental origin which enhances evaporation. The enhanced evaporation not only cools the surface waters but also increases the surface salinity. Cooling of surface waters of the northern Arabian Sea along with increased salinity leads to increase of density. This initiates convective mixing and transports nutrients from the upper nutracline to surface layers (see Fig.2b). Thus, winter blooms (Fig.2a) in the Arabian Sea are triggered by the process of winter cooling and convective mixing which supply nutrient to the euphotic zone [13-15].

In the Bay of Bengal the surface chlorophyll biomass showed a weak seasonality (Fig.1b). The chlorophyll biomass as well as the productivity was highest during winter followed by spring inter-monsoon. Unlike the Arabian Sea, the chlorophyll biomass as well as the productivity was the lowest during summer in the Bay of Bengal (Fig.1e). This low productivity in the Bay of Bengal was due to strong stratification of the upper waters (Fig.1f) under the influence of fresh water influx from rivers as well as oceanic precipitation under the monsoon conditions. The low salinity waters during summer increases the stratification of the upper layers and the strong monsoon winds are unable to break this stratification to initiate wind-driven mixing to supply subsurface nutrients to euphotic zone [16]. The oligotrohic upper ocean led to the presence of subsurface chlorophyll maxima (SCM), which was a characteristic feature of the vertical distribution of chlorophyll in all the seasons. Though the surface chlorophyll biomass showed a weak seasonality, the mesoscale eddies played an important role in enhancing the biological productivity through upward-pumping of nutrients (Fig1f) note the doming ISO therms.

In spring intermonsoon eddy-pumping supported comparatively high biological productivity in the Bay of Bengal compared to Arabian Sea. During summer monsoon in spite of the presence of eddies the biological productivity was low. This suggested the possibility of light limitation during summer-falls intermonsoon period when the river discharge is high and carries large amount of sediment load into the Bay of Bengal. During winter, though cooling takes place in the northern Bay of Bengal, it did not lead to winter convection due to the presence of low salinity surface waters. However, away from the influence of low salinity waters, the stratification of the upper layers was weak and the moderate winter monsoon winds were able to initiate wind-mixing and supply nutrients to the euphotic zone (Fig.2d). Thus, wind-driven mixing along with subsurface cyclonic eddies supported the highest biomass and productivity in the Bay of Bengal during winter (Fig.2c). The physical and biogeochemical measurements showed that eddies are ubiquitous in the Bay of Bengal and underscored the role of eddies in enhancing biological productivity [17].

In the EIO, the data collected so far suggest very low chlorophyll biomass and productivity. Deep subsurface chlorophyll maxima (SCM), a characteristic of the EIO, indicated a deeper euphotic zone compared to the Arabian Sea or the Bay of Bengal.

5. CONCLUDING REMARKS

A decade of observational programmes greatly enhanced our understanding of the coupling between the physical and biogeochemical fields in the northern Indian Ocean over the seasonal time scale. Our understanding of the inter-annual and decadal variability still remains to be rudimentary. Efforts are needed to develop a sustained regional observational network through international collaboration which would include repeat sections, moored arrays as well as drifters for understanding the inter-annual, decadal and climate variability.

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Table. 1 Details of the period of seasonal sampling in the Arabian Sea (AS) during 1993-1997 under Joint Global Ocean Flux Study (JGOFS) in the Bay of Bengal during 2001-2006 under Bay of Bengal Process Studies (BOPBS) and in the Equatorial Indian Ocean (EIO) during 2005-2012. SK and SS denote the Indian research ships ORV Sagar Kanya and FORV Sagar Sampada respectively.

Region	**Season**	**Cruise number**	**Sampling period**
Arabian Sea	Spring inter-monsoon	SK-91	12 April - 12 May 1994
	Winter	SK-99	4 Feb - 4 March 1995
	Summer	SK-115	3-25 August 1996 (13-21ºN)
Bay of Bengal	Summer	SK-166	6 July- 2 August 2001
	Fall inter-monsoon	SK-182	14 September - 12 October 2002
	Spring inter-monsoon	SK-191	10 April - 10 May 2003
	Winter	SS-240	25 November 2005 - 7 January 2006
Equatorial Indian Ocean	Spring inter-monsoon	SK-220	10 May - 8 June 2005
	Summer	SK-227	1-29 August 2006

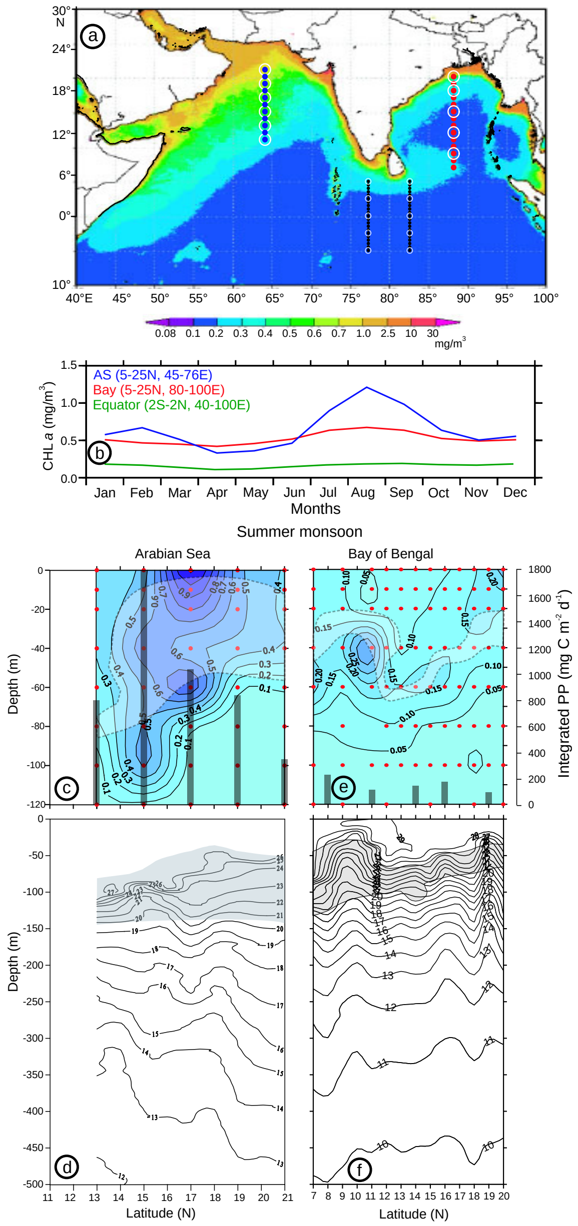

Figure 1. Map showing the (a) station location of CTD (dark circles) and biological (open circles) sampling carried out during JGOFS in the Arabian Sea, BOBPS in the Bay of Bengal and EIOPS in the equatrial Indian Ocean (see text for details). Shading is the annual mean climatology (1998-2008) of chlorophyll pigment concentration (mg/m^3) obtained from SeaWiFS. Map generated by NASA's Giovani (giovani.gsfc.nasa.gov). (b)The basin-averaged monthly mean climatology of chlorophyll pigment concentrations from SeaWiFS. (c & e) Vertical distribution of chlorophyll a (mg/m^3) and (d & f) temperature in the Arabian Sea (c &d) and the Bay of Bengal (e & f) during summer onsoon. The shaded region within the broken line in c & e denotes the region with nitrate concentration of 0.2 to 4 µM and vertical bar is the column integrated (up to 120 m) primary productivity (mg C m^{-2} d^{-1}). The shading in d & f is the region of nitracline with nitrate concentration of 2 to 20 µM.

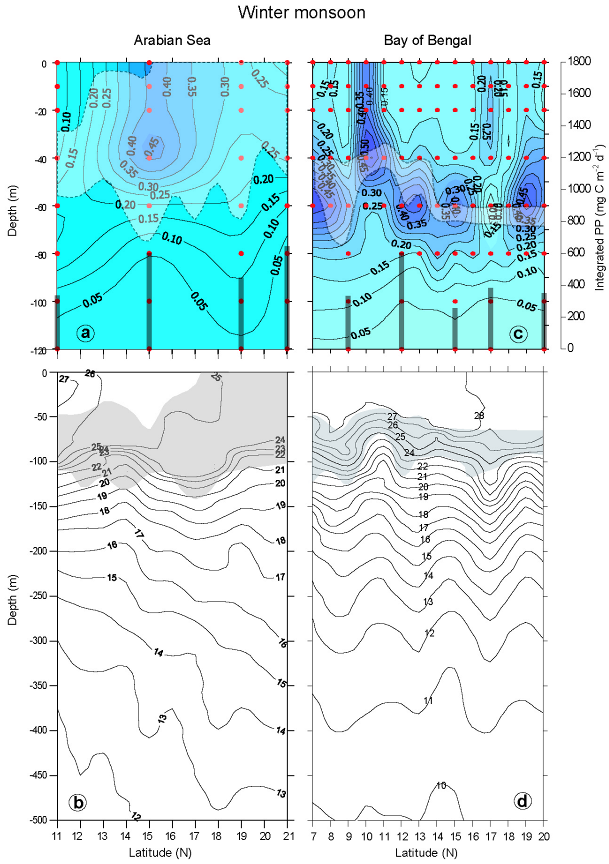

Figure 2. Vetical distribution of chlorophyll a (mg/m^3) (a & c) and temperature (b & d) in the Arabian Sea (a & b) and the Bay of Bengal (c & d) during winter monsoon.The shaded region within the broken line in a & c denotes the region with nitrate concentration of 0.2 to 4 µM and vertical bar is the column integrated (up to 120 m) primary productivity (mgC m^{-2} d^{-1}). The shading in b & d is the region of nitracline with nitrate concentration of 2 to 20 µM.