Is the Arabian Sea getting more productive?

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Recent observations based on ocean colour show that summer productivity in the western Arabian Sea has been increasing during the last seven years, reportedly due to the warming of the Eurasian land mass. Our analysis of eight years' record of satellite ocean colour data over northeastern Arabian Sea suggests that chlorophyll concentration has not changed significantly in this region, and is thrice that in the southeastern part. Although we see some seasonal variations in different parts of the Arabian Sea, a significant secular trend is not discernible. The reported trend in Chl *a* in the western Arabian Sea is not observed in the eastern Arabian Sea. Hence, we conclude that the increasing trend in the western Arabian Sea may not be entirely attributable to global warming.

Keywords: Arabian Sea, chlorophyll concentration, global warming, summer productivity.

THE Arabian Sea is one of the most productive regions in the world[1–5] and is characterized by strong seasonal oscillations in biological production[6]. In summer, the strong southwest monsoon causes intense upwelling in the western Arabian Sea, while in winter surface cooling in the north results in enhanced vertical mixing. In both the above cases the photic zone gets nutrients from below which results in high productivity, i.e. phytoplankton fixes carbon through photosynthesis[7]. The Arabian Sea also has a global significance; the increased production in the above two seasons leads to the formation of oxygen minimum zone (at depths of 150–1000 m) where denitrification takes place[8,9], in the northern part of Arabian Sea. Emission of N_2O as a result of denitrification, which is a potent greenhouse gas, is a cause of concern and has significant implication to the global warming.

During the Indian JGOFS, the Arabian Sea was studied in detail[10] – the biological and chemical properties of the ocean and the physical forcings responsible for the same. However, these studies were limited to a seasonal time span. There is still not much detail about the interannual variability in terms of biological properties. The only possible way to monitor the variation in biological properties of the ocean on a larger spatial scale is by remote sensing[11], a method of collecting information about the constituents of water using optical signals in the visible range. It is well established that the concentration of phytoplankton influences the colour of the ocean water. Chlorophyll *a* (Chl *a*), which is the main photosynthetic constituent in the phytoplankton, absorbs more in blue than in green; as the concentration of phytoplankton increases, the backscattered light progressively shifts towards the green. This property is successfully used to derive the Chl *a* concentration with the help of a satellite. Phytoplankton and sunlight are the fundamental requirements for primary production in the oceans. In the tropics, where variation in sunlight is not significant on an interannual scale, variation in chlorophyll concentration can indicate variation in primary production. Satellite ocean colour data provide the spatial and temporal variations in phytoplankton biomass and hence in the primary production on a larger scale[12]. Since the launch of SeaWiFS (sea-viewing wide field of view sensor) in August 1997, global ocean colour data are available to the science community on a regular basis.

Gregg *et al.*[13] were the first to report an increase in the primary production of northern Indian Ocean (which includes both the Arabian Sea and the Bay of Bengal). This was confirmed by Goes *et al.*[5]. They used satellite data to show that summer productivity in the western Arabian Sea (47°–55°E and 5°S to 10°N; 52°–57°E and 5°S to 10°N) has been increasing, and proposed the cause to be the warming of the Eurasian land mass – the melting of the Himalayan snow cover in the recent past due to global warming resulted in enhancement of the land–sea contrast in summer temperature, thus enhancing monsoon winds. Notably this attribution was not made by Gregg *et al.*[13]. It is known from the literature on palaeomonsoon[14,15] that whenever the southwest monsoon weakened (e.g. at the last glacial *c.* 21,000 years ago), the northeast monsoon strengthened and vice versa. If this is taken in conjunction with the result of Goes *et al.*[5], one would expect a decreasing trend in the winter productivity in the northeastern Indian Ocean. To verify this we have analysed the chlorophyll data over a period of eight years (1997–2005), obtained from SeaWiFS to characterize the interannual variation in the northeastern Arabian Sea, where winter cooling in the north and upwelling in south are prominent, causing an increase in the primary production. To see the variation in the chlorophyll concentrations over the last eight years (from 1997–2005), we have taken monthly composites Level-3 Version 4, 9 km resolution mapped SeaWiFS chlorophyll images. From these images chlorophyll values were obtained using SEADAS software (provided by NASA for ocean colour image processing). SeaWiFS uses OC2 algorithm for deriving Chl *a* values from the recorded radiance. This algorithm[16] overestimates Chl *a* when it is more than 1.5 mg Chl m^{-3}. Sensitivity studies on the algorithm for Chl *a* retrieval from measured sensor-detected radiances show that the retrieved Chl *a* values have the accuracy of ~30% (the radiance has an error of ~1%)[16]. For this analysis, pixels having values more than 5 mg Chl m^{-3} are not considered, but such values are rare.

The seasonality of the northeast Arabian Sea SST (sea surface temperature) is also inspected over the same region

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*For correspondence. (e-mail: satyap@prl.res.in) for the same period in order to analyse the effect of sea-surface cooling due to upwelling on the Chl *a* concentration. Monthly composite SST data are taken from AVHRR (Advanced Very High Resolution Radiometer) pathfinder version 5 (June 1997 to December 2004) and MODIS (Moderate Resolution Imaging Spectroradiometer) data (January 2005 to June 2005). We have also analysed version 3 QuickScat data in order to monitor changes, if any, in wind speed over 7 years (1999–2005).

One of the major limitations of ocean colour remote sensing is that it is sensitive to meteorological conditions. The present sensors used in SeaWiFS and MODIS give abnormal values when cloud cover or some other interference like land, etc. is present. We could not get enough data for June–August because of dense cloud cover in this area.

For the present study, we have divided the eastern Arabian Sea into two zones (Figure 1): zone 1 extends from 20 to 25°N and 62 to 75°E, and zone 2 extends from 20 to 10°N and 62 to 75°E. This division into two different zones is based on the observed physical forcing responsible for high production in each zone. Zone 1 is characterized by high production during winter monsoon (February–March). During this period the cool dry continental air, brought by the northeast trade wind, causes intensification of evaporation, which leads to the surface cooling. This leads to reduction in SST (reduces by up to 4°C) and deepening of the mixed layer[7,17] (deepens up to 100 m). Deepening of the mixed layer brings nutrients into the surface layer from the base of the mixed layer, which increases the productivity (up to 2000 mgC/m^2/day) and hence the sequestration of CO_2 from the atmosphere[7,18].

Zone 2 is characterized by the summer monsoon (June–September) when upwelling along the southwest coast of India[19] is the dominant mechanism that triggers high production in this area[20]. During summer monsoon, because of the surface heating on the continental part, low pressure is created and the wind starts flowing from the ocean towards the land. This wind carries water vapour along with it and causes rainfall. During this season strong upwelling is seen along the coast of Somalia, Arabia and southwestern coast of India. This brings ample nutrients to the surface waters and increases the productivity (up to 1700 mgC/m^2/day) in this region drastically[18].

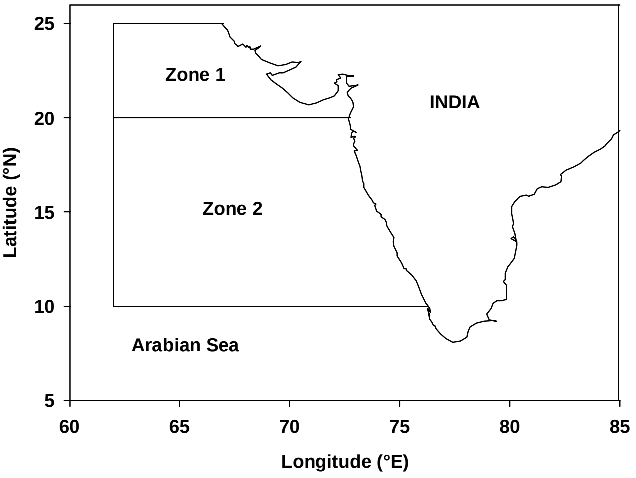

Figure 1. Study area.

Recently, Goes *et al.*[5] have argued using ocean colour data, that productivity in the western Arabian Sea has increased over the last seven years. Our analysis of eight years' record of satellite ocean colour data over northeastern Arabian Sea (Figure 2 *a*), from September 1997 to June 2005, suggests that chlorophyll concentration has not changed significantly in terms of its monthly average value but two seasonal peaks can be seen clearly; one during the winter monsoon (February/March) and the other during summer monsoon (September). There is no monotonic increase in the Chl *a* concentration as reported for the southwest Arabian Sea. On the other hand, the southwest Arabian Sea is not clearly bimodal in chlorophyll peaks.

In zone 1, over the past eight years the chlorophyll concentration has remained more or less similar during October to December (Figure 2 *a*). In most years there is a seasonal increase from January to March. This is because of the input of nutrients from the deeper levels to the surface layer due to the deepening of the mixed layer caused by the winter cooling and convective overturning. Also, wind blowing from the continent to the ocean supplies nutrients and iron dust. According to a pervious study[21], NH_4^+ input was the highest (0.69 ± 0.31 μg/m^3) during the declining phase of the NE monsoon (March). The increased input of nutrients into the photic zone through convective mixing and atmospheric input causes increase in productivity in February/March sometimes leading to blooms. The average Chl *a* concentration in March over the last eight years is 1.45 mg Chl/m^3, the maximum being 1.96 mg Chl/m^3 in 2002 and the minimum 0.92 mg Chl/m^3 in 2004. After March, again Chl *a* concentration starts decreasing till the onset of the summer monsoon. Because of dense cloud cover, little data is available for June–August. From September onwards, as the cloud cover decreases it is easier to obtain remotely sensed Chl *a* data. In September the chlorophyll concentration is fairly high (but less relative to February/March) because of the input of nutrients due to upwelling in the southwest coast and possible lateral advection[20].

The SST, an indicator of vertical mixing, has remained almost the same (Figure 2 *b*) over past eight years. Thus the SST data do not show significant reduction in the winter cooling. In this zone, during winter significant fall in SST can be seen (3–4°C). The decrease in SST is due to the mixing of the deeper water with the surface water which causes increase in the productivity. The decrease in SST can also be seen in the period of the SW monsoon when moderate upwelling takes place, although it is not that prominent in this zone. During summer too the SST falls, but the magnitude of decrease is less (1–2°C). This clearly

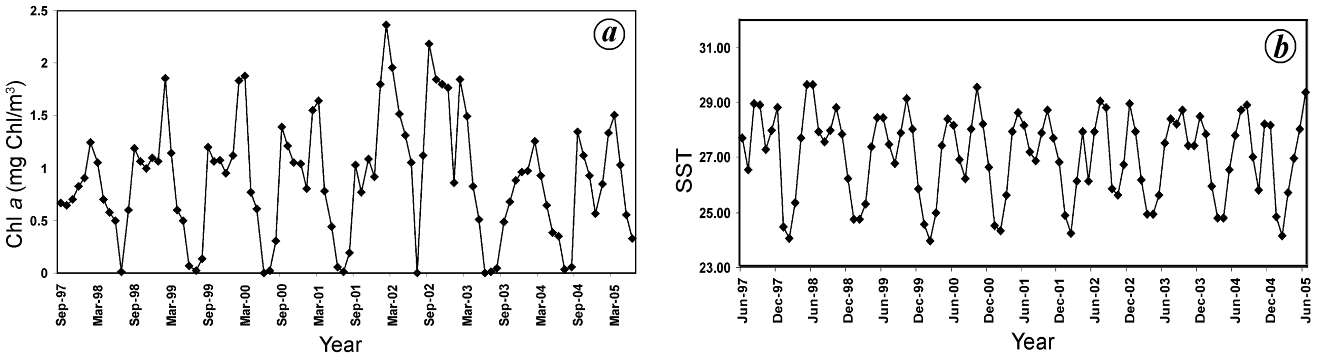

Figure 2. Satellite-derived Chl *a* (***a***) and SST (***b***) over zone 1.

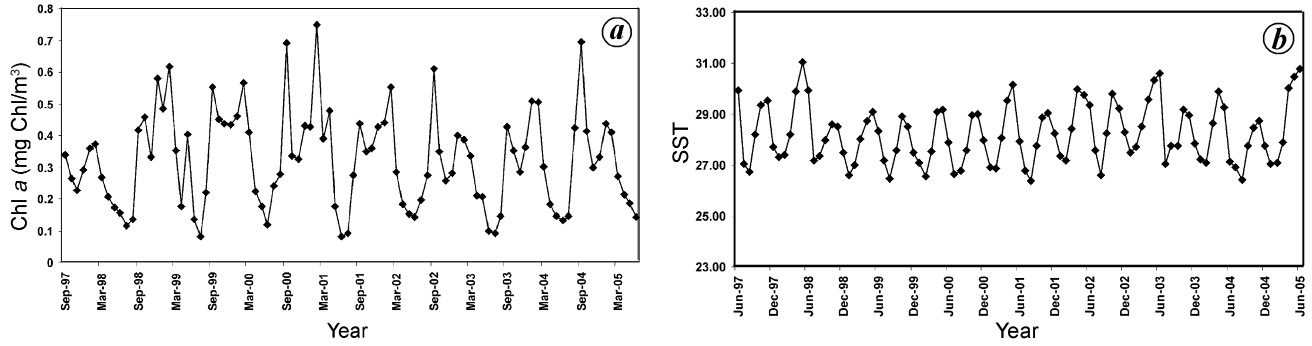

Figure 3. Satellite-derived Chl *a* (***a***) and SST (***b***) over zone 2.

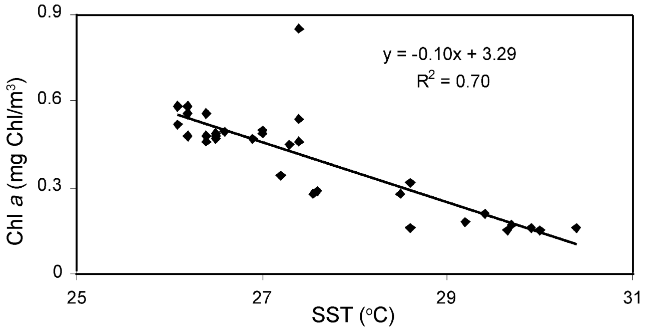

Figure 4. Satellite-derived Chl *a* data and SST from May to September from the region 52 to 57°E and 5°S to 10°N (source: Goes *et al.*[5]).

suggests that winter cooling has greater control on productivity than upwelling in this zone.

In zone 2, chlorophyll concentration remains low compared to zone 1 throughout the year. However, two prominent peaks can be seen every year (Figure 3 *a*); one in September when upwelling/vertical mixing takes place and the other in February/March, when winter cooling in the north triggers high production. Chlorophyll concentration is highest during September. The average value over the last eight years in September is 0.52 mg Chl/m^3, the maximum being 0.69 mg Chl/m^3 (2004) and the minimum being 0.33 mg Chl/m^3 (1997). Chlorophyll concentration is also high during October to March, being the highest in March. The average chlorophyll concentration in March is 0.33 mg Chl/m^3. In this part of the Arabian Sea, the satellite-derived SST shows a bimodal temperature cycle with lows during SW (2–3°C) and NE (1–2°C) monsoons (Figure 3 *b*). This change in temperature has a profound effect on the mixed layer through change in water density. Increase in the mixed layer depth causes the transport of nutrient-rich cold water from the deeper levels to the surface and supply of nutrients for production. This enhances the Chl *a* value in this region during these months.

Goes *et al.*[5] have argued, on the basis of the correlation between SST and satellite-derived chlorophyll (Figure 4; $R^2 = 0.70$), that summer productivity has increased over the years due to increasing sea surface wind.

We also analysed the correlation between SSTs and Chl *a* over zones 1 and 2 for the boreal winter, i.e. October to March for the same time period and have observed that the slopes of the regressions are similar (~ – 0.10) for all the three regions. Our analysis of sea surface wind data also does not show any significant change in wind speed over north-eastern Arabian Sea (Figure 5 *a* and *b*). In zone 2 we do not find any change in the wind strength. Wind speed pattern over this region has remained similar over past 7 years. Some small variations in wind speed can be seen in zone 1, but there is no significant secular trend. These small changes cannot be attributed to global warming because had it been due to temperature contrast between the Eurasian plateau and Arabian Sea, it should have

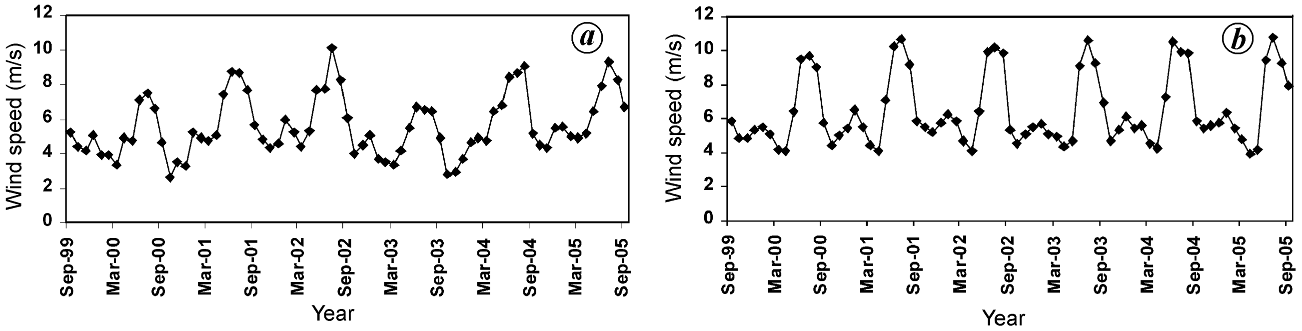

Figure 5. Satellite-derived wind speed over zone 1 (***a***) and zone 2 (***b***).

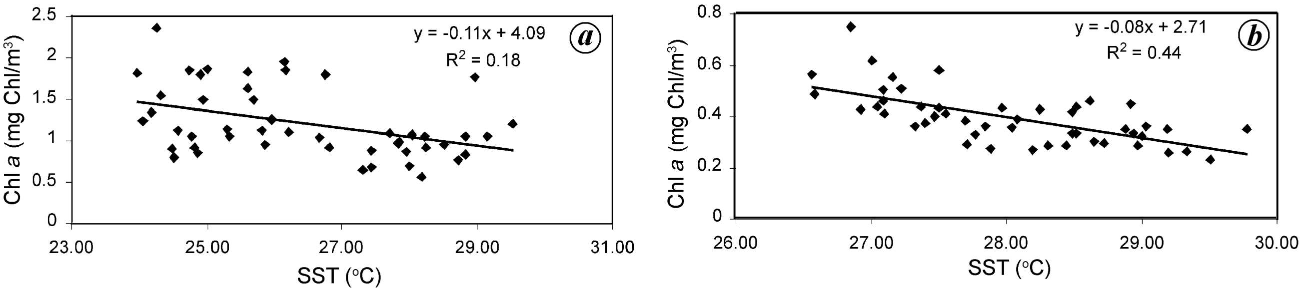

Figure 6. Satellite-derived Chl *a* data and SSTs over zone 1 (***a***) and zone 2 (***b***) in winter (October to March).

affected both the zones. It is also difficult to relate these changes to decadal-scale oscillatory events using these datasets.

Satellite-derived chlorophyll and SST data do not show significant correlation in winter in zone 1 (Figure 6 *a*; R^2 = 0.18), but a significant correlation in zone 2 (Figure 6 *b*, R^2 = 0.44).

This suggests that both upwelling (SW monsoon) and convective mixing (NE monsoon) are responsible for seasonal high productivity in this zone. Transportation of the deeper, colder, nutrient-rich water to the surface triggers high production in the western as well as in northern Arabian Sea. The average chlorophyll concentration in zone 1 is thrice the average concentration in zone 2, suggesting greater control of winter cooling for observed high production in this area. Although winter cooling has greater control on the production in the northeast Arabian Sea, it is not the only factor.

In summary, the interannual, remotely sensed monthly composite chlorophyll data suggest high chlorophyll concentrations in the eastern Arabian Sea. Chlorophyll concentration in the northeastern part of the Arabian Sea is thrice that in the southeast part. March is the most productive month due to winter cooling, while September is the most productive month during the summer monsoon. This is due to the difference in the physical forcing. The southeastern Arabian Sea is equally productive in both summer and winter, whereas the northeastern part is more productive in winter than in summer. Overall, winter cooling has a more pronounced effect on chlorophyll concentration and hence on the productivity in the eastern Arabian Sea compared to the summer monsoon. Although we see some seasonal variations in different parts of the Arabian Sea, there is no significant secular trend. Our analysis also shows that the trend reported by Goes *et al.*[5] in the western Arabian Sea is not observed in the eastern Arabian Sea. Increase in chlorophyll reported by the Goes *et al.*[5] is probably restricted to the west. Also, their proposal that the intensification of the southwest monsoon due to global warming has caused the increase in the productivity appears untenable, as we fail to observe any corresponding decreasing trend in the productivity of the northeastern Arabian Sea. Any change in the monsoonal pattern because of land–sea temperature contrast should affect the northeastern Arabian Sea more because of its close proximity to the Himalaya compared to the southwestern Arabian Sea, which is not borne out in our analysis.

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Subsidence of southern part of erstwhile Dhanushkodi township, Tamil Nadu – evidences from bathymetry, side scan and underwater videography

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The southern part of erstwhile Dhanushkodi township, Tamil Nadu, experienced subsidence and submergence during AD 1948–49. Shallow bathymetric and side-scan surveys together with sampling and underwater videography confirm the extent and quantum of subsidence. The studies reveal that a vertical tectonic movement (fault) parallel to the coastline with a displacement of ~ 5 m led to the subsidence of the southern part of the township. This fault movement has occurred 57 years ago and hence could be the latest neo-tectonic movement ever recorded along the east coast of India.

Keywords: Dhanushkodi, neo-tectonic activity, subsidence, submergence, vertical displacement.

THE coastal zone, the link between ocean and land margins, constantly experiences several dynamic processes, which at times result in various hazards to human beings. Such processes include erosion, accretion, upliftment, subsidence, submergence and their combined influence.

The extreme southeastern part of Rameswaram Island (Figure 1), known as Dhanushkodi Foreland, is well-known in Hindu mythology and is of religious importance. High-intensity storms and cyclones have frequently attacked this area and led to vast material and human losses in the past, particularly the cyclone of AD 1964. The erstwhile Dhanushkodi township (presently in ruins) underwent subsidence during the mid-twentieth century. This communication documents the marine geo-scientific investigations at Dhanushkodi area and provides evidences for coastal subsidence in the southern part of the erstwhile Dhanushkodi township in the Gulf of Mannar (Figure 1) and geological reasons for subsidence during AD 1948–49. Bathymetry, side scan and sampling surveys provide an insight into subsidence through underwater videography.

The southeastern tip of peninsular India assumes much importance from a geological point of view. However, till date, geological studies around Dhanushkodi are meagre, except for limited geomorphological observations by

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