12. Mishra, R., *Ecological Workbook*, Oxford & IBH, New Delhi, 1968, pp. 31–51.
13. Mueller-Dombois, D. and Ellenberg, H., *Aims and Methods of Vegetation Ecology*, John Wiley and Sons, New York, 1974.
14. Bentham, G. and Hooker, J. D., *Flora of British India*, 1872–1897, vols 1–7.
15. Stevens, A., *C Development*, BPB Book Centre, New Delhi, 1989, pp. 20–28.
16. Connell, J., *Beginning Visual Basic 6 Programing*, Wrox Press Ltd, 1998, pp. 83–96.
17. Koegent Solution Inc, *Visual Basic 2008 Programing Black Book (Platinum Edition)*, Dreamtech Press Edition, New Delhi, 2009, pp. 829–858.
18. Ved, D. K., Kinhal, G. A., Ravikumar, K., Prabhakaran, V., Ghate, U., Sankar, R. V. and Indreshu, J. H., Conservation assessment and management prioritization for the medicinal plants of Jammu & Kashmir, Himachal Pradesh and Uttaranchal, FRLHT, Bangalore, 2003, pp. 7–8.
19. Chowdhery, H. J., Himachal Pradesh. In *Floristic Diversity and Conservation Strategies in India* (eds Mudgal, V. and Hajra, P. K.), Botanical Survey of India, Ministry of Environment and Forest, Government of India, 1999, vol. II, pp. 844–904.
20. Lomolino, M. V., Elevation gradients of species density: historical and prospective views. *Glob. Ecol. Biogeogr.*, 2001, **10**, 3–13.
21. Chawla, A., Rajkumar, S., Singh, K. N., BrijLal and Singh, R. D., Plant species diversity along an altitudinal gradient of Bhabha valley in western Himalaya. *J. Mt. Sci.*, 2008, **5**, 157–177.

ACKNOWLEDGEMENTS. We thank the National Bioresource Development Board (NBDB), Department of Biotechnology, Government of India for providing financial support. This is IHBT communication number 1075.

Received 26 October 2009; revised accepted 4 June 2010

What drives the increased phytoplankton biomass in the Arabian Sea?

S. Prasanna Kumar[1,]*, Raj P. Roshin[1,2], Jayu Narvekar[1], P. K. Dinesh Kumar[1,3] and E. Vivekanandan[1,4]

[1]National Institute of Oceanography, Dona Paula, Goa 403 004, India
[2]Present address: Bjerknes Centre for Climate Research, University of Bergen, Norway
[3]Regional Center of National Institute of Oceanography, Kochi 682 018, India
[4]Central Marine Fisheries Research Institute, Kochi 682 018, India

The seasonal variability of phytoplankton biomass in the Arabian Sea, though a well researched topic, its inter-annual variability is less explored and understood. Analysis of the satellite-derived chlorophyll pigment concentration in the Arabian Sea during 1997–2007 showed a weak increasing trend. Contrary to the earlier hypothesis, our analysis showed that this increased phytoplankton biomass was not driven by the strengthening winds during summer monsoon. In fact, the basin-averaged chlorophyll concentrations during summer monsoon tend to decline, whereas those in September–October and during the winter monsoon showed an increasing trend. Based on the analysis of wind and aerosol optical thickness data, we attribute the increased phytoplankton biomass during September–October to dust-induced iron fertilization when there is sufficient buildup of nitrate in the upper ocean. During winter, the enhanced evaporative cooling under the strengthening winds led to the increased convective mixing. Subsequent supply of subsurface nutrients to the euphotic zone coupled with the increased dust delivery support the observed increase in phytoplankton biomass during winter.

Keywords: Aerosol optical thickness, chlorophyll pigment concentration, iron fertilization, monsoon wind, nutrients, upwelling.

THE Arabian Sea is one of the most biologically productive regions of the world oceans[1]. Being in the tropical region and subjected to seasonally reversing monsoonal wind system, the biological productivity of the basin shows strong seasonality with blooms occurring in summer monsoon (June–August) and winter monsoon (December–February). The summer bloom is driven by upwelling along the coasts of Somalia, Arabia and the southern parts of the west coast of India[2–4]. In addition to coastal upwelling, processes such as wind-mixing, lateral advection, Ekman pumping, mesoscale eddies and filaments (see Lee *et al.*[5] and the references therein) also play an important role in supplying nutrients to the euphotic zone during summer. The winter bloom occurs due to winter-cooling and convective mixing[6–9]. During spring-inter monsoon (March–May) these waters are largely oligotrophic with very low chlorophyll pigment concentrations, whereas the fall-intermonsoon (September–November) representing the tapering phase of the summer monsoon sees rapidly declining chlorophyll pigment concentrations. The seasonality of the phytoplankton blooms and the associated high biological productivity of the Arabian Sea are well researched and understood phenomena (see for e.g. Banse[6], Smith[10] and the references therein, Prasanna Kumar *et al.*[11], Wiggert *et al.*[12]). However, the inter-annual variability of the phytoplankton biomass in the Arabian Sea remains less explored and understood. In a recent study, Goes *et al.*[13] argued that the increase in the phytoplankton biomass in the western Arabian Sea during 1997–2003 was driven by the strengthening of surface winds and enhanced upwelling due to the strengthening of the land–ocean thermal gradient associated with declining winter and spring snow cover over Eurasia. Subsequently, Prakash and Ramesh[14] showed

*For correspondence. (e-mail: prasanna@nio.org)

that the chlorophyll concentration in the northeastern Arabian Sea had not changed significantly during 1997–2005 and argued that the proposal of increased phytoplankton biomass in the western Arabian Sea due to global warming[13] was untenable as any change in the monsoonal pattern from the land–sea thermal contrast should affect the northern Arabian Sea more because of its proximity to the Himalayas, which is not seen from their analysis. This was the motivation behind the present study. Since the Arabian Sea has a strong seasonal signal and the amplitude varies spatially, we chose to use the data for the entire Arabian Sea rather than selecting a particular region. We then analysed the data in accordance with the seasons that support the enhanced biological productivity to understand the mechanisms that support increased phytoplankton biomass during 1997–2007.

The data on chlorophyll pigment concentration and aerosol optical thickness at 865 nm between 5–25°N and 45–80°E in the Arabian Sea were extracted from the sea-viewing wide field-of-view sensor (SeaWiFS) (ftp://oceans.gsfc.nasa.gov/SeaWiFS/Mapped/Monthly) during the period September 1997 to February 2007, which is the global 9 km monthly product. The pigment concentration maps usually show a red band along the coasts. This is largely due to sediments and should be neglected. For the present analysis, we have eliminated data within one-third of a degree from the coasts. Similarly, the monthly mean wind data were obtained from the Tropical Rain Measuring Mission (TRMM) Microwave Imager (TMI) (http://apdrc.soest.hawaii.edu/las/servlets/dataset?catitem=934) for the period December 1997 to February 2007 which is global 0.25 degree product. We also used QuikSCAT winds available during 1999–2005 (http://www.ssmi.com) to ascertain the robustness of the inference derived from the wind data. From these data, the basin-averaged monthly mean and the seasonal mean for summer and winter monsoons were computed. Summer mean was computed by averaging from June to August, whereas for winter mean from December to February were considered. The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis winds[15] were used to generate the monthly mean climatology. The Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data (HOAPS) at 0.5 degree spatial resolution[16] were used for the computation of basin-averaged winter mean evaporation. A linear trend line was fitted to all the given data, except for QuikSCAT winds, and the correlation coefficient (r^2) as well as the probability value (P-value) was determined.

The basin-averaged monthly mean satellite-derived chlorophyll pigment concentration in the Arabian Sea during 1997–2007 showed a strong seasonality with a primary peak in August followed by a secondary peak in February (Figure 1 *a*) representing the signature of summer and winter phytoplankton blooms. The primary peak of chlorophyll pigment concentration during summer monsoon showed a large variability, while the secondary peak in winter monsoon did not show much change. Note that the month of occurrence of the primary peak until 2001 was August, which shifted to September from 2002 until 2006. However, during 2003 and 2004 the chlorophyll pigment concentrations in August and September were the same. The linear trend line showed a weakly-increasing trend. To understand what contributed to the weakly-increasing trend and the shift in the peak from August to September, we analysed the seasonal mean during summer and winter monsoons with the monthly mean for September and October (Figure 1 *b* and *c*). The summer chlorophyll pigment concentration showed a declining trend (~ 0.95–0.8 mg/m^3) during 1997–2006 (Figure 1 *b*), while that in winter showed a marginal increase (from less than 0.6–0.65 mg/m^3, Figure 1 *c*). In contrast, a substantial increase in the pigment concentration (~0.8–1.3 mg/m^3) was noticed during September (Figure 1 *b*),

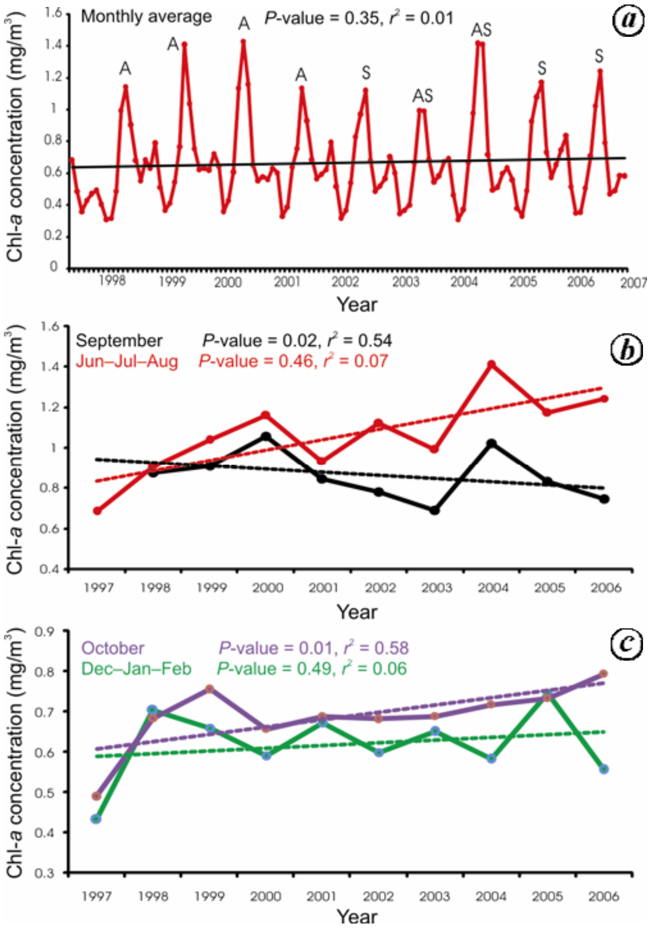

Figure 1. Basin-averaged chlorophyll pigment concentrations (mg/m^3) derived from SeaWiFS. ***a***, Monthly mean during September 1997 to February 2007. ***b***, Summer mean (averaged for June to August, JJA) (black line) and September (red line). ***c***, October (blue line) and winter mean (averaged during December to February, DJF) (green line). The dashed line in all the diagrams indicates the linear trend line. The alphabets A and S over the peaks in (***a***) represent August and September respectively.

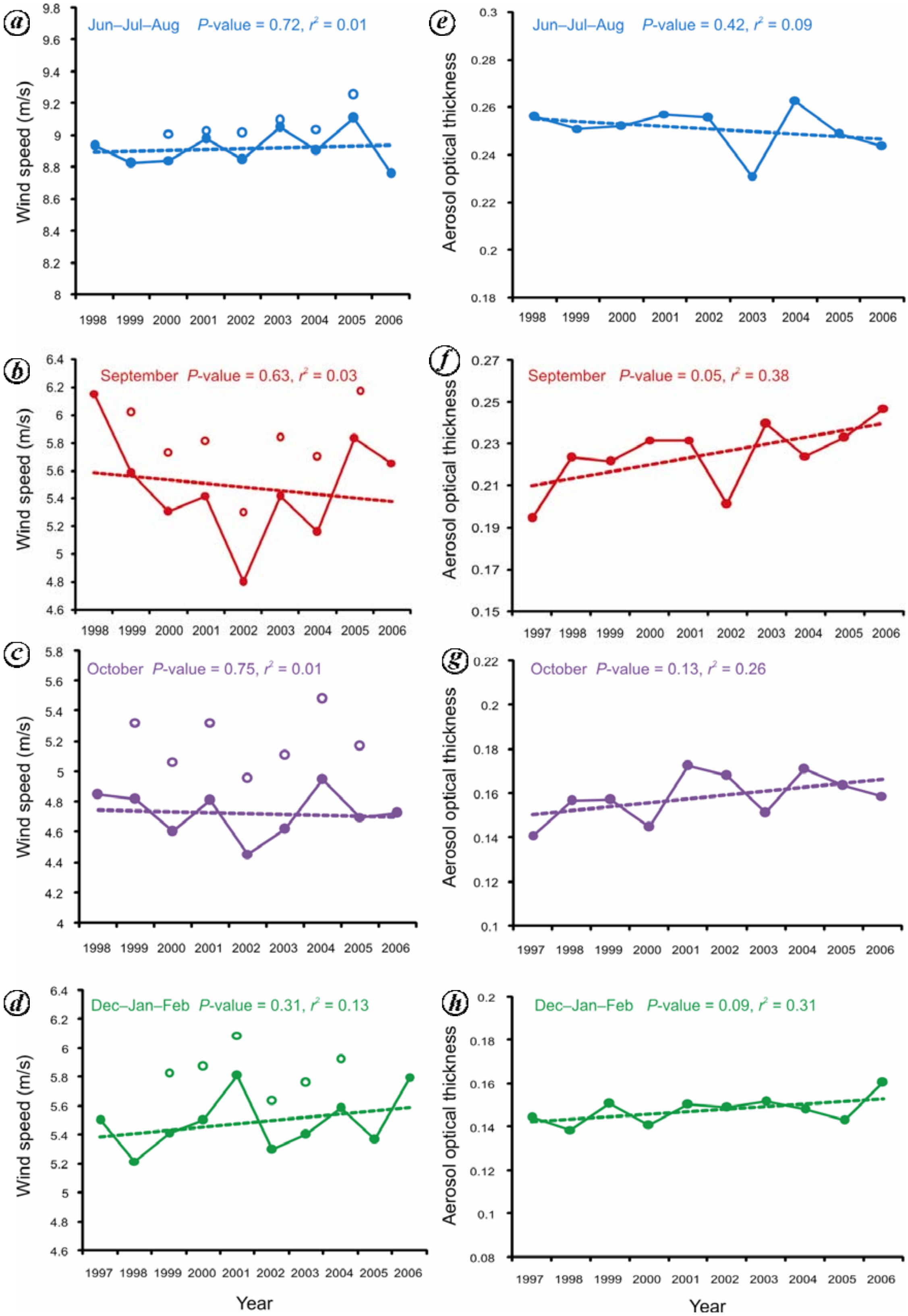

Figure 2. Basin-averaged (left panels) wind speed (m/s) and (right panels) aerosol optical thickness for (***a***, ***e***) summer (averaged for June to August, JJA), (***b***, ***f***) September, (***c***, ***g***) October and (***d***, ***h***) winter (averaged for December to February, DJF). The dashed line in all the diagrams indicates the linear trend line. Winds are from TMI (filled circles) and QuikSCAT (open circles). Note that the QuikSCAT winds are during 1999–2005. See text for details. The trend lines in ***a***–***d*** are based only on the filled circles.

followed by October (~ 0.6–0.75 mg/m^3, Figure 1 *c*). This amounted to an increase of about 6.97% per year in the September mean chlorophyll pigment concentration (*P*-value of 0.02 and $r^2 = 0.51$), while that in October was about 4.52% per year (*P*-value of 0.01 and $r^2 = 0.58$). Thus, from the given analysis it is clear that the increase in the chlorophyll pigment during September, October and the winter monsoon months contributed to the weakly-increasing trend during 1997–2007.

In order to understand the process responsible for the increased chlorophyll we analysed the TMI wind data. The basin-averaged winds showed an increasing trend in later years during both summer and winter monsoons, with the latter being more pronounced (Figure 2 *a* and *d*). For example, in summer the average wind during the second half of the period was about 0.06 m/s stronger than that of the first half. In winter, the average wind during the second half was about 0.1 m/s stronger than that of the first half. In contrast, the winds during September and October showed a decreasing trend in later years (Figure 2 *b* and *c*). These inferences were consistent with data from the QuikSCAT winds (open circles in Figure 2). This indicated that the summer monsoon winds were unable to drive an increase in either upwelling or wind-driven mixing, both of which are capable of supplying nutrients to the upper ocean. In contrast, the increased winter monsoon winds (Figure 2 *d*) tended to be correlated with increased chlorophyll. This could be explained as follows. The trade winds during winter are of continental origin and hence dry. With the decadal increase in the wind speed during winter, one would expect an increase in the evaporative cooling and subsequent increase in the convective mixing[8]. The evaporative cooling leads to the creation of heavier surface water mass and its detrainment into subsurface layer initiates deep mixing. An examination of HOAPS data showed a significant increase of evaporation during winter from 1997 to 2004 (Figure 3). This in turn could inject more nutrients to the upper ocean from the nutricline by deeper convection in the water column. However, the increased chlorophyll pigment concentrations during September and October could not be explained in the context of the wind. Thus, from the analysis of wind and chlorophyll data, we conclude that the pigment concentration increasing with years was not driven by the strengthening of summer monsoon winds as hypothesized by Goes *et al.*[13]. The observed decadal increase in the chlorophyll pigment concentration during September, October and in winter would need another explanation. Since atmospheric dust influences the aerosol optical depth[17], we analysed the aerosol optical thickness from the SeaWiFS, which showed a weakly decreasing trend during summer (Figure 2 *e*) and an increasing trend during September, October (Figure 2 *f* and *g*) and winter (Figure 2 *h*) (see strong *P*-values). Since the wind speed during September and October showed a decreasing trend, the increase in aerosol optical thickness during this period cannot be attributed to the increase in salt spray. This suggests the possible role of atmospheric dust input in regulating the observed phytoplankton pigment concentrations during September, October and in winter. It could be explained by the seasonal change in the basin-scale wind pattern.

During summer monsoon (June to August) the low-level atmospheric Findlater jet[18], with a broad region of strong southwesterly winds with remarkable steadiness in the direction and strength, blows from the ocean onto the continent (Figure 4). At this time of the year, the strong upwelling along the coasts of Somalia, Arabia and the southwest coast of India supplies nutrients to the upper ocean and sustains summer blooms[2,6]. Wiggert and Murtugudde[19] using the model studies suggested that the continuous build up of macronutrients during the summer monsoon due to upwelling may lead to subsequent iron limitation, which in turn limits the phytoplankton growth. Though the Arabian Sea is in close proximity to the major desert regions, the Findlater jet acts as a barrier to the direct transport of dust from the desert source regions in the north/northwest[20] into the Arabian Sea. Thus, with the progress of the upwelling and summer monsoon as the Findalter jet cuts off the dust input to the Arabian Sea, the phytoplankton growth becomes iron-limited. This leads to the underutilization of macronutrients such as nitrate and its buildup in the upper ocean. As the summer-monsoon tapers off, the wind direction changes from southwesterly to north/northwesterly during September–October, followed by north/northeasterly winds in winter (see the shaded region in Figure 4). These winds of continental origin may be capable of supplying the much-needed iron to the upper ocean via increased dust-delivery. Thus, the observed increase in the phytoplankton during September–October and in winter may well have been triggered by the dust induced iron fertilization.

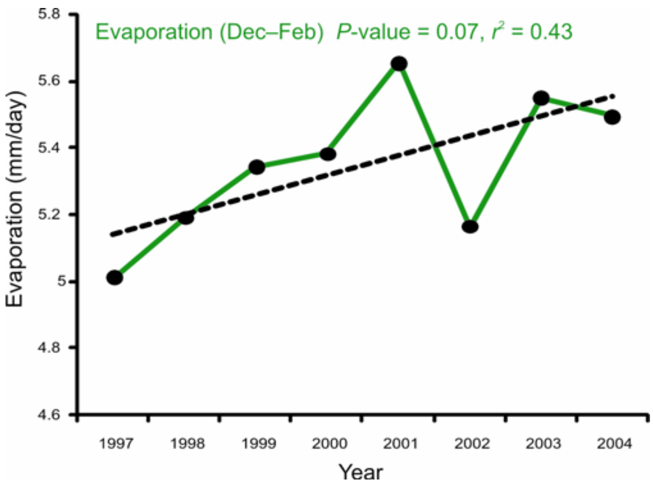

Figure 3. Basin-averaged evaporation (mm/day) during winter (averaged for December to February, DJF) from HOAPS data in the Arabian Sea. The dashed line is the linear trend line.

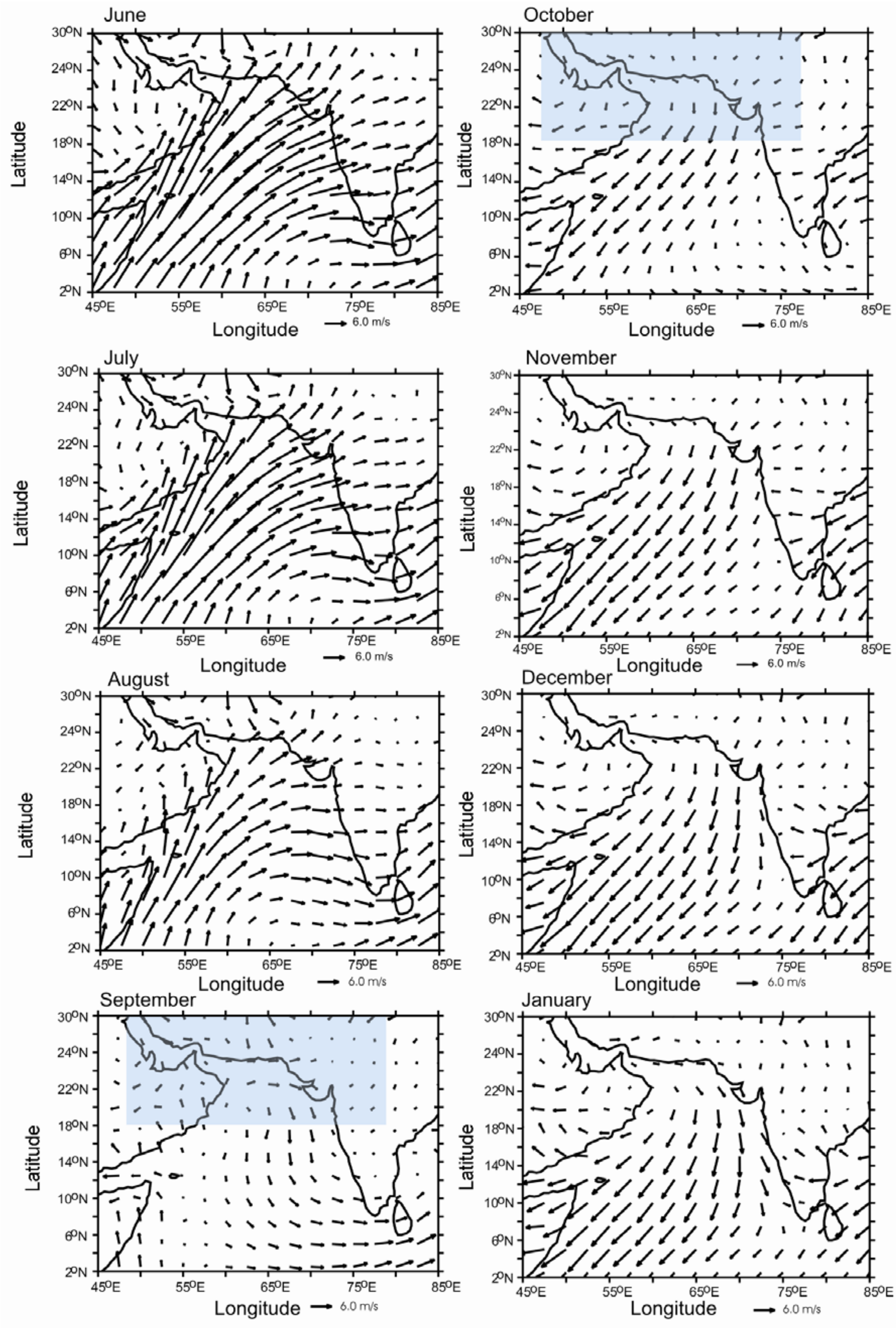

Figure 4. Monthly mean climatology of winds during June to January in the Arabian Sea from NCEP/NCAR re-analysis data. Note the change in the direction of the winds in the shaded panels. These winds of the continental origin are capable of transporting dust into the Arabian Sea.

The analysis of chlorophyll pigment concentration data during September 1997 to February 2007 in the Arabian Sea revealed a weak increasing trend over the years. Contrary to the earlier studies of Goes *et al.*[13], our study suggests that the basin-averaged increase in chlorophyll pigment concentration resulted from the increase during September–October and winter rather than summer. During summer monsoon, the upwelling in the Arabian Sea is able to supply nutrients to the upper ocean which sustains high biological productivity. It is during this period that the Findlater jet, with its broad region of strong southwesterly winds, acts as a barrier to the direct transport of dust from the desert source regions in the north/northwest into the Arabian Sea. With the continuous supply of macronutrients and the lack of dust input from the northwestern desert regions of the Arabian Sea, the phytoplankton growth may be limited by the lack of micronutrients such as iron. As the season changes and monsoon winds taper off, the wind direction changes from southwesterly to north/northwesterly during September–October and then to northeasterly in winter. These winds of continental origin are capable of supplying the dust to the Arabian Sea and thereby triggers the iron induced fertilization during September–October. In winter, the increased strength of the winds drives enhanced evaporative-cooling which in turn strengthens the convective mixing. This results in the enhanced nutrient supply to the euphotic zone from the subsurface and the increased dust input during winter, which augments the much needed iron, supporting the increased phytoplankton biomass.

As a concluding remark, we would like to add that our approach was based on the consideration that the changes in the chlorophyll concentrations can be understood by considering the resources driving the growth rates such as nutrients, light, etc. There is, however, always a top-down regulation, a delicate balance between growth and mortality from grazing and virus kills, which cannot be estimated from satellites.

1. Ryther, J. H., Hall, J. R., Pease, A. K., Bakun, A. and Jones, M. M., Primary organic production in relation to the chemistry and hydrography of the western Indian Ocean. *Limnol. Oceanogr.*, 1966, **11**, 371–380.
2. Smith, S. L. and Codispoti, L. A., Southwest monsoon of 1979: chemical and biological response of Somali coastal waters. *Science*, 1980, **209**, 597–600.
3. Brock, J. C. and McClain, C. R., Interannual variability in phytoplankton blooms observed in the northwestern Arabian Sea during the south west monsoon. *J. Geophys. Res.*, 1992, **97**, 733–750.
4. Banse, K., Sumitra-Vijayaraghavan and Madhupratap, M., On the possible causes of the seasonal phytoplankton blooms along the west coast of India. *Indian J. Mar. Sci.*, 1996, **25**, 283–289.
5. Lee, C. M., Jones, B. H., Brink, K. H. and Fischer, A. S., The upper-ocean response to monsoonal forcing in he Arabian Sea: seasonal and spatial variability, *Deep-Sea Res. II*, 2000, **47**, 1177–1226.
6. Banse, K., Seasonality of phytoplankton chlorophyll in the central and northern Arabian Sea. *Deep-Sea Res.*, 1987, **34**, 713–723.
7. Madhupratap, M., Prasanna Kumar, S., Bhattathiri, P. M. A., Kumar, M. D., Raghukumar, S., Nair, K. K. C. and Ramaiah, N., Mechanism of the biological response to winter cooling in the northeastern Arabian Sea. *Nature*, 1996, **384**, 549–552.
8. Prasanna Kumar, S. and Prasad, T. G., Winter cooling in the Arabian Sea. *Curr. Sci*., 1996, **71**, 834–841.
9. Prasanna Kumar, S. *et al.*, Physical forcing of biological productivity in the Northern Arabian Sea during the Northeast Monsoon. *Deep-Sea Res. II*, 2001, **48**, 1115–1126.
10. Smith, S. L. (ed.), The 1994–1995 Arabian Sea expedition: oceanic response to monsoonal forcing, Part 1. *Deep-Sea Res. II*, 1998, **45**, 1905–2501.
11. Prasanna Kumar, S., Madhupratap, M., Kumar, M. D., Gauns, M., Muraleedharan, P. M., Sarma, V. V. S. S. and de Souza, S. N., Physical control of primary productivity on a seasonal scale in central and eastern Arabian Sea. *Proc. Indian Acad. Sci.* (*Earth Planet. Sci*.), 2000, **109**, 433–441.
12. Wiggert, J. D., Hood, R. R., Banse, K. and Knindle, J. C., Monsoon-driven biogeochemical processes in the Arabian Sea. *Prog. Oceanogr.*, 2005, **65**, 176–213.
13. Goes, J. I., Thoppil, P. G., Gomes, H. do R. and Fasullo, J. T., Warming of the Eurasian landmass is making the Arabian Sea more productive. *Science*, 2005, **308**, 545–547.
14. Prakash, S. and Ramesh, R., Is the Arabian Sea getting more productive? *Curr. Sci.*, 2007, **92**, 667–671.
15. Kalnay, E. *et al.*, The NCEP/NCAR 40-year reanalysis project. *B. Am. Meteorol. Soc*., 1996, **77**, 437–471.
16. Fairall, C. W., Bradley, E. F., Rogers, D. P., Edson, J. B. and Young, G. S., Bulk parameterization of air-sea fluxes for tropical ocean–global atmosphere coupled-ocean atmosphere response experiment. *J. Geophys. Res*., 1996, **101**, 3747–3764.
17. Dey, S., Tripathi, S. N. and Singh, R. P., Influence of dust storms on the aerosol optical properties over the Indo-Gangetic basin. *J. Geophys. Res*., 2004, **109**, doi:10.1029/2004JD004924.
18. Findlater, J., A major low-level air current near the Indian Ocean during northern summer monsoon. *Q. J. R. Meteorol. Soc*., 1969, **95**, 362–380.
19. Wiggert, J. D. and Murtugudde, R. G., The sensitivity of the southwest monsoon phytoplankton bloom to variations in Aeolian iron deposition over the Arabian Sea. *J. Geophys. Res*., 2007, **112**, doi: 10.1029/2006JC003514.
20. Tindale, N. W. and Pease, P. P., Aerosols over the Arabian Sea: atmospheric transport pathways and concentrations of dust and sea salt phytoplankton responses in the North Pacific. *Deep-Sea Res. II*, 1999, **46**, 1577–1595.

ACKNOWLEDGEMENTS. R.P.R. and J.N. acknowledge the Council of Scientific and Industrial Research, New Delhi for fellowships. We thank the Director, NIO, Goa and CSIR, New Delhi for all the support and encouragement. We also thank the anonymous reviewers whose suggestions helped improve the manuscript. This is NIO contribution number 4748.

Received 18 May 2009; revised accepted 23 April 2010