6. Caius, J. F., *The Medicinal and Poisonous Plants of India*, Scientific Publ., Jodhpur, 1998, pp. 426–427.
7. Bruneton, J., *Pharmacognosie–Phytochime. Plantes Medicinales*, Technique and Documents Lavoisier, Paris, 1993, 2nd edn, p. 300.
8. Shetty, B. V., Kaveriappa, K. M. and Bhat, G. K., *Plant Resources of Western Ghats and Lowlands of Dakshina Kannada and Udupi Districts*, Pilikula Nisarga Dhama Society, Moodushedde, Mangalore, 2002, pp. 48, 66.
9. Patil, A. D. *et al.*, The inophyllum, novel inhibitors of HIV-1 reverse transcriptase isolated from the Malaysian tree *Calophyllum inophyllum. J. Med. Chem.*, 1993, **36**, 4131–4138.
10. Kashman, Y. *et al.*, The Calanolides, a novel HIV-inhibitory class coumarin derivatives from the tropical rainforest tree, *C. lanigerum. J. Med. Chem.*, 1992, **35**, 2735–2743.
11. Claude, S., Marco, D. and Sotheeswaran, S., Anti-HIV coumarins from *Calophyllum* seed oil. *Bio-org. Med. Chem. Lett.*, 1998, **8**, 3475–3478.
12. Tsutomu, I., Anti HIV-1 active *Calophyllum* coumarins: Distribution, chemistry and activity. *Heterocycles*, 2000, **53**, 453–474.
13. Dharmaratne, H. R. W., Tan, G. T., Marasinghe, G. P. K. and Pezzuto, J. M., Inhibition of HIV-1 reverse transcriptase and HIV-1 replication by *Calophyllum* coumarins and xanthones. *Planta Med.*, 2002, **68**, 86–87.
14. Wainhouse, D., Murphy, S., Greig, B., Webber, J. and Vielle, M., The role of bark beetle *Cryphalus trypanus* in the transmission of the vascular wilt pathogen of takamaka (*Calophyllum inophyllum*) in the Seychelles. *For. Ecol. Manage.*, 1998, **108**, 193–199.
15. Nair, L. G. and Seeni, S., *In vitro* multiplication of *Calophyllum apetalum* (Clusiaceae), an endemic medicinal tree of the Western Ghats. *Plant Cell Tiss. Org. Cult.*, 2003, **75**, 169–174.
16. Ranjit Daniels, D. J. and Patil, V., Value addition: A threat to *Calophyllum* species. *Curr. Sci.*, 1995, **68**, 243–244.
17. Loyd, C. and McCown, B., Commercially feasible micropropagation of mountain laurel, *Kalmia latifolia* by use of shoot tip culture. *Int. Plant Propagation Soc. Proc.*, 1980, **30**, 421–427.
18. Murashige, T. and Skoog, F., A revised medium for rapid growth and bioassay with tobacco tissue cultures. *Physiol. Plant.*, 1962, **15**, 473–497.
19. Snedecor, G. W. and Cochran, W. G., *Statistical Methods*, Oxford and IBH, New Delhi, 1967, pp. 569–571.
20. Ye, G., McNeil, D. L., Conner, A. J. and Hill, G. D., Multiple shoot formation in lentil (*Lens culinaris*) seeds. *N. Z. J. Crop Hortic. Sci.*, 2002, **30**, 1–8.
21. Visser, C., Qureshi, J. A., Gill, R. and Saxena, P. K., Morphoregulatory role of thidiazuron. *Plant Physiol.*, 1992, **99**, 1704–1707.
22. Meyer, H. J. and Staden Van, J., *In vitro* multiplication of *Ixia flexuosa. Hortic. Sci.*, 1988, **23**, 1070–1071.
23. Lu, C. Y., The use of thidiazuron in tissue culture. *In vitro Cell. Dev. Biol.–Plant*, 1993, **29P**, 92–96.

ACKNOWLEDGEMENTS. Financial assistance in the form of a project by DBT, New Delhi is acknowledged. We are thankful to Dr S. P. Taware, Agarkar Research Institute, Pune; Dr M. M. Sardesai, Department of Botany, M.E.S's Abasaheb Garware College, Pune and Mr S. R. Bhosle, Department of Botany, University of Pune for help and suggestions.

Received 22 July 2005; revised accepted 20 January 2006

Influence of northeasterly trade winds on intensity of winter bloom in the Northern Arabian Sea

R. M. Dwivedi[1,*], Mini Raman[1], Sushma Parab[2], S. G. P. Matondkar[2] and Shailesh Nayak[1]

[1]Space Applications Centre (ISRO), Ahmedabad 380 015, India
[2]National Institute of Oceanography, Goa 403 004, India

Chlorophyll and wind pattern retrieved from remote sensing data have been used to study biological activity in the oceanic waters of Northern Arabian Sea (NAS) during February–March 2002–05. Occurrence of algal bloom in these waters during this period was noticed with the help of ship observations in the past. The same was detected from OCEANSAT I/OCM with time series chlorophyll images for January–March 2000. Occurrence of this bloom was later re-confirmed using OCM data in the subsequent years also. The time-series chlorophyll images established that the bloom develops every year during February–March. This period happens to coincide with the presence of northeasterly trade winds over the NAS. Two ship cruises were conducted with the help of research vessels FORV *Sagar Sampada* (SS-212 during 26 February–7 March 2003 and SS-222 during 21 February–11 March 2004) during this period at the bloom site. The aim was species identification of the bloom and to study various environmental parameters associated with the bloom. Two diverse situations in the context of biological activity were observed while collecting *in situ* data in 2003 and 2004. Distribution of the bloom was found uniform over a large area and concentration of phytoplankton was relatively higher in 2003. Compared to this, it was observed during the same period in 2004 that phytoplankton was distributed in scattered and small patches and its concentration was relatively less. Corresponding to this observation, it was noticed from the ship data that wind strength was significantly weaker and the oceanic waters were less turbulent in 2004 compared to the same in 2003. In light of this elementary observation, an attempt was made to observe variations in the wind pattern during 2003 and 2004 using QuikSCAT/SeaWinds scatterometer data. It could be established that occurrence of the bloom as well as the observed inter annual variability in chlorophyll pattern were coupled with prevailing trade winds. It was found that density of surface water increased (inversion) during this period, which could result in convective action and the observed bloom. The vertical density gradient revealed an increasing pattern with increase in wind speed. Moreover, it was observed that response of chlorophyll to acting wind force is delayed by one to two weeks. This led to an important inference that wind can be treated as a precursor to predict

*For correspondence. (e-mail: rmdwivedi@rediffmail.com)

variations in chlorophyll pattern in the context of the observed event of the bloom.

Keywords: Chlorophyll, Northern Arabian Sea, OCM data, trade winds, winter bloom.

INTER annual variability in the Northern Arabian Sea (NAS) winter bloom along 18–22°N lat. has been studied here using weekly averaged time-series chlorophyll images generated from Oceansat I/OCM and wind speed from QuikSCAT data. OCM, an operational ocean colour sensor on-board Oceansat I satellite, has eight spectral bands in the visible and infrared, which enable retrieval of chlorophyll from space. Occurrence of algal bloom was detected in open ocean waters of the NAS using time-series chlorophyll images (February–March 2000), as shown in Figure 1. Chlorophyll concentration can be seen to increase by the end of February and reaches a peak by middle of March. Chlorophyll images reveal this in the form of yellow and orange colour patches with concentration in the range 0.5–1.4 mg m^{-3}. Decreasing trend of chlorophyll concentration is seen towards the end of March. It has been reported that cooling of surface waters due to evaporation caused by northeasterly trade winds during January–March supplements the seasonal cooling, which ultimately results in high density at near-surface level. Subsequently, convection follows, which causes overturning of the water in a column[1–4]. Convective mixing brings nutrients to the upper euphotic column and stimulates biological productivity. Eventually, this is seen as waters of dark green colour attributed to *Noctiluca millaris* bloom[5] in open waters of the NAS at depths greater than 2000 m.

It was realized from ship-based observations (in February–March, 2003–04) in the NAS that distribution of chlorophyll pattern was homogeneous and concentration was higher in 2003 unlike the same in 2004. In 2004, the bloom was seen developed with discrete distribution and in small patches. Intensity of the bloom in terms of cell density was also relatively less. This patchy distribution of the bloom dictated use of near real-time OCM chlorophyll images on-board the ship to locate bloom waters. Ship measurements as well as QuikSCAT data indicated that winds were of larger magnitude in 2003 compared to that in the succeeding year. Stronger wind force can cause excess evaporation of surface waters, which would result in increased density. This may eventually initiate convection and in due course, increased productivity. Compared to this, wind forces of weaker magnitude generate moderate convection and relatively less productivity. Both these scenarios were observed in practice during the two ship cruises. Moreover, detailed study of behaviour of the two parameters indicated a time lag between changing pattern of wind force and its manifestation in the form of variation in productivity of oceanic waters.

Two ship cruises were conducted in the deep waters of the NAS to measure optical, bio-geochemical and meteorological parameters during the time when the winter bloom prevailed (26 February–7 March 2003 and 21 February–11 March 2004). These include chlorophyll and primary productivity along with optical parameters. Water samples of 1 l volume were used to extract chlorophyll and the extracted chlorophyll was dissolved in 90% acetone. Chlorophyll measurements were made using Turner Design fluorometer. Depth profile of chlorophyll, temperature and salinity was recorded with a modular CTD system at each ship station. A modular SEARAM CTD system was used for *in situ* temperature and salinity measurements. The CTD also has a fluorometer to record chlorophyll profile. It uses Paroscientific Digiquartz pressure transducer for sensing depth that enabled selection of depths for water sample collections. A quick look at the time series chlorophyll images just before the ship cruise (third week of February) had given an indication that development of the bloom was taking place in the form of patches in 2004. Therefore, an arrangement was to be made to receive near real-time chlorophyll images from the shore station on-board the ship through e-mail. It enabled positioning of the ship accurately within the bloom patch.

Daily and weekly averaged chlorophyll images were generated from the OCM data for the period January–March 2003–04 using OCM data. An approach of clear water radiance[6,7] for atmospheric correction was implemented with OCM data. An empirical algorithm[8] also known as Ocean Chlorophyll 2 or OC2 was implemented in the waters of the Arabian Sea to retrieve chlorophyll from OCM normalized water-leaving radiances. Chlorophyll estimated this way from OCM data was compared with the *in situ* data collected during OCEANSAT I OCM validation cruises synchronous with satellite over-pass. Data from 47 stations were used in the analysis[9], mainly coming from the open ocean. The OC2 algorithm showed a match-up with $R^2 = 0.85$ and rms error of 0.175. Weekly averaged chlorophyll (OCM) and wind speed data (QuikSCAT) were generated covering the period of the bloom (January–March) and temporal profile and inter annual variability of the two parameters were studied.

A set of images for the eastern part of the NAS showing relative chlorophyll distribution and wind pattern during active bloom has been presented in Figure 2. Weekly averaged wind speed (February 3rd week and March 1st week) and chlorophyll images (February 4th week and March 2nd week) for the two years 2003 and 2004 are also shown in the figure. It can be seen from Figure 2 *c* that high chlorophyll concentration (seen as yellow colour) is uniformly spread over a large area in 2003. Also, traces of orange colour can be seen, which corresponds to chlorophyll concentration of magnitude 1 mg m^{-3} and more. Water samples collected from the ship measured chlorophyll in the range 1–2 mg m^{-3}, which complies with satellite observations. These values are higher at least by a factor

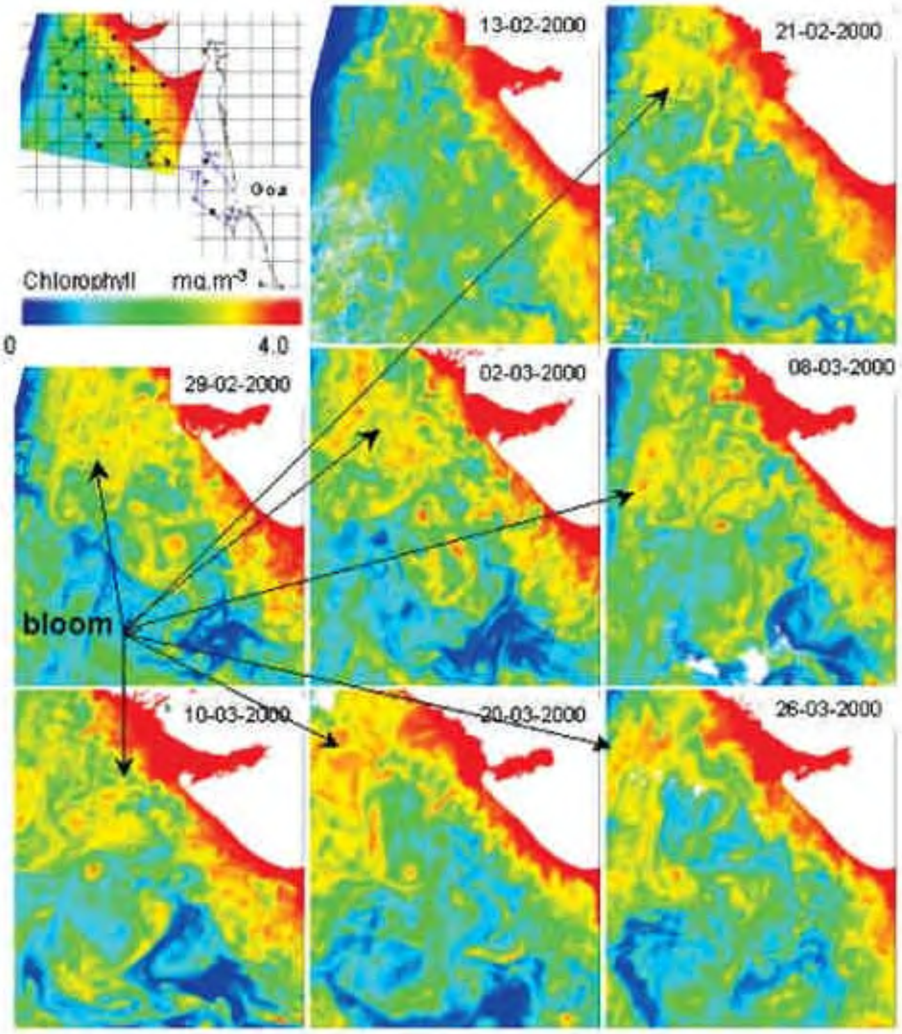

Figure 1. Ship cruise track (top left corner) and time evolution of winter bloom observed from chlorophyll images generated from OCM data.

of two compared to the normally observed values in these waters. Typical chlorophyll concentration in this area was found to be in a range 0.2–0.5 mg m^{-3} during the pre-bloom period (November 2001 and December 2004). Moreover, the observed concentration of chlorophyll during February–March should be considered unusually high as it is from the open ocean (depths 2000–3200 m). In comparison to this, Figure 2 *d* shows patches of high chlorophyll concentration of similar magnitude but smaller in size and scattered in nature, in 2004.

Corresponding to this pattern of chlorophyll in 2003 and 2004, it was observed during the two ship cruises that wind speeds were significantly higher in 2003 and moderate to weak in 2004. It can also be seen from Figure 2 *a* and *b*, which represents QuikSCAT images for average wind speed for the period one week prior to above mentioned chlorophyll images, i.e. 16–22 February 2004 and 15–21 February 2004. The QUikSCAT images were downloaded from the SSM/I website at http://www.remss.com/qscat/qscat_browse.html. It can be seen from Figure 2 *e* and *f* that wind speeds were significantly less in 2004 compared to 2003. Square marked in Figure 2 *e* and *f* represents the bloom site where ship measurements were taken. It can be seen within the square that when wind speed is higher in 2003 relative to the adjacent image in 2004, correspondingly chlorophyll levels in the successive week are found relatively higher in 2003 (Figure 2 *g*).

These preliminary observations indicate that there are distinct variations in wind speeds from 2003 to 2004 and they coincide with corresponding variations in chlorophyll pattern with some time lag. The detailed discussions follow.

Temporal profiles of daily chlorophyll and wind speed generated from the satellite data for four years 2002–05 are shown in Figures 3 and 4. For this, four locations were selected in the bloom site at 19.25°N 66.25°E, 19.75°N 66.25°E, 19.25°N 66.75°E, 19.75°N 66.75°E. Figure 3 represents average wind and chlorophyll from these locations, which are estimated from QuikSCAT and OCM

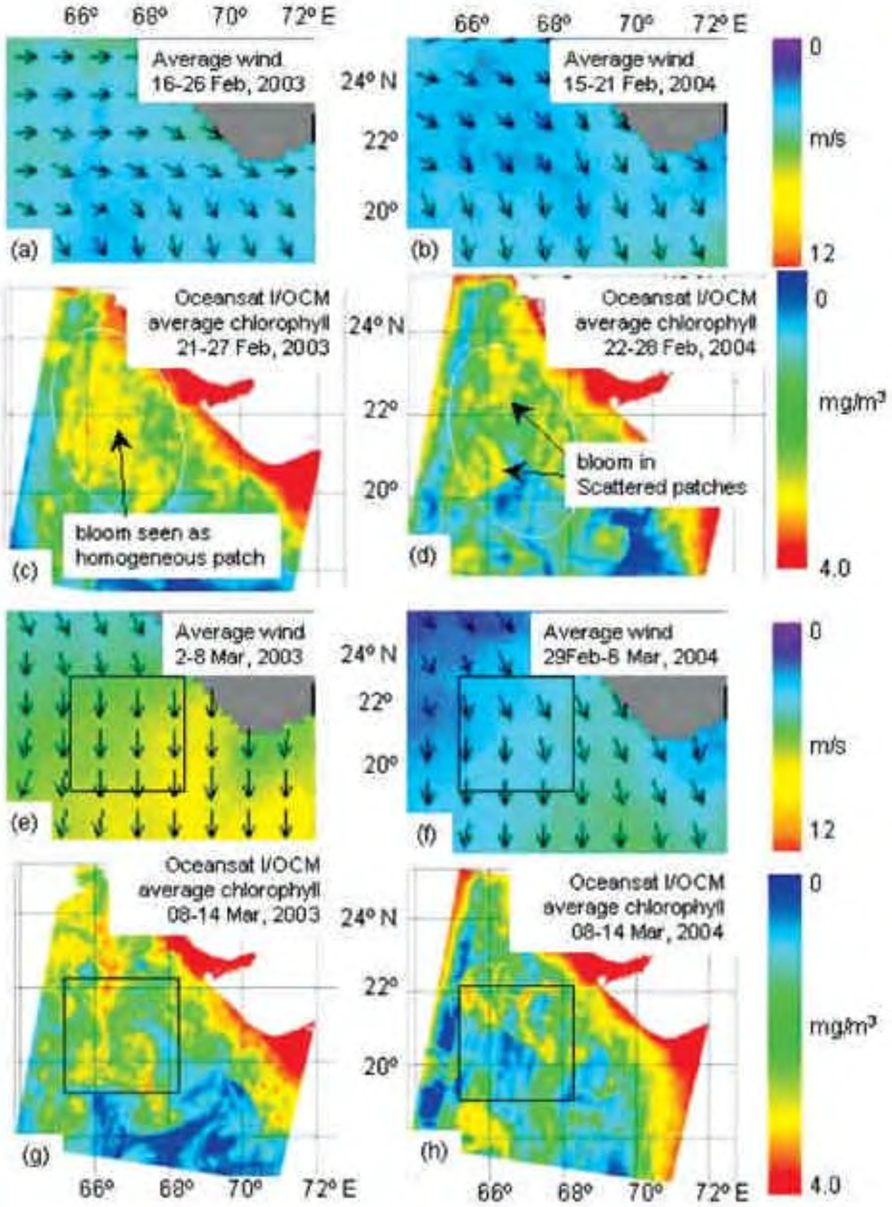

Figure 2. Typical distribution pattern of phytoplankton in February (4th week), March (2nd week) 2003 (homogeneous) and correspondingly in 2004 (discrete). Wind pattern (QuickSCAT) for the two years shows overall higher wind speed in 2003. Square window shows areas of ship observations.

data respectively. It can be seen from Figure 3 that wind speeds are relatively less (1–7 m/s) overall during February–March in 2004 and 2005. This might exert a relatively weak force at the surface, which would cause moderate convection. As a consequence, chlorophyll values are found on the lower side in the range 0.25–0.5 mg/m^3 in these two years. However, anomalous peak in chlorophyll (0.82 mg m^{-3}) is observed during the third week of January 2005. This might be corresponding to high wind speed (8 m/s), which occurred two weeks before in the first week of January in the same year. Wind pattern of 2002 is quite different from the remaining years. Consistently high wind speeds (6–7 m/s) are observed over a long period during January first week to February second week. Correspondingly, chlorophyll contents are also consistently higher till February first week and then decrease with decreasing wind speed. In comparison, wind profile of 2003 shows magnitude of wind speed in the range of 3–8 m/s. Correspondingly, values of chlorophyll concentration are at a higher level in the range 0.3–0.9 mg/m^3.

Inter annual variance of the two parameters, wind and chlorophyll can also be seen in Figure 3. It can be observed that chlorophyll maxima lag behind wind maxima by one to two weeks in most cases. Also, it is found that during the period when wind speed is increasing, chlorophyll content decreases. Convective mixing triggered by sink-

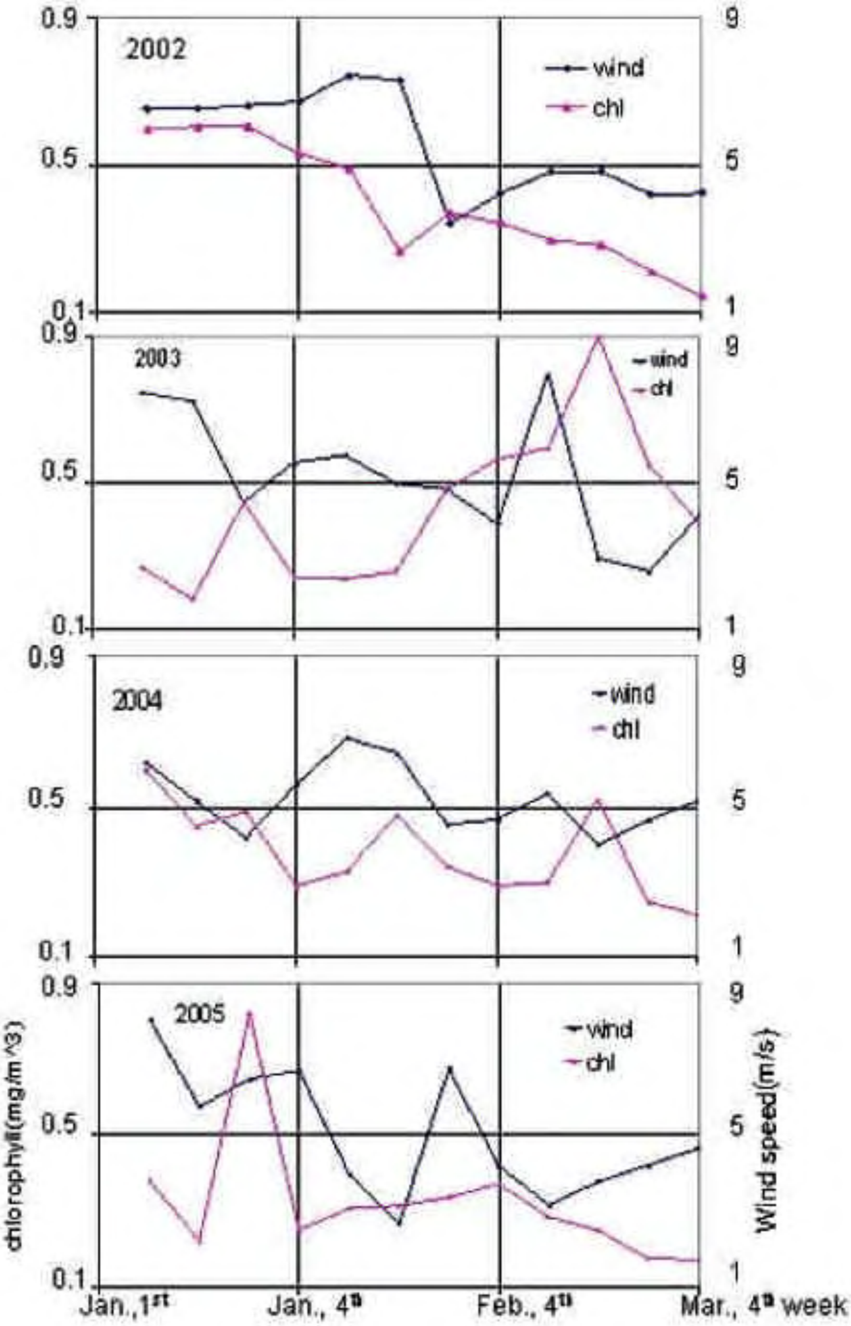

Figure 3. Year-wise inter-comparison of wind speed (QuickSCAT) and chlorophyll (OCM); weekly averaged retrievals over an area 19–20°N, 66–67°E.

ing of denser surface layer causes entrainment of nutrients from deeper layers below the thermocline. The time required in arrival of nutrients in the euphotic zone and subsequent biological response gets reflected in the observed lag (one to two weeks) between chlorophyll and wind force.

In order to quantify the time lag in the increase in the chlorophyll content, cross-correlation was calculated between wind speed and chlorophyll content for different lags. Figure 4 shows the cross-correlation between wind speed and chlorophyll content for time lags 0, 1 and 2 weeks. The correlation pattern reveals that chlorophyll (biological response) lags behind the wind force by at least one to two weeks. The delay in biological response subsequent to the exertion of wind stress on a surface of water mass may be because a series of events follow after the water masses are acted upon by a wind force. For example, cooling of surface waters, densification, sinking of dense surface waters, arrival of nutrients in the euphotic zone and ultimately favouring photosynthesis, etc. All these actions require certain finite time and the observed lag in chloro-

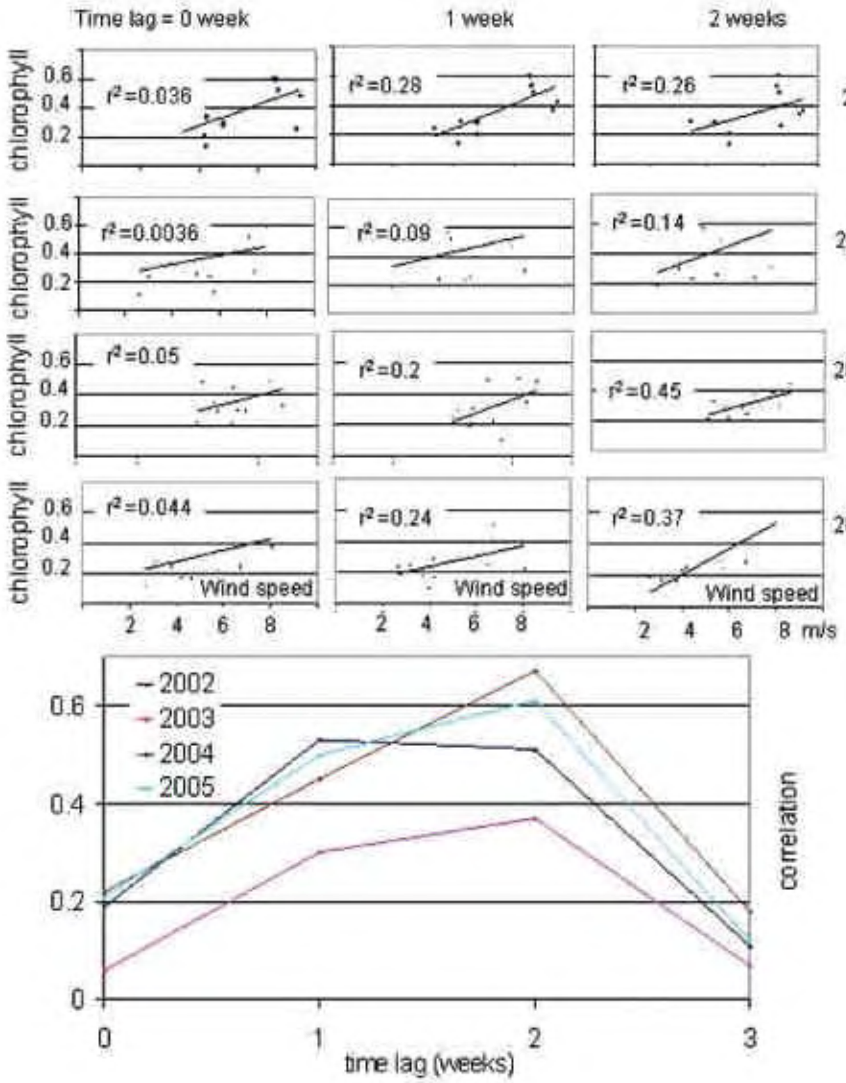

Figure 4. Cross-correlation as a function of time lag between wind speed (m/s) and chlorophyll (mg/m^3).

Table 1. Comparison between chlorophyll and related parameters for the years 2003 and 2004 in the bloom site. The parameters are averaged for different ship stations in the NAS (cruises FORV SS212 and FORV SS222 during February–March 2003 and 2004 respectively)

		Parameters averaged over cruise period			
Cruise	Period	Wind (m/s)	Surface temperature (°C)	Surface density	Chlorophyll (mg/m^3)
FORV SS212	28 Feb–3 Mar 2003	7.1	24.9	24.4	1.37
FORV SS222	29 Feb–6 Mar 2004	4.4	25.5	23.1	0.93

phyll response to fluctuating wind forces manifests the cumulative time consumed in all these processes. A distinct pattern of delayed response of chlorophyll indicates that sudden increase in wind can be treated as a precursor to increase in productivity in the oceanic waters of the NAS. It means that monitoring of wind pattern from a time series data from satellite scatterometer in these waters could provide an early signal as regards likely increase in productivity in the next one or two weeks, which could be used to predict variations in productivity levels ahead of time.

The correspondence of wind speed with chlorophyll is further substantiated by observations from ship data as summarized in Table 1. It can be seen that higher wind

Table 2. Comparison between wind speed and associated hydrographic parameters for a common location (at 20°39′N, 66°58′E) in the bloom site in the NAS during 2003 and 2004 ship cruises

	Cruise SS212 (3 March 2003)	Cruise SS222 (1 March 2004)
Wind speed (m/s)	8.9	6.2
MLD (m)	31	20
Ekman depth (m)	61	45
Nutrient (NO_3 + NO_2, µm/l) at surface	1.05	0.14
Nutrient (NO_3 + NO_2, µm/l) integrated up to 1% light level	50.6	66.4
Chlorophyll (mg/m^3) at surface	1.60	1.17
Chlorophyll (mg/m^3) integrated	61.8	53.7

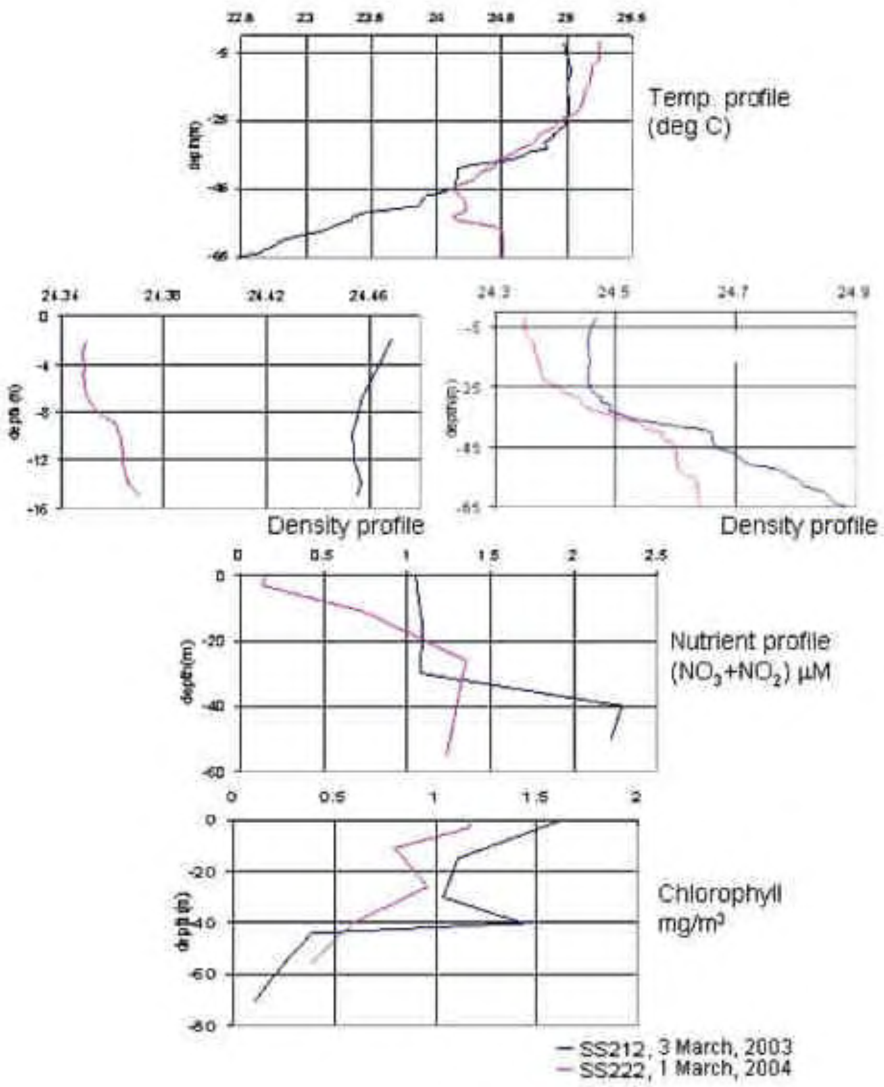

Figure 5. Comparison of temperature and density profile generated from common location (at 20°39′N, 66°58′E) in the NAS during 2003 and 2004 ship cruises.

speed in 2003 compared to that in 2004 resulted in excess cooling of surface water (due to evaporation) and ultimately in increased density. A consequence of this could be intense convective mixing in 2003 and it could inject nutrients up into the surface waters from deeper layers in the NAS during winter. Its effect can be seen in the form of increase in biological activity. Average chlorophyll concentration in the bloom site is comparatively higher in 2003 (Table 1).

It is also evident from Table 2 that MLD and Ekman depth are more in 2003 due to higher wind speed/stress. This is an indication of convective mixing as a repercussion

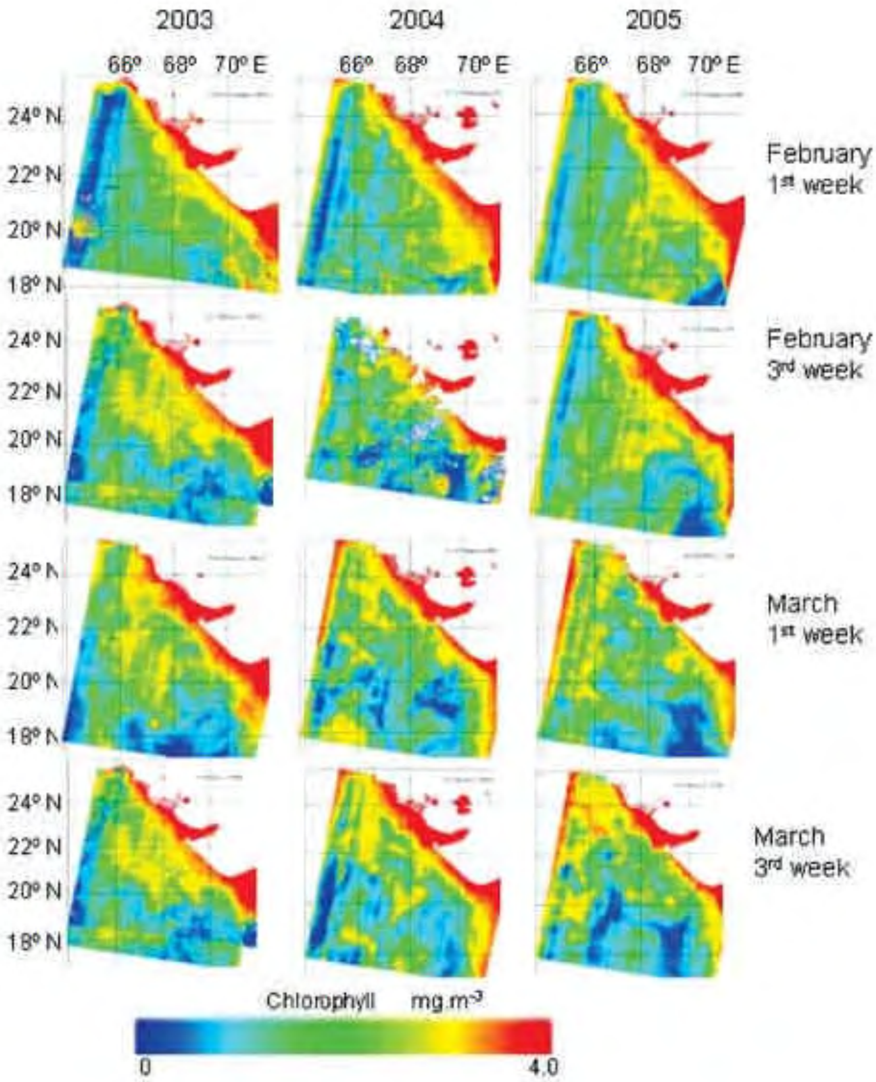

Figure 6. Oceansat I/OCM weekly chlorophyll images of 2003–05. A common line segment as shown in 2003 images is considered for spatial profile (Figure 7).

Table 3. Average *Noctiluca millaris* concentration observed during 2003 and 2004

	Ship cruise FORV 212 (2003)	Ship cruise FORV 222 (2004)
Noctiluca (cells/l)	1354	596
Noctiluca (%)	42.5	8.0

of increased density of water masses at the surface, which ultimately might result in vertical transport of nutrients in the euphotic zone due to entrainment. Nutrient profile in Figure 5 reflects this pattern. Nutrient enrichment and correspondingly larger increase in chlorophyll levels can be seen in 2003 compared to the same in 2004. Chlorophyll concentration is as high as 1.6 mg/m^3 at the surface, which is more compared to that in 2004 (Figure 5, Table 2). Thus, relatively more chlorophyll concentration in 2003 can be a result of the combined effect of convection due to densification of surface waters and increased MLD. Wind plays a role in both the cases.

The discussion to follow now provides further explanation for higher concentration of chlorophyll in 2003 as against that in 2004. Common location of the ship stations was considered (at 20°39′N, 66°58′E) for inter comparison of hydrographic parameters measured from both the cruises with near coincident dates, 3 March 2003 and 1 March 2004. Vertical profiles of density and temperature for these two stations have been generated using CTD data and are shown in Figure 5. Corresponding to strong winds in 2003, the surface waters are found cooler due to evaporative action as can be seen from Figure 5. Moreover, vertical profile of 2003 reveals relatively higher density near the surface compared to that in deeper waters. In both

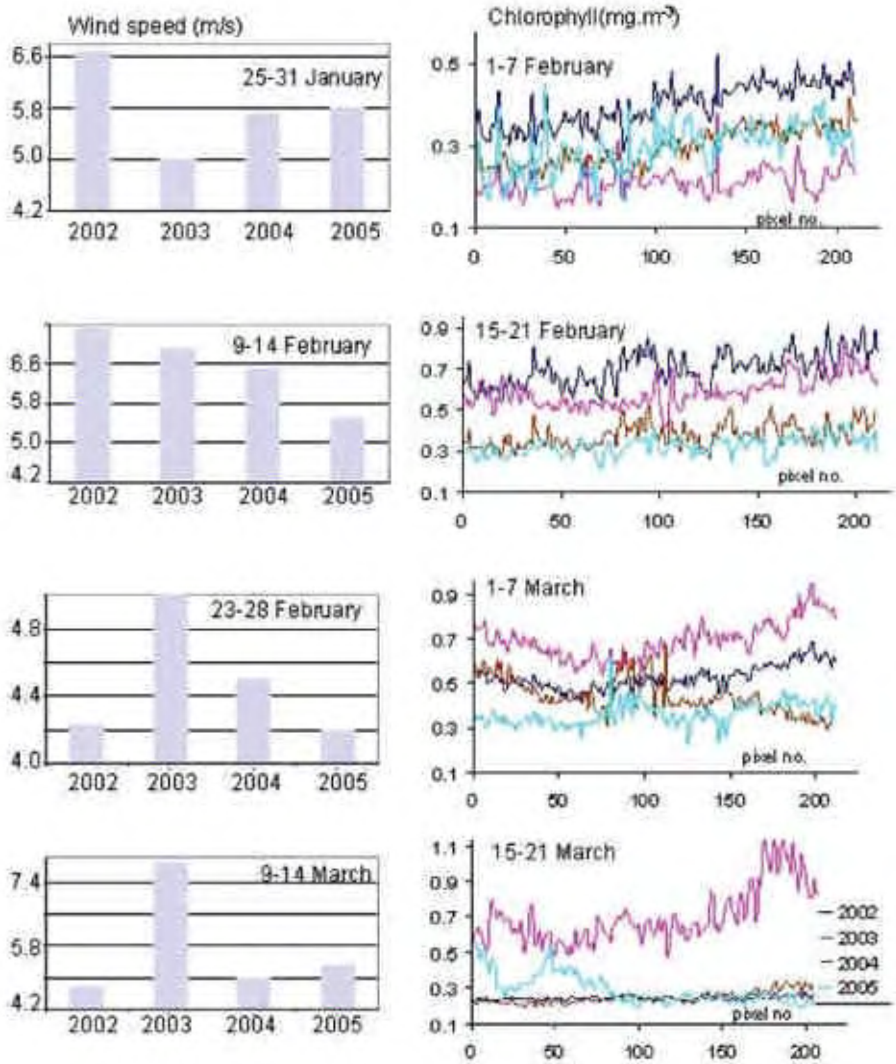

Figure 7. Weekly averaged wind speed (QuickSCAT) and spatial profile of surface chlorophyll (OCM) with time difference of one week.

cases, surface density is higher than in a column below indicating an unstable situation. A situation like this would trigger sinking of surface waters leading to convection. Densification of surface waters is found to be relatively stronger in 2003 compared to that in the successive year. Higher density in the top layers can be seen extending up to 10 m in 2003 profile compared to a thinner, dense layer of 4 m in 2004. Table 1 shows a comparison of wind speed and associated hydrographic parameters for a common location and near coincident dates. It can be seen that surface water is comparatively cooler with higher density in 2003 when wind speed is more. Increased evaporation due to stronger winds could result in a pattern like this. This might lead to sinking of water mass.

Average concentration of *Noctiluca* from the bloom site was computed and is presented in Table 3. Relatively higher cell concentration of *Noctiluca* was measured in 2003 when wind forces responsible for setting convection were relatively stronger. A pattern of this nature (strong wind followed by high productivity) indicates that productivity of the water masses in this area is controlled by wind-triggered convection that is activated by inversion of density of surface waters.

Comparisons of weekly averaged chlorophyll images (February first and third week, March first and third week) of 2003–05 can be made from Figure 6, to study inter-annual variance. Location of the segment from which the spatial profiles have been generated is marked in the chlorophyll images of 2003 on the left. A pattern of spatial profiles in Figure 7 shows that concentration of chlorophyll remains on a higher side all the time in a season of 2003 compared to the same in 2004, except during the first week of February 2003. Wind pattern of the previous week (with reference to chlorophyll pattern) as shown in

Figure 7, indicates that increase or decrease in chlorophyll is in accordance with previous week's wind pattern, i.e. with a time lag of one week. It can be seen from Figure 7 that wind speed is less in 2003 in the fourth week of January compared to the same in 2004 and 2005. This gets reflected in chlorophyll pattern of the first week of February, in the form of lower chlorophyll in 2003. For the remaining period, chlorophyll content in 2003 is higher compared to that in 2004 and 2005. Accordingly, wind speed of the previous week is always more in 2003.

Inter-annual variance in chlorophyll of deep waters of the NAS is observed from satellite and ship data. Though northeasterly winds over the Arabian Sea are seasonally regular, there are variations in their magnitude from year to year. Variations in chlorophyll pattern in these waters are consistent with those in the prevailing northeasterly winds. This happens through a combined mechanism of wind-induced increase in density and Ekman depth, which causes nutrient enrichment in euphotic depth. Thus, the two parameters, biological (chlorophyll) and physical (wind, surface density, etc.) co-vary and the response of chlorophyll to changing wind pattern is observed with time lag of one to two weeks. For this reason, wind can be used as an indicator to predict chlorophyll pattern.

1. Banse, K. and McClain, C. R., *Mar. Ecol. Prog. Ser.*, 1986, 201–211.
2. Barber, R. T. and Chavez, F. P., *Limnol. Oceanogr.*, 1991, **36**, 1803–1815.
3. Madhupratap, M., Prasannakumar, S., Bhattathiri, P. M. A., Dileepkumar, M., Raghukumar, S., Nair, K. K. C. and Ramaiah, N., *Nature*, 1996, **384**, 549–552.
4. Prasanna Kumar, S., Madhupratap, M., Dileep Kumar, M., Gauns, M., Muraleedharan, P. M., Sarma, V. V. S. and De Souza, S. N., *Deep Sea Res.*, 2000, 433–441.
5. Matondkar, S. G. P., Bhatt, S. R., Dwivedi, R. M. and Nayak, S. R., *Harmful Algae News, IOC Newsl.*, pp. 4–5.
6. Gordon, H. R., *J. Geophys. Res.*, 1997, **102**, 17081–17106.
7. Gordon, H. R. and Wang, M., *Appl. Opt.*, 1994, **33**, 443–452.
8. O'Reilly, J. E., Maritonena Mitchell, B. G., Siegal, D. A., Carder, K. L., Graver, S. A., Kahru, M. and McClain, C. R., *J. Geophys. Res.*, 1998, **103**, 24937–24963.
9. Chauhan, P., Mohan, M. and Nayak, S., Proceedings 4th Berlin Workshop on Remote Sensing '5 Years of MOS-IRS, 2001, pp. 45–61.

ACKNOWLEDGEMENTS. We are grateful to the Centre for Marine Living Resources, Department of Ocean Development, Govt of India for extending services of research vessel, FORV *Sagar Sampada*, to carry out *in situ* observations during winter bloom in the northern Arabian Sea for two consecutive years.

Received 21 February 2005; revised accepted 31 January 2006

Crustal structure at the epicentral zone of the 2005 Kashmir (Muzaffarabad) earthquake and seismotectonic significance of lithospheric flexure

D. C. Mishra* and R. P. Rajasekhar

National Geophysical Research Institute, Hyderabad 500 007, India

The Bouguer anomaly map of the epicentral zone of Kashmir earthquake is compiled from different sources. The observed gravity high related to Lahore–Sargodha ridge is attributed to flexural bulge due to collision of the Indian and Eurasian plates. A gravity profile is modelled across this region constrained from the available deep seismic sounding profiles, which suggest a flexural bulge of 3–4 km due to the load of the Himalayas. The hypocentre of this earthquake at a depth of 26 km lies at the junction of this flexural bulge with crustal thickening (70–72 km) towards the north under the Karakoram–Hindukush ranges, which represent the central core complex of collision tectonics. In fact, the hypocentres of all major seismic activities along the Southern Himalayan Front, which are mostly confined between 5–10 and 30–35 km coincide with this junction. These levels may represent shallow decollement plane and an intermediate weak zone caused by differential stress due to plate movement and flexural bulge, that would have caused extension and compression in the upper and lower crusts respectively. The depth to intermediate crustal zone under the Himalayas and Tibet approximately coincides with the effective elastic thickness in this region, implying weak part of the crust that may be caused by the presence of fluids.

Keywords: Effective elastic thickness, flexural bulge, gravity anomalies, Himalayan seismicity, Muzaffarabad earthquake.

THE Himalayan collision zone is one of the most active plate boundaries that generated several large and great earthquakes[1]. The recent Kashmir earthquake[2] of magnitude of 7.6 with focal depth of about 26 km occurred south of the Main Boundary Thrust (MBT), where it takes an inverted U-turn from NNW to SSE (Figure 1). Historically, this region known as Hazara Kashmir Seismic Zone (HKSZ) along with the Hindukush Seismic Zone (HSZ), NW of it, forms an active zone[3] (Figure 1). The inverted U-turn of MBT and other tectonic elements of this region forms the Hazara Kashmir Syntaxis. Two major trends, viz. N–S of the Sullaiman range and E–W of the Himalayan range interact in this section to form the syntaxis. Such turns and interactions of trends form the knot, which is the most preferred site for stress accumulation.

*For correspondence. (e-mail: dcm_ngri@yahoo.co.in)