Surface chlorophyll-*a* distribution in Arabian Sea and Bay of Bengal using IRS-P4 Ocean Colour Monitor satellite data

Remote sensing of ocean colour yields information on the constituents of sea water such as the concentration of phytoplankton pigments, suspended sediments and yellow substance. The methods of detecting and mapping sea water constituents from aircraft and from space-borne platform have been successfully developed during the past three decades[1–3]. Routine monitoring of the regional and temporal variability of ocean chlorophyll provides information on primary production and subsequent assessment of secondary and higher order production processes such as zoo-planktons and marine fisheries.

On 26 May 1999, Indian Space Research Organization (ISRO) launched the IRS-P4 satellite, carrying Ocean Colour Monitor (OCM), which is designed to measure ocean colour, the spectral variation of water-leaving radiance that can be related to concentration of phytoplankton pigments, suspended matter and coloured dissolved organic matter in coastal and oceanic waters, and the characterization of atmospheric aerosols. The details of the technical specifications of OCM payloads can be found in ref. 4.

In the remote sensing of ocean, the radiance backscattered from the atmosphere and/or sea surface (specular reflection) is typically at least an order of magnitude larger than the desired radiance scattered out of the water, known as water leaving radiance L_w. The goal of atmospheric correction is to retrieve L_w from the total radiance measured at the sensor, L_t.

In the ocean colour remote sensing, the total signal received at the satellite altitude is dominated by radiance contribution through atmospheric scattering processes and only 8–10% of the signal corresponds to oceanic reflectance. Therefore it is mandatory to correct for atmospheric effects, to retrieve any quantitative parameter from space. The radiance received by a sensor at the top of the atmosphere (TOA) in a spectral band located at a wavelength λ_i, $L_t(\lambda_i)$ can be divided into the following components:

$$L_t(\lambda_i) = L_a(\lambda_i) + L_r(\lambda_i) + T(\lambda)L_g(\lambda_i) + t(\lambda_i)L_w(\lambda_i), \quad (1)$$

where L_a and L_r are the radiance generated along the optical path by scattering in the atmosphere due to aerosol and Rayleigh scattering, respectively, L_g is the specular reflection or sun glitter component and L_w is the desired water-leaving radiance. In (eq. (1)), T and t are the direct and diffuse transmittance terms, respectively. Gordon and Clark[5] have shown that for NIR channels the water-leaving radiance coming out of the ocean can be assumed near zero, and if the effect of sun glitter is also neglected, then eq. (1) can be written as:

$$L_t(\lambda_i) = L_a(\lambda_i) + L_r(\lambda_i)$$
$$\text{for } \lambda_i > 765 \text{ nm, i.e. } L_w \approx 0. \quad (2)$$

From eq. (2) it is clear that over the clear oceanic water regions, the TOA radiances in 765 nm and 865 nm channels, mainly correspond to the contribution coming only from the atmosphere, as the water-leaving radiance L_w (765 and 865 nm) can be safely assumed to be equal to zero. The Rayleigh scattering term $L_r(\lambda)$ is computed using the well-established theory. Using eq. (2), once L_r is known, L_a can be determined as:

$$L_a(\lambda_i) = L_t(\lambda_i) - L_r(\lambda_i)$$
$$\text{for } \lambda_i \geq 765 \text{ nm.} \quad (3)$$

IRS-P4 OCM payload has 765 and 865 nm channels in NIR region; using these two bands a relationship is obtained for the spectral dependence of the aerosol optical depth on pixel by pixel basis. Gordon and Wang[6] have proposed an exponential relationship for spectral behaviour of aerosol optical depth compared to a power law-based spectral relationship of aerosol optical depth for marine aerosols. A similar approach is used to estimate an epsilon function for 765 and 865 nm bands for each pixel. The epsilon function is defined as:

$$epsilon = L_a(765)/L_a(865), \quad (4)$$

$$L_w (\lambda_{i < 750}) = (L_{ac}(\lambda_i) - L_a(865)$$
$$*\exp [\log(epsilon)/(865 - 765)]$$
$$*(865 - \lambda))/t(\lambda), \quad (5)$$

where $L_{ac}(\lambda_i)$ is the Rayleigh and ozone corrected radiance for $\lambda_i < 750$ nm and $t(\lambda_i)$ is diffuse transmittance term. Using eq. (5) water-leaving radiance images were generated for short-wavelength channels of 412, 443, 490, 510 and 555 nm, respectively.

A number of bio-optical algorithms for chlorophyll retrieval have been developed to relate measurements of ocean radiance to the *in situ* concentrations of phytoplankton pigments. More recently, O'Reilly *et al.*[7] have proposed an empirical algorithm (also known as Ocean Chlorophyll 2 or OC2) to be operated on SeaWiFS ocean colour data. This algorithm captures the inherent sigmoid relationship between $R_{rs}490/R_{rs}555$ band ratio and chlorophyll concentration C, where R_{rs} is remote sensing reflectance. The algorithm operates with five coefficients and has the following mathematical form:

$$C = 10^{\wedge}(0.319 - 2.336*R + 0.879*R^2 -0.135* R^3) - 0.071 \quad (6)$$
$$\text{for } 0.01 \text{ mg/m}^3 \leq C \leq 50 \text{ mg/m}^3,$$

where $R = \log_{10} [R_{rs}(490)/R_{rs}(555)]$.

IRS-P4 OCM data sets for 29 and 30 January 2000 were processed using the above-described processing method. The chlorophyll-*a* images were generated for path 9, 10 and 11 covering parts of Arabian Sea and Bay of Bengal. Figure 1 shows a mosaic image of all these passes. This mosaic image shows chlorophyll-*a* spatial distribution at 360 m spatial resolution. The higher resolution of IRS-P4 OCM data helps in identifying the small-scale coastal features of plankton distribution. Figure 1 shows higher chlorophyll concentration values in the northern Arabian Sea and in the riverine estuaries of the Narmada and the Mahi on the west coast of India, the Ganga on the east coast of India and
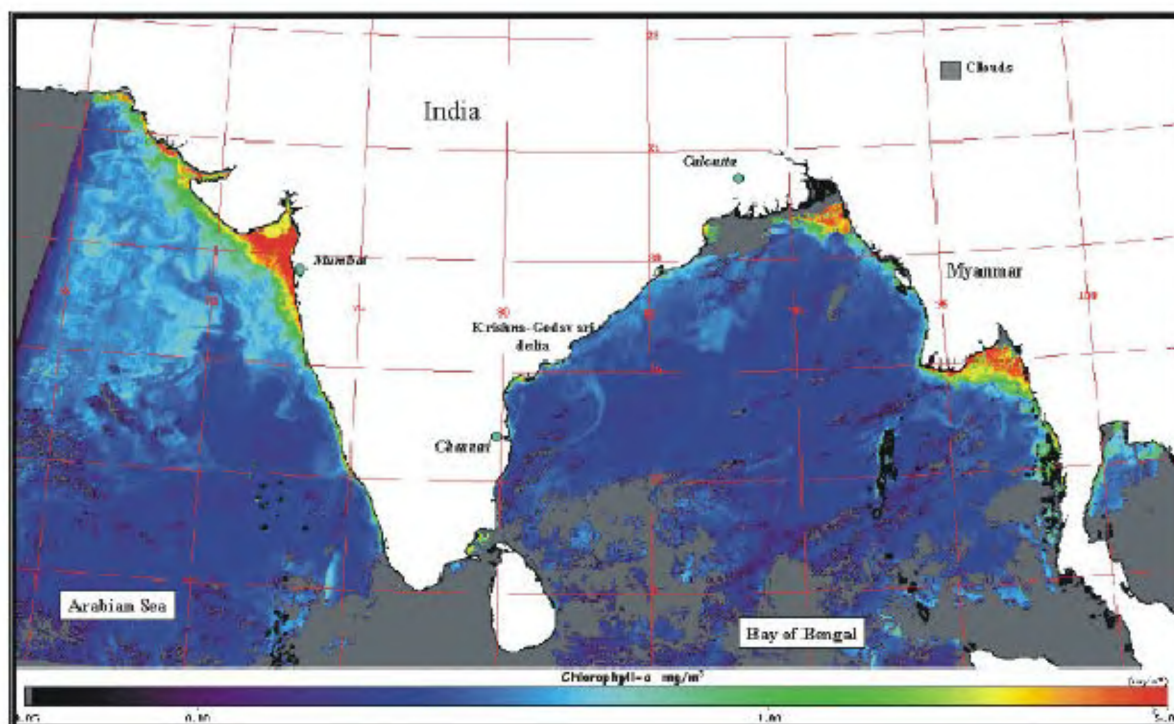
Figure 1. IRS-P4 OCM-derived chlorophyll-*a* image for Arabian Sea and Bay of Bengal for 29 and 30 January 2000. High pigment concentration in northern Arabian Sea is attributed to the winter cooling phenomenon. A meso-scale nutrient-rich river plume emerging out of Krishna–Godavari delta is also depicted.
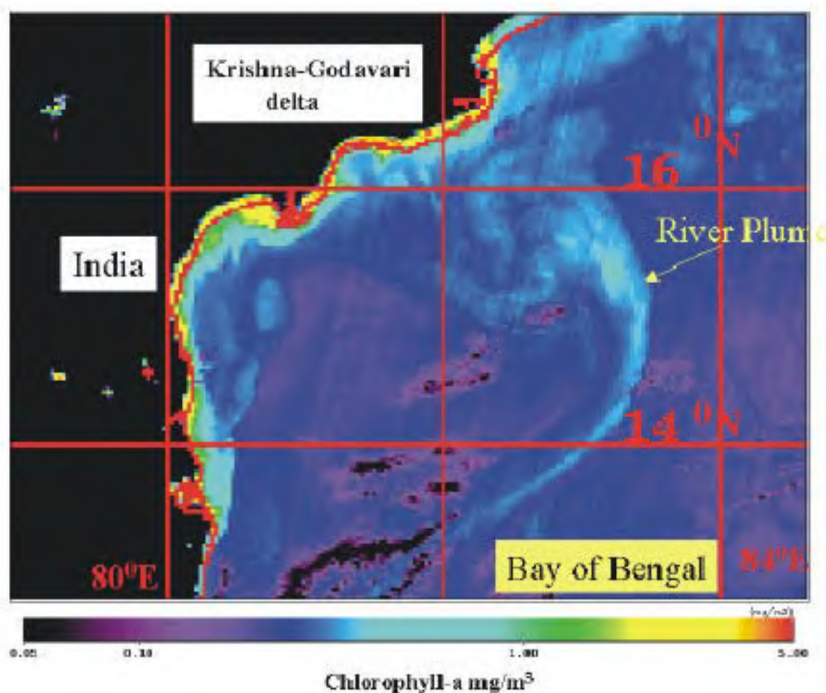
Figure 2. IRS-P4 OCM-derived chlorophyll-*a* image, depicting a meso-scale riverine plume, associated with high pigment concentration. The plume is emanating from Krishna–Godavari delta on the east coast of India.

the Iravadi, off Myanmar coast. On the east coast of India, a large-scale river plume extending deep into the open ocean has been detected, which is emanating out of the Krishna and Godavari delta (Figure 2). Such a pattern provides information on the fresh water transport into the open ocean and mixing of fresh water and saline water in oceanic environment. The open ocean waters of Bay of Bengal were found to be oligotrophic and are characterized by the chlorophyll concentration values less than 0.30 mg/m^3.

Higher chlorophyll values in the northern Arabian Sea are associated with the winter cooling phenomenon, normally reported to occur during January to March in the Arabian Sea[8]. During this period atmospheric forcing, that leads to the observed changes in the upper layer of the ocean, is a combination of enhanced evaporation under the influence of dry continental air from the north brought by the prevailing northeasterly trade winds and reduction in solar insolation. Accordingly, the Arabian Sea, north of 15°N, experiences

cooling (i.e. reduction in sea surface temperature (SST) by about 4°C) and densification. This leads to the formation of Arabian Sea High Salinity Waters (ASHSW)[8], which further leads to sinking and convective mixing and injection of nutrients into the surface layers from the thermocline region. The nutrient injection to the upper layers of the water column triggers the higher primary production and often leads to winter blooms in offshore regions. Figure 1 shows an example of one such bloom condition in northern Arabian Sea, chlorophyll concentration values range between 0.35 and 0.85 mg/m^3 for the open ocean waters beyond 14°N latitude. Very high chlorophyll concentration values of more than 1.0 mg/m^3 are observed around 15°N and 66°E region, characterizing a typical offshore bloom situation.

IRS-P4 OCM satellite data for paths 9, 10 and 11 of 29 and 30 January 2000 were processed for atmospheric correction and chlorophyll-*a* concentration retrieval using OC-2 bio-optical algorithm. The processed strips of different paths were used in creation of Arabian Sea and Bay of Bengal chlorophyll distribution mosaic image. The retrieved chlorophyll concentration values were found to match reasonably with expected chlorophyll variations in Bay of Bengal and Arabian Sea, during the month of January. In general, IRS-P4 OCM-derived chlorophyll product has been found to be very useful in studying basin scale oceanic and coastal processes and assessment of primary production areas.

1. Arvensen, J. C., Millard, J. P. and Weaver, E. C., *Astronaut. Acta*, 1973, **18**, 229–239.
2. Clarke, G. L., Ewing, G. C. and Lorenzen, C. J., in Proc. Sixth Int. Symp. Remote Sensing in the Environment, Ann Arbor, 1969, vol. 2, pp. 991–1001.
3. Dorffer, R. and Fischer, J., *J. Geophys. Res.*, 1994, **99**, 7457–7466.
4. Report on IRS-P4 (*Oceansat-1*) mission, Indian Space Research Organisation, Banglore, India, August 1999.
5. Gordon, H. R. and Clark, D. K., *Appl. Opt.*, 1981, **20**, 4157–4180.
6. Gordon, H. R. and Wang, M., *Appl. Opt.*, 1994, **33**, 443–452.
7. O'Reilly, J. E., Maritorena, Mitchell, B. G., Siegal, D. A., Carder, K. L., Graver, S. A., Kahru, M. and McClain, C. R., *J. Geophys. Res.*, 1998, **103**, 24937–24953.
8. Prasanna Kumar and Prasad, T. G., *Curr. Sci.*, 1996, **71**, 834–841.

PRAKASH CHAUHAN*
C. R. C. NAGUR
M. MOHAN
S. R. NAYAK
R. R. NAVALGUND

Remote Sensing Applications Area,
Space Applications Centre (ISRO),
Ahmedabad 380 053, India
*For correspondence.