

An empirical method to estimate bulk particulate refractive index for ocean satellite applications

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ABSTRACT

An empirical method is presented here to estimate bulk particulate refractive index using the measured inherent and apparent optical properties from the various water types of the Arabian Sea. We have used the empirical model, where the bulk refractive index is modeled in terms of the backscattering ratio and the hyperbolic slope of the particle size¹. Empirical models are obtained to determine the slope of the particle size and backscattering ratio as a function of the remote sensing reflectance. We have used these algorithms with the IRS-P4 OCM satellite data and derived the refractive index image. The values of indexes are found to be lower for the open ocean and relatively higher for the coastal waters. Distinct features are observed even in the waters with similar chlorophyll concentrations. This algorithm provides scope for the classification of water types and detection of blooms.

Keywords: refractive index, particle size distribution, backscattering ratio, bloom, IRS-P4 OCM,

1. INTRODUCTION

Light scattering by particles depends on the particle's size, index of refraction, composition, and shape². The refractive index (or index of refraction) of a material is the factor that relates the phase velocity of electromagnetic radiation in that material, relative to its velocity in another medium or material. The absolute refractive index is relative to the velocity of light in the vacuum. The refractive index is a complex value, $m = n - in'$. Here the real part n is the refractive index indicating the phase velocity as above, while the imaginary part n' is called the extinction coefficient, which indicates the amount of absorption loss when the electromagnetic wave propagates through the material. ($i = \sqrt{-1}$).

Presently most of the carbon estimation and primary productivity use the bulk chlorophyll estimated from in-situ measurements using standard fluorometric, spectrophotometric and chromatographic methods and from the ocean colour satellite sensors. Bulk chlorophyll values provide information of the large population of cells that could be of heterogeneous in nature.

Refractive index is approximately proportional to the density of the substance and the real part of the refractive index of phytoplankton depends on the water and solid contents of the cell, rather than the chemical composition. The study shows that the real part of the refractive index is proportional to the intracellular specific carbon concentrations and the imaginary part in the higher wavelength in the red region is shown to correlate well with the intracellular specific concentration of chlorophyll. Through a limited few species of phytoplankton, it has been shown that the relationships between specific carbon concentration with the real part of refractive index, n and the specific chlorophyll concentrations with the imaginary part of refractive index n' is found to hold for a variety of planktonic species regardless of interspecies and intraspecies variability in cellular carbon and chlorophyll content and also the size³. Thus determining refractive indices of water could provide information about the phytoplankton community and also better estimation of carbon.

Refractive index is determined using theoretical and empirical methods with some assumptions and measured values. Various methods of direct measurements for determining the refractive indices are employed depending on the type of materials⁴. Refractive index of liquids are measured using refractometer that use the classical approach using the angular dependence of reflectance or the critical angle. The other broad class of instruments to determine refractive index that employ interferometric methods are Rayleigh refractometer, Mach-Zehnder, Jamin, Michelson and Fabry- Perot interferometer. Marine biological samples such as phytoplankton are measured using flow cytometer and the refractive indexes are retrieved applying the Mie theory^{5, 6}. Metabolic composition of phytoplankton also provides information about its refractive index⁷. Phase contrast microscopic methods are also used for determining refractive index.

The standard values of the absolute refractive index, at 589.3 nm light, atmospheric pressure of 760 mm Hg and temperature of 20.0°C are 1.333336 for water and 1.000272 for air. The refractive index of water is the lower limit for biological materials and it is assumed that the water of the algae has the same density and refractive index as seawater and its value is taken as 1.339 at density of 1.025 g/cm³, which correspond to the salinity 35.0 psu, at temperature 20.0°C and the wavelength 589 nm. For most of the marine biological applications the refractive index is taken relative to the seawater and here too all values of refractive indexes are relative to the seawater.

The living organic materials have lower refractive indexes close to unity, which is due to their high water content. Most of the phytoplankton volume consists of water and the main organic constituents or major metabolites are proteins, carbohydrates and fats. Metabolite composition of phytoplankton also provides information about its refractive index⁷. Several cellular structures are observed in the phytoplankton. Some species have an external silica shell, calcite scales, internal silica and some have gas vacuoles. Here for the mean refractive index of the alga, the structure has been neglected and all constituents have been regarded as evenly distributed. The bulk indexes of relative refraction for phytoplankton are in the range of 1.02 to 1.07⁸ and for inorganic particles such as quartz and aragonite within 1.15 and 1.24. The spectral variations of refractive indexes of marine particles are marginal, except in the strong absorption bands⁷.

2. METHOD

The refractive index of particle m_p is given as a complex value, $m_p = n_p - i n_p'$. The real part of the bulk particulate refractive index n_p is the value that reproduces the bulk scattering properties of a particle assemblage. It is equivalent to the average of the individual indices of refraction weighted by the scattering cross sections of all the particles. The inverse methods that have been used in extracting these properties require knowledge of volume scattering and other optical properties, which are not easy to measure. Here we use an empirical method to derive refractive index, which is modeled in terms of optical properties, which can be measured. Using the Mie theory it was shown that for realistic oceanic particle assemblages, the particulate backscattering ratio (the ratio of backscattering to total scattering by particles, b_{bp}/b_p) could be related to the bulk index of refraction of the assemblage¹ and the bulk refractive index n_p is given as

$$n_p(b_{bp}, \gamma) = 1.0 + A[B_0 + B_1 + B_2] \quad (1)$$

where

$$A = b_{bp}^{\sim k}$$

$$k = 0.5377 + 0.4867(\xi-3)^2$$

$$B_0 = 1.4676$$

$$B_1 = 2.2950 (\xi-3)^2$$

$$B_2 = 2.3113 (\xi-3)^4$$

The value of ξ is determined from the spectral particulate beam attenuation coefficient $c_p(\lambda)$, as

$$c_p(\lambda) \propto \lambda^{-\gamma} \quad (2)$$

Since the slope of the spectral variations of beam attenuation γ is found to covary with the slope of the hyperbolic particle size distribution model ξ , the γ is related to ξ as $\gamma = \xi - 3$ which is refined to a value of $\xi = \gamma + 3 - 0.5e^{-6\gamma}$. Though the range is $2.5 < \xi < 5.0$, for most oceanic particles $3.0 < \xi < 4.5$ and the value of ξ decreases with increases in mean particle size⁹.

2.1 Optical Data

The bio-optical data were measured in the eastern Arabian Sea during the cruise SK-171 on board the research vessel, O.R.V. Sagar Kanya from 3 to 17 November, 2001. The measurements covered all water types from coastal to deep ocean, oligotrophic, highly productive and turbid waters. The measurements and processing of the optical data were carried-out adhering to the protocols recommended by NASA for the ocean color program. We have used the profiling instruments ac-9 (<http://www.wetlabs.com>) and Hydroscat-2 (<http://www.hobilabs.com>) to obtain the inherent optical properties and radiometer OCP-100/OCI-200 (<http://www.satlantic.com>) to measure apparent optical properties at very fine depth resolution of the water column. The instrument ac-9 provide absorption $a(\lambda)$ and beam attenuation $c(\lambda)$ data at nine discrete wavelengths of 412, 443, 488, 510, 532, 555, 650, 676 and 715 nm and Hydroscat-2 measure the backscattering coefficients at two discrete wavelengths, 470 nm and 676 nm. The ac-9 provides data without the contribution from the water molecular scattering and absorption, while Hydroscat-2 data include the scattering contribution from the water. The profiling unit of the radiometer provides downwelling irradiance and upwelling radiance at discrete wavelengths of 412.4, 442.8, 491, 509.2, 554.2, 669.4 and 683.5 nm and the reference unit at the deck provides the solar irradiance at these wavelengths. The ac-9 data is processed with salinity and temperature corrections using the CTD data obtained at the stations. Thereafter scattering corrections are applied using the Method 3 as the recommended in the protocol for the analysis of ac-9 data¹⁰. The sigma corrections are performed on the backscattering coefficient profiles using the data obtained from the ac-9. The sigma correction algorithm to correct for attenuation of the source beam was applied using the $a(\lambda)$ and $c(\lambda)$ measured with the ac-9¹¹. The inherent optical properties used for the study are the values averaged over the euphotic depth. The surface remote sensing reflectance values are obtained from processing the radiometer data using the proprietary software Prosoft 7.7 of the instrument. We also determined chlorophyll from the water samples collected at discrete depths, using the standard fluorometric method.

The bulk refractive n_p as given in equation 1 is a function of the backscattering probability and the slope of the spectral variation of the beam attenuation coefficient, which can be derived using the measured optical parameters.

2.2 Refractive index model

Here we use an empirical method to determine the backscattering ratio and the hyperbolic slope of the particle size distribution (PSD) slope with the in-situ measured optical properties of the Arabian Sea.

Empirical relation of γ

We find a relationship between the ratio of remote sensing reflectance at two bands and the index γ of the spectral variation of the particulate beam attenuation $c_p(\lambda)$.

The beam attenuation measured by the ac-9, $c(\lambda)$ is given as

$$c(\lambda) = c_t(\lambda) - c_w(\lambda) \quad (3)$$

$$c_p(\lambda) = c(\lambda) - a_d(\lambda) \quad (4)$$

where $c(\lambda)$ is the beam attenuation measured by the ac-9 instrument, which excludes the contribution from water $c_w(\lambda)$, from the total beam attenuation, $c_t(\lambda)$. The measured values of beam attenuation coefficients from ac-9 are contribution from the particulate matter $c_p(\lambda)$ and the dissolved or detrital matter. Since there is no scattering from the dissolved matter, the beam attenuation coefficient is a sum of the contribution due to absorption from phytoplankton $a_p(\lambda)$ and the detrital and dissolved matter $a_d(\lambda)$ and scattering from particulate matter, $c(\lambda) - a(\lambda)$. The absorption measured by the ac-9 excludes contribution from the water and includes absorption due to phytoplankton and detrital and dissolved matter.

$$a(\lambda) = a_p(\lambda) + a_d(\lambda) \quad (5)$$

Using a bio-optical model, we determine the absorption due to phytoplankton, $a_p(\lambda)$ with the measured chlorophyll¹². The chlorophyll values are available at discrete depths, obtained from the analysis of the water samples at these discrete depths, using the standard protocol. This value of the chlorophyll at the given depth is subtracted from the value of $a(\lambda)$ at the same depth to provide the contribution of detrital and dissolved organic matter at discrete depths. We use these spectral values to determine the mean spectral variation of the detrital and the dissolved component for the station, which is subtracted from all the values of $c(\lambda)$ to obtain the $c_p(\lambda)$ as given in equation 4 above.

The value of γ which is an index of the spectral variation of particulate beam attenuation $c_p(\lambda)$ is obtained by a robust fit using all the spectral values at the wavelengths of ac-9. We did not find large variations in the values of γ obtained using $c_p(\lambda)$ and $c(\lambda)$. The range of values of γ obtained is within 0.33 to 1.597 and the equivalent range of values for ξ is in the range of 3.268 and 4.597. The empirical model for γ using the ratio of measured remote sensing reflectance is given below.

$$\gamma = A + B \left[\frac{Rrs(555)}{Rrs(670)} \right] \quad (6)$$

where $A = 0.30067$ and $B = 0.11$ and ($r^2 = 0.9$, after discarding few outliers). See Fig. 1.

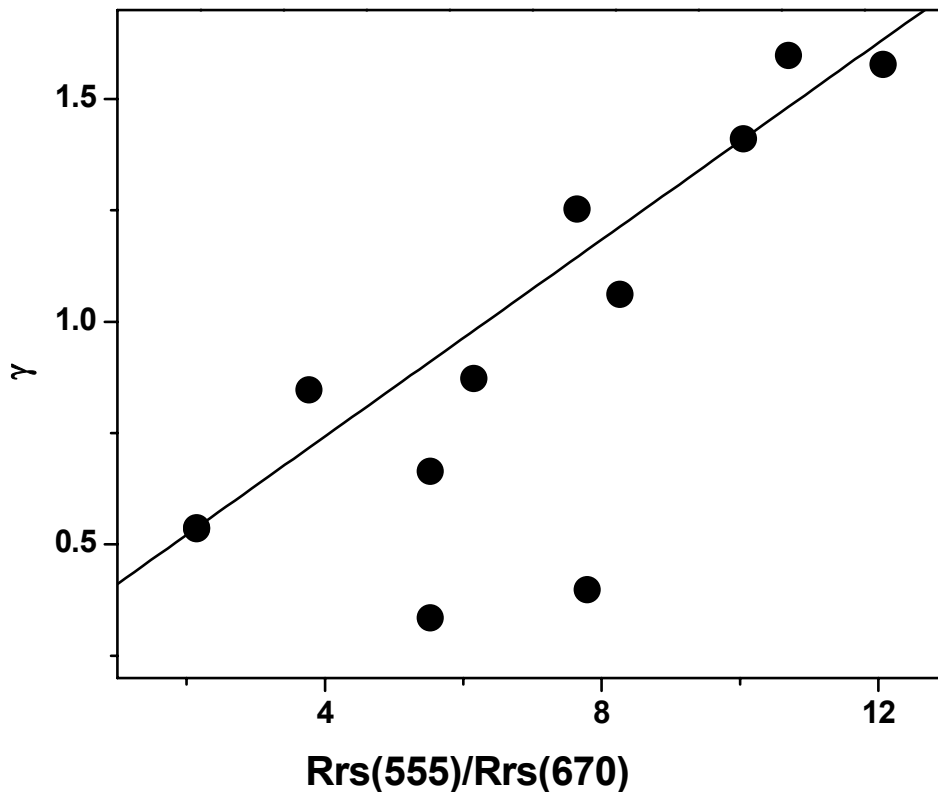


Fig. 1 Empirical relation to determine γ

Empirical relation for \tilde{b}_{bp}

The backscattering ratio or the backscattering probability is defined as $\tilde{b}_{bp}(\lambda) = b_{bp}(\lambda)/b_p(\lambda)$, where $b_p(\lambda)$ is the particulate scattering coefficient and $b_{bp}(\lambda)$ is the particulate backscattering coefficient. The values of $b_{bp}(\lambda)$ at two wavelengths 470 and 676 nm are obtained subtracting contribution of water from the total backscattered values measured from the Hydrosat-2. The particulate scattering $b_p(676)$ is obtained from ac-9, $b_p(676) = c(676) - a(676)$.

The particulate backscattering ratio is found to be largely a function of the composition of the particulate material. Backscattering ratio holds strong relationship with chlorophyll concentration and it shows gradual decrease with increasing chlorophyll^{12, 13}. For most studies and models, backscattering ratio is assumed to be a constant or modeled as a function of chlorophyll^{12, 13, 14}. The backscattering ratio is generally greater for smaller particles. Backscattering ratio for mineral particles is three-to-six times greater than for phytoplankton¹. The backscattering ratios are found to be spectrally independent in the visible spectrum¹⁴ and the same are observed for our measured data. (See Fig. 2).

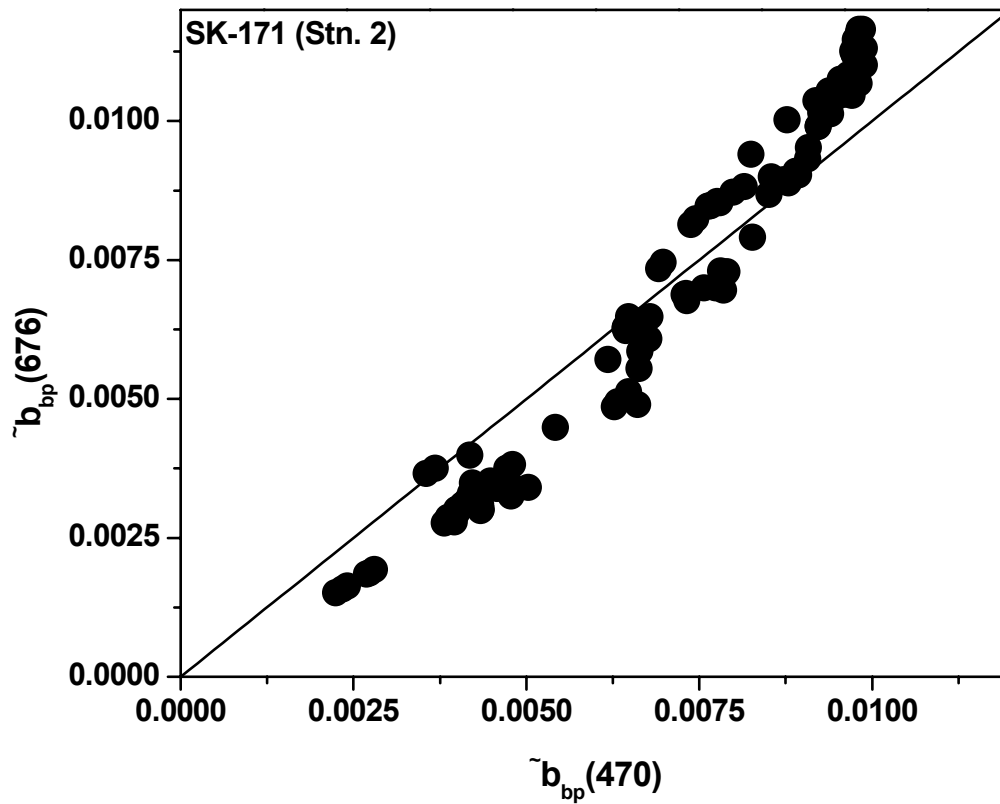


Fig. 2 Particulate backscattering ratios at 470 and 676 nm from the measured data.

The empirical relationship derived for particulate backscattering ratio at 490 nm as a function of the ratio of the remote sensing reflectance at two wavelengths, 555 and 670 nm is given as

$$\tilde{b}_b(490) = X \left(\frac{Rrs(670)}{Rrs(555)} \right)^Y \quad (7)$$

where $X = 0.000475$ and $Y = -1.4975$. ($r^2 = 0.61$). (See Fig. 3).

Since we assume the spectral independence of the backscattering ratio, we have $\tilde{b}_{bp}(\lambda) = \tilde{b}_{bp}(676)$.

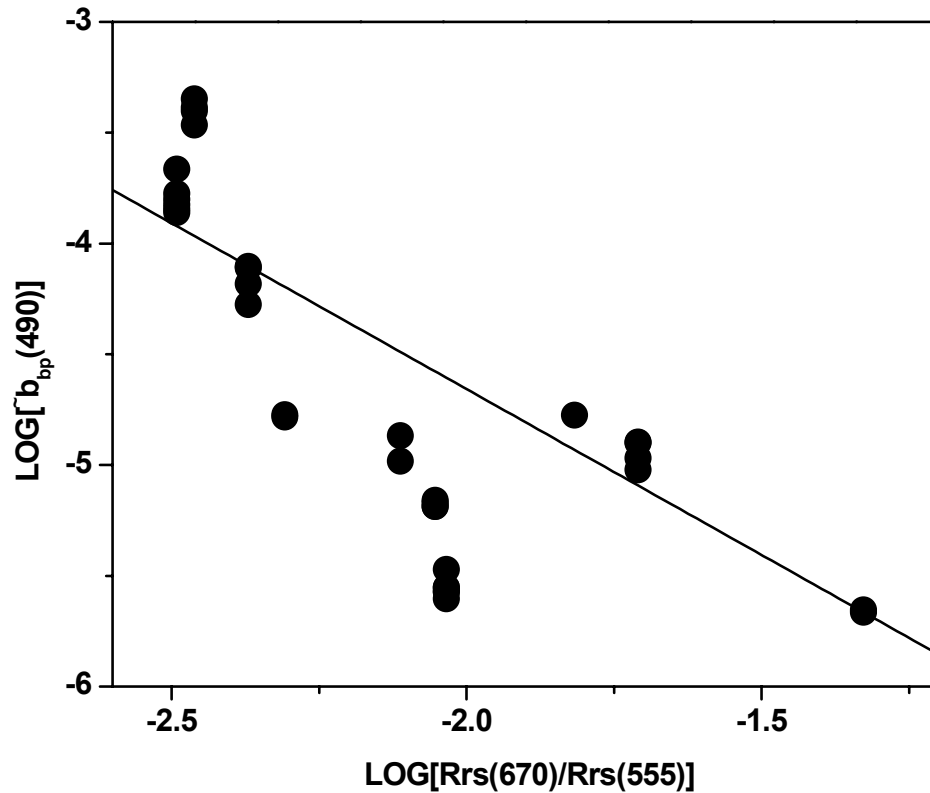


Fig. 3 Empirical relation to determine particulate backscattering ratio at 490 nm

3. RESULTS

The image of the refractive index generated from the IRS-P4 OCM show marked variations for the coastal and open ocean waters. Relatively higher values of refractive indexes are observed at the coastal regions, which indicate of more non-organic and mineral material than the open ocean. (See Fig. 4). The regions away from the costal regions have relatively lower refractive index.

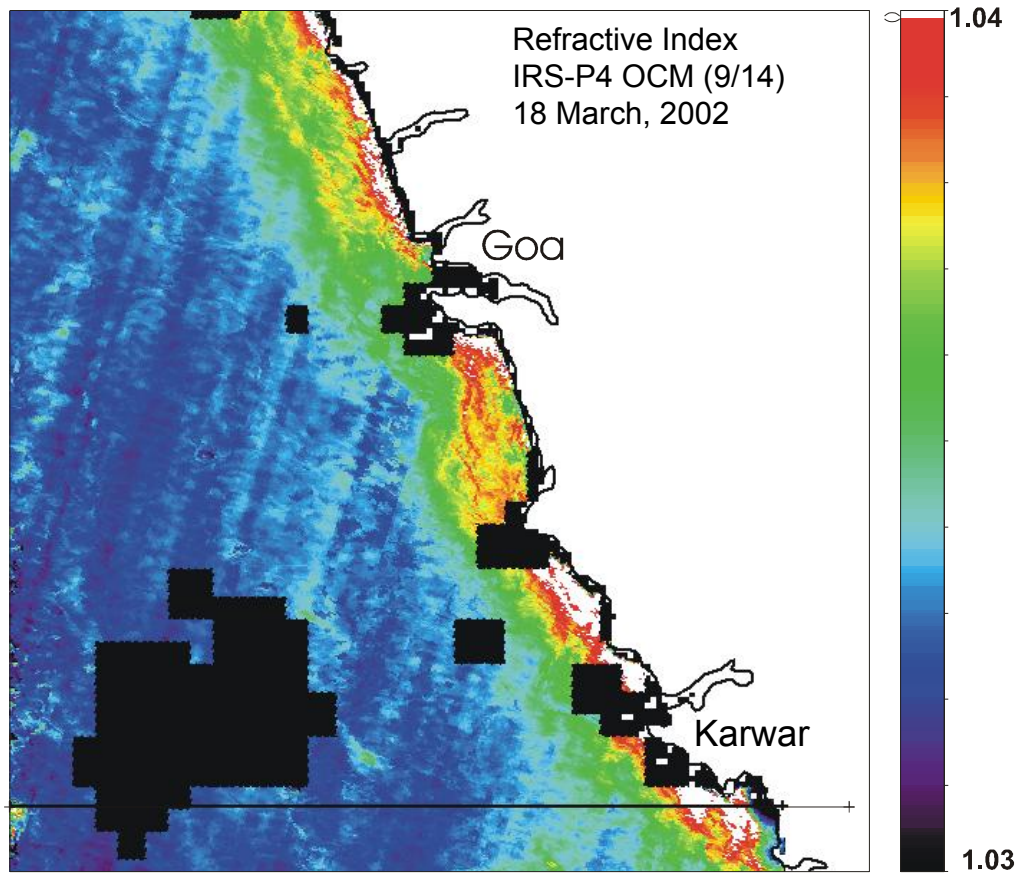


Fig. 4. The image of refractive index derived from the IRS-P4 OCM data.

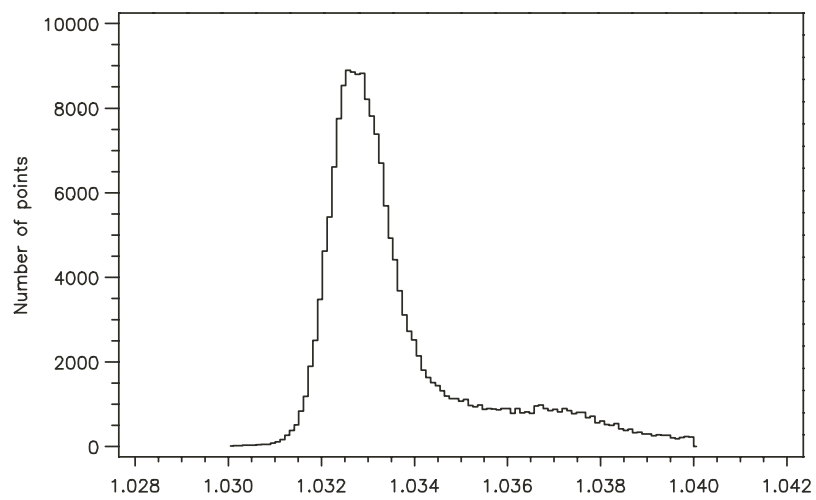


Fig. 5. Histogram of the refractive index image given in Fig. 4.

The image of the refractive index in Fig. 4 is obtained using the algorithm given here, using the remote sensing data derived from the ocean color sensor IRS-P4 OCM. (18 March 2002, path 9/14, coastal waters off Goa and Karwar, Latitude 14.6° to 15.8° N and Longitude 73.2° to 74.4° E). The IRS-P4 OCM data was processed using the software module developed in-house and integrated in SeaDAS 5.0. The image distinctly identifies regions with lower refractive indexes, which are assumed to be those with relatively higher organic particles such as phytoplankton and coastal waters with higher refractive index. The histogram shown in Fig.5 indicates abundance of particles within lower range of refractive index with peak around 1.032 and 1.034 and secondary maxima, though a small hump around 1.036 and 1.038, which is due to the particles of the costal waters. The chlorophyll image of the same region is shown in Fig. 6. The image shows the typical variations of chlorophyll observed in the coastal waters and open ocean, with relatively higher chlorophyll in the coastal waters. There are features with marked contrast and variations clearly seen in the image of refractive index, which are not observed in the chlorophyll image. One of the reasons could be attributed to the large variations in values of chlorophyll from 0.2 mg/m³ in the open ocean to the above 5 mg/m³ values in the coastal waters, that the selected color table tends to merge all such features. Though this seems to be plausible reason, our close examination of the image of refractive index does indicate regions with almost similar values of chlorophyll to have dissimilar values of refractive indexes.

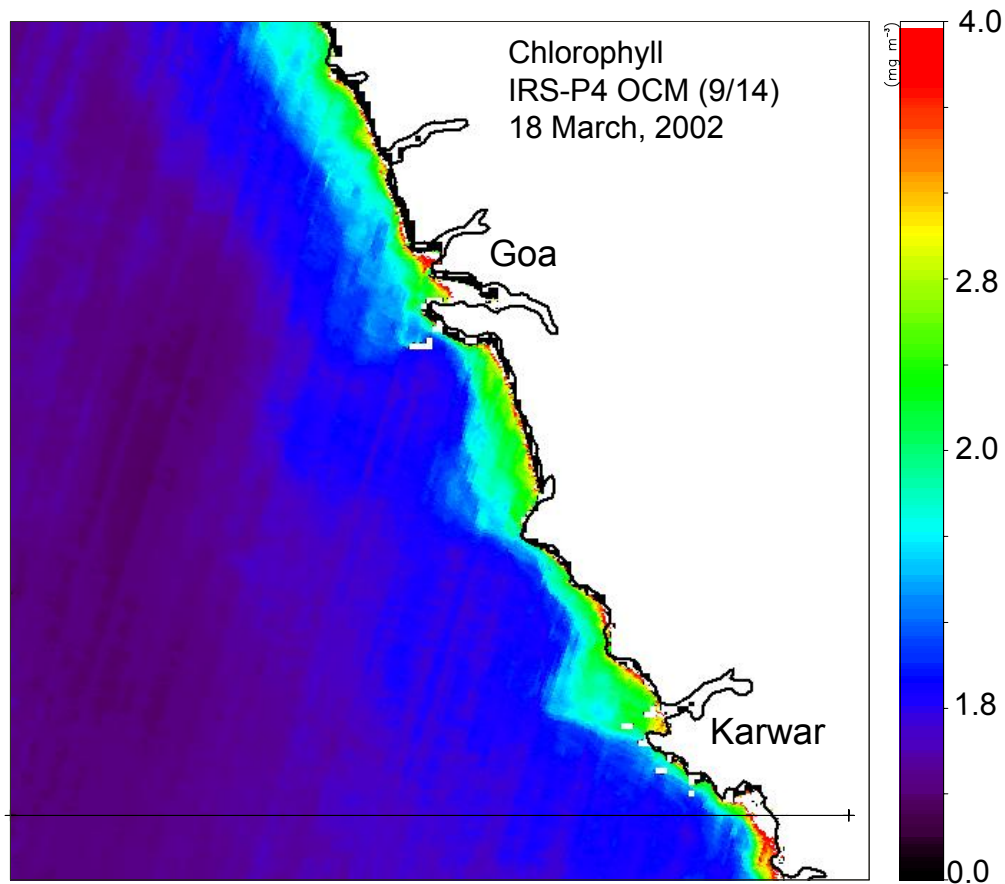


Fig. 6 Chlorophyll image derived from IRS-P4 OCM

The values of chlorophyll and refractive index taken along a transect from the images are given in Fig. 7. (See the dark line in the image, beginning from the region south of Karwar on the right side, 14.691° N, 74.279° E and going to the open ocean on the left side, 14.691° N, 73.201° E). There are distinct variations of the refractive index observed in the segment from 74.0° to 74.1° E, while the chlorophyll values are found to be around 1.0 mg/m³, with no significant change in the values. The region in the extreme left near the coast around 14.691° N, 73.201° E, is found to be an isolated patch that exhibits very low values of refractive index, with highest values of chlorophyll, and enclosed by relatively higher values of refractive indexes. Thus we could explore such regions and examine the characteristics of water.

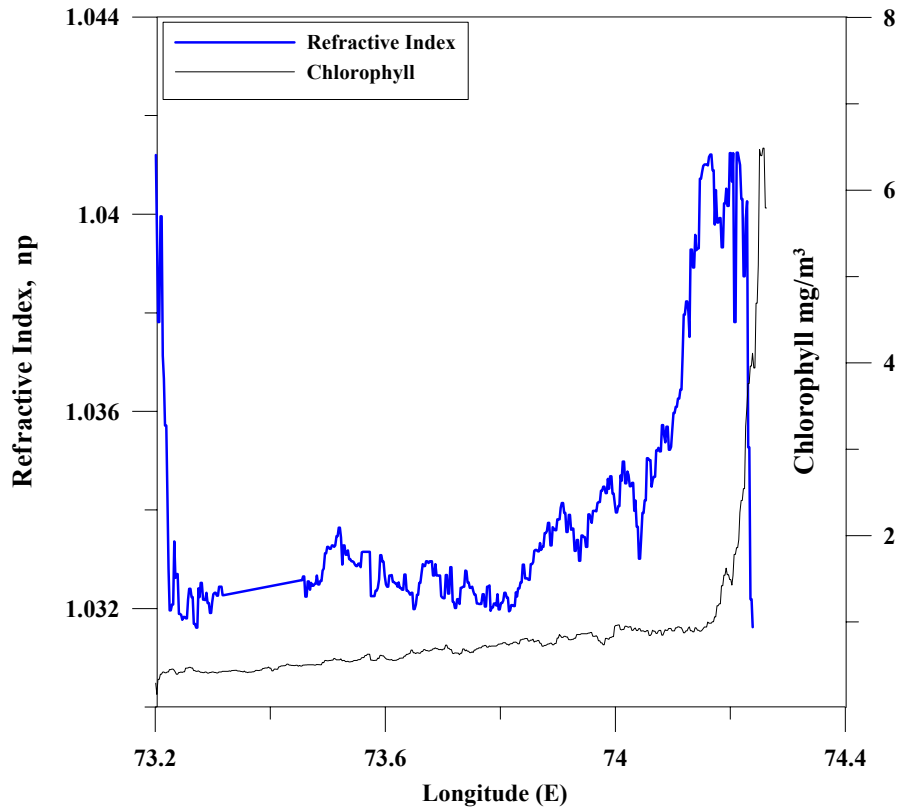


Fig. 7. Refractive index and chlorophyll values along a transect off Karwar.

4. CONCLUSION

Empirical algorithms are derived to estimate the optical properties that characterize the particles in the water, namely the slope of the particle size distribution and the probability of backscattering or the backscattering ratio. We have applied these properties to derive bulk refractive index of the particulate matter in the water. The algorithm is applied to the ocean color satellite data from IRS-P4 OCM to derive image of the refractive index of the water. The image of the refractive index product show coastal regions with relatively higher values of refractive index compared to the open ocean. The index of refraction is an indicator of the bulk particulate composition and inorganic minerals has high indices of refraction relative to oceanic organic particles such as phytoplankton and detrital material that typically have high water content. There are distinct regions with similar chlorophyll values but with varying values of refractive index. Hence the information derived from the image of refractive index would allow us to explore and examine the characteristics of the water, distinguish various water types. Since the refractive index is an indicator of the particulate composition and the refractive indexes vary for different species of phytoplankton, we could also use this method to identify regions of blooms and phytoplankton species.

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