CHAPTER 03

FUNDAMENTALS OF OCEAN COLOUR REMOTE SENSING

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Remote sensing refers to collection of information about an object without being in direct contact with the object. Remote sensing aids in measuring remote areas which are inaccessible by any other means and offer less expense than *in-situ* measurements. Remote sensing facilitates creation of long time series and extended measurement. This has the advantage that several parameters can be measured at same time and satellite-based remote sensing measurements allow global observations. Remote sensing has its own advantages and disadvantages. The limitation includes indirect measurements of large areas which are not of interest to the user. The automated instrument degradation creates retrieval errors and are affected by several factors/processes, and not only by the object of interest. Additional assumptions and models are needed for the interpretation of the measurements and before using these models in oceanographic studies, it is extremely important to validate the performance of the various ocean colour algorithms with *in-situ* observations (Swirgon *et al.*, 2015).

Two different types of remote sensing include active and passive remote sensing. Passive remote sensing measures naturally available energy *viz.* solar light which are either attenuated scattered and reflected. In active remote sensing, the sensor emits visible radiation towards target and reflected radiation in emitted bands are detected and measured. These type of sensors can work day and night and can use wavelengths not available from natural sources. LIDAR comes under this category of active ocean colour remote sensing.

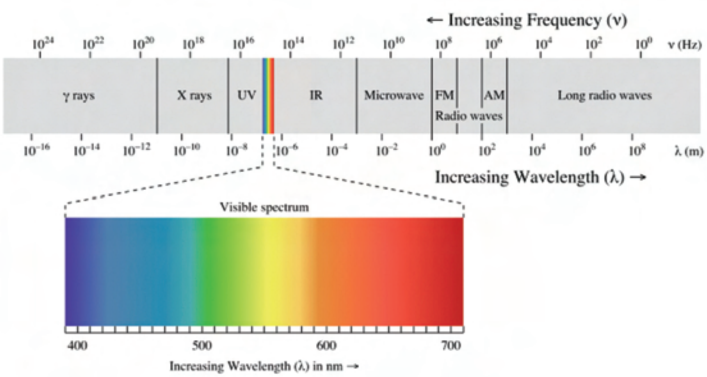

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Fig. 1. Illustration of the Visible spectrum of the light

Solar light is an electromagnetic radiation where waves are fluctuations of electric and magnetic fields, which can transport energy from one location to another (Figure 1). When sunlight strikes the ocean, some of it reflects off the surface back into the atmosphere. The amount of energy that penetrates the surface of the water depends on the angle at which the sunlight strikes the ocean. Near the equator, the sun's rays strike the ocean almost perpendicular to the ocean's surface. Near the poles, the sun's rays strike the ocean at an angle, rather than directly. The direct angle of the sun's rays to the surface of the water at the equator means that more energy penetrates the surface of the water at the equator than at the poles.

Water absorbs almost all of the infrared energy from sunlight within 10 centimetres of the surface. Visible red light has slightly more energy than invisible infrared radiation and is more readily absorbed by water than other visible wavelengths. Light with longer wavelengths is absorbed more quickly than that with shorter wavelengths. Because of this, the higher energy light with short wavelengths, such as blue, is able to penetrate more deeply (Figure 2). The depth of the water not only affects the colours of light that are noticeable underwater, it also affects the intensity, or amount of light. Within the first 10 m, water absorbs more than 50 percent of the visible light energy. Even in clear tropical water only about 1 percent of visible light, mostly in the blue range, penetrates to 100 m. Light attenuation is the gradual decrease in light intensity as it travels through matter.

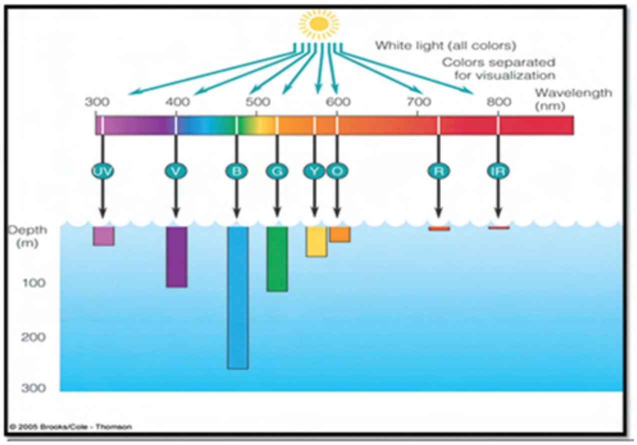

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Fig. 2. Illustration showing penetration of visible spectrum in the ocean

Ocean colour is the colour of ocean resulted due to the change in the characteristics of the incident solar radiation after interacting with the Optically Active Substances (OAS) prevailing in the water column. Ocean Optics is the branch of physics concerned with the interactions of light with ocean as the light propagates through the ocean. The incoming solar radiation is affected by several factors *viz.* scattering by inorganic suspended material, scattering from water molecules, absorption by the Dissolved Organic Matter, absorption by Phytoplankton and reflection off the bottom. These factors/substances that modify the incoming radiations are known as optically active substances. These can be categorized into two properties- Inherent and apparent optical properties. Inherent Optical Property (IOP) is an optical property of the water body which is totally independent of the spatial distribution of the radiation and Apparent Optical Property (AOP) is an optical property of the water body that is dependent upon the spatial distribution of the incident radiation. Absorption (a) and scattering ($b=b_f+b_b$) are the main IOP's and reflectance (R_{rs}) and attenuation (K_d) form the AOP which are interlinked. 'b_f' and b_b represents forward and backward scattering, 'μ_d' represents average cosine of downwelling light (Morel *et al.*, 2006).

$k_d = (a + b_b) / \mu_d$ ....(1)

$R_{rs} = (f/q)\ (b_b / a + b_b)$........................(2)

Downwelling solar irradiance penetrating through the air-water interface into the water and from the subsurface layer into deeper layers is absorbed and scattered on its way by water itself as well as by OAS in the water (Figure 3). Partial radiation are also back scattered and reflected. These leaves the ocean surface as water leaving radiance (L_w) and is measured by ocean colour satellites. Remote sensing reflectance corresponds to the fraction of downwelling radiance (E_d) and upwelling radiance (L_w) which is further affected by the IOP of oceans.

After leaving the ocean, these radiations are again exposed to scattering and reflection by various substances present in the atmosphere such as aerosols, water vapour, dust particles *etc*. Hence, there is need for accurate measurement of these radiances top of atmosphere (TOA). Ocean colour algorithms incorporated with various atmospheric corrections serve the functions. The accurate retrieval of Chlorophyll in case 2 waters also requires the selection of a suitable atmospheric correction scheme (Minu *et al.*, 2014b). In turbid waters, sensor-derived R_{rs} at blue wavelengths is often biased downward and sometimes even negative. This problem often results from assumptions that water-leaving radiance is negligible at near-infrared (NIR) bands (Siegel *et al.* 2000).

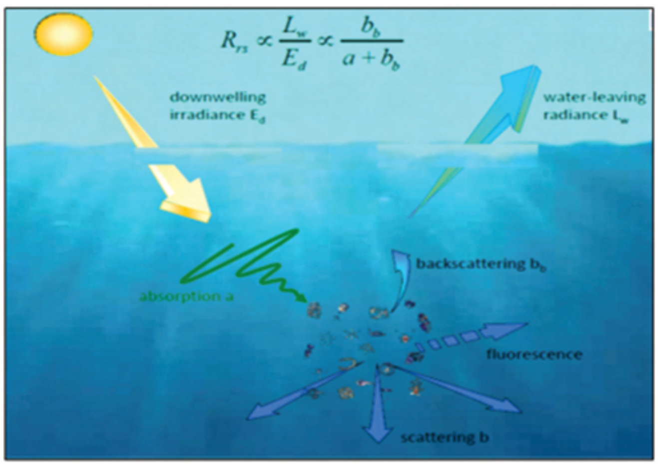

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Fig. 3. Illustration showing the modifications of underwater light

For the ocean–atmosphere system, top-of-atmosphere (TOA) reflectance, $\rho_t(\lambda)$, as measured by the satellite sensor, can be written as a linear sum from various contributions (ignoring whitecaps and sun glint):

$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_a(\lambda) + t(\lambda)\rho_w(\lambda) \qquad (3)$$

where $\rho_r(\lambda)$, $\rho_a(\lambda)$, and $\rho_w(\lambda)$ are the reflectance contributions from molecules (Rayleigh scattering), aerosols (including Rayleigh-aerosol interactions), and ocean waters, respectively, and $t(\lambda)$ is the diffuse transmittance of the atmosphere.

The concentration of OAS determines the magnitude and shape of in- water R_{rs}. The difference can be mainly observed in the blue wavelength region of visible spectrum. Oceanic waters are partitioned into Case I and Case II waters (Figure 4). Case I waters are waters in which phytoplankton are the principal agents responsible for the variations in optical properties of water whereas Case II waters are influenced by phytoplankton and other substances that vary independently of phytoplankton notably, inorganic particles in suspension and yellow substances.

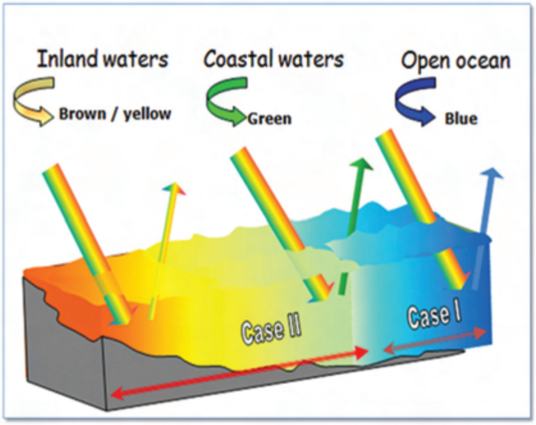

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Fig. 4. Illustration of interaction of visible radiation

Ocean colour algorithms are developed inorder to retrieve different oceanic parameters using water leaving radiance derived from satellite data incorporating reliable atmospheric correction models. These algorithms can be empirical / semi-empirical. Empirical algorithms are based on statistical relationship with less intensive computations and are easy to implement operationally. The derived relationships can be applied to other regions also. Semi-empirical algorithms are based on radiative transfer solutions and offer intensive computations with *in-situ* data to train the models. Radiative transfer theory is based on the assumption that as a beam of radiation travels, it loses energy to absorption, gains energy by emission, and redistributes energy by scattering. The equation that connects the IOPs and the radiance is called the radiative transfer equation (RTE) and is expressed as

$$L_T(\lambda) = L_w(\lambda)T(\lambda) + Lg(\lambda)\,T(\lambda) + L_a(\lambda) + L_r(\lambda) + L_b(\lambda) \qquad (4)$$

Where L_T(ë) is the radiance reaching remote sensor and L_w is the water leaving radiance

$$L_w(\lambda) = L_{ww}(\lambda) + L_{wp}(\lambda) + L_{wCDOM}(\lambda) + L_{ws}(\lambda) + L_{wb}(\lambda) \qquad (5)$$

Subscripts 'g' for sky-glitter, 'a' for aerosols, 'w' for water, 'p' for phytoplankton, CDOM for coloured dissolved organic matter (gelbstoff), 's' for inorganic suspended sediments and 'b' for reflection off the bottom.

As phytoplankton concentration increases, the reflectance in the blue decreases and in the green it increases slightly. Thus a ratio of blue to green water reflectances are used to derive quantitative estimates of pigment concentration. Empirical algorithms are developed based on this principle. Each sensor is assigned a default chlorophyll algorithm. The default algorithm varies by sensor based on available spectral bands. The default algorithms by sensor is given by equation (4) and the wavelength of each algorithm / sensor is provided in the table 1:

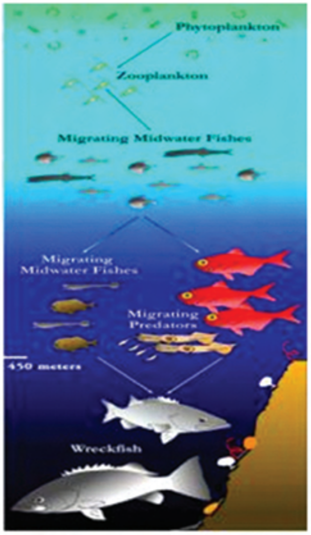
$$log_{10}(chlor\_a) = a_0 + \sum_{i-1}^{4} a_i log_{10?}\left(\frac{R_{rs}(\lambda_{\text{blue}})}{Rrs\ (\lambda_{green})}\right)^i \text{.........................(6)}$$

Table 1. Operational algorithms and respective wavebands.

Ocean colour algorithm	Sensor	blue	green
OC3C	CZCS	443>520	550
OC4	SeaWiFS	443>490>510	555
OC4E	MERIS	443>490>510	560
OC4O	OCTS	443>490>516	565
OC3M	MODIS	443>488	547
OC3V	VIIRS	443>486	550

Applications of Ocean Colour Remote Sensing

Ocean colour remote sensing has wide applications and is applicable for societal benefits. The societal benefits include coastal zone protection and management, fisheries-detection and management *etc*. Coastal zones are prone to pollution and sedimentation due to anthropogenic activities. High chlorophyll concentration indicates harmful algal blooms and quantification of CDOM and TSM performs as good indicators of coastal pollution. Figure 5 shows the trophic relation of fishes with zooplankton and phytoplankton. Cross-trophic level models linking phytoplankton to ûsh production enables long term forecasting of potential fishery zones (PFZ) (Dulvy *et al*., 2009). Indian National Centre for Ocean Information Services (INCOIS) at Hyderabad disseminates PFZ advisories along the coastal states of India. Species specific advisories for Tuna are also delivered as operational product by INCOIS.



(Image courtesy : IOCCG 2009)
Fig. 5. Illustration of trophic relation of fishes with zooplankton and phytoplankton

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