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SHORT NOTE

In Situ Time Series Estimation of Downwelling Diffuse Attenuation Coefficient at Southern Bay of Bengal

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Abstract The present study is aimed to determine the bio-optical characteristics of oceanic waters during South west monsoon in Bay of Bengal using hyperspectral radiometer. The variability of diffuse attenuation coefficient, $K_d(\lambda)$, with chlorophyll *a* showed a good relation at shorter wavelengths, indicating the effect of phytoplankton on $K_d(\lambda)$. The determination coefficient, R^2 at 412, 443, 490 and 555 nm were greater than 0.931. A good linear relation between $K_d(490)$ and $K_d(\lambda)$ was observed at shorter wavelengths. These relationships of $K_d(\lambda)$ provides a platform to study the underwater light field during Southwest monsoon in Bay of Bengal.

Keywords Diffuse attenuation coefficient · Chlorophyll *a* · Photosynthetically active radiation · Tropical convergence zone · Bay of Bengal

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Introduction

During South-west monsoon, the west India coastal current merges with the eastward flowing Equatorial Counter Current and the part of this whole eastward flowing South-west Monsoon Current, flows northward into Bay of Bengal. This region experiences very turbulent environment with higher levels of waves and winds because of the Inter Tropical Convergence Zone located over the warmest surface waters that are associated with eastward oceanic currents (Philander et al. 1995; Pickard and Emery 2003; Francis and Gadgil 2010).

Inside and outside of the intercontinental tropical convergence zone, the fluxes of heat, moisture, momentum and radiation through the surface of the ocean and in the atmosphere itself differ dramatically and the absorption properties of the water column have significance. One of the important water column property to study the characteristics of the water and light availability is diffuse attenuation coefficient for downwelling irradiance, $K_d(\lambda)$. It is a quasi apparent optical property, that is influenced by the angular distribution of light field as well as the nature and quantity of substances present in the medium, is of particular interest because it quantifies the presence of light, the nature of particles present in it and the depth of the euphotic zone. K_d is an indicator of the penetrating component of solar radiation. For most waters $K_d(\lambda)$ is largely determined by absorption properties of water and is very well correlated with chlorophyll *a* concentration (Case I waters). Some researchers studied the variations in diffuse attenuation coefficient and its vertical distribution of chlorophyll *a* concentration (Parsons et al. 1984). To characterize the water column, the diffuse attenuation coefficient needs to be determined precisely (Mobley 1994). The lack of information on the optical properties like attenuation in the study area characterized by the seasonally reversing monsoon winds that blow from the southwest during the summer (May – September) (Vinayachandran et al. 2004) makes this study important for increasing the efficiency of ocean colour algorithms and understanding of water column properties from the satellite platform.

Materials and Methods

In-situ time series measurement of bio optical characteristics measured at 06° 15'N and 86 ° 00' E of Bay of Bengal Sea during the 30th cruise of ORV Sagar Nidhi from July 23 to 25, 2009 (Fig.1). Spectral radiance and irradiance were measured by using Satlantic hyperspectral radiometer (Hyper OCR II model). At each station Satlantic™ hyperspectral radiometer (Hyper OCR II) was operated with utmost care to avoid ship shadow, maintain the vertical velocity of 0.5–1 ms^{-1} and minimize the instrument tilt. The data from Hyper

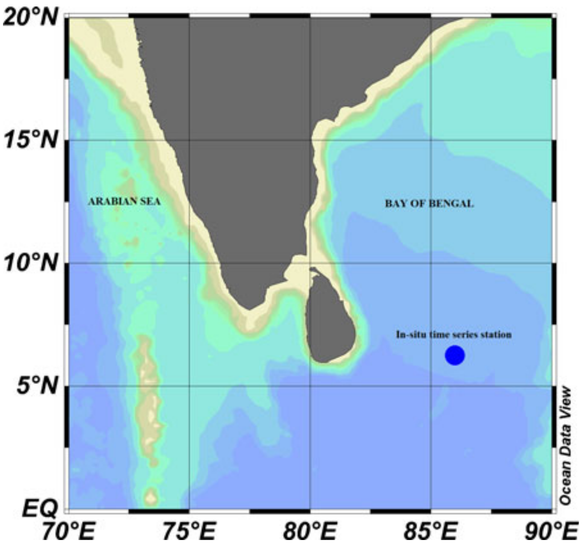

Fig. 1 Study area where the time series measurements were carried out

OCR II were processed using Prosoft™ software. The optical parameters such as incoming solar surface irradiance (E_s), profiles of downwelling irradiance (E_d) and upwelling radiance (L_u) were obtained for the wavelength range 400–900 nm with an interval of 1 nm. As a part of initial quality control, the profiles having tilt of more than 5° and vertical velocity less than 0.5 ms^{-1} were discarded. The equipment was deployed during Indian Standard time (IST) 9.45, 11.45, 13.45 and 15.45 h for 3 days. Chlorophyll *a* measured by fluorescence sensor embedded with the hyperspectral radiometer and recorded simultaneously with radiometric measurements. Photosynthetically Active Radiation (PAR) in μMol $m^{-2}s^{-1}$ and downwelling attenuation Coefficient K_d (λ) were also measured using the Hyperspectral radiometer.

Results and Discussion

Chlorophyll *a* and PAR

Variation of photosynthetically active radiation (PAR) in percentage and chlorophyll *a* concentration with depth and time was shown in Figs. 2 and 3 respectively. Chlorophyll *a* varied from 0.2 to 0.7 mgm^{-3} from surface to 100 m. The chlorophyll *a* concentration was less than 0.5 mgm^{-3} in surface and 1.5 mgm^{-3} in deep chlorophyll maximum (DCM). The DCM varied between 20 to 50 m depths during the measurements and

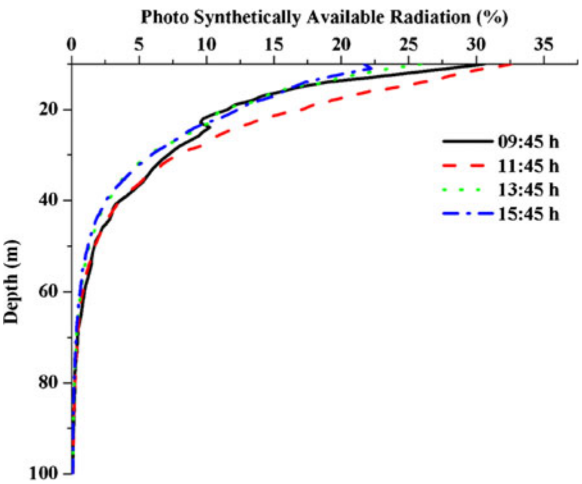

Fig. 2 The average of 3 days time series Photosynthetically Active Radiation as percentage of that at the at southern Bay of Bengal

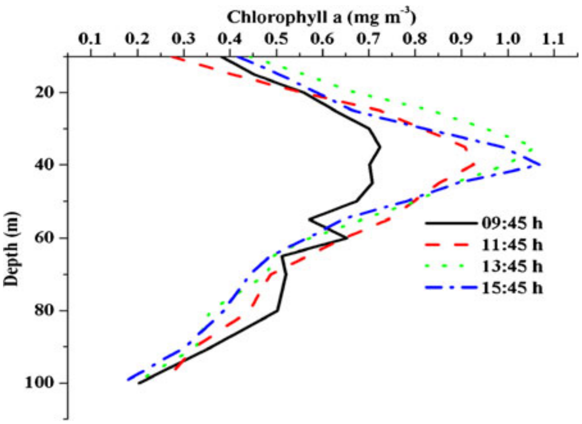

Fig. 3 Variation of 3 days average chlorphyll *a* concentration at different time during the time series measurements at southern Bay of Bengal

most of the time it was at around 40 m. At 11.45 h the DCM was found between 35–40 m depth and at 13.45 h it shifted upwards to 30–35 m according to the upward movement of phytoplankton population. During 15.45 h the DCM shifted to 40 m depth region, further showing the downward movement of planktons. This may be due to the variation in light intensity, nutrient availability and changes in the mixed layer during the day. The photosynthetically active radiation decreased with depth and the rate of decrease was high in the 30 to 55 m depth, where maximum chlorophyll *a* concentration was shown.

Variation in Diffuse Attenuation Coefficient with Chlorophyll *a*

Variability in diffuse attenuation coefficient depends on the composition of sea water. Morel (1988) and Morel and Maritorena (2001) have developed a bio-optical model for the relationship between $K_d(\lambda)$ and Chlorophyll *a*. The Fig.4 shows the impact of Chlorophyll *a* on $K_d(\lambda)$ for 6 spectral wave bands in Bay of Bengal. The determination coefficient R^2 at 412, 443, 490 and 555 nm were greater than 0.931, where as for longer wavelengths, 620 and 665 nm, the values were 0.867 and 0.629 respectively. The correlation between $K_d(\lambda)$ and Chlorophyll *a* was similar to those of reported (Morel and Maritorena 2001; Wang et al. 2008) indicating that phytoplankton concentration affected the $K_d(\lambda)$. The significantly higher correlation at the shorter wave lengths between $K_d(\lambda)$ and Chlorophyll *a* in Bay of Bengal showed the phytoplankton as an important factor that affects the diffuse attenuation coefficient for downwelling irradiance. But the disagreement of linear function between $K_d(\lambda)$ and Chlorophyll *a* at longer wavelengths may be due to the following reasons. Seawater itself has strong absorption at longer wavelengths so that light attenuates quickly with depth (Mobley 1994; Wang et al. 2008). For shorter wave lengths (412, 443 and 490 nm), inelastic scattering effect on attenuation coefficient for downwelling irradiance (K_d) was negligible and in the case of 555 nm the inelastic component affect only at greater depths (above 60 m) (Zheng et al. 2002).

Spectral Model of Diffuse Attenuation Coefficient

The diffuse attenuation coefficient for downwelling irradiance at any wavelength can be described as a good linear function of $K_d(\lambda)$ at a reference wavelength especially at shorter wavelengths (Austin and Petzold 1990; Wang et al. 2008). The relationship between $K_d(\lambda)$ and $K_d(490)$ has been studied by many researchers (Jerlov 1976; Austin and Petzold 1986, 1990; Wang et al. 2008). The Fig. 5 shows the relation between $K_d(\lambda)$ and $K_d(490)$ derived for five wavelengths (412, 443, 555, 620 and 665 nm).

$$K_d(\lambda) = a\,K_d(\lambda) + b \qquad (A.1)$$

Where 'a' is the slope and 'b' is the $K_d(\lambda)$ intercept. For wavelength 412, 443 and 555 nm the determination coefficient R^2 was above 0.983 as similar as reported by Wang et al. (2008). For longer wavelengths poor linear relation was exhibited and may be due to the high attenuation capability of seawater itself. $K_d(\lambda)$ depended strongly on components of seawater and the intercept 'b' indicates the spectral variations with diffuse attenuation of seawater, $K_w(\lambda)$. The spectral model of $K_d(\lambda)$ has provided a simple and convenient way to calculate the variability of $K_d(\lambda)$ in Bay of Bengal at shorter wavelengths of visible spectra. Understanding the characteristics of $K_d(\lambda)$ would provide information about how much light

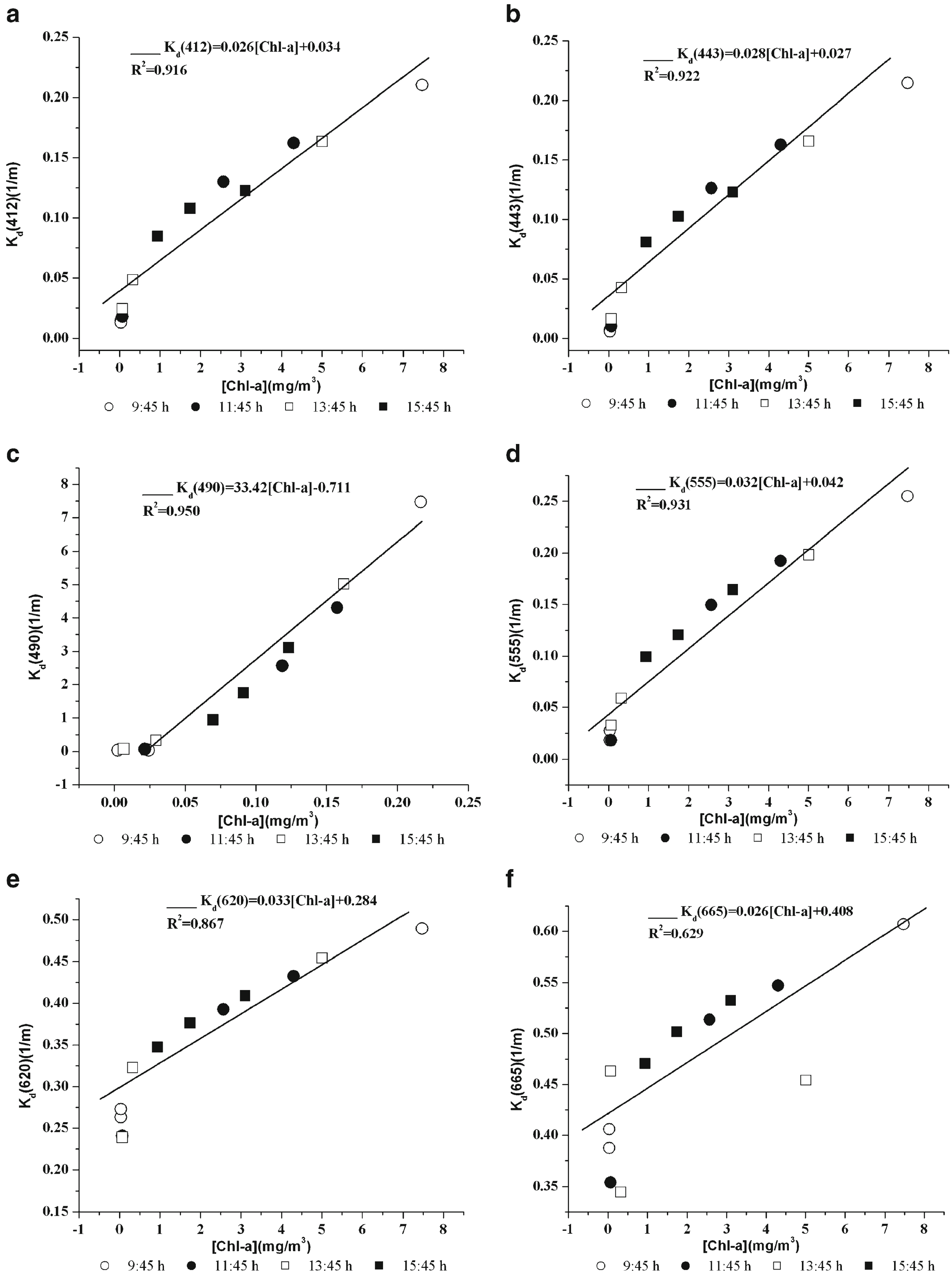

Fig. 4 Kd(λ) at 412, 443, 490, 555, 620 and 665 nm (plot **a** to **f**) as functions of chlorophyll *a* concentration with different time. The lines are the linear functions during different hours of 3 days

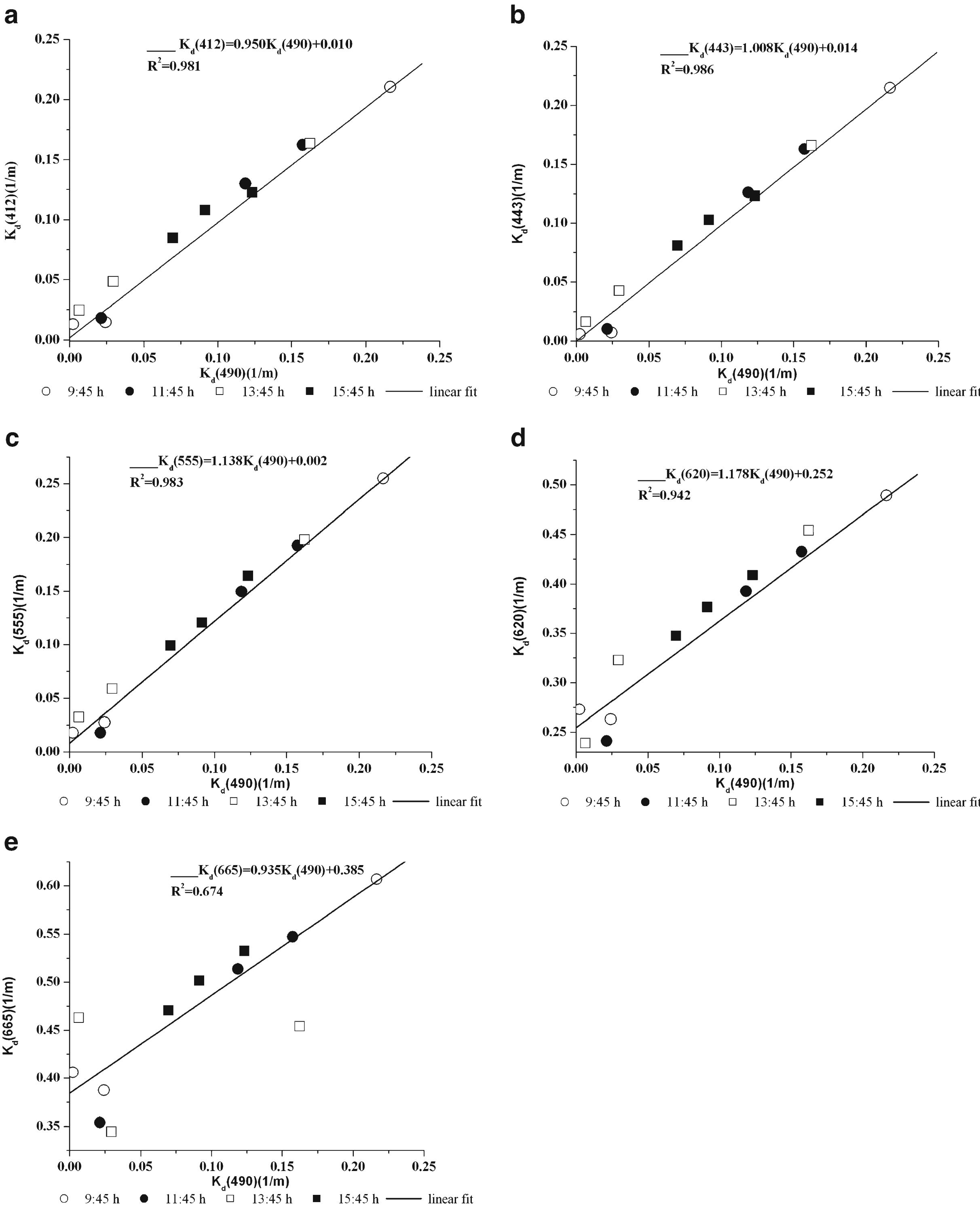

Fig. 5 Linear relationship between diffusion attenuation coefficient at 412, 443, 555, 620 and 665 nm against k_d (490) (plot **a** to **e**) with different time during the day

was available for photosynthesis and improved our studies on under water light field especially in Bay of Bengal.

Conclusion

We have studied the *in-situ* time series underwater light characteristics and vertical variation of optically active substances like Chlorophyll *a* with diffuse attenuation coefficient, Bay of Bengal during south west monsoon. The relationship between $K_d(\lambda)$ and Chlorophyll *a* at shorter wavelength can be well described within a linear function highlighting that phytoplankton is an important factor causing variability in $K_d(\lambda)$, whereas at longer wavelengths this relation is not prominent because of strong absorption by sea water. A very good linear relation was also found between $K_d(\lambda)$ at shorter wavelength with $K_d(490)$. If more *in-situ* time series measurement data are available refined algorithm could be applied to understand the underwater light field and productivity of the region correctly and precisely.

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