

EVALUATION OF SATELLITE DERIVED SPECTRAL DIFFUSE ATTENUATION COEFFICIENTS

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ABSTRACT

Spectral diffuse attenuation $K_d(\lambda)$ is an important apparent optical property that provide information about the attenuation of the spectral downwelling solar irradiance with depth in water. Here we have compared the spectral $K_d(\lambda)$ at $\lambda = 412, 443, 490, 510, 555$ and 670 nm derived from the ocean color satellite sensor, SeaWiFS with the in-situ measured values from the Arabian Sea. The satellite derived values are found to be comparable to the measured values in the lower wavelengths and are found to deviate from the measured values in the red band of 670 nm. It compared well for lower values of K_d in the blue green bands and overestimated at larger values of K_d . The comparison is good within 20% of error for bands at 490 and 510 nm. This indicated that the estimation could provide large errors in the productive and coastal waters, which is attributed to the atmospheric correction procedures used for the retrieval of water leaving radiance and other related products.

INTRODUCTION

Solar light entering the water is a source of energy for various biological, chemical and physical interactions in the ocean. Diffuse attenuation $K_d(\lambda)$ is an important apparent optical property (AOP), that provide information about the attenuation of the spectral downwelling solar irradiance $E_d(z, \lambda)$ with depth z in water. Information about $K_d(\lambda)$ is important for studies of heat budgets (Lewis, 1990, Morel, 1994), photosynthesis and primary productivity models (Platt, 1986, Sathyendranath., 1989), to classify water types (Jerlov, 1976) and it can be an important parameter that describe the transparency of water.(Suresh, 2006). The $K_d(\lambda)$ is strongly correlated with phytoplankton chlorophyll concentration, thus they provide a relationship between biology and optics.(Morel, 2001). $K_d(\lambda)$ has also been used to determine the absorption coefficient of pure water. (Smith, 1981).

Thus $K_d(z, \lambda)$ (unit = m^{-1}) is given as

$$K_d(z, \lambda) = \frac{-1}{E_d(z, \lambda)} \frac{dE_d(z, \lambda)}{dz} \quad (1)$$

The $K_d(z, \lambda)$ as defined from above is a value at depth z and z is increasing downward from the surface of water.

We can summarize the properties of $K_d(z, \lambda)$ as given below

- It is an apparent optical property that varies with angular distribution of light. (Preisendorfer, 1976, Gordon, 1975, 1989b, Kirk, 1984).
- It varies with depth, z and reaches an asymptotic value at great depths. (Zaneveld, 1989).

Thus the solar irradiance entering the water will be attenuated following the Beer-Lambert Law.

$$E_d(\lambda, z) = E_d(\lambda, 0)e^{-K_d(\lambda, z)z} \quad (2)$$

The $K_d(z, \lambda)$ as defined by equation 1 require that $E_d(z, \lambda)$ be measured at fine interval, which is not possible during field measurements using radiometer and often the $E_d(z, \lambda)$ need to be extrapolated to the surface. Since $K_d(z, \lambda)$ varies with depth, it is usually represented as an average value. (Lee, 2005). The average $K_d(z, \lambda)$ over the layer between two depths z_1 and z_2 is given as

$$K_d(z_2 - z_1, \lambda) = \frac{-1}{z_2 - z_1} \ln \frac{E_d(z_2, \lambda)}{E_d(z_1, \lambda)} \quad (3)$$

Hereafter we refer to the $K_d(\lambda)$ as the average value of determined from surface ($z_1 = 0$) to the euphotic depth ($z_2 = Z_{eu}$). Euphotic Depth, Z_{eu} , is the depth at which the downwelling irradiance is reduced to 1% of the value at the surface i.e. $\frac{E_d(z, \lambda)}{E_d(0, \lambda)} = 0.01$. This reduces to,

$Z_{eu} = \frac{4.6}{K_d}$. Though $K_d(\lambda)$ is a spectral quantity, Z_{eu} is usually defined for wavelength around 500 nm.

One of the earliest products derived from the ocean color satellite sensor, CZCS that stood the test of time has been the $K_d(490)$ (Austin, 1981). This has become a standard product available from most of the ocean color satellite sensors. It was of recent that the spectral $K_d(\lambda)$ is available as a standard product from the satellite processing software SeaDAS, the algorithm for which has been derived from semi-analytical methods. (Lee, 2002).

METHOD

Data

The in-situ optical measurements were carried-out in the Arabian Sea (Latitude 15.15 – 21.63° N, Longitude 68.20 - 73.72° E) during three cruises on the research vessel, *ORV Sagar Kanya* and they are SK-149C (15 to 29 November, 1999), SK-152 (30 March to 12 April, 2000) and SK-171 (3 to 17 November, 2001). The cruise stations included varied water types with turbid and productive coastal stations to deep oceanic oligotrophic sites and also locations with *Trichodesmium spp.* and diatom blooms. The transparency of the water indicated by the Secchi depth, varied from shallow depth of 1 m in the coast waters, to a maximum depth of 30 m in the clear open ocean. A distinct seasonal variation in the Secchi depth in the Arabian Sea, with relatively higher transparency is observed during summer compared to the winter. (Suresh, 2006).

The spectral diffuse attenuations were derived from the downwelling irradiance profiles measured using the multippectral radiometer with wavelengths at 412, 443, 490, 510, 555, 670 and 683 nm (this last channel is to detect fluorescence). The free falling profiling radiometer has three sensors, with two sensors integrated in the profiling unit for measuring upwelling radiance and downwelling irradiance and another unit used as a reference using to measure surface irradiance. (<http://www.satlantic.com>). The data is acquired online and processed using the proprietary software of the instrument ProSoft. (Elgar, 2001). The remote sensing reflectance $R_{rs}(\lambda)$ is obtained from the profile data of upwelling radiance $L_u(\lambda, z)$ and the downwelling irradiance $E_d(\lambda, z)$ as per the NASA protocol (Mueller, 2002). The diffuse

attenuation profiles were obtained from the downwelling irradiance data, $E_d(\lambda)$, which were analyzed following the standard approach.(Smith,1981). Most of the measurements were taken on sunny days and under clear sky conditions. The solar zenith angles during the measurements were within 8° and 72° and a mean of 37° . We have not included the data at 683 nm.

The mean values of K_d are 0.11,0.103,0.091,0.098,0.126,0.326 (m^{-1}) for 412, 443, 490, 510, 555 nm respectively. The equivalent Chlorophyll value corresponding to the K_d is about 1 mg/m^3 and as observed in the Arabian Sea, except under bloom conditions, the Chlorophyll variations are less than 1 mg/m^3 . (Morel, 2001).

We have used the Level_1 SeaWiFS data received from the station HGOA at National Institute of Oceanography, Goa. We have processed the SeaWiFS ocean color satellite data for the corresponding days during the cruise using the software SeaDAS Version 5.0 (<http://seadas.gsfc.nasa.gov>). We have obtained the average of the K_d values within a box grid of 0.01° centered on the pixel corresponding to the station location.

Algorithm

We have derived the spectral values of $K_d(\lambda)$ from the satellite data, where $\lambda = 412, 443, 490, 510, 555$ and 670 nm , which are the bands of the satellite sensor.(Lee, 2005). This spectral algorithm to derive spectral $K_d(\lambda)$ given as Kd_Lee in SeaDAS, is described here.

The $K_d(\lambda)$ is modeled into a form derived using the radiative transfer equations (Stavn and Weidemann, 1989).

$$K_d(\lambda) = m_0 a(\lambda) + v b_b(\lambda) \quad (4)$$

Here $a(\lambda)$ and $b_b(\lambda)$ are the spectral absorption and backscattering coefficients respectively. This is similar to the simple relationships observed by (Smith, 1981) as give below

$$K_d(\lambda) = a(\lambda) + b_b(\lambda) \quad (5)$$

$K_d(\lambda)$ is sensitive to the solar zenith angle. (Kirk, 1984). Another similar relationship as above but taking into consideration the direction of light in the water is given as (Sathyendranath, 1997, Gordon, 1989a).

$$K_d(\lambda) = \frac{a(\lambda) + b_b(\lambda)}{\mu_w} \quad (6)$$

where μ_w is the cosine of the refracted solar zenith angle in water.

Using the *Hydrolight* software (<http://www.sequoia.com>) to simulate the underwater light field, the parameter v is modeled as a function of absorption, a . Even the relationship given in equation 6, which takes into consideration the direction of light, is only a rough approximation. The parameter m_0 depend on the solar zenith angle and can be approximated as, $m_0 = 1 + 0.005\theta$, where θ is the solar zenith angle in air. The following empirical

relationships provide the value of $K_d(\lambda)$ as a function of absorption and backscattering coefficients.

$$K_d(\lambda) = m_0 a(\lambda) + m_1 [1 - m_2 e^{-m_3 a(\lambda)}] b_b(\lambda) \quad (7)$$

where m_0 , m_1 , m_2 and m_3 are coefficients whose values depend on the depth and solar zenith angle. (See Table in Lee, 2005). Here in SeaDAS, however an optimal values are used with $m_1 = 4.18$, $m_2 = 0.52$ and $m_3 = -10.80$. The quasi analytical algorithm, QAA (Lee, 2002) is used to determine $a(\lambda)$ and $b_b(\lambda)$ using the remote sensing reflectance, $R_{rs}(\lambda)$, which is derived from the satellite data after the atmospheric correction and other procedures.

RESULTS AND DISCUSSION

We have derived the $K_d(\lambda)$ from the SeaWiFS satellite data and compared them with the measured. We have evaluated the satellite-derived values using the Root mean Squared Error (RMSE), mean of the absolute percentage difference (apd) (Lee, 2005), mean percent deviation (MPD) and coefficient of determination (r^2). The RMSE and apd provide information about the absolute deviations from the measured values, r^2 show the correlations and the MPD is used to indicate if the values have been under or over estimated.

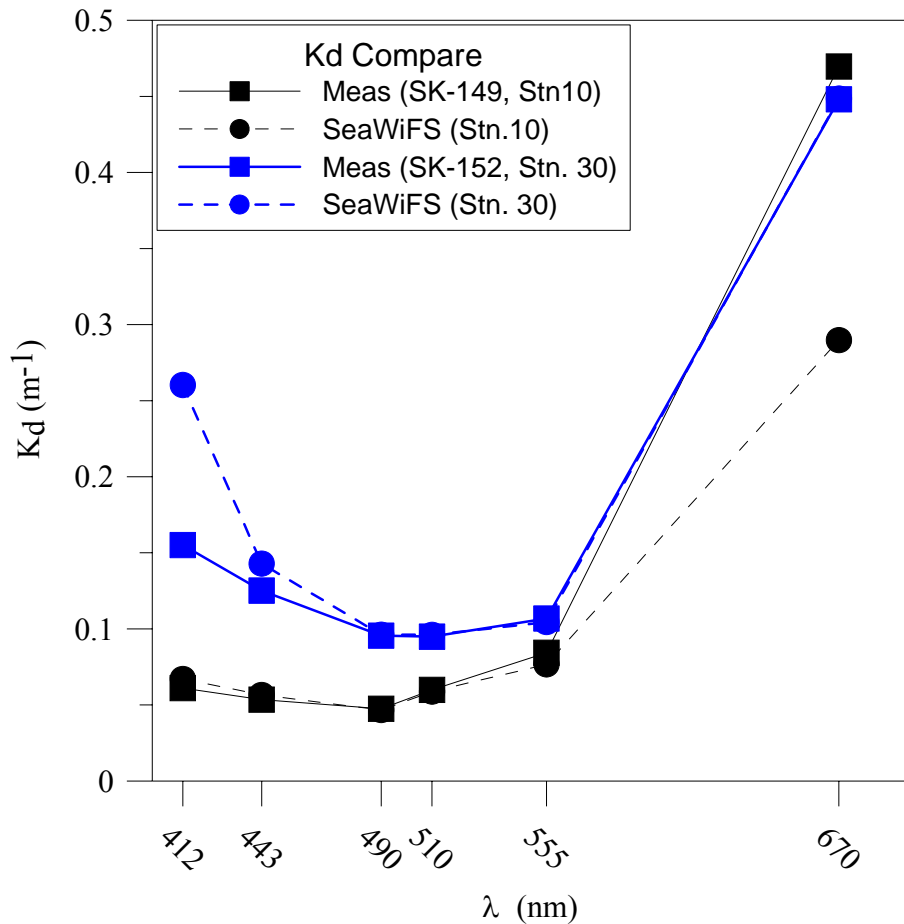


Fig. 1. Comparison of $K_d(\lambda)$ obtained from the measurement (Square box, straight line) and those derived for the same station location from the satellite SeaWiFS (Round, dashed line).

We have analyzed the spectral $K_d(\lambda)$ derived from the SeaWiFS satellite data with the measured values and they are listed in Table I for all bands. It can be observed that the comparison is good within 20% of error for bands at 490 and 510 nm, while they are poor for band at extremes, 412, and 670 nm. (See Fig. 1). Satellite derived values are overestimated in almost all the bands. A closer look at the comparison show that, there is a good agreement between the measured and the satellite derived values for lower values of K_d . (See Fig. 2). For $K_d(490)$ less than 0.15 m^{-1} , the agreement is much better, which is equivalent to a chlorophyll value of about 2 mg/m^3 .(Morel, 2001).

Table 1. Error analysis of the satellite derived $K_d(\lambda)$ compared to the in-situ measured.

λ (nm)	RMSE	APD %	R^2	MPD %
412	0.094	54.5	0.31	66.31
443	0.035	27.5	0.57	21.54
490	0.028	20.2	0.66	2.94
510	0.021	15.5	0.41	5.38
555	0.025	15.2	0.12	-5.91
670	0.163	45.0	0.13	-25.08

CONCLUSION

The satellite derived spectral values of the diffuse attenuation is found to agree with the measured values in the blue-green region of the spectra, while it is found to be poor in the red region. It is also observed that the lower values agree well, which indicate that the $K_d(\lambda)$ values derived from the open ocean oligotrophic and Case I waters can be retrieved with less errors as compared to the coastal and productive waters. The reason could be due to the $K_d(\lambda)$ algorithm or the retrieved $R_{rs}(\lambda)$ values. The error in the $R_{rs}(\lambda)$ derived from the satellite data could be due to the atmospheric correction algorithm. (Elgar, 2001). Thus we need to examine the empirical algorithms and also the atmospheric correction algorithms and have better, robust and refined algorithms for the productive and coastal waters. The spectral diffuse attenuation coefficient values using this algorithm will be derived from satellite data with less error in the blue-green spectral range for oligotrophic and open ocean waters.

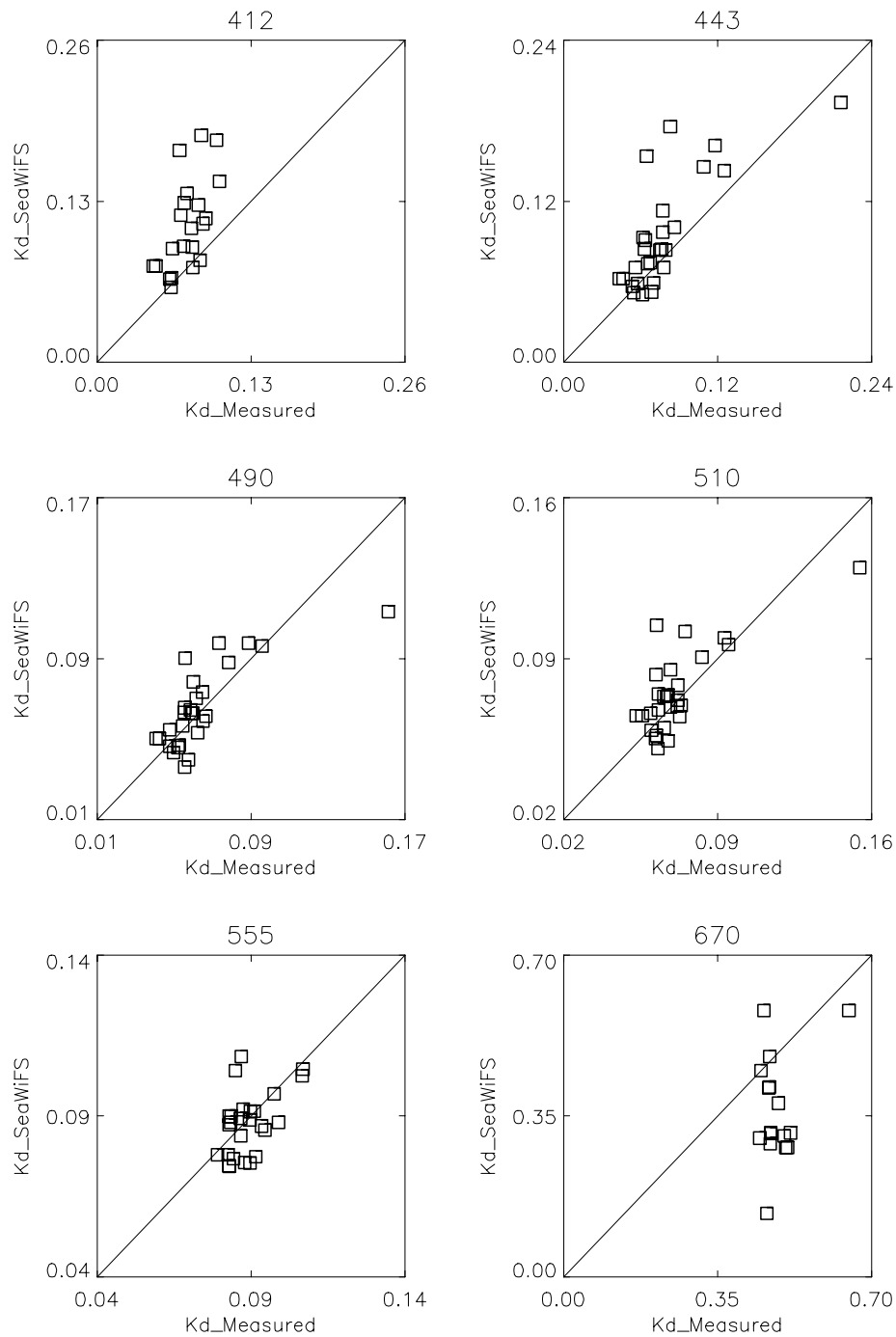


Fig. 2. The comparisons of $K_d(\lambda)$ measured in the Arabian Sea and those derived from the satellite data of SeaWiFS for various bands of 412, 443, 490, 510, 555 and 670nm.

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