

Optical closure of apparent optical properties in coastal waters off Goa

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Abstract

Inherent and apparent optical properties were measured for coastal waters off Goa, a site on the west coast of India using the in-situ measuring profiling optical instruments. The optical closure was obtained using the radiative transfer model, Hydrolight (Sequoia Inc.). Hydrolight simulations were carried out at all stations using “average particle” Petzold phase function and Fournier Forand phase function with optimum b_{bp}/b_p value. The optical properties derived from Hydrolight simulations were then compared with the measured optical properties. The widely used “average particle” phase function measured by Petzold 1972 for coastal waters was found to provide poor results for most of the stations while for few others it was found to produce results comparable to Fournier Forand phase function. The mean percentage deviation for water leaving radiance (remote sensing reflectance) simulated using Petzold and Fournier Forand phase function for wavelength 488 nm varied from 3.8 to 240.7% (3.8 to 240.8%) and 1.0 to 48.9% (1.0% to 49.0%) respectively. These closure studies are essential in strengthening the confidence in models or algorithms developed for ocean color remote sensing and also in better understanding of the marine optical properties of waters of the study area

Keywords: Inherent optical properties, apparent optical properties, optical closure, Hydrolight, coastal waters.

1 Introduction

Inherent optical properties (IOPs) and the apparent optical properties (AOPs) together describe the complete optical nature of any aquatic medium. Having complete set of measured or modeled optical properties is important for understanding the marine optical environment and their interrelationships which can be then used for developing the algorithms for ocean color remote sensing. The apparent optical properties such as spectral underwater average cosine, spectral scalar irradiance and others whose measurements cannot be done due to nonexistence of commercial instruments, they can be derived from radiative transfer models such as Hydrolight or using empirical relationships. Under some circumstances such as non-availability of instruments to measure remote sensing reflectance, diffuse attenuation coefficient etc, they can be modeled by radiative transfer models with absorption and beam attenuation properties of water as its input. The data set generated by radiative transfer models is an output from a controlled experiment with minimum measurement errors. Thus it can be efficiently used for developing empirical algorithms for ocean color remote sensing. For example International Ocean Color Coordinating Group (IOCCG) in 2006 modeled IOPs for waters with varying phytoplankton concentration to generate AOPs using Hydrolight simulations. This synthetic dataset is being widely used for developing testing and comparison of algorithms (Maritorena et al. 2002; IOCCG 2006; Defoin-Platel et al. 2007; Shanmugam et al. 2011; Jamet et al. 2012). The performance of the algorithms developed using simulated data depends on the degree to which the optical closure is obtained between the measured and the modeled optical properties.

The process of optical closure involves solving the radiative transfer equations using the measured inherent optical properties and certain boundary conditions to generate AOPs. These AOPs are then matched against the measured AOPs to obtain the closure between them. The demonstration of optical closure may enhance the confidence in the models or the algorithms derived using radiative transfer modeling (Zaneveld 1994a; Chang et al. 2003; Tzortziou et al. 2006, 2007; Sundarabalan et al. 2013) and can also reveal critical uncertainties in the measured data (Bulgarelli et al. 2003). Chang et al. (2007) carried out the optical closure for $E_d(\lambda)$ and $L_u(\lambda)$ at 4 m depth. They found good agreement for blue green wavelengths with coefficient of determination 0.94. Tzortziou et al. (2006) and Sundarabalan et al. (2013) also carried out the optical closure to investigate the effect of assumed inputs on the output generated by Hydrolight. All the above optical closure studies were carried out for coastal waters and using the measured IOPs as input.

Coastal waters are optically complex waters where the concentrations of the Optically Active Substances (OAS) such as phytoplankton, Colored Dissolved Organic Matter (CDOM), detritus and suspended sediments vary independently. Thus, the universally acceptable algorithms for estimating water constituents from ocean color satellite sensors produce poor results for such waters. One of the approaches used for developing local or region specific algorithms involves the use of radiative transfer models. Since the optical properties generated by the radiative transfer models are free from measurement errors they can be efficiently used for developing, testing and comparing ocean color algorithms (Maritorena et al. 2002; IOCCG 2006; Defoin-Platel et al. 2007; Shanmugam et al. 2011; Jamet et al. 2012).

Water leaving radiance ($L_w(\lambda)$) which is defined as the light intensity per solid angle exiting from the surface of water resulting from absorption and scattering processes in water is a fundamental quantity underlying ocean color remote sensing. It varies both in magnitude and spectral shape with changing concentrations of optically active substances (Lee et al. 2011). Since the magnitude of $L_w(\lambda)$ is highly affected by factors such as passing clouds, the ratio of $L_w(\lambda)$ to irradiance incident on to the sea surface is used as a quantitative measure of ocean color information. This quantity is called remote sensing reflectance $R_{rs}(\lambda)$ and it mimics the spectral shape of $L_w(\lambda)$ but varies in magnitude and is defined as

$$R_{rs}(\lambda) = \frac{L_w(0^+, \lambda)}{E_s(0^+, \lambda)} \quad (1)$$

Here we present the results of the optical closure obtained for the coastal waters off Goa, a site on the west coast of India. Since no measurements were available of volume scattering function which is considered to be one of the important inputs to the Hydrolight (Tzortziou et al. 2006), the simulations were carried out using Petzold (Petzold 1972) and Fournier Forand (Fournier and Forand 1994) (FF) phase functions. The objectives of the study were to demonstrate the need in selecting the accurate phase function for efficient simulations and to obtain good optical closure between measured and model estimated $R_{rs}(\lambda)$ and $L_w(\lambda)$ for the development of efficient empirical ocean color algorithms.

Methodology

1.1. Study area

Apparent and inherent optical properties were measured for coastal waters off Goa for 5 stations of depth ranging from 6 to 20m (Fig 1). These waters are highly influenced by the two main estuaries of Goa, Mandovi and Zuari. All the optical measurements were carried out during clear sky days and fair weather condition for the year 2010 and 2011 for the months January, February, March, April and November (See Table 1). The zenith angle which is an important parameter required for modeling the apparent optical properties varied from 16 to 55 degrees during the measurements. Diffuse attenuation coefficient at 490nm averaged over euphotic zone for these waters varied from 0.207 to 1.109 m^{-1} with most of the values lying between 0.2 to 0.4 m^{-1} .

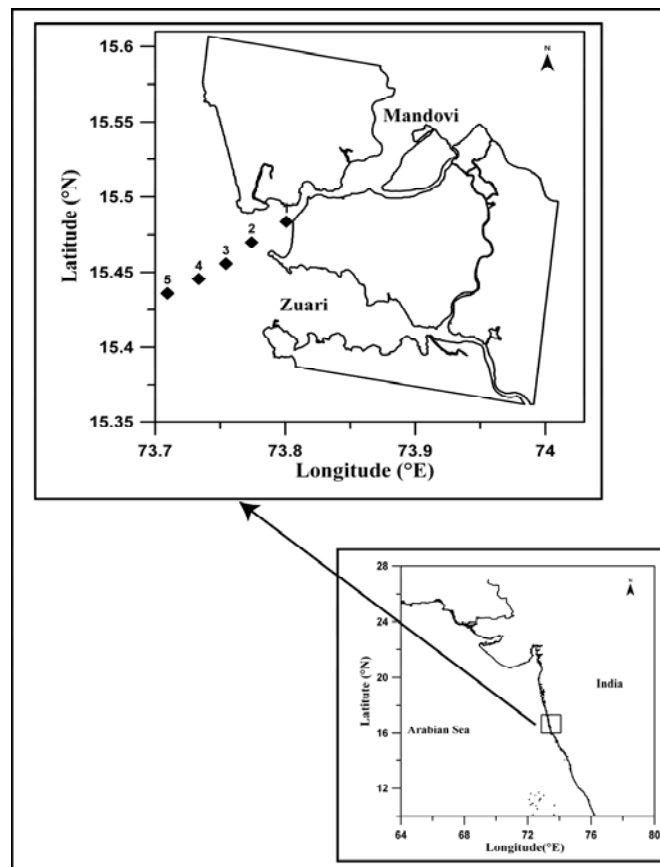


Fig1. Station locations where AOPs and IOPs were measured. Stations are separated from each other by 2.5 km

Table 1. Details of the stations where optical measurements were carried out.

Station Number	Location		Data available for months	Variations in optical properties	
	Latitude (°N)	Longitude (°E)		$K_d(\lambda)$ (m^{-1})	b_b/b
1	15.48064	73.79406	January, February, March, November	0.289 - 1.109	0.01 - 0.016
2	15.46931	73.77426	January, February, March, November	0.206 – 0.619	0.006 – 0.022
3	15.45743	73.75633	January, February, March, November	0.297 – 0.366	0.01 – 0.026
4	15.44653	73.73364	January, February, March, November	0.261 – 0.451	0.012 – 0.03
5	15.43326	73.71198	January, February, March, April, November	0.211 – 0.363	0.005 – 0.028

1.2. Measurement of optical properties

Inherent optical properties: The absorption and beam attenuation coefficients were measured using AC-9 (Wetlabs) for 9 wavelengths 412, 440, 488, 510, 532, 555, 650, 676, 715nm. The AC-9 was calibrated in the laboratory prior to every fieldtrip. The optical data measured by AC-9 were corrected for temperature and salinity effects using the data measured with CTD (Pegau et al. 1997) and the absorption data was corrected for scattering artifacts using proportionate correction method suggested by Zaneveld (1994b).

The apparent optical properties: Hyperspectral radiometer HyperOCR (Satlantic) was used to measure downward irradiance (E_d) and upward radiance (L_u) for wavelengths 350 to 800nm. The other associated optical properties such as remote sensing reflectance and the diffuse attenuation coefficient were derived using the software Prosoft provided with the instrument by manufacturer. The instrument was deployed in “fish out” mode positioning the boat such as to keep the radiometer well under the sun avoiding the boat shadow. Care was taken to deploy the radiometer with tilt less than 5 degrees (Suresh et al. 2012). The solar irradiance at the surface (E_s) was measured using the reference sensor of hyperspectral

radiometer. It was mounted at a height, away from shadow of any structure and reflections from water and other adjacent objects.

The optical instruments were deployed to obtain depth profile data at close intervals of depths from the surface to a depth safe and operable for the instruments. The radiometer was operated in free fall mode from surface to maximum operable depth with a descent rate of 0.3m/s. Most of the measurements were taken during noon time between 11 am to 2 pm. Software package developed in-house was used for quality checking the data and selecting the best one as an input to Hydrolight (Silveira et al. 2014).

1.3. Optical closure

The radiative transfer model Hydrolight (version 5.1.4) was used to solve radiative transfer equation to obtain optical closure between the measured and the modeled optical properties. Hydrolight employs mathematically sophisticated invariant imbedding techniques to solve the radiative transfer equations and it has been explained in detail by Mobley et al. (1993) and Mobley (1994). Hydrolight has been widely used by many bio-optical researchers for simulating the optical properties of natural water (Albert and Mobley 2003; Sundarabalan et al. 2013) and also to generate synthetic data set for development and validation of bio-optical algorithms (IOCCG 2006).

Input parameters to the Hydrolight simulations were absorption and beam attenuation coefficient without the pure water contribution measured by AC-9 and corrected for temperature, salinity and scattering effects (Pegau et al. 1997; Zaneveld 1994b). The ancillary parameters such as wind speed and relative humidity measured by automatic weather station (AWS) installed at National Institute of Oceanography (Goa) (NIO) were provided during the simulations assuming that the meteorological conditions between the AWS, NIO and the stations do not vary significantly. The furthest station of the study area was only around 15km away from the AWS installed at NIO, Goa. The surface irradiance measured by the reference sensor of the radiometer was used as the input for calculating the sky radiance. This surface irradiance is assumed to be of good quality with fewer uncertainties than that obtained from the solar radiation models. Bottom reflectance was calculated using the method suggested by Lee et al. (1999). The Hydrolight simulations were carried out neglecting the effect of elastic scattering. Since there were no measurements made for phase function or spectral backscattering coefficients, we had to seek a suitable phase function for every station where measurements were carried out. For each station, the simulations were carried out using “average particle” Petzold phase function

(with $b_{bp}/b_p = 0.018$) (Petzold 1972) for coastal waters which is the default available in Hydrolight and the Fournier Forand (FF) phase function. The FF phase function is modeled using only the fraction of particle backscattering $B_p = b_{bp}/b_p$, where b_{bp} is the particle backscattering coefficient i.e excluding the contribution of water from total backscattering coefficient and similarly for scattering coefficient b_p (Mobley et al. 2002). B_p indicates the probability that the light will be scattered for scattering angle $\psi > 90$ degree. The Hydrolight contain multiple FF functions for B_p varying from 0.0001 to 0.50, which were used for simulations keeping all other inputs unchanged. $R_{rs}(\lambda)$ generated by all these Hydrolight runs were then compared against the $R_{rs}(\lambda)$ measured using the radiometer. The Fournier Forand phase function that generated the best matching $R_{rs}(\lambda)$ with minimum percentage deviation from the measured $R_{rs}(\lambda)$ was selected as the optimum Fournier-Forand phase function for that station (Taulikar et al. 2014).

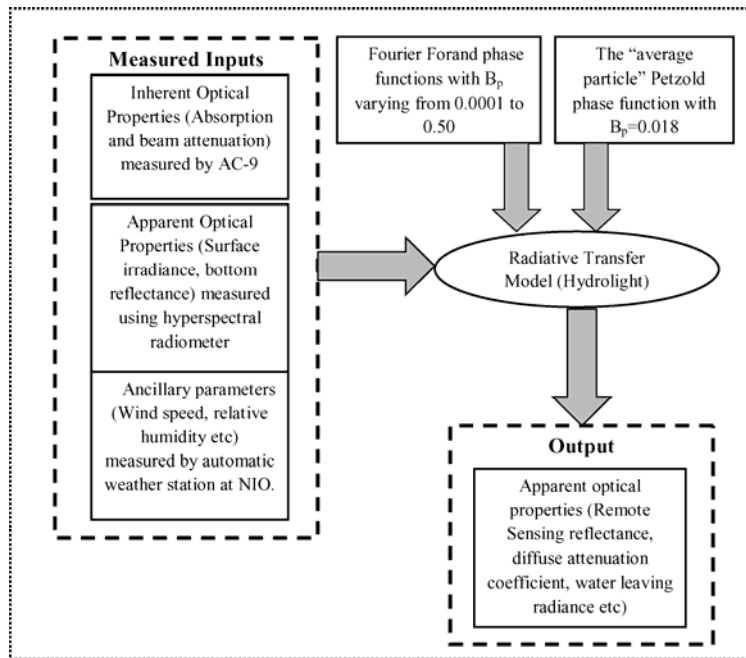


Fig2. Steps involved in Hydrolight simulations

2 Results

The B_p values for the study area varied from 0.005 to 0.03 with most of them falling in the range 0.008 to 0.016. The B_p values were found to vary spatially as well as temporally. Since $L_w(\lambda)$ and $R_{rs}(\lambda)$ are the fundamental quantities used for ocean color remote sensing, we compared $L_w(\lambda)$ and $R_{rs}(\lambda)$ derived from the simulations using “average particle” Petzold and the optimum FF phase functions with those

measured in situ using hyperspectral radiometer. The comparisons were carried out at nine wavelengths of AC-9. The mean absolute percent deviation for these wavelengths is found to be much better for simulations carried out using the optimum FF phase functions, with percent deviation greater than 30% for wavelengths 412 and 715 nm whereas for rest of the wavelengths it was around 20% (Fig 3). Marginal increase in blue region could be attributed to wide range variations in absorption and beam attenuation properties of water as compared to the green spectral region. Whereas, for 715nm the errors could be due to uncertainties in measurement and scattering correction used for absorption data from AC-9.

The $R_{rs}(\lambda)$ simulated using Petzold and optimum FF phase functions correlated linearly with measured one with R^2 of 0.58 and 0.89 respectively and similarly for, $L_w(\lambda)$ with R^2 of 0.62 and 0.91 respectively (Fig 4). The lower values of R^2 and higher values of mean percent deviation observed for simulations carried out using “average particle” Petzold phase function is due to the selection of wrong phase function.

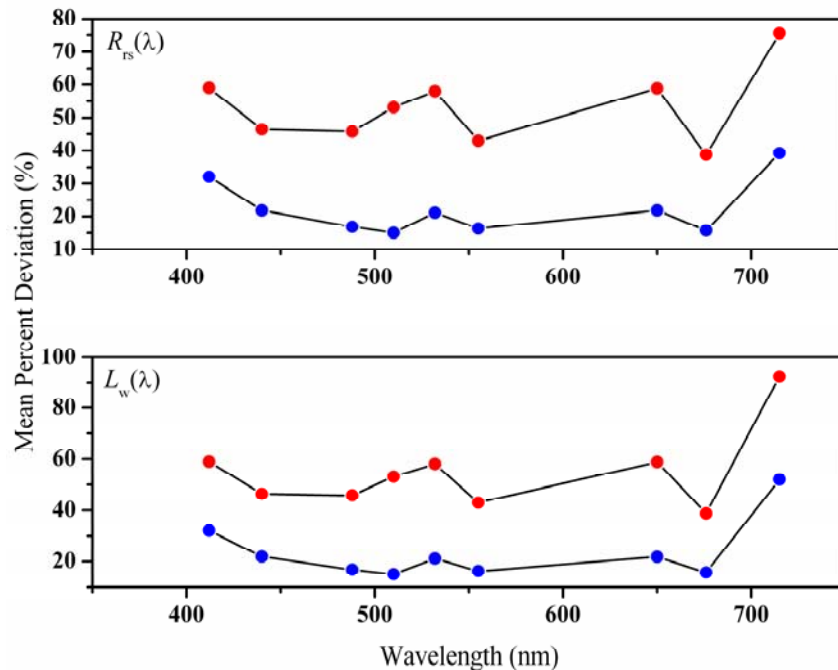


Fig3. Mean percentage deviation for $R_{rs}(\lambda)$ (Top) and $L_w(\lambda)$ (below) modeled using optimum Fourier Forand phase function (Blue) and “average particle” Petzold phase function (Red). Percent deviation is calculated as $(\text{Modeled} - \text{Measured})/\text{Measured} * 100.0$

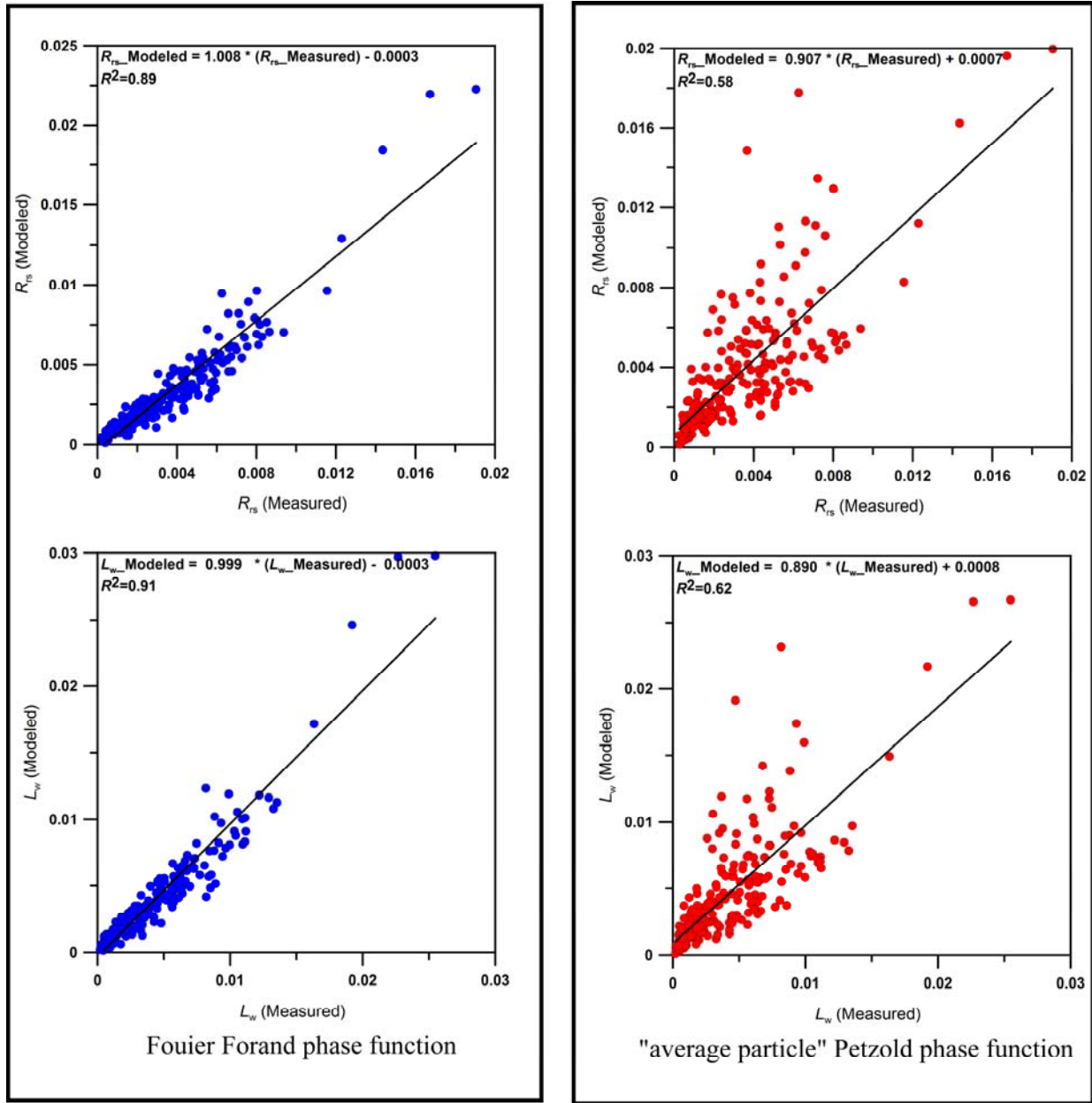


Fig4. Comparison of $R_{rs}(\lambda)$ and $L_w(\lambda)$ modeled using Fourier Forand and Petzold phase function with measured

3 Discussion

The performance of the ocean color algorithms developed for coastal and estuarine waters depend on the accuracy of the data used for development and validation of the algorithms. Since radiative transfer models generate a complete set of optical properties using analytical models and are assumed to be free from measurement errors, these data sets are mostly used for the development of ocean color algorithms

(Stramska et al. 2000; Talaulikar et al 2012; Sundarabalan et al. 2013). In order to enhance the confidence in these algorithms and to validate the assumptions made during the simulations, it becomes critical to first obtain the optical closure between the measured and the model estimated optical properties. In this study, we have used the radiative transfer model Hydrolight for obtaining the optical closure for in situ optical data measured for coastal waters off Goa. The simulations carried out using Petzold phase function provided poor results with coefficient of determination 0.58 and 0.62 for $R_{rs}(\lambda)$ and $L_w(\lambda)$ respectively. Since $L_w(\lambda)$ and $R_{rs}(\lambda)$ are strongly influenced by backscattering coefficient (Gordon et al. 1988; Morel and Gentili 1991; Mobley 1994; Morel and Gentili 1996) the errors between the measured and simulated values were attributed to phase function selected during the simulations. Hence it is essential to find the optimum phase function suitable for the water types. From the selected FF phase function, it was found that the B_p values for the study area varied spatially as well as temporarily ranging from 0.005 to 0.03. The B_p values for each station are given in Table 2. Most of the inshore waters (Station 1 and 2) had lower B_p values than offshore waters (Stations 3, 4 and 5) indicating the dominance of forward scattering and thus presence of larger particle, while relatively higher values of B_p in the offshore waters showed abundance of relatively smaller particles as B_p increase with sub-micron particles (Ulloa et al. 1994).

Table 2. B_p ratios for all stations that provided the best match between measured and modeled remote sensing reflectance

Sr.No	Cruise	Stations				
		1	2	3	4	5
1.	18 February 2010	-	0.022	-	-	0.016
2.	19 March 2010	0.014	-	-	-	0.014
3.	18 November 2010	-	0.012	0.010	0.012	0.008
4.	24 November 2010	-	-	-	-	0.016
5.	11 January 2011	0.01	0.006	0.020	0.016	0.018
6.	4 February 2011	0.012	0.022	0.024	0.030	0.028
7.	6 March 2011	0.010	0.016	0.026	0.022	0.026
8.	21 April 2011	-	-	-	-	0.005

Fig 5 and 6 shows the spectral comparison of $L_w(\lambda)$ and $R_{rs}(\lambda)$ for all 5 stations of the cruise conducted on 11 January 2011. For stations 3, 4 and 5 the B_p values were 0.020, 0.016 and 0.018 respectively which were close to B_p value of “average particle” Petzold phase functions and for these stations, the optical closure obtained using “average particle” Petzold phase function was comparable to that of Fournier Forand. Whereas for stations 1 and 2 the optimum B_p value that provided the closest match

between the measured and simulated optical properties were 0.010 and 0.006 which were far less than B_p value of Petzold thus providing poor simulations using “average particle” Petzold phase function. Hence it is evident that finding the right B_p value either through measurements or other means will provide good optical closure between the optical properties measured and simulated using Fournier Forand phase function.

The errors observed between the model estimated and measured $L_w(\lambda)$ and $R_{rs}(\lambda)$ could be also due to the uncertainties in measuring the inherent optical properties such as absorption and beam attenuation measured by AC-9 and apparent optical properties such as surface irradiance measured by hyperspectral radiometer supplied as input to the Hydrolight and apparent optical properties ($L_w(\lambda)$ and $R_{rs}(\lambda)$) used for comparison. It is difficult to measure water leaving radiance used for calculation of remote sensing reflectance close to the sea surface using the free fall radiometer of Satlantic make due to instrumental errors such as tilt of the instrument (Suresh et al. 2012) and is often extrapolated to the surface. The other assumed parameters such as cloud cover percentage may also contribute to the error (Tzortziou 2006).

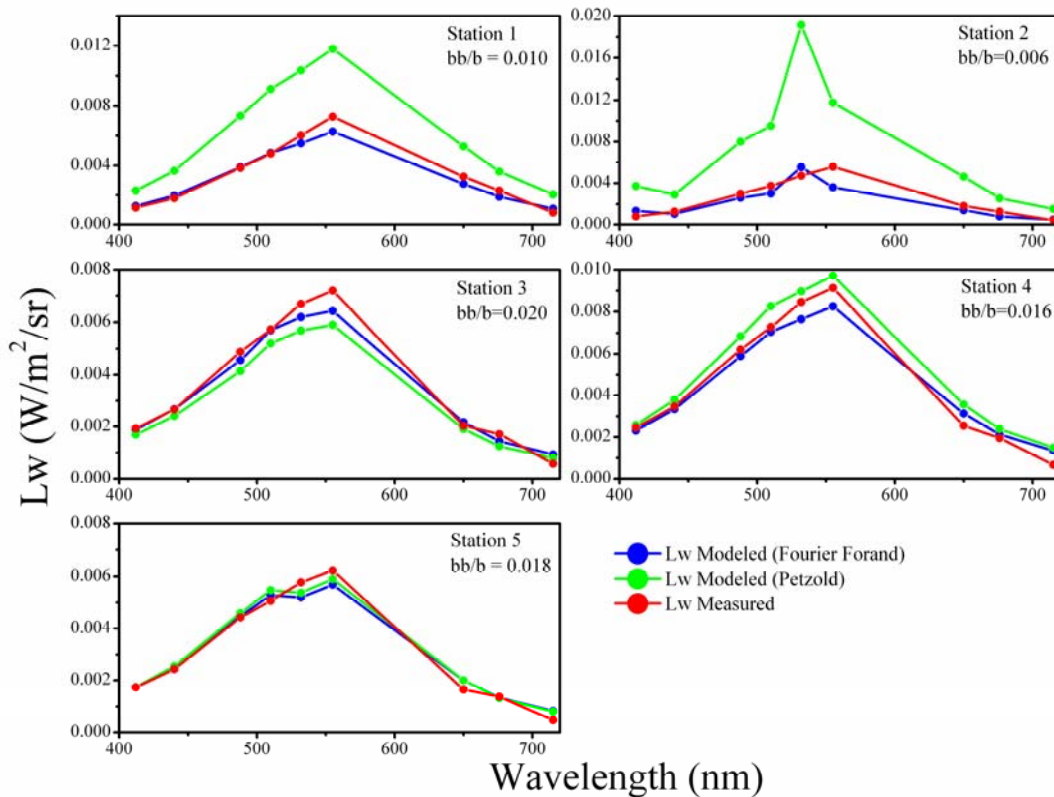


Fig5. Comparison of $L_w(\lambda)$ generated from Hydrolight simulations using Petzold (Green) and Fourier Forand (Blue) phase function with measured (Red).

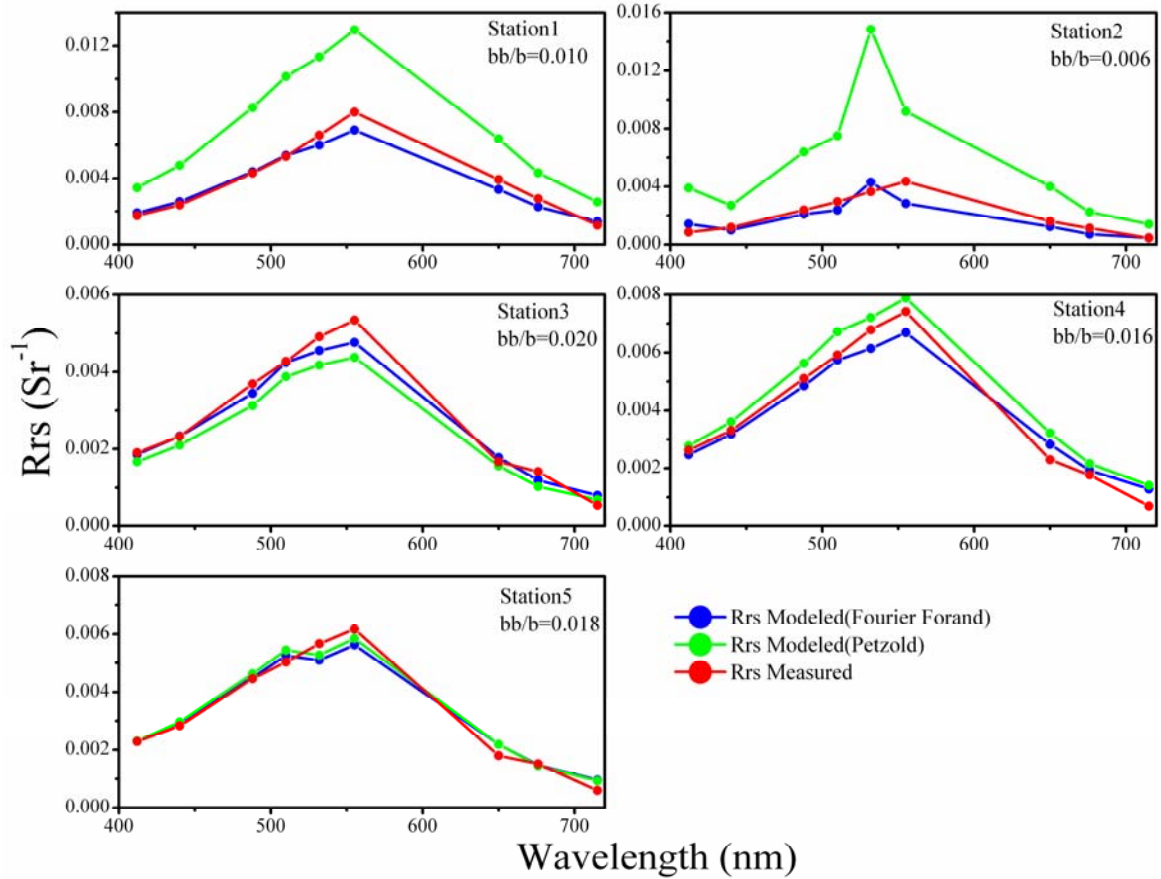


Fig6. Comparison of $R_{rs}(\lambda)$ generated from Hydrolight simulations using Petzold (Green) and Fourier Forand (Blue) phase function with measured (Red).

4 Summary and Conclusion

Under circumstances where no measured phase functions are available for optical simulations, using semi analytical or empirical phase functions that closely match with the water type will provide good optical closure. Hence we have opted to use Fournier Forand phase function which uses only a single parameter of particulate back scattering ratio and the results of closure has proven that the this phase function could be the optimum choice. The backscatter and scattering coefficients can be measured using commercial instruments or obtained from empirical methods and this will help in quantifying the phase functions for the waters of the region. Here the phase functions obtained can be used as a representative of the waters of these regions or stations and the errors could be comparatively less than assuming just a single phase function as of Petzold. Since $L_w(\lambda)$ and thus $R_{rs}(\lambda)$ are the fundamental optical properties underlying ocean color, this study was limited to the surface parameters and the same method could be extended to study and compare the other optical parameters.

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