

Particle Backscattering Variability in the Coastal Waters of Bay of Bengal: A Case Study Along Off Kakinada and Yanam Regions

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Abstract—The distribution and variability of particulate back scattering coefficient (b_{bp}) in the Godavari basin are reported for the first time using *in situ* measurements. A coastal cruise was conducted in the coastal waters Off Kakinada and Yanam along the East coast of India, from 2–9 March 2012. Hyperspectral underwater radiometer was used to collect the *in situ* bio-optical data as function of wavelength in 21 sampling stations from the coast (~ 10 m) to toward the open ocean (~ 150 m). Data from these sites exhibits two orders of magnitude in b_{bp} and covered the typical coastal and estuarine waters. The b_{bp} at a single wavelength, i.e., 700 nm was measured with the embedded echo-VSF (Wetlabs) series sensor. In this letter, an attempt was made to: 1) describe the variability of particle b_{bp} of estuarine coastal system using *in situ* measurements; 2) model the b_{bp} from Quasi Analytical Algorithm (QAA) and verify its accuracy by comparing with *in-situ* measurements of b_{bp} ; and 3) examine the relationship of b_{bp} and chlorophyll-*a* concentration in the coastal system. A significant relationship was observed between the *in-situ* and model derived b_{bp} values. The *in-situ* measured b_{bp} values vary from 0.01 to 0.065 m^{-1} in this region. The relationship between chlorophyll-*a* concentration and the b_{bp} has been studied. The large spread in the scatter in the chlorophyll Vs. *in-situ* b_{bp} infers that chlorophyll-*a* is a poor predictor of b_{bp} . The relationship between chlorophyll-*a* concentration and the b_{bp} shows an inverse relationship for the Godavari Estuarine waters.

Index Terms—Hyperspectral, *in situ*, particulate backscattering.

I. INTRODUCTION

QUANTITATIVE interpretation of the remotely-sensed signal in terms of the constituents of the water requires that to identify and isolate the effect on the signal arising from variations in the incident light field. Therefore, a necessary step in modeling ocean color is to express remote-sensing reflectance in terms of inherent optical properties [22], which are independent of variations in the angular distribution of the incident light field, and are solely determined by the type and

concentration of substances present in the medium (IOCCG-3). Several rigorous studies of radiative transfer in the ocean have been undertaken to understand the relationships between ocean color and inherent optical properties of the water. The two main inherent optical properties are absorption and back scattering, again these two parameters are functions of various constituents present in the water column and the sea water itself. Because the composition and concentrations of in-water constituents influence the optical characteristics, *in-situ* measurements of the optical properties are very important to study [1].

Methods and techniques for retrieving these inherent optical properties using remote sensing as well as from the *in-situ* data are in progress for several decades. Some of these methods include analytical, semi analytical, quasi analytical, linear matrix inversion and artificial neural networks, etc. For example, Loisel and Stramski [17] developed an analytical inverse algorithm to retrieve the total absorption, scattering and back scattering coefficients from the irradiance reflectance just beneath the surface and the mean vertical diffuse attenuation coefficient over the first optical depth based on Monte Carlo and Hydrolight simulations.

The importance of determining spectral values of b_{bp} in the ocean stems from the tight link to essential physical and chemical characteristics of particles [10], [11]. Accurate determinations of b_{bp} carry information (both shape and slope of the spectral curve) about the composition of particles [7], [8], [11], [15]. When spectral b_{bp} measurements are available, parameters of a log-linear particle size distribution can be estimated with some limitations [5]. Understanding the particle size distribution has tremendous importance because it provides a measure of the structure and functioning of the pelagic ecosystems [3], [9].

However, many questions are still unresolved concerning the variability and controls on b_{bp} . Many researchers studied the spectral behavior of b_{bp} and its relationship with chlorophyll-*a* (Chl-*a*) concentration. Large uncertainties remain, in particular about b_{bp} in the coastal oceanic waters. One way to progressively answer these questions is to analyze more concurrent *in-situ* measurements of b_{bp} and other in-water constituents and their concentrations such as chlorophyll, non-algal particles, sediment types, since IOPs are directly linked to in-water constituents. This is precisely the focus of the present work, through the *in-situ* bio-optical measurements. In this paper, the main objective of the study is to: (1) describe the variability of particle b_{bp} of estuarine coastal system using

Manuscript received September 14, 2012; revised January 22, 2013 and April 18, 2013; accepted April 22, 2013.

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Digital Object Identifier 10.1109/LGRS.2013.2261275

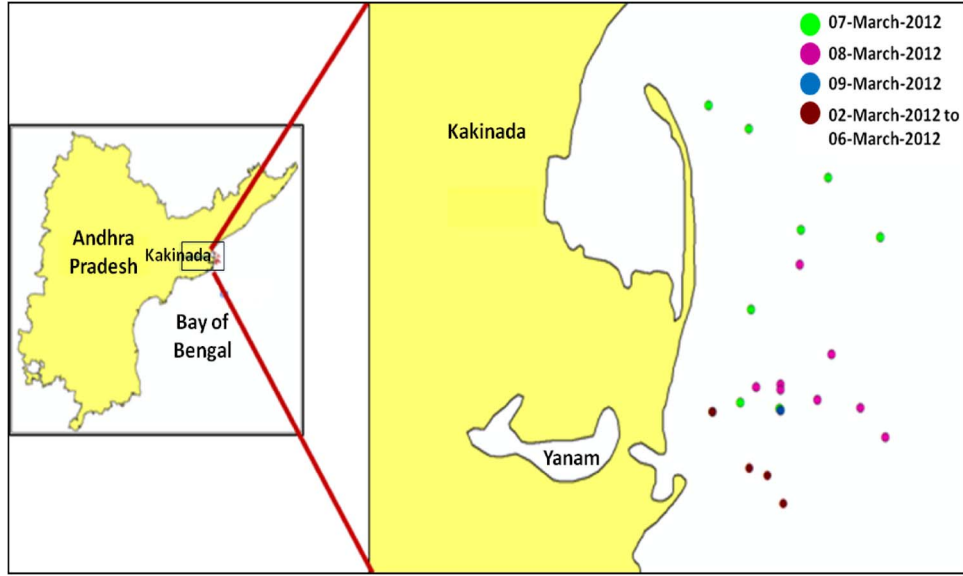


Fig. 1. Study area and *in situ* sampling stations during 02–09 March 2012 cruise along Off Kakinada and Yanam regions.

in situ measurements; (2) model the b_{bp} from Quasi Analytical Algorithm (QAA) and verify its accuracy by comparing with *in-situ* measurements of b_{bp} ; and (3) examine the relationship of b_{bp} and chlorophyll-*a* concentration in the coastal system.

II. MATERIALS AND METHODS

The *in-situ* bio-optical data collected in the coastal waters of Off Kakinada and Yanam during 2–10 March 2012 covers from 16°41.125' N to 16°58.099' N latitudes and 82°32.141' E to 82°23.425' E longitudes. The area is often called Kakinada–Godavari Basin (KG Basin) and very significant for petroleum reserve. The geographical distribution of *in-situ* sampling locations are shown in Fig. 1. The *in-situ* data was collected in two modes one as a transect and the other as time series mode.

Description of Field Sites and in-situ Data: The *in-situ* sample collection varies from 10 m to 150 m bathymetry of the region covering estuarine, coastal turbid waters and open ocean stations in the Godavari basin as shown in Fig. 1. NASA Ocean Optics Protocols [12] were followed for all sampling collection, handling, preservation and analysis. Hyperspectral underwater radio meter was used to measure the *in situ* optical variables such as upwelling radiance (L_u), downwelling irradiance (E_d), surface irradiance (E_s) which are further considered for computing the water leaving radiance (L_w), normalized water leaving radiance (nL_w) and remote sensing reflectance (R_{rs}) as a function of wavelength (Prosoft 7.7.2). Multiple, usually three measurements or casts were made in quick succession and 73 m away from the boat to avoid the influence of ship shadow. A deck unit mounted to the open structure of the boat provided contemporaneous measurements of above-water surface incident irradiance (E_s) during the HyperPro profiler. However, during this cruise due to the malfunctioning of the E_d sensor we used E_s for computing the nL_w and R_{rs} values. The hyperspectral underwater radiometer has echo-VSF (Wetlabs) triplet enclosed to it with a backscattering sensor to measure the particulate back scattering coefficient at 700 nm, chlorophyll

fluorescence sensor to measure the chlorophyll-*a* concentration and CDOM fluorescence sensor for CDOM absorption measurements. The sensors of the triplet are calibrated at Wetlabs to maintain the accuracy limits of the sensors provided by the manufacturer.

The Quasi-Analytical Algorithm (QAA) developed by Lee *et al.* [13] has been used for calculating the b_{bp} . The QAA approach uses the above surface remote sensing reflectance, R_{rs} and converts into the surface remote sensing reflectance, r_{rs} [2]. The b_{bp} is calculated using the following analytical relation:

$$b_{bp}(555) = \frac{u(555)\alpha(555)}{1 - u(555)} - b_{bp}(555) \quad (1)$$

$$u(\lambda) = \frac{[-g_0 - [(g_0)^2 + 4g_1r_{rs}(\lambda)]]^{1/2}}{2g_1} \quad (2)$$

where u is the ratio of backscattering coefficient to the sum of the absorption and backscattering coefficient which can be derived from r_{rs} as show by Gordon *et al.* (1988) [20] as shown below

$$b_{bp}(\lambda) = b_{bp}(555) \left(\frac{555}{\lambda} \right)^Y \quad (3)$$

where $g_0 = 0.0895$ and $g_1 = 0.1247$ are the averaged values of Gordon *et al.*, and Lee *et al.*, for the both open and coastal waters.

The particle backscattering can be calculated from one wavelength to another wavelength by the following relation wavelength dependent factor, Y is used by an empirical relation derived by Lee *et al.* [21] as shown in (4), but at the wavelengths of 440 and 555 nm as an exponent value in the backscattering:

$$Y = 2.2 \left\{ 1 - 2.2 \exp \left[-0.9 \frac{r_{rs}(440)}{r_{rs}(555)} \right] \right\}. \quad (4)$$

If the power value Y is known, then b_{bp} at any wavelength can be calculated.

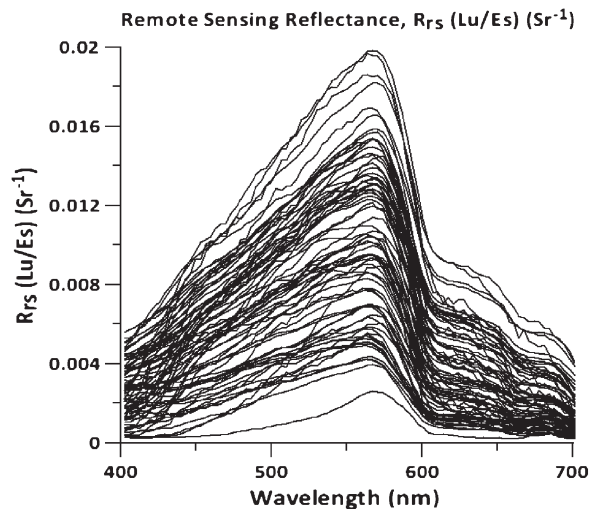


Fig. 2. Radiometric profiles of normalized water leaving radiance and surface remote sensing reflectance at sampling locations of the study area.

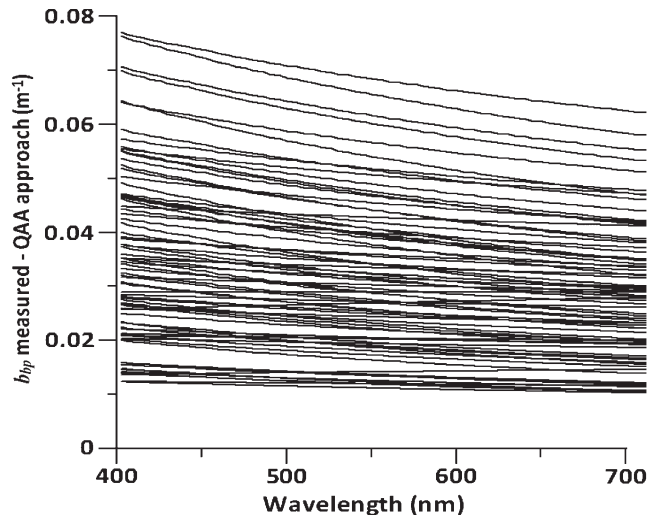


Fig. 4. Particulate backscattering estimated using QAA approach for all the sampling locations.

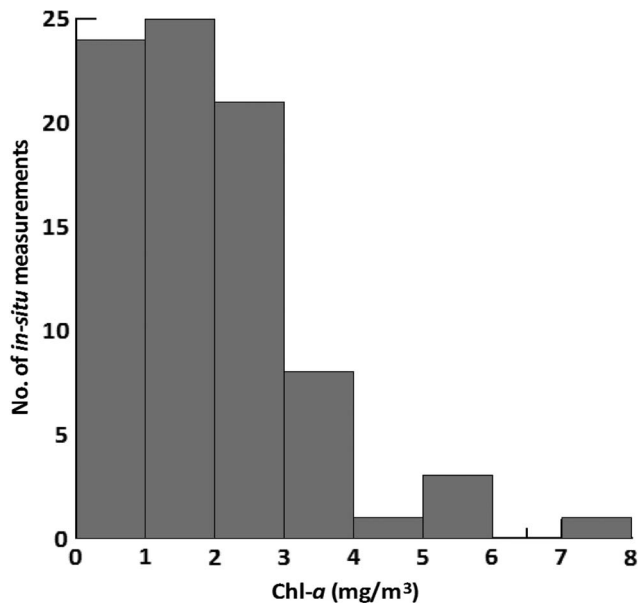


Fig. 3. Frequency distribution of Chl-*a* conc. (mg/m^3) measured during the cruise in the Godavari basin, 02-09 March 2012.

III. RESULTS AND DISCUSSION

In-situ R_{rs} spectra measured in the coastal waters of Off Godavari as a function of wavelength are shown in the Fig. 2. The remote sensing reflectance showing a broad spectral peak confirms the presence of turbid coastal waters and a narrow spectral peak at high chlorophyll-*a* concentration (at three stations of 30 m depth near the Godavari estuary). A high reflectance peak at 550–560 nm confirms the presence of high chlorophyll concentration which was collected at 30 m depth bathymetry near Godavari estuary.

The Chl-*a* concentration varies from 0.5 to 7.1 mg/m^3 with an average value of 2 mg/m^3 in the study area and the distribution of the concentrations along with the range measured at different locations is shown in the Fig. 3. The spectral behavior of b_{bp} estimated from QAA algorithm is shown in the Fig. 4. The b_{bp} shows 1 to 2 orders of magnitude ranging from 0.015 to

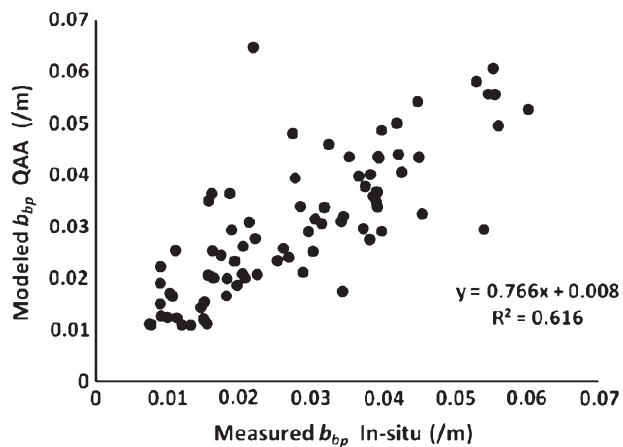


Fig. 5. Comparison of *in-situ* measured particulate backscattering: b_{bp} at 700 nm and b_{bp} derived using QAA approach.

0.184 m^{-1} . Most of the particulate backscattering values range from 0.015 to 0.075 m^{-1} with an average value of 0.034 m^{-1} for the study area. From this study, it is observed that b_{bp} is high in the shorter wavelengths compared to the longer wavelengths or in the NIR region, the particulate backscattering is decreasing as a function of wavelength in the coastal waters of Godavari basin.

Large variations were observed in the particulate backscattering ranging from 0.01 to 0.065 m^{-1} measured at 700 nm. Higher b_{bp} values were observed at the near shore sites compared to the other stations covering the open ocean.

A comparative study was made between the *in-situ* measured b_{bp} and the QAA modeled b_{bp} values. A good correlation was observed between these two measurements with an R^2 value of 0.6 with an RMSE value of 0.014 as shown in Fig. 5.

A. Variation of b_{bp} With Chl-*a* Concentrations

The b_{bp} provides information about characteristics of the bulk particle population (i.e., particle composition, size, shape, etc.) [4]. The ratio between the *in situ* measured b_{bp} and

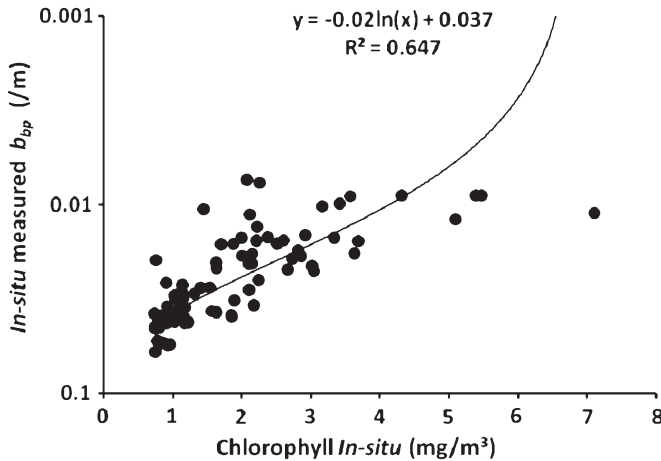


Fig. 6. Particulate backscattering co-efficient as a function of Chlorophyll-*a* concentration.

chlorophyll (b_{bp}/Chl) has been calculated. Huot *et al.* [6] made extensive analysis on b_p and b_{bp} Vs. Chl relationship in different wavelengths and found that b_{bp}/b_p brings information about the composition, not b_{bp} . The spectral slope of b_{bp} provides information about particle size distribution (PSD). The b_{bp}/Chl values show a minimum value of 0.0015 and a maximum value of 0.079 for the *in-situ* observations. From the spectral slope of b_{bp} it is inferred that the small particle sizes in the off shore waters and little larger particle sizes in the near shore waters. The QAA model derived b_{bp}/Chl ratio values range from 0.002 to 0.24. We did not have the dominant particle information from the water samples at discrete depths of the study area. The relationship between the b_{bp} and chlorophyll-*a* is stronger at the first optical depth of the water column. Fig. 6 illustrates the relationship between *in situ* measured concentrations of Chl-*a* and the particulate backscattering coefficient at 700 nm, with a correlation coefficient, R^2 value of 0.6.

IV. CONCLUSION

The main objective of the study is to examine the variability of particulate back scattering coefficient in the coastal estuarine waters using the *in-situ* measurements, model the b_{bp} with the existing QAA algorithm and compare the modeled and *in-situ* b_{bp} values. Finally, the relationship between *in-situ* b_{bp} and chlorophyll concentration has been studied. For this purpose, we analyzed the *in-situ* data collected at different locations of Off Godavari basin. During the study period we collected and analyzed 84 data points of *in-situ* b_{bp} , chlorophyll concentrations and b_{bp} was modeled for those points using QAA algorithm. From the study it is observed that, the *in-situ* and modeled b_{bp} correlated well with R^2 value of 0.6 and the relationship between *in-situ* measured chlorophyll and b_{bp} is strong up to 5 mg/m^3 concentration range and beyond this, chlorophyll concentration range the relationship is weak. The particulate back scattering coefficient has increased with the increase in the chlorophyll concentration, in the study area. The spectral shape and slope of the b_{bp} curve and the b_{bp}/Chl ratio analysis gave information about the particle size distribution. From this study it can be inferred that small particles are

present in the offshore waters and particles with slightly larger size occur in near shore waters.

This infers the small particle sizes in the off shore waters and little larger particle sizes in the near shore waters. These results confirm the poor predictability of b_{bp} using chlorophyll over a wide range of conditions, as there are many cellular and population level processes that can affect the relationship between b_{bp} and chlorophyll. Furthermore, different phytoplankton groups and community structure will have different particle size distribution, cellular geometries, and/or composition, all of which can lead to different b_{bp} and Chl-*a* relationships and this will be studied in future with more *in-situ* measurements in this region.

ACKNOWLEDGMENT

Sincere thanks are due to Dr. V.K. Dhadwal, Director, NRSC, Dr. C.B.S. Dutt, DD, ECSA and Dr. M.M. Ali, GD, AOSG for their consistent support and encouragement to carry out this work. The authors would like to express their sincere thanks to the respective collaborators for participating in the cruise for collecting the data and project funding support and cooperation to carry out this work in a big way.

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