VARIABILITY IN THE BACKSCATTERING TO SCATTERING AND F/Q RATIOS OBSERVED IN NATURAL WATERS

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ABSTRACT

Variability of the backscattering to scattering (b_b/b) and the upwelling irradiance/upwelling radiance (f/Q) ratios affect the accurate retrieval of inherent optical properties from ocean color satellite algorithms (SeaWiFS and MODIS). We investigate the variability of b_b/b and the f/Q in coastal and open-ocean surface waters of the Northern Gulf of Mexico and U.S. East Coast off New Jersey. In situ measurements of scattering (b) from an ac9 probe were collected with concurrent measurements of b_b from a six channel Hydroscat sensor. We compare the measured b_b/b values with values derived from the Petzold Volume Scattering Functions (Petzold[14]), examine the spectral variability of the ratio and examine the variability in different water types related to the changes in the Volume Scattering Function (VSF). In addition, we estimate the T*f/Q (Mobley[9]) term from above-water measurements of remote sensing reflectance (Rrs) coupled with direct measurements of absorption (a) and backscattering (b_b) coefficients. We will examine the spectral dependence of the T*f/Q term and its relationship to the b_b/b ratio, which we use as a substitute for the changing VSF. Finally, we will show how the estimated T*f/Q values vary from the commonly used value of 0.051 used for satellite processing.

INTRODUCTION

Remote sensing algorithms for ocean color visible imagery are based on relationships between remote sensing reflectance and such inherent optical properties as absorption and scattering. Previous studies have simplified these relationships and are currently used in present ocean color algorithms such as with SeaWiFS. The limitations of the relationships in different optical water types are under investigation. This effort is directed at examining different water types defined by the backscattering to scattering ratio and the changes in the T*f/Q term (where Q is the ratio of upwelling irradiance to upwelling radiance). Both the ratios affect the accurate retrieval of the inherent optical properties.

The remote sensing reflectance (Rrs) is dependent on the angular scattering described by the volume scattering function (VSF). The VSF describes the angular distribution of scattered light in the water column. The integral of the VSF over full solid angle is the scattering coefficient (b); the integral over angles in the backward direction only (90-180 degrees) is the backscattering coefficient (b_b). The VSF is influenced by particle characteristics such as shape, index of refraction, and size distribution. Because the VSF is difficult to measure (new instruments are just now becoming available), we use the b_b/b ratio (or probability of backscattering) as a substitute for the VSF to describe water mass differences. This ratio provides a method to describe the differences in the VSF for different water masses and how the angular differences influence the Rrs. Understanding the differences in b_b/b for different water masses will help characterize the changes in the VSF, which affect Rrs estimates, and provide better estimates of inherent optical properties in coastal and open-ocean waters (Northern Gulf of Mexico and New Jersey Coast) where different b_b/b water types are observed. This is important for researchers to model optical remote sensing algorithms, visibility and laser propagation in seawater.

We will use in situ measurements for various water types to determine how the b_b/b changes both spectrally and in a wide variety of coastal and open-ocean waters and how it compares with the linear Petzold[14] b_b/b ratio. Our second objective is to evaluate the relationship between measured remote sensing reflectance, backscattering and absorption through the ratio $[b_b/(a+b_b)]$. We will examine the spectral nature of the T*f/Q term and show how the estimated T*f/Q values vary from the commonly used value of 0.051 used for satellite processing

BACKGROUND

The availability of VSF, b_b and b measurements has been limited in the past. VSF measurements (515nm) made in San Diego Harbor over 30 years ago by Petzold[14] were used by Gould et al.[5] to estimate a linear relationship between b_b and b:

$$b_b = 0.01829 * b + 0.00006, \quad (r^2 = 0.99) \tag{1}$$

This is a limited data set of 15 angular scattering coefficients and attenuation coefficients of 15 phase functions, collected at a single wavelength that does not describe the differences in the VSF for different water types. New instruments are currently available that measure the VSF (Haltrin et al.[6]), backscattering and scattering directly.

Irradiance reflectance or diffuse reflectance coefficient is defined as:

$$R = E_u/E_d \tag{2}$$

Using different approaches, Morel and Prieur[13] and Gordon et al.[2] related irradiance reflectance (R) to water inherent optical properties (absorption and backscattering) through a factor *f*:

$$R = f^*[b_b/(a+b_b)] \tag{3}$$

where *f* varies in a range of 0.28 – 0.42 for most "Case 1" waters and for solar zenith angles less than 70 degrees (Morel and Gentili[10]). Remote sensing reflectance is defined as:

$$Rrs = L_w/E_d \tag{4}$$

To convert R to Rrs (in order to relate satellite measurements to in-water optical properties), we must apply an irradiance-to-radiance conversion factor Q (L_u/E_d) and push the radiance/irradiance values through the air/sea interface. Following notation in Mobley[9]:

$$Rrs = (T/Q) * R \tag{5}$$

(See Mobley[9] for derivation of T term). Substituting for R from equation 3

$$Rrs = (T^*f/Q) * [b_b/(a+b_b)] \tag{6}$$

The value of T is approximately 0.54 and only varies by a few percent (Mobley[9]). From a theoretical perspective, f/Q varies with sun and satellite viewing angle and changing inherent optical properties and ranges from 0.07 to 0.11 over realistic angles for remote sensing applications (Morel and Gentili[11]). It changes in different water types in response to VSF and angular scattering. So considering the variability in both T and f/Q, we would expect a range of approximately 0.0366 to 0.0612 for the T*f/Q term in equation 6. Using in situ measurements, we describe how this term changes spectrally and in different water masses.

Lee et al.[7] are further refining the estimation of f/Q by analyzing and modeling the effect of the VSF shape on this term. The new model, weighted by relative contribution of particle scattering, provides improved estimations of f/Q. This refined estimation of f/Q will further improve estimations of Rrs and in-water properties, but does require a priori knowledge of a and b_b.

METHODS

We collected data at 174 stations in different waters types (open ocean and coastal). These included two cruises in the Northern Gulf of Mexico in May 2001 and May 2002 off of Mobile Bay for a total of 83 stations. The remaining 91 stations were collected in New Jersey in July 2000 and July 2001. The Gulf of Mexico represents a wide variety of highly scattering waters with elevated suspended sediment loads and high CDOM where as the New Jersey cruises represent clearer waters with less sediments. We collected above-water measurements of Rrs using an Analytical Spectral Device

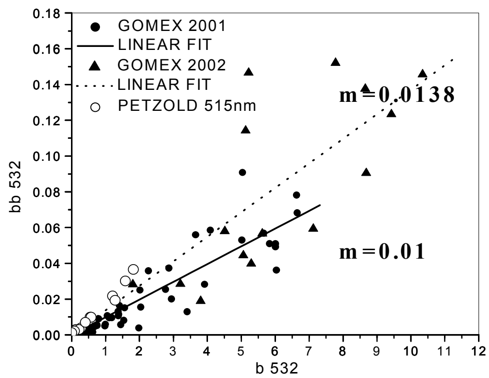
(ASD) field spectroradiometer which was processed using near-infrared (NIR) surface glint removal algorithms (Gould et al.[5]). This is required to account for the Rrs at near-infrared wavelengths in high scattering waters. The ASD measures the spectrum at 1.3 nm resolution from 400 – 800 nm and a 12% spectralon (gray) card was used for calibration. Absorption and beam attenuation (a and c) were measured using a WetLabs ac9 at 9 wavelengths (412, 440, 488, 510, 532, 555, 650, 676, 715nm). The instrument was calibrated using milli-Q water and the Zaneveld scatter correction was applied (Zaneveld et al.[16]). We derive scattering by difference (c-a). The spectral backscattering coefficient was measured with the Hydroscat instrument, which measures the scattering at 140 degrees and extrapolates the b_b at 6 wavelengths (442, 488, 532, 589, 620, 676nm) (Maffione and Dana[8]). The instrument was calibrated at the factory prior to the deployments. We removed the backscattering and scattering due to pure water using Smith and Baker[15] to investigate the differences in the spectral b_b/b ratio.

RESULTS

Backscattering to Scattering Relationship

We plotted measured b_b and b for two regions (Gulf of Mexico and New Jersey) to investigate the relationship for 440, 488, 532, and 676nm and differences for different water types. Figure 1 shows the relationship between b_b and b at 532nm for the Gulf of Mexico 2001 and 2002 including Petzold[11] data at 515nm. The Gulf of Mexico data seems to depict two different water types, although there is much spread in the data and considerable overlap. The first water type includes Gulf of Mexico data from the 2002 cruise (triangles and dotted linear fit) and is similar to the Petzold[14] relationship (open circles). The second water type is defined by the Northern Gulf of Mexico from 2001 cruise (filled circles and solid linear fit). Both Northern Gulf of Mexico cruises were conducted in the same vicinity one year apart.

Figure 2 shows the relationship between b_b and b at 532nm for the New Jersey cruises. The data displayed in Figure 2 more clearly depict two distinct water types. The first water type includes data from the 2000 cruise (filled circles and solid linear fit) and is similar to the Petzold relationship (open circles). The second water type is defined by the data from the 2001 cruise (triangles and dotted linear fit). This water type consist of mostly open ocean waters dominated by biological rather than inorganic particles and produced a b_b/b ratio lower than the other cruises. Note that the New Jersey cruises were also conducted in same vicinity one year apart.



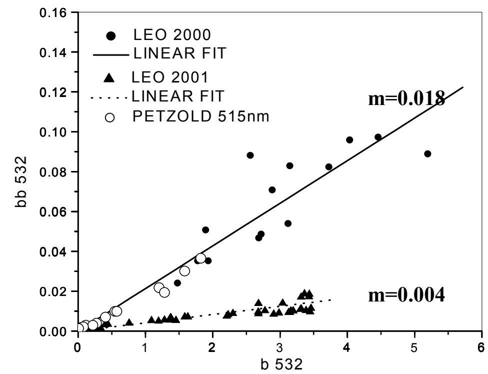
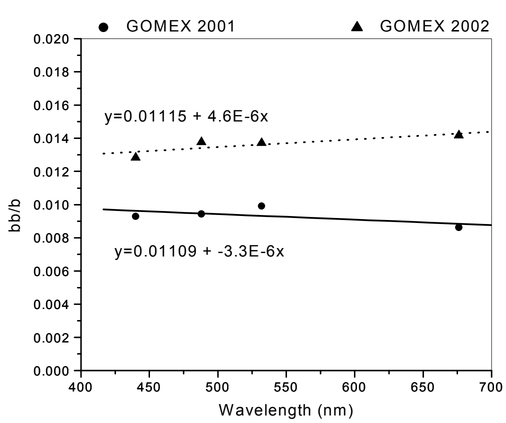


Figure 1. Measured b_b (532nm) vs. b (532nm) for the two Gulf of Mexico Cruises

Figure 2. Measured b_b (532nm) vs. b for the two New Jersey Cruises.

By using the slopes of the lines in figures 1 and 2, which is essentially the b_b/b ratio for all stations in the relationship, and using the other measured wavelengths (440,488,676) in common between the two instruments, we can examine the spectral dependence of the b_b/b ratio. Figures 3 and 4 represent the b_b/b ratios derived from Figures 1 and 2 plotted as function of wavelength. Figure 3 shows the two distinct water types for the Northern Gulf of Mexico region. Figure 4 shows the two distinct water types for the New Jersey region. The spectral shape of both regions is nearly flat. We will further examine the statistical difference at a later time. The Northern Gulf of Mexico waters during 2002 and the New Jersey 2000 waters are similar to that of Petzold[14] type waters. We note that for the New Jersey waters the spectral shapes are somewhat similar and the water types show more distinct difference than the Northern Gulf of Mexico cruises. Results show the b_b/b relationship is not always related to the Petzold[14] relationship. The changes in the b_b/b ratio can possibly be used to characterize the VSF in different water types and agrees with the behavior seen in actual VSF measurements (Haltrin et al.[6]).



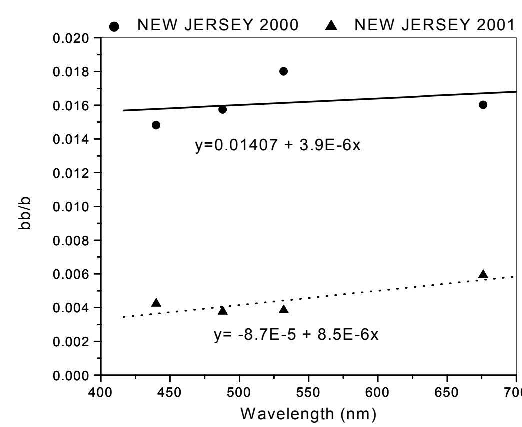


Figure 3. Measured b_b/b ratio (y-axis) as a function of wavelength (x-axis) for two Gulf of Mexico Cruises.

Figure 4. Measured b_b/b ratio (y-axis) as a function of wavelength (x-axis) for two New Jersey Cruises.

F/Q Ratio

We took the measured properties of a, b_b, and computed the ratio $[b_b/(a+b_b)]$ for the Gulf of Mexico and New Jersey stations combined (Figure 5). The regions were plotted separately (not shown) but did not show a regional dependence for this study. We plotted the relationship between the measured Rrs at 440 (top left), 488 (top right), 532 (bottom left) and 676nm (bottom right) versus the $[b_b/(a+b_b)]$ ratio. These relationships show the spectral variance in the (T*f/Q) term used in equation 6 for these two regions. From theoretical studies, this term should range between approximately 0.0366 – 0.0612. Based on measured values, our results show that the term ranged from 0.04 (532nm) - 0.07 (440nm). A value of 0.051 is commonly used in satellite ocean color processing (Carder et al.[1]). The 532nm (lower left) channel shows higher scatter than the others. This scatter could be because the 532nm channel has a higher in-water transparency than other channels and is where the minimum absorption occurs. Any small variation in absorption, whether it is due to the error in measurement or stability of the instrument, could possibly cause such high variations for this relationship.

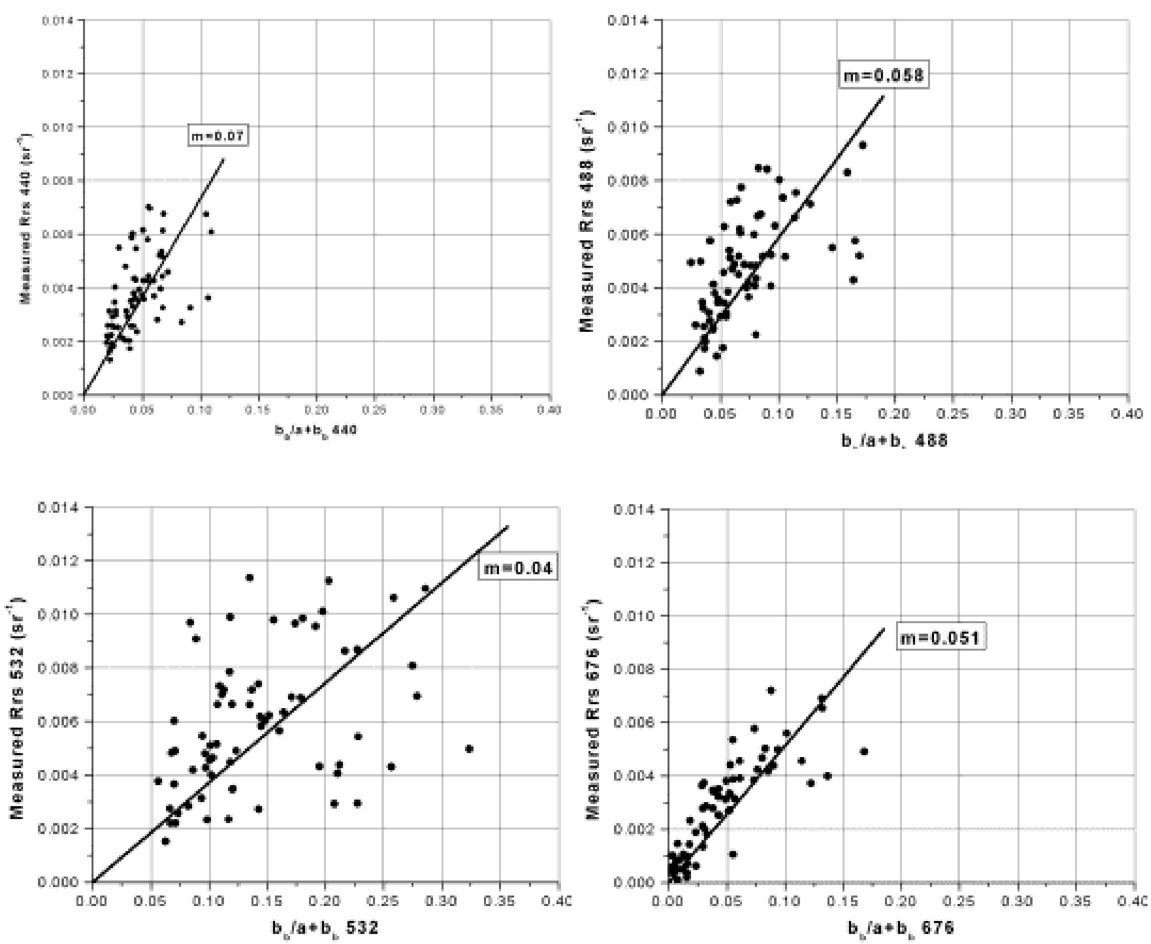


Figure 5. Measured Rrs vs. bb/(a+bb) ratio for all stations collected in the Northern Gulf of Mexico and New Jersey regions.

We took the mean of the T*f/Q terms estimated by dividing measured reflectance by the measured ratio [$b_b/(a+b_b)$] and plotted as a function of wavelength shown in figure 6. Morel and Gentili[11] also looked at the f/Q term as a function of wavelength. They found that the values for f/Q to be 0.0936 (440nm), 0.0944 (500nm), 0.0929 (565nm), and 0.0881 (665nm), which would result in T*f/Q estimates of 0.0505, 0.0509, 0.0502, and 0.0476. Their results are stable and linear as a function of wavelength whereas results in this study show a larger variation. Morel and Gentili[11] observed Case I waters and radiances encountered in the vicinity of the vertical direction. The measurements of Rrs in this study were measured 40 degrees from nadir and collected in non-Case I waters. Morel and Gentili[11] documented that before interpreting the marine signals, the discrimination between Case I and sediment-dominated Case II waters has to be made, therefore a separate knowledge of the Q factor is needed.

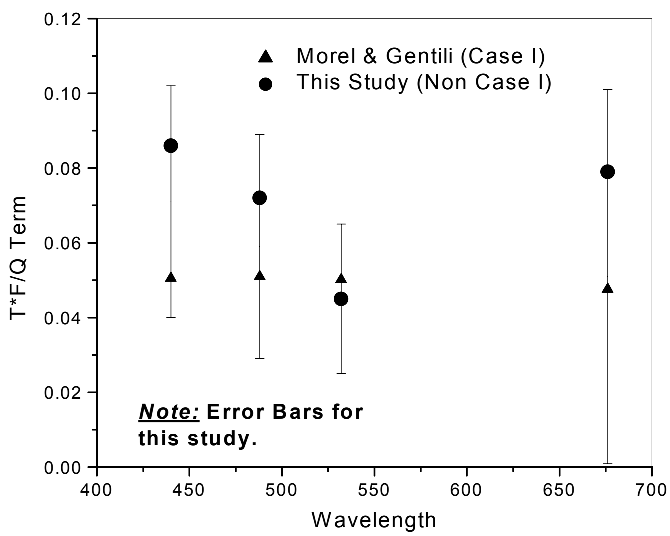


Figure 6. Mean T*F/Q calculated from equation 6 vs. wavelength. Error Bars indicate + or – one standard deviation.

CONCLUSION

The b_b/b ratio derived from in situ measurements varies spectrally over different water types (mostly turbid). This variability maybe related to regional differences in the VSF. We looked at four different cruises (two in the Northern Gulf of Mexico and two off the coast of New Jersey). We clearly observed two different water types for each region but the bb/b ratio as a function of wavelength was nearly flat spectrally. In some cases for the Gulf of Mexico and New Jersey region the bb/b ratios were quite similar to the ones derived from the Petzold[14] data while in others it was not. This ratio provides a method to describe the differences in the VSF for different water masses and how the angular differences influence the Rrs.

We estimated the T*f/Q term from above-water measurements of Rrs coupled with direct measurements of absorption and backscattering. We show in this study that the estimated T*f/Q term in non-Case I waters has more spectral variability compared to values presented by Morel and Gentilli[11] in Case I waters. From theoretical considerations, T*f/Q from equation 6 should range between 0.0366 and 0.0612. In our current satellite processing we use a constant value for T*f/Q equal to 0.051. Based on in situ measurements, we found the spectral range of the term to be between 0.04 (532nm) and 0.086 (440nm) for the four wavelengths examined in this study. We did not note any separation due to water type when looking at the four cruises.

The understanding of the differences in the b_b/b relationship will help characterize the changes in the VSF, which affect Rrs estimates, and the parameterization of the f/Q term for different water types certainly can improve the accuracy of algorithms applied to remotely sensed ocean color data.

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