Revisiting the role of oceanic phase function in remote sensing reflectance

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Abstract

The effect of angular structure differences between measured and best-fit analytical phase functions of the equivalent backscattering ratio on calculated reflectance values was studied and shown to be significant. We used a Monte Carlo radiative transfer code to check the effect of choosing different analytical (several Fournier-Forand (1994) and Henyey-Greenstein (1941)) phase functions with backscattering ratios identical to the 'classical' average Petzold function. We show that the additional variability of the resulting water leaving radiance is about 7% (4% between the Fournier-Forand functions themselves) for most scenarios. We also show a previously unknown maximum of the discrepancy (up to 10%) for highly scattering waters. We discuss the importance of relative differences in phase function for different angular ranges to this maximum and to the behaviour of the discrepancy as a function of solar zenith angle.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

1. Introducton

Remote sensing reflectance (RSR) is the ratio of upwelling vertical radiance L_u to downwelling irradiance E_d, both observed above the sea surface. It is usually approximated as

$$\mathrm{RSR} = k\frac{b_b}{a}, \tag{1}$$

where b_b is backscattering, a is absorption and k is a proportionality factor (for historical reasons, often presented as the ratio of two coefficients $k \equiv f/Q$; the approximation was originally proposed by Morel & Prieur (1977) for diffuse reflectance with a proportional coefficient f, which required an additional coefficient Q when the formula was adapted for RSR). Most remote sensing students using the formula are probably aware that the value of the coefficients f and Q, and hence k, depend on the angular distribution of the downwelling radiation (Morel & Gentili 1993; for a recent review of solar radiation, see Dera & Woźniak 2010), especially the solar zenith angle (Gordon 1989), and on sea surface roughness (Gordon 2005; for a recent review of surface roughness, see Massel 2010). However, many would be surprised that the coefficients also depend on the shape of the in-water scattering phase functions.

Volume scattering functions (VSFs) describe the angular variation of scattered light intensities. Normalizing the VSF to the scattering coefficient gives the scattering phase function. Knowledge of the phase function and other inherent optical properties (IOPs) enables the radiance transfer to be calculated for a beam of light. Seawater phase functions are strongly asymmetrical. According to the measurements of Petzold (1972), whose phase functions are still widely used in radiative transfer modelling, between 46% and 64% of light is scattered into angles smaller than 5°. More than 96% of light is scattered into the forward hemisphere. The backscattering ratio is defined as the integral of volume scattering function (VSF) over the backward hemisphere b_b divided by the total scattering coefficient b (VSF integrated over the total sphere). This b_b/b value describes the probability of scattering into the backward direction during a single scattering process.

It would seem that, because the backscattering coefficient is used explicitly in the RSR approximation (1), the angular shape of the phase function is already accounted for. However, there are an infinite number of possible phase function shapes that correspond to the same backscattering ratio. Of course, only a limited subset of them are actually relevant to oceanic radiative transfer calculations, but it is important to check how much variability in the calculated RSR value may result from the choice of a phase function even with a fixed b_b/b value. This possible source of the radiative transfer calculation error of RSR was studied by Chami et al. (2006) (this study is henceforth referred to as CMLK06), who compared the water leaving radiance for experimentally derived and Fournier-Forand (FF) parameterized phase functions with identical backscattering ratios using the Mobley et al. (2002) parameterization (and building on the results of that paper, which also discussed the effect of phase function shape on computed light-field quantities). However, because there is more than one way to parameterize FF phase functions for identical scattering and absorption coefficients (including the backscattering ratio) (Freda & Piskozub 2007), we decided to compare the effect of choosing a different FF function for a given b_b/b value on calculated remote sensing reflectance. In addition to that, we also included the average Petzold function and Henyey-Greenstein functions, as they are often used in radiative transfer modelling. This approach means that any discrepancies in calculated RSR values found in our study are independent of the ones previously reported by Chami et al. (2006), broadening the range of potential scattering phase functions for a given b_b/b.

2. Method

The RSR was calculated with a 3D Monte Carlo radiative transfer algorithm, originally created to study self-shading instrumentation measurement artifacts (Piskozub 1994, Piskozub et al. 2000) but subsequently used in ocean radiative transfer studies (Flatau et al. 1999, Piskozub et al. 2008). The algorithm makes it possible to calculate the RSR separately for photons leaving the marine environment and for photons, which as a result of reflection from a roughened sea surface, increase the value of the reflectance. These two parts of the RSR will be called the water leaving radiance reflectance and the reflective part of the RSR. The former depends on both the optical properties of seawater (like the VSF and the absorption coefficient) and the illumination conditions above the sea (like the Sun's position, the amount of light coming from a diffusive sky and sea surface roughness); the latter (the reflective part of RSR) depends on the illumination conditions above the sea surface only.

The input data of the algorithm include the number and depths of layers, the IOPs of each layer, the absorption coefficient of the bottom, light conditions (zenith and azimuth solar angles, ratio of light coming from a diffuse sky) as well as the wind conditions (speed and direction) to calculate wave roughness (see Cox & Munk 1954). For each calculation a diffuse light ratio of 0.3 was used, and the atmospheric phase function was approximated by Rayleigh theory. The depth of 2000 m was chosen as being large enough to avoid any bottom-related effects; the wind speed was set at 5 m s^{-1}. The phase functions used as input data for our modelling where chosen to fit the same value of the backscattering ratio. They are the average Petzold phase function (Mobley 1994), the Henyey-Greenstein phase function with average cosine $g = 0.9185$, and four Fournier-Forand phase functions. All have the same value of the backscattering ratio $b_b/b = 0.0183$. Freda & Piskozub (2007) showed that the refractive index parameter n of Fournier-Forand phase functions, best fitted to measurements, can vary from less than 1.01 to about 1.25. Consequently, values of n equal to 1.01, 1.05, 1.1 and 1.2 were chosen to obtain various shapes of FF phase functions, calculated using (Forand & Fournier 1999):

$$\widetilde{\beta}_{cum} = \frac{1}{(1-\delta)\delta^v}\left[1-\delta^{v+1}-\frac{1}{2}\sin(\theta/2)(1-\delta^{v+1})\right]+ + \frac{1-\delta_{180}^v}{16\pi(\delta_{180}-1)\delta_{180}^v}\left[\cos(\theta)-\cos^3(\theta)\right], \tag{2}$$

where $v = \frac{3-\mu}{2}$, $u = 2\sin\left(\frac{\theta}{2}\right)$, $\delta = \frac{u^2}{3(n-1)^2}$, and δ_{180} is δ determined for a scattering angle $\theta = 180$ deg.

Values of the second FF parameters μ, for given b_b/b, were obtained from

$$\mu = 2\frac{\log(2b_b/b(\delta_{90}-1)+1)}{\log\delta_{90}}, \tag{3}$$

where δ_{90} is δ determined for a scattering angle $\theta = 90$ deg.

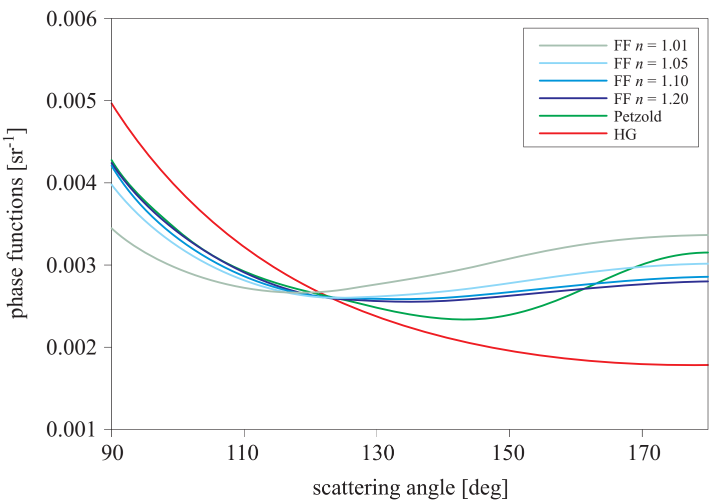

Figure 1. Phase functions used for Monte Carlo modelling. All have the same value of b_b (= 0.0183)

The input phase functions were prepared in cumulative form. But they are shown (see Figure 1) as phase functions (non-cumulative) so as to depict more details for backward angles (90–180 degrees).

3. Results and discussion

Because for an infinitely deep ocean, the IOP parameter controlling the light field as a function of optical depth is the single scattering albedo $\omega_0 = b/c$, we present our results as its function (unlike Figures 6 and 7 of CMLK06, which used b_b/a). This choice of presentation was arbitrary because we limited ourselves to one backscattering ratio (one of the average Petzold functions) and therefore the only free parameter we had was the absorption coefficient a. We simply decided that b/c was a more 'natural' way of showing this variability than b_b/a. The results are presented in Figure 2 as the ratio of the Monte Carlo calculated RSR for a given phase function to the value calculated for the average Petzold phase function.

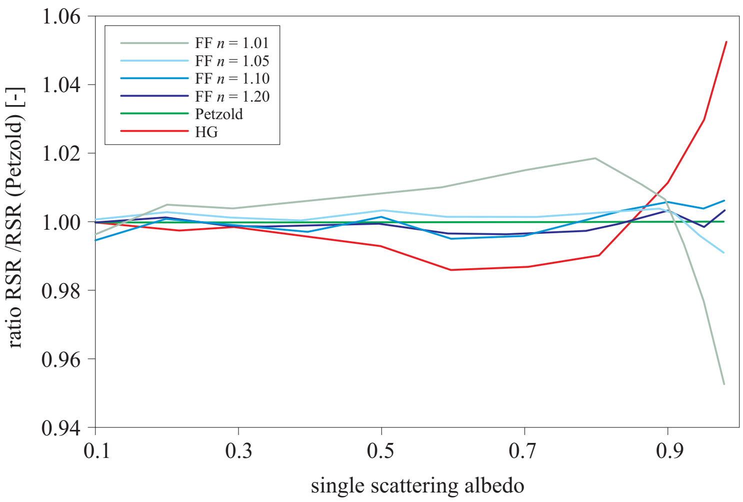

Figure 2. Ratio of RSR for each phase function to RSR for the average Petzold phase function for attenuation coefficient $c = 0.3$ m^{-1} and solar zenith angle 30° as a function of the single scattering albedo

The results show that in most of the single scattering albedo domain the choice of FF functions of identical b_b/b may result in a difference of up to 5% in calculated RSR values. This variability is independent of the variability between FF-modelled and measured phase functions observed in CMLK06. As in CMLK06, our results show convergence of RSR with decreasing single scattering albedo. This is easy to explain because when the particle single scattering albedo drops to zero, the particle scattering coefficient vanishes, and the choice of phase functions cannot therefore affect the value of RSR.

A more interesting result is the divergence of RSR for a high single scattering albedo. The presence of this effect means that one should expect especially large divergences between water leaving radiance levels when modelling highly scattering waters (for example, bubble clouds). The results presented in CMLK06 do not show this effect, which is surprising because the highest ω_0 value of the rightmost points in CMLK06 Figures 6a and 7a are about 0.98, whereas the effect we observe starts around $\omega_0 = 0.8$. The only explanation we have of why Chami et al. (2006) did not see this effect is that the measured and FF-modelled phase functions they compared have similar shapes in the relevant forward scattering region (see next paragraph), unlike some of the different analytical functions that we have been studying.

It is important to notice that the two outliers in this highly scattering regime (the HG function and FF for $n = 1.01$) are also outliers in the phase function (Figure 1) for a wide scattering region (about 4 to 120 degrees – forward scattering is not shown in the figure). For a single scattering albedo lower than 0.9, the two functions are also outliers but with inverted signs. This suggests that for single scattering albedo values smaller than 0.9 the major part of the water leaving reflectance comes from backscattering, while for a highly scattering regime the dominant angular region is forward scattering (but not into small angles). This result (the dominance of 4 to 120 degree scattering angles) seems to be a slight modification of the conclusion of CMLK06 (see Figure 10 in that publication) that for highly scattering waters, the dominant scattering regime in the history of photons leaving the water is forward scattering.

Chami et al. (2006) assumed, after performing a number of simulations, the 'angular reciprocity of the sensor viewing angle relative to the solar zenith angle' and therefore tested the effect of different sensor viewing angles for a fixed solar zenith angle. Because changing the solar zenith angle and calculating RSR for each of them seems more natural (one that does not add any additional systematic error) and because the form of graphic presentation chosen in Figures 6 and 7 of CMLK06 makes it very difficult to determine the functional relationship of RSR vs. the solar zenith angle, we decided to study this effect with a series of different solar zenith angles. The water leaving radiance reflectances (which are parts of RSR) are shown in Figure 3. The results show that the phase functions used in the study may lead to an up to 7% variation in calculated water leaving reflectance values (4% between the FF functions only). The discrepancies are largest

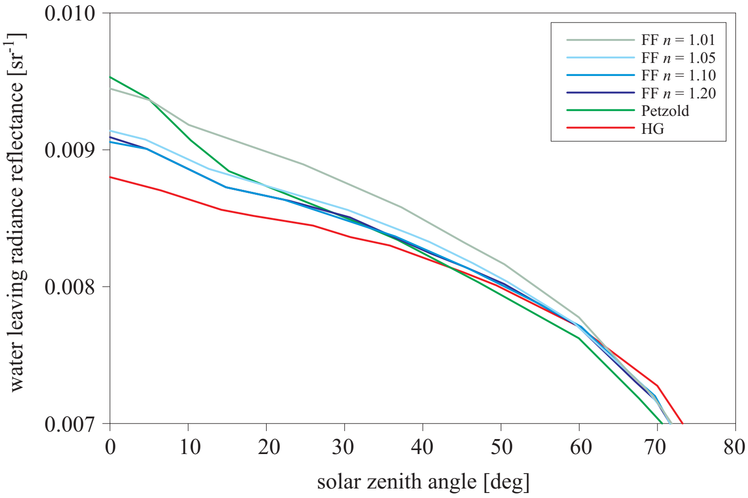

Figure 3. Water leaving radiance reflectance as a function of solar zenith angle modelled for light coming from both point sources (70%) and sky light (30%)

for a zenith solar angle of 0°, suggesting that backscattering angles close to 180° of different phase functions with the same b_b/b ratio control the discrepancy, at least for the $\omega_0 = 0.8$ value used.

The importance of backscattering angles close to 180° for water leaving radiance with a fixed backscattering ratio stems from the fact that in the first order of scattering, not all backscattered photons are able to leave the water, with the Fresnel reflection coefficient increasing as the backscattering direction recedes from the zenith until at 48.6° (for flat sea surface), total internal scattering makes it impossible for the photons to leave the water. This means that for a light source at the zenith, the first order of scattering photons may leave the water only if scattered between 131.4° and 180°. This is why this scattering region (see also Sullivan & Twardowski 2009), as opposed to total backscattering, is so important for reflectance, especially in the small single scattering albedo regime (where a single order of scattering is dominant). For RSR which takes into account only vertical water leaving radiance, the first order of scattering influences RSR only through a single backscattering angle $180° - \varphi$, where φ is the (in-water) source zenith angle. Therefore, the existence of a scattering peak at 180° translates directly into a RSR peak for $\omega = 0°$ (the solar zenith angle in Figure 3 is defined above the water, but obviously the zenith angle of 0° is identical in and above the water). Therefore, the different values of the 180° scattering peak for different phase functions (with Henyey-Greenstein having no peak and Petzold having the largest one) seem to be the source of RSR variability close to a solar zenith angle of 0°.

Zaneveld (1995), who analytically considered the variability of the remote sensing reflectance, showed that the approximation of RSR is proportional to the value of the phase function for an angle $\pi - \Psi$ (where Ψ is the zenith angle of maximum of radiance).

Apart from Petzold's functions, the values of the water leaving radiance for various phase functions (Figure 3) are arranged in the same way as the scattering angles for values less than 180°. The highest water leaving radiance for the zenith Sun's position (angular distance from the zenith) from 0 to about 60° is observed for the function FF with $n = 1.01$, and the lowest value in that range of angles has the function of HG. For larger zenith angles the situation is reversed: phase functions are arranged in the same way for angles $180 - \Psi$. For Ψ from 0 to about 60, the highest phase function values are those for FF with $n = 1.01$, while the lowest ones are the values of HG.

4. Conclusions

We show that the difference in angular shape between measured and analytical (Fournier-Forand) functions of the same backscattering ratio is not the only source of discrepancy in calculated remote sensing reflectances. The choice of analytical function may cause about 5% of additional variability in most of the single scattering variability range. This is important in closure studies using radiative transfer to solve algorithms for relating IOPs to reflectance, especially when using the same FF family of functions, which may cause about 4% RSR variability depending on the parameterization used (at present there is more than one available, namely Mobley et al. (2002) and Freda & Piskozub (2007), and none of them seem to be the last word in this field). However, the same variability is important more generally in radiative transfer calculations that still use several different families of analytical function as well as the 'classical' Petzold functions.

We also show a previously unknown effect of high (up to 10%) discrepancy in RSR values calculated using the same functions in the high ω_0 value range (highly scattering waters). This may impact on radiative transfer calculations of waters with bubble clouds.

Finally, we discuss the reasons for the peak in the studied discrepancy for solar zenith angles close to 0°. We argue that this peak is caused by differences in the backscattering peak between the phase functions of identical b_b/b as a direct result of the effect of solar zenith angles and backscattering angles on vertical water-leaving radiance values.

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