Effects of Winds on Ocean Color

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Abstract— **Previous studies suggested that winds would indirectly affect the remote sensing of ocean color. Moderately roughened sea enhances the probability of specular reflection of solar disk by randomly orientated wave facets. Whitecaps due to breaking waves increase the diffuse reflectance of sea surface and hence radiant energy received at a color sensor. In this study we will investigate the effect of bubbles, primarily formed in the upper ocean as a result of breaking waves, on the color of the ocean. Bubbles are ubiquitous in the upper ocean. Field observations suggested that the bubble plumes, initially injected by breaking waves, will evolve into a more or less horizontally uniform stratus layer of bubbles when wind speeds are over 7 m s^{-1}, and this bubble layer could last 3 or 4 hours after waves cease breaking. The density distribution of the bubble layer is modeled as a function of wind speeds and its contribution to the surface reflectance is investigated using radiative transfer model. The results indicate that wind will increase the overall surface reflectance with the contributions to the blue and green wavelengths primarily due to the subsurface bubble layer and the red and infrared due to whitecaps. The planetary albedo, the spectrally integrated reflectance for the entire visible domain and used for global radiative budget study, however, is largely determined by the underwater bubble layer. Our study suggests that only applying whitecap correction for the retrieval of water-leaving radiance from satellite observation will still lead to overestimate of chlorophyll concentration and this effect is more severe in clear oceans. Also previous estimates of global albedo for wind-roughened sea might be underestimated because the contribution by bubbles has not been taken into account.**

Keywords: bubbles; whitecaps; ocean color; wind;

I. INTRODUCTION

Remote observations of the spectral distribution of light reflected from the upper ocean, namely ocean color, provide the only practical means for diagnosing the spatial and temporal variations in the concentrations of phytoplankton in the near-surface ocean [1, 2], which in turn play a critical role in regulating the global carbon sequestration and the earth's climate [3]. While the color of the global ocean is primarily determined by the photosynthetic pigment of phytoplankton and its optically active detritus, studies have suggested that surface winds would also affect the detection of ocean color, mainly through physical processes.

Randomly orientated capillary wave facets generated by light to moderate winds will enhance the possibility of recording Sun glint by an airborne or space-borne sensor and the probability will increase with wind speeds [4, 5]. To reduce the contamination by Sun glint, most ocean color sensors, therefore, have a capability of tilting away from the direction of specular reflection of solar disk [6]. Under continuous influence of the wind, waves grow and eventually the water surface becomes unstable locally; the waves then break to dissipate excess energy provided by the wind. The breaking is marked by whitecaps — patches of bubbles in the water and foam on the surface. Foam, with a laboratory estimated reflectance of 50% in the visible domain [7] and an effective reflectance of 22% *in situ* considering its decay [8], increase the diffuse reflectance of sea surface. Due to the strong absorption by water molecules in the NIR, the foam reflectance decreases rapidly towards near infrared (up to 80% less at 860 nm) [9, 10], a situation will pose a more serious problem [11] to atmospheric correction than previously estimated based on a more monotonic spectral reflectivity of foam [12].

Field observations suggested that bubble plumes, initially injected by breaking waves, will evolve into a more or less horizontally uniform stratus layer of bubbles when wind speeds are over 7 m s^{-1} [13], and this bubble layers could last 3 or 4 hours after waves cease breaking [14] due to blockage of gas transfer across bubble-water interface by surfactant material adsorbed onto bubble surface [15]. In this study, we will investigate the effect of this bubble layer on the color of the ocean, an impact indirectly exerted by winds.

II. METHODOLOGY

A. Characteristics of underwater bubble layer

Under intensive breakings of waves, bubbles injected locally will be advected by wave-wave interaction and Langmuir circulation, forming a horizontal stratus layer. The concentration of bubbles decreases with depth exponentially [16], as in

$$\begin{aligned} N(z) &= N(0)\exp\left(-\frac{z}{z_0}\right) \\ N(0) &= A\,U_{10}^4 \\ z_0 &= 0.16(U_{10}-2.5) \end{aligned} \qquad (1)$$

Where $N(0)$ (m^{-3}) is the number density of bubbles at the surface, and is dependent on wind speed, measured at 10 m (U_{10}) above sea surface.

B. Model Simulations

We used an in-water radiative transfer model, HydroLight [17], to estimate water leaving radiance over a range of solar zenith angles and wind speeds. We assumed a cardioidal skylight distribution. The background waters are assumed to be case 1, and their optical properties are calculated with the built-in models. The phase function for bubble populations is calculated using Mie theory for bubbles of sizes between 1 and 300 µm with a protein coating of 0.1 µm thick [18], and the mean scattering cross-sectional area is 3.6×10^{-8} m^2, a value representative of wind-generated bubbles [16]. For comparison, we estimate the Fresnel reflectance based on classical theory, with Cox-Munk dependence on winds [19]. For whitecaps, we use estimates from Moore et al. [10] to relate the wind to fractional whitecap coverage and spectral albedo. Note, for winds > ~ 30 m s^{-1}, these are really just extrapolations based on data at lower wind speeds.

III. Results and Discussion

Within an instantaneous field of view of an ocean color sensor, say, 1 km × 1 km for SeaWiFS, the sea surface will be patched with foam as waves start breaking and the fractional coverage will increase with wind speeds. Underneath, there will be a layer of bubbles, whose concentration also increases with wind speeds. The total reflectance by ocean within a pixel of satellite measurements is,

$$
\begin{aligned}
R &= W(R_F + R_W) + (1 - W)(R_C + R_W) \\
&\approx WR_F + R_C + R_W
\end{aligned}
\tag{2}
$$

where W is the fractional coverage of foam, the subscribes F, C, and W indicate foam, clear (foam free), and water-leaving, and R represent reflectance (note the wavelength dependence of reflectance is omitted for simplicity). The approximation takes place because the foam reflectance is much higher than the reflectance of water.

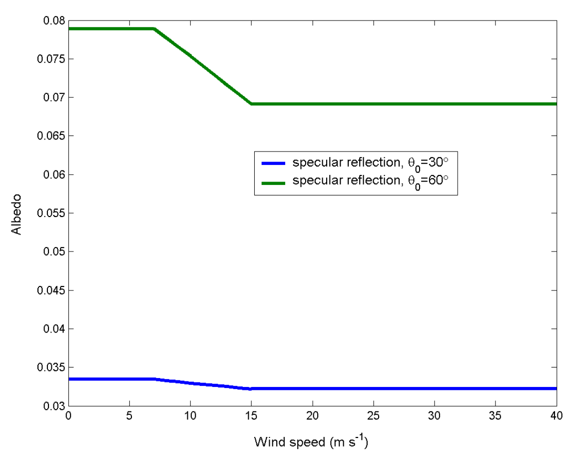

Figure 1. Surface reflection for the wavelengths 400 – 900 nm (albedo) for foam free water as a function of wind speeds and solar zenith angles.

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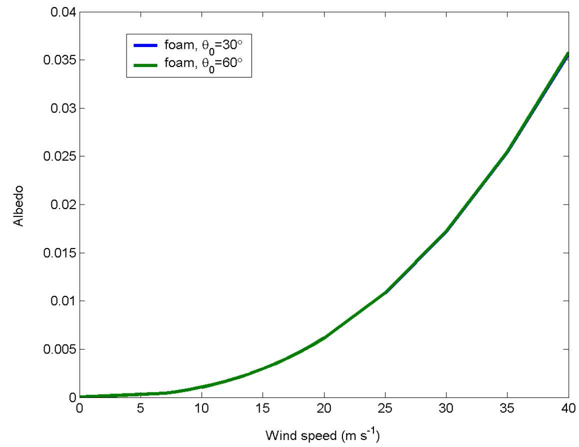

Figure 2. The same as Fig. 1 but for foam. Note the curves for the Sun zenith angles of 30° and 60° coincide with each other.

The surface reflectance for water clear of foam (R_C) is due to Fresnel reflection of incident radiation, and it is primarily determined by solar zenith angles. As shown in Figure 1, the surface reflectance for foam free waters increases rapidly for large solar zenith angles and for solar zenith angles < 30°, the albedo is almost constant with a value of ~ 3.3% with little dependence on wind speeds and spectra. Note the albedo is a measure of total upwelling irradiance relative to the downwelling irradiance. Even though the reflectance for a particular angle may increase (or decrease) with wind speeds, the total reflectance by surface is less affected by the wind.

Figure 2 shows the effective foam reflectance (the WR_F term of Eq. 2) as a function of wind speeds. As can be expected, the diffuse reflectance by foam does not change with the solar zenith angles. As the wind speeds increase, the more foam are formed, and the higher contribution of reflection by foam to a pixel.

The reflectances by water body (R_W of Eq. 2) are show in Figure 3 for the wavelengths of 765 nm (Fig. 3-a) and 445 nm (Fig. 3-b), corresponding to the bands 5 and 2 of SeaWiFS, respectively. For comparison, the reflectances by foam for each band are also shown. In the near infrared, the contribution to the reflectance of a satellite pixel by foam is almost an order of magnitude higher than reflectance by water body. However, even under moderate wind speeds >8 ms^{-1}, the reflectance in NIR by water body, primarily due to bubbles, is bigger than one digital count of the sensor, suggesting that the black pixel assumption routinely used in atmospheric correction is no longer valid even if the foam effect would be successfully corrected. At the shorter wavelengths (445 nm), because of a much weaker absorption by water molecules, the reflectance of water body is significantly higher than (by 1-2 orders of magnitude) that by foam. This is consistent with previous studies suggesting that bubbles can account for up to 90% of backscattering in the ocean [18, 20]. The presence of bubbles

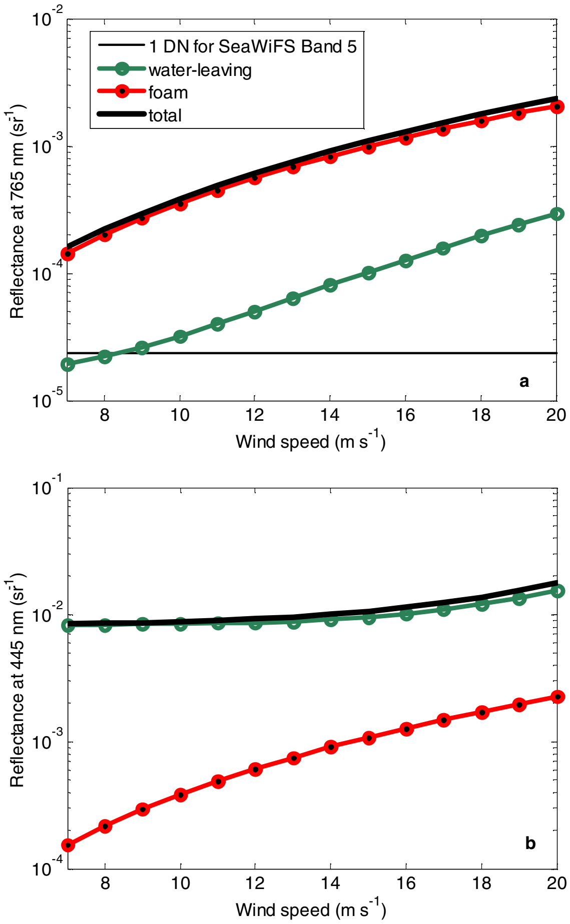

Figure 3. Reflectance by water body (green line) and foam (red line) at wavelengths 765 nm (a) and 445 nm (b) as a function of wind speed. The black lines are the total reflectance due to foam and water body. The dashed line represents the value of reflectance corresponding to 1 digitalcoutn of the SeaWiFS band 5.

will shift the color of the ocean towards green, resembling the coloring effect by phytoplankton, which, if uncorrected, will translate into an overestimate of phytoplankton concentration up to a factor of two [20].

Figure 4 shows the total reflectance for the wavelengths 400 – 900 nm and the component contributions according to Eq. 2, as a function of wind speeds. At wind speeds < 15m s^{-1}, the albedo by ocean is dominated by Fresnel surface reflectance, which increases with solar incident angles. Despite its high reflectance, the contribution by foam to the broadband albedo by ocean is limited, primarily because the fractional coverage is rather small even for high wind speeds, e.g., ~ 5% for a 20 ms^{-1} wind [21]. For wind speeds > 20 ms^{-1}, on the other hand, the broadband albedo is dominated by in-water contribution, which is primarily due to bubbles. For the bubbly water under strong wind, the albedo could be significantly higher than 6%, a typical value of reflectance used as the air-sea boundary condition for global circulation models. Analyzing year long observation of ocean surface albedo, Jin *et. al.* [22] found that the systematic underestimate of albebo by their model can be significantly reduced or eliminated by

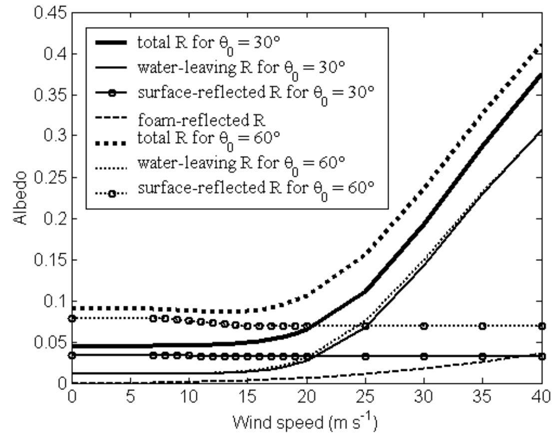

Figure 4. The total reflectance (400 – 900 nm) and its break down according to Eq. 2. The groups of solid and dotted lines are for solar zenith angle of 30° and 60°, respectively. The dashed line is for foam reflectance (no dependence on incident angles).

including bubbles and/or suspended material. This is consistent with Fig. 4, which shows that the contribution to the ocean surface albedo by bubbles is important or can be even dominant.

IV. CONCLUSIONS

Winds can change the boundary condition of air-sea interface through 1) surface modification and 2) bubble injections. While wind-roughened surface may reflect more downwelling irradiance into a sensor, the reflection by the ocean surface is primarily determined by Fresnel reflectance, mainly a function of solar incident angles. However, wind would still increase the overall reflectance with the contributions to the blue and green wavelengths primarily due to the subsurface bubble layer and the red and infrared due to whitecaps. The albedo, spectrally integrated reflectance for the entire visible and NIR domain, and used for global radiative budget study, however, is largely determined by the underwater bubble layer. Bubbles, by virtue of their strong backscattering, which are further enhanced by organic coating [20], can play a dominant role in reflecting back the solar radiation. Through the genesis of bubbles, winds will influence the remote sensing of ocean color in (1) atmospheric correction and (2) biological properties derived with color ratios. Under conditions with high winds peeds, the assumption that there is negligible reflectance in red and near IR will be invalid. The ocean color tends to be greener because of bubbles, and the chlorophyll concentration would, therefore, be overestimated. Also previous estimates of global albedo for wind-roughened sea might be underestimated because the contribution by bubbles has not been taken into account.

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