

Remote sensing of bubble clouds in sea water

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(Received 7 September 1999; revised 28 February 2000)

SUMMARY

We report on the influence of submerged bubble clouds on the remote-sensing properties of water. We show that the optical effect of bubbles on radiative transfer and on the estimate of the ocean colour is significant. We present a global map of the volume fraction of air in water derived from daily wind speed data. This map, together with the parametrization of the microphysical properties, shows the possible significance of bubble clouds on the albedo to incoming solar energy.

KEYWORDS: Bubble clouds Radiative transfer Remote-sensing reflectance

1. INTRODUCTION

“The effect of bubbles on the color of the sea may be observed in breaking waves. . . . Where a great many bubbles have been entrained by a breaking wave it is white. But where there are fewer of them it is blue-green or green, brighter than the sea but not as bright as the foamiest parts of the wave. Even after a wave has broken and the water is again quiescent, a pastel green patch often remains, slowly fading into the surrounding sea as the bubbles dissipate. Thus the effect of bubbles on the color of the sea is similar to that of solid particles”—Bohren (1987).

Bubbles within the water and foam on its surface (Stramski 1994; Bukata 1995; Frouin *et al.* 1996) can predominate in determining the radiative transfer properties of the sea surface at higher wind speeds. However, there is limited knowledge about the radiative transfer properties of bubble clouds, their inherent optical properties, and their global climatology. Mobley (1994) and Bukata (1995) discuss qualitatively the surface properties of bubble clouds. Frouin *et al.* (1996) performed spectral reflectance measurements of sea foam at the Scripps Institution of Oceanography Pier. They observed a decrease of the foam reflectance in the near-infrared and proposed that the foam reflectance cannot be decoupled from the reflectance by bubbles. Stramski (1994) concentrates on light-scattering by submerged bubbles in quiescent seas, and shows the scattering coefficient and the backscattering coefficient at 550 nm in comparison with scattering and backscattering coefficients of sea water as estimated from the chlorophyll-based bio-optical models for Case 1 waters[†]. In this exploratory paper, we report on the influence of bubble clouds generated by breaking waves on the remote-sensing reflectance and calculate, not only the inherent optical, but also apparent optical properties using the radiative transfer model. We show that the optical effects of bubbles on remote sensing of the ocean colour are significant. Furthermore, we present a global map of volume fraction of air in water. This map, together with the parametrization of the microphysical properties, shows the significance of bubble clouds on the global albedo to incoming solar energy. By proxy, we show the influence of the bubble clouds on the remote-sensing retrieval of organic and inorganic components

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[†] Case 1 waters are waters in which the concentration of phytoplankton is high compared with non-biogenic waters; they may range from very clear to very turbid water. Case 2 waters are waters where inorganic particles or dissolved organic matter dominate, so absorption by pigments is relatively less important in determining total absorption (Mobley 1994).

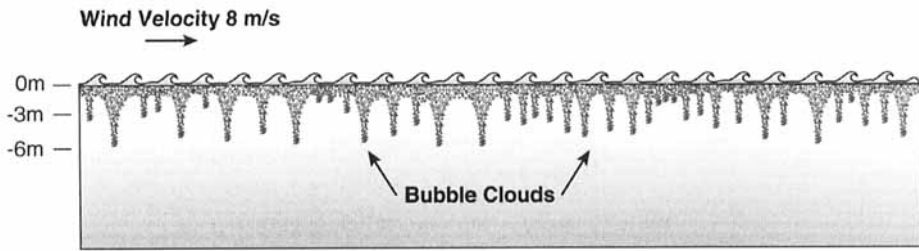


Figure 1. Bubble-stratocumulus layer generated by breaking waves with inhomogeneous deeper intrusions. The depth of the cloud is related to the maximum significant wave height.

of the natural waters. It is worth mentioning that the bubble clouds coincide with the upper range of the euphotic zone and will, therefore, contribute to the dynamics of the upper-ocean boundary layer, heat distribution, and sea surface temperature (Thorpe *et al.* 1992). In fact, our initial motivation for this work was an observation that the asymptotic radiance distribution is established close to the ocean surface in apparent contradiction to theoretical studies (Flatau *et al.* 1999). Thus, the light field must become diffuse at shallower depths than usually modelled. This leads to a search for alternative mechanisms influencing the light distribution. Thus, the importance of the bubble clouds to light scattering goes beyond the remote-sensing issues considered in this work.

In the next section we discuss in more detail the microphysical and morphological properties of bubble clouds, because these have a direct bearing on their optical properties and radiative transfer.

2. PHYSICAL PROPERTIES OF BUBBLE CLOUDS

(a) *Morphology of bubble clouds*

Individual bubble clouds are generated by breaking waves, persist for several minutes (Thorpe 1995), and reach to mean depths of about $4H_s$, where H_s is the significant wave height, but with some clouds extending to about $6H_s$. Figure 1 shows ‘bubble-stratocumulus’ (b-Sc) and is based on a sonograph of Thorpe (1984). The b-Sc is often observed by acoustic means (Farmer and Lemon 1984; Thorpe 1995). The depth of the b-Sc layer is related to the wind speed and wind variability, but more specifically it is set by larger waves, such as those breaking predominantly in groups (Thorpe 1995). There is evidence that at high wind speeds separate bubble clouds near the surface coalesce, producing a continuous ‘stratus layer’ (Thorpe 1995); this is bubble stratus (b-St, plot not presented) which we model in our paper. The ‘stratus layer’ description should not be taken too literally. For sufficiently high winds there will be significant concentrations throughout the upper layer, but the variability within this layer can be very high.

(b) *Bubble cloud climatology*

According to Thorpe *et al.* (1992), in the absence of precipitation and in wind speeds exceeding about 3 m s^{-1} , wave breaking generally provides the dominant source of bubbles. The wind speed at 10 m above the mean sea-surface level, W_{10} , is used to parametrize the volume fraction of air in water, $f = V_{\text{air}}/V_w$, where V_{air} is the volume of air, and V_w is the volume of water. This parametrization is an approximation of a more complex wind–wave relationship. Figure 2 shows f estimated from W_{10} for January 1992. The volume fraction and the wind speed are assumed to follow a nonlinear

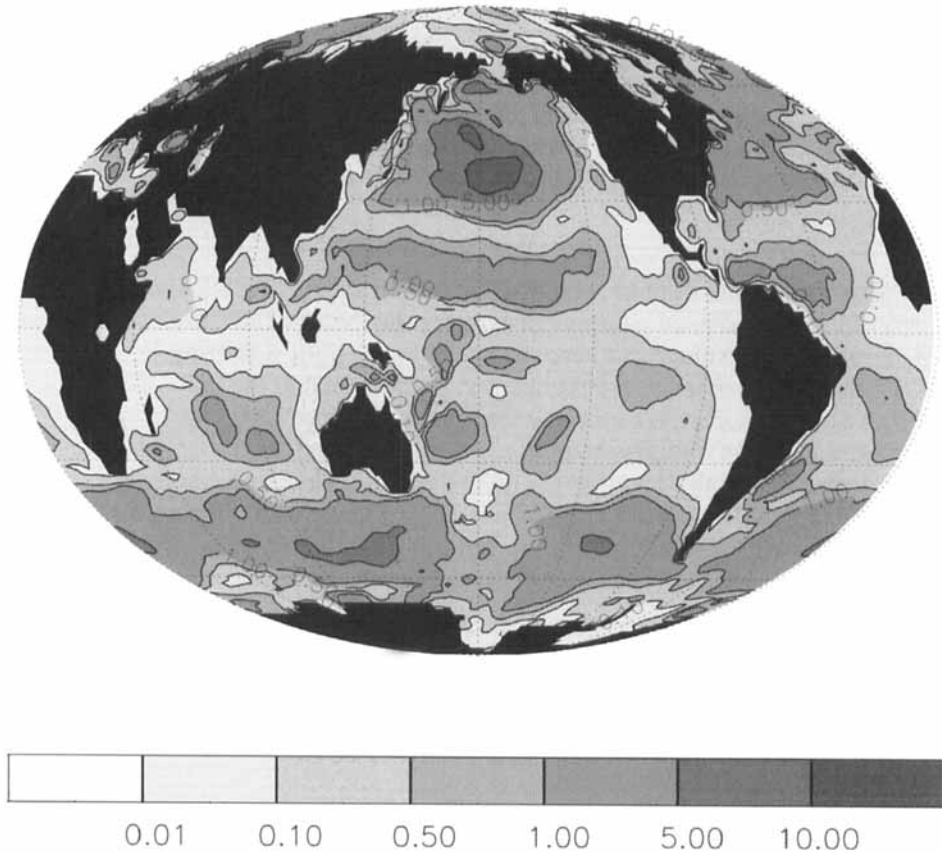


Figure 2. January 1992 monthly averaged volume fraction ($\times 10^6$) of air in water near the sea surface.

relationship (Walsh and Mulhearn 1987):

$$f = f_0 W_{10}^{4.4} + f_1. \quad (1)$$

The coefficients f_0 and f_1 were calculated at 2 m assuming that $f = 10^{-8}$ for $W_{10} = 6.2 \text{ m s}^{-1}$ and $f = 10^{-7}$ for $W_{10} = 10.5 \text{ m s}^{-1}$ (Walsh and Mulhearn 1987). Vagle and Farmer (1992) show that the volume fraction decreases with depth, changing from about 10^{-6} at 0.3 m to 10^{-7} at 2.7 m. We base our parametrization on these findings and extrapolate Eq. (1) to near-sea-surface depth using exponential fit.

The monthly averages of f were obtained by employing 1992 daily surface winds from the NCAR/NCEP* (Kalnay *et al.* 1996) re-analysis project, and averaging the daily volume fractions for each month. Thus, Fig. 2 is based on the variability of the wind field on the scale of one day. In the winter of the northern hemisphere, one can observe maxima associated with the mid-latitude storm tracks in the northern Pacific. Cyclogenesis, common in western parts of the ocean during the winter, contributes to mixing and a large bubble cloud volume fraction. This can be observed to the east of the North American continent. The intertropical convergence zone (ITCZ) region, with its associated deep convection, may also be a region of enhanced production of bubbles. The winds of the southern ocean have a strong effect on bubble formation during both

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summer and winter. In subtropical regions, to the west of the continents, the subsidence associated with the descending branch of the Hadley circulation is responsible for the relative minimum in f . It should be stressed that these results are qualitative, and that they can be improved by more detailed breaking-wave climatology models (Kraus and Businger 1994). The data in Fig. 2 are indicative of regions where bubble clouds are potentially important in the interpretation of remotely sensed reflectance.

(c) *Optical thickness*

The size distribution of bubble clouds determines the optical thickness and is, therefore, one of the most critical parameters entering the theory. There are two assumptions which simplify the development here: (i) we consider light scattering in the geometric optics regime for which the size parameter, x , proportional to the ratio of bubble radius, r , and inversely proportional to the wavelength, λ , i.e. $x = 2\pi r/\lambda$, is large; and (ii) we assume that there is an effective radius, r_{eff} , which determines the optical properties of the size distribution. Both (i) and (ii) are quite probable. The size parameter, $x = 50$, corresponding to a bubble radius of approximately $5 \mu\text{m}$, is already in the geometric optics regime, and $r_{\text{eff}} = 10 \mu\text{m}$ will satisfy (i). For bubbles with r_{eff} , the volume attenuation (equal to scattering for a non-absorbing sphere) can be expressed as:

$$b = Q_{\text{sca}} \frac{N}{V_{\text{w}}} s = 2 \frac{V_{\text{air}}}{V_{\text{w}}} \frac{N}{V_{\text{air}}} s = 2f \frac{s}{v}, \quad (2)$$

thus, for bubbles with an effective radius r_{eff} the volume scattering (equal to volume attenuation for non-absorbing spheres) can be expressed as:

$$b = 2 \frac{f}{r_{\text{eff}}}, \quad (3)$$

where Q_{sca} is the (non-dimensional) scattering efficiency, $s = \pi r^2$ is the cross-section of a bubble with radius r , v is the volume of such a bubble, N is the number of bubbles in V_{w} , and f is the fraction of air in a volume of water. The effective radius is defined as $r_{\text{eff}} = v/s$ (Bricaud and Morel 1986; Stephens *et al.* 1990; King *et al.* 1993). Scattering efficiency defines how much of incoming light is being 'blocked' by a particle due to scattering processes; for large size parameters Q_{sca} tends to 2. This issue is discussed in detail by Bohren and Huffman (1983).

The physical significance of f comes from the fact that it is determined by the large-scale forcing such as the wind field. Thus, for a given synoptic or climatological setting, f is to some extent pre-determined. On the other hand, r_{eff} depends on processes of much smaller scale. These processes are coagulation, coalescence, coating by organic material, saturation, buoyancy, pressure, etc. Thus, Eq. (3) defines the optical properties of bubble clouds on both the large- and sub-scales. Equation (3) holds for polydispersions, and the only difference from a monodispersion is that r_{eff} is defined via distribution-averaged s and v .

(d) *Effective radius of the size distribution*

Numerous observations of bubble size distributions are reported in the literature based on acoustic, photographic, optical, and holographic methods (Wu 1988a). Akulichev and Bulanov (1987) summarize results from 22 experiments using different techniques. As the origins of bubbles are biological (within the volume and at the bottom) as well as physical (at the rough surface), we may expect large regional and

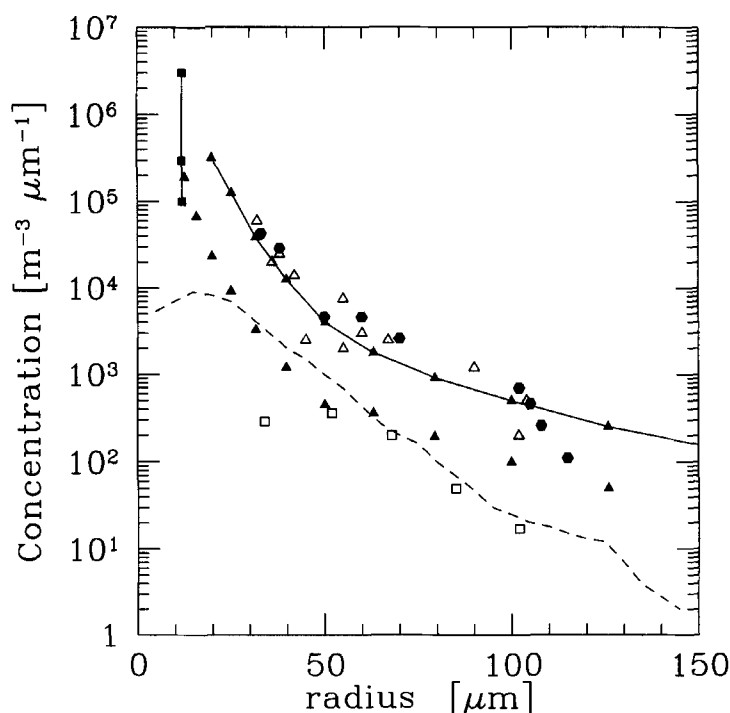


Figure 3. Comparison of bubble spectra under breaking waves and quiescent sea. The solid squares connected by the vertical solid line are from laser holographic data of O'Hern *et al.* (1988). Open triangles are from Baldy (1988) and include data at 30 cm depth with wind and swell, and at 25 cm with wind only. The solid hexagons are data based on Medwin and Breitz (1989) obtained in the open sea at 25 cm depth under the water surface during winds of 12 m s^{-1} . The solid triangles joined by the solid line and free-standing solid triangles are average bubble densities measured under comparable conditions at different seasons. The joined solid triangles are concentrations at 4 m depth with 3.3 m s^{-1} wind speed on 7 August 1975 in Monterey Bay. The free-standing solid triangles are for mid-afternoon 10–16 February 1965 at Mission Bay, San Diego, 3 m below the surface with winds of $1.7\text{--}2.8 \text{ m s}^{-1}$. The dashed line is from a numerical model (Thorpe *et al.* 1992). The mean concentrations in the steady-state model are plotted at a temperature of 0°C . The open squares show observations at 4 m in wind speeds of $11\text{--}13 \text{ m s}^{-1}$ (Johnson and Cooke 1979).

temporal variations of bubble concentration between coastal and open oceanic waters and between plankton bloom or no-bloom conditions (Thorpe *et al.* 1992).

Figure 3 presents a comparison of bubble spectra under breaking waves and quiescent sea. Recently published observations, using laser holography near the ocean surface, have shown that the densities of bubbles of 10 to $15 \mu\text{m}$ radius can be as high as 10^6 (per cubic metre per micron radius increment) within 3 m of the surface of quiescent seas (O'Hern *et al.* 1988). These results are plotted as solid squares connected with a vertical solid line. The majority of bubbles injected into the surface layers of natural waters are unstable, either dissolving due to enhanced surface tension and hydrostatic pressures or rising to the air–water interface where the bubbles break (Johnson and Wangersky 1987). However, bubbles with long residence times, i.e. stable microbubbles, have been observed. For example Medwin (1977) observed nearly 2.5×10^6 of bubbles per cubic metre in the radius range $18\text{--}355 \mu\text{m}$ for low wind speeds. One of the stabilization mechanisms (Mulhearn 1981; Johnson and Wangersky 1987) assumes that the surfactant material is a natural degradation product of chlorophyll, present in almost all photosynthesizing algae. Isao *et al.* (1990) observed very large populations of

neutrally buoyant particles with radii between 0.1 and 1 μm . Johnson and Wangersky (1987) and Thorpe *et al.* (1992) proposed another stabilization mechanism based on monolayers of adsorbed particles. Numerical modelling (Thorpe *et al.* 1992) can be used to study the effects of water temperature, dissolved gas saturation levels, and particulate concentrations on the size distribution of subsurface bubbles. The results from such numerical models provide additional evidence for the existence of a small-size bubble fraction which is not adequately measured by acoustic or photographic techniques. The dashed line on Fig. 3 presents the mean concentration in the model steady-state for a water temperature of 0 °C. It can be seen that the maximum concentration is around 15 μm and is 2.5 orders of magnitude larger than for 100 μm bubbles. Other results presented in Fig. 3 include those observations of Johnson and Cooke (1979) at 4 m in wind speeds of 11–13 m s^{-1} (open squares). *In situ* acoustic measurements of microbubbles at sea by Medwin (1977) are plotted as solid triangles. The solid triangles joined by a solid line are concentrations at a depth of 4 m and wind speed 3.3 m s^{-1} . These spectra were obtained on 7 August 1975 in Monterey Bay. The free-standing solid triangles are for mid-afternoon, 10–16 February 1965 at Mission Bay, San Diego, 3 m below the surface, and in 1.7–2.8 m s^{-1} winds. The open triangles are from Baldy (1988) and include data at 30 cm depth with wind and swell, and at 25 cm with wind only. They are based on extensive laboratory experiments. The solid hexagons are data from acoustic measurements by Medwin and Breitz (1989) obtained in the open sea at 25 cm depth under the water surface during 12 m s^{-1} winds under spilling breakers. The literature reviewed here and encapsulated in Fig. 3 is a mixture of descriptions of the effect of active wave-breaking, and of stabilized microbubbles observed largely in coastal situations. Currently it is not clear how to parametrize the stabilized bubbles. From results such as those presented in Fig. 3 in the case of ‘transient’, open-ocean bubbles, it can be estimated that the size distribution follows the power law dependence $n(r) \propto r^{-a}$ and $a \approx 4$ (Walsh and Mulhearn 1987; Wu 1988a). Even though small microbubbles may not contribute to the total mass, they may be important for the scattering of light. Therefore, it is of interest to estimate the contribution of small bubbles to the optical thickness. Assuming that microbubbles are spherical ($V_{\text{air}} = (4/3)\pi r^3 N$) we can show that the optical thickness, $\tau = bh$, of a layer with geometrical thickness h is

$$\tau \propto h V_{\text{air}}^{2/3} N^{1/3}, \quad (4)$$

where both h and V_{air} are assumed to be fixed. It can be seen from Eq. 4 that the contribution to optical thickness by very small particles will be the same as that by very large particles if their concentration varies as N^3 (or steeper). Indeed this is the case (Walsh and Mulhearn 1987; Wu 1988a).

What remains to be defined is r_{eff} . On the basis of measurements, estimates of small-particle fraction, existence of background 1 μm microbubbles, modelling predictions, and the steep slope of microbubble size distributions, we decided to use $r_{\text{eff}} = 10 \mu\text{m}$ as a typical ‘radiative response radius’. This choice does not exclude the existence of larger or smaller particles. The real value may be between 1 μm for stabilized particles and 50 μm for the open ocean, and will depend on many environmental factors such as storm passage, wind speed, swell, wind variability, phytoplankton concentration, water temperature, gas saturation, and other properties. The 10- to 15-fold increase in the size of effective radius, or a similar decrease in the air volume fraction, will reduce the importance of air bubbles such that they have a very small effect. It may be instructive

to calculate b for a typical size distribution of bubbles in water. In such case we have:

$$b = \int Q_{\text{sca}} \pi r^2 \frac{dN(r)}{V_w}, \quad (5)$$

or $b = 2fs/v$ where $s = \int \pi r^2 dN(r)$ and $v = \int (4/3)\pi r^3 dN(r)$, and $dN(r)$ is the number of bubbles between r and $r + dr$ in a volume of water V_w . For typical size distributions of bubbles in water $dN(r)/dr \propto 1/r^4$ and we have:

$$r_{\text{eff}} = \frac{4}{3} \ln(r_1/r_0) / \left(\frac{1}{r_0} - \frac{1}{r_1} \right). \quad (6)$$

Consider $r_1 = 150$ and $r_0 = 10 \mu\text{m}$. This gives $r_{\text{eff}} \sim 3.6r_0$, which shows that the choice of small bubble cut-off is important for the bubbles' optical properties. However, the choice of this cut-off is non-trivial because the spectrum of small bubbles is not well understood at present.

We close this section with some general comment about the effective radius. It is not a directly measurable quantity and, in essence, it defines how dispersed the given amount of mass is. Scattering of incoming solar radiation is sensitive to total projected surface rather than to total mass. For this reason the effective radius is commonly used in radiation calculations. It carries information not only about the size itself, but also about the orientation of particles, their morphology, coating, size distribution, or departure from a spherical shape. In addition, estimates of effective radius, as used in satellite remote sensing, often contain bias due to unrealistic assumptions about other optical properties such as optical thickness, leakage of photons due to horizontal transfer, wavelengths, and the technique employed in retrieval. In that sense the effective radius is also used (or abused) as a semi-apparent optical property.

3. RESULTS

(a) Numerical model

The numerical radiative transfer model used in this study is a slightly modified version of the Hydrolight 3.0 code (Mobley 1994; Mobley *et al.* 1994). In brief, this model computes from first principles the radiance distribution within, and leaving, any plane-parallel water body. Input to the model consists of the absorbing and scattering properties of the water body, the natures of the wind-blown sea surface and of the bottom of the water column, and the sun and sky radiance incident on the sea surface.

Pure sea water absorption and scattering coefficients are determined from the data of Pope and Fry (1997). Thirty-five model wavebands were specified to cover the 400–700 nm region with a typical resolution of 10 nm. The water column was specified as infinitely deep. Up to 62 depth layers, extending to 50 m, were specified with a resolution of 0.5 m close to the surface. A clear sky was assumed, but the diffuse sky radiance was included. Three- or four-component systems were considered, consisting of pure water, particulates with or without bubble clouds, and dissolved organic matter. The spectral absorption of dissolved organic matter was defined as:

$$a(\lambda) = a(\lambda_0) \exp\{-0.014(\lambda - \lambda_0)\} \quad (7)$$

where $a(\lambda_0) = 0.1 \text{ m}^{-1}$, $\lambda_0 = 440 \text{ nm}$ (Bricaud *et al.* 1981). The phase function of phytoplankton was defined as an average of three phase functions measured by Petzold in clear ocean, coastal ocean, and turbid harbour cases (Tyler 1977; Mobley 1994).

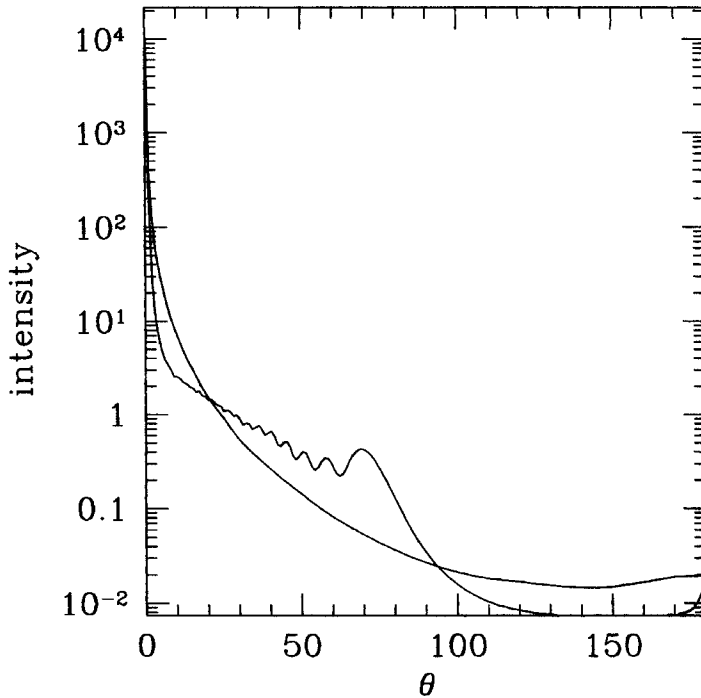


Figure 4. Unpolarized phase function for a uniform distribution of bubbles between size parameters 100 and 300 (see text) and refractive index $m = 3/4$ as a function of scattering angle θ . Also shown is Petzold's phase function. The bubble phase function has a peak at $\theta = 70$ degrees.

The bubble cloud phase function was calculated for the real relative refractive index $m = 0.75$, as an average for the size parameter range between $x = 100$ and $x = 300$ with a resolution $\Delta x = 1$ using Wiscombe (Fiedler-Ferrari *et al.* 1991) code. Figure 4 compares Petzold and bubble phase functions. The main reason for the average size distribution was to remove transient spikes. This normalized phase function is scaled by b calculated from Eq. 3. The volume scattering and absorption coefficients for particulates (b_p) were determined from the Gordon–Morel model (Gordon and Morel 1983; Morel 1988; Mobley 1994):

$$b_p = \frac{550}{\lambda} 0.3C^{0.62}, \quad (8)$$

$$a^{\text{Case 1}}(\lambda) = \{a_w(\lambda) + 0.06a_c^*(\lambda)C^{0.65}\}[1 + 0.2 \exp\{-0.014(\lambda - 440)\}]. \quad (9)$$

Here $a_w(\lambda)$ is the absorption coefficient of pure water, a_c^* is the chlorophyll-specific absorption coefficient, and C is the chlorophyll concentration in mg m^{-3} (Mobley 1994). The chlorophyll concentration was set as constant (well-mixed) with depth and equal to 0.8 mg m^{-3} or 0.08 mg m^{-3} . We used Case 1 water parametrization but assumed that not all dissolved organic material is correlated with the chlorophyll concentration. In an apparent contradiction, the wind speed which defined surface reflectance and transmittance functions due to the wind-blown water surface was set to zero. The reason for this was to estimate the effect on remote-sensing properties of the sub-surface bubble clouds. However, we investigated the sensitivity of the reflectance to changes in the wind speed between 0 and 10 m s^{-1} , and the effect was small compared with the influence of bubbles. The azimuth direction was divided into 24 equally spaced

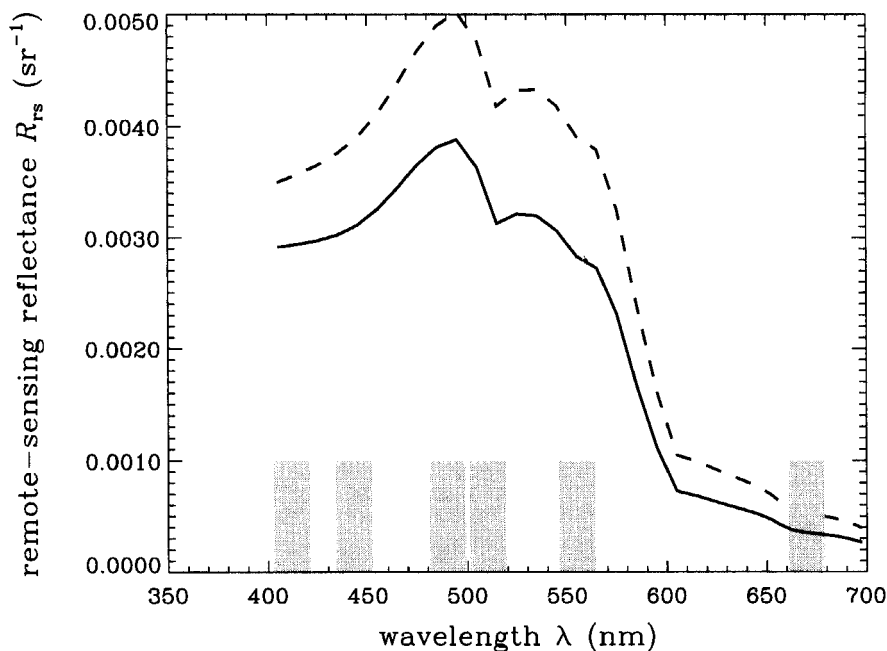


Figure 5. Hydrolight model run with 62 layers, maximum depth 50 m, maximum bubble depth 8 m, 35 wavenumbers between 400 and 700 nm, sun zenith angle 50° . The solid line is the remote-sensing reflectance for the 3-component system composed of water, dissolved organic material and particulates (no microbubbles) and the dashed line is for the 4-component system, that is including microbubbles. The chlorophyll concentration is 0.8 mg m^{-3} in both cases; the effective radius is $10 \text{ }\mu\text{m}$. The grey rectangles indicate SeaWiFS (ocean colour satellite) wavelengths.

sectors, the zenith–nadir range was divided into 20 equally spaced sectors. The profile of the bubble cloud volume fraction f at depth z was determined by the expression:

$$f(z) = f_0(f_1/f_0)^p, \quad (10)$$

where $f_0 = f(z_0) = 10^{-6}$, $f_1 = f(z_1) = 10^{-7}$, $z_0 = 0 \text{ m}$, $z_1 = 8 \text{ m}$, and $p = (z - z_0)/(z_1 - z_0)$. Our choice of the speed of attenuation is perhaps unreasonably gradual, except for the case of stable microbubbles. On the other hand this choice is of secondary importance for the remote-sensing properties of bubble clouds which are dominated by the surface volume fraction. In-water asymptotic light field is discussed by Flatau *et al.* (1999). The scattering was conservative. The volume attenuation was determined from the asymptotic expression Eq. (3). The probability distribution function for scattering was discretized and was set as constant throughout the depth range. We calculated the asymmetry parameter g to be ≈ 0.85 . This parameter defines the probability of photon scattering towards the forward or backward hemisphere.

(b) Remote sensing of reflectance

The reference-model runs were performed with the three-component system of phytoplankton, pure water, and dissolved organic material (DOM) with a constant chlorophyll profile. Two cases were computed (but only one is presented) representative of clear coastal ($C = 0.8$) and oceanic ($C = 0.08$) water. The remotely sensed reflectance

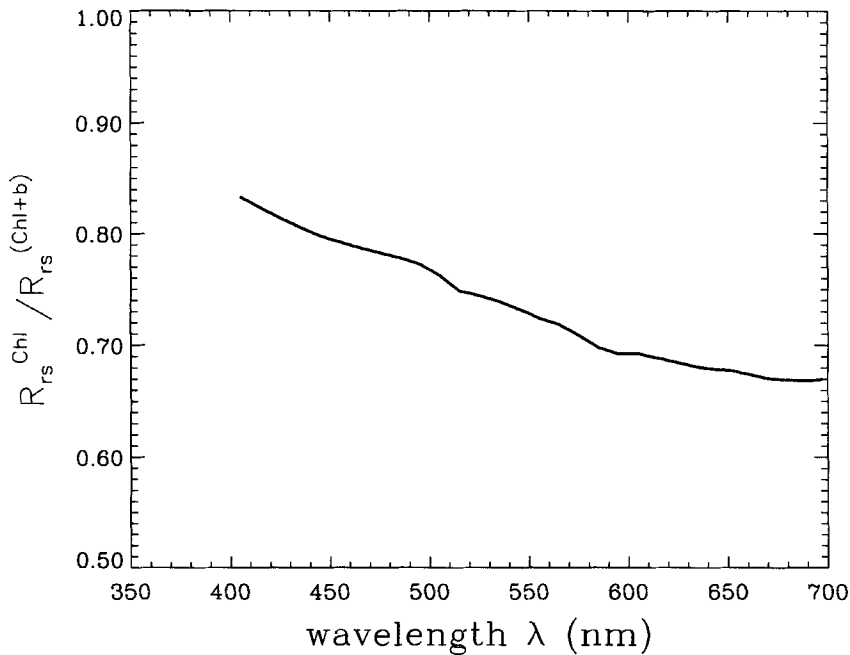


Figure 6. Experiment as in Fig. 5 but showing the ratio of remote-sensing reflectances with and without microbubbles: $\text{ratio}(\lambda) = R_{rs}^{chl} / R_{rs}^{chl+b}$. See text for details.

is defined as:

$$R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_d(\lambda)}, \quad (11)$$

where E_d is the downwelling irradiance onto the sea surface, and $L_w(\lambda)$ is the upwelling water-leaving radiance. The remote-sensing radiance is a measure (Mobley 1994) of how much of the downwelling light that is incident onto the water surface is returned into the zenith direction. The remote-sensing reflectances are plotted in Fig. 5. The physical importance of the remote-sensing reflectance is evident from asymptotic theories which relate R_{rs} to inherent optical properties (Zaneveld 1995):

$$R_{rs} \propto \frac{\beta(\pi - \theta_m)}{a}, \quad (12)$$

where β is the phase function, θ_m is related to the sun zenith angle, and a is the absorption coefficient. Thus, R_{rs} is approximately proportional to the probability of back- or side-scattering, and inversely proportional to the absorption of water column. Figure 5 shows the remote-sensing reflectance for the 3- and 4-component system with and without ocean bubbles but with constant pigment amount. The total single scattering albedo is strongly influenced by scattering from air bubbles. This leads to enhanced reflectance at all wavelengths. The results for $C = 0.08$ (not presented) show even larger sensitivity. In Fig. 5 the grey rectangles indicate bands (wavelengths) which are used by the current ocean colour satellite instrument (SeaWiFS*). It is of interest to comment on the remote sensing of pigments and bubble cloud retrievals. We consider an algorithm based on the ratio of remote-sensing reflectance, and define the ratio of remote-sensing

* Sea Viewing Wide field-of-view Sensor.

reflectances without (Chl) and with (Chl+b) microbubbles as:

$$\text{ratio}(\lambda) = R_{rs}^{\text{Chl}} / R_{rs}^{\text{Chl+b}}. \quad (13)$$

Figure 6 shows $\text{ratio}(\lambda)$. Performance of the pigment algorithms based on the ratio of reflectances will depend on $\text{ratio}(\lambda_1)/\text{ratio}(\lambda_2)$. Submerged microbubble clouds seem to be wavelength-selective, and even the ratio algorithms may require slight systematic correction. Given the increased sensitivity of the current generation of ocean colour instruments, the absolute value of the radiances at the top of the atmosphere can be used for pigment retrievals.

4. SUMMARY

Our calculations indicate that the optical effects of submerged microbubbles on the remote-sensing reflectance of the ocean colour are significant. These results are of importance for the retrievals of pigments from the ocean colour measurements and for studies of the energetics of the ocean mixed layer. We provide information on how to reduce the systematic error due to microbubbles in pigment retrieval schemes via the $\text{ratio}(\lambda)$. We also derive apparent optical property (AOP) of bubbles (remote-sensing reflectance) for the whole solar spectrum. This AOP is directly observable by the satellites and remote sensors. We expect that these and similar AOPs will have to be invoked in the case of hyperspectral retrievals for Case 2 waters where the signals from minerals, bubbles, chlorophyll and DOM (CDOM) are not well correlated. New algorithms for current satellite instruments such as MODIS* and SeaWiFS should employ this information.

We also present a global map of the volume fraction of air in water, derived from daily wind speed data. We expect that such a map can be improved by knowing the day-to-day variability of the wind-wave relationship and better estimates of the volume fraction.

This paper is exploratory. Therefore, it is perhaps worth playing *advocatus diaboli* and speculate why the bubble clouds may not be important, at least in current satellite ocean colour retrieval practice. Here are some reasons: (i) The strong wind and cloud amount are correlated; this masks (bias) the effect of bubbles as observed from the satellites; (ii) whitecaps (Wu 1988b; Gordon and Wang 1994; Frouin *et al.* 1996) and bubble clouds are correlated via their dependence on wind speed. Therefore, our results, as well as the hypothesis of Frouin *et al.* (1996), indicate that reflectance of foam has to be considered together with the reflectance due to bubble clouds. On the other hand, there are cases in which strong wind is not correlated with clouds. For example, the cross-equatorial flow during the summer monsoon in the southern Indian Ocean is strong but the ITCZ is in the northern hemisphere.

It is interesting to note that stabilized, coated microbubbles are hypothesized to be correlated to phytoplankton and CDOM concentrations; we need parametrization of this process. The optical properties of the first several metres below the surface are difficult to measure and are often removed from data due to experimental problems such as ship shadow or wave activity. This is the region where more detailed studies are needed.

ACKNOWLEDGEMENTS

P. J. Flatau was supported in part by the Office of Naval Research Young Investigator Program and NASA SIMBIOS program. M. Flatau acknowledges NOAA/UCAR

* MODerate resolution Imaging Spectroradiometer which is flying on the Terra spacecraft.

Global Climate Change Fellowship and J. R. V. Zaneveld acknowledges support of the Environment Optics program of the Office of Naval Research and the Biogeochemistry program of NASA. C. D. Mobley acknowledges support of the Environmental Optics program of the Office of Naval Research, which also supported in part the development of the Hydrolight model.

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