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A PARAMETERIZATION OF SPECTRAL AND BROADBAND OCEAN SURFACE ALBEDO

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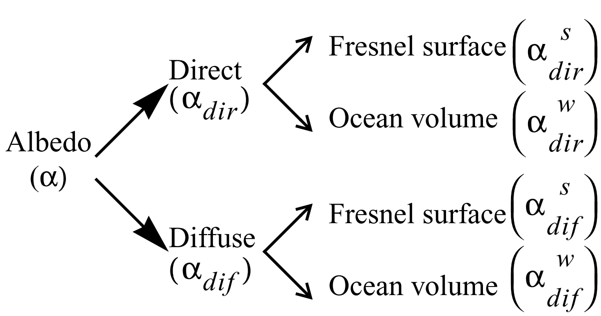
1. INTRODUCTION

Over 70% of the Earth surface is covered by ocean. Ocean surface albedo (OSA) is required for a determination of the atmospheric radiation budget and the solar heating in the upper ocean. Our measurements at a sea platform clearly show that the OSA varies significantly with solar elevation, wind speed, atmospheric conditions (aerosols/clouds), and ocean optical properties as well as wavelength (see examples shown in Figures 1-4). However, current OSA parameterizations generally ignore the spectral dependence and ocean optics. As climate models are developed to include more biological processes and as more detailed surface reflecting information is required for many remote sensing applications, a more accurate parameterization of spectral OSA is needed.

Based on years of observation data and the coupled ocean atmosphere radiative transfer (COART) model, we developed an OSA look up table for the retrieval of atmospheric radiation budget for NASA CERES program. Using this table and the attached reading code, users can obtain the spectral OSA at any specified wavelength range, solar zenith angle, wind speed and ocean chlorophyll concentration (Chl). (http://snowdog.larc.nasa.gov/jin/getocnlut.html). However, this table format is not convenient for some applications. In this paper, we present a simplified spectral and broadband OSA parameterization.

2. PARAMETERIZATION



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The OSA depends on many parameters. Parameterizing OSA directly as one function of all the dependent parameters would be formidable. To simplify the parameterization process, we divide the OSA into the direct and the diffuse and each is then further divided into two components: the Fresnel surface reflection and the ocean volume scattering (as illustrated above). Each of these four components depends on different parameters and is parameterized separately with fewer dependents than for the total albedo.

2.1 Surface Direct

We have incorporated the ocean surface roughness into the COART recently and now the albedo contribution from surface Fresnel reflection for various wind speeds can be calculated accurately by COART (Jin et al., 2006). The direct surface albedo depends on incident angle (θ), wind speed (*w*) and water refractive index (*n*). The wavelength dependence of this part of albedo is through the dependence on *n*. Figure 5 shows an example of the direct surface albedo (Fresnel) for two refractive indices (1.34 and 1.20) and three wind speeds (0, 3 and 12 m/s). As shown in the figure, this direct Fresnel surface albedo has a slight increase as wind increases at small to moderate incident angles but it decreases at large angles. It can be expresses as

$$\alpha^{s}_{dir}(\lambda, \theta, w) = \alpha^{s}_{dir}(n(\lambda), \mu(\theta), \sigma(w)) = r_f(n, \mu) - \frac{r_f(n, \mu)}{r_f(1.34, \mu)} f(\mu, \sigma) \qquad (1)$$

where μ=cos(θ). σ is the mean slope distribution width of the Gaussian function defining the surface roughness and is related to wind speed (w). If the Cox-Munk model (1954) is used, this relationship is

$$\sigma^2 = 0.003 + 0.00512w \qquad (2)$$

$r_f(n,\mu)$ is the flat surface Fresnel reflectance and its formulation can be found in any optics textbook (e.g., Hecht, 1990).

$$r_f(n, \mu) = \alpha^{s}_{dir}(n, \mu, \sigma = 0) \qquad (3)$$

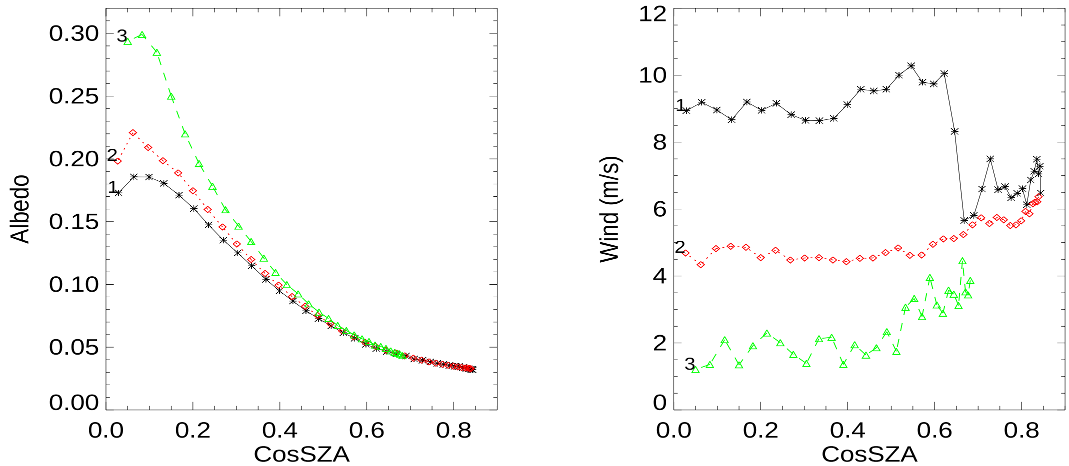

Fig.1. Wind effect on ocean surface albedo. The left panel shows the measured broadband albedo in selected three days and the right panel shows the corresponding wind speeds in these days. Note the high albedo corresponds to low wind and the low albedo corresponds to high wind.

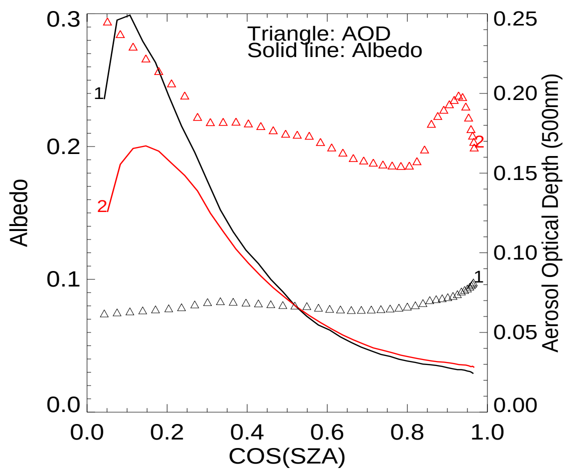

Fig.2. Aerosol effect on OSA. The solid lines represent the measured albedo in two selected days with similar low winds but with very different aerosol optical depths (the triangles)

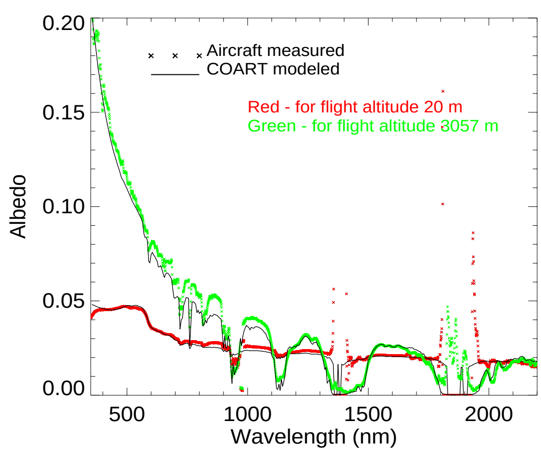

Fig.4. Aircraft measured and modeled spectral OSA at COVE.

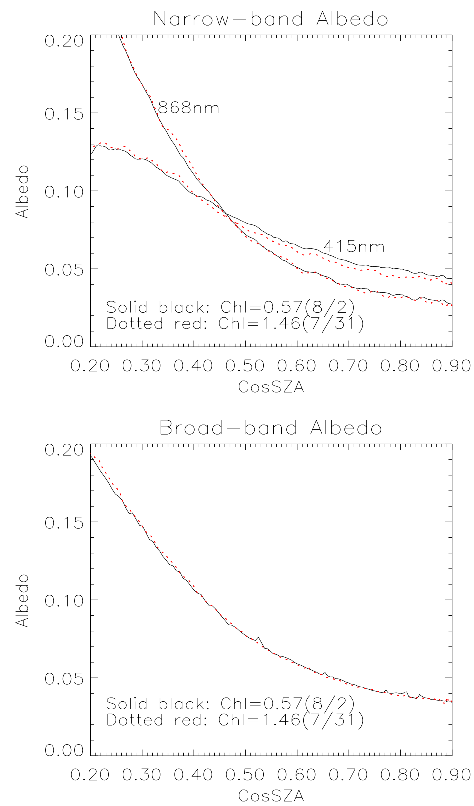

Fig.3. Ocean chlorophyll (Chl) effects on surface albedo. Upper panel: the MFRSR measured albedo at 415 nm and 868 nm for two days with different Chl. Lower panel: the measured broadband albedo on the same two days. Due to the chlorophyll absorption at 415nm, increasing Chl will decrease albedo in this blue band. But Chl has little effect on the 868nm band because of strong water absorption and on the broadband albedo because of the compensating effect between the blue and green.

$$f(\mu, \sigma) = (p_0 + p_1\mu + p_2\mu^2 + p_3\mu^3 + p_4\sigma + p_5\mu\sigma)\exp(p_6 + p_7\mu + p_8\mu^2 + p_9\sigma + p_{10}\mu\sigma)$$

$f(\mu, \sigma)$ is the regression function (f=0 when w=0) and the fitting coefficients $p(0{:}10)$=[0.0088445, -1.03884, 4.008862, -4.98572, 2.366114, -4.4432, 0.70689245, -7.840964, -3.5638735, -2.358853, 10.05397]

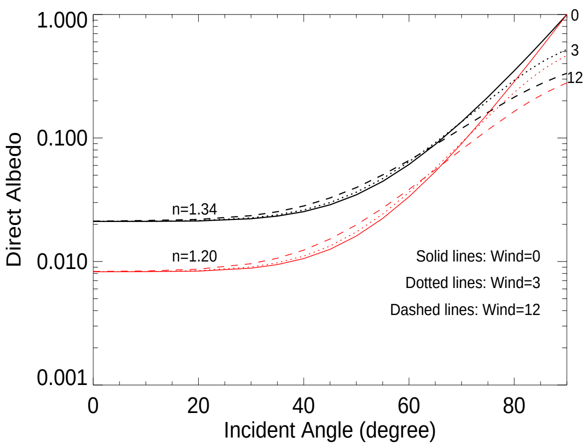

Fig. 5. The calculated direct surface albedo (Fresnel) for two refractive indices and three wind speeds.

Note, we used the surface roughness parameter σ instead of the wind speed (w) directly in the parameterization (Equation (1)). This is for the flexibility. The surface slope distribution describing the ocean surface roughness is commonly considered as a Gaussian function. However, the formulation to relate the σ to wind varies and equation (2) is one of them. The parameterization equation (1) lets the users to choose this relationship without a need to change the parameterization.

A comparison between the parameterized surface direct albedo using equation (1) and the exact calculations are presented in Figure 6. The upper panel shows the direct comparison for four wind speeds. The lower panel shows the relative difference in percentage for wind range from 0 to 24 m/s for all solar zenith angles. Within this wind range, the relative error is generally less than 3% as shown in Figure 6.

2.2 Surface Diffuse

Given the diffuse incident distribution pattern, the diffuse Fresnel surface albedo component can be calculated from the direct Fresnel surface albedo. This diffuse surface component depends on the refractive index and wind speed. Assuming an uniform (isotropic) incidence, the diffuse Fresnel surface albedo can be parameterized as

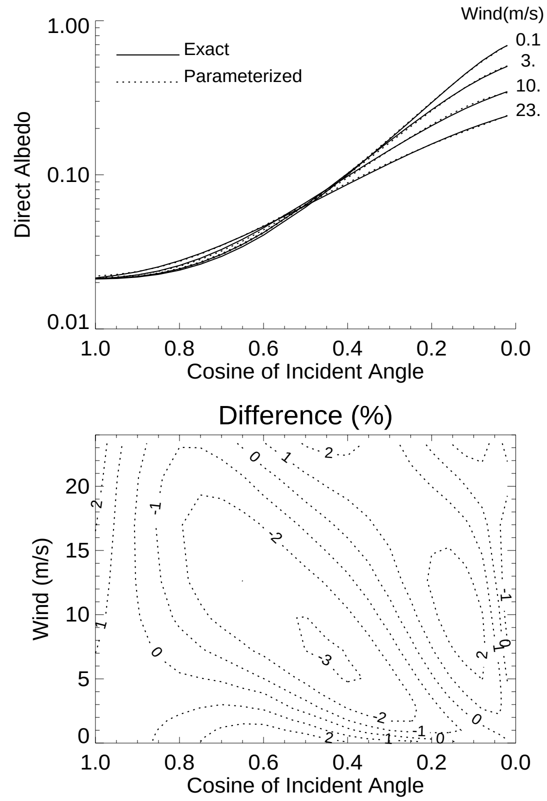

Fig. 6. Comparison of the parameterization by eq. (1) and the exact calculations for the surface Fresnel direct albedo. The lower panel shows the relative error (in percentage) of the parameterization.

$$\alpha^{s}_{dif}(\lambda, w) = \alpha^{s}_{dif}(n(\lambda), \sigma(w))$$
$$= (-0.1479 - 0.0161\sigma + 0.1609n - 0.0193n\sigma) \qquad (4)$$

For the same reason as for the direct, the surface roughness parameter σ instead of the wind speed (w) is used in the parameterization.

Figure 7 shows a comparison of the parameterized diffuse surface albedo by Equation (4) with the exact calculations. The relative error (lower panel) is less than 2% for refractive index from 1.20 to 1.45 (about the variation range of the water refractive index in the solar spectrum) and for wind speed from 0 to 24 (m/s).

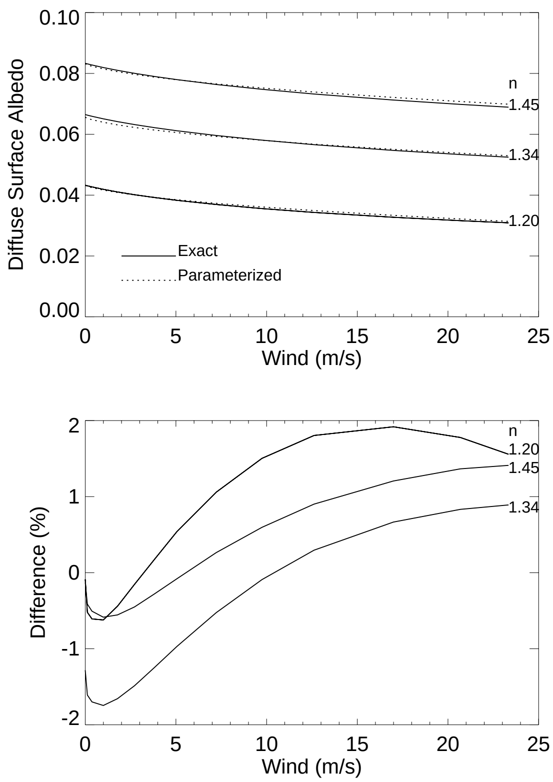

Fig. 7. Comparison of the parameterization by eq. (4) and the exact calculations for the surface Fresnel diffuse albedo.

2.3 Ocean Volume Direct

For the contribution by ocean volume scattering below the surface, we consider the so-called case 1 waters which consist 99% of the ocean and its optical properties can be parameterized as a function of chlorophyll concentration (i.e., Chl). Coastal waters are usually case 2 water and their optical properties are more complicated. However, ocean surface albedo is dominated by the surface reflection described above. The ocean volume scattering component is limited in the visible spectrum and is usually small, especially for large incident angles. The ocean volume albedo for direct incidence can be expressed as

$$\alpha^{w}_{dir} = \alpha^{w}_{dir}(\lambda, \mu, w, chl) = \frac{R_0(1-r_w)\left(1-\alpha^{s}_{dir}\right)}{1-r_w R_0} \quad (5)$$

where r_{w} represents the surface reflectance (albedo) for diffuse water-incidence from below, which is usually considered as a constant of 0.48, but actually varies

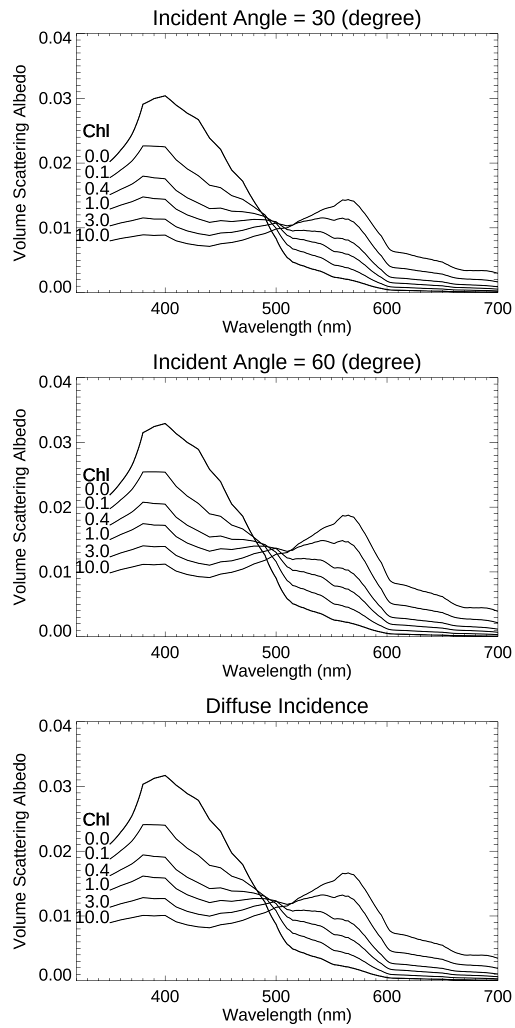

Fig. 8. The parameterized ocean volume albedo based on equation (5) (the upper two panels) and Equation (7) (the lower panel).

slightly with surface roughness (Jin et al., 2006). Using COART model, we can fit this term as

$$r_w = 0.4817 - 0.0149\sigma - 0.207\sigma^2$$

R_0 is the irradiance reflectance (albedo) just below the surface. This is a classic AOP (Apparent Optical Property) of ocean optics and has been studied extensively. It is proportional to the backscattering coefficient, b_b, inversely proportional to the absorption, a, and is generally expressed as

$$R_0(\lambda, \mu, chl) = \beta(\mu)\frac{b_b(\lambda, chl)}{a(\lambda, chl)} \quad (6)$$

Here β is the proportionality constant and is expressed as (Morel and Gentili, 1991)

$$\beta = 0.6279 - 0.2227\eta_b - 0.0513\eta_b^2 + (0.2465\eta_b - 0.3119)\mu$$

Here η_b is the ratio of backscattering by water molecules to total backscattering. b_b and a depend on *Chl* and their formulations are available from Morel and Maritorena (2001) (see their Eqs (11), (13) and (16)).

2.4 Ocean Volume Diffuse

For uniform diffuse incidence, the ocean volume albedo can be simply represented by the direct ocean volume albedo at an effective incident direction, μ_e. Based on Morel and Gentili (1991), μ_e=0.676. Therefore, the ocean volume diffuse albedo is

$$\alpha_{dif}^{w} = \alpha_{dif}^{w}(\lambda, w, chl) = \alpha_{dir}^{w}(\lambda, \mu_e, w, chl) \qquad (7)$$

Figure 8 shows an example of the ocean volume albedo calculated by the Equations (5) and (7). Note, the albedo component decreases as Chl increases in the blue, but increases as Chl increases in the green. The combined effect of Chl on broadband albedo is small.

2.5 Total Spectral Albedo

Having the four components of the surface albedo given above, we can now obtain the total spectral surface albedo:

$$\alpha(\lambda) = f_{dir}\left(\alpha_{dir}^{s} + \alpha_{dir}^{w}\right) + f_{dif}\left(\alpha_{dif}^{s} + \alpha_{dif}^{w}\right) \qquad (8)$$

$$f_{dir} + f_{dif} = 1.0 \qquad (9)$$

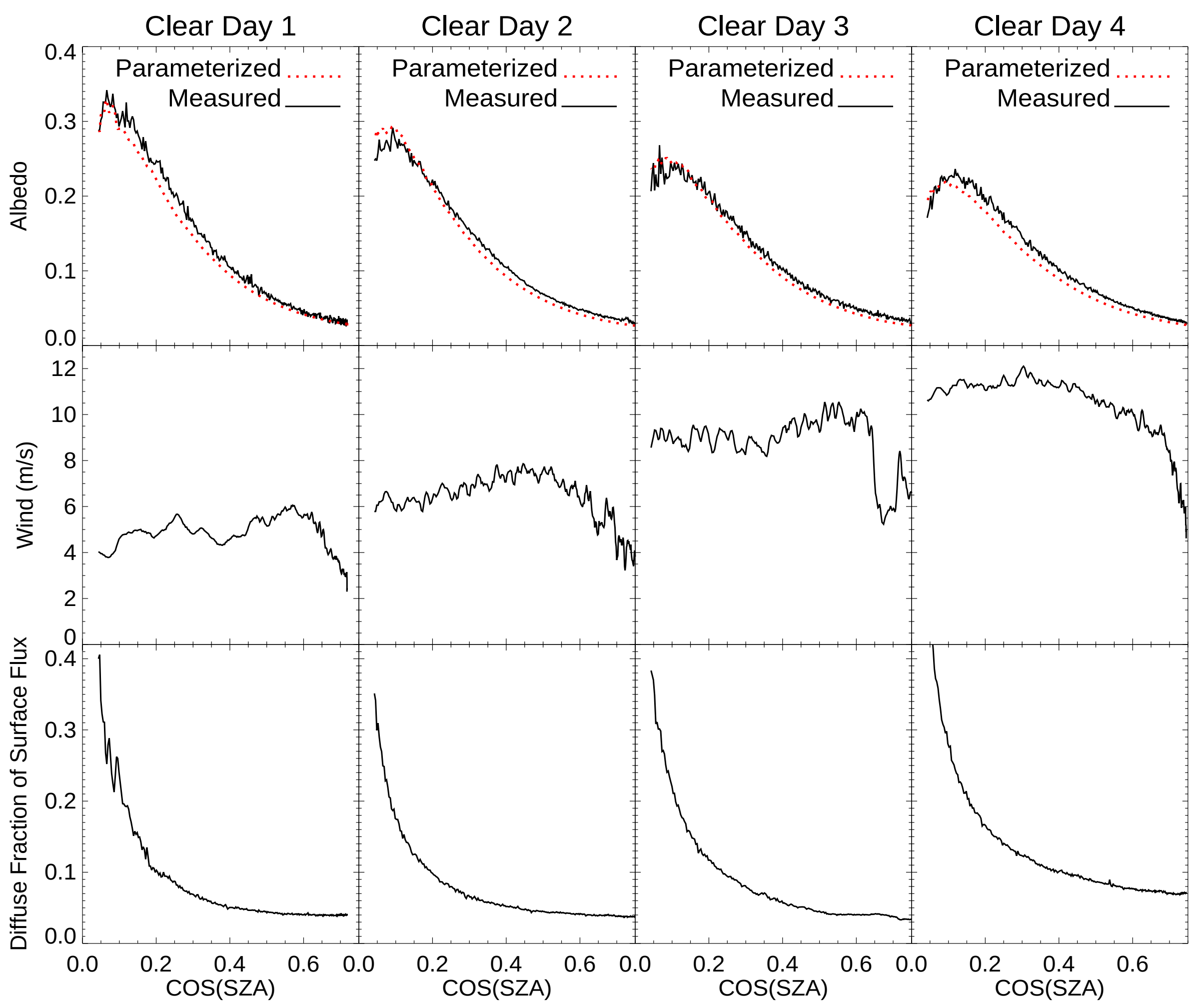

Fig. 9. Comparison of measured and parameterized albedo (865 nm) in four clear days. The wind speed (middle panels) and the diffuse fraction (lower panels) for parameterization input are also from measurement data.

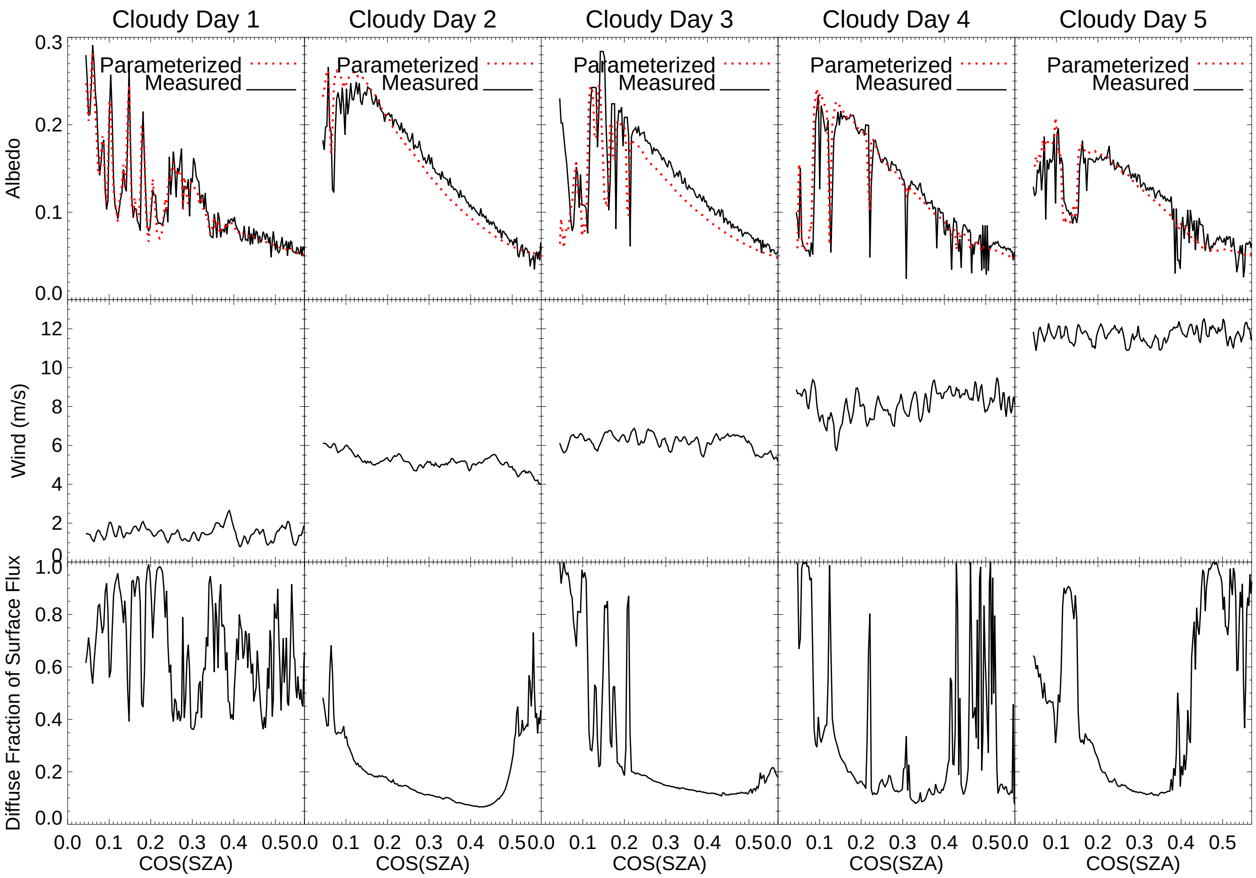

Fig. 10. Similar to Figure 9, but for comparison of measured and parameterized albedo (865 nm) in five cloudy days.

Where f_{dir} and f_{dif} represent the direct and diffuse fractions of the downward flux at the surface, respectively.

2.6 Broadband Albedo

For broadband albedo, the surface components can be represented by the spectral parameterizations (Eqs (1) and (4)) using n=1.34 (i.e., the refractive index in visible). The broadband ocean volume component is approximately 0.006. Therefore, the broadband albedo can be written as

$$\alpha = f_{dir}\alpha^{s}_{dir}(n=1.34) + f_{dif}\alpha^{s}_{dif}(n=1.34) + 0.006 \quad (10)$$

Here f_{dir} and f_{dif} are for broadband.

3. DISCUSSION AND CORRECTION

The diffuse albedo is closely related to the incident radiance distribution at the surface, which has been assumed unchanging. Under actual atmospheric conditions, the diffuse downward radiance distribution is seldom uniform or in a certain distribution pattern, but varies with SZA and atmospheric condition. Subsequently, the diffuse albedo is not a constant but varies with SZA and atmosphere. A portion of the diffuse radiation is in the vicinity of the solar incident direction due to lower orders (single and second) of aerosol/cloud particle scattering. In terms of albedo, this part of diffuse radiation can be considered as "direct" incidence. Therefore, a correction is required to obtain the effective direct and diffuse flux fractions. This correction amount can be approximated as

$$f_c = 0.6\mu_0 f_{dif}\exp(-3f_{dif}^{40}) \quad (11)$$

Here μ_0 is the cosine of SZA. Then, the direct and diffuse flux fractions (f_{dir} and f_{dif}) in Equations (8) and (10) should be replaced by the effective flux fractions as following

$$f^{e}_{dir} = f_{dir} + f_c \quad (12)$$

$$f^{e}_{dif} = f_{dif} - f_c \quad (13)$$

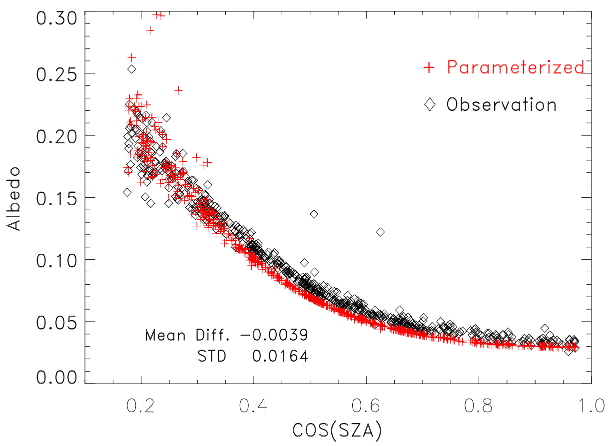

Fig. 11. Comparison of measured and parameterized broadband albedo under clear skies. The data are 30 minute averaged.

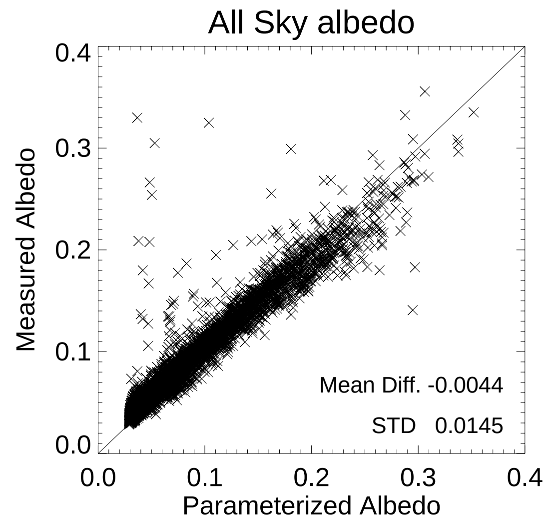

Fig. 12. Similar to Figure 11, but for comparison of measured and parameterized broadband albedo under all skies.

In addition, the parameterizations above don't include the effect of ocean foams (white-caps), which could be significant at high wind speeds. However, measured foam reflectances differ greatly with large uncertainty. But this foam correction can be easily adopted if it is desired. A simple foam correction proposed by Koepke (1984) assumed a constant foam albedo of 0.55 and he related the fractional surface coverage of white-caps, f_{wc}, to the wind speed (w) as

$$f_{wc} = 2.95\times10^{-6}W^{3.52} \quad (14)$$

The foam corrected albedo is simply the area averaged foam albedo and the albedo parametrized above as

$$\alpha_e = 0.55f_{wc} + \alpha(1-f_{wc}) \quad (15)$$

4. COMPARISON WITH OBSERVATION

Figure 9 compares the measured and parameterized albedo in four clear days at 865 nm. The ocean volume scattering can be neglected at this wavelength. The wind speed (middle panels) and the diffuse fraction (lower panels) for the parameterization input are also from the coincident measurements. The wind speed increases and hence the albedo decreases from day 1 to day 4. Foam effects are not included here.

Similar to Figure 9, Figure 10 show the comparisons for five cloudy days. The albedo variation with wind for the cloudy days are not as significant as for the clear days, but its correlation with the diffuse fraction is obvious.

Figure 11 compares the measured and parameterized broadband albedo for two years of data (30 minute averaged). It is expected that the parameterized albedo is lower than the observation for small to moderate solar zenith angles, because there was more particle scattering at the observation site (COVE) than the case 1 water used by the parameterization.

Figure 12 is similar to Figure 11, but compares the broadband albedo for all skies. The wind speed and the diffuse fraction required for the parameterization are directly from coincident measurements.

5. CONCLUSION

A spectral and broadband ocean surface albedo parameterization is developed. To simplify the parameterization, the albedo is divided into four components (surface direct, surface diffuse, ocean volume direct, and ocean volume diffuse). Each is parameterized separately as a function of different parameters.

The parameterization is designed to be flexible for users to choose or update the formulations of some dependent parameters, for example, the relationship between the surface roughness and wind speed, and the relationship between ocean optical properties and Chl. There is no need to redo the albedo parameterizations when these relationships are changed.

More refining works are still required. The updates, the basic data required for the parameterization (e.g., spectral refractive indices and sea water absorption coefficients), and the code for the parameterization presented here will be posted online at http://www-cave.larc.nasa.gov/cave/ (simply search "ocean albedo" on Google).

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