Radiative Transfer Modeling of Ocean Surface Albedo for CERES SARB

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by

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1. The Coupled Radiative Transfer Model for the Atmosphere and Ocean system

Most radiative transfer models treat the radiative transfer in the atmosphere and in the ocean separately. Modeling radiative transfer in the atmosphere specifies an ocean surface albedo, while modeling radiative transfer in the ocean assumes a certain downwelling radiance distribution incident upon the ocean surface.

The coupled radiative transfer model we developed [1] treats the scattering and absorption in both the atmosphere (by aerosols and clouds) and the ocean (by water molecules and hydrosols) **explicitly** and considers the radiative transfer in the coupled system **consistently**.

Figure 1 schematically shows the radiative transfer in the atmosphere and ocean system. The main difference in solving the radiative transfer equation consistently in such a coupled system from a solution that treats only the atmosphere is caused by *the refractive index change across the air-water interface.* This refractive index change changes the formulation of the radiative transfer equation and complicates the interface radiance continuity conditions and therefore gives rise to different solution of the radiative transfer equation. This theoretical problem was solved using the discrete ordinate method [1]. The refraction and reflection at the air-water interface was taken into account in the radiative transfer equation and its solution **analytically**. Therefore the coupled model considers the ocean just as *additional* “atmospheric” layers.

The windblown ocean surface roughness is modeled using the Cox and Munk surface slope distribution for a given wind speed[2] . The surface roughness affects both the reflected (into the atmosphere) and the refracted (into the ocean) light at the air-water interface.

Due to the consistent treatment of the radiative transfer processes in the atmosphere-ocean system, the coupled radiative transfer model can calculate the ocean surface albedo. It can also calculate the extinction of solar radiation and thereby the solar heating in ocean with depth, which is important for the thermodynamic and dynamic processes of the ocean mixed layer.

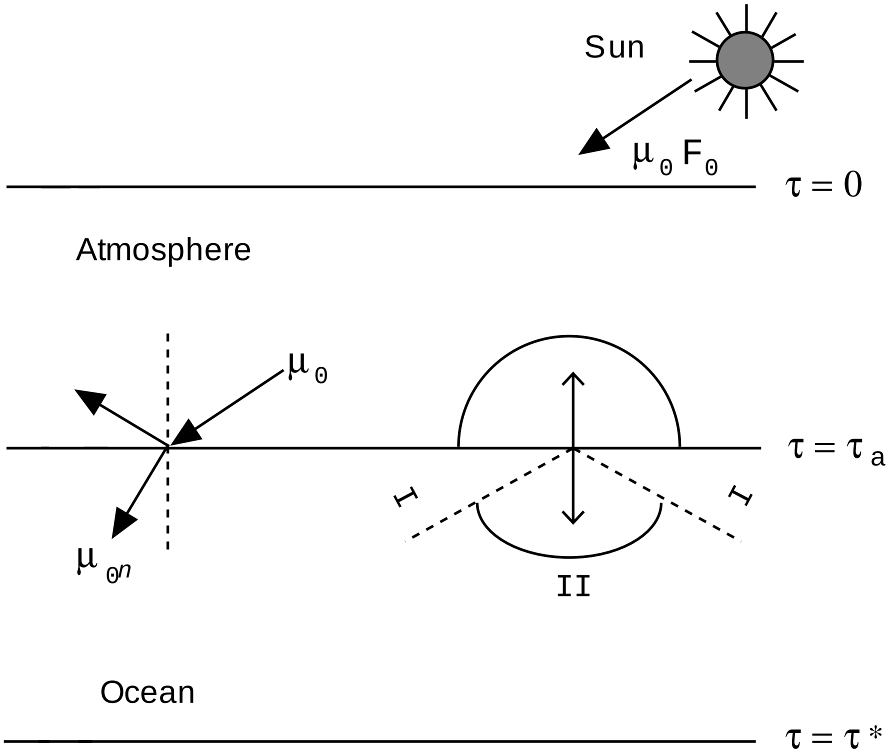


Figure 1, Schematic diagram of the coupled radiative transfer model for the atmosphere and ocean system.

2. Some Modeling Results

In CERES SARB processing, the surface spectral albedo is required for flux and optical depth retrievals. This spectral albedo over the ocean varies not only with the atmospheric conditions but also with the ocean status, such as phytoplankton pigments and dissolved organic matter (DOM). Therefore, understanding the relationship between the ocean surface albedo and the ocean optical properties is important for the retrieval algorithm in SARB.

The following figures show some modeling results for ocean surface albedo. For most ocean conditions, the surface albedo is basically consists of two components, the Fresnel reflectance from the surface due to the refractive index change and the reflectance from the volume scattering by water and hydrosols below the surface - so called underlight.

Figure 2 is an example of the model calculated spectral ocean surface albedo. The atmospheric model for midlatitude summer and the solar zenith angle of 30 were used in the modeling. The solid line is for the total spectral albedo, the dashed line is for the underlight. The left panels are for pure water and the right panels are for sea water with chlorophyll concentration of 0.3 mg/m^3. It is apparent that the chlorophyll will change the spectral pattern of the underlight and therefore the spectral pattern of the total ocean surface albedo. Actually, the spectral pattern of the total ocean surface albedo is determined by the underlight. The spectral albedo used in the SARB algorithm is also shown for comparison with the dotted lines, which is calculated based on Hu-Cox-Munk parameterization for Fresnel reflection, a constant underlight and a wind-speed dependent foam reflectance but does not consider the ocean chlorophyll. Apparently, the current SARB ocean surface albedo overestimates the albedo for longer wavelengths but underestimates for shorter wavelengths. The strong absorption of chlorophyll a at 443nm is also obvious, this channel is selected by SeaWiFS and MODIS for chlorophyll concentration retrieval in ocean. The lower two panels are for wind speed of 10 m/s. In this case, the wind speed does not have much effect on the ocean surface albedo. In fact, the wind effect on albedo is small unless the solar zenith is large or the wind speed is high. Figure 3 is similar as Figure 2, but for solar zenith angle 60. Because the solar zenith angle is larger, the total spectral albedo is higher.

One of the most important components in the ocean to affect the surface albedo is the phytoplankton. Figure 4 shows the ocean surface albedo for different chlorophyll concentrations. As the figure showed, the chlorophyll will reduce the albedo in blue but increase the albedo in green. This explains the blue ocean seen in open seas where chlorophyll concentration is low and the greenish ocean in some coastal regions where chlorophyll concentration is usually high such as at COVE site by the Chesapeake Bay.

Another important component to affect the ocean spectral albedo is the dissolved organic matter (DOM) liberated by algae and their debris, also from land drainage in coastal waters. Figure 5 shows the dependence of the ocean surface albedo on the DOM. The DOM has strong absorption in the blue and so it shifts the maximum ocean surface reflectance from blue to yellow. If the DOM concentration is high, the ocean will appears as yellow. So this stuff is also called yellow substance. This figure also shows that the sensitivity of the ocean surface albedo to the DOM becomes lower as the DOM concentration becomes higher.

Figure 6 is the modeled ocean surface albedo for 3 chlorophyll concentrations, 2 bottom albedos, and 3 water depths. The left panel is for pure water, the central panel is for chlorophyll concentration of 0.3 mg/m^3 and the right panel is for chlorophyll concentration of 10.0 mg/m^3. As expected, the bottom reflectance has the largest effect on the shallowest water with 1 m of depth. When the depth reaches 100 m, the bottom has almost no effect on the ocean surface albedo (the red dashed line overlapped with the black dashed line), even for the pure water. For the case of high chlorophyll concentration (the right panel), the albedos for depth of 11 m and 100 m are the same and the bottom has no effect for these depths (albedos for all these 4 cases overlapped).

Figure 7 is a preliminary comparison of the model and observation for the global shortwave fluxes and albedo over the ocean surface at the COVE site. The comparison is only for two days - one with very low aerosol loading (aerosol optical depth less than 0.05) and one with moderate aerosol loading. Except for the aerosol optical depth, the observed wind speed and total precipitable water at COVE were also used for the model input. The model predicts higher total downwelling fluxes (panel e) than observation but lower total upwelling fluxes for most of the times. Therefore, the model predicts lower surface albedo than the observation (panels a and b). The underestimation of the upwelling flux at the ocean surface is probably due to that some scattering mechanisms were missed in the modeling (e.g., scattering by sediments and/or air bubbles near the subsurface ocean water).

To check the model performance, Figures 8 and 9 show a comparison between model and ERBE observation for the anisotropic reflectance factor (ARF) at the TOA. The midlatitude atmospheric model, the wind speed of 8 m/s, and the chlorophyll concentration of 0.2 mg/m^3 were used in the radiative transfer calculations. The model catches the right position for sun-glint and the anisotropic reflectance patterns between the model and observation are similar, but the ARF values between the model and the observation have pretty large differences. These differences are expected considering the possible large differences in the atmospheric and the oceanic parameters between the model and the actual ERBE observations.

3. Application to CERES SARB

The flux retrieval in CERES SARB requires the surface spectral albedo.

The current SARB input for surface spectral albedo over ice-free ocean uses the Hu-Cox-Munk parameterization on Fresnel reflection for the air-water interface and assumes a constant underlight contribution (the volume scattering from water below the surface). However, results here showed that the underlight is not constant which depends on wavelength and ocean optical properties.

The advanced coupled model includes phytoplankton pigment concentration and dissolved organic matter (DOM), also sediments, and an ocean bottom of finite depth for coastal waters -- in addition to aerosols and clouds in the atmosphere. Therefore, the model can simulate the dependence of the radiance, irradiance and ocean surface albedo on these parameters.

The model will be used to parameterize the ocean surface albedo using data (e.g., concentrations of chlorophyll and DOM) which can be obtained from new sources like SeaWIFS, MODIS and GLI, and thereby improve fluxes and optical depths retrieved in SARB.

The model can also be applied to simulate the radiation extinction and thereby the solar heating in sea with depth using the surface flux products of CERES SARB.

4. Conclusion

- A coupled radiative transfer model for the atmosphere-ocean system has been developed. The model treats the scattering and absorption in both the atmosphere and the ocean explicitly and consistently.

- Model simulations show that the ocean parameters such as phytoplankton pigments and DOM concentrations are important for ocean surface albedo.

- The model will be validated by field measurement data and applied to parameterize the spectral ocean surface albedo for more accurate flux and optical depth retrievals in CERES SARB.

Reference

[1]. Z. Jin and K. Stamnes, Radiative transfer in nonuniformly refracting layered media: atmosphere-ocean system. ***Appl. Opt.***, 33, 431-442, 1994.

[1]. Z. Jin and J. Simpson, Bidirectional anisotropic reflectance of snow and sea ice in AVHRR channel 1 and 2 spectral regions - Part I: Theoretical analysis. ***IEEE Trans. Geosci. Remote Sens.***, 37, 543-554, 1999.

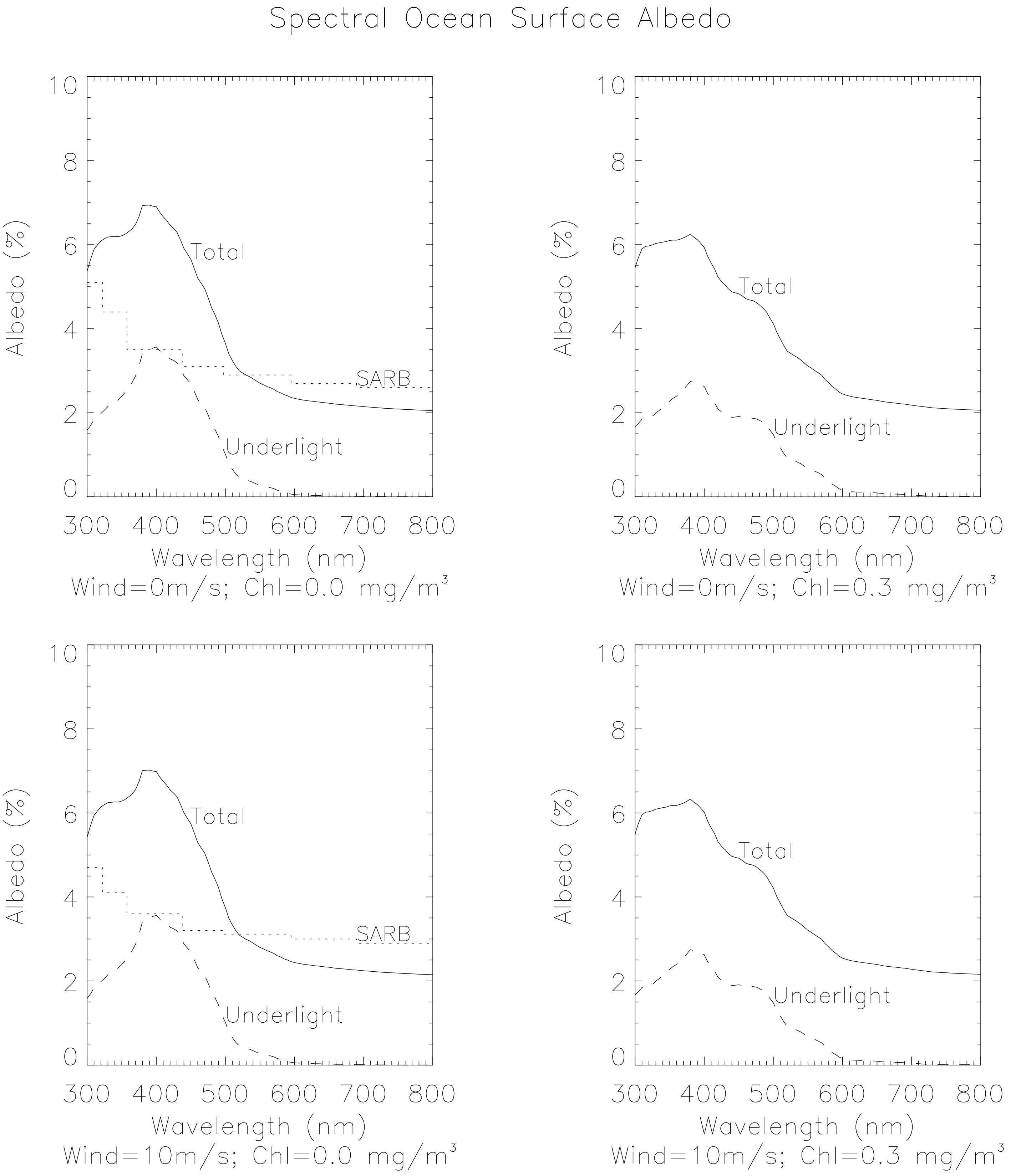

Spectral Ocean Surface Albedo
Albedo (%)
0
2
4
6
8
10
300
400
500
600
700
800
Wavelength (nm)
Total
SARB
Underlight
Wind=0m/s; Chl=0.0 mg/m³
Total
Underlight
Wind=0m/s; Chl=0.3 mg/m³
Total
SARB
Underlight
Wind=10m/s; Chl=0.0 mg/m³
Total
Underlight
Wind=10m/s; Chl=0.3 mg/m³

Figure 2

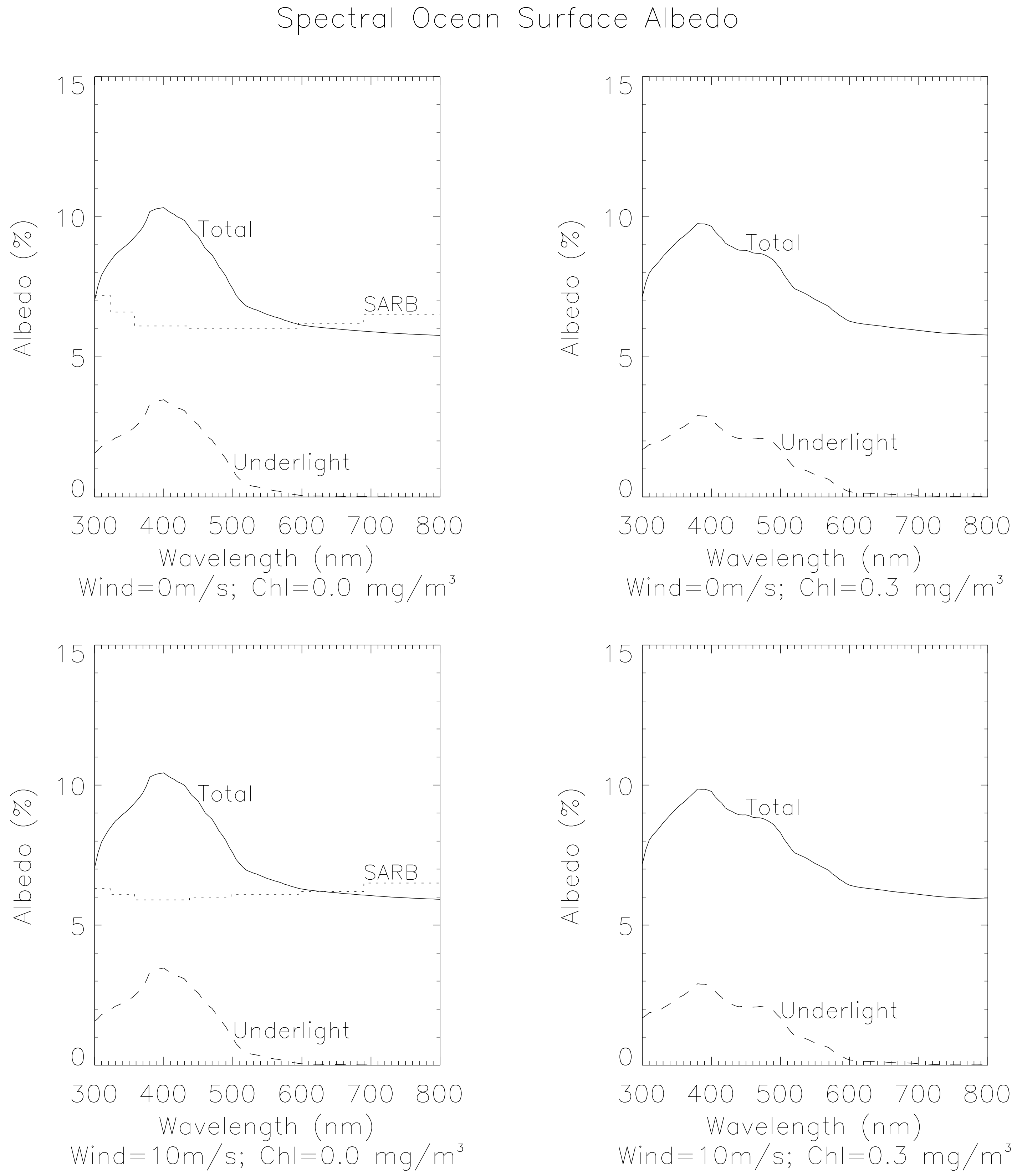

Spectral Ocean Surface Albedo
Albedo (%)
15
10
5
0
300
400
500
600
700
800
Wavelength (nm)
Total
SARB
Underlight
Wind=0m/s; Chl=0.0 mg/m³
Wind=0m/s; Chl=0.3 mg/m³
Wind=10m/s; Chl=0.0 mg/m³
Wind=10m/s; Chl=0.3 mg/m³

Figure 3

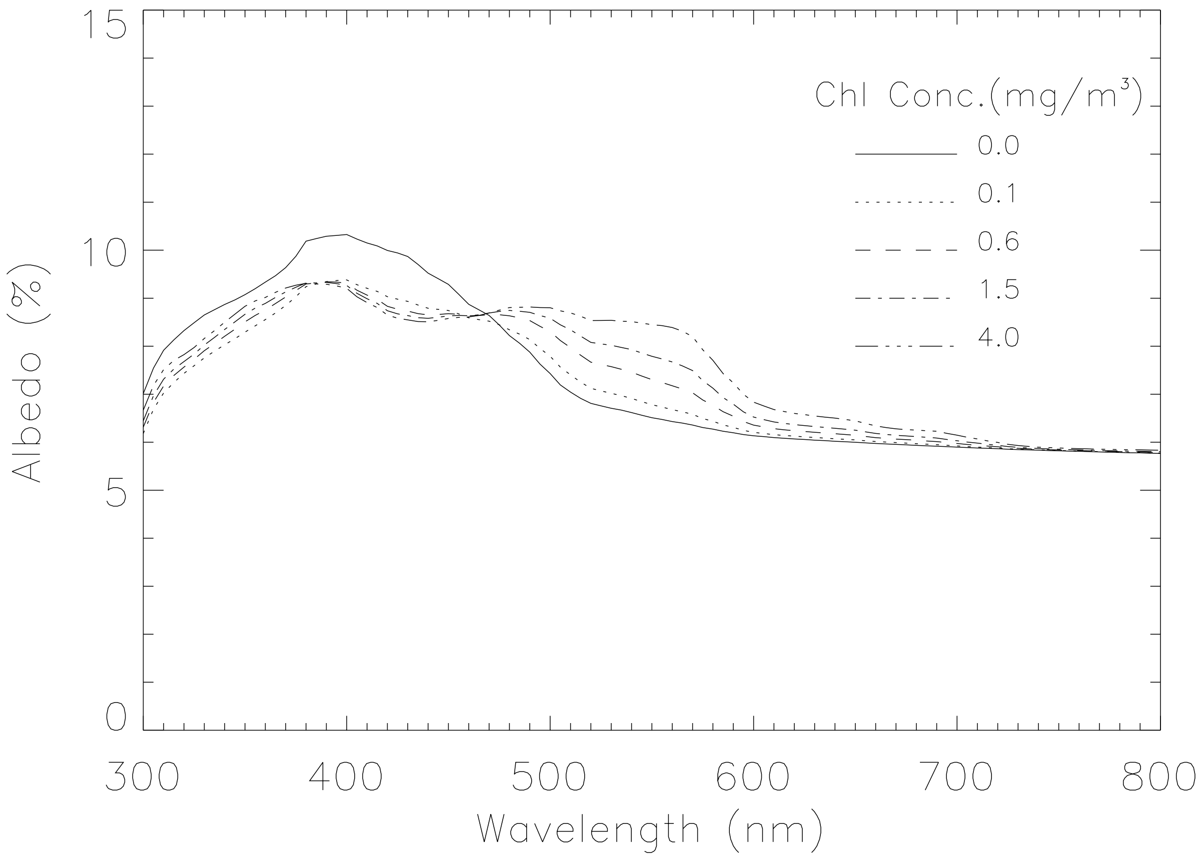

Chl Conc.(mg/m³)
0.0
0.1
0.6
1.5
4.0
Albedo (%)
0
5
10
15
300
400
500
600
700
800
Wavelength (nm)

Figure 4

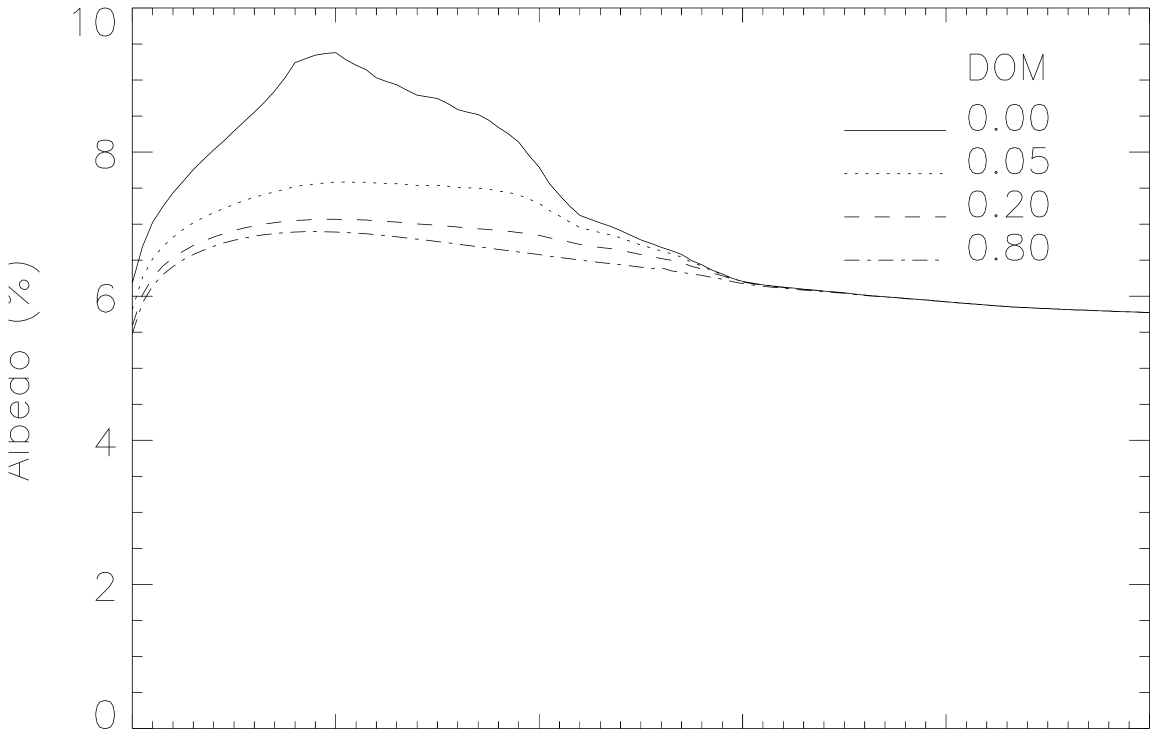


Figure 5

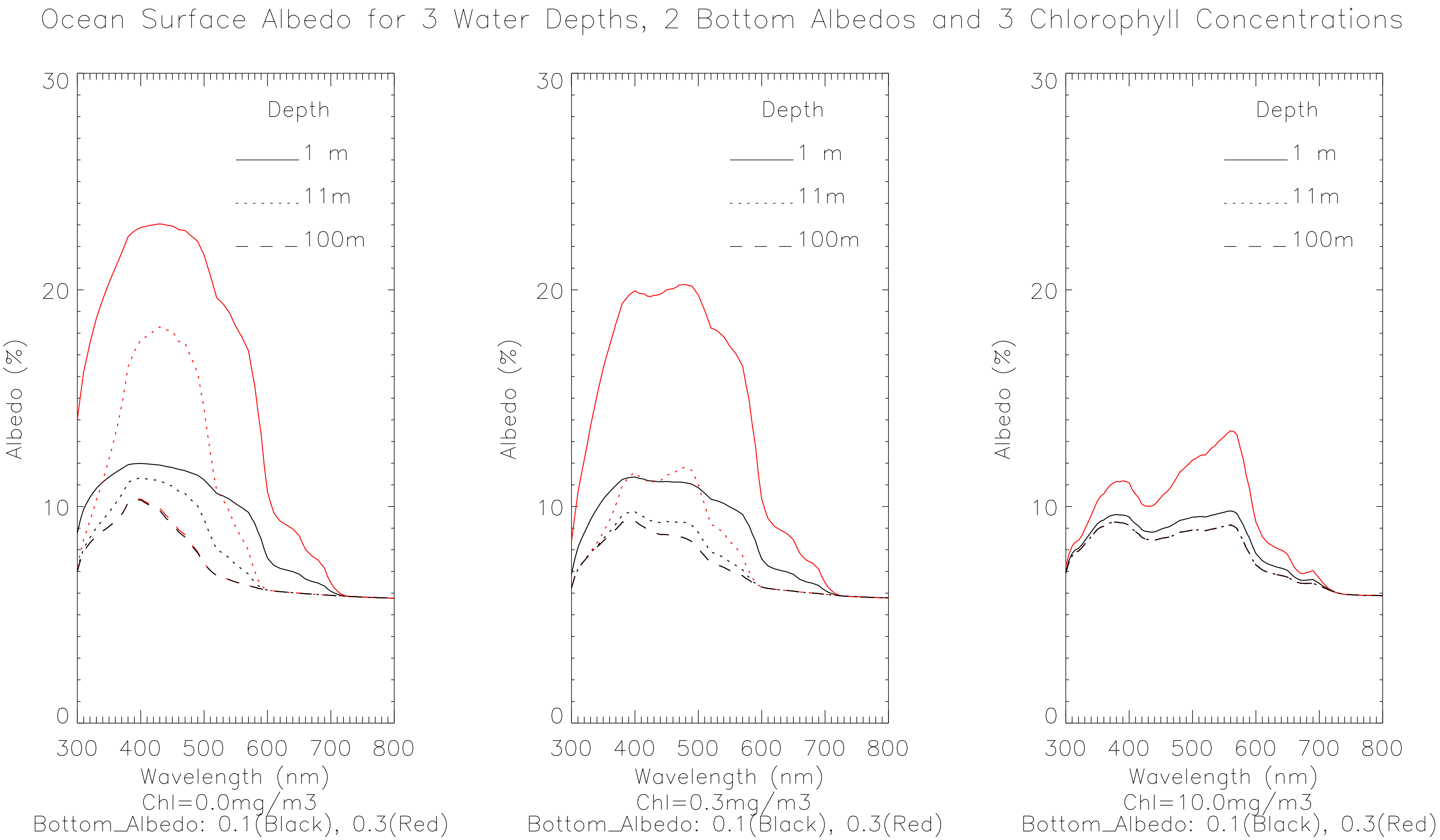

Ocean Surface Albedo for 3 Water Depths, 2 Bottom Albedos and 3 Chlorophyll Concentrations
Albedo (%)
0
10
20
30
Depth
1 m
11m
100m
300
400
500
600
700
800
Wavelength (nm)
Chl=0.0mg/m3
Chl=0.3mg/m3
Chl=10.0mg/m3
Bottom_Albedo: 0.1(Black), 0.3(Red)

Figure 6

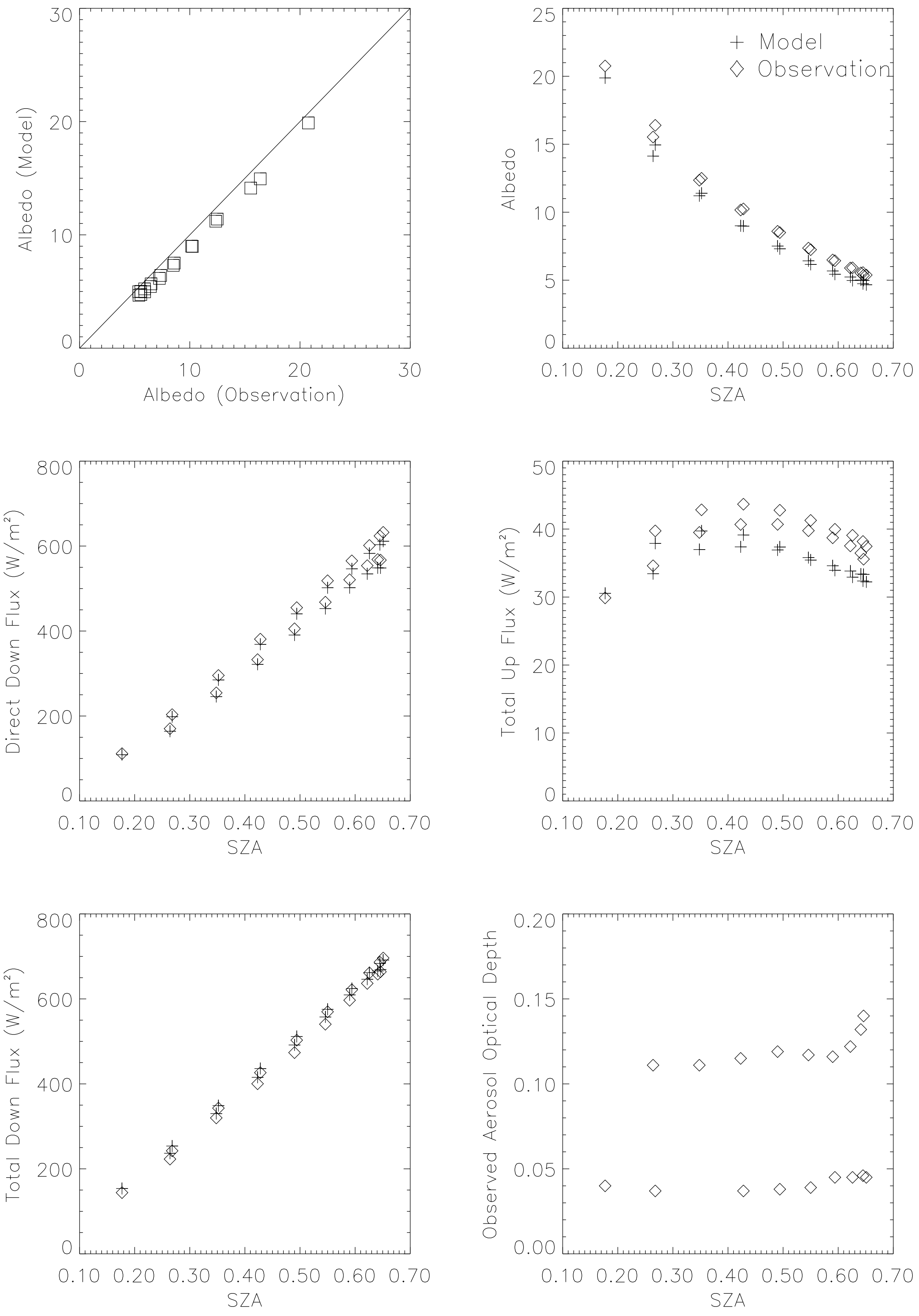
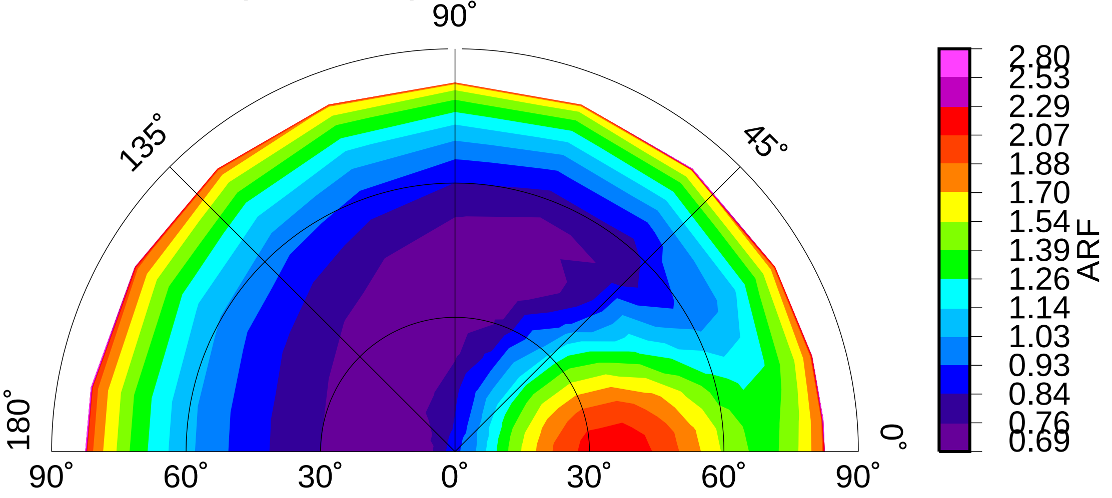

Albedo (Model)
Albedo (Observation)
0
10
20
30
Albedo
SZA
+ Model
◇ Observation
0
5
10
15
20
25
0.10
0.20
0.30
0.40
0.50
0.60
0.70
Direct Down Flux (W/m²)
0
200
400
600
800
Total Up Flux (W/m²)
0
10
20
30
40
50
Total Down Flux (W/m²)
Observed Aerosol Optical Depth
0.00
0.05
0.10
0.15
0.20

Figure 7

Model (SZA=30°)



ERBE (SZA=25.8 - 36.9°)

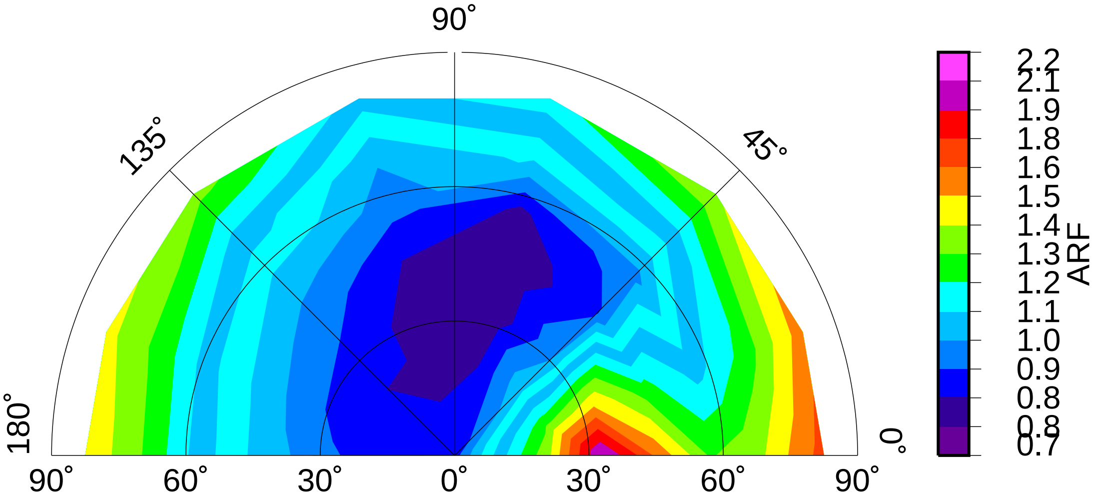
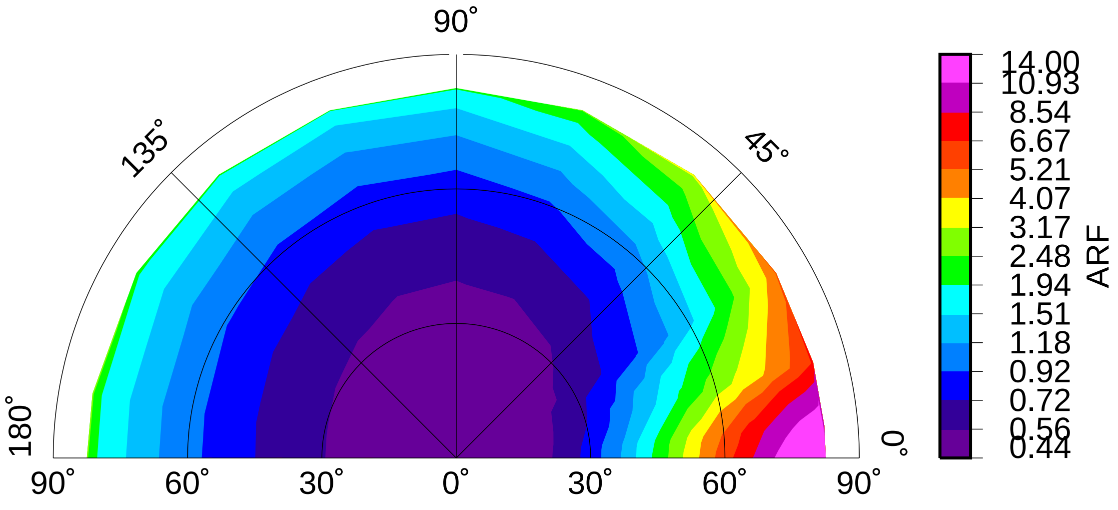


Figure 8

Model (SZA=63°)



ERBE (SZA=60.0 - 66.4°)

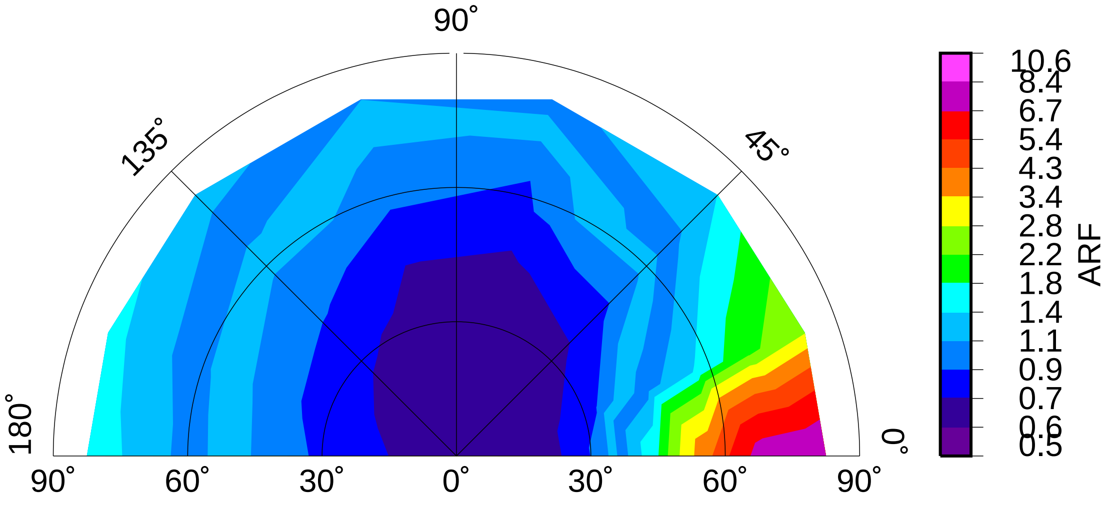


Figure 9