Preliminary Results for 3D effects

We investigated the effects of 3D cloud structures on the spectrally-invariant behavior using Monte Carlo simulations. We assume a cloud that is infinite in the north-south direction, 2.5 km long in the east-west direction, and 0.4 km deep, as illustrated in Fig. A1(a). The cloud is homogeneous in the north-south and vertical directions, but inhomogeneous in the east-west direction with one sharp edge and one diffuse edge where the cloud optical depth falls monotonically from 3 to 0. Our discussion here focuses on the diffuse edge because it has a cloud optical depth change similar to the cases shown in the paper. We also include two illumination cases: (1) the sun in the east so that the cloud edge of interest is illuminated; simulated radiances at visible wavelengths are shown in Fig. A1(b); (2) the sun in the west so that the cloud edge of interest is shaded.

The radiances from 1D SBDART and 3D calculations are illustrated in Fig. A2(a) using the 440 nm wavelength as an example. When the sun is in the east, the two radiances are very close. When the sun is in the west, the illuminated side (the sharp cloud edge) scatters more photons into the radiometer in a 3D model than in a 1D model, which leads to a significant radiance increase at cloud optical depth of 3. The 3D effect on simulated radiance rapidly becomes less significant as the distance from the sharp cloud edge increases. In general, for this case, the 3D effects on radiance at other wavelengths are similar to those at 440 nm.

Figure A2(b) shows radiance ratios at a cloud optical depth of 2 for band B1 (400–870 nm wavelengths). Similar to Fig. 1d in the paper, the 3D model points demonstrate a spectrally-invariant linear relationship. The sum of the slope and intercept is close to unity, the same as we found in both observations and 1D simulations. However, both the slope and intercept may depend on the sun-cloud illumination geometry, as shown in Fig. A3. Overall, our conclusions are: (1) when the sun is in the east, no significant difference is found between 1D and 3D calculations; (2) when the sun is in the west, 3D calculations change the spectrally-invariant relationship substantially. These conclusions are also true for band B5 (2110–2200 nm wavelengths).

In short, the spectrally-invariant relationship found in 1D simulations is still valid in 3D simulations, although the slope and intercept of the relationship depend on both the sun-cloud-geometry and the sharpness of cloud edges. When the sun illuminates a cloud edge that has a gradual change in cloud optical depth, 3D effects have negligible impact on the spectrally-invariant behavior. However, when the illuminated side has a sharp cloud edge, 3D effects could significantly change the linear relationship. Note that the sharp edge assumed in the latter case has a cloud optical depth change of 3 in only a 50 m distance, which might be rare in nature. Therefore, more cases are needed in order to better quantify the 3D effects on the spectrally-invariant behavior.

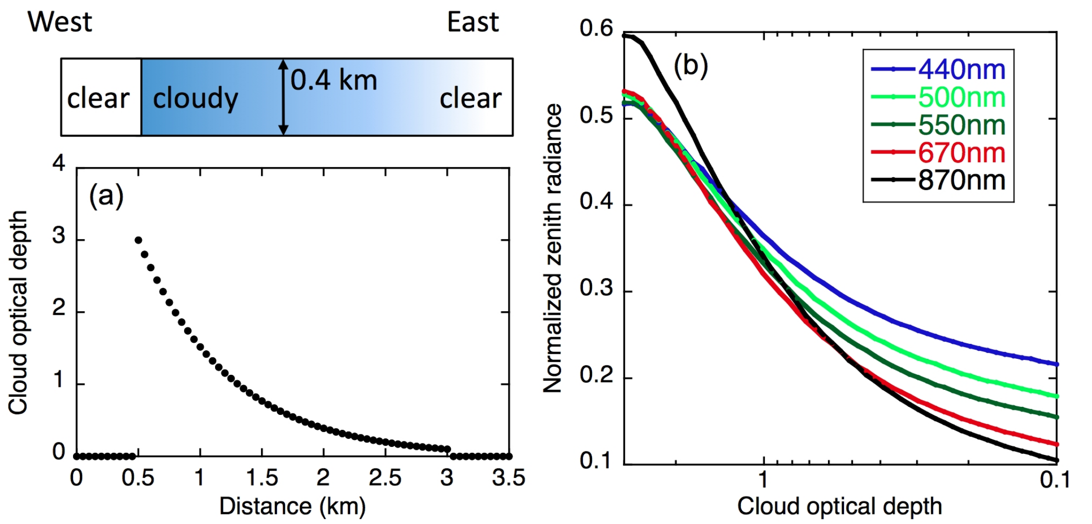

Figure A1. (a) A schematic illustration of a 2.5 km long and 0.4 km deep cloud with optical depth falling monotonically from 3 to 0 in the east-west direction, and a graph of the cloud optical depth vs. distance. (b) Normalized zenith radiance from 3D simulations vs cloud optical depth, using a Mie phase function for clouds. For this case, the sun is in the east; other input parameters are listed in Table 1.

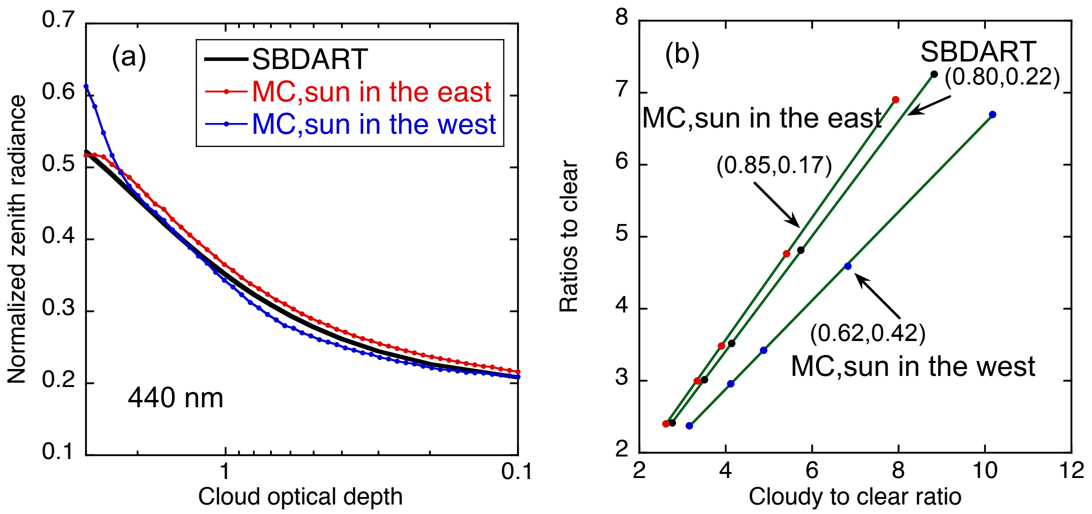

Figure A2. (a) Radiances at 440 nm wavelength, simulated from 1D SBDART and a 3D Monte Carlo model. (b) Spectrally-invariant linear relationships at cloud optical depth $\tau_c = 2.0$ for band B1 (400–870 nm) with a cloud effective radius of 4 μm. Numbers in parentheses are the slope and intercept of the linear regression relationships.

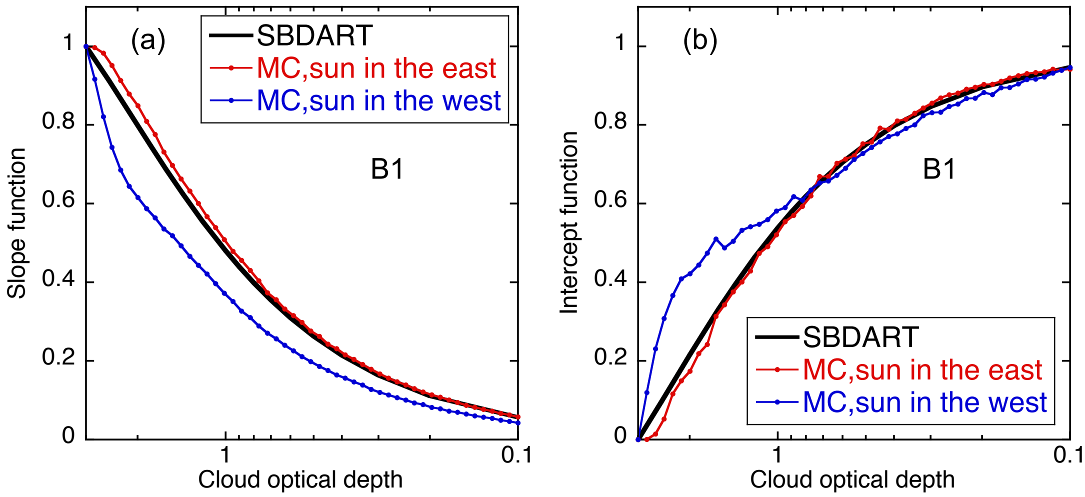

Figure A3. (a) Slope and (b) intercept functions derived from band B1 (400–870 nm wavelengths), using 1D SBDART and 3D Monte Carlo (MC) simulations. For MC simulations, we used two illumination cases: one is that the sun is in the east; the other is that the sun is in the west.