Simulation of high-spectral-resolution infrared signature of overlapping cirrus clouds and mineral dust

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[1] Numerical simulations have been carried out to understand the effects of overlapping cirrus clouds and mineral dust on the high-spectral-resolution infrared spectrum in the 600–2400 cm^{-1} region. A combination of the discrete ordinates radiative transfer and line-by-line models that account for the multiple scattering and monochromatic molecular absorption in the atmosphere is utilized to simulate the down-looking infrared spectrum at the top of the atmosphere with a resolution of 0.2 cm^{-1}. It is demonstrated that the spectral slope of the infrared radiance in the 800–1000 cm^{-1} region can be used to discriminate coexisting cirrus-dust scenes from those associated only with cirrus clouds or dust alone. In a case for a cirrus cloud overlapping with a dust layer, the spectral features in the 1100–1200 cm^{-1} and 1400–1850 cm^{-1} regions can be potentially useful for retrieving the optical thicknesses of the dust layer and cirrus cloud, respectively. **Citation:** Hong, G., P. Yang, H.-L. Huang, S. A. Ackerman, and I. N. Sokolik (2006), Simulation of high-spectral-resolution infrared signature of overlapping cirrus clouds and mineral dust, *Geophys. Res. Lett.*, *33*, L04805, doi:10.1029/2005GL024381.

1. Introduction

[2] Both cirrus clouds, covering more than 20% of the globe [*Liou*, 1986], and dust, a dominant feature of the global aerosol system [*Kaufman et al.*, 2002], play important roles in the Earth's climate system [*Lynch et al.*, 2002; *Sokolik et al.*, 2001]. Numerous techniques based on the infrared radiative spectrum for retrieving the properties of cirrus clouds have been explored [*Ackerman et al.*, 1995; *Smith et al.*, 1998; *Kahn et al.*, 2003; *Huang et al.*, 2004; *Wei et al.*, 2004]. However, for the retrieval of dust, many existing algorithms utilize the solar spectral bands [*Mishchenko et al.*, 2003; *Chu et al.*, 2005; *Remer et al.*, 2005], although the narrowband infrared observations have also been utilized to retrieve dust properties [*Ackerman*, 1997; *Legrand et al.*, 2001]. *Sokolik* [2002] simulated the high-spectral-resolution infrared spectrum pertaining to wind-blown mineral dust and noticed that the radiative signatures of dust are significantly different from those of clouds and the greenhouse gases in the atmosphere. Because of the unique infrared spectral features of dust, some recent efforts have been carried out to retrieve aerosol properties from the high-spectral-resolution infrared measurements. For example, *Pierangelo et al.* [2004] developed an approach based on pre-computed look-up tables to retrieve the altitude and optical thickness of a dust layer, using the infrared spectra acquired from the Atmospheric Infrared Radiation Sounder (AIRS) aboard the EOS Aqua satellite.

[3] The intent of our study is to understand the effects of overlapping cirrus clouds and mineral dust on the high-spectral-resolution infrared spectrum in the 600–2400 cm^{-1} region, a spectral region covered by many spaceborne or airborne infrared spectrometric instruments, for example, AIRS, the Scanning High-resolution Interferometer Sounder (S-HIS), HIS, and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounder Testbed-Interferometer (NAST-I).

2. Method

[4] The discrete ordinates radiative transfer (DISORT) model [*Stamnes et al.*, 1988], implemented with 16 streams in conjunction with a line-by-line (LBL) model [*Heidinger*, 1998], is employed to simulate the down-looking infrared spectrum in the 600–2400 cm^{-1} (16.67–4.17 μm) region with a spectral resolution of 0.2 cm^{-1}. The optical thicknesses of atmospheric layers, pertaining to the atmospheric molecular absorption, are calculated from the LBL model on the basis of the U.S. 1976 standard atmospheric profile. The emissivity of the surface is assumed as 1 in the present radiative transfer simulations.

[5] The optical properties of mineral dust are obtained from a computational package developed by *Levoni et al.* [1997]. The refractive indices of dust aerosols are taken from *d'Almeida et al.* [1991]. The size distribution of dust particles is assumed to consist of three size modes specified in terms of lognormal functions [*d'Almeida et al.*, 1991; *Levoni et al.*, 1997]. Furthermore, the Lorenz-Mie theory is employed to compute the bulk extinction coefficient, single-scattering albedo and phase function of aerosol particles with a certain size distribution. The optical properties of realistic dust aerosols may differ from the model simulation because of the nonsphericity and complicated composition of dust particles.

[6] In the present radiative transfer simulation, a dust layer is assumed to be uniformly distributed between the surface and an altitude of 3, 5, or 7 km. The optical thickness of this dust layer at a visible (0.55 μm) wavelength is assumed to range from 0.2 to 5.0, and the effective diameter of the dust aerosols is assumed to range from 3.0 to 5.0 μm, following the analyses by *Kaufman et al.* [2001].

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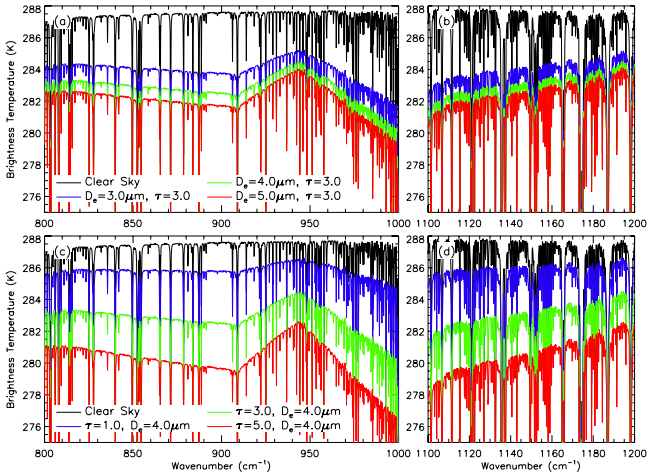

Figure 1. Simulated nadir-viewed spectral brightness temperatures at the top of atmosphere as a function of wave number for three effective particle sizes (D_e = 3.0, 4.0, or 5.0 μm in conjunction with an optical thickness of τ = 3.0) and three values of optical depth (τ = 1.0, 3.0, or 5.0 in conjunction with an effective diameter of D_e = 4.0 μm).

A single layer of homogenous cirrus cloud with a thickness of 1 km is specified between altitudes 10 and 11 km. The bulk optical properties of cirrus clouds are derived on the basis of a database that was recently developed by *Yang et al.* [2005] for the single-scattering properties of various ice crystal habits. The effective diameter and visible optical thickness of the cirrus cloud defined for the present simulations are assumed as 30 μm and 0.5, respectively.

3. Results

[7] Figure 1 shows the dependence of the nadir-viewed infrared spectrum on the optical thickness and effective size of mineral dust distributed uniformly below an altitude of 5 km. In addition to the negative slope associated with dust in the 810–910 cm^{-1} region, which was reported first by *Sokolik* [2002], other interesting features can be noticed from Figure 1. A spectral folding near 945 cm^{-1} is noted, which is resulted from a positive spectral slope in the 910–945 cm^{-1} region and a negative spectral slope in the 945–1000 cm^{-1} region. Moreover, in the spectral proximity of the 945-cm^{-1} wave number, the overall variation patterns of the two spectral segments corresponding to the positive and negative slopes are nearly symmetric although the absolute values of the positive slopes are slightly smaller than those of the corresponding negative slopes.

[8] *Kahn et al.* [2003] showed that, under a thin cirrus cloudy condition, the spectrum in the 800–1000 cm^{-1} region is featured with a positive slope whereas the corresponding spectral segment in the 1100–1200 cm^{-1} region is essentially flat. Unlike the case for cirrus clouds, the spectra pertaining to mineral dust in the 1100–1200 cm^{-1} region are featured with positive spectral slopes in the 1100–1200 cm^{-1} region, as evident from Figures 1b and 1d. An interesting point to note is that the slope of the spectrum in the 1100–1200 cm^{-1} region for mineral dust is not sensitive to the effective size of dust particles (Figure 1b), which, however, increases with the increase of the optical thickness of dust (Figure 1d). These spectral features can be used to retrieve the optical thickness of mineral dust. Furthermore, in this study it is found that mineral dust has little effect on the spectrum in the 1400–1850 cm^{-1} region (not shown here) because this spectral region is in a strong absorption band of water vapor and the corresponding spectrum is not sensitive to the radiative properties of the lower atmosphere.

[9] *Sokolik* [2002] pointed out that subvisible cirrus clouds frequently occur in the regions affected by dust transport. Figure 2 shows the nadir-viewed infrared spectra simulated for a cirrus cloud overlying a mineral dust layer. The effective size and optical thickness of the cirrus cloud are assumed as D_e = 30 μm and τ = 0.5, respectively. The effective size of the underlying mineral dust is assumed as D_e = 4 μm, whereas the corresponding optical thickness value is assumed as 0.2, 0.5, 1.0, 3.0, or 5.0. Similar to the mineral dust cases shown in Figure 1, the brightness temperatures shown in Figure 2 for the 800–1000 and 1100–1200 cm^{-1} regions are depressed with increasing the optical thickness of the mineral dust layer. However, the slopes of the infrared spectra for the cirrus-dust coexisting conditions are different from those for only cirrus cloud or mineral dust alone. In the 800–910 cm^{-1} region, the spectral slopes for the overlapping cirrus clouds and dust are positive, similar to the case for cirrus clouds without the contamination of underlying dust. The positive spectral slope for the 800–910 cm^{-1} region slightly decreases with the increase of the optical thickness of the dust layer. In the 910–1000 cm^{-1} region, the spectral folding shown in Figure 2 becomes more pronounced as the optical thickness of the dust increases. Moreover, it is evident from Figure 2 that, the slope in the 945–1000 cm^{-1} region is slightly positive or nearly zero when the optical thickness of the underlying mineral dust is smaller than the cirrus cloud optical thickness. When the optical thickness of the underlying mineral dust is larger than that of the cirrus

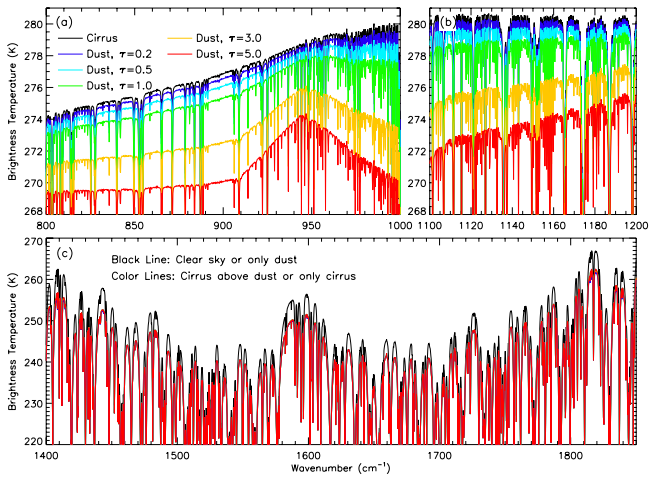

Figure 2. Simulated nadir-viewed spectral brightness temperatures at the top of atmosphere as a function of wave number for cirrus cloud contaminated by underlying mineral dust with different loading (τ = 0.2, 0.5, 1.0, 3.0, and 5.0 in conjunction with an effective particle size of D_e = 4.0 μm). The cirrus cloud has an effective particle size of D_e = 30 μm and an optical thickness of τ = 0.5.

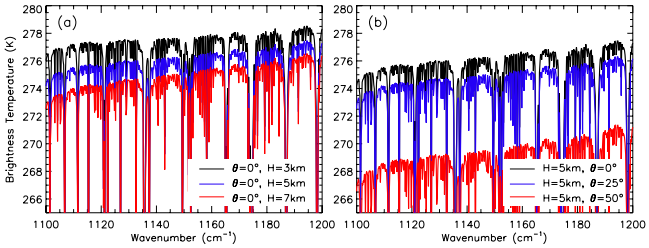

Figure 3. The effect of the altitude of the (a) underlying mineral dust layer and the (b) viewing angles on the spectrum in the 1100–1200 cm^{-1} region.

cloud, the overall variation patterns of the two spectral segments in the 910–1000 cm^{-1} region, corresponding to the positive and negative spectral slopes, are quite similar to the case for mineral dust only. However, in the cases shown in Figure 2 the magnitudes of the positive slopes are slightly larger than those of the corresponding negative slopes.

[10] The spectral characteristics discussed in the preceding context can be used to detect the co-presence of cirrus clouds and mineral dust. Specifically, the infrared spectral signature of cirrus clouds contaminated by underlying mineral dust that has an optical thickness larger than that of the overlying cirrus clouds can be detected by using the spectral folding due to the positive and negative slopes in the 910–945 cm^{-1} and 945–1000 cm^{-1} regions, respectively (note that the magnitude of the positive slope is slightly larger than that of the negative slope). Additionally, the spectral feature that the slope in the 800–910 cm^{-1} region is positive when a cirrus cloud and a dust layer coexist can also be useful.

[11] The infrared spectral signatures have been used to retrieve the properties of cirrus clouds [*Huang et al.*, 2004; *Wei et al.*, 2004] and also the properties of dust [*Pierangelo et al.*, 2004]. As cirrus clouds and dust often coexist, it is a natural progression of the previous studies to explore whether the properties of cirrus clouds overlying mineral dust can be inferred from the infrared measurements. It is evident from Figure 2 that the characteristics of the spectral slopes in the 800–1000 cm^{-1} region provide quite useful information for differentiating cirrus clouds and mineral dust. In the 1100–1200 cm^{-1} region, the positive slope is sensitive primarily to the optical thickness of the underlying mineral dust, and the information about this spectral segment can be used to retrieve the optical thickness of a dust layer overlaid by a thin cirrus cloud. The infrared spectral signature in the 1400–1850 cm^{-1} region is sensitive primarily to the optical thickness of cirrus clouds contaminated by underlying mineral dust (Figure 2c). Furthermore, in this study it is also found that infrared brightness temperatures in the 1400–1850 cm^{-1} region are essentially insensitive to the effective sizes of the clouds. Thus, this spectral segment can be useful for retrieving the optical thickness of a cirrus cloud with or without the contamination of underlying dust.

[12] Figure 3 shows the effects the altitude of a dust layer and the down-looking viewing angle on the infrared spectrum when a cirrus cloud overlies the dust layer. The effective size and optical thickness of the underlying dust are $D_e = 4.0$ μm and $\tau = 3.0$, respectively. The altitude of the dust layer slightly affects the spectral slope in the 1100–1200 cm^{-1} region (Figure 3a) that, however, is essentially independent of the viewing angle (Figure 3b). Similarly, in the 800–1000 cm^{-1} region (not shown here), the effects of the dust height and viewing angle are not significant. Furthermore, the spectrum in the 1400–1850 cm^{-1} region is insensitive to the altitude of the dust layer because of the strong absorption of water vapor in the lower atmosphere.

4. Conclusions

[13] The effects of cirrus clouds and mineral dust on the high-spectral resolution infrared radiative signatures have been investigated separately and also under their coexisting conditions. The different spectral features are noticed in the 800–1000 cm^{-1} and 1100–1200 cm^{-1} spectral regions for cirrus clouds and dust. It has been shown that the infrared spectral signature of cirrus clouds contaminated by underlying mineral dust is quite unique as compared with those for only cirrus clouds or mineral dust alone. The underlying mineral dust diminishes the positive slope in the 800–910 cm^{-1} region and enhances the positive slope in the 910–945 cm^{-1} region. The effect of dust results in a negative slope in the 945–1000 cm^{-1} region and a positive slope in the 1100–1200 cm^{-1} region. These spectral features can be used to discriminate the infrared spectra pertaining to coexisting cirrus clouds and mineral dust from those associated only with cirrus clouds or mineral dust alone. It has also been found that, under coexisting cirrus cloud and mineral dust conditions, the slope in the 1100–1200 cm^{-1} region is predominantly sensitive to the optical thickness of mineral dust, and the brightness temperature depressions in the 1400–1850 cm^{-1} region are sensitive to the optical thickness of cirrus clouds. Thus, it is feasible to use these two spectral segments to retrieve the optical thicknesses of cirrus clouds and underlying mineral dust. The follow-up effort of the present study will be focused on analyzing the AIRS or NAST-I measurements under three conditions (cirrus only, dust only, and coexisting cirrus and dust) over the typical dust regions.

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