The spectral radiative signature of wind-blown mineral dust: Implications for remote sensing in the thermal IR region

Irina N. Sokolik

Program in Atmospheric and Oceanic Sciences, University of Colorado at Boulder, Boulder, Colorado, USA

Received 18 July 2002; revised 3 September 2002; accepted 2 October 2002; published 19 December 2002.

This study investigates how the loading and composition of atmospheric dust affect IR radiances observed by satellite narrowband and high-resolution sensors. To compute monochromatic radiances accounting for multiple scattering and absorption by aerosols and atmospheric gases, we employed a new radiative transfer code which combines the line-by-line algorithm and discrete ordinate technique. New dust optical models required for such computations were developed for the representative mineral mixtures. We demonstrate that dust decreases the brightness temperature observed by satellite sensors depending mainly on the dust burden and composition, though the sensitivity to the composition differs between the satellite sensors. We found that mineral dust has a unique radiative signature (termed here a “negative slope”) which separates the effect of dust from that of clouds and gases. We conclude that dust decreases the daytime brightness temperature, BT, and proposed a tri-spectral algorithm to detect dust by combining observations at channels centered approximately at 8.5, 11 and 12 µm. Their analysis of HIRS/2 observations combined with the AVHRR revealed that the differences BT8 and BT11 vs. BT11 and BT12 might be a good indicator of the presence of dust, though no dust models considered in their study could reproduce the observed differences in the IR channels. Here we employ improved dust models which account for size-resolved dust composition to re-examine these effects, as well as to investigate the impact of dust on high spectral resolution measurements (such as Fourier transform interferometers, FTIR). The goal of this study is to explore the extent to which the presence of atmospheric dust and its varying composition can affect the IR satellite narrowband and high-resolution radiances over the oceans.

2. Approach

To adequately compute the monochromatic radiances in dust laden conditions, we developed a radiative transfer code LBL-MS (Line-By-Line with Multiple Scattering) by combining the line-by-line algorithm and discrete-ordinate technique. The LBL-MS code enables computation of the monochromatic radiances and irradiances correctly accounting for gaseous absorption and for both absorption and multiple-scattering by atmospheric aerosols. The line-by-line model incorporated in the LBL-MS code is a modified version of the LBLRTM code developed in AER Inc. [Clough et al., 1992]. The DISORT code is used to solve the radiative transfer equation with multiple scattering [Stamnes et al., 1988]. HITRAN-96 database was used to provide the line parameter input for line-by-line calculations [Rothman et al., 1998]. The HITRAN database consists of about million lines of 36 atmospheric gaseous species, which all were included in our calculations. The vertical profile of gaseous species and structure of the atmosphere (temperature, pressure, density as a function of altitude) were taken from the standard atmospheric models. In particular, we considered several atmospheric models (e.g., Tropic and U.S. 1976) to cover the range of atmospheric conditions in the regions frequently affected by dust transport.

First, the top-of-the-atmosphere (TOA) radiances were calculated with a high resolution of about 0.002 cm⁻¹ (called monochromatic radiances). Then they were averaged over 0.5 cm⁻¹ to match observations by high-resolution sensors (such as AIRS (Atmospheric InfraRed Sounder) and FTIR). To simulate the radiance which would be observed by a given sensor, TOA monochromatic radiances were inte-
grated over the bandwidth of each narrowband sensor considered in this study (see Table 1).

Calculated monochromatic radiances require high spectral resolution aerosol models in the IR region. Although basic physics of absorption and scattering by particulate matter is well understood, the quantitative prediction of aerosol effects in the IR remains an unresolved issue. In particular, we are not aware of any aerosol model specifically designed for high spectral resolution remote sensing.

The IR absorption spectra of aerosols are mainly controlled by particle composition and sizes. Aerosol absorption spectra are not as complex as those of gases, though each aerosol species, particularly minerals whose absorption in the IR is mainly due to lattice vibrational-rotation transitions, has its own spectral refractive indices and thus a specific spectrum of optical properties [Sokolik et al., 1998]. Since atmospheric dust is a mixture of various mineral species, it is critical to account for its composition. Following the approach described by Sokolik and Toon [1999], we developed a high-resolution optical model of mineral dust accounting for size-resolved mineralogical composition. This is a key improvement compared to models currently incorporated in HITRAN and MODTRAN since each mineral has a specific absorption spectrum which must be taken into account to accurately compute IR spectral radiances in the dust laden conditions.

In this study, we used the library of the spectral refractive indices which we have been compiling during the past years. Available data of spectral refractive indices of minerals are of the variable resolution, so we interpolated the refractive indices to the resolution of line-by-line computations.

3. Results and Discussion

To estimate the extent to which the presence of dust affects IR remote sensing, we considered several realistic scenarios of loadings and compositional mixtures of atmospheric dust. In particular, we considered light and moderate dust loadings, assuming that dust is distributed in the 3 kilometers of the lowest atmosphere. The light loading is representative of the dust plumes at the large distances from the source, while the moderate loading is appropriate closer to the source. Heavy dust loadings were not considered here since we focus on the effects of dust over the oceans.

For each loading type, several different composition mixtures were considered. Sokolik and Toon [1999] identified major minerals which are important for modeling IR radiation. For a simplicity, here we consider the mixtures of quartz and clays only. Quartz and clays are always the dominant species in the overall dust load, though their relative fractions vary depending on the specific dust source and production mechanisms, as well as removal processes during dust transport in the atmosphere. Three types of mixtures were considered: Mixture 1: 50% quartz and 50% clays; Mixture 2: 20% quartz and 80% clays; and Mixture 3: 80% quartz and 20% clays. These mixtures are representative of dust samples collected at several locations (see Table 2 in Sokolik and Toon, 1999). A lognormal function was used to model the aerosol size spectra consisted of two (accumulation and coarse) size modes, following Sokolik et al. [1998]. These compositional mixtures result in distinct spectral optical characteristics in the IR spectral region.

Figure 1 illustrates the effect of dust on the brightness temperature, BT, that would be observed by satellite narrowband sensors for considered dust mixtures for light (optical depth of about 0.2 at 10 μm) and moderate (optical depth of about 0.9 at 10 μm) loadings. The open columns show BT for clear (dust-free) atmospheric conditions in each channel. The light and dark color columns show BT for three compositional mixtures for the light and moderate loadings, respectively.

The presence of dust decreases the brightness temperature in all narrowband channels. This decrease is largely controlled by the dust loading. However, some channels are more sensitive to the dust composition than the others. In particular, the MODIS 8.4–8.7 μm channel is extremely sensitive to dust composition because this range of wavelengths partly covers the main absorbing bands of clays and quartz.

Also, one can notice that the difference in BT11-BT12 is not always a reliable indicator of dust. For each sensor considered, BT11-BT12 differences are always positive for dust-free conditions, in agreement with clear sky IR satellite observations. Under the light dust loading, BT11-BT12 remains positive for the AVHRR and GOES sensors, but BT11-BT12 become negative for the moderate dust load. In contrast, BT11-BT12 for the MODIS channels are negative for both dust loadings. It is important to point out that, because dust effects differ among channels, various discrepancies might exist in the atmospheric and oceanic properties retrieved from different sensors if dust composition is not properly accounted for. In particular, it is a critical issue for SST retrieved from AVHRR and MODIS since both retrieval algorithms use the channels centered at about 11 and 12 μm.

Figure 2 illustrates the effect of dust on the brightness temperature that would be observed by high-resolution sensors. Again, the presence of dust decreases the brightness temperature across the IR region, though various features can be pointed out. One of the important features is the change in the slope of BT in the about 820–920 cm⁻¹ (10.87–12.2 μm) range relative to clear sky spectra. Our modeling shows that this spectral signature (termed here a "negative slope") is a unique feature of mineral dust and cannot be reproduced by altering the temperature profile or the amount of water vapor for considered atmospheric conditions. Based on our modeling studies, we conclude that the negative slope in high spectral resolution BT, being a unique radiative signature of mineral dust, provide a reliable way to detect dust over the oceans.
The magnitude of the negative slope is not too sensitive to dust composition and thus can be used to retrieve the dust optical depth in this spectral region. In contrast, the region about 1099–1220 cm$^{-1}$ (8.2–9.1 μm) is very sensitive to dust composition and can provide important constrains on dust mixtures. Thus, the high spectral resolution remote sensing provides the unique capability in characterizing the properties of wind-blown atmospheric dust.

Furthermore, the spectral signature of dust differs from that of sub-visible cirrus clouds. For instance, measurements reported by Smith et al. [1998] demonstrate that the presence of thin ice crystal clouds increase a positive slope in the 820–920 cm$^{-1}$ spectral region, whereas BT of relatively thick cirrus clouds is wavelength-independent in this region. This is opposite to the negative slope as well as other specific spectral features caused by dust as shown above. Since sub-visible cirrus clouds frequently occur in the regions affected by dust transport, it is feasible that high resolution spectral observations provide enough information for separating a dust signal from the cirrus clouds in TOA radiances under some circumstances.

4. Summary

In this paper we estimated the effect of atmospheric mineral dust on the IR radiances observed by the narrowband and high-resolution sensors. We demonstrated that the presence of dust decreases the brightness temperature depending mainly on the dust loading, though the composition becomes important as the loading increases. The moderate dust loading can result in a decrease of brightness temperature by 5–10 K in the IR window over the oceans. Given the SST desirable accuracy of about 0.2 K, even the light dust loading can causes non negligible errors.

Our analysis revealed that narrowband sensors (e.g., MODIS, AVHRR, GOES) have different sensitivity to dust composition depending on a particular channel. We also found that dust has a unique spectral radiative signature (a “negative slope”) which separates the IR radiative effect of dust from that of clouds and atmospheric gases. This finding is supported by data from the NPOESS Airborne Sounder Testbed Interferometer (NAST-I) acquired during test flights over the Yellow Sea in Spring of 2001 [Sokolik et al., 2002].

We conclude that narrowband satellite sensors are capable of detecting dust but the quantitative characterization of dust properties requires a higher spectral resolution. The potential of high spectral resolution remote sensing in providing compositional information is especially important since no other means of remote sensing from space are capable of providing such data.

In turn, dust must be included in atmospheric correction algorithms if the retrievals of the sea surface temperature, atmospheric water vapor and trace gases from the thermal and near IR radiances are to be of high accuracy.
An additional analysis will be required to demonstrate whether a dust spectral signal can be uniquely identified from the measurements over the land, because the spectral emissivity of various surfaces can mask the dust effect on the TOA radiances.

Acknowledgments. This research was supported by ONR grant N00014-98-1-0121 and MURI/University of Wisconsin grant G066990.

References


I. N. Sokolik, Program in Atmospheric and Oceanic Sciences, University of Colorado at Boulder, Campus Box 311, Boulder, CO 80309-0392, USA. (Irina.Sokolik@colorado.edu)