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The infrared spectral signature of volcanic ash determined from high-spectral resolution satellite measurements

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ABSTRACT

High-spectral resolution infrared spectra of the earth's atmosphere and surface are routinely available from satellite sensors, such as the Atmospheric Infrared Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI). We exploit the spectral content of AIRS data to demonstrate that airborne volcanic ash has a unique signature in the infrared (8–12 μm) that can be used to infer particle size, infrared opacity and composition. The spectral signature is interpreted with the aid of a radiative transfer model utilizing the optical properties of andesite, rhyolite and quartz. Based on the infrared spectral signature, a new volcanic ash detection algorithm is proposed that can discriminate volcanic ash from other airborne substances and we show that the algorithm depends on particle size, optical depth and composition. The new algorithm has an improved sensitivity to optically thin ash clouds, and hence can detect them for longer (~4 days) and at greater distances from the source(~5000 km).

1. Introduction

Identifying and observing the movement of volcanic ash clouds from space are done at Volcanic Ash Advisory Centres (VAACs) around the world in order to provide hazard warnings to general aviation. Volcanic eruptions can eject ash (composed mainly of SiO_2) into the atmosphere to great heights (more than 20 km) and hence ash can intersect air-routes. Volcanic ash is a known aviation hazard (Casadevall et al., 1996), causing multiple engine failure as well as interfering with important avionics equipment.

The identification of volcanic ash in meteorological satellite imagery is not straightforward because at visible wavelengths, depending on solar and satellite-sensor viewing geometry, ash clouds may appear similar to water and ice clouds. In single-band thermal imagery, ash clouds are identified by using high temporal frequency data which can often reveal the origin and movement of a volcanic plume or cloud, once an eruption has started or is in process. Previous publications in *Remote Sensing of Environment* by Simpson et al. (2000, 2001), Prata et al. (2001) and Tupper et al. (2004) have high-lighted and discussed some of the problems and challenges in detecting volcanic ash using two-channel infrared data. More sophisticated satellite-based detection algorithms have been devised by utilizing multiple channels in the thermal infrared, mid-infrared and visible wavelengths (e.g. Prata, 1989; Hillger & Clark, 2002a,b; Ellrod et al., 2003; Pergola et al., 2004; Pavolonis et al., 2006).

The purpose of this study is to demonstrate that measurements from high-spectral resolution infrared imagers and sounders may be exploited to provide good discrimination of ash clouds from other clouds and hence may help to overcome some of the problems discussed in the earlier papers using two-channel IR measurements. We show that the new algorithm has an increased sensitivity over a current two-channel method used with several lower spectral resolution multi-spectral scanners. We use data from the Atmospheric Infrared Sounder (AIRS) that provides imagery covering the infrared window region from 700 to 1400 cm^{-1} (7–14 μm) at approximately 0.5 cm^{-1} spectral resolution.

The paper is organised as follows: we first provide a short description of the AIRS instrument, the data analysis and processing. Then we present the AIRS observations and introduce some ideas regarding the spectral shape and principal character of the spectra of ash clouds. We use the recent Chaitén eruption in Chile (42.833°S, 72.646°W, 1120 m asl) to illustrate a new detection algorithm and we compare this to the 'reverse' absorption algorithm (Prata, 1989). A radiative transfer model is used to assess the effects of particle size, optical depth and ash composition on the spectra and we conclude with a discussion of the new algorithm and suggest areas needing further work.

2. Data analyses—AIRS

AIRS is an echelle spectrometer with channels operating over the infrared region from about 3.6 μm to 15 μm (600–2800 cm^{-1}) (Chahine et al., 2006). The spectrometer can image the earth and atmosphere below by cross-track scanning and by using the forward motion of the

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Aqua satellite platform on which it resides. For ease of analysis, the AIRS images are provided as data granules consisting of 2378 channels × 90 pixels × 135 lines. This results in a granule covering a region of approximately 1800 km wide by 2700 km long, with an instantaneous field of view (IFOV) of approximately 13.5×13.5 km^2 at nadir. In our analyses we have used v5.0 Level 1b data which consists of calibrated and geolocated radiances.

3. The 'reverse' absorption algorithm

The detection of volcanic ash in the atmosphere using satellite data is hampered by the presence of other absorbers including water vapour, liquid water and ice particles. Prata (1989) suggested that two channels in the infrared window between 8 and 12 μm could be used to discriminate ash clouds from water/ice clouds because the wavelength dependence of the absorption by ash, principally composed of SiO_2, is opposite or the reverse of that by water and ice. Using two-band infrared satellite imagery and a radiative transfer model it was shown that under many circumstances ash clouds could be clearly discriminated from water and ice clouds. Improvements to this algorithm to account for water vapour absorption have been suggested by Yu et al. (2002) and extensions of the radiative transfer model to calculate particle size, mass and infrared optical depth have been proposed by Wen and Rose (1994) and Prata and Grant (2001). The simplicity of the algorithm, the availability of multiband thermal satellite imagery (e.g. AVHRR, MODIS, SEVIRI and others) and the fact that the algorithm may be used during the night have seen the 'reverse' absorption algorithm receive widespread acceptance and use at Volcanic Ash Advisory Centres (VAACs) to locate hazardous ash clouds for aviation warnings, despite certain limitations (Simpson et al., 2000; Prata et al., 2001; Simpson et al., 2001).

More recently, high-spectral resolution satellite infrared measurements have become available from NASA's AIRS instrument and from EUMETSAT's IASI instrument. These instruments provide 100's of channels across the infrared window (8–12 μm) compared to the multiband imagers (e.g. AVHRR, MODIS, SEVIRI, GOES and GMS-VISSR) that typically provide 2–5 channels. With such a wealth of information now available from the high-spectral resolution sensors, it seems likely that improvements can be made over the multiband methods for detecting, discriminating and quantifying volcanic ash in the atmosphere. In the following we discuss an approach using spectral signatures that exploits the measurements' high-spectral content.

4. Spectral signatures

The AIRS spectra contain a large amount of information about the vertical temperature and moisture structure of the atmosphere and are affected by gases, aerosols, clouds and the radiative properties of earth's surface. Away from the large absorption regions due to gases (e.g. the ozone band near 1040 cm^{-1}), and within the atmospheric window region between 700 and 1400 cm^{-1}, the spectra are strongly influenced by clouds and aerosols. To illustrate the information content of the AIRS spectra, Fig. 1A shows a slice taken along a constant pixel number (approximately in a N–S orientation) of one AIRS granule (granule 187 on 3 May, 2008, 18:41–18:47UT) over the spectral region from 800 to 1130 cm^{-1}. The spectra are shown as brightness temperature differences ($BTD = BT[\nu] - BT[\nu_{ref}]$), using a reference wavenumber (ν_{ref}) of 1000 cm^{-1} (an arbitrary choice, but see later). The BTDs are generally positive, except in regions of very strong gaseous absorption (cf. the 9.6 μm O_3 band). In this example the transect passes over a cloud of ash particles erupted from Chaitén volcano in southern Chile, which began erupting at 08:00UT on 2 May, 2008. A striking feature of the spectrum is the enhanced positive BTDs near line 115, stretching from 800 to 980 cm^{-1}. This feature coincides exactly with the position of the Chaitén ash cloud (see Fig. 1B). Below this feature (lower line numbers) there is a region of strongly negative BTDs—these are associated with meteorological clouds.

The shape of the spectra in the region between 800 and 1130 cm^{-1} is sensitive to the composition, size and optical depth of clouds and aerosols and hence can be exploited to retrieve this information. We illustrate these effects by considering actual AIRS spectral measurements for six atmospheric conditions: (1) a high-level ice cloud, (2) a water cloud, (3) a clear scene, (4) desert dust, (5) a basaltic ash cloud (Etna ash), and (6) a rhyolitic ash cloud (Chaitén ash). The spectra consist of Top Of the Atmosphere (TOA) radiances as a function of wavenumber, but to illustrate the spectral signatures, the brightness temperature spectra are computed and they are normalized by dividing by the brightness temperature at a reference wavenumber and then plotted as non-dimensional spectra. Fig. 2 shows the ratio between the spectral brightness temperature (BT) and a reference brightness temperature at 1000 cm^{-1} (BT_{ref}) for the six conditions. The idea behind dividing by a reference brightness temperature is to approximate the emissivity variation of the spectra; the choice of 1000 cm^{-1} is arbitrary, but it is necessary to avoid absorption regions and the region around 1000 cm^{-1} is quite transparent. Within the region between 850 and 1000 cm^{-1}, the ratio for ice (blue line) increases with wavenumber, whereas for ash and desert dust it decreases. For a clear atmosphere there is a slight increase with wavenumber due to water vapour absorption. Water clouds generally have a slope between that of the ice cloud and the clear scene. Ice and water clouds behave this way because the radiance spectra for ice and water over this region decrease with increasing wavenumber (Smith et al., 1993), which is a consequence of the decrease in cloud emissivity with increasing wavenumber, which in turn is related to the spectral variation of the refractive indices of ice and water. This change of slope of the spectral ratio with wavenumber can be used to discriminate ash from ice, water clouds and clear scenes. For spectra of clear scenes over bare soil and desert, there is a balance between the competing effects of water vapour, which tends to increase the ratio with increasing wavenumber, and surface emissivity, which tends to decrease the ratio with increasing wavenumber. The slopes are also sensitive to the optical depth of the cloud in the scene as well as the microphysics of the cloud particles (refractive index, size, size distribution, and shape).

Ash clouds and desert dust have positive slopes in the region between 1070 and 1130 cm^{-1}, opposite to that for ice clouds and opposite to the slope in the 850–1000 cm^{-1} region. DeSouza-Machado et al. (2006) have previously exploited the spectral signature of desert dust in AIRS data to show how dust affects the optical depth at 900 cm^{-1}. They describe the dust signature as having a "V" shape depression in the 800–1200 cm^{-1} region, similar to that for our dust example. It is apparent that the spectral shapes do not vary in a linear manner with wavenumber, and as can be seen for the Chaitén ash, there is a peak in the curve at around 850 cm^{-1}. The spectral variation of ash is a consequence of the variation of the refractive index with wavenumber and this is explored in Section 6 by using a radiative transfer model and a microphysical model for ash. After analyzing many (>100 AIRS granules) spectral curves for ash clouds, it was found that a quadratic function would fit the spectral variation between 800 and 900 cm^{-1}, and linear fits were adequate between 910–980 cm^{-1} and 1070–1130 cm^{-1}. Because of the peculiar concave shape of the curves for ash clouds in the interval 800–1000 cm^{-1}, we use this as a discriminant for ash clouds and call this the "concavity algorithm".

To check on the efficacy of this approach we analyzed three months of AIRS data (approximately 900 granules) over the Australian continent, where it is unlikely that significant amounts of volcanic ash occur, to determine the frequency of occurrence of particular spectral signatures. In addition, we used the concavity algorithm on two months of global IASI data. These analyses showed that persistent negative concavity occurred only over desert regions, particularly the Sahara, and that very few "false detections" happened.