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Improved volcanic ash detection based on a hybrid reverse absorption technique

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ABSTRACT

A noble volcanic ash (VA) detection method based on a hybrid reverse absorption technique was successfully applied in the analysis of major volcanic eruptions that occurred in Russia, Iceland, Chile, Italy, and Japan by using the MODerate-resolution Imaging Spectroradiometer (MODIS) observation data. Sensitivity studies using radiative-transfer simulations by using various environmental parameters such as ash loadings, sizes, layer heights, and surface emissions, revealed that VA effects on brightness temperatures (BT) can reach up to 40 K. The advantage of the hybrid algorithm is its ability to detect distinct VA pixels during the day and night from satellite observations. The results showed that the hybrid algorithm can minimize the false detection of VA pixels, while well-known reverse absorption methods show abundant false VA pixels over bright surfaces and cloud formations. Further, the time-and-space distribution of the VA pixels is in good agreement with the data pertaining to operational aerosol products obtained from the scanning imaging absorption spectrometer for atmospheric cartography (SCIAMACHY) instrument on board ESA's Envisat and the cloud-aerosol Lidar and infrared pathfinder satellite observations (CALIPSO). This novel algorithm is expected to provide a fine spatial and temporal resolution of VA monitoring from high spectral or geostationary satellite observation data.

1. Introduction

Volcanic eruptions have led to the release of excessive amounts of volcanic ash (VA) aerosols and volcanic gases into the atmosphere, presenting both aviation and human health hazards. In general, people exposed to VA commonly experience various eye, nose, and throat irritations and ailments (Baxter, 1999). Thick VA plumes can cause transportation hazards by reducing visibility and causing engine malfunction (Wilson et al., 2012). For example, in 2010 during the recent eruption of Eyjafjallajökull, in Iceland, aircraft observed VA layers between altitudes of 2 km and 8 km with peak mass concentrations typically between 200 and 2000 mg/m^3 (Johnson et al., 2012). This eruption caused significant disruptions of air traffic over Europe during April–May 2010. Aerosol measurements after the Eyjafjallajökull eruption in May 2011 have also been reported by Kvietkus et al. (2013). Carlsen et al. (2012) reported that short-term exposure was associated with upper-airway irritation symptoms and exacerbation of pre-existing asthma cases. Additionally, VA particles are one of the major atmospheric variables influencing both the transfer of radiative energy and global climate (McCormick et al., 1995; Robock, 2000). Previous modeling studies have used various methods to study the effect of volcanic aerosols (Stenchikov et al., 1998; Kirchner et al., 1999; Thomas et al., 2009; Meronen et al., 2012).

Satellite remote sensing provides the spatial and spectral resolution necessary to monitor the atmospheric aerosols (Lee et al., 2009). By the end of the 1980s, it was determined that volcanic clouds containing silicate ash can be identified by using the two thermal-infrared (TIR) window channels of

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meteorological satellites (Prata, 1989). Water particles, in either ice or liquid form, absorb more infrared radiation at longer wavelengths, while silicate ash absorbs more at shorter wavelengths. Therefore, ash particles in the size range of 1–7 μm in radius cause a negative brightness temperature difference (BTD < 0 K) between 10.8 μm and 12.0 μm. TIR remote sensing offers several advantages, including daytime and nighttime observations and the ability to determine aerosol/cloud layer altitude; further, such detection is possible over both oceans and land. However, limitations exist in this method, which are temperature inversions, barren surface, tropopause overshooting clouds, water vapor burdens, weak ash plumes, and instrument noise (Prata et al., 2001; Tupper et al., 2004). Nevertheless, many satellite remote sensing for VA detection are still based on TIR technique combined with mid-infrared and visible channel data. Such measurements are obtained from the Advanced Very High Resolution Radiometer (AVHRR) (Wen and Rose, 1994), geostationary operational environmental satellites (GOES) (e.g., Rose and Schneider, 1996; Ellrod and Schereiner, 2004), from the MODerate resolution Imaging Spectro-radiometer (MODIS) (e.g., Watson et al., 2004; Pavolonis et al., 2006; Corradini et al., 2008), from the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) (e.g., Corradini et al., 2009), from the Advanced Spaceborne Thermal Emission and Reflectance radiometer (ASTER) (e.g., Pugnaghi et al., 2006), and also the Atmospheric Infrared Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI) (e.g., Carn et al., 2005; Gangale et al., 2010).

In this study, a newly developed hybrid algorithm is applied for the volcanic ash detection and retrieval using MODIS data. This algorithm is performed by means of brightness temperature threshold tests and look up table (LUT) based inversion calculations. This paper is organized as follows. Section 2 presents the sensitivity tests of the method. Section 3 briefly describes the method developed in this study. The results of VA detection and retrievals and their consistency with the other operational satellite data products such as the ultraviolet absorbing aerosol index (AAI) by the SCanning Imaging Absorption spectrometer for Atmospheric Cartography (SCIAMACHY) and the aerosol extinction profile by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) are discussed in Section 4. Finally, the conclusions of the study are summarized in Section 5.

2. Sensitivity study

In this section, we discuss the effect of VA particles on satellite derived brightness temperatures (BT) studied in this paper. In particular, we consider their loading and size, height, and sun-satellite geometries. The BT presented here are the result of simulations using the Santa Barbara DISORT atmospheric radiative-transfer (SBDART) code (Ricchiazzi et al., 1998). SBDART uses a numerically stable solver for plane-parallel radiative transfer in a vertically inhomogeneous atmosphere. Refractive index data from Shettle and Fenn (1979) were used for the sensitivity analysis.

To estimate the effect of VA on satellite observed BT, let ΔBT be the differences between BT for clear sky and VA ($\Delta BT = BT_{clear} - BT_{ash}$) and let us assume that $\varepsilon(\Delta BT)$ is a function of the AOT at 0.55 μm wavelength ($\tau_{0.55}$), effective radius (r_{eff}), VA layer altitudes (H_{ash}), sun zenith angle (θ_0), satellite view angle (θ_S), and relative azimuth angle (φ). Because the error in ΔBT is proportional to the errors in these input parameters, we can write the absolute error as follows:

$$\varepsilon(\Delta BT) \cong \Delta\tau_{0.55}\left(\frac{\partial BT}{\partial\tau_{0.55}}\right) + \Delta r_{eff}\left(\frac{\partial BT}{\partial r_{eff}}\right) + \Delta H_a\left(\frac{\partial BT}{\partial H_{ash}}\right) + \Delta\theta_0\left(\frac{\partial BT}{\partial\theta_0}\right) + \Delta\theta_S\left(\frac{\partial BT}{\partial\theta_S}\right) + \Delta\varphi\left(\frac{\partial BT}{\partial\varphi}\right). \quad (1)$$

Table 1 summarizes the results from this sensitivity analysis. In general, errors in VA properties ($\tau_{0.55}$, r_{eff}, H_{ash}) for 10.8 μm and 12.0 μm are relatively larger than those for the other two wavelengths, while errors in geometry parameters (θ_0, θ_S, φ) are negligible effects on the accuracy of the ΔBT results. Thus the changes in the VA parameters have the largest impact on the VA retrieval. The results in Table 1 further suggest that the sensitivity of ΔBT to changes in all of the input parameters is fairly linear in the range of parameters considered here.

Fig. 1 shows an example of the sensitivity study for each of the retrieval-related factors. For each panel in figure, only one variable is changed, with the others keeping their "reference" value: $\tau_{0.55} = 3.0$, effective radius = 2 μm, VA layer height = 2000 m, and surface emissivity = 0.98 at the specified viewing geometry (sun zenith angle = 30º, satellite view angle = 30º, and relative azimuth angle = 60º). Fig. 1a shows ΔBT calculated with different AOT values ($\tau_{0.55}$: 0–5, step size = 0.2) for the four MODIS IR channels at 3.7 μm (band 20), 6.8 μm (band 27), 10.8 μm (band 31), and 12.0 μm (band 32). In general, BT is particularly sensitive to AOT increases except for 6.8 μm water vapor channel. There were positive ΔBT–$\tau_{0.55}$ relationships for 10.8 μm and 12.0 μm, and considerable negative ΔBT– $\tau_{0.55}$ relationships for 3.7 μm. Strong

Table 1
Uncertainty of input parameters for radiative transfer calculations and the resulting errors in computed $\Delta BT = BT_{clear} - BT_{ash}$.

Input parameters	Input range	Resulting error range in ΔBT			
		λ = 3.7 μm	λ = 6.8 μm	λ = 10.8 μm	λ = 12.0 μm
$\tau_{0.55}$	±0.1	−0.59 ± 0.19	0.07 ± 0.06	1.40 ± 0.43	1.34 ± 0.46
r_{eff}	±1 μm	0.39 ± 0.57	0.11 ± 0.17	2.09 ± 1.10	2.46 ± 1.40
H_{ash}	±1 km	−0.15 ± 0.16	−0.07 ± 0.39	1.59 ± 0.85	1.63 ± 0.85
BT_{surf}	±1 K	−0.49 ± 0.24	0	−0.44 ± 0.26	−0.35 ± 0.22
θ_0	±1°	0.011 ± 0.002	~0	~0	~0
θ_S	±1°	−0.01 ± 0.001	~0	0.012 ± 0.001	0.012 ± 0.001
φ	±1°	0.002 ± 0.001	~0	~0	~0