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Investigating the use of the Saharan dust index as a tool for the detection of volcanic ash in SEVIRI imagery

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ABSTRACT

Despite the similar spectral signatures of ash and desert dust, relatively little has been done to explore the application of dust detection techniques to the problem of volcanic ash detection. The Saharan dust index (SDI) is routinely implemented for dust monitoring at some centres and could be utilised for volcanic ash detection with little computational expense, thereby providing a product that forecasters already have some familiarity with to complement the suite of existing ash detection tools. We illustrate one way in which the index could be implemented for the purpose of ash detection by applying it to three scenes containing volcanic ash from the 2010 Eyjafjallajökull eruption, Iceland and the 2011 eruption of Puyehue, Chile. It was also applied to an image acquired over Etna in January 2011, where a volcanic plume is clearly visible but is unlikely to contain any ash. These examples demonstrate the potential of the SDI as a tool for ash monitoring under different environmental and atmospheric conditions. In addition to presenting a valuable qualitative product to aid monitoring, this work includes a quantitative assessment of the detection skill using a manually constructed expert ash mask. The optimum implementation of any technique is likely to be dependent on both atmospheric conditions and on the properties of the imaged ash (which is often unknown in a real-time situation). Here we take advantage of access to a 'truth' rarely available in a real-time situation and calculate an ash mask based on the optimum threshold for the specific scene, which is then used to demonstrate the potential of the SDI. The SDI mask is compared to masks calculated from a simplistic implementation of the more traditional split window method, again exploiting our access to the 'truth' to set the most appropriate threshold for each scene, and to a probabilistic method that is implemented without reference to the 'truth' and which provides useful insights into the likely cloud-/ash-contamination of each pixel. Since the sensitivity of the SDI and split window methods to the tailored thresholds was not tested (such tailoring is unlikely to be possible in a real situation), this study presents the maximum anticipated skill for the SDI in the context of the maximum skill anticipated for the split window method, although both are likely to be lower in a real-time situation. The results for the SDI are comparable to those of the other methods, with a true skill score of 80.02% for the Eyjafjallajökull night-time scene (compared to 88.81% and 46.63% for the split window and probabilistic method respectively) and 90.06% for the Eyjafjallajökull day-time scene (compared to 97.61% and 56.96%). For the Puyehue image, the SDI resulted in a true skill score of 74.85%, while the split window approach achieved 99.62%. These results imply that the SDI, which is already implemented operationally at some centres for dust detection, could be a useful complement to existing ash monitoring techniques.

1. Introduction

Ash clouds are one of the most significant and economically costly hazards associated with volcanic eruptions. The clouds, comprised of silicates, minerals, glass shards and large quantities of gases (Karagulian et al., 2010), can be damaging to buildings and infrastructure (Spence et al., 2005), destroy crops and local livelihoods and present a danger to the health of humans and animals (Tobin and Whiteford, 2004; Horwell, 2007). This dynamic and geographically far-reaching hazard also poses a threat to aviation (Casadevall, 1994; Dunn and Wade, 1994). Previous encounters between aircraft and ash clouds have caused damage to airframes and engines and have resulted in potentially life threatening situations (Miller and Casadevall, 2000; Pieri et al., 2002). Historically, a cautionary approach has been followed in order to minimise the risk to human life (Guffanti et al., 2010). However such an approach can cause severe and widespread disruption and

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Abbreviations: BT, Brightness temperature; BTD, Brightness temperature difference; dSDI, Daytime Saharan dust index; IASI, Infrared atmospheric sounding interferometer; FAR, False alarm rate; HR, Hit rate; PC, Principal component; PCA, Principal component analysis; PP, Proportion of perfect classifications; SDI, Saharan dust index; SEVIRI, Spinning enhanced visible and enfrared imager; TIR, Thermal infrared; TSS, True skill score.

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have significant economic consequences, as demonstrated by the Eyjafjallajökull eruption in Iceland, 2010, when 100,000 flights were cancelled causing an estimated revenue loss of US $ 1.7 billion within the first six days of the eruption IATA Economic Briefing (2010).

Successful management of ash hazards depends on the effective monitoring and forecasting of the location and concentration of ash in the atmosphere (Prata, 2009). Remote sensing tools form an important part of this effort, exploiting observations from instruments on ground, air and satellite platforms that are sensitive to different parts of the electromagnetic spectrum (Thomas and Watson, 2010). As each technique is subject to limitations, observations from different sources are used in combination and alongside other techniques to minimise error (Tupper et al., 2004) and there is a strong incentive to improve existing techniques and develop new methods to complement those already in use (Prata et al., 2014a).

Satellite imagery, particularly at thermal infrared (TIR) wavelengths, is a valuable tool offering wide spatial coverage at a reasonable spatial resolution and a high temporal resolution (up to every 5 min from the rapid scan service for the spinning enhanced visible and infrared imager (SEVIRI) on board the geostationary platform Meteosat Second Generation (Stuhlmann et al., 2005), thereby capturing both the dynamic and potentially geographically far reaching nature of volcanic ash hazards (Prata, 2009). Such data can be used for monitoring both day and at night and can cover remote areas where observations by other means may be logistically difficult (Thomas and Watson, 2010). Volcanic ash is generally associated with a broad absorption feature in the TIR region, which can be exploited to detect its presence in TIR satellite observations. This can be seen in the complex part of the refractive indices (which is associated with absorption) measured for materials that volcanic ash is typically composed of (e.g. Pollack et al., 1973; Volz, 1973; Balkanski et al., 2007). The absorption feature is strongest at wavelengths around 10 μm (the strength and exact location of the maximum differs slightly for different ash compositions (Mackie et al., 2014)), creating a positive transmission gradient between 10 and 12 μm. A particularly strong example of this feature is shown in the ash spectrum in Fig. 1a. In general, meteorological clouds (ice/water clouds) preferentially absorb radiation at longer wavelengths in this region, creating a negative transmission gradient in this region. Pixels can be interrogated for the sign of the transmission gradient by taking the difference between observations recorded at two different wavelengths within the region. A positive gradient can be interpreted to indicate the presence of ash (Prata, 1989a), and the magnitude of the difference between the brightness temperatures (BTs) in the two selected channels can be further used to retrieve properties such as the ash concentration (Wen and Rose, 1994). Many more recent methods for detecting ash and/or retrieving properties such as concentration rely on exploiting a brightness temperature difference (BTD) that stems from this absorption feature, for example Schneider et al., 1995; Corradini et al., 2008; Webley et al., 2009; Bailey et al., 2010; Francis et al., 2012. The BTD method, also known as the split window technique, has been used for ash detection problems with a temporally- and spatially-specific local threshold applied to the BTD (Pergola et al., 2004a; Filizzola et al., 2007), and has been combined with threshold tests applied to observations made at additional wavelengths (Ellrod et al., 2003). A more detailed description of the split window method is provided in Section 3.2.1. Other methods to interpret TIR satellite imagery in terms of volcanic ash have also been developed, for example Gangale et al. (2010) and Clarisse et al. (2010, 2013) present methods for interpretation of hyperspectral data based on comparing observation spectra. These methods can only be applied to data from hyperspectral sensors, which are currently only aboard polar orbiting platforms and therefore do not offer the same temporal coverage as data from geostationary platforms. Pavolonis (2010) and Pavolonis et al. (2013) present a technique based on ratios of emissivities at different wavelengths, which can be used alongside scene-specific information to determine whether a pixel contains ash. Mackie and Watson (2014) demonstrate a probabilistic technique, whereby scene-specific information is exploited to model observations of ash, cloud and clear sky. The modelled observations are combined with uncertainties to create pixel-specific probability density functions for observations of each of the three atmospheric states. These are then combined with the actual observation using Bayes' Theorem to calculate the posterior probability that the observed atmosphere corresponds to a clear, cloud or ash state. This method is described more fully in Section 3.2.2.

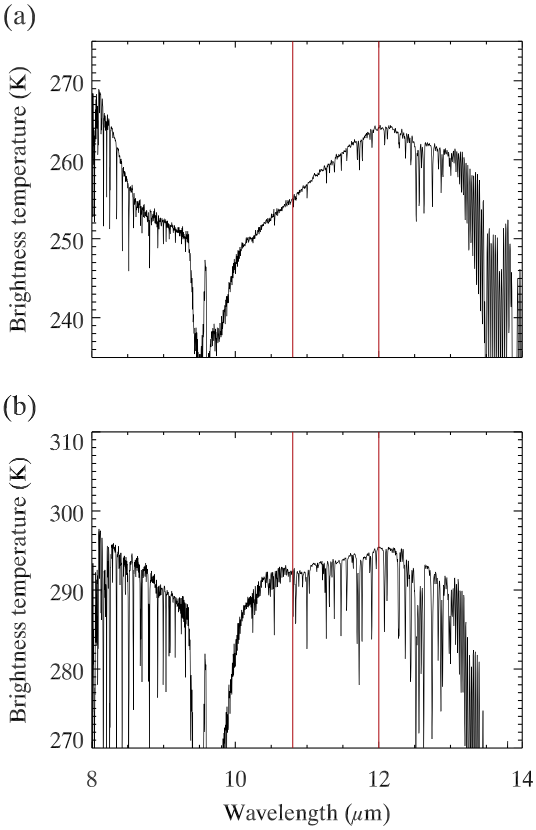

Fig. 1. Spectra observed by the IASI sensor: (a) ash cloud from the Eyjafjallajökull eruption on 6th May 2010, (b) Saharan dust storm event on 16th of September 2010. Red lines show the location of the 10.8 and 12 μm wavelengths (where two of the channels of the SEVIRI sensor are centred).

The spectral characteristics of ash in the TIR region are similar to those of desert dust, which is also associated with a positive transmission gradient between 10 and 12 μm (DeSouza-Machado et al., 2006; Lee et al., 2014). Fig. 1 shows spectra recorded by the IASI sensor for observations of a volcanic ash cloud from Eyjafjallajökull in 2010, and of a Saharan dust storm event in 2010. In both cases, the transmission increases between 10 and 12 μm. This spectral similarity between the two aerosols means that automated methods for ash detection based on the anticipated ash BTD signature are likely to misclassify dust pixels as ash, and rely largely on expertise held at Volcanic Ash Advisory Centres to determine which of the aerosols is most likely (Simpson et al., 2003), although newer methods, such as those using hyperspectral data (e.g. Clarisse et al., 2010; Gangale et al., 2010; Clarisse et al., 2013), are less likely to be affected by this. Similarly, dust detection methods are likely to produce false alarms in the presence of volcanic ash, as noted in Park et al. (2014). The similarity is demonstrated by Pavolonis et al. (2013), who successfully follow the same method to detect both volcanic ash and Saharan desert dust. This suggests that the methods used for dust detection may potentially be used to detect volcanic ash.

Windblown dust is one of the most abundant aerosols on Earth (Textor et al., 2006). Saharan dust is transported regularly towards both North and South America (Goudie and Middleton, 2001; Petit et al., 2005; Prospero et al., 2014) and towards Europe (Ryall et al.,