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Shona Mackie
Matthew Watson

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Shona Mackie* and Matthew Watson

University of Bristol, School of Earth Sciences, Wills Memorial Building, Queens Road,
Bristol BS8 1RJ, United Kingdom

Abstract. Volcanic ash can travel great distances and sometimes persist for several weeks, necessitating the monitoring of large areas for potential aviation hazards. Ash can affect aircraft in several ways, from engine failure to manageable impacts if the ash concentration is low. The location and properties of even low levels of ash are, therefore, required in order to make informed safety decisions. Infrared (IR) satellite-borne sensors are vital to this monitoring because of their high spatial coverage day and night. Interpretation of IR ash observations generally relies on exploiting the difference between an observation and the observation anticipated for the same scene under ash-free conditions, the so-called ash signal. We apply forward-model observations of andesitic ash with a fixed particle size distribution to investigate the sensitivity of ash signals to the ambient atmosphere. The variability in the ash signals attributable to atmospheric effects is found to be at least as high as the variability attributable to differences in ash concentration and altitude, implying that different concentrations could be retrieved if atmospheric effects were ignored. Ash with different optical properties is likely to correspond to a slightly different ash signal and may exhibit a different sensitivity to atmospheric effects to that presented here. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JRS.9.095080](https://doi.org/10.1117/1.JRS.9.095080)]

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1 Introduction

The serious threat posed to aircraft by volcanic ash even at large distances from the eruption site is widely recognized.¹ Ash clouds from the eruption of Eyjafjallajökull in Iceland in 2010 caused widespread disruption to aviation, with the cost to the aviation industry estimated at over £1 billion as ash was carried by strong winds from Iceland to congested areas of European airspace.² Large areas of airspace were closed, causing flights to be cancelled or rerouted, leaving an estimated 10 million passengers unable to travel.³

Sensors with a wide range of detection capabilities were used to monitor the ash during the Eyjafjallajökull crisis, exploiting already existing techniques as well as developing new ones. Some established methods for ash detection and monitoring use visible and ultraviolet (UV) imagery (e.g., see Ref. 4), while others consider only infrared (IR) (e.g., see Ref. 5), and further approaches combine the information from these different parts of the spectrum (e.g., see Refs. 6–8). Here, we concentrate on IR imagery since at night, only data recorded at these wavelengths are available. It is likely that in the daytime, with the addition of information from visible and UV measurements, ash can be more reliably detected and its properties can be more reliably retrieved in all atmospheric conditions.

No ash detection technique for satellite-acquired imagery is capable of detecting all volcanic ash under all circumstances⁹ and the effectiveness of any technique is likely to vary according to the properties of both the imaged atmosphere and the ash itself^{10,11} (for the purposes of this work, we use the term “atmospheric” to refer to both atmospheric and surface properties since our aim

*Address all correspondence to: Shona Mackie, E-mail: shona.mackie@bristol.ac.uk

is to isolate all “nonash” factors to which an observation may be sensitive). This is because most techniques for detecting ash and for retrieving properties such as column loading or concentration, rely on exploiting a relationship between ash concentration and signal strength. The “signal” referred to here and throughout this work is the difference between an observation made for ash and one made under the same atmospheric conditions in the absence of ash (clear sky), in other words the sensitivity of the observation to ash. The threshold is often placed on the signal in order to identify the presence of ash, and the strength of the signal is often used to infer ash column loading, from which concentration can be estimated using an assumed (or observed through other means) geometric cloud thickness,^{8,12–14} although recently more sophisticated techniques have become available (e.g., see Refs. 15–18).

If the variability in the signal attributable to atmospheric effects is found to be comparable to the variability attributable to ash concentration, then atmospheric effects must be taken into account in order for any relationship between the signal and ash properties to be used reliably. Two atmospheric parameters to which ash detection success is often particularly sensitive are water vapor and surface temperature (ST).^{10,12,19} Here, we consider a column of atmosphere containing ash that is identical in all respects except the atmosphere in which it is present. We thereby aim to isolate the contribution to the signal variability attributable to atmospheric effects. We use a realistic set of possible atmospheres, grouped into day/night, land/sea, and tropical/nontropical categories and examine the variability of the signal produced by the ash both within each group and between the groups. We also vary the altitude and concentration of the ash in order to see how the variability attributable to atmospheric effects changes with these properties in different types of atmosphere. In other words, is the effect of the atmosphere on the signal stronger in some atmospheres than in others or stronger for higher/lower altitudes/concentrations of ash? And how much does the signal vary for the same ash cloud in response to small changes in atmospheric effects within broadly similar atmospheres? If the signals were only sensitive to ash, then we would expect the variance of the signal to be close to zero for ash with the same concentration, composition, particle size distribution (PSD), and altitude regardless of the range of atmospheric conditions that were observed. This would imply that meteorological data are not necessary to interpretation of ash observations, and furthermore would mean that the uncertainties attributable to such interpretations stem only from assumptions about ash and sensor characteristics, and are independent of any meteorological assumptions. It is important to know whether or not this is the case.

It is likely that atmospheric effects become more significant to the ash signal when an ash cloud is thin and the underlying atmosphere has a stronger influence on the upwelling radiance. In one study, the failure of ash detection in IR observations, on an occasion where ash was clearly detected in space-borne LIDAR data, was attributed at least partially to the ash cloud being thin and at a low altitude.⁸ Observations of ash from the 2010 eruption of Eyjafjallajökull showed that thin ash clouds are, at least for some eruptions, not unusual far from the volcanic source. For example, ash was observed in layers with thicknesses ranging from less than 500 m to ~1.5 km by Devenish et al.,²⁰ and in layers between 400 m and 1 km thick by Flentje et al.,²¹ while Winker et al.²² found the plume to be ~1 km thick. In this study, we simulate ash clouds that are 1 km thick.

Warnings issued by the London Volcanic Ash Advisory Centre (VAAC) are graded low, medium, or high according to the concentration of ash that is predicted for a given location.²³ It is, therefore, important that mass concentration is retrieved reliably from the observations. To achieve this, it is necessary to understand what factors may contribute to the ash signal (either weakening or strengthening it) other than a change in ash concentration, in order that these factors can be accounted for either in the calculation of the retrieved mass concentration or in the estimation of uncertainty that should properly accompany such retrievals.

1.1 Ash Signal

The absorption spectrum for volcanic ash has a strong peak around 10 to 11 μm , the exact position and magnitude of which depends on the composition of the ash.¹¹ By contrast, water and ice clouds absorb preferentially at 12 μm and longer wavelengths, so the difference between observations recorded at 12 μm and at a channel centered around 10 to 11 μm is often used to infer the

presence of volcanic ash [the so-called brightness temperature difference (BTD)] and to discriminate it from meteorological clouds.¹² Different techniques consider different relationships between the two channels to discriminate ash and to retrieve properties such as mass concentration. Since most methods are based on an expected absorption at 10 to 11 μm , with the second channel being used as a control for the signal and/or anticipated to be particularly sensitive to something else, e.g., meteorological clouds, then the sensitivity of a channel centered around 10 to 11 μm can be interpreted as a significant limiting factor for the detection of ash clouds. The work presented here investigates whether a discernible signal always exists in this channel for ash clouds, or whether there are atmospheres in which ash clouds are unlikely to be detected by methods relying on this absorption feature.

Ash can have different optical properties depending on the material of which it is composed, the shape of the particles and the size distribution of the particles. These different optical properties correspond to different ash signals, which may have slightly different sensitivities to atmospheric parameters. We do not investigate this here, but we keep the ash optical properties fixed and focus on how the signal is affected by atmospheric and surface effects. We examine how far atmospheric effects can influence both the single channel signal and the BTD signal for ash clouds. Because the properties of the ash are fixed, any variability in the sensitivity of either of these signals is attributable to atmospheric effects only and shows the importance of accounting for the atmospheric properties specific to the imaged scene when interpreting IR observations of ash using either of these signals.

1.2 Spinning Enhanced Visible and InfraRed Imager

One IR sensor that has been used in studies looking at volcanic ash^{16,24} is the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) instrument. SEVIRI sits on the geostationary platform Meteosat Second Generation and provides data every 15 min. This high temporal resolution and its high spatial coverage make it a useful instrument for monitoring a moving and evolving atmospheric hazard such as volcanic ash. We simulate observations from the SEVIRI sensor in channels centered at 10.8 and 12.0 μm to investigate whether a discernible signal always exists for thin ash clouds.

2 Method

We calculate the likely range of signals that could be produced by the same ash cloud (“the same” in terms of the same PSD, composition, mass concentration, cloud altitude, and geometric thickness) when present in a range of different atmospheres. We use this range to investigate whether reliable retrieval of properties such as mass concentration is possible for thin ash clouds on the basis of the observed absorption signal without scene-specific atmospheric information.

A dataset of 10,000 atmospheric profiles from the archived output of the European Centre for Medium-range Weather Forecasting short-term forecast model was used—their locations are shown in Fig. 1. For each profile location, the surface emissivity was taken from a global atlas of monthly mean surface emissivities.²⁵ The profiles are not selected to be geographically representative but are sampled to be as representative as possible of global and temporal variations in temperature and water vapor, see Ref. 26 for a full description of the dataset and the sampling techniques used. The frequency distribution for the ST and total column water vapor (TCWV) amounts represented in the dataset are shown in Fig. 2. The presence of large amounts of water vapor is known to sometimes make ash detection in IR data challenging.^{10,27} Since it is important to detect volcanic ash in the tropics, where both water vapor amount and ST are generally higher and there are a large number of active volcanoes, e.g., Mount Kelud in Indonesia, it is helpful to know whether detection of ash clouds is likely to be less (or more) reliable in IR data for these regions than for other regions. Profiles in the dataset with properties similar to a “tropical” atmosphere were, therefore, considered separately to other profiles, which were assigned to a “nontropical” group. “Tropical” profiles were defined as those with TCWV > 15 kg/m² and ST > 285 K, regardless of their geographical location. In addition, profiles were grouped according to whether they corresponded to day or night and land or sea, as shown in

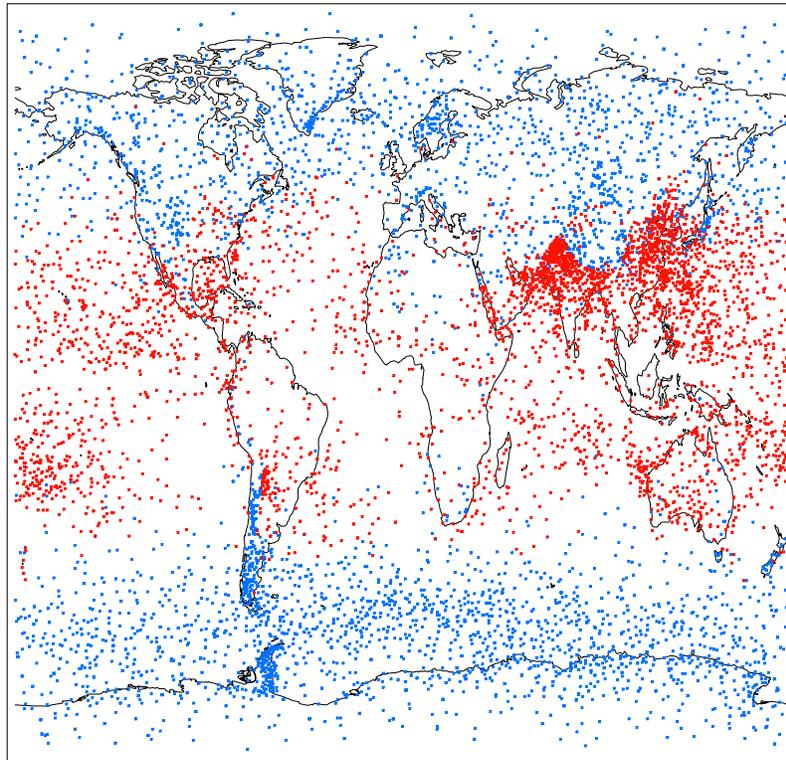


Fig. 1 Locations of the atmospheric profiles contained in the dataset of profiles sampled from the European Centre for Medium-range Weather Forecasting short-term forecast model archive. Sampling is designed to capture temporal and spatial variations in water vapor and temperature. The profiles are separated into a “tropical” group and a “nontropical” group, shown in red and blue, respectively, based on their atmospheric characteristics rather than their geographical location.

Table 1. 713 profiles were discarded from the original dataset of 10,000 because they corresponded to model grid cells containing both land and sea and this study focuses on sea and land cases, rather than coastal observations.

The radiative transfer model RTTOV v11²⁸ was used to simulate brightness temperatures (BTs) observed by the SEVIRI sensor, both under clear sky conditions and in the presence

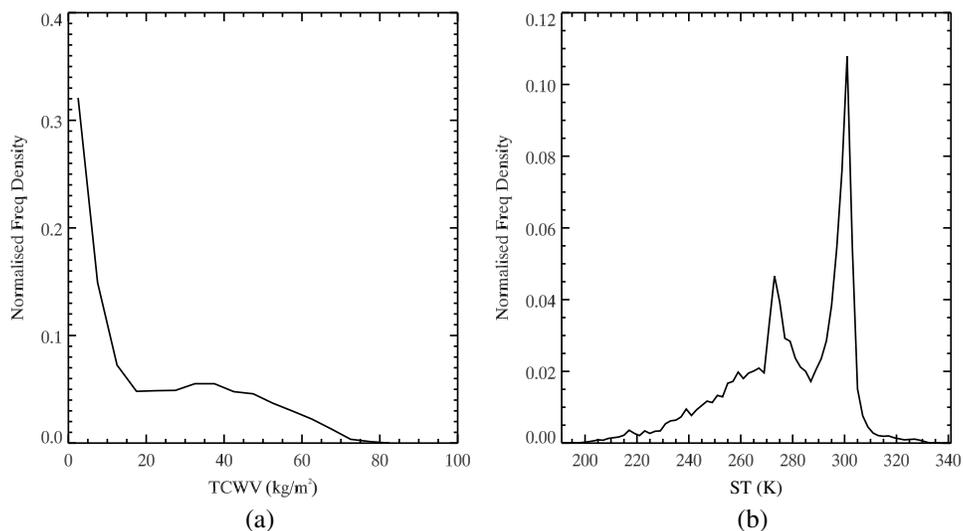


Fig. 2 Distribution of (a) total column water vapor, (b) surface temperature for atmospheric profiles in the dataset.

Table 1 The number of atmospheric profiles in each group.

	Number of profiles	
	Day	Night
Land, tropical	916	508
Sea, tropical	782	1818
Land, nontropical	916	1642
Sea, nontropical	1151	1554

of volcanic ash. Radiative transfer models simulate the attenuation of radiation emitted from, or reflected by, the surface of the Earth as it travels through the atmosphere to be recorded at the sensor. Ash clouds with a geometric thickness of 1 km, with ash concentrations ranging from 7 to 4000 $\mu\text{g}/\text{m}^3$ were simulated at 1 km intervals for altitudes between 1 and 10 km above the surface. Ash clouds with a geometric thickness of 500 m were also simulated, but the results were not markedly different to those for the 1-km clouds and so are not included here (this is not surprising since observations are sensitive to the column loading of ash rather than to the volumetric concentration—by using a fixed geometric thickness here, changes to the concentration are equivalent to changes to the column loading). The difference between the observations simulated for ash from a specific atmospheric profile and those simulated for clear sky using the same profile can be viewed as the sensitivity of the satellite observation to the presence of volcanic ash in that particular atmosphere, i.e., the ash signal modeled for that atmospheric profile.

Observations were simulated for channels centered at 10.8 and 12.0 μm , and both the single channel signal at 10.8 μm and the BTD signal were calculated, $\text{BTD} = \text{BT}(10.8 \mu\text{m}) - \text{BT}(12.0 \mu\text{m})$.

The signal is calculated for every ash cloud in every atmospheric profile. This means that many signals are calculated within each atmospheric group—corresponding to the different ash cloud altitudes, concentrations, and atmospheric profiles modeled within each group (the atmospheric groups are listed in Table 1). Within each atmospheric group, the simulated ash signals are grouped according to ash cloud altitude and mass concentration, and the mean and variance is calculated for the signals in each of these subgroups. This provides the altitude- and concentration- dependent mean ash signal and its variance for each atmospheric group.

The mean signal is plotted as a function of ash concentration and altitude to demonstrate whether a clear relationship exists between it and the ash concentration and to examine to what extent the altitude of the ash affects this relationship. The variance of the signal is also plotted as a function of ash concentration and altitude. This would be near zero everywhere if only the ash affected the signal (since the only differences between the simulations for a specific ash concentration and altitude are the atmospheric profiles in which the ash is modeled). The variance is, therefore, a measure of the sensitivity of the ash signal to nonash atmospheric effects. Nonzero values for the variance indicate that ash at that particular altitude, with that particular concentration, appears differently in IR observations when it is present in a different atmospheric column. A high variance in the ash signal modeled for a given concentration and altitude implies that the signal is highly sensitive to the atmospheric effects, while a narrow range implies that atmospheric effects can be largely ignored since this would show that the signal is not strongly affected by atmospheric effects and is likely to be more sensitive to properties of the ash such as mass concentration.

The optical properties used to simulate the ash observations, which are based on a lognormal PSD and the complex refractive indices measured for andesite by Ref. 29, see Fig. 3. The Pollack measurements for andesite have been used for interpretation of satellite observations of volcanic ash in other works;^{16,30} however, the composition of volcanic ash varies between eruptions and IR observations are known to be sensitive to this¹¹ and to the PSD of the ash grains.¹⁶ The PSD used here is a fit to observations recorded by aircraft following the eruption of Eyjafjallajökull in 2010.³¹ This study is not an investigation into the sensitivity of observations to these properties,

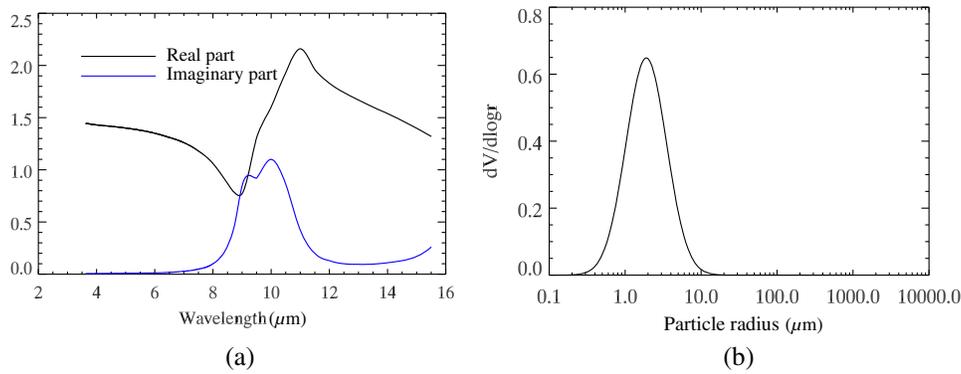


Fig. 3 Assumptions made for calculation of the optical properties of volcanic ash. (a) Complex refractive indices presented in Pollack (1973) for andesite and (b) particle size distribution.

but rather into the sensitivity of observations to atmospheric effects, and so it is appropriate that they remain fixed. It should be noted, however, that we have not investigated how the sensitivity of observations to atmospheric effects changes with ash composition or PSD. The results presented here, therefore, may not reflect sensitivity to atmospheric effects for IR observations of ash with a nonandesitic composition or with a different PSD.

3 Results

Passive observations from space-borne instruments are generally more sensitive to total column amounts of ash than to concentration by volume, as a dense but geometrically thin ash cloud may appear indistinguishable from a sparse geometrically thick cloud when viewed from directly above. Thus the results are presented here in terms of the total column amount of volcanic ash (all the simulated ash clouds are 1 km thick and so the concentration, in g/m^3 , is simply the total column amount divided by 1000). The lowest ash concentration to trigger a VAAC to be issued is $200 \mu\text{g}/\text{m}^3$, which corresponds to $0.2 \text{ g}/\text{m}^2$ for a 1-km thick ash cloud. Each of the atmospheric groups listed in Table 1 is plotted separately so that sensitivities can be compared for different types of atmosphere. Figure 4 shows how the mean signal in the $10.8 \mu\text{m}$ channel changes with ash concentration and altitude and Fig. 5 shows the same for the BT signal. Figure 6 is a plot of the variance of the signal, calculated for each concentration and altitude. The variance is a measure of the range of signals produced by the same ash in different atmospheres, even when the atmospheres share similar characteristics and so belong to the same group in Table 1. Figure 7 shows the variance for the BT signal and how the variance changes with ash concentration and altitude in the different atmospheric groups.

4 Interpretation and Discussion

The mean plots show the mean signals produced by ash under different atmospheric conditions and show that a different relationship exists between concentration, altitude, and the ash signal when the ash is present in a different type of atmosphere (Figs. 4 and 5). The variance plots indicate the certainty with which the relationships in the mean plots can be assumed to apply to ash when it is present in each type of atmosphere (Figs. 6 and 7). In this section, we discuss each of the figures in turn.

4.1 Mean Single Channel Signal

Ash is generally anticipated to absorb radiation around $10.8 \mu\text{m}$, and so is usually associated with a negative signal at $10.8 \mu\text{m}$ [i.e., a lower brightness temperature (BT) for ash than for clear sky]. However, Fig. 4 shows that the presence of ash in some atmospheres can actually increase the radiance received in this channel, giving a positive signal. Detection methods based on

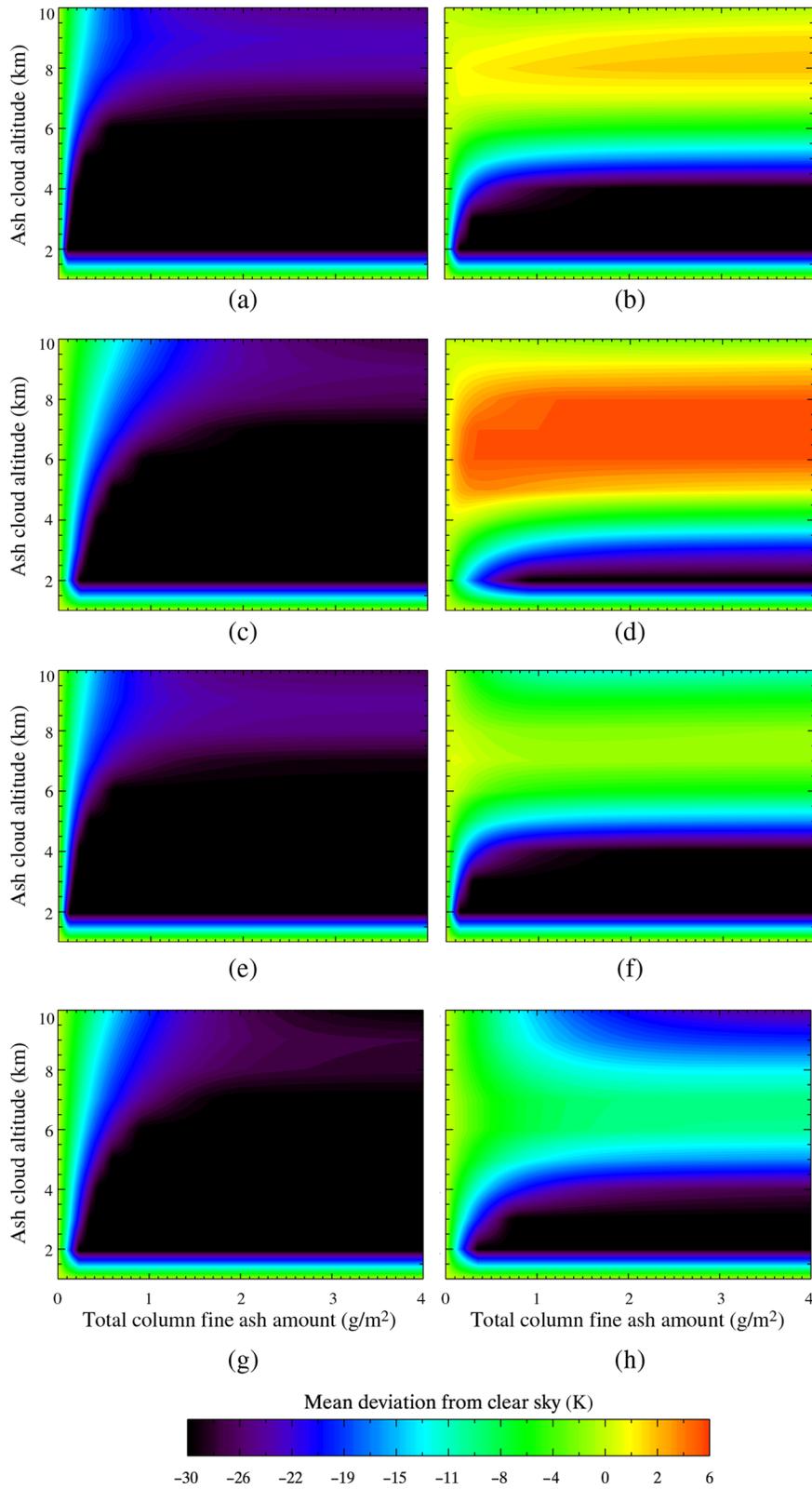


Fig. 4 The mean change in brightness temperature in the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) channel centered at $10.8 \mu\text{m}$ for a range of atmospheric profiles that occurs when ash is added [i.e., the brightness temperature (BT) signal for ash]. (a) Day, tropical, land; (b) day, nontropical, land; (c) night, tropical, land; (d) night, nontropical, land; (e) day, tropical, sea; (f) day, nontropical, sea; (g) night, tropical, sea; and (h) night, nontropical, sea.

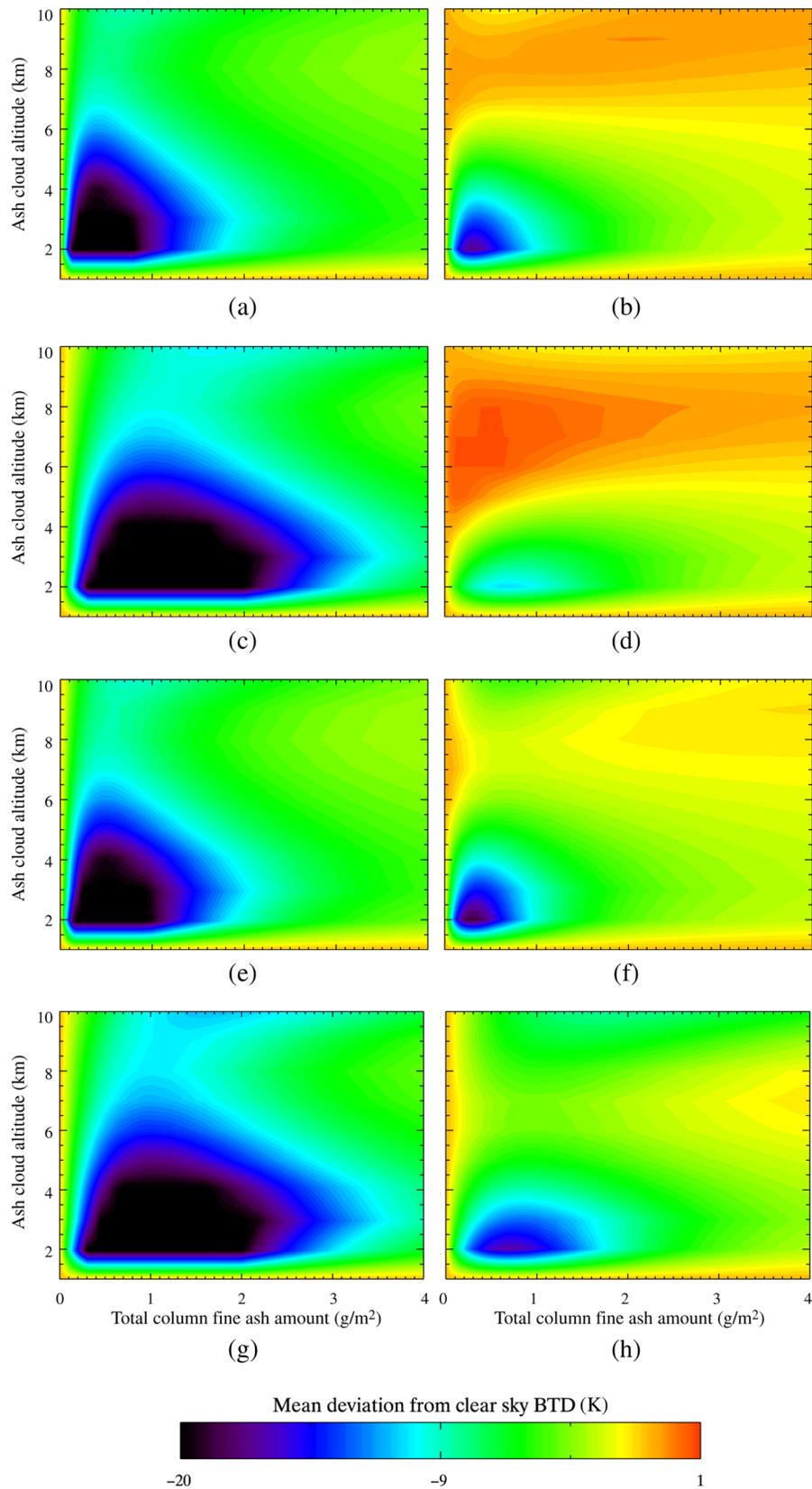


Fig. 5 The mean difference in brightness temperature difference (BTD) ($BT_{10.8\mu m} - BT_{12.0\mu m}$) for a range of atmospheric profiles that occurs when ash is added (i.e., the BTD signal for ash). (a) Day, tropical, land; (b) day, nontropical, land; (c) night, tropical, land; (d) night, nontropical, land; (e) day, tropical, sea; (f) day, nontropical, sea; (g) night, tropical, sea; and (h) night, nontropical, sea.

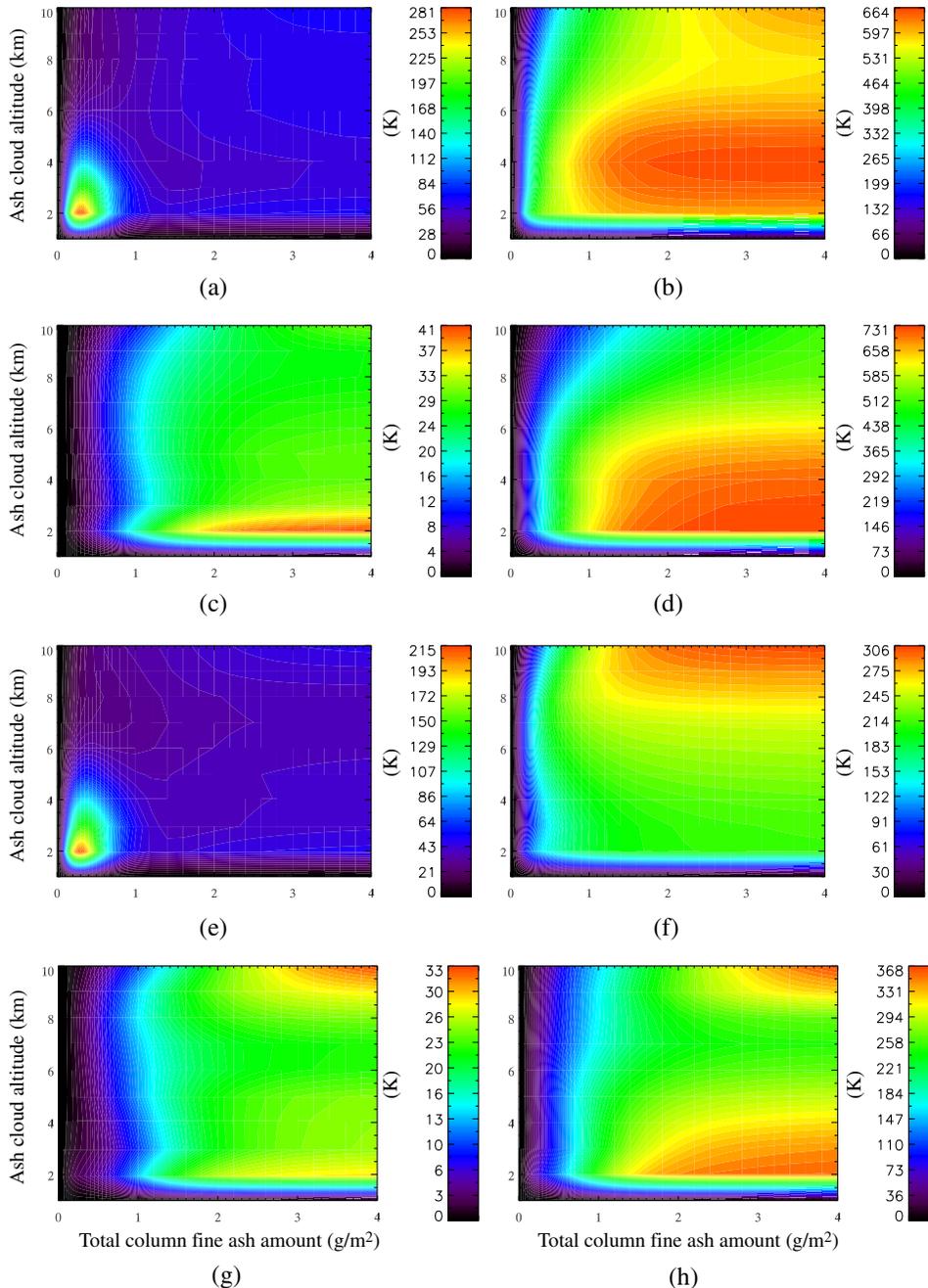


Fig. 6 The variance of the BT signal in the SEVIRI channel centered at $10.8 \mu\text{m}$. There are large differences between the variances found for different atmospheric profile groupings, and so individual color scales are used. (a) Day, tropical, land; (b) day, nontropical, land; (c) night, tropical, land; (d) night, nontropical, land; (e) day, tropical, sea; (f) day, nontropical, sea; (g) night, tropical, sea; and (h) night, nontropical, sea.

exploiting the absorption of ash at this wavelength are unlikely to be successful where Figure 4 shows a mean signal of 0 or greater. This is only seen when the ash is present over land in a nontropical atmosphere at altitudes greater than about 7 and 4 km for day and night, respectively (plots b and d) and, to a lesser extent, for very low concentrations of ash in a nontropical atmosphere over sea during the day (plot f). The positive signals in Fig. 4 are due to temperature inversions, whereby an ash cloud at altitude emits at a higher temperature than the underlying surface, causing the signal to become increasingly positive as ash concentration increases. The tropopause is a temperature inversion that is always present, with an altitude that is generally

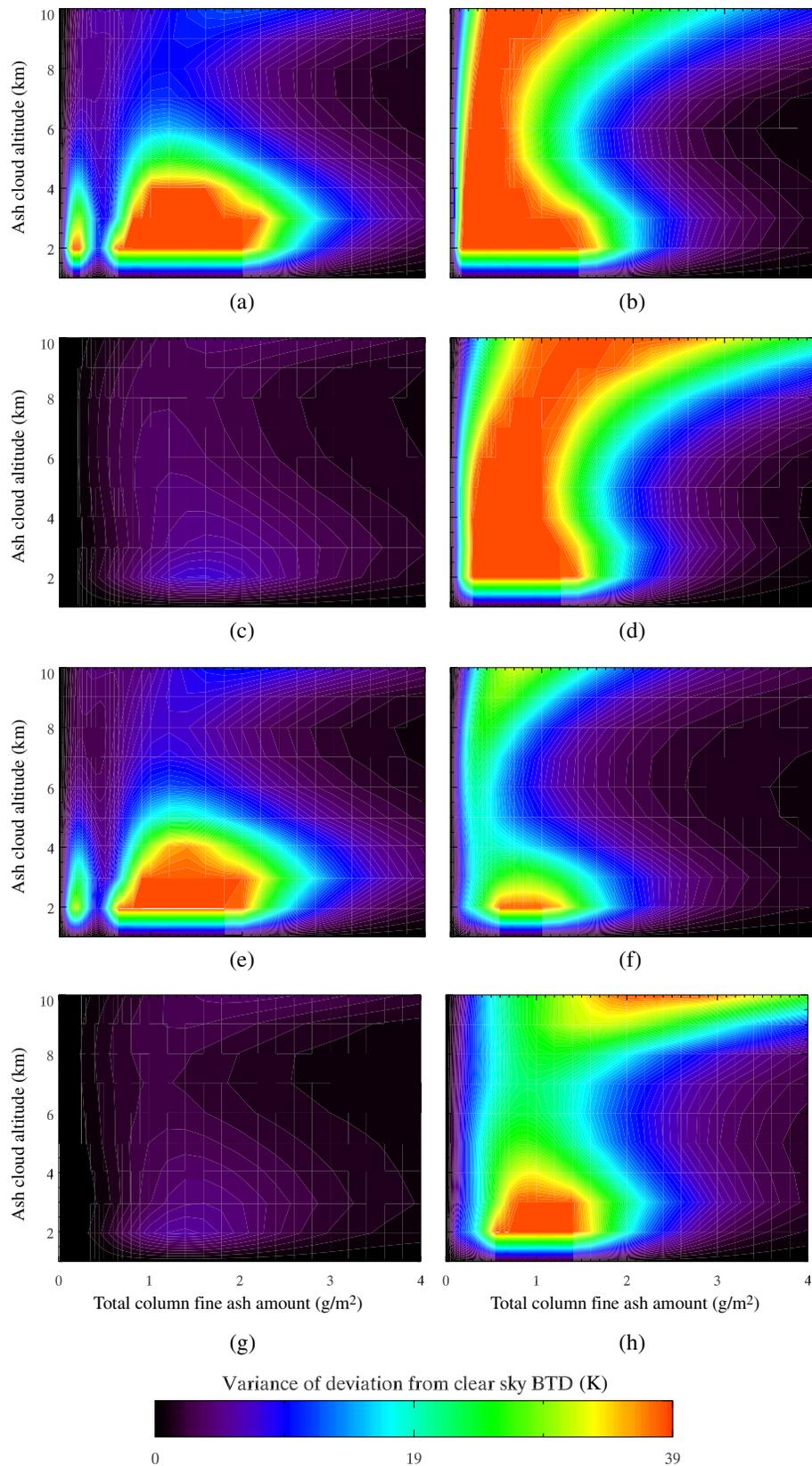


Fig. 7 The variance of the BT signal. There are large differences between the variances found for different atmospheric profile groupings, and so individual color scales are used. (a) Day, tropical, land; (b) day, nontropical, land; (c) night, tropical, land; (d) night, nontropical, land; (e) day, tropical, sea; (f) day, nontropical, sea; (g) night, tropical, sea; and (h) night, nontropical, sea.

lower where the surface and overlying air are cooler, which could explain why this effect is seen for ash at lower altitudes over land at night (plot d) than during the day (plot b) (since for warmer surfaces the effect requires the ash to be at a higher altitude). In tropical atmospheres, it is unlikely that the tropopause would be low enough for the modeled ash to be above it, and so it is not surprising that the effect is more pronounced in the nontropical results. Temperature inversions are more prevalent over land than sea, which could explain the relative prevalence of the positive signal in plots b, d, f, and h. The magnitude of the positive change for nontropical profiles over land at night is greater than during the day in plots b and d, suggesting that the altitude difference between the ash and the tropopause is greater for the night-time cases than for the day-time cases (and the air at the ash altitude is, therefore, relatively warmer). For both day and night, the magnitude of the positive change increases with ash amount. The mean signal for ash at higher altitudes in nontropical atmospheres over sea (plots f and h) is more difficult to interpret, particularly at night where the signal becomes less negative and then more negative as altitude increases (plot h). This could indicate the presence of some weaker temperature inversions in the dataset (weaker relative to those in the nontropical land groups). Figure 4 suggests that the single channel ash signal becomes less negative (and possibly less discernible) as ash altitude increases toward the tropopause, above which it may become positive. This altitude-dependency could make discrimination of ash from clear sky problematic when the altitude of either the ash or the tropopause is not known reliably. If our interpretation is correct and the altitude at which such effects come into play is related to the tropopause, then this could be a problem for ash detection at altitudes used by aviation, particularly over cold, dry land at night when the tropopause is likely to be lower. In contrast to nontropical atmospheres, Fig. 4 shows that ash in tropical atmospheres always produces a negative signal. At low concentrations, the signal becomes increasingly negative with increased concentration indicating absorption (plots a, c, e, and g). It should be noted that we are investigating variability in the signal used to discern ash from clear sky and are not considering meteorological clouds, which are likely to be more prevalent in tropical atmospheres where more water vapor is available.

4.2 Mean BTD Signal

A similar analysis can be made of the BTD signal for ash in the different atmospheric groups in Fig. 5. A negative signal corresponds to greater absorption at $10.8 \mu\text{m}$, relative to that at $12.0 \mu\text{m}$, than would be experienced by the same radiation emitted from the Earth and traveling through a column of clear sky atmosphere. Following the theory presented in Ref. 10 and many other radiative transfer-based studies, the BTD signal for ash should be increasingly negative with increasing ash concentration until optical saturation in both channels is approached. As for the single channel signal in Fig. 4, Fig. 5 shows the BTD signal to be stronger for tropical atmospheres (plots a, c, e, and g). For tropical atmospheres, the signal becomes stronger with increasing concentration at low concentrations and weakens as the concentration increases toward optical saturation, which occurs at lower concentrations during the day than at night. The signal becomes less negative as altitude increases, highlighting the importance of taking the ash cloud altitude into account (often available from dispersion models if not from direct observations) when interpreting the signal in terms of concentration. The situation is less clear for nontropical atmospheres (b, d, f, h). The signal is almost always negative in these atmospheres but is noticeably weaker than for the same ash concentrations and altitudes in tropical atmospheres. Temperature inversions in the nontropical dataset could explain this. If the ash is present above a temperature inversion (such as the tropopause), then it may emit radiation at both 10.8 and $12 \mu\text{m}$ at a higher temperature than the underlying surface. If the emissivity is higher at $10.8 \mu\text{m}$ than at $12 \mu\text{m}$, then this could offset the negative BTD signal. This demonstrates that the characteristics of the imaged atmosphere should be taken into account when a BTD signal is interpreted in terms of ash concentration. The mean signal for low concentrations of ash in nontropical atmospheres over land at night (plot d) becomes positive at altitudes around 6 to 8 km, possibly as a result of the effects discussed in Sec. 4.1 in relation to Fig. 4. The difference between the plots in Fig. 5 shows that the BTD signal is strongly affected by the atmosphere in which the ash is

present and that the same signal could correspond to a different ash concentration and/or altitude in a different atmosphere.

Both Figs. 4 and 5 suggest that, in theory, discrimination of ash from clear sky should be more straightforward in tropical atmospheres, where both the mean single channel and the mean BTM signal are stronger and consistently negative. This is surprising, given that several previous works have been shown that ash detection by means of identifying the ash absorption feature around 10 to 11 μm is challenging in moist atmospheres, see for example, Refs. 4 and 31. Water vapor, like water and ice clouds, absorbs radiation at 12 μm more strongly than at 10 to 11 μm , so its presence can weaken or even cancel out the BTM effect produced by the ash. In this work, however, the water vapor signature is already accounted for in the simulated clear sky observations, and it is the deviation from these clear sky observations that is plotted as the ash signal. A moist atmosphere that produces a strong positive BTM in a clear sky observation may continue to produce a positive BTM when ash is present, but if the ash has caused a reduction in the BTM, then the signal in Fig. 5 will be negative. Figures 4 and 5 show that sophisticated implementations of techniques focused on these signals for tropical atmospheres can be expected to be successful for discrimination of ash from clear sky when the water vapor specific to the imaged atmosphere is known, for example, from numerical weather predictions. Discrimination of ash from meteorological clouds, which are common in moist atmospheres, is more challenging. The problem of a potentially “masking” signal from meteorological clouds is the same as for water vapor, but clouds are generally not located in time and space with pixel-specific accuracy in numerical prediction models and are, therefore, more difficult to account for than water vapor.

4.3 Variance of the Signals

If observations are sensitive to atmospheric effects, then greater atmospheric variability within a group will correspond to greater variance in the signal for that group. Since the dataset of atmospheric profiles is representative of global variations in temperature and water vapor distributions, we can view those groups for which the variance of the signal is highest as corresponding to atmospheric conditions for which the characteristics of individual imaged atmospheric columns are likely to be most heterogeneous, and the sensitivity of the ash signal to atmospheric effects is likely to be high. Atmospheric groups for which the signal exhibits high variance, therefore, tell us the characteristics of atmospheres where the ash signal is most likely to be influenced by atmospheric effects.

4.3.1 Variance of the single channel signal

The variance of the single channel signal is vastly different for the different atmospheric profile groups and so different color scales are used for the individual plots in Fig. 6. For all atmospheric groups, the variance at most altitudes and for most concentrations is higher than the magnitude of the mean signal in Fig. 4. This means that even for ash altitudes, concentrations and atmospheric groups where the mean signal in Fig. 4 is negative, a positive signal is possible under some atmospheric conditions.

For tropical profiles (plots a, c, e, and g) in Fig. 6, the greatest variance in the signal is seen for ash present in daytime atmospheres over land (plot a). Atmospheric properties, such as temperature, are likely to vary more over land than over the sea, due to variations in emissivity and topography-driven turbulent mixing effects. Similarly, solar heating during the day is likely to be spatially and temporally heterogeneous over land surfaces as a result of slope and shade effects and differences in the thermal properties of the surface. The surface and near-surface conditions represented in the land atmospheric groups are, therefore, likely to vary more widely than those represented in the sea groups. The variance of the signal within an atmospheric group is a measure of the sensitivity of the signal to these properties when the ash is present in an atmosphere that is characteristic of that group. The greatest variance in the signal from ash in a daytime tropical atmosphere over land (plot a) occurs for low ash concentrations at low altitude, when the underlying surface is most likely to be “visible” to the sensor. The variance is very high for these conditions, meaning that the signal for low ash concentrations in a tropical atmosphere could change by a large amount for the same ash concentration, at the same altitude,

when the ash is present in an atmosphere with slightly different properties, even if it remains a tropical daytime atmosphere over land. This presents a challenge for interpretation of the signal and for calculation of the uncertainties that should accompany any interpretation. The next highest variance in the ash signal for tropical profiles is for ash in the daytime over sea (plot e). Again, the variance is highest for low concentrations at low altitude. It is surprising that the variance of the signal for ash in tropical atmospheres is only slightly lower when the ash is present over land than sea, since land is more heterogeneous than sea and this is reflected in the atmospheric profiles. It may be that the surface is obscured in the presence of large amounts of water vapor and low concentrations of ash at low altitudes then make the water vapor “visible” to the sensor. If this is the case, then variability in the amount of water vapor, or its distribution at low altitudes, could explain the high variance in the signal for ash. The signal is far less variable for low concentrations of ash in tropical atmospheres over both land and sea at night (plots c and g). In fact, for all concentrations and altitudes, ash in these atmospheric conditions results in the most consistent signal. Even in these conditions, however, the same concentration of ash at the same altitude can result in a range of signals that differ by tens of Kelvin, showing that interpretation of the signal in terms of ash concentration requires consideration of atmospheric effects.

Ash in nontropical atmospheres results in a single channel signal with far higher variance than the same ash in a tropical atmosphere. The highest variance is seen for ash over land (plots b and d), possibly reflecting the variance in the surfaces represented in the profiles. It is interesting that for low concentrations of ash, the variance increases with increasing concentration in all cases and that this effect becomes more pronounced with altitude (plots b, d, f, and h). This could show the ash signal response to a variable tropopause altitude as discussed in Sec. 4.1. The variance of the ash signal in all nontropical atmospheres is extremely high, reaching hundreds of Kelvin for concentrations of ash above about 1.5 g/m^2 . This shows that for nontropical atmospheres, it is essential that any interpretation of the single channel signal takes into account the atmospheric effects and does not assume the mean relationship in Fig. 4 to apply for ash in all atmospheres. The high variance seen in the individual plots in Fig. 6 shows that even when the atmosphere in which the ash is present is characterized as in this study, the mean relationships between ash concentration, altitude, and the single channel signal should not be assumed to be appropriate for all imaged atmospheres in the same category.

4.3.2 Variance of the BTD signal

The BTD signal appears more consistent than the single channel signal when the variances are compared (Fig. 7), which is encouraging because the BTD signal is widely used for ash detection and/or for retrieval of ash concentration and altitude. Figure 7 shows that differences in the atmosphere in which the ash is present, however, do cause the signal produced by the same concentration of ash at the same altitude, to vary by tens of Kelvin in most types of atmosphere. This means that a positive signal is possible for ash, even when it is present in atmospheric conditions where the mean BTD signal it produces is negative. The signal has the lowest variance when the ash is present in tropical atmospheres at night (plots c and g) and it is likely that the BTD signal in Figs. 5(c) and 5(g) can be realistically interpreted in terms of ash concentration and altitude with only a small contribution from atmospheric effects under such conditions. The signal produced by ash in tropical atmospheres during the day (plots a and e) is highly variable at lower altitudes and caution should be exercised if the BTD signal here is interpreted in terms of ash concentration and/or altitude through the assumption that the relationship follows the mean relationship shown in Figs. 5(a) and 5(e). Ash at higher altitudes produces a more consistent signal within each tropical atmospheric group, however, for concentrations between 1 and 2 g/m^2 , this approaches 10 K.

The variance of the BTD signal is higher for ash present in nontropical atmospheric conditions (plots b, d, f, and h) and is highest for low concentrations over land (plots b and d), probably reflecting the heterogeneity of the land surfaces that are “visible” to the sensor through low concentrations of ash. The BTD signal for ash in nontropical atmospheres varies by more than 10 K for ash in each of the grouped atmospheric conditions for all but the very

lowest concentrations, but it decreases again for higher concentrations as optical saturation is approached.

The fact that the variance for both signals is so different for the different atmospheric groups demonstrates that the uncertainty in any interpretation of the signal (for detection or for retrieval of ash properties) that is attributable to atmospheric effects should be considered in light of the characteristics of the imaged atmosphere.

5 Conclusions

If the altitude, composition, PSD, and concentration of volcanic ash are known, then the effect of the ash on an IR observation of otherwise clear sky cannot generally be predicted without taking into account the specific atmosphere in which the ash is present. The same consideration is, therefore, necessary for interpretation of an observed signal in terms of any of the above properties. The signal produced by the same ash concentration, at the same altitude, with the same composition can vary greatly when the ash is present in an atmosphere with different properties, even if the two atmospheres being compared share similar characteristics. This is particularly the case for ash in nontropical atmospheres over land. The high variance seen for the ash signals investigated here suggests that there exist a range of atmospheric conditions for which interpretation of either of these ash signals without consideration of the imaged atmosphere would be inappropriate, even in conditions where the mean signal is clearly related to ash altitude and/or to concentration. The BT signal is more consistent and more reliable than the single channel signal, however, the same ash concentration at the same altitude can have a very different effect on the observed BT when the ash is present in different atmospheric conditions, particularly over land and particularly during the day. The sensitivity of the signals to atmospheric effects varies between tropical and nontropical atmospheres. Interpretation of these signals should be associated with uncertainties that are attributable to atmospheric effects, which are dependent on the characteristics of the imaged atmosphere.

In nontropical atmospheres, and to a lesser extent in tropical atmospheres, the effect of the ash on both the BT in the 10.8 μm channel and on the observed BT may be to increase it from the clear sky value. This occurs for some ash concentrations that are considered hazardous in some nontropical atmospheres. Both the altitude of the ash and the properties of the atmosphere in which it is present are required in order to predict the sign of the change affected by the ash to both the single channel and the BT observations in nontropical atmospheres. Without this information, it is likely that some ash will not be discriminated since it is likely to correspond to a deviation from the observation for clear sky with the opposite sign to that which is expected.

Interpretation of either the single channel or the BT signal in terms of ash amount is only possible if the altitude of the ash is known, and the properties of the imaged atmosphere, such as water vapor amount and tropopause height, are accounted for. Hazardous ash concentrations may not be identified if these effects are not considered, as "medium" hazard levels of ash may give the same signal as "low" hazard levels of ash if the ash altitude or the properties of the atmosphere are different, even if the atmospheres are similarly "tropical" or "nontropical."

The BT and single channel signals for ash can only be interpreted in terms of ash concentration if the ash altitude is known, and the high variance in both signals evident in most atmospheric conditions for nearly all altitudes shows that ignoring atmospheric effects could lead to very high uncertainties associated with such interpretations. Since the properties of the ash modeled for calculation of the signal mean and variance were identical, the spread seen in the signals is wholly attributable to atmospheric effects. It should, therefore, be possible to reduce uncertainties by accounting for the imaged atmosphere, for example, from numerical weather predictions for the scene.

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References

1. T. J. Casadevall, "The 1989–1990 eruption of Mount Redoubt Volcano, Alaska: impacts on aircraft operations," *J. Volcanol. Geotherm. Res.* **62**, 301–316 (1994).
2. G. N. Petersen, "A short meteorological overview of the Eyjafjallajökull eruption 14 April–23 May 2010," *Weather* **65**, 203–207.
3. IATA, "The impact of Eyjafjallajökull's volcanic ash plume. Economic Briefing May 2010," (2010).
4. S. A. Carn et al., "Volcanic eruption detection by the Total Ozone Mapping Spectrometer (TOMS) instruments: a 22-year record of sulphur dioxide and ash emissions," in *Volcanic Degassing*, Vol. **213**, pp. 177–202, Geological Society, London (2003).
5. I. M. Watson et al., "Thermal infrared remote sensing of volcanic emissions using the moderate resolution imaging spectroradiometer," *J. Volcanol. Geotherm. Res.* **135**, 75–89 (2004).
6. M. J. Pavolonis et al., "A daytime compliment to the reverse absorption technique for improved automated detection of volcanic ash," *J. Atmos. Oceanic Technol.* **23**, 1422–1444 (2006).
7. L. Clarisse et al., "A correlation method for volcanic ash detection using hyperspectral infrared measurements," *Geophys. Res. Lett.* **37**, L19806 (2010).
8. A. J. Prata and A. T. Prata, "Eyjafjallajökull volcanic ash concentrations determined using Spin Enhanced Visible and Infrared Imager measurements," *J. Geophys. Res.* **117**, D20 (2012).
9. A. Tupper et al., "An evaluation of volcanic cloud detection techniques during recent significant eruptions in the western 'Ring of Fire'," *Remote Sens. Environ.* **91**, 27–46 (2004).
10. J. J. Simpson et al., "Failures in detecting volcanic ash from a satellite-based technique," *Remote Sens. Environ.* **72**, 191–217 (2000).
11. S. Mackie, S. Millington, and I. M. Watson, "How assumed composition affects interpretation of observations of volcanic ash," *Meteorol. Appl.* **21**, 20–29 (2014).
12. A. J. Prata, "Infrared radiative transfer calculations for volcanic ash clouds," *Geophys. Res. Lett.* **16**, 1293–1296 (1989).
13. S. Wen and W. I. Rose, "Retrieval of sizes and total masses of particles in volcanic clouds using AVHRR bands 4 and 5," *J. Geophys. Res.* **99**(D3), 5421–5431 (1994).
14. S. Corradini, L. Merucci, and F. Arnau, "Volcanic ash cloud properties: comparison between MODIS satellite retrievals and FALL3D transport model," *IEEE Geosci. Remote Sens. Lett.* **8**(2), 248–252 (2011).
15. M. J. Pavolonis, "Advances in extracting cloud composition information from spaceborne infrared radiances—a robust alternative to brightness temperatures. Part I: Theory," *J. Appl. Meteorol. Climatol.* **49**, 1992–2012 (2010).
16. P. N. Francis, M. C. Cooke, and R. W. Saunders, "Retrieval of physical properties of volcanic ash using Meteosat: a case study from the 2010 Eyjafjallajökull eruption," *J. Geophys. Res.* **117**(D00U09) (2012).
17. L. Clarisse et al., "A unified approach to infrared aerosol remote sensing and type specification," *Atmos. Chem. Phys.* **13**, 2195–2221 (2013).
18. S. Mackie and M. Watson, "Probabilistic detection of volcanic ash using a Bayesian approach," *J. Geophys. Res.* **119**(5), 2409–2428 (2014).
19. T. Yu, W. I. Rose, and A. J. Prata, "Atmospheric correction for satellite-based volcanic ash mapping and retrievals using "split-window" IR data from GOES and AVHRR," *J. Geophys. Res.* **107**(D16), AAC 10-1–AAC 10-19 (2002).
20. B. J. Devenish et al., "A study of the arrival over the United Kingdom in April 2010 of the Eyjafjallajökull ash cloud using ground-based lidar and numerical simulations," *Atmos. Environ.* **48**, 152–164 (2012).
21. H. Flentje et al., "The Eyjafjallajökull eruption in April 2010- detection of volcanic plume using in-situ measurements, ozone sondes and lidar-ceilometer profiles," *Atmos. Chem. Phys.* **10**, 10085–10092 (2010).
22. D. M. Winker et al., "CALIOP observations of the transport of ash from the Eyjafjallajökull volcano in April 2010," *J. Geophys. Res.* **117**, D20 (2012).

23. Volcanic Ash Advisory Service, London, "Volcanic ash concentration forecasts," 31 March 2011, http://www.metoffice.gov.uk/media/pdf/j/3/Changes_To_Ash_Concentration_Forecasts_V12web.pdf accessed (28 January 2015).
24. S. C. Millington et al., "Simulated volcanic ash imagery: A method to compare NAME ash concentration forecasts with SEVIRI imagery for the Eyjafjallajökull eruption in 2010," *J. Geophys. Res.* **117**, D00U17 (2012).
25. E. Borbas and B. Ruston, "The RTTOV UW iremis IR land surface emissivity module," Satellite Application Facility for Numerical Weather Prediction, Associate Scientist Mission Report, Mission No. AS09-04, NWP-SAF-MO-VS-042, v1 (2010).
26. F. Chevallier, S. Di Michele, and A. P. McNally, "Diverse profile datasets from the ECMWF 91-level short-range forecasts," EUMETSAT NWP-SAF Doc ID: NWPSAF-EC-TR-010 1.0 (2006).
27. A. Prata et al., "Comments on "Failures in detecting volcanic ash from a satellite-based technique,"" *Remote Sens. Environ.* **78**, 341–346 (2001).
28. R. Saunders et al., "RTTOV-11 science and validation report," EUMETSAT NWP-SAF Doc ID: NWPSAF-MO-TV-032 1.1 (2013).
29. J. B. Pollack, O. B. Toon, and B. N. Khare, "Optical properties of some terrestrial rocks and glasses," *Icarus* **19**, 372–389 (1973).
30. A. Stohl et al., "Determination of time- and height-resolved volcanic ash emissions and their use for quantitative ash dispersion modelling: the 2010 Eyjafjallajökull eruption," *Atmos. Chem. Phys.* **11**, 4333–4351 (2011).
31. B. Johnson et al., "In situ observations of volcanic ash clouds from the FAAM aircraft during the eruption of Eyjafjallajökull in 2010," *J. Geophys. Res.* **117**, D00U24 (2012).

Shona Mackie achieved an MSc in physics from the University of Bristol and an MSc in glaciology from Aberystwyth University before investigating remote sensing techniques for cloud detection at the University of Edinburgh to achieve a PhD in 2009. Since then, she has worked on wind forecasting for renewable energy applications and more recently on methods for monitoring and modeling the dispersion of airborne volcanic ash.

Matthew Watson has a BSc in chemistry and an MSc in physics from the University of Leicester and completed his PhD in remote sensing of tropospheric volcanic plumes at the University of Cambridge in 2000. He completed a postdoctoral fellowship at Michigan Tech working on volcanic ash clouds, before moving to Bristol in 2004. He is currently a reader and works on remote quantification of volcanic emissions used for physical volcanology and environmental and climatological applications.