OBSERVING VOLCANIC PLUMES USING SINGULAR VECTOR DECOMPOSITION OF MIPAS SPECTRA

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ABSTRACT

A simple flagging of MIPAS spectra based on ratios of radiances in a narrow section of the A-Band (685–970 cm^{-1}) can mark suspected volcanic plumes when their signal is strong and uncontaminated, but is not hugely sensitive to weaker signals. Using singular vector decomposition (SVD) to remove modes of spectral variability due to normal atmospheric conditions, a more accurate indicator of volcanic ash plumes in the Oxford MIPAS cloud retrieval can be obtained. As time progresses, the strength of the signal can fall off, but it is still possible to be tracked. SVD also allows one to obtain information about the spectral signature of a specific eruption. Since individual events have different signatures, once a training set has been obtained, signals from different events can be distinguished.

Key words: Volcanic ash; MIPAS; SVD.

1. INTRODUCTION

In recent years, detection of volcanic ash has become a topic of increased interest as the eruption of Eyjafjallajökull highlighted its hazards to aviation [1]. Spectral signatures from SO_2 and stratospheric H_2SO_4 aerosol are relatively simple to characterise, but ash signatures are much more problematic, depending on mineral content, size and shape, which vary dramatically between eruptions, and as plumes age.

1.1. MIPAS cloud retrievals

Oxford has has a microphysical cloud parameters retrieval from MIPAS data which is described in [2]. Retrievals are provided online at `http://www.atm.ox.ac.uk/group/mipas`. The method does not attempt to characterise the type of cloud seen. Just its optical thickness, cloud top height, and cloud top temperature. This means that the method also sees aerosols, including volcanic ash, and stratospheric H_2SO_4.

1.2. Simple plume flagging using broadband channel ratios

Using simple flagging of radiance ratios, strong volcanic signals can be detected. Fig. 1 shows a volcanic plume from the eruption of Puyehue-Cordón Caulle, Chile in June 2010 standing out as a green signal against the blue background of normal clouds.

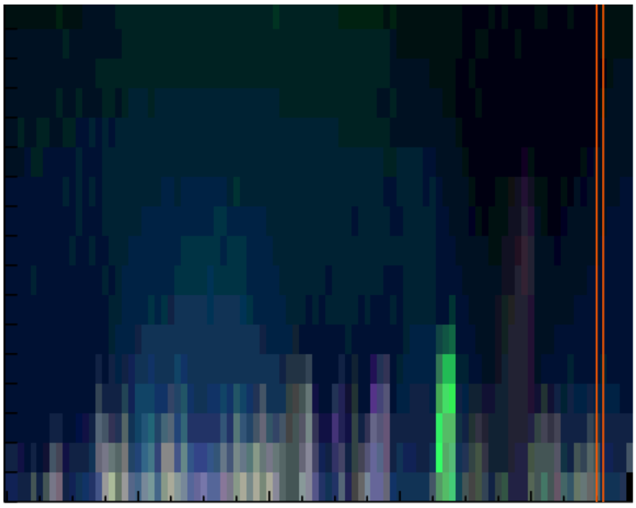

Figure 1. MIPAS false colour image of orbit 48522. Red is given by 12.02 µm, green by 10.45 µm, and blue by 8.7 µm. A volcanic plume from the eruption of Puyehue-Cordón Caulle shows up green against the more blue cloud signals.

Plumes can be flagged roughly by inspecting the ratio of radiances from different areas of the MIPAS continuum. For ash, it was found that an appropriate flag is:

$$\frac{R_{(800\text{–}830\ \mathrm{cm}^{-1})}}{R_{(935\text{–}960\ \mathrm{cm}^{-1})}} < 1.3, \quad (1)$$

where R is the mean continuum radiance between the indicated wavenumbers. This flag correctly identifies many areas where volcanic output from the Puyehue and Nabro eruptions was observed in MIPAS measurements. It is particularly good at picking out strong signals, but in ar-

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eas with less clear ash loadings, the method is not effective.

2. SINGULAR VECTOR DECOMPOSITION

Singular vector decomposition (SVD) is a method of characterising the modes of variability in a series of vectors. For MIPAS data, we take a set of spectra, $[\mathbf{R}_0, \mathbf{R}_1, \ldots, \mathbf{R}_n]$, as an SVD training set. Any spectra, $\mathbf{R}_j$, from this set can be written as a linear combination of the calculated singular vectors:

$$\mathbf{R}_j = \sum_i \lambda_{i,j}\, \mathbf{v}_i, \qquad (2)$$

where $\mathbf{v}_i$ is the i-th singular vector, and $\lambda_{i,j}$ is its weighting. Since most of the variability can be contained with the first few vectors, and the remainder can be disgarded (truncation of the series after 5 terms was able to capture almost all variability). A full description of SVD is given in [3].

2.1. Method

An approach similar to [4] is adopted, although in that case simulated radiances and not measured atmospheric spectra were used. MIPAS spectra taken from a specific latitude and altitude range, before a volcanic eruption, can be used to build a training set of singular vectors that contain the pre-eruption spectral variability. These will contain the variability of clear (i.e. non-cloudy and cloudy) atmospheres, but we assume they do not contain any volcanic signal. As such we expect that volcanic signals in the spectra will not be well represented by this set of singular vectors, leading to large characteristic residues.

For measurements taken after an eruption, the radiance flag given in Eq. 1 can find cases with a strong volcanic signal. These signatures are then fitted with the 'clear' SV, and the residuals from the fit recorded. Several days worth of these residuals are used to obtain a new set of SVs which contain the principal orthogonal signals for volcanic plumes.

We now have a method for recreating all measurements as a linear combination of 'clear' and 'volcanic' modes of variability:

$$\mathbf{R} = \sum_{i=0,4} \lambda_{\text{clear},i}\, \mathbf{v}_{\text{clear},i} + \sum_{k=0,1} \lambda_{\text{volc},k}\, \mathbf{v}_{\text{volc},k}. \qquad (3)$$

If a significant value of λ_{volc} is required in order to fit any scene, then the probability of a volcanic plume being present is high.

Fig. 2 shows example fits for seven days either side of the Nabro eruption for the most important singular vectors. Fits were obtained by linear regression of the MIPAS spectra using Eq. 3. For the first clear singular vector, $\mathbf{v}_{\text{clear},0}$ (which is the principle mode of variability), $\lambda_{\text{clear},0}$ clearly shows the diurnal cycle as MIPAS measurements (in chronological order) are taken. The second vector, $\mathbf{v}_{\text{clear},1}$, also contains weaker diurnal signals, but mainly characterises clouds (at points with strong peaks in $\lambda_{\text{clear},1}$).

The first volcanic singular vector is not required in order to replicate the MIPAS signal measured before the eruption (i.e. $\lambda_{\text{volc},0} \simeq 0$ prior to the eruption). Afterwards, peaks match the originally flagged profiles, marked with arrows (as would be expected since these were used to train $\mathbf{v}_{\text{volc}}$), but additional areas, not picked up by the flag are also marked. These are weaker volcanic signals that are now able to be seen. Notice also that volcanic signals also match areas where $\lambda_{\text{clear},1}$ has indicated that clouds are present. This is consistent since clouds and aerosols are both obstructions to MIPAS viewing through to dark space.

2.2. Puyehue-Cordón Caulle eruption, June 2011

The Puyehue-Cordón Caulle volcanic complex is located in Chile, and forms part of the Andes. Seismic activity was detected begining in late April 2011, and were followed by explosions of 4th June that produced a volcanic plume of gas and ash. Volcanic activity continued for the next few weeks, and the plume spread the circumference of the globe, leading to cancellation of flights in Argentina, Uruguay, Brazil, Australia, and New Zealand.

Fig. 3 shows a comparison of the characteristic volcanic signals from the Puyehue-Cordón and Nabro eruptions. Clear differences between the two signals are evident, especially a peaking at the very far end of the A-band at much higher wavenumbers than in Nabro, where the peak is around 900 cm^{-1}. In the B-band, there is also far less structure. The Puyehue-Cordón eruption did not emit large quanitities of SO_2, but a comparison between the spacial extent of the volcanic signature measured by this method, and an IASI SO_2 retrieval [5], as presented in Fig. 4 shows good agreement, providing confidence that the flag is reliable.

2.3. Nabro eruption, June 2011

Nabro, located in the Afar depression in Eritrea, is a stratovolcano. With very little preceeding seismic activity, a volcanic plume was emitted beginning on 12th June 2011. Plumes spread rapidly over central Asia, and were seen for more than a month following the eruption.

In contrast to the Puyehue-Cordón Caulle eruption, a huge amount of SO_2 was emitted by Nabro. Comparing the profiles from the two eruptions in Fig. 3, the ν_1 (1152 cm^{-1}) and ν_3 (1362 cm^{-1}) absorption bands

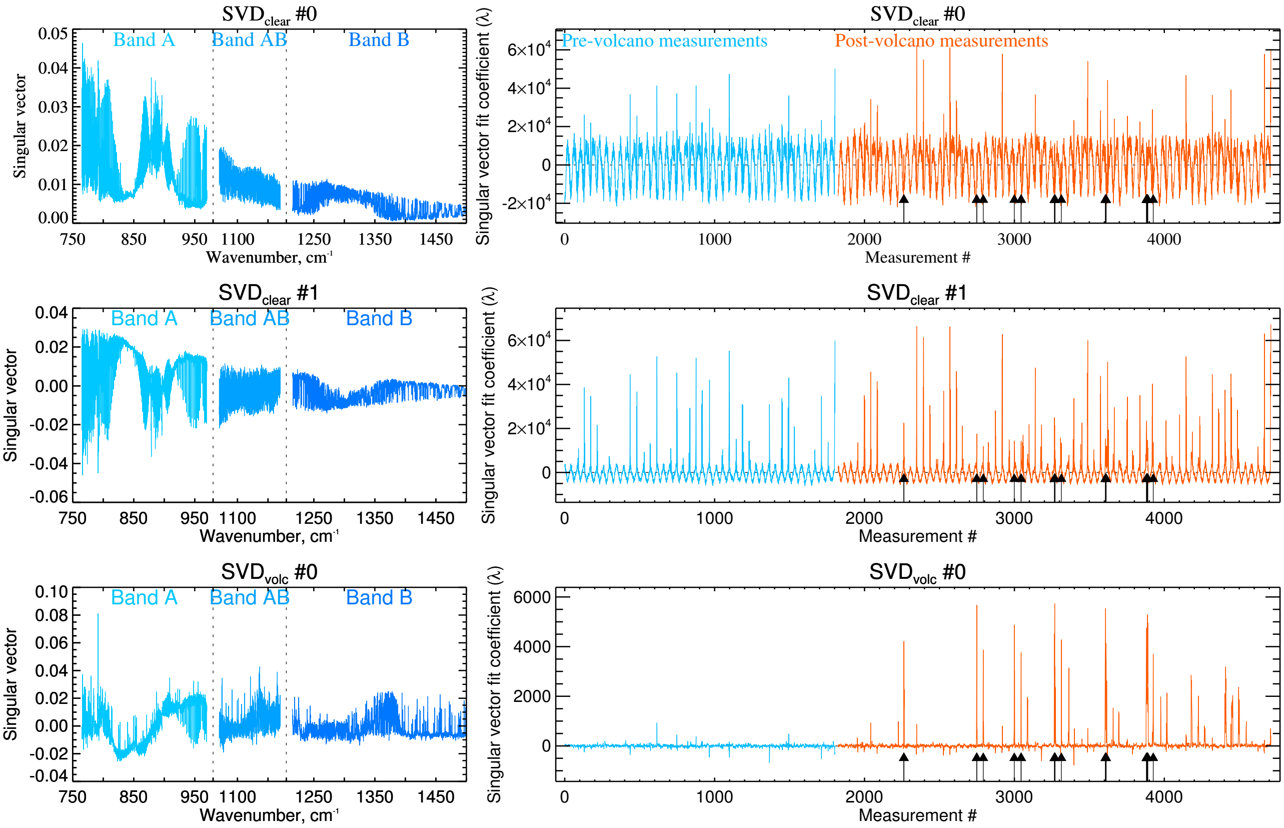

Figure 2. The first two 'clear' singular vectors, and the first 'volcanic' singular vector calculated for the Nabro eruption, for measurements with tangent height of 15 ± 1.5 km. The left hand plots show $\mathbf{v}$*, and the right had plots the corresponding values of λ fitted for MIPAS measurements, in chronological order. Arrows show the points at which volcanic signals were flagged using the mask given in Eq. 1. The blue section of the plot shows measurements before the eruption, and orange shows measurements taken after the eruption.*

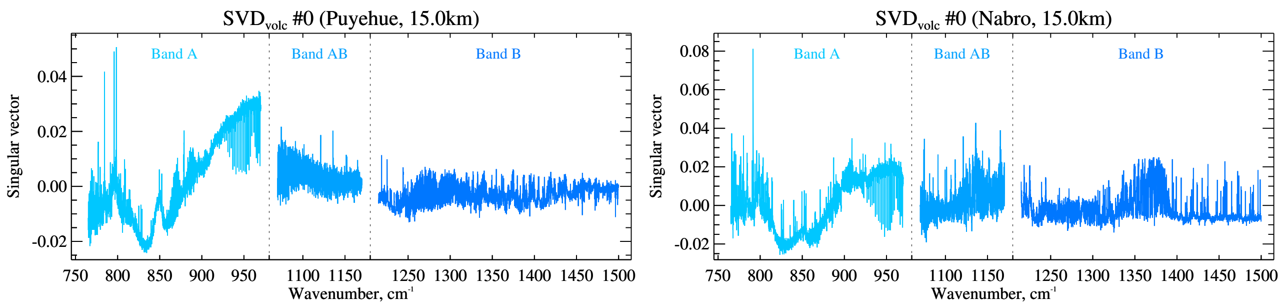

Figure 3. Comparing the first volcanic singular vectors at 15 ± 1.5 km from the Puyehue-Cordón Caulle, and Nabro eruptions. Clear differences between the spectral signatures from the two eruptions can been seen, as discussed in the main text.

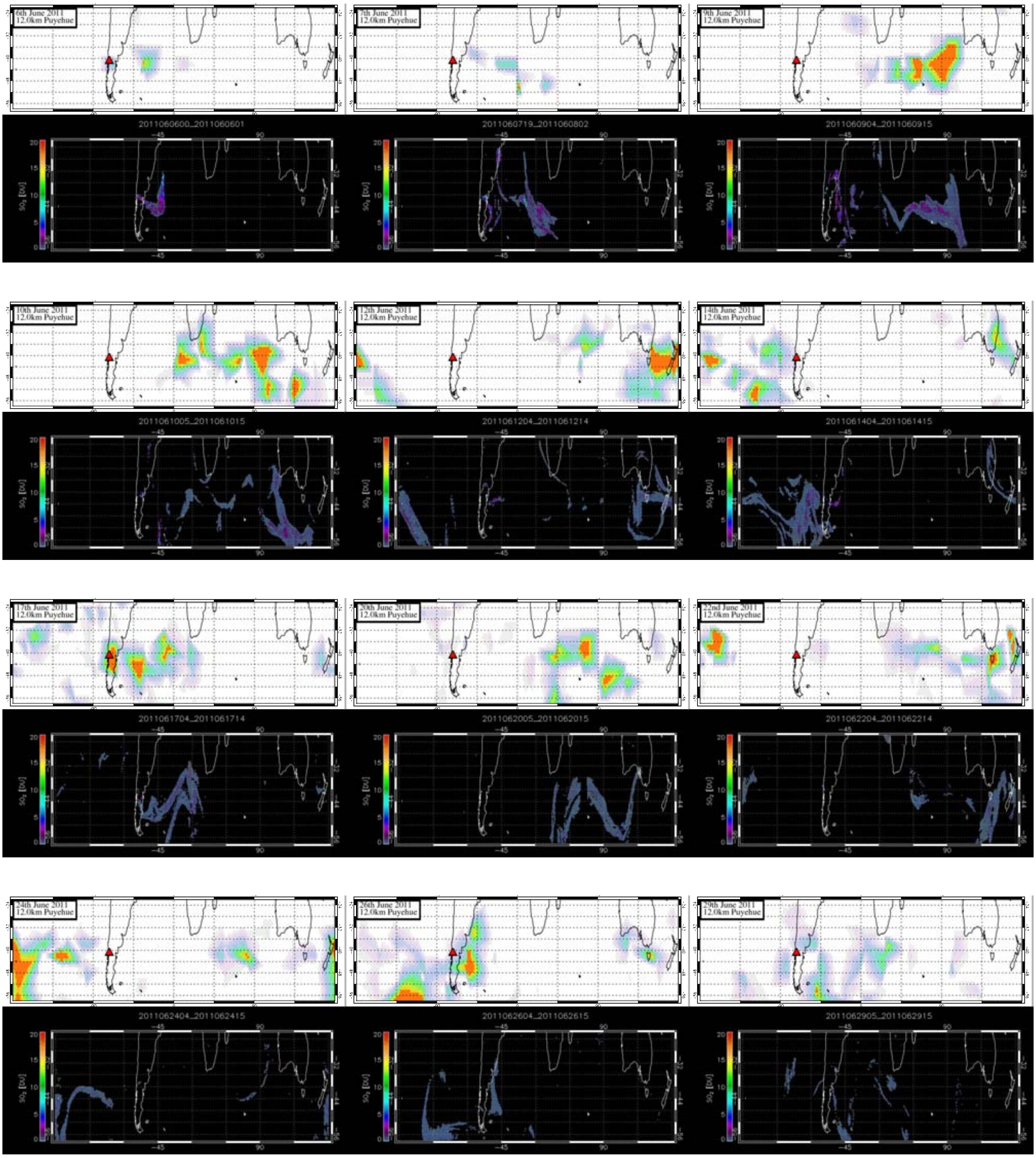

Figure 4. Comparing SVD MIPAS plume locations with an IASA SO_2 retrieval described in [5]. Spatial agreement is extremely coherent, despite the fact that ash and SO_2 plumes do not necessarily have to coincide.

of SO_2 can clearly be seen in the Nabro signal, but not the other. As the eruption continued, recalculating the volcanic singular vectors showed a gradual fall off in the SO_2 signal, which was replaced with an signal similar to H_2SO_4 aerosol modelled using data from [6]. This suggests that the SVD method will be sensitive enough to detect the evolution of stratospheric SO_2 into sulphate aerosol.

3. CONCLUSIONS

Using SVD, a more sensitive test for volcanic ash and gases is possible than using simple radiance flags, that do not make full use of the large amount of spectral data provided by FTS instruments such as MIPAS. The mixing of the plume with other signals is no longer a significant issue, since the separation of the volcanic signal from other signals is the entire purpose of the method. The first volcanic singular vector, $\mathbf{v}_{\mathrm{volc},0}$ contains the vast majority of useful information about the spectral signature of an eruption. Information about the composition of specific eruptions can be obtained.

However, singular vectors do not show signals from an individual species or aerosol type. They show the variability of any combined signals that are correlated. Disentangling what is going on is non-trivial. Information about the spectral evolution of a plume can be obtained, but each new eruption requires a new training set, and so this method in its current form would not be suitable for real-time flagging of volcanic plumes.

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