Observing volcanic plumes using singular vector decomposition of MIPAS spectra

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Abstract

A simple cloud index (CI) 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 can be obtained. Volcanic spectral signatures with a much smaller signal can be tracked than is possible using the CI method.

Since individual events have different spectral signatures, once a training set has been obtained, signals from different events can be distinguished. Time evolution of the spectral signals can also be observed. Results from analysis of two eruptions from June 2011, the Puyehue-Cordon Caulle eruption in Chile, and the Nabro eruption in Eritrea are presented. Using the Oxford MIPAS cloud retrieval, properties of the plume such as extinction, top-height, and top-temperature can be obtained.

Background

Volcanic plumes formed from explosive eruptions are generally a combination of gases (such as SO_2) and aerosol particles (mainly silicate material and sulphate). Interest in detection of atmospheric volcanic ash is high for several reasons including being a hazard to aircraft, altering the short term global radiation balance, and human health issues.

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

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

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

Method

SVD is a method of characterising the modes of variability in a series of vectors. Any spectra, $\mathbf{R}_j$, which is added to a training set can be written as a linear combination of the calculated singular vectors (SV):

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

where $\mathbf{v}_i$ is the i-th singular vector, and $\lambda_{i,j}$ is its weighting.

An approach similar to Hurley et al. [2009] is adopted, although in that case simulated radiances and not measured atmospheric spectra were used. First, several days of MIPAS spectra at a specific latitude and altitude are taken as a 'clean atmosphere' training set. These measurements are expected to include both clear and cloudy scenes, but no volcanic signal. Singular vectors, $\mathbf{v}_{\mathrm{clean},i}$, are fitted using the method given by Press et al. [1992]. These SV can be expected to fit any 'clean' scene. There are as many SV as measurements used in the training set, but principal modes of variation are found in the first few terms, allowing the sum in Eq. 2 to be truncated after five terms.

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 'clean' 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 'clean' and 'volcanic' modes of variability:

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

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. 1 shows example fits for seven days either side of the Nabro eruption for the most important singular vectors. Weaker volcanic signals that were not picked up by the original test have been flagged using the SVD method. Fig. 2 shows the evolution of the Nabro volcanic plume at an altitude of 15 ± 1.5 km for the month after the eruption.

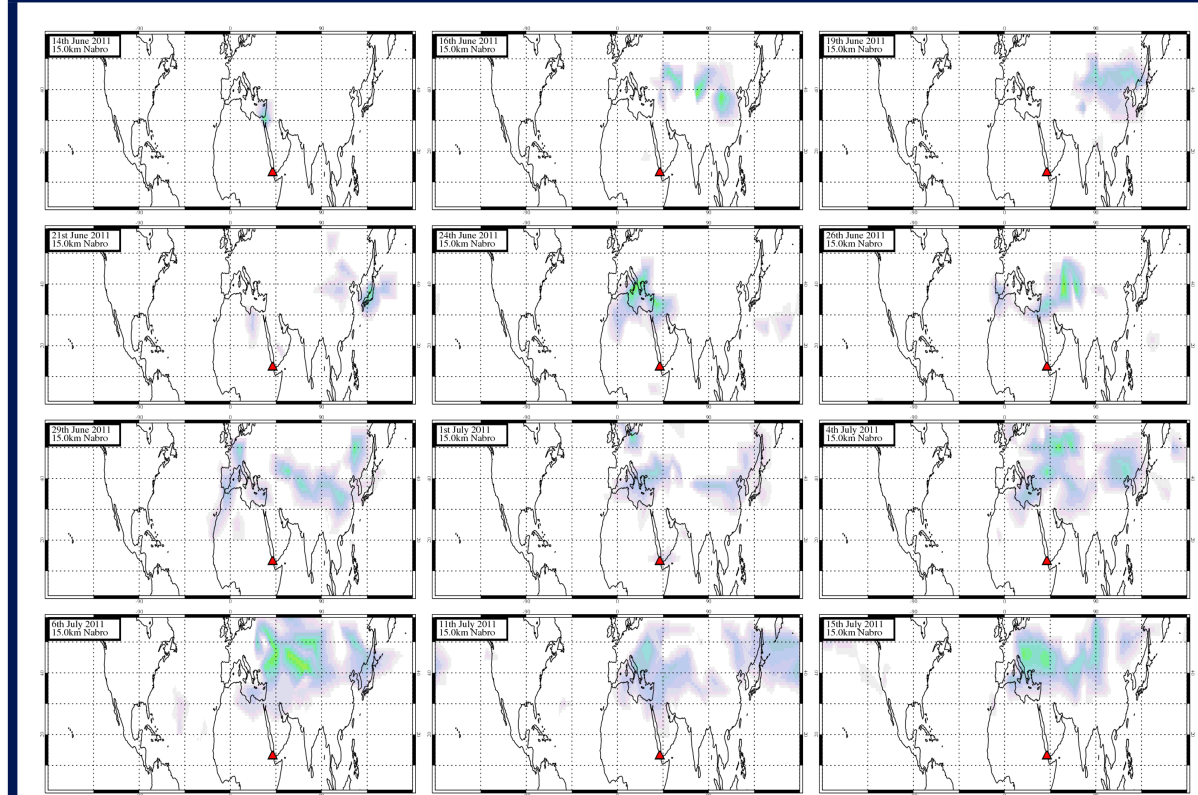

Figure 2: Snapshots showing time evolution of the plume from the Nabro eruption at an altitude of 15 ± 1.5 km. The scale is arbitrary, since it is the strength of the first volcanic SV. MIPAS is a limb viewing instrument, so does not have high horizontal resolution, however the area in which the plume is flagged agrees well with reports from other sources.

Plume variation

A useful outcome of the method is the ability to inspect differences between different eruptions, and also between the same eruptions at different time periods. Fig. 3 compares signals from the Puyehue and Nabro eruptions. The peak in the Nabro signal at around 900 cm^{-1} is not present in the Puyehue volcanic singular vectors, suggesting a different aerosol size distribution. The Nabro signal (for periods soon after the eruption) also contains strong SO_2 signals, not present in the Puyehue signal, consistent with the fact that Nabro was well known to be one of the largest injections of SO_2 into the stratosphere since the eruption of Mount Pinatubo in 1991.

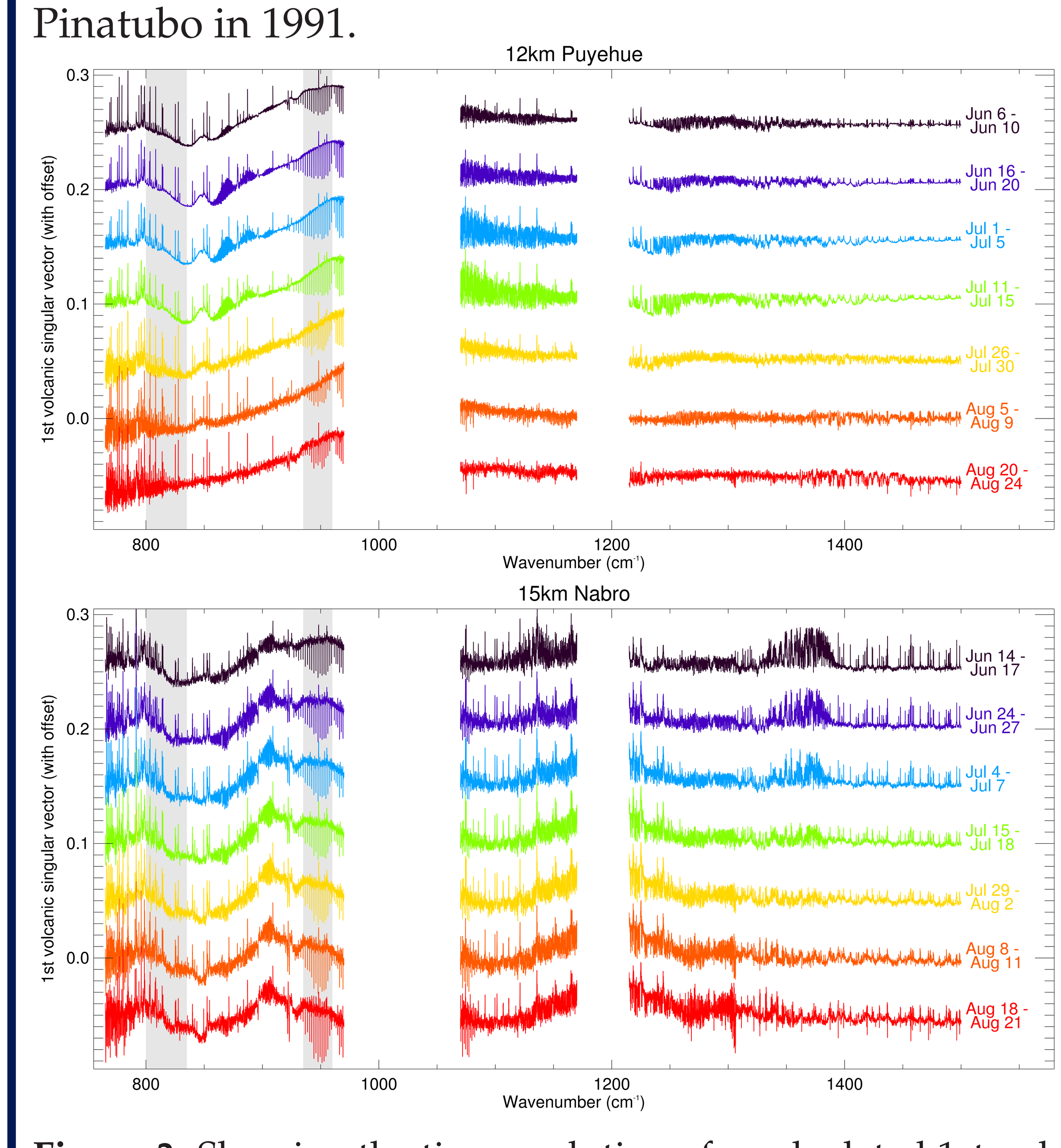

Figure 3: Showing the time evolution of recalculated 1st volcanic singular vectors at various times after the Nabro and Puyehue eruptions. The Puyehue eruption has a constant signal over time, whereas the Nabro eruption begins with a clear signal showing in the SO_2 ν_1 and ν_2 bands (at 1152 and 1362 cm^{-1}). As time progresses, this signal decreases as the SO_2 changes to sulphate aerosol.

Singular vector decomposition

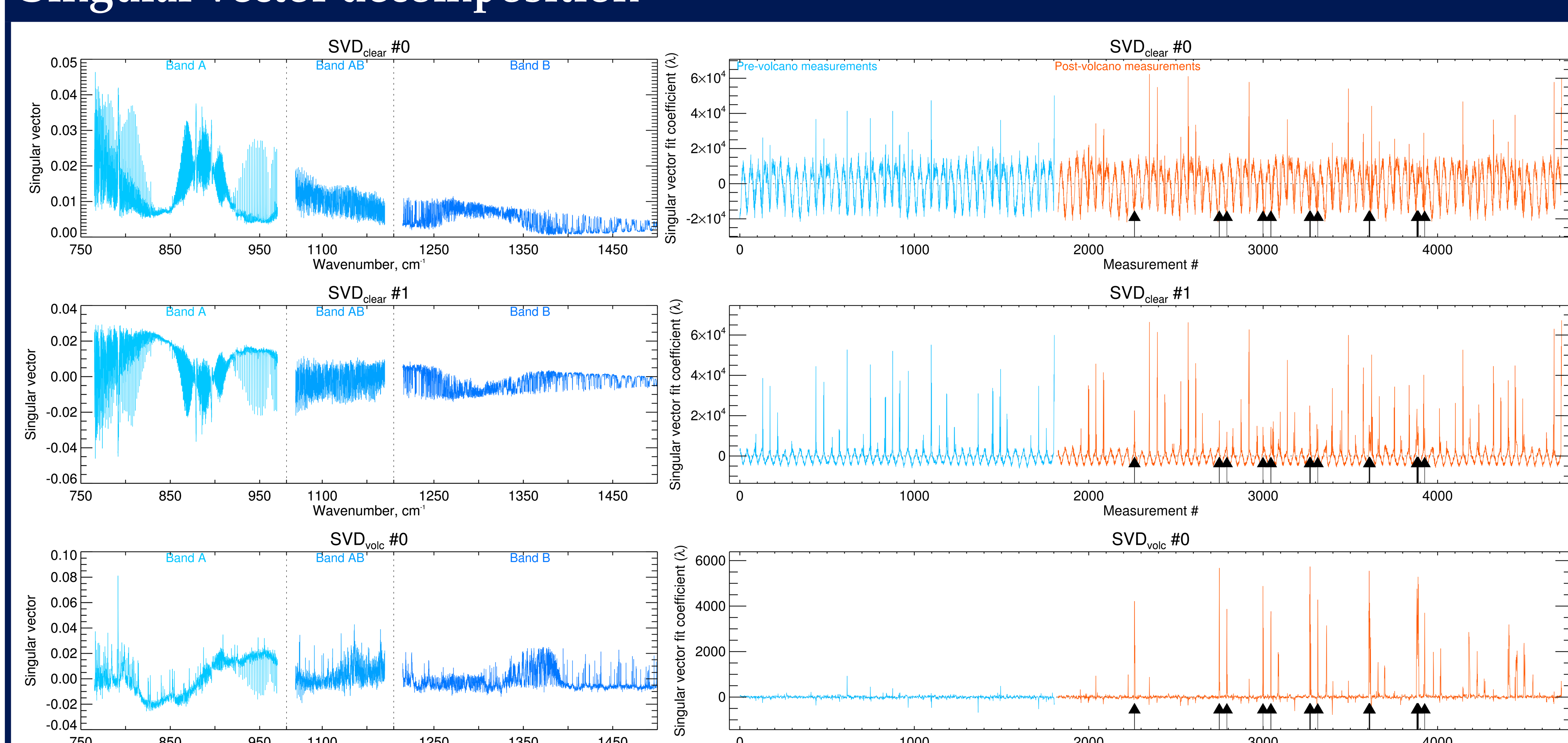

Figure 1: Showing the first two 'clean sky' SV (which capture 70 % of all variability), and the first 'volcanic' SV for the Nabro eruption at an altitude of 15 ± 1.5 km. The left-hand figures show the SV, while the right-hand figures show the fitting coefficient for MIPAS measurements before (blue) and after (orange) the eruption. Volcanic profiles flagged using Eq. 1 are marked by arrows. The diurnal cycle can clearly be seen in the first two vectors. The large peaks in the second clear vector's coefficents are due to the presence of thick cloud. Peaks in the first volcanic vector only begin to appear after the eruption.

References

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