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AUTOMATIC DETECTION OF VOLCANIC ASH USING METEOSAT

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1. INTRODUCTION

Volcanic ash clouds are a significant hazard to aviation, as they can cause damage to an aircraft that is not only costly to repair but can lead to in-flight engine shutdown. Several aircraft have experienced total engine failure following an ash cloud encounter, with the engines only being restarted after significant altitude loss (Casadevall 1992, Sparks et al. 1997). Similar incidents will continue to occur until timely and accurate information on ash cloud locations is reliably available to the aviation community (Salinas 1999).

Forecasting the movement of ash at aircraft cruising levels is the responsibility of Volcanic Ash Advisory Centres (VAACs) (Servranckx 1999), but first they need to know that an eruption has occurred. Notification usually comes from eyewitnesses or volcano monitoring centres, but this can be a slow and unreliable process, particularly for volcanoes in isolated areas. There is thus a need for a remote sensing system that can automatically detect ash producing eruptions from volcanoes worldwide.

Such a system, based on satellite data, is being developed by the Met Office for use by the London VAAC. This paper describes the current state of the system, and considers possible future improvements.

2. METEOSAT

The eruption detection system uses infrared images from Meteosat. The full disk images cover Iceland, the London VAAC's area of responsibility, as well as the Caribbean, the Atlantic, Europe and Africa. Importantly, they are available every half an hour both day and night, allowing the detection of an eruption soon after onset. They are calibrated to brightness temperatures before use.

All the images shown in this paper use lighter colours for colder brightness temperatures, and have a range of 50 K. They are centred on the volcano in question.

3. ERUPTION CHARACTERISTICS

Although low level volcanic emissions may not always be apparent in infrared images, those reaching aircraft cruising levels should have cooled sufficiently to be observable, providing they are not obscured by water or ice cloud.

The form of an eruption cloud as seen in an infrared image will depend on the characteristics of the eruption. An important factor is whether the cloud remains in the troposphere or rises into the stratosphere. The detection system has been designed to detect the former type of cloud, as these are produced by the more common weaker eruptions.

Such clouds may take up to half an hour to reach their maximum altitude. For sustained eruptions they may be distorted by the wind into a plume spreading downwind from the volcano. For non-sustained eruptions they can detach from the volcano and drift downwind, perhaps retaining a circular shape (Self and Walker 1994).

The observed brightness temperature of the cloud will depend on the cloud top temperature. Assuming an opaque cloud, and temperature equalisation between cloud and atmosphere, brightness temperature can be converted to cloud top height using a temperature profile of the atmosphere (Sparks et al.1997).

4. THE DETECTION ALGORITHM

The detection system works by identifying candidate eruption clouds and then checking that these clouds have certain characteristics consistent with being of volcanic origin.

A candidate eruption cloud is a cloud near a volcano that has either a circular shape, or a plume shape spreading downwind. Since the downwind direction varies with height, and the height reached by an eruption cloud is unknown in advance, an assumed cloud top height must be used when establishing the downwind direction. Candidate clouds are thus identified for a range of assumed cloud top heights, between the pressure levels of 850 and 150 hPa.

Wind data used in finding candidate clouds are operationally available from the Met Office's global numerical weather prediction model. The volcano location data were obtained from the Smithsonian Institute Global Volcanism Program.

A candidate cloud is confirmed as an eruption cloud if it meets three conditions:

1. the cloud is within a short distance of the volcano, or downwind of the volcano *(the location test*)
2. the cloud top height, as determined from observed cloud top brightness temperature, is consistent with the assumed height used in identifying the candidate cloud *(the height test*)

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3. the cloud stands out clearly against its background (*the contrast test*).

The identification of a candidate cloud, and the testing of the above three conditions for that cloud, will now be illustrated for the eruption of Hekla in Iceland on 26 February 2001.

4.1 Identifying a candidate cloud

A candidate cloud is identified by finding a good shape match between a cloud and a kernel containing an expected cloud shape. This shape can be circular or plume-like, the latter being a triangle originating at the centre of the kernel and spreading downwind. The match is measured in terms of a convolution result, which must be greater than a pre-defined threshold. The convolution is between a region of an infrared image around a volcano, and the kernel.

The downwind direction for the Hekla eruption is shown in figure 1, for an assumed cloud top height of 300 hPa. A kernel containing a corresponding plume-like shape is shown in figure 2. The best match between image and kernel occurs when the kernel is positioned over the image as shown in figure 3. This position gives a convolution result of 0.86, where the results are normalised to lie between –1 and 1.

The cloud top brightness temperature of a candidate cloud is the coldest brightness temperature within the cloud, occurring at the cloud top location. This is also shown in figure 3 for the Hekla eruption.

4.2 Testing a candidate cloud

4.2.1 Location

The cloud top location of a candidate cloud must be within a pre-defined region. This region consists of a circular region around the volcano and a rectangular region extending downwind, as is illustrated in figure 4 for the Hekla eruption.

The circular region allows for errors associated with image and kernel pixellation, the fact that lower altitude winds may have affected the position of the cloud, and the fact that the cloud may have risen from a vent or pyroclastic flow some distance away from the nominal location of the volcano.

The rectangular region allows for the fact that the cloud may have been blown downwind before being observed. The extent of this region is limited to the distance the cloud could have been blown within a certain time, given the wind speed. Beyond this limit it is reasonable to expect the cloud to have been detected in a previous image.

4.2.2 Height

The cloud top height of a candidate cloud must be

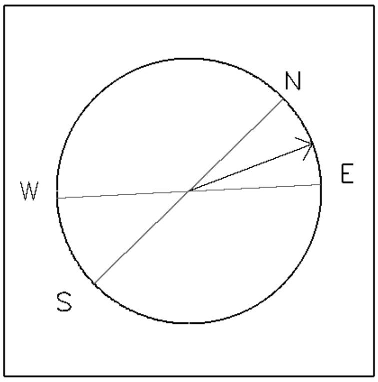

Figure 1: Forecast wind direction at 300 hPa above Hekla at the time of its eruption, in the projection of a Meteosat image. The axes are skewed because Hekla is near the edge of the Meteosat field of view.

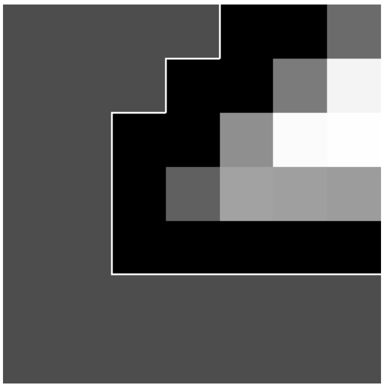

Figure 2: Kernel containing a plume-like shape for the wind direction shown in figure 1. Pixel values represent pixel coverage by the plume, except for the case of the black pixels. These have zero pixel coverage by the plume, but are set to negative values to offset the plume against its background and to give the kernel a mean of zero.

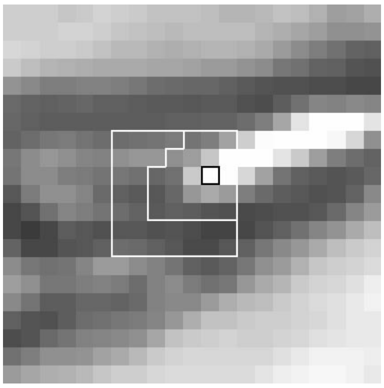

Figure 3: The Hekla eruption cloud half an hour into the eruption. When this image is convolved with the kernel shown in figure 2 the best result is obtained with the kernel positioned as shown. The outlined pixel is the corresponding candidate cloud top.

consistent with the assumed height used in identifying that cloud. The cloud top height can be found by comparing the observed cloud top brightness temperature with a numerical weather prediction temperature profile of the atmosphere.

For the Hekla eruption the cloud top brightness temperature of the candidate cloud is 215.4 K. From the temperature profile shown in figure 5 it can be seen that this temperature occurs at a height of about 300 hPa. This is consistent with the assumed height used in identifying the candidate cloud.

4.2.3 Contrast

The candidate cloud must contrast significantly against its background. This is to eliminate clouds that are just minor variations in the cloud top brightness temperatures of widespread cloud cover.

The contrast, which must be greater than a pre-defined threshold, is taken to be the brightness temperature variance of the candidate cloud. For the Hekla eruption this variance is calculated over the region outlined by the plume-like shape in figure 3.

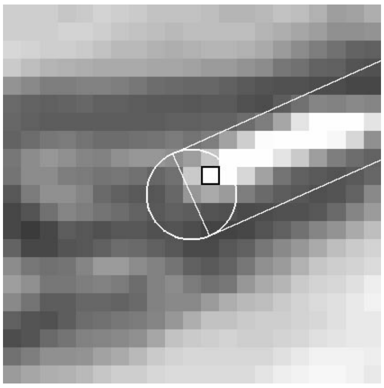

Figure 4: The region in which the candidate cloud top must lie, for the Hekla eruption.

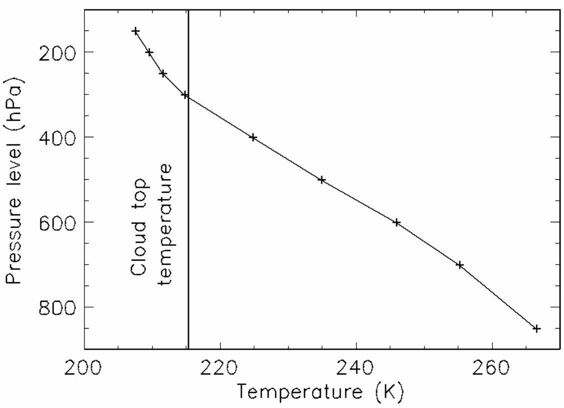

Figure 5: Temperature profile above Hekla showing that the observed cloud top brightness temperature corresponds to a height of approximately 300 hPa.

5. SETTING THE SYSTEM THRESHOLDS

The previous section has shown that the detection system has several free thresholds. These alter the balance between the probability of detection and the false alarm rate. They have been set to just allow the detection of 7 test eruptions.

6. THE PROBABILITY OF DETECTION

Since the development of the eruption detection system there have been three observable eruptions in the Meteosat field of view.

6.1 Etna (from 17 July 2001 to August 2001)

The cloud from this eruption was not at first detected because it was too low. However as the eruption strengthened, detections began to occur. The first was near midday on 21 July 2001 for a height of 850 hPa, for which the image is shown in figure 6. Most of the detections occurred during the day close to the volcano, when the cloud was over land with a warm brightness temperature such that the contrast between cloud and background was maximised.

6.2 Montserrat (4 August 2001)

The Washington VAAC reported that the eruption produced two clouds at altitudes of 4.6 and 9.7 km. One of these was briefly visible in a Meteosat infrared image, as shown in figure 7. This was presumably the higher of the two, yet it had a cloud top brightness temperature corresponding to a height of just 500 hPa (~5.9 km). It also contrasted poorly against the background. These problems, which could have been caused by the large viewing angle from Meteosat to Montserrat, meant that the cloud was not detected.

6.3 Nyiragongo (17 January 2002)

The cloud from this eruption was detected as soon as it appeared in a Meteosat infrared image, for a height of 200 hPa. This image is shown in figure 8.

7. THE FALSE ALARM RATE

The false alarm rate for the system is about 0.025 alarms per monitored volcano per image. This is too high for it to be of operational use to the London VAAC, particularly if all 90 or so historically active volcanoes in the Meteosat field of view are to be monitored (Smith 2002).

There are several possibilities for reducing the false alarm rate without affecting the probability of detection. The most promising are:

- Better modelling of the expected cloud shape used in identifying candidate clouds, for given atmospheric conditions and an assumed eruption strength.

- Use of a more sophisticated shape matching technique than convolution.

- Incorporating detection conditions based on temporal information. For example a candidate cloud should not be present in a previous image upwind of the volcano.

- Incorporating detection conditions based on spectral information. The spectral characteristics of a candidate cloud should correspond to volcanic ash, not water or ice. It will be possible to include such conditions once multi-spectral infrared images become available from Meteosat Second Generation (Watkin and Ringer, 2000).

8. CONCLUSIONS

This paper has described an eruption detection system designed to provide timely warnings of volcanic eruptions that may compromise aviation safety. It uses pattern recognition techniques to automatically detect eruption clouds in infrared images from Meteosat.

The use of a pattern recognition technique for volcanic cloud detection appears promising. Eruptions of Etna and Nyiragongo have been detected, and although an eruption of Montserrat was missed this may have been because it was small and near the edge of the field of view.

It thus seems worthwhile to put further effort into improving the false alarm rate. There is considerable scope for this, from better modelling of the expected cloud, to the use of temporal and spectral information. Should this work prove successful then such a technique could become a valuable tool for supporting the work of the VAACs.

9. REFERENCES

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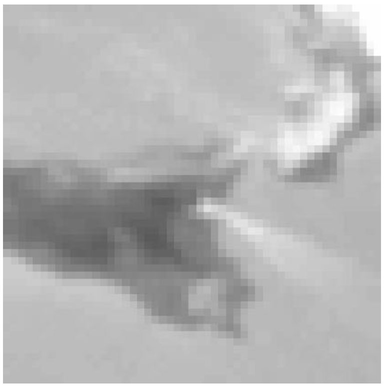

Figure 6: A detected eruption cloud from Etna.

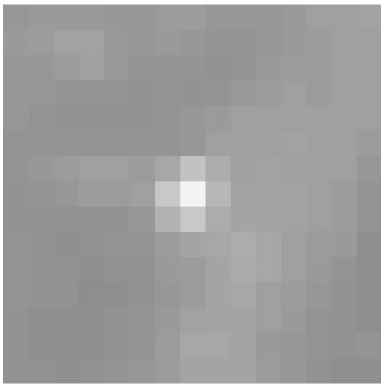

Figure 7: A missed eruption cloud from Montserrat.

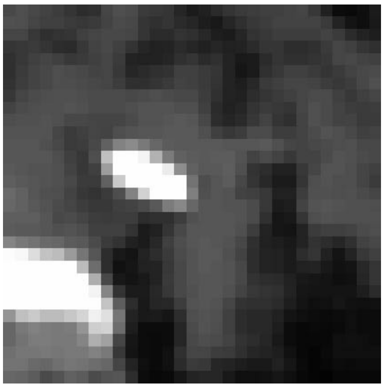

Figure 8: A detected eruption cloud from Nyiragongo.