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Near real-time monitoring of the April–May 2010 Eyjafjallajökull ash cloud: an example of a web-based, satellite data-driven, reporting system

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Abstract: During the 2010 eruption of Eyjafjallajökull volcano (Iceland) we set up a system designed to ingest satellite data and output volcanic ash cloud products. The system (HVOS = HotVolc Observing System) ingested on-reception data provided every 15 minutes by the SEVIRI sensor flown aboard the Meteosat Second Generation (MSG) satellite. Data were automatically processed and posted on the web to provide plume location maps, as well as to extract plume metrics (cloud top height and mass flux), in near-real time. Given the closing speeds for aircraft approaching such hazardous ash clouds, reporting delays for such products have to be minimised.

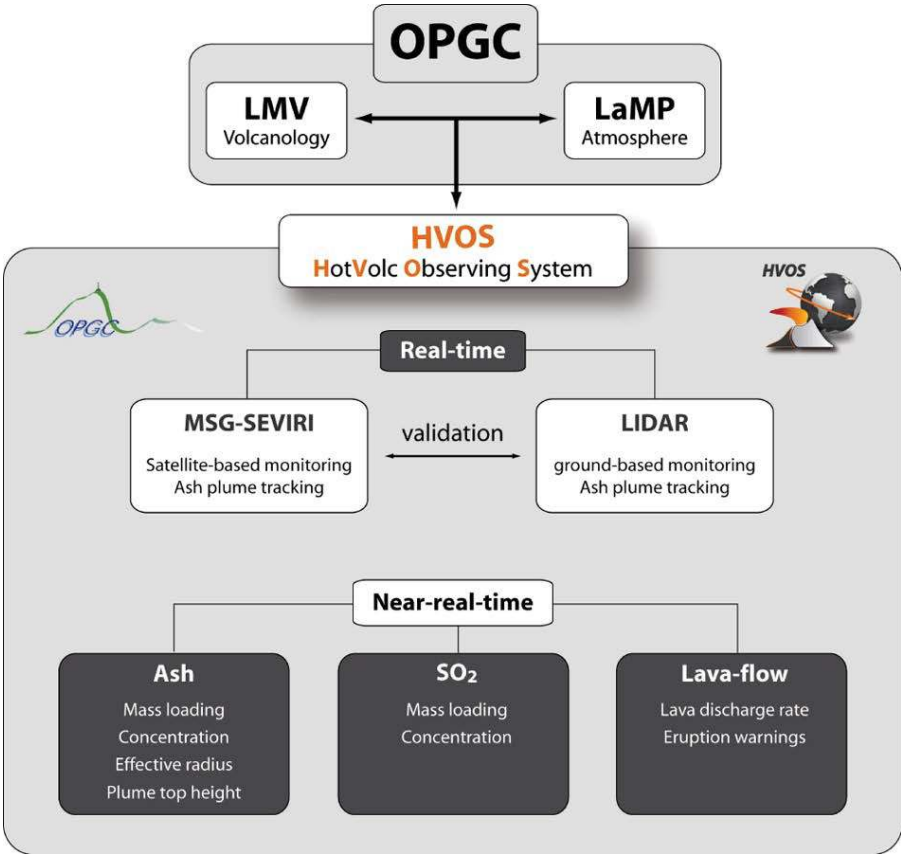
1 Introduction

Thermal Infrared (IR) sensors flown aboard geostationary and polar orbiting satellites provide data well suited to volcanic ash cloud detection and tracking for three reasons. First, wavebands located in thermal infrared allow ash clouds to be detected and distinguished from meteorological clouds (e.g., Prata, 1989a, 1989b). Second, cloud extent, altitude and dynamics can be extracted using methodologies that have been in place since the 1980s (e.g., Sawada, 1985; Holasek et al., 1996). Third, methodologies that extract ash mass loading and particle size distribution (for particle sizes of $< 20 \mu\text{m}$) from IR data are also available (e.g., Wen and Rose, 1994). The use of high temporal resolution data typically collected every 15 m by sensors located on geostationary platforms allows early detection and warning of the presence of ash in the atmosphere, as well as retrieval of quantitative volcanic parameters in near real time (if access to a direct reception facility is available). The potential of airborne ash to inflict damage on aircraft (e.g., Bernard and Rose, 1990; Casadevall, 1994a, 1994b; Grindle and Burcham, 2002) and impact aircraft operations (e.g., Casadevall, 1994b; Hufford et al., 2000) has led to the same data and procedures being promoted to track and warn of the presence of ash clouds in air routes (Prata, 2009). In addition, the immediate availability of such satellite data-derived parameters are extremely important, because values such as mass flux, ash cloud altitude, and ash concentration are essential source term inputs and

validation for predictive cloud trajectory and dispersal models (e.g., Woods et al., 1995; Searcy et al., 1998; Witham, et al., 2007; Barsotti et al., 2008; Peterson and Dean, 2008).

We present a web-based system developed to achieve near real-time tracking of volcanic ash clouds using onsite ingestion of satellite data and output of useable products via implementation of off-the-shelf algorithms. The system, named the HotVolc Observing System (HVOS: <http://www.obs.univ-bpclermont.fr/SO/televolc/hotvolc/>), was set up in 2009, and is driven by real-time reception and processing of geostationary satellite data. HVOS is hosted by the Laboratoire Magmas et Volcans (LMV) – a section of the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC) – and is based at the Université Blaise Pascal (Clermont-Ferrand, France) (Figure 1). The HVOS system was first tested for plume tracking during the crisis caused by the April-May 2010 eruption of the Eyjafjallajökull volcano (Iceland) using data from the SEVIRI sensor (Spinning Enhanced Visible and InfraRed Imager) on board the Meteosat Second Generation (MSG) satellite. MSG-SEVIRI operates at a maximum temporal resolution of 1 image every 5 m (typically 1 image every 15 m), and provides data in 12 wavebands at nominal spatial resolutions of between 1 and 3 km. Ash cloud detection and quantification is possible using the thermal wavebands (8–14 μm), allowing cloud parameters mapping at a spatial resolution of 3 km (e.g., Prata and Kerkmann, 2007). We complement this data stream with near real-time processing of data from Terra/Aqua-MODIS, Aura-OMI, and Calipso-CALIOP.

Figure 1 Flow chart showing the organisation and output of the HotVolc Observation System (HVOS). Both the Laboratoire Magmas et Volcans (LMV) and the Laboratoire de Météorologie Physique (LaMP) are part of the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC). The system focuses on ingestion, processing and interpretation of satellite (MSG-SEVIRI) and LIDAR data to allow the output and validation of satellite-data-derived volcanic cloud tracking products (see online version for colours)

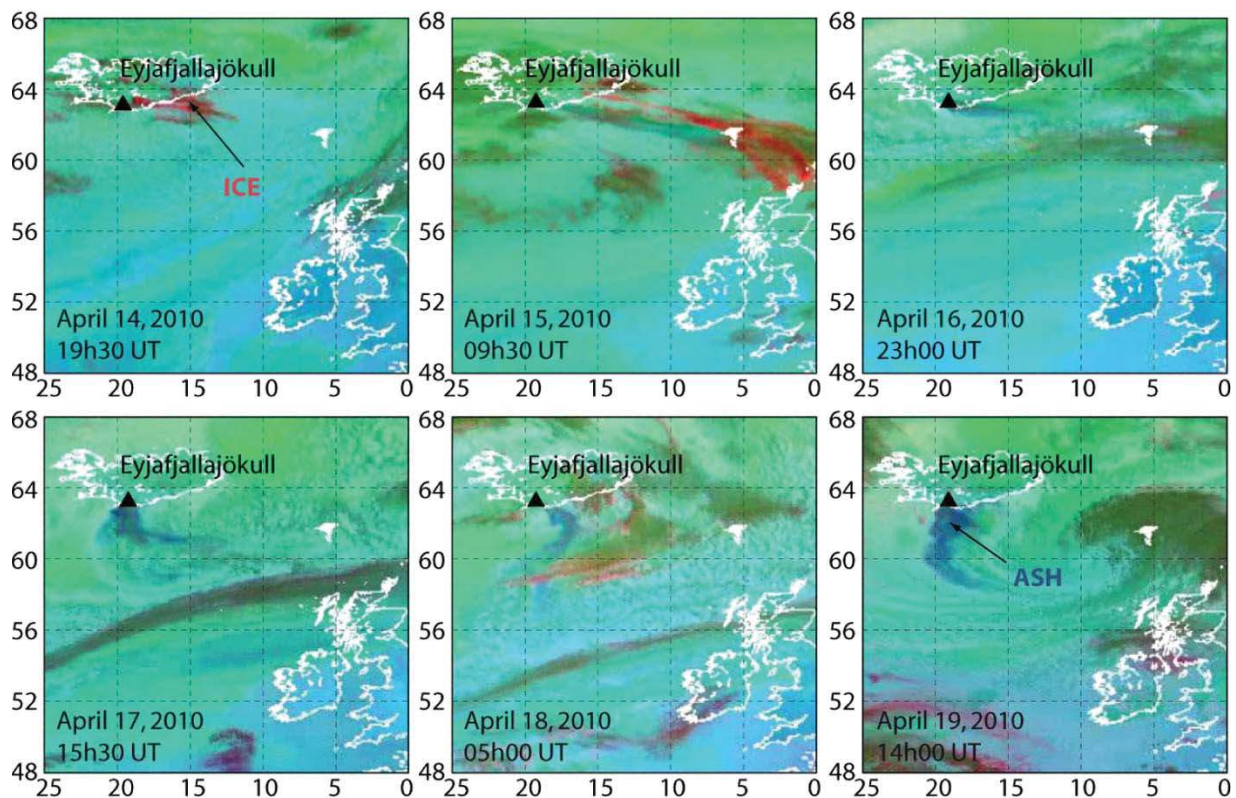


2 Eruption and HVOS background

The 2010 eruption of Eyjafjallajökul (Iceland) began on March 20 and ended on April 13 (Gudmundsson et al., 2010). The main explosive phase started during April 13–14, when an eruptive fissure opened in the glacier capping Eyjafjallajökul to trigger the first phase of ash emissions. This phase was characterised by phreatomagmatic activity that led to explosive events, producing very fine ash (Davies et al., 2010). As a consequence, a dark-grey volcanic cloud was released on April 14, which drifted eastward, extending over Europe at an altitude of 6–7 km (Figure 2). The result was well documented by the media, and involved global travel chaos and losses running into billions of Euros and Dollars.

Although an embryonic form of HVOS had been in development since 2008 (Guéhenneux, 2009), the events in Iceland caused us to accelerate development of the site to allow automated, near real-time processing of satellite data to generate ash cloud products and explore the possibility of building a widely accessible web-based resource for eruption tracking. The tool represents a low-maintenance, 24/7 resource with open access; being similar to other web-sites designed to generate and disseminate volcano hot spot information using satellite sensor-derived IR data (e.g., Harris et al., 2002; Wright et al., 2004). Acceleration was largely driven by the French Volcanology Warning Group, at the request of the French Ministère de l'Ecologie, de l'Energie, du Développement Durable et de la Mer, during the 2010 crisis.

Figure 2 MSG-SEVIRI-generated ash cloud detection products: Example of a three-channel IR composite using MSG-SEVIRI data, highlighting the presence of ash (in dark blue), ice (bright red) and water droplets (green) during the first period of intense ash emission between April 14 and 19, 2010 (see online version for colours)



3 Methods and results

3.1 Plume mapping and tracking

From April 14, 2010, HVOS posted data for the unfolding events in Iceland in near realtime. MSG-9 images were automatically processed every 15 m (up to every 5 m for MSG-8 RSS – Rapid Scan Service – images) and posted on the HVOS website at http://www.obs.univ-bpclermont.fr/SO/televolc/hotvolc/Islande_Avril2010/. The delay between data reception and product generation was less than five minutes. Products posted on this web-site included three-channel composite images that allowed us to distinguish ash clouds from meteorological clouds (i.e., ice crystals and water droplets). The generation of our three-channel composites is based on the differential extinction features of volcanic aerosols through the 8–12 μm waveband range, following the standard method of Prata (1989a, 1989b). Following this methodology, these RGB composites are generated by combining the following bands on the red (R), green (G) and blue (B) colour guns:

$$R = 10.8 \text{ minus } 12 \mu\text{m};$$

$$G = 10.8 \text{ minus } 8.7 \mu\text{m};$$

$$B = 10.8 \mu\text{m}.$$

In this combination, while the ash cloud appears dark blue, water droplets appear deep green and ice crystals are bright red (Guéhenneux, 2009). High Resolution Visible images and 24-hour-long movies were also generated at a time resolution of 1 image every 5 m (using MSG-8 RSS data), and posted manually once a day.

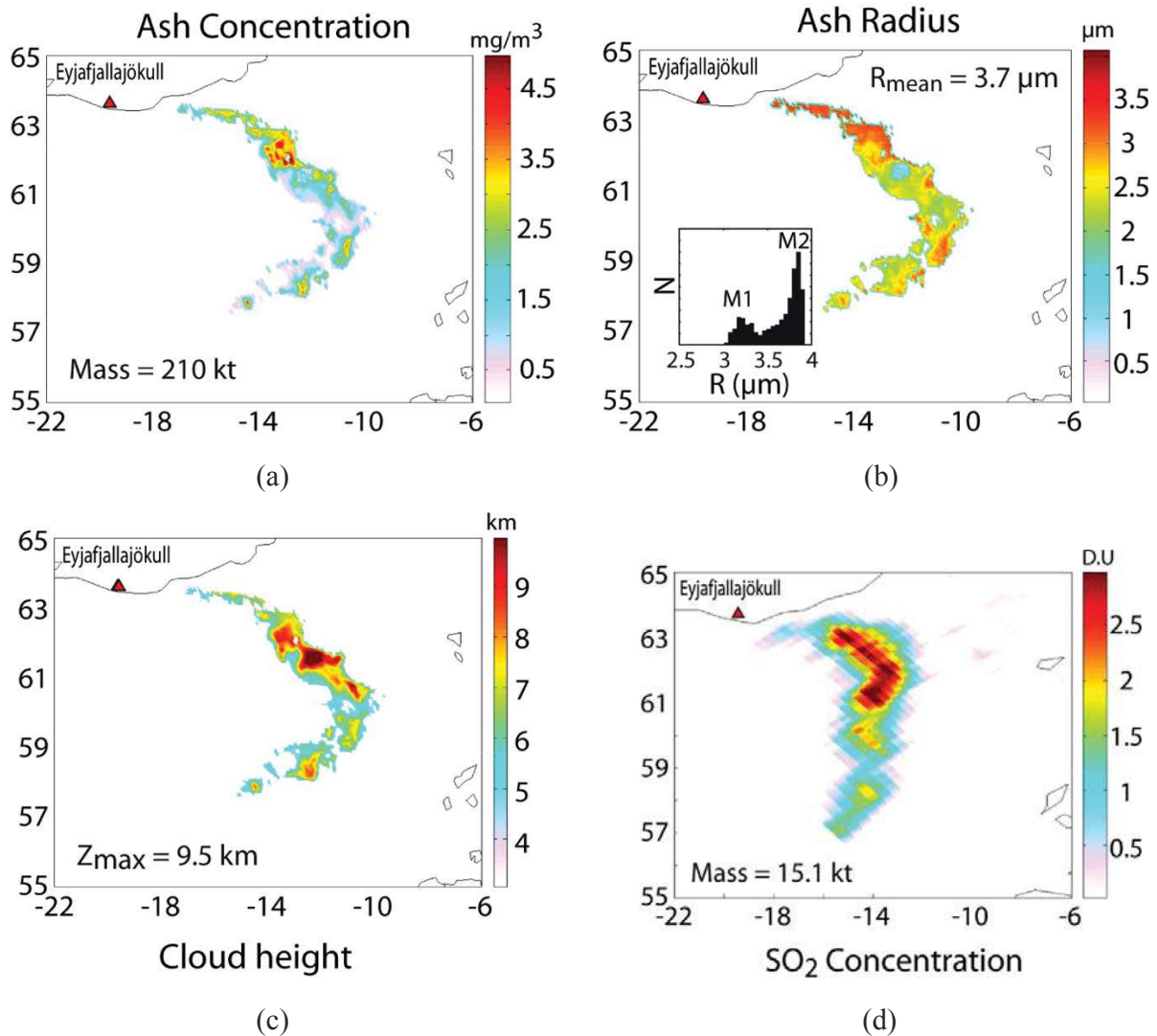
3.2 Quantification of particle concentration, cloud height and SO_2 content

Inversions of the MSG-SEVIRI infrared data were also carried out following the forward modelling approach of Wen and Rose (1994). This method is designed to allow assessment and mapping of ash mass concentrations and radii within the cloud. The method gives a minimum estimate for fine ash mass loading inside the cloud at a given instant. By way of example, we provide an ash mass concentration map for May 6 in Figure 3a.

From this image, we calculated that 210 kt of ash were airborne at that time, with the cloud having a maximum concentration of $5 \text{ mg}\cdot\text{m}^{-3}$. The distribution of ash radii can be mapped simultaneously using the same model, as shown in Figure 3b. The temperature of the ash cloud top, which is expected to be in equilibrium with that of the surrounding atmosphere, can also be used to derive the cloud top altitude. Cloud top temperatures were calculated from the 10.8 μm band data, and the altitude to which that temperature related was retrieved from vertical atmospheric soundings (from the Torshavn station, <http://www.uwyo.edu>). For May 6, the highest point of the volcanic cloud was 9.5 km a.s.l. (Figure 3c). The SO_2 burden was next obtained using the Aura-OMI instrument, an instrument which operates in Ultraviolet (UV), and whose data allows estimation of SO_2 loadings (e.g., Krotkov et al., 2006; Carn et al., 2009). This yielded an estimate

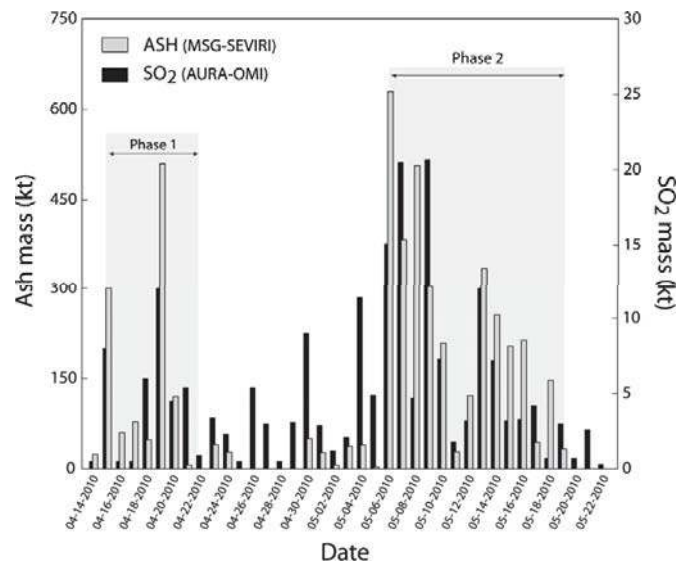
of 15.1 kt for SO₂ from the May 6 image (Figure 3d). Quantitative information was routinely calculated within a few hours of image reception during the whole eruption, where we used a total of about 3000 images to track the eruption (SEVIRI being available at a typical rate of 96 images/day).

Figure 3 Quantitative (higher level) products posted by HVOS. Inversion of MSG-SEVIRI IR data permits generation of products such as: (a) ash concentration; (b) ash radius; (c) ash cloud altitude, with Aura-OMI data being used to obtain and (d) SO₂ mass. The example here is for the cloud as imaged on May 6, 2010 (see online version for colours)



The combination of both MSG-SEVIRI and Aura-OMI data allows us to provide a daily estimate of ash and SO₂ injected into the atmosphere. The time evolution of this flux, as tracked on HVOS, is given in Figure 4. While ash emissions were focused in two main phases spanning April 14–21 and May 6–19, SO₂ was emitted more or less constantly during the entire period. By integrating daily mass fluxes over the whole eruptive episode, we found that 4.8 Mt of ash and 0.2 Mt of SO₂ were released into the atmosphere.

Figure 4 Daily mass fluxes of: (a) fine ash and (b) SO₂ with time as posted on HVOS. The high temporal resolution of MSG-SEVIRI permitted us to estimate the mean daily mass fluxes and hence, provide a first order estimate of the total fine ash and SO₂ masses released into the atmosphere during the eruption

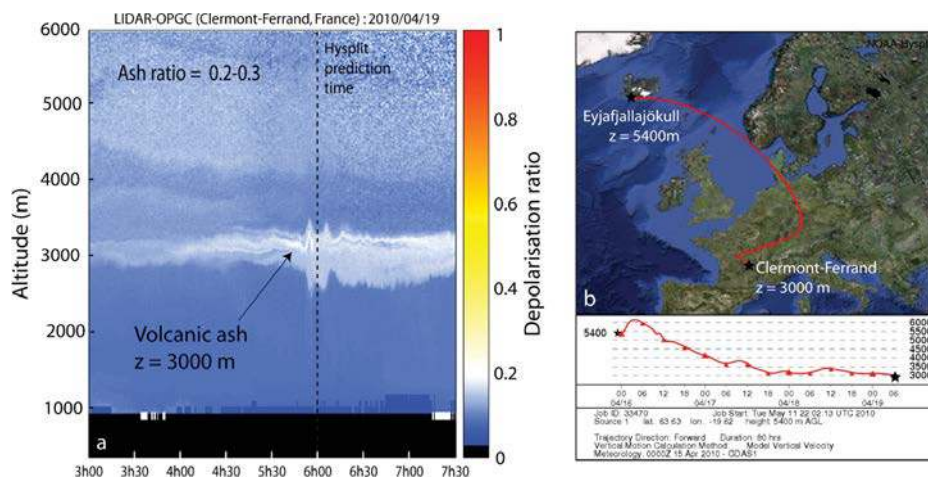


3.3 Modelling and validation

Ground-based LIDAR operated by the OPGC were used to detect the arrival of the ash cloud over Clermont-Ferrand (Figure 5a). On April 19, at 06h00 UTC, the OPGC LIDAR detected an ash cloud with a thickness of 500–1000 m, lying at an altitude of 3000 m. The arrival of this ash layer could be seen from an increasing signal at an altitude of 3000 m from 03h00 onwards. The cloud height and time of arrival information derived from the ground-based LIDAR allowed us to validate trajectory and dispersal models.

For instance, the backward trajectory calculated from the NOAA-HYSPLIT model (Draxler and Hess, 1997, 1998; Draxler, 1999) indicates that the ash layer observed above Clermont-Ferrand on April 19 was most likely related to atmospheric ash injection to a height of 5400 m by Eyjafjallajökull on April 16 (Figure 5b).

Figure 5 LIDAR ash cloud detection: (a) The ground-based LIDAR located at Clermont-Ferrand permitted detection of ash above this site at an altitude of 3000 m on April 19 and (b) Backward trajectory modelling carried out using the NOAA-HYSPLIT model of Draxler (1999) showed that, for arrival of a layer at this altitude and time, eruption of a cloud to 5400 m above Eyjafjallajökull volcano on 16 April was the most likely source candidate



4 Conclusion

When correctly treated, remote sensing data can be used to accurately assess the location, extent, ash concentration, mass flux and altitude of a volcanic ash cloud. These data can be automatically processed and posted online – every 15 m – with minimal manpower resources, allowing up-to-date (near real-time) ash cloud tracking. Making such data widely available allows their ingestion into routines for improved plume monitoring and tracking; it also facilitates improved communication to, and understanding of the event by, the media. However, dissemination must come with the caveat that there are limits to the data, and pit falls with the techniques, such as non-detection of ash due to ice contamination or high level cloud cover.

Following the lead of other satellite data-driven dissemination services, we achieved a near real-time dissemination system by posting our data online with the shortest delay possible. Such data can then be downloaded by any interested party. We initially tested the dissemination capability on the volcanic cloud released during Iceland's 2010 eruption of Eyjafjallajökull. This test involved setting up of a web-based, near real-time monitoring system which involved automated ingestion of satellite data and output of all maps and values reported here to allow ash cloud tracking every 5 to 15 m. Also output and updated were cloud trajectory and dispersal models driven by the satellite data. In this way, up-to-date quantitative information was available to scientists, monitoring agencies and media communities across the globe.

Due to the closing speed of aircraft with hazardous ash clouds, our capability to react as quickly as possible following an explosive is fundamental. If routines are already running to allow detection and tracking of ash clouds using real-time feeds of high temporal resolution geostationary satellite data, then the reaction time is close to zero. Following the model of the Alaska Volcano Observatory (Dean et al., 1998, 2002), we showed that we could provide data within a few minutes of event onset, and then maintain a system which updates every 15 m. Our fully transparent information broadcasting system is then aimed to help achieve a fully informed and unified event synopsis.

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