# NEAR REAL-TIME MONITORING OF THE APRIL-MAY 2010 EYJAFJÖLL'S ASH CLOUD

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**Abstract**:
On April 14, 2010, an eruptive fissure opened in Iceland's Eyjafjallajökull glacier to trigger an explosive phase of the eruption of Eyjafjöll volcano, initiating a phreatomagmatic stage due to the interaction of ice and magma. The eruption stopped some weeks later on May 23, leading to a dormant phase. The April 14 explosive activity of fed a cloud of ash and gas that drifted eastward at an altitude of 5-7 km, due to the prevailing wind-directions that distributed the fine-ash over NE Atlantic and Europe and, as a consequence, causing complete closure of European airspace for several days. The eruption has been characterized by two main phases of intense ash emissions spanning April 14-21 and May 1-10, with a maximum intensity recorded on May 6. However, as a comparison to common eruptions occurring annually on Earth close to urban regions, the Eyjafjöll eruption was quite small, with an unspectacular ash plume though leading to global chaos. The main reasons for such a chaos probably lie on the lack of practice related to an unprecedented scenario in the west Europe. Particularly, generic atmospheric models were executed with some delay, quantitative input parameters were dramatically missing, and poorly informed decisions were made causing huge sectors of air space to be shut down. However, we show in this paper that the HotVolc Observation System (HVOS) was the first able to monitor the plume and provide near-real-time quantitative parameters. Finally, we were able to give ground-based validation of space-based tracking of the active plume.

***Key words:*** *Remote sensing, Volcanology, Lidar, Near-real-time monitoring, Eyjafjöll eruption, Iceland, Ash cloud, Aerosols*

## INTRODUCTION

The first sign of this eruption was in April 2009 when 20-25 km deep earthquakes occurred beneath Eyjafjallajökull glacier. On March 20, 2010, primitive basalt has erupted by the eccentric crater in the Fimmvörduháls pass between the two central volcanoes, Eyjafjöll and Katla. This first phase was characterized by lava fountains up to 200m height, going with degassed activity showing lava effusions, and eventually ceased on April 13, 2010. Few hours later (13-14 April) a seismic crisis began beneath the summit crater of Eyjafjöll capped by the 300m thick Eyjafjallajökull glacier. A long eruptive fissure opened in the glacier with more silicic magma, first leading to large water flash floods and mud flows (locally called jökulhaups) northward to the volcano due to ice melting. Main consequences were local; about 1000 farmers have been evacuated, as well as cattle and some inhabitants living in the ash-fall area. This type of phreatomagmatic eruption is characterized by highly explosive phases due to magma-water interaction increasing pyroclasts' fragmentation. As a consequence, a large dark-grey volcanic cloud have been released at the end of April 14, drifting eastward at about 5-7 km of altitude, leading the European air space to be shut down a few hours later.

Given the potential of volcanic ash and gas clouds to damage aircraft operations (Bernard, A. and W.I. Rose, 1990; Casadevall, T.J, 1994 and 2003; Carn, S. et al., 2008; Prata, A.J., 2009) the closure was a necessary one, but one which directly impacted millions of people. The impact of the event on global communications and economic activities, as well as the potential for tragedy had air space not been closed down, required rapid but careful analysis of all data capable of tracking the cloud in relation to vulnerable air routes. We present here the HotVolc Observation System (HVOS), validated during the Icelandic crisis, as a great potential for the monitoring and broadcasting of fundamental near-real-time quantitative parameters on volcanic ash clouds. The immediate availability of these data is extremely important because these parameters (mass flux, ash cloud altitude, ash concentration, etc.) are used as input into predictive dispersal models (Woods, A.W. et al., 1995; Searcy, C. et al., 1998; Witham, C.S. et al., 2007; Barsotti, S. et al., 2008; Peterson, R.A. et al., 2008; Mastin, L.G. et al., 2009).

The HotVolc group is based at the Laboratoire Magmas et Volcans (LMV), part of the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC), at the Université Blaise Pascal (Clermont-Ferrand, France). The HVOS (Fig. 1) is first dedicated to the real-time monitoring of thermal anomalies and to the tracking of volcanic clouds related to the eruptive activity using geostationary satellites. The OPGC stands for a reception platform for geostationary satellites data (EUMETSAT convention), and hence permits us the real-time products exploitation of MSG satellite (Meteosat Second Generation). The MSG-Seviri sensor (Spinning Enhanced Visible and InfraRed Imager) operates at a very high temporal resolution (1 image every 5 minutes maximum), which ensure the detailed study of volcanic plumes dynamics through time (Prata, A.J. and J. Kerkmann, 2007). Further implementation of our observation service allows near-real-time quantitative assessment of volcanic parameters using multiple satellite-based tools (Terra/Aqua-MODIS, Aura-OMI, Calipso-CALIOP, etc.).

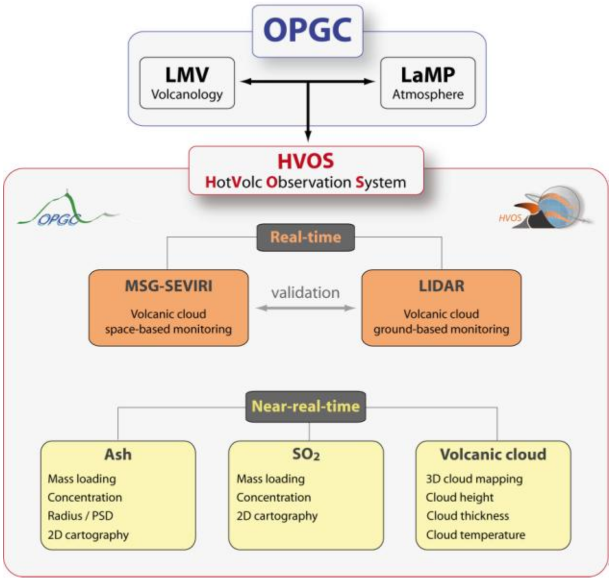


Figure 1. Organigram of the HotVolc Observation System (HVOS). Both the Laboratoire Magmas et Volcans (LMV) and the Laboratoire de Météorologie Physique (LaMP) are part of the Observatoire de Physique du Globe de Clermont-Ferrand (OPGC). Both structures are very complementary having volcanological and atmospheric sciences skills.

HVOS has been involved in the 24/7 monitoring survey of the April-May 2010 eruption of Eyjafjöll volcano (Iceland) and belonged to the French Volcanology Warning Group, at the request of the MEEDDM (Ministry for ecology, energy, sustainable development and sea). At the same time, the OPGC is home of the Laboratoire de Météorologie Physique (LaMP), which brings to the LMV a valuable contribution in term of ground-based and in-situ atmospheric measurements. The synergy between both laboratories is unique in France, and allows unprecedented broad range measurements on a volcanic ash cloud.

## METHODS AND RESULTS

### *1. Plume mapping and Tracking*

From April 14, 2010, we provided reliable real-time MSG-9 images to the community every 15 minutes (up to every 5 minutes with MSG-8 RSS -Rapid Scan Service- images), immediately delivered to the scientific community on the HVOS website (http://wwwobs.univ-bpclermont.fr/SO/televolc/hotvolc/Islande_Avril2010/). Among the images and the data delivered on the website, there were 3-channels complex thermal compositions (Fig. 2a) enabling the observer to distinguish volcanic ash from water droplets and ice crystals (Prata, A.J., 1989a and b). The 3-channels compositions are based on the differential extinction features of volcanic aerosols between different wavelengths. The first channel is assigned the band difference 10.8µm-12µm, the second channel is 10.8µm-8.7µm, and the third one is 10.8µm. The ash cloud hence appears in dark blue, while water droplets are deep green and ice crystals are bright red. High Resolution Visible images (HRV MSG-8 RSS data, every 5 minutes) and movies were also available in real-time (Fig. 2b).

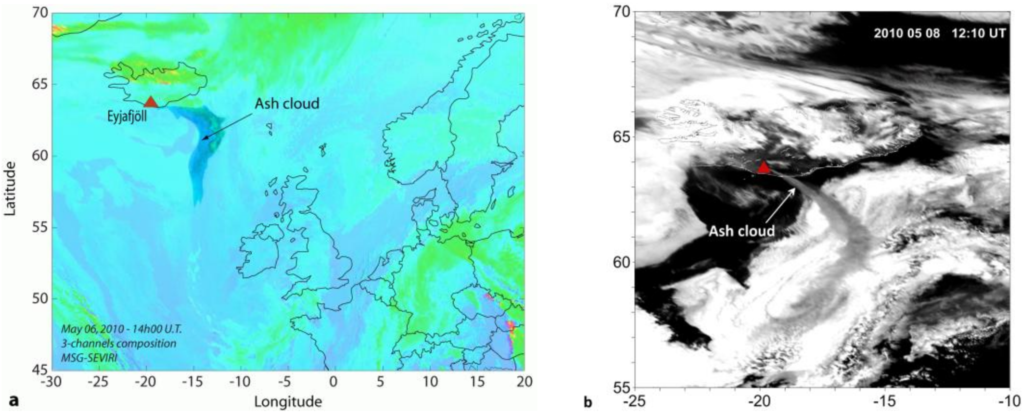


Figure 2. Real-time MSG-SEVIRI monitoring. a) Example of a 3-channels IR compositions using MSG-SEVIRI data, highlighting the presence of ash in dark blue, on May 6 at14h00 UT. b) HRV (High Resolution Visible, 1km) MSG-8 RSS image, showing the grey ash cloud, on May 08 at12h10 UT.

In addition to early detection, we were able to track the ash plume on West Europe and provide important information on the cloud dispersal and location. Besides qualitative information we have provided a wide range of near-real-time quantitative parameters during the whole eruption.

### *2. Quantification of particle concentration, cloud height and $SO_2$ content*

Inversion of the MSG-SEVIRI infrared data have also been carried out using the forward modelling approach of Wen, S. and W.I. Rose (1994) to assess and map ash mass concentrations within the cloud. This method gives a minimum estimate of 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 (Fig. 3a). From this image we calculate that 210kt of ash were airborne at that time, with the cloud having a maximum concentration of 5 $mg.m^{-3}$. The ash radius distribution can be mapped simultaneously using the same model (Fig. 3b). For the May 6 image this showed a bi-modal distribution with a median radius at about 3.7 µm (Fig. 3b). The temperature of the ash cloud top, which is expected to be in equilibrium with the atmosphere, can also be used to derive its altitude. Cloud temperatures were calculated from the 10.8 µm channel, and the altitude to which that temperature related was retrieved from vertical atmospheric soundings (Torshavn station, http://www.uwyo.edu). For the May 6 example, the highest point of the volcanic plume was 9.5 km a.s.l., with the highest point located a few hundred km north-west of Scotland (Fig. 3c). The $SO_2$ burden was next obtained using the Aura-OMI instrument which operates at UV wavelengths (Krotkov, N. et al., 2006; Carn, S. et al., 2007). This yielded an estimate of 15.1kt for $SO_2$ from the May 6 image (Fig. 3d). Quantitative information were routinely calculated within a few hours of image reception during the whole eruption, where we used a total of about 3000 images, with SEVIRI being available at a typical rate of 96 images/day (one image every 15 minutes).

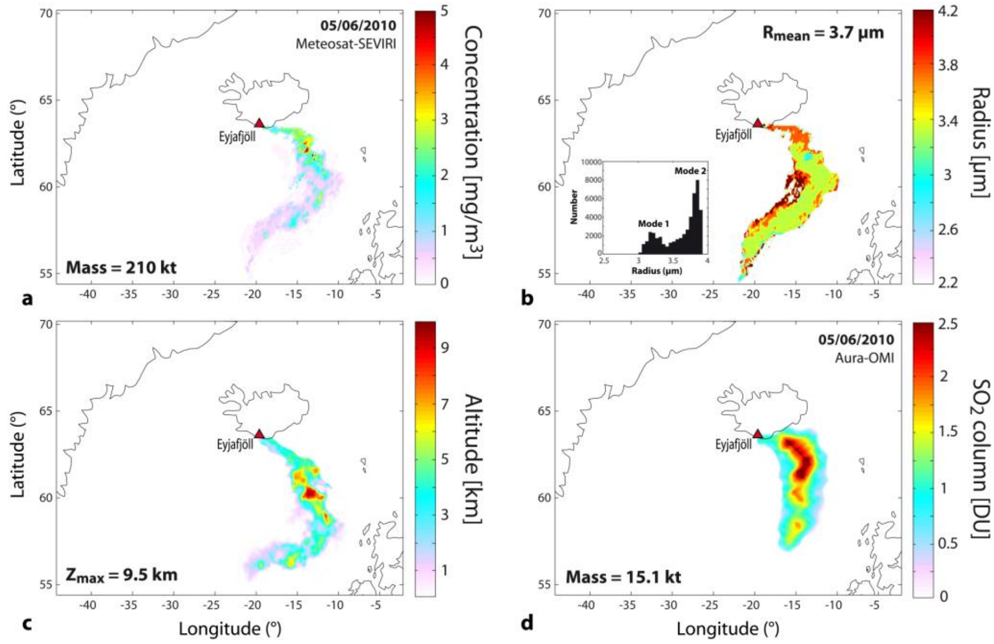


Figure 3. Quantitative volcanic products mapping. The inversion of MSG-SEVIRI IR data permits the estimation of various volcanic products such as (a) the concentration of ash, (b) the radius of ash, (c) the ash cloud altitude, and (d) the mass of $SO_2$.

The high temporal resolution of MSG-SEVIRI data has allowed the accurate mass fluxes estimation of fine ash emitted in the atmosphere. The mean flux calculated on the whole eruption is found to be about 1.33$t.s^{-1}$ with maximum and minimum values of 5.3 $t.s^{-1}$and 0.02 $t.s^{-1}$ respectively. Thus, using mean daily mass flux values we can infer a first order estimate of the total mass loading of fine ash injected in the atmosphere. From April 14 to May 9, the total ash and $SO_2$ emissions in the atmosphere were estimated at 2.3 Mt and 0.28 Mt, respectively (Fig. 4). The ash emissions were focused on 2 main phases, 14-21 April and 1-10 May, while $SO_2$ were emitted much more constantly during the whole studied period, even if with higher values when ash were emitted. Note that these values stand for the finest ash fraction drifted by the wind in the atmosphere, far from the vent.

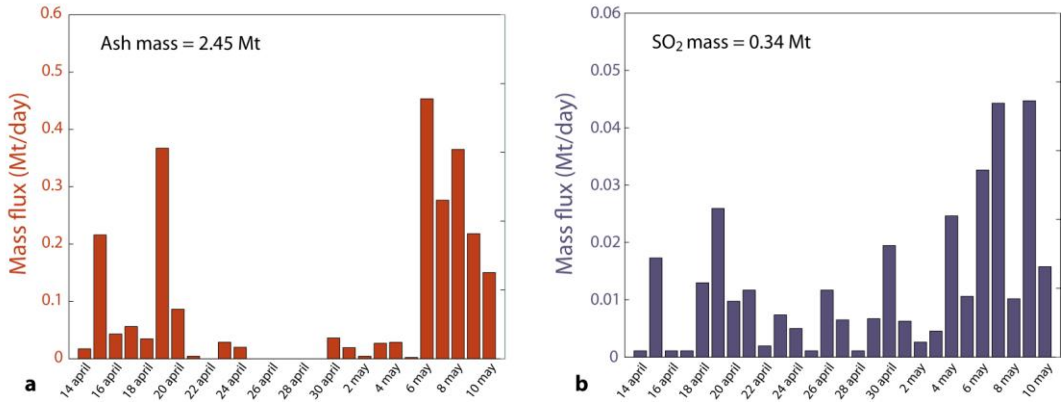


Figure 4. Mass fluxes of (a) fine ash and (b) $SO_2$ variation with time. The high temporal resolution of MSG-SEVIRI permits us to estimate the mean daily mass fluxes and hence provide a first order estimate of the total fine ash and $SO_2$ masses released into the atmosphere.

### *3. Modelling and validation*

The ground-based Lidar located at the OPGC were used to track and monitor the evolution of the ash cloud above Clermont-Ferrand region (Fig. 5). On April 19, from 03h00 UTC the Lidar-OPGC has detected a dense ash cloud 500-1000m thick in average, and lying at an altitude of 3000m. The high ash reflectivity using the polarized backscatter show that the aerosols are non spherical, as expected from ash ones. The capability to derive such information from ground-based instrument also permits to validate dispersal and trajectory models. For instance, the backward trajectory calculated from Hysplit-NOAA model clearly show that ash observed above Clermont-Ferrand at an altitude of 3000 on April 19, are clearly related to the ash emission of Eyjafjöll volcano on April 16, having an altitude ranging from 5000-5500m above the vent deduced from the simulation model, that is in good accordance with in-situ radar observations (Icelandic experts reports).

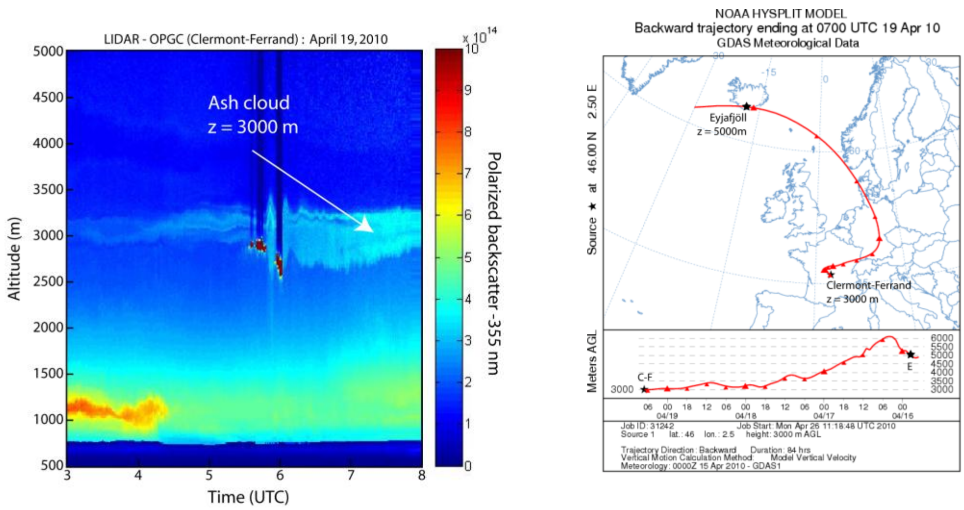


Figure 5. Lidar ash cloud detection. The ground-based Lidar-OPGC located at Clermont-Ferrand, has permitted the very accurate detection of ash above Clermont-Ferrand (France), at an altitude of 3000m, on April 19. The backward trajectory calculation carried out with NOAA-Hysplit model permits to validate and confirm source information such as the altitude and start date of the ash cloud emission at Eyjafjöll volcano.

## DISCUSSION

When correctly treated, remote sensing data can be used to accurately assess the exact location, extent, ash concentration, mass flux and altitude of a volcanic plume. These data cannot only be used to improve plume monitoring and tracking, but also to allow improved communication and understanding of the event by the media and the population. Such an approach may have led to more positive coverage than that provided by newspapers such as the *Mail on Sunday* who printed on April 25, "*even at its worst, ash over UK was only a twentieth of safe flying limit*" and "*predictions were wildly inaccurate*". So just where was the plume and how dense was it?

Our maps show that it was likely of Europe-wide extent, although our inability to detect any cloud in the south of France from satellite data suggests that at many locations the ash cloud was extremely dilute. In addition, ground-based or satellite LIDAR soundings revealed that the cloud was low and below the level of most transatlantic routes. The question that remains today and that will need an argued answer in the next future is the following: *"Could planes have flown over it?"*

Calls for a "*single sky*" response and monitoring policy have already been published in the popular press. In the past, studies have tended to either track and measure $SO_2$ or ash. We show here that, using a fully integrated data set of IR and UV images, we can track plumes in near-real-time at a high temporal resolution. By way of test, we set up a web-based, real-time monitoring system which involved automated ingestion of satellite data and output of all maps and values reported here to allow real-time ash cloud tracking as well as updating of cloud trajectory and dispersal models. In this way, quantitative near-real-time information was available to the scientists, monitoring and media communities across the whole of Europe, and was part of the official crisis response implemented by the French government. Our capability to react in real-time is fundamental, as we can warn of the presence of an ash cloud within a few minutes after the onset of a volcanic eruption, and then provide a tracking system which updates every 15 minutes. Our fully transparent information broadcasting system is aimed to help achieve a fully informed and unified decision making and reporting process in the event of a volcanic ash crisis.

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