Icelandic Holuhraun plume: balloon borne measurement of aerosol size distribution

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● ***Summary:***

Volcanic eruptions have enormous societal and economic consequences. In Iceland, one of the best known examples is the Laki eruption (1783-84 CE) which caused the deaths of > 20% of the Icelandic populations and likely increased European levels of mortality through air pollution. The recent fissure eruption at Holuhraun (31 August 2014 – 27 February 2015) was a major source of sulfur gases and aerosols and causes also both local and European-wide deteriorations to air quality.

The capability of atmospheric models to predict volcanic plume impacts is limited by uncertainties in the near-source plume state. Most in-situ measurements of the elevated plume involve interception of aged plumes that have already chemically or physically evolved. Small portable sensors airborne drone or balloon platforms offer a new possibility to characterize volcano plumes near to source.

We present the results of a balloon borne flight through the plume emitted by Baugur the main vent during the night of the January 22th 2015. The balloon carrying a novel aerosol counter called LOAC (Renard et al. 2016) has intercepted the plume at 8km distance downwind from the crater which represents a plume age of approximately 15 minutes. The plume was located in altitude between 2 and 3.1km above the sea level. Two layers were observed, a non-condensed lower layer and a condensed upper layer. The lower layer of 400m thick was characterized by a modus of fine particles centered on 0.2µm in diameter and a second modus centered on 2.3µm in diameter and a total particle concentration around 100 particles per cubic centimeter. The upper layer of 800m thick was a cloud-like signature with droplets centered on 20 µm in diameter and a fine modus, the total particles concentrations was 10 times higher than the first layer. The plume top height was determined between 2.7 and 3.1 km, the plume height is in good agreement with an estimate made by analysis of IASI satellite remote sensing data, thus demonstrating in-situ validation of this recent satellite algorithm (Carboni et al. 2015).

This experimentation shows that under such difficult field campaign conditions (strong wind, low temperatures, only car batteries for power supply, night time and active volcano close to the launch site) it is possible to launch meteorological balloons with novel payloads to directly sample in-situ the near-source plume, determine the plume altitude, identify dynamical phases of the plume and document the size distribution of particles inside a plume which is only a quarter of an hour old.

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Eruption overview

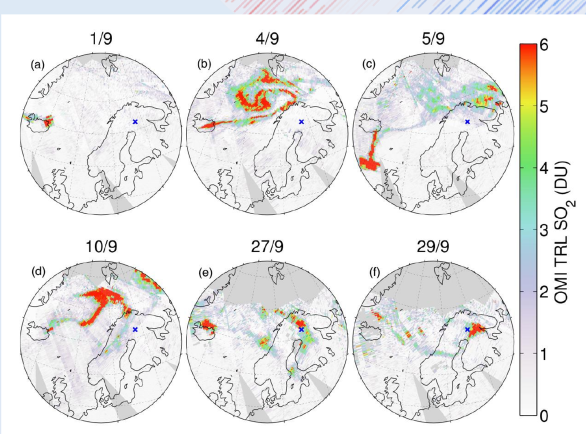
Aerial view of the eruption December 2014 Credits : Egill/visir.is

Eruption key-points:

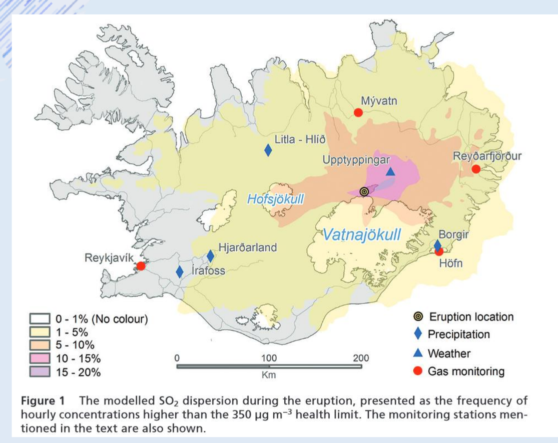
Six month effusive eruption
(August-February 2015/16)
Largest eruption in Iceland for 200 years

Lava emitted:
Total of 1.6 ± 0.3 km^3
Average of 100 m^3s^{-1}

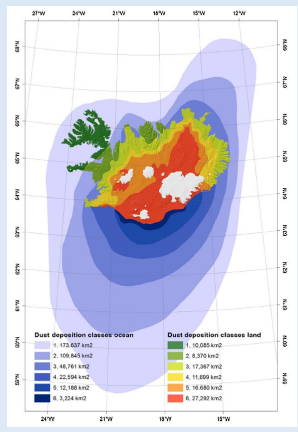
SO_2 emitted:
Total of 11 ± 5 Tg
Average of 400 $kg.s^{-1}$



Total SO_2 columns as seen from OMI SP TRL (Ialongo et al. 2015)



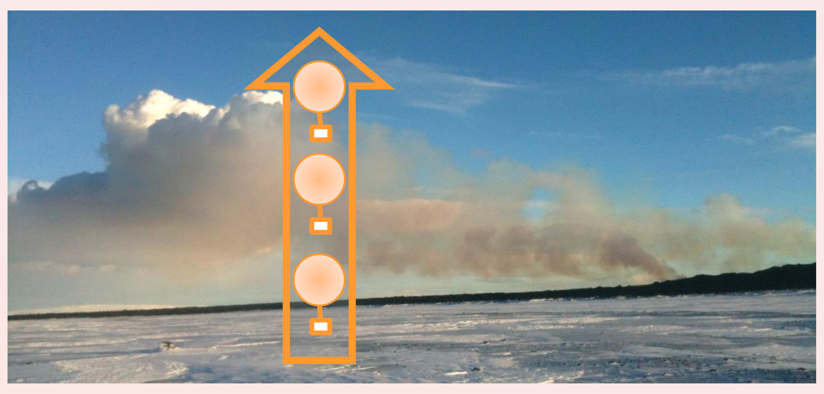
The modelled SO_2 dispersion during the eruption (Gislason et al. 2015)



Dust deposition rate on land and ocean (Arnalds et al. 2016)

Volcanic eruptions influence long range atmospheric composition but also have local direct impacts such as pH of precipitation, composition of snow, and indirect impacts such as pollution/fertilisation by ash fallout, and floods.

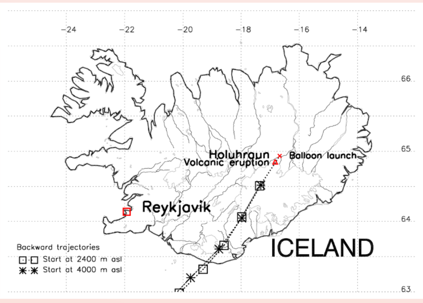
Holuhraun "Young" plume state caught by a balloon



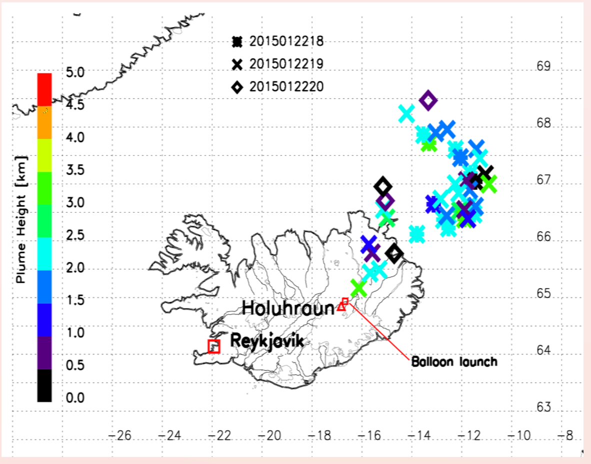
Plume as it was the afternoon before the balloon launch on January 22th 2015

The capability of atmospheric models to predict volcanic impacts is limited by uncertainties in the near-source plume state. Most in-situ measurements of the elevated plume involve interception of more aged plumes that have already chemically and physically evolved.

Our balloon intercepted the Holuhraun plume at 8km distance downwind from the crater which represents a "young" plume age of approximately 15 minutes.



FLEXTRA backward trajectories



Retrieved plume altitude from IASI SO_2 data using Carboni algorithm (Carboni et al. 2012)

The altitude given by the Carboni algorithm of the closest measurement from the crater is 3.0 ±1.1 km

In-situ measurements are able to produce a better estimation of plume altitude for a specific localisation

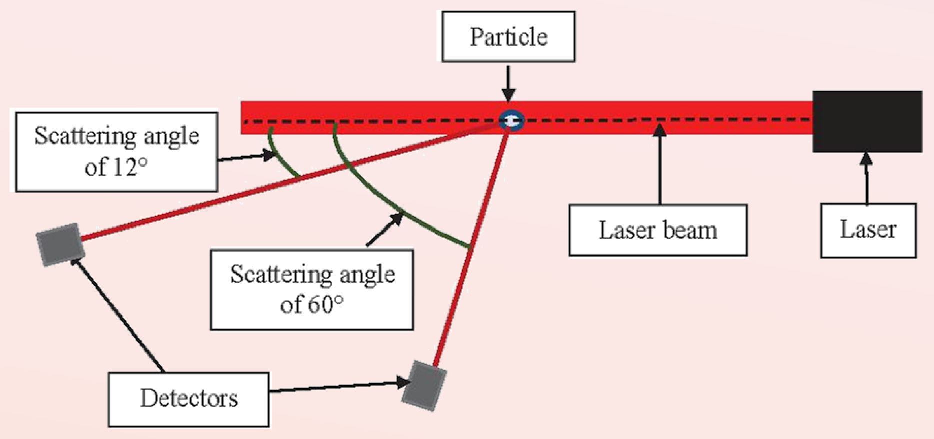
Balloon instrumentation - LOAC

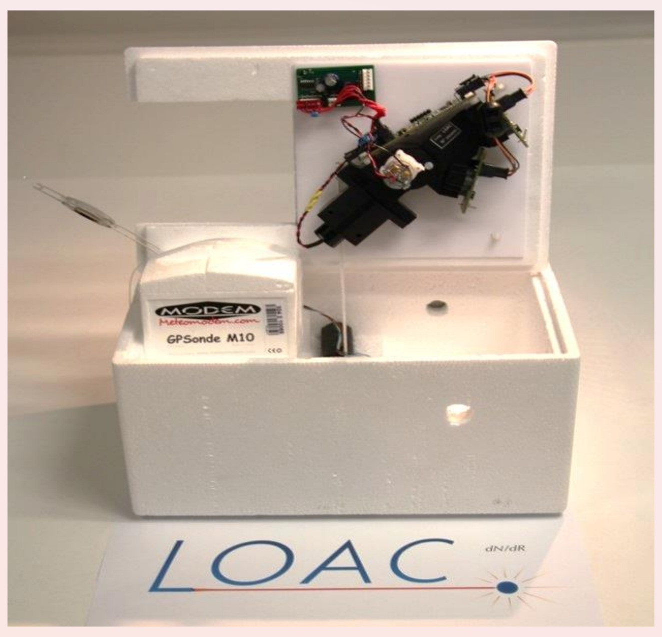
Measurements at 2 scattering angles (field of view of a few degrees)

~12°, low sensitivity to the refractive index of the particles (mainly diffraction)
=> accurate size determination and counting

~60°, strongly sensitive to the refractive index of the particles
=> indication of the nature of the particles (topology)

Concentrations for 19 size classes in the 0.2 – 100 µm diameter range
Weight of 300g; electric consumption of 3 W





Balloon borne results from LOAC

During the balloon ascent, we intercepted two plume layers, 8 km from the crater. The first one is assumed to be the plume in a non condensed phase and the second above is the same plume turned in a cloud phase. Altitude, optical properties and particle size distribution for both of these layers is presented, alongside conditions above and below the plume.

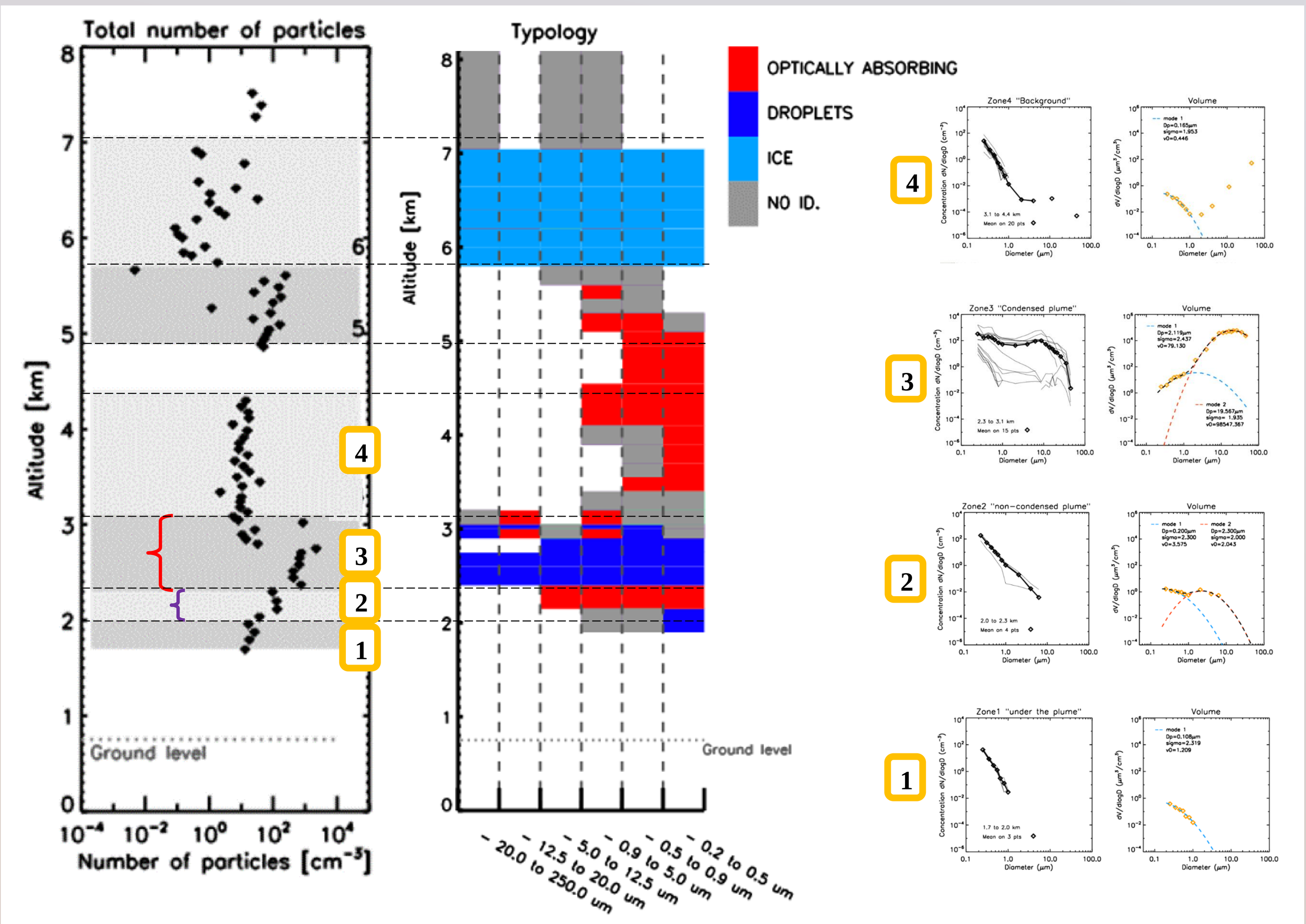
Plume altitudes

2 layers measured :

Condensed phase :
From 2.3 to 3.1 ± 0.1km

Non condensed phase :
From 2.0 to 2.3 ± 0.1km

Plume altitude retrieved from IASI data gives:
3.0 ±1.1 km asl
LOAC shows an altitude at 3.1 ± 0.1 km asl



Comparison with other datasets & flux estimation

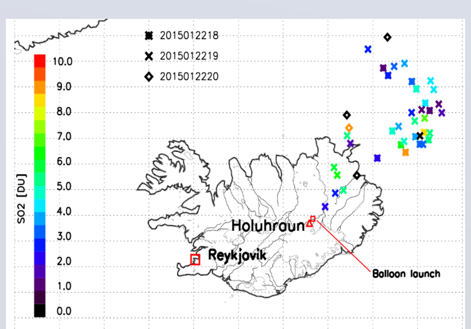
Establishing ratios between gas measurements and aerosols is a big challenge. This kind of information can be used in models in order to retrieve the aerosols emission from a volcano. These ratios remain very uncertain but we try to coarsely estimate the ratio of SO_2 mass per number of particles (within size range 0.2 to 100 µm).

The emission of SO_2 column from Holuhraun was measured both by IASI on METOP satellite and a NOVAC scanning DOAS on the same day.

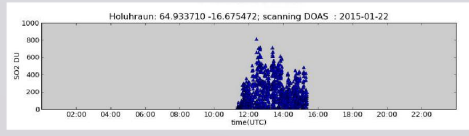
Using the concentration measured by LOAC in the non condensed phase plume (from 2.0 to 2.3 km), assuming a relative homogeneity of the plume in time and space (omitting the condensed phase layer) we calculate a ratio of mass of SO_2 per number of particles around 10^{13} – 10^{15} kg/nb in the near source plume.

Measurements with LOAC and gas sensors on a previous campaign on the Mont Etna by Roberts (2016) shows similar ratios of SO_2 per aerosol number.

We estimated that a total of 6 x 10^{20} volcanic particles in the range of 0.2 to 100 µm have been emitted on the day of the flight and between 10^{22} and 10^{24} particles in the same size range for the whole eruption. This ratio remains highly uncertain due to the constant evolution of aerosols along the plume.



SO_2 Dobson units from IASI
Data for 3 hours nearest



SO_2 Dobson units from NOVAC
Data for 3 hours nearest

Perspectives

- **Tests in Bordeaux (South of France) have demonstrated that a LOAC can be carried by drone (Renard et al. 2016). McGonigle (2008) demonstrated that a drone heli-type drone with SO_2 and CO_2 sensors can fly into a volcanic plume, whilst Robert et al. (2016) shows good correlation between LOAC particles and volcanic SO_2. The future association of a LOAC with gas sensors on a drone in a volcanic plume can allow to spatially quantify the local variations of plume altitude, plume evolution and dispersion.**
- **Two flights with a LOAC under meteorological balloons have been made from the Reunion Island (Indian ocean 21°S 55°E) through the stratospheric part of Calbuco plumes. These studies are presented on Lurton poster's** ***(poster number :*** X3.7 ***session : Stratospheric aerosols, volcanic eruptions and their radiative effects*** *(IE2.5/AS3.5/CL2.07) Tuesday 19th April 2016 Hall X3)*
- **Partnership with meteorological offices from France and Iceland have been set up and several instruments are ready to be launched in case of volcanic eruption. The purposed is to provide information to air-traffic regulators on the concentrations and size distributions of aerosols to allow a better knowledge on air traffic risks due to volcanic particles.**

References : **Arnalds, O.**, Dagsson-Waldhauserova, P., Olafsson, H., 2016. The Icelandic volcanic aeolian environment: Processes and impacts — A review. Aeolian Res. 20, 176–195. doi:10.1016/j.aeolia.2016.01.004 / **Carboni, E.**, Grainger, R., Walker, J., Dudhia, A., Siddans, R., 2012. A new scheme for sulphur dioxide retrieval from IASI measurements: application to the Eyjafjallajökull eruption of April and May 2010. Atmos Chem Phys 12, 11417–11434. doi:10.5194/acp-12-11417-2012 / **Carboni, E.**, Grainger, R.G., Mather, T.A., Pyle, D.M., Thomas, G., Siddans, R., Smith, A., Dudhia, A., Koukouli, M.L., Balis, D., 2015. The vertical distribution of volcanic SO₂ plumes measured by IASI. Atmospheric Chem. Phys. Discuss. 15, 24643–24693. doi:10.5194/acpd-15-24643-2015 / **Gíslason, S.**, Stefánsdóttir, G., Pfeffer, M.A., Barsotti, S., Jóhannsson, T., Galeczka, I., Bali, E., Sigmarsson, O., Stefánsson, A., Keller, N.S., Sigurdsson, á., Bergsson, B., Galle, B., Jacobo, V.., Arellano, S., Aiuppa, A., Jónasdóttir, E.B., Eiríksdóttir, E.S., Jakobsson, S., Guðfinnsson, G.H., Halldórsson, S.A., Gunnarsson, H., Haddadi, B., Jónsdóttir, I., Thordarson, T., Riishuus, M., Högnadóttir, T., Dürig, T., Pedersen, G.B.M., Höskuldsson, á., Gudmundsson, M.T., 2015. Environmental pressure from the 2014-15 eruption of Bárðarbunga volcano, Iceland. Geochem. Perspect. Lett. 84–93. doi:10.7185/geochemlet.1509 / **Ialongo, I.**, Hakkarainen, J., Kivi, R., Anttila, P., Krotkov, N.A., Yang, K., Li, C., Tukiainen, S., Hassinen, S., Tamminen, J., 2015. Comparison of operational satellite SO2 products with ground-based observations in northern Finland during the Icelandic Holuhraun fissure eruption. Atmospheric Meas. Tech. 8, 2279–2289. doi:10.5194/amt-8-2279-2015 / **Lurton, T.,** Jégou, F., Berthet, G., Renard, J.-B., Vignelles, D., Bègue, N., Portafaix, T., Bencherif, H., Couté, B., Duverger, V., Payen G., Metzger, J.-M., Posny, F.: Quantifying the impact of moderate volcanic eruptions on the stratosphere – poster EGU 2016 Geophysical Research Abstracts Vol. 18, EGU2016-7673, 2016 / **McGonigle et al.**: Unmanned aerial vehicle measurements of volcanic carbon dioxide fluxes, Geophys. Res. Lett., 35, L06303, doi:10.1029/2007GL032508; 2008. / **Renard, J.-B.**, Dulac, F., Berthet, G., Lurton, T., Vignelles, D., Jégou, F., Tonnelier, T., Thaury, C., Jeannot, M., Couté, B., Akiki, R., Verdier, N., Mallet, M., Gensdarmes, F., Charpentier, P., Duverger, V., Dupont, J.-C., Mesmin, S., Elias, T., Crenn, V., Sciare, J., Giacomoni, J., Gobbi, M., Hamonou, E., Olafsson, H., Dagsson-Waldhauserova, P., Camy-Peyret, C., Mazel, C., Décamps, T., Piringer, M., Surcin, J., Daugeron, D., 2015. LOAC: a small aerosol optical counter/sizer for ground-based and balloon measurements of the size distribution and nature of atmospheric particles – Part 1: Principle of measurements and instrument evaluation. Atmospheric Meas. Tech. 8, 9993–10056. doi:10.5194/amtd-8-9993-2015 / **Roberts et al.**: (2016) Advances in in-situ real-time monitoring of volcanic emissions: HCl, and size-resolved aerosol at Mt Etna (passive degassing), submitted to Geochimica et Cosmochimica Acta.