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## Airborne Measurements of Volcanic Ash and Current State of Ash Cloud Prediction

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### Synopsis

Eyjafjallajökull 2010 and Grímsvötn 2011 eruptions created great problems for commercial aviation in the North Atlantic because of the large extent of the predicted ash clouds from these eruptions. Comparison to satellite pictures showed the predictions very much larger than the ash cloud. Measurements also showed lower ash concentrations over Europe than the predicted. Papers on simulation of the Eyjafjallajökull Ash cloud in peer reviewed journals, usually tried to simulate the VAAC predictions rather than the satellite pictures, an example is shown. In the newest eruption in Iceland (Holuhraun – Bardarbunga) mostly SO<sub>2</sub> was produced but if its output had been ash, it could have produced similar problems for the aviation as Eyjafjallajökull did. The plume was successfully modeled using the WRF-chem model. Kyoto Universities measurements and research of eruptions in Sakurajima has shown weak points in the diffusion theory used for ash cloud prediction of tropospheric plumes that tend to ride in stable temperature inversions. Gravitational deformation of the plume and a streak fallout process are missing, they both make estimated ash content of clouds, based on diffusion theory, larger than the actual. The dispersion coefficient in gravitational flattening is an order of magnitude smaller than in the diffusion case. Streak fallout takes all grain sizes as it is a vertical flow of air. This makes airborne measurements of volcanic ash important to use, they provide calibration data for local concentrations and grain sizes and thereby improve the predictions. New rules from ICAO, effective from November 2014, stress that jetliners should avoid visible ash. This makes detection of visible ash important. Most VAAC's use satellite pictures to localize visible ash. The procedure used by JMA's Tokyo VAAC is very advanced unique approach where corrections of the modeled ash cloud ensure that predicted clouds are comparable to the observed ones in size.

**Keywords:** Sakurajima, volcanic ash, airborne measurements, plume dispersion.

### 1. Introduction

All volcanic eruptions in the Volcanic Ash Advisory Council (VAAC) London area, happen in Iceland. Eyjafjallajökull 2010 and Grímsvötn 2011 eruptions created great problems for commercial aviation (Perkins, 2010) in the North Atlantic because of the large extent of the predicted ash clouds from these eruptions. When a visible plume was

photographed by satellites and compared to the predicted ash clouds, the satellite pictures showed the predicted clouds very much larger than the actual ash clouds or plumes. No satisfactory explanation of this discrepancy can be found in the literature (Elíasson et al, 2014a), (Elíasson et al, 2014b).

Papers on simulation of the Eyjafjallajökull Ash cloud in peer reviewed journals, usually tried to

simulate the VAAC predictions rather than the satellite pictures (Folch et al, 2012) is an example.

Disaster Prevention Research Institute's research effort on airborne measurements of volcanic ash started in 2011. From the start it was a collaboration effort between Research Division of Disaster Management for Safe and Secure Society and Sakurajima Volcano Research Center. The main focus was from the start on in-situ measurements of volcanic ash plumes and the chosen site was the Sakurajima volcano that frequently emits several ash explosions a day. It is therefore a unique laboratory for airborne in-situ measurements. From 2012 the volcanic ash concentrations have been measured with OPC meters. This paper focuses on how the results obtained in the airborne measurement campaigns of the volcanic ash emitted by Sakurajima, relate to the current state of prediction technology, rather than numerical values of the OPC observations.

The measurement program brought significant results; several presentations were made in the Scientific Assembly of the International Association of Volcanology and Chemistry of the Earth's Interior, Kagoshima 2013. Scientists from the University of Applied Sciences (UAS) in Düsseldorf in Germany, under the leadership of Professor Konradin Weber, participated in the program (IAVCEI 2013). The UAS team had previously reported that ash concentrations over Germany were less than predicted (Weber et al, 2012).

The current theory for the dispersion of ash clouds is based on the advection-diffusion theory (Suzuki, 1983), this theory is usually just named the diffusion theory. It disregards all density currents due to the gravitational effects of the ash content in the plume, but the in situ measurements revealed that they have to be taken into account (Eliasson et al, 2014b).

## 2. Modeling and simulations

It was not only Eyjafjallajökull 2010 that created great problems for commercial aviation in the North Atlantic because of the large extent of the predicted ash clouds from these eruptions. So did the Grímsvötn 2011 eruption but it lasted shorter.



Fig. 1 Ash cloud May 11th (Icelandic State TV).

The visible ash cloud was more often than not photographed by satellites as Fig. 1 shows. This comparison of the satellite pictures and the predicted ash clouds showed the prediction larger than the ash cloud in ratio 40:1. Other comparisons showed ratios 10:1 to 100:1 for both Eyjafjallajökull and Grímsvötn clouds, except in the end of the eruptions as the VACC models do not include resuspended ash.

This discrepancy has not been fully explained yet. Papers on simulation of the Eyjafjallajökull ash cloud 2010 in peer reviewed journals, usually tried to simulate the VAAC predictions rather than the satellite pictures. One example is in Fig. 2 (Folch et al 2012). This one is predicting a cloud 8 - 10 milligrams/m<sup>2</sup> (ash column value) over central Europe. Such a high concentration ash cloud would have been characterized as dangerous, they would have been clearly visible in the sky, created haze on the ground and made people with respiratory problems sick. Nothing such happened.

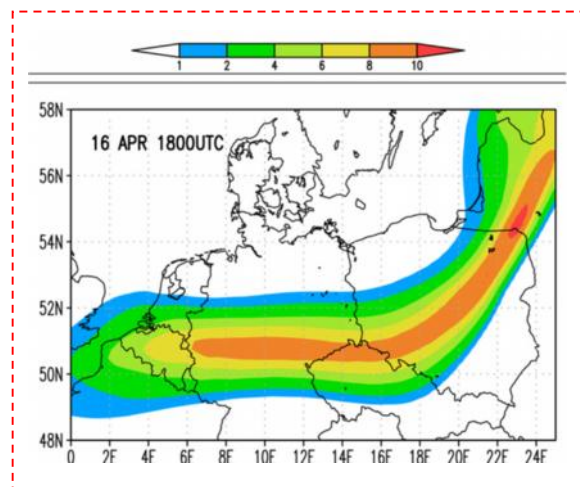


Fig. 2 Simulation by Folch et al

Measurements showed much lower ash concentrations over Europe than the predicted (Weber et al, 2012). The newest eruption in Iceland (Holuhraun - Bardarbunga) is less productive than Eyjafjallajökull but has lasted longer.

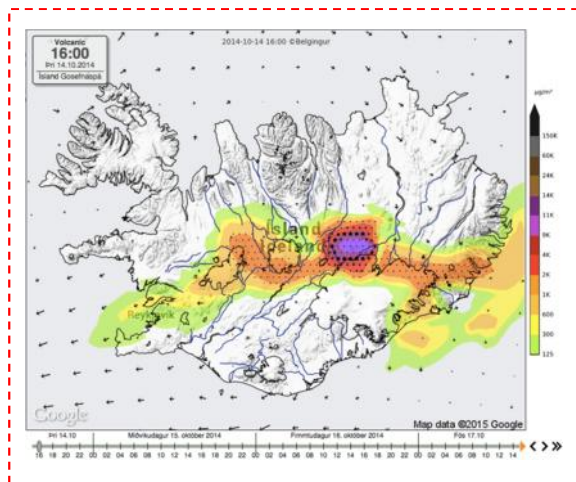


Fig. 3 Twelve hour forecast of SO<sub>2</sub> concentration (color scale in µg/m<sup>3</sup>), and ash (black dots) valid at 16 UTC 10, November 2014.

It produced lava, not ash, because it emerged in a dry place just north of the glacier where the caldera Bardarbunga is, but not in the caldera as the seismicity prior to the eruption indicated it would do. If its output had been ash, it could have produced greater problems for the aviation than experienced in 2010 and 2011. The plume contained mostly SO<sub>2</sub>; it was successfully modeled using the WRF-chem model.

The data obtained in the measurement campaign was used for calibration of the WRF-Chem model (Peckham et al, 2011) of the dispersion of SO<sub>2</sub> and ash. The model was run in operational forecast mode in the period mid October 2014 to the end of the eruption February 27<sup>th</sup>, 2015 for both ash and SO<sub>2</sub> concentrations (Fig. 3).

The forecasts were compared to ground observations and proved reliable more often than not. Observed uncertainty of the forecast was found due to combining factors such as the model not being able to resolve important flow features because of too coarse resolution, and errors in the source terms of pollutants.

This good result is also due to the fact that there are very little gravitational effects in the plume as the ash content is very low and even though the SO<sub>2</sub> content was high, SO<sub>2</sub> does not carry the same gravitational effects as volcanic ash does.

### 3. Dispersion physics

Two weak points in ash cloud prediction have been studied in Kyoto University's measurements and research of eruption plumes in Sakurajima. They are gravitational deformation of the plume and the streak fallout process. It turns out that both make ash content of clouds estimated with horizontal diffusion theory, larger than the actual.



Fig. 4 The weak points in dispersion modeling with diffusion-advection theory only.

There are three weak points in using the theory of diffusion-advection only without any gravitational terms when simulating dispersion of volcanic ash plumes. They are shown in Fig. 4. The first is well known, it is the inaccuracy of the Spark-Mastin formula that usually is applied to estimate the erupted mass rate. The two others are discoveries of the Sakurajima research.

This makes it important to use airborne measurements of volcanic ash as calibration data for simulations to improve prediction methods.

#### 3.1. Gravitational deformation of plumes

Tropospheric plumes tend to ride in stable inversions where the top layer of ambient air is slightly lighter (not necessarily hotter but with slightly less density) than the lower layer (Fig. 5). The plume must have approximately the average

density of the two layers to be buoyant. Under these conditions there will be slightly higher pressure in the center of the plume than in the ends. This creates a pressure gradient from the center out to the ends that forces the air to flow sideways in both directions and thereby flatten out the plume like an oil drop on water. In the same time the plume gets thinner, this is sometimes called pancaking of plumes.

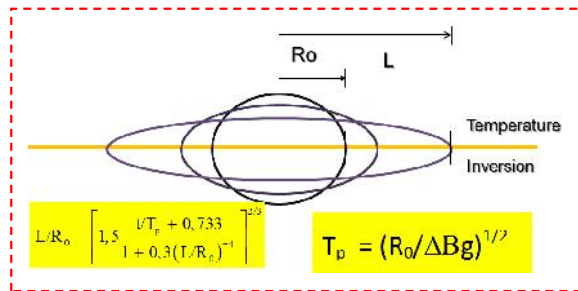


Fig. 5 Gravitational deformation from  $R_o$  to  $L$  in the time  $t$  with time constant  $T_p$ , relative density difference of ambient air layers is  $\Delta$ , and correction factor  $B$ . The  $g$  is the acceleration of gravity.

The relative density difference does not have to be more than 1 % to make the plumes spread out like oil slick on water, much faster than the velocity in the diffusion. But to model the process, temperature and density of the plume is needed and also data from radiosonde profiles on the properties of the ambient air. This data is not readily accessible. But satellite photos show visible ash clouds and provide data of the spreading that can be used in support of ash cloud predictions, this was tested on the Eyjafjallajökull plume (Eliasson et al 2014b).

But for an accurate model, data for the relative density difference ( $\Delta$ ) and the correction factor ( $B$ ) necessary to compute the plume time constant ( $T_p$ ) is needed and it may be difficult to obtain for running prediction models. Gravitational flattening spreads the plume out in the horizontal direction but the mixing layer is just a thin boundary between the plume and the ambient air. Measurements in Sakurajima have shown that mixing layers are thin and, concentration gradients high and diffusion constants low compared to what is used in horizontal diffusion models (Eliasson 2014b). In such models the whole plume is a mixing layer and the diffusion coefficient has to be an order of magnitude greater

than where gravitational flattening is active (Fig. 6).

The difference between the pure diffusion (PD) and gravitational dispersion (GD) is mainly that PD models must use the very high diffusion coefficients ( $K$ ) to get a realistic spreading of the plume that matches the observations on satellite pictures. In GD models one can use low  $K$ 's and this is more realistic and in better agreement with the measurements in Sakurajima.

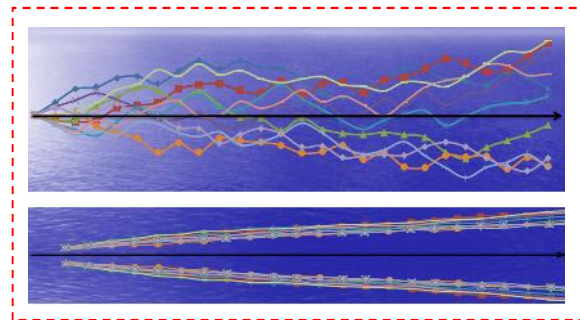


Fig. 6 Random walk models with small and large standard deviation used to demonstrate the effect of gravitational dispersion (lower picture) versus diffusion with high  $K$  (higher picture) and no gravitational effect.

### 3.2. Streak fallouts

The streak fallout process is most active close to the source where the plume is becoming horizontal and its temperature is cooling down.

The explanation of this phenomenon is that the downside of the plume gets denser as the heavy grains with higher terminal velocity fall down into and through the relatively thin diffusion layer (Fig. 6) and it cools down due to mixing. Eventually the underside loses its buoyancy and a chunk of cloud is falling down to earth. Fig. 7 shows an example from the Sakurajima measurements, July 2013.

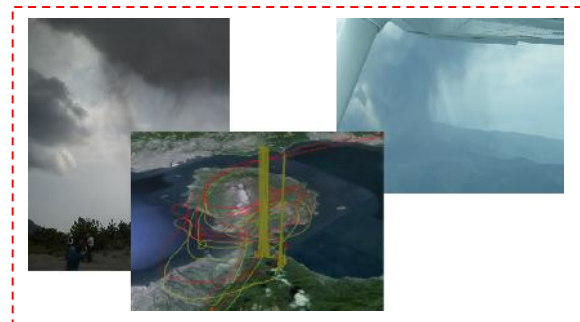


Fig. 7 A streak fallouts measured in Sakurajima

July 27 2013. Right: A picture taken 7 minutes before the measurement of this streak fallout. Center bottom: Google Earth presentations of the streak fallout measurement, yellow bars indicate ash concentration values; note the small concentrations on each side of the streak. Red dots show the GPS track.). Left: A group of scientists watching the streaks formed (Eliasson et al 2014b).

Fig. 7 (center) shows the biggest streak fallout as a yellow column. The downwards air current has a velocity 0.34 m/s and maximum concentration more than  $44 \text{ mg/m}^3$ , while the concentration in the side points is in tens or hundreds of  $\mu\text{g}$ . The hydrodynamics of the density currents in the streaks are very complicated and the onset of the streaks and the fallout flux they cause is not clear yet. There are indications that streaks are responsible for the majority of the fallout in the neighborhood of the source. In the Grímsvötn eruption 2011, which happened in the middle of the Vatnajökull glacier, the majority of the ash never got outside the glacier. This means not farther away from the source than 60 km, while the simulations predicted it to go to Greenland, several hundred kilometers to the north. Streaks diminish the ash flux, the flux of fine grained ash too, as they contain all grain sizes, so fallout of small grains may be large even though it is close to zero according to terminal fallout velocity theory. This increases the uncertainty of the simulation results.

In diffusion-advection models all fallout is modeled as grains falling through still air with the terminal velocity of the grains. But the aerosol size particles have so low terminal velocity that there is practically no fallout. But streak fallout takes all grain sizes as it is a vertical down flow of air, so actual plumes will contain less fine grained ash than the simulated ones while the streak fallout effect is not present in the models.

### 3.3 Satellite data corrections

The use of GD models is hampered by the fact that inversion data for the atmosphere is not readily available and the streak fallout theory is not developed yet. But a lot of information can be obtained from satellite pictures and used in practical

modeling and this has been nicely demonstrated by the Tokyo VACC (Fig. 8). This procedure is very effective and unique.

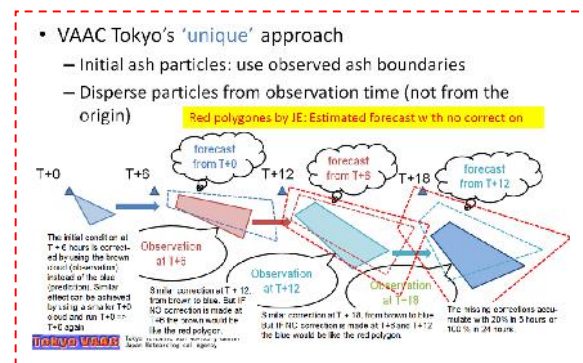


Fig. 8 Correction method with additions by JE. (Courtesy of Tokyo VACC)

The text on Fig. 8 explains the method. It is remarkable that in each 6 hours step, a reduction in the size of the cloud is necessary. If the simulation in Fig. 8 is done without the corrections, the red squares indicate how the error accumulates from each 6 hour step to the next step. In 24 hour this accumulation will mean a 3 times bigger cloud. This will further accumulate to 40 times in 3 - 4 days. This is close to the time it takes moderate northerly winds to carry volcanic ash clouds the 1000 - 2000 kilometers from Iceland to Europe.

## 4. Future aspects

New rules from ICAO, effective from November 2014, stress that jetliners should avoid visible ash. This relates to the current main interest in jet engine safety research by the manufactures. Here we take only one example from Rolls Royce it is Fig. 9. The yellow circle indicates the current area of interest. It circles jet engine operation for 6 minutes up to 10 hours in concentrations  $200 \mu\text{g}$  to  $10000 \mu\text{g/m}^3$ .

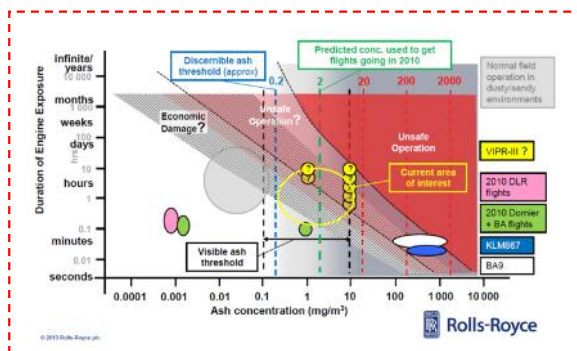


Fig. 9. The current area of interest in ash research (Courtesy of Rory Clarkson Rolls Royce).

The midpoint concentration in this interval is the green punctuated line in Fig. 9. It indicates the concentration  $2 \text{ mg/m}^3$ , this is almost the same concentration as the visible ash threshold (Elíasson 2014a). Most VAAC's use satellite pictures to localize visible ash.

The new rules from ICAO, the main area of interest in jet engine research tell us that the unique approach used by JMA's Tokyo VAAC is very advanced. Fig. 8 shows an example of how satellite picture information can be evaluated and put into practical use in forecasting. When we observe ash clouds on satellite imagery, we set 'initial particle distribution' in accordance with the observed ash cloud boundaries, and start the dispersion model from the observation time, and update the size of the prediction in such a way that accumulation of error is prevented. And because the predominant information from satellite pictures is the visible cloud, this procedure is in accordance with best practices, as defined by ICAO and in the research concerning jet engine safety.

## 5. Conclusions

The in situ measurements of volcanic ash in Sakurajima are a research that has brought valuable data that can be used for calibration of plume models and construction of new ones.

Contemporary ash cloud predictions are done using the horizontal advection-diffusion equation in Lagrangian or Eulerian models, mostly with the plume height and the Spark-Mastin equation as

source flux data and atmosphere data from NWP models, but no further calibration. This does not include the gravitational flattening and the streak fallouts processes that have been discovered in the in situ airborne measurements in Sakurajima.

The absence of gravitational flattening and streak fallouts processes cause concentration to become higher in the predictions than in nature. This can make source models too inaccurate. We need adjustment of source data using satellite photos to a larger extent. New models may need radiosonde data for air density not available in the NWP models.

The satellite imaginary data is very valuable in this situation. The most advanced method today is used by the Tokyo VAAC, it prevents accumulation of errors in the prediction that over long distances can become very large

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