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Original paper

The role of in-situ measurements of volcanic ash concentrations in preventing economic disasters due to volcanic ash clouds

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Abstract During the Eyjafjallajökull eruption in 2010 and the Grimsvotn eruption in 2011, a lot of airports where closed because ash cloud predictions were much on the safe side compared to the actual ash clouds. This created a staggering economic disaster. An extent of predicted ash clouds, up to 40 times the size of the real clouds, are documented. Modern methods in disaster prevention can probably not eliminate airport closures altogether, but including in-situ airborne measurements of volcanic ash concentrations with OPC technology and other scientific methods of ash cloud assessment can reduce unnecessary airport closings to insignificant levels. Airborne measurements by a team of German, Icelandic and Japanese scientists have shown that important methods, additional to computer simulations by source models, are available. An example of parameter and ash volume predictions is shown, supported by measurements from Iceland, Germany and Japan. It is concluded, that point source diffusion models can only have a limited value in predicting scenarios of ash clouds, unless supported by in-situ observations of good quality.

Key words Volcanic ash; disaster prevention; in-situ observations; OPC measurements; dispersion models.

1. INTRODUCTION

Mitigating volcanic ash in civil aviation: State of the art

The worldwide network of Volcanic Ash Advisory Centers was set up by the International Civil Aviation Organization (ICAO), an agency of the United Nations. As at 2010, there are nine Volcanic Ash Advisory Centers located around the world, each one focusing on a particular geographical region. They are responsible for coordinating and disseminating information on volcanic ash that may endanger aircraft. [5] Generally, the system has worked well.

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[5] The system is shown on http://en.wikipedia.org/wiki/VAAC

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Sometime in the late nineties, the London VAAC, operated by UKMO, started to use its NAME dispersion model - originally devised for dispersion of radioactivity from the Chernobyl disaster -, to simulate volcanic ash clouds for their predictions. When insufficient volcanological and meteorological data[6] hampered the predictions, the safety first principle seems to have been used to estimate the missing parameters, turning relatively moderate volcanic plumes into huge clouds (Jonas Eliasson; 2012b). The Eyjafjallajökull ash cloud predictions from the London VACC were particularly notorious, sometimes predicting clouds 40 times wider than the visible plume (Figure 1)[7]. Similar predictions appeared when Grímvotn in Iceland erupted 2011.

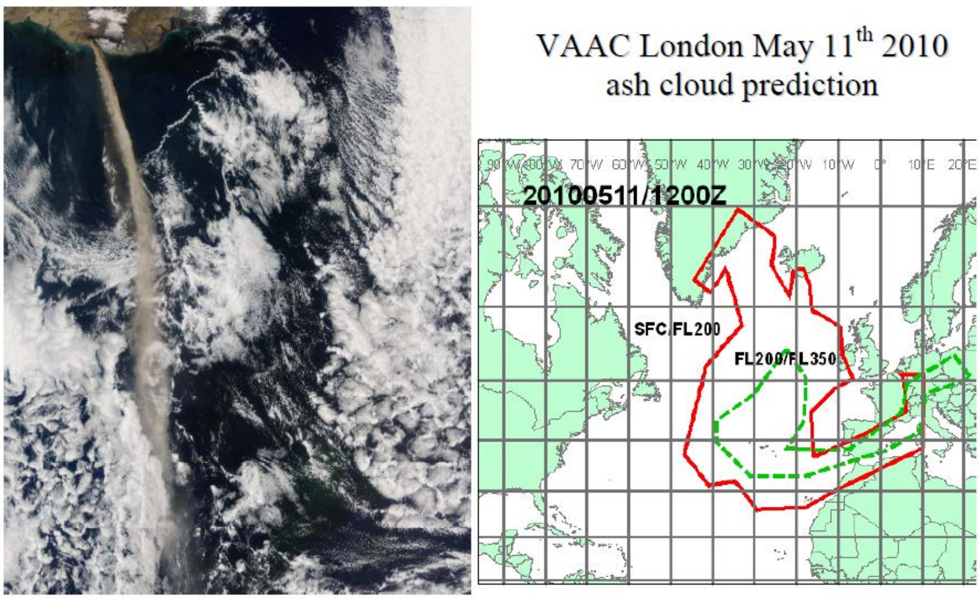

Figure 1. The Eyjafjallajökull plume for May 11th and the corresponding VAAC prediction.

Eyjafjallajökull and Grímsvotn eruptions were small to moderate events. Without the VAAC simulations, they would not have disturbed air traffic more than did the Grímvotn eruptions in 1996, 1998 and 2004, (Grímsvotn 2013). It does not look like ICAO is going to change VAAC system operation tactics; it is also difficult as all other VAAC's do not have a story of unnecessary airport closures behind

[6] Total mass flux from the vent, gas concentration, plume height and grain size distribution is unknown from the onset of the eruption. The only thing that can be direcly observed on a day to day basis is the plume height and VAAC London uses it to estimate mass flux. The most important thing however, is the fallout due to grain size, only aerosol size particles stay in the air long enough to harass airplanes that keep a safe distance off the vent. Meteorological observations of such quality that turbulent mixing and dispersion can be estimated from them, are almost non-existing over the North Atlantic Ocean, e. g., there are no radiosonde data from the region.

[7] The following air traffic chaos and economic disaster was due to the inexperience of the London VAAC because Eurocontrol and the ANSP′s followed their advisory (International Mini-Seminar on Icelandic Volcanic Eruption and Impacts on Aviation Systems: Hazard, Socio-Economic Impact, and Global Risk Governance, Kyoto University 2010, conference summary by Dr. Cornelia Templin, Frankfurt Airport, Germany).

them, comparable to the Eyjafjallajökull event in 2010. This means in practice all efforts have to be made to produce dispersion models that can be used in air navigation service without causing unnecessary airport closings. This is not easy and it is probably not possible to avoid unnecessary closings entirely, but the economic loss should not reach billions of dollars. A closer discussion is in Appendix A.

2. DEVELOPMENTS IN MITIGATING VOLCANIC ASH PROBLEMS IN CIVIL AVIATION

2.1 OPC measurement technology

Modern technology offers the possibility to measure the concentration of volcanic ash in-situ from airplanes equipped with optical particle counters. In one hour, such observations easily render 600 results from a streak of 150– 200 km. In actual air navigation service operations, instruments must be calibrated and observation quality has to be assured.

The technology of using OPC meters to observe concentrations of volcanic ash in the air is adequately described (Weber *et al.* 2011b) with examples of actual measurements in Iceland and Germany and also quality control and analysis. To ensure good quality of airborne ob-servations it is helpful to have two OPC meters at the aircraft.

The measurements thus performed can show an accurate concentration value. This value has two components, one is the pseudo steady value representing the average dispersion process, which is the value actually wanted. The other component is the instantaneous value of a random fluctuation. The ratio between the random fluctuation and the pseudo steady value is relatively large compared to other geophysical observations (Elíasson 2012a). The random component cannot be modeled in the time domain and does not correlate between measurements. So when the observation values are processed, the random component has to be filtered out by using a Gaussian (or another appropriate) filter. But when this is done the two meters correlate nicely if properly calibrated and the observation result can be compared to expected values and predictions. Comparing unfiltered values to dispersion model results can give very misleading results. To take an example, comparing maximum model values to maximum observed values will almost certainly render inaccurate conclusions.

Care must be taken when observing plumes close to the source vent. In a measurement campaign in the plume from Mount Sakurajima in Japan concentrations up to 20 mg/m3 were observed (IAVCEI (2013) all papers). It is questionable if measurements should be tried in higher concentrations.

However, in the case of mitigating danger from Icelandic volcanoes, it is hardly necessary to measure high concentrations. Experience from 2010 and 2011 confirms that only plumes with low concentrations thin concentrations reached Europe (Weber et al 2011b), (Weber et al 2011c), (Schuman et al 2011). If clear satellite pictures are not available, plumes can be tracked by a similar method as used on the Eyjafjallajökull plume May 11th 2010 (Eliasson et al. 2010).

The boundary tracking method used in Elíasson et al. (2010) can be used as a general method of tracking the extent of volcanic plumes. During its course, the plume thins out because of dispersion and fallout (Figure 1). Where it is sufficiently thinned out for safe crossing in a piston motor powered aircraft, measurements can be made with OPC meters and GPS tracking and concentrations, particle sizes, dispersion parameters and fallout parameters estimated. (Eliasson et al. 2010), (Weber et al 2011b), (Eliasson 2010a). The GPS track can then be used as an initial boundary condition in plume simulation and prediction.

It is very important that the meters are calibrated for the properties of the actual ash they are measuring. Properties like grain density and refraction index are particularly important in order to achieve accurate measurements of the concentration (Weber *et al.* 2012b).

The concentration of volcanic gasses is important especially the sulfur, i.e. SO2 and H2S. These are also poisonous. Several technologies exist for airborne measurement of the concentration of gas in the air (Weber *et al.* 2012b).

2.2 Airport measurements

During the Grimsvotn eruption May 21st – 26th, Keflavik International airport in Iceland closed on May 22nd opened again on May 23rd, but on May 24th unfavorable ash cloud predictions were issued. From May 24th - May 26th the UI (University of Iceland) performed an in-situ airborne OPC measurements campaign for the Icelandic ANSP (Air Navigation Service Provider) Isavia, in cooperation with the UAS (University of Applied Sciences) in Düsseldorf Germany.

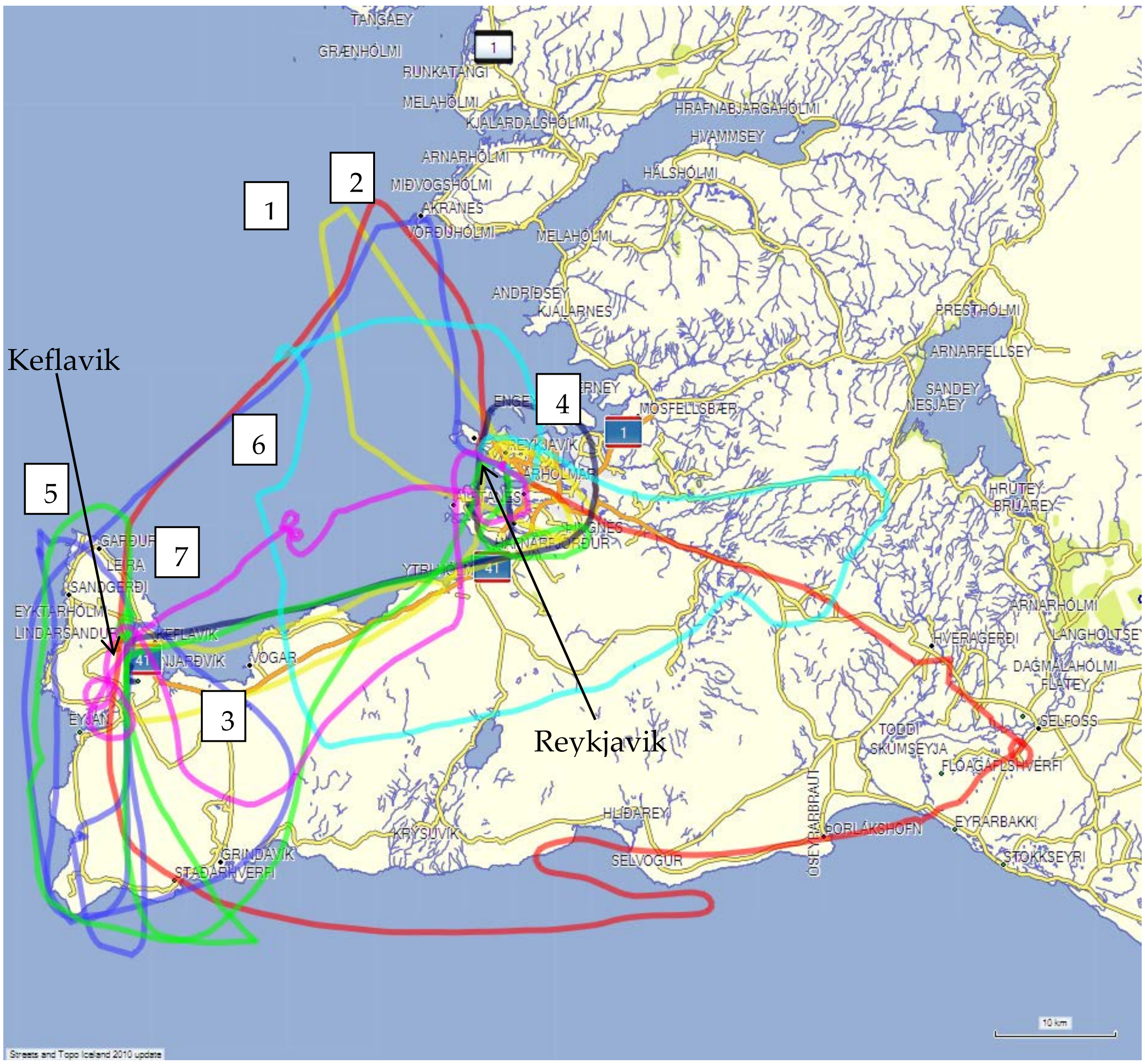

Figure 2. Measurement campaign for Isavia May 2011, flight tracks No 1 to 7. No significant ash clouds detected.

Figure 2 shows the flight tracks of the seven measurement flights flown for Isavia May 24th – 26th. The aircraft was a Cessna 206 (Weber *et al* 2011b) with two different instruments in the plane, a Grimm 109 and a DustMate industrial OPC. They were arranged in different ways for quality control purposes. The two arrangements available are the well-known isokinetic method on one hand and the slip stream method on the other. Figure 3 shows the slip stream arrangement. It is so constructed, that one of the passenger's seats in the plane is taken out and the stool put there instead. The hose is connected to the ventilation system of the plane and the butterfly valve is used to adjust the velocity in the pipe so the airspeed through the ventilation inlet opening on the outside of the plane matches the plane's cruising speed (usually 80 – 120 knots) and is thus isokinetic. Thus, the correct concentration will enter a closed duct, where the airflow is carried to the intake of the OPC meter. A wide intake opening is placed in very low air velocity so that the concentration errors due to different velocities in the intake and the outside air are insignificant.

The observations acquired were sent over the internet to Isavia and the Icelandic Meteorological Office. They showed that volcanic ash pollution in the air was insignificant all the time and thus it was possible to keep Keflavik International airport and Reykjavik airport open until the eruption ended. (Elíasson *et al.* 2011a). This is the first time OPC technology was used as a tool in practical air navigation service to avoid closing an airport because of an unfavorable ash cloud prediction.

The airborne OPC measurement technology is relatively new and this is a very important example of an ANSP using this technique, but this cooperation with the meteorologists who prepare the SIGMET´s for the aviation and the ANSP´s that prepare the NOTAM´s for the pilots, proved to be very valuable in avoiding unnecessary airport closures. Moreover, the German Weather Service DWD used aircraft measurements during the Grimsvötn eruption also as information source for evaluation of the ash plume over Germany and will use aircraft measurements for additional information about ash plume concentrations in case of another future volcanic eruption in Europe (DWD Air Measurements).

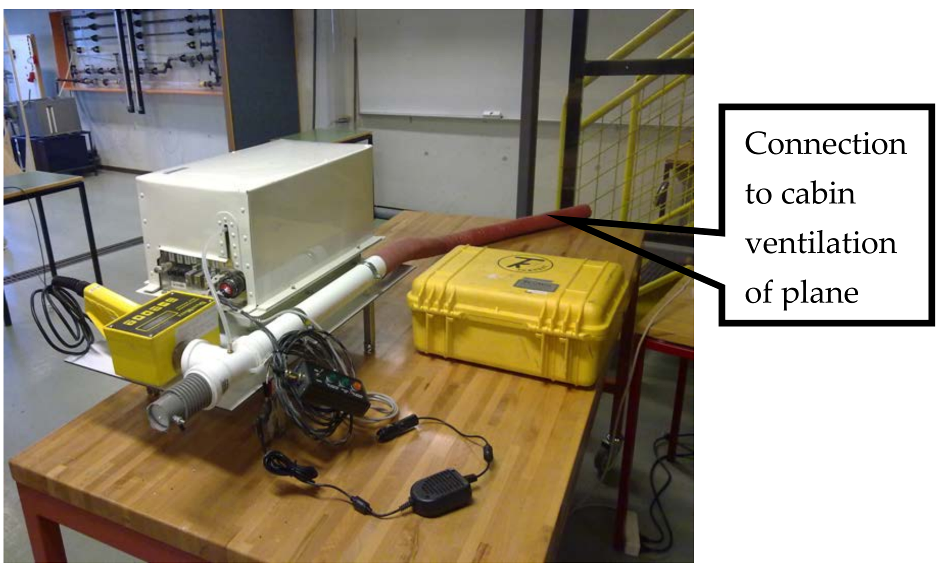

Figure 3. A SKY OPC and an industrial DUSTMATE OPC slip stream mounted on a stool for easy installation in a Cessna 206.

Since 2010 there have been many eruptions, for example, Indonesia, New Zealand and South America. They have not caused continental flight bans.

Airborne measurements of volcanic ash are ideal to prevent disasters like the Eyjafjallajökull incident. The Icelandic Civil defense service maintains preparedness to step in when natural disasters occur. Their system has scenarios of probable volcanic events that can cause a major disaster. An example of such events are the volcanos Katla (1918), Hekla (1947) and Askja (1875 and 1961) in Iceland. The Icelandic civil defense service has prepared evacuation and assistance plans in case of such eruptions, but they do not yet include airborne observations of ash concentrations.

3. DISPERSION MODELING

There are two main kinds of dispersion models: Firstly is the Lagrangian method, the concentration of ash along the streamlines is tracked and a sub grid model used to allude the turbulent mixing with a random walk subroutine. Secondly there are the Eulerian models that solve a Reynolds transport equation in a fixed grid. The dispersion models are very complicated software, they accept only initial and boundary values at the source, i.e. the volcanoes crater. Several models are described in accessible internet sources (Atmospheric_dispersion_modeling 2013). There is also free software on the internet, e.g. the FLEXPART and WRF models; they are both downloadable from their homepages.

Dispersion models use a known wind field from a numerical weather prediction model. This means that the effects of ash gravity on airflow and, therefore the dust concentration, are not included, this may be a serious drawback in the near-field. In the Grímvotn eruption 2011 the hot eruption column sank down and left the majority of the ash on the surface of the Vatnajökull glacier. This is assumed to have been the main reason for that no ash was detected in the Keflavik airport measurement campaign on May 24 – 26th (Eliasson *et al.* 2011b).

A concentration 2 mg/m^3 in an ash cloud with a significant extent is visible with the naked eye (Appendix A). Therefore, clouds of volcanic ash, dangerous for jet aircraft, can be photographed. Such photographs give very good information as they show exactly the visual part of the cloud, but the visual part is sometimes difficult to identify from LIDAR or radar pictures. Here satellite photos are especially valuable. Figure 1 shows the plume boundary clearly (Elíasson *et al* (2010) and it shows also where the visible plume ends about 600 – 800 km south of Iceland due to dispersion and fallout. Here the fallout is the major factor. It is possible to adjust simulation results to satellite pictures like this and airborne measurement data. This is difficult to do in a Lagrangian global model however; the simulators have to change the source data and the dispersion parameters using a hands-on technique. This is a much better method than using the "safety first" principle all the time to produce an educated guess for missing parameters.

Better time histories of source data from remote sensing may help, but they don't give any dispersion parameters or fallout data. It is also a problem, that due to vertical air movements and other unmapped meteorological phenomena, the clouds can undergo enormous changes over the distances of hundreds of kilometers from Iceland to Europe. This is especially true when clouds are carried from the sea and move in over land, so we need more than new volcanological data if reliable ash cloud predictions are to be produced. Better plume dynamics, with gravitational effects on the flow included, are also needed.

Cooperation between the scientific community and the civil service organizations is ideal to construct an effective aviation disaster prevention system. The first task is likely to be eruption scenarios and estimation of their consequences with and without airborne measurements of volcanic ash. The Sakurajima research, measurements models and scaling of them (see later), is likely to be an effective tool in this work.

Figure 4 shows a proposal to the Icelandic Civil Aviation Authorities from 2011. In-situ airborne ash concentration measurements, as shown in Figure 2, would be performed around the airfields shown by violet dots in the picture. The results would be anchor points in ash cloud simulation and prediction. The measurements results serve as starting values in the prediction of ash concentrations over these airports and the flight routes between them. This is just like in-situ weather observations; they are used as anchor values to produce reliable weather predictions. If this system is adopted, the airport measurements would, besides aiding the ANSP, increase the accuracy of the simulations also.

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The first step in this plan is a preparedness contract, recently completed between the UAS in Düsseldorf and the German Weather Service. This contract covers Germany and neighborhood areas and ensures that concentrations over a large area are known.

The data can be assimilated into the simulations so the predictions cannot stray as far off as they do when the only initial data is 1000 km up north. This assimilation of measurements to models can be done using Kalman filtering and related methods, this technique is under development.[8] This process is a difficult task, a continuous stream of concentration data is needed alongside the model runs and the measurement results must be assimilated into the model using a technique that is still under development. However, this method of using local observations as anchor points in a regional prediction is the normal practice in weather forecasts and is much more reliable than a sole Lagrangian tracking from the source to the point of prediction, a transport that can take several days for volcanic ash from Iceland to Europe.

4. MEASUREMENT EXAMPLES

4.1 Iceland

During the Eyjafjallajökull events in 2010 the airborne in-situ measurement technology with OPCs´ was in its beginning. The four measurements of the Eyjafjallajökull plume avail-able from that time are posted on UI´s website9. The seven airport measurements runs for Isavia have already been described. Two other measurements are available on the same URL. The measurement May 22nd is very interesting, it shows an ash front, visually observed in Selfoss, migrating north and south of a mountain. It reached Reykjavik, but not Keflavik airport. But Keflavik airport was closed, not Reykjavik. These measurements are also in (Weber et al 2011c) and (Weber et al 2012) where they are displayed using a new technology.

[8] http://www.hi.is/sites/default/files/oldSchool/ThPAssimilation%20of%20VA%20Forecasting..pdf
[9] http://www.hi.is/umhverfis_og_byggingarverkfraedideild/greinar

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4.2 Germany

Measurements over Germany during the volcanic events in 2010 and 2011 are shown in Weber *et al* 2012. The work shows the very inhomogeneous nature of the ash cloud over northern Europe on May 18th 2010. It is demonstrated in this paper, that the prediction that day is missing a lot of the details uncovered in the OPC measurements.

4.3 Mount Sakurajima Japan

Volcanic eruptions are rare, so calibration of models and training of personnel for observation and modeling is difficult. The volcano Sakurajima in Kagoshima prefecture emits isolated ash puffs in several eruptions every day so the opportunity to get valuable measurements, train personnel and develop new technologies is better in the Sakurajima area than other places in the world.

Figure 4. 30 possible sites for airport measurements of local dust pollution

A measurement campaign was performed in January 2013 by Kyoto University in cooperation with UI and UAS around Sakurajima. Only the special features directly related to the subject of this paper will be described here.

The possibility of scaling smaller clouds to bigger ones (IAVCEI 2013, Eliasson *et al.* 2011a) adds a new dimension to in-situ measurements. Volcanic plumes can be scaled; even plumes from the same eruption of the same mountain can be scaled according to plume height and wind velocity.

The scaling equation is the diffusion-advection equation used in Suzuki (1983) and many other papers since for dispersion of volcanic plumes.

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \Delta(K\Delta C) \qquad \text{Eq. 1}$$

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Here, C is the concentration of ash, U the wind velocity, K the eddy diffusivity and Δ the gradient/divergence operator in the horizontal coordinates x and y. When this equation is used to derive the scales, following scale relations are derived for the model and the prototype

$[UT/L]_m = [UT/L]_p$ and $[KT/L^2]_m = [KT/L^2]_p$. Eq. 2

Here U, T and L are characteristic velocity, time and length in model (m) and prototype (p). When Eq. 2 holds, geometric and dynamic similarity is assured between model and prototype according to the classical modelling theories of hydrodynamics.

The strength of the eruption source at the source is a big problem. The VACC simulators mostly accept the popular formula by Wilson *et al* (1978) and Settle (1978) that the total mass output in kg/s is proportional to plume height in 4^{th} power. When this holds, most volcanic eruptions are models of each other, provided the wind field is the same.

The method presupposes that relative grain size distribution does not change, e. g. $d_{50,old}$ size particles unscaled, scale to a new size $d_{50,new}$ but their relative position is still 50 % in the total grain distribution curve.

Table 1. Properties and scaling of puff No. 1, Sakurajima plume

Diffusion paramers			**Puff size and grain size**			**Scaled puff**		
a (a^2=4Kt)	1630	meters	Puff mass	363	tons	Puff mass	17805	tons
Center C	10250	μgr/m^3	Total rad	3357	m	Total rad	8886	m
Correl	98 %	e-$(r/a)^2$	Visible r	1660	m	Visible r	4395	m
St error	984	μgr/m^3	Eff. rad	1791	m	Eff. Rad	4740	m
K	346	m^2/s	d_{90} μm	d_{50} μm	d_{10} m	d_{90} μm	d_{50} μm	d_{10} μm
			10,1	4,7	1,4	13,2	6,2	1,8

To show how this works, Table 1 shows a scaling of a puff, created 15.01. 2013 by an explosion in Sakurajima to a maximum height of H_m = 1700 m in a U_m wind 7 m/s. The puff is scaled to H_p = 4500 m and wind U_p = 12 m/s.

In estimating dangerous eruption scenarios and associated ash plumes from mountains with a recorded eruption history, the scaling method is a tremendous help. To mention an example, the eruption of Reventador Nov. 3rd 2002[10] is reported to have "probably" caused a serious flight incident on Nov. 23/24th 2002 (Tupper *et al* 2006) over Micronesia 14000 km away. The eruption was explosive, reached an altitude of 18000 meters but lasted only 8 hours. The source location could have been further supported if the eruption had been scaled to a known Andean eruption with the properties displayed in Fig. 1, i.e. source location, widening of plume (for estimation of K) and the end point where visible plume disintegrates.

Simulated ash clouds created by similar meteorological histories can be scaled in exactly the same manner as actual plumes. However, the above mentioned example shows clearly, that tracking by simulation, even supported by satellite imaginary has its limitations. This is especially true in the tropics

[10] http://disc.sci.gsfc.nasa.gov/education-and-outreach/images/Reventador_Nov3_2002.jpg

when there is heavy convection and cloud formation to great heights.

The uncertainty about the column height – eruption mass relation of Wilson and Settle is a problem. But if other information on the output is available, a length scale can be deduced from that information and used instead.

5. CONCLUSIONS

The use of OPC technology for airborne measurements of volcanic ash is a young science with great development potential. This science includes several fields, such as instrument arrangement, instrument calibration and quality assurance for various ash properties, data analysis and display, calibration of dispersion models, measurements of mass flux in plumes, fallout estimations and many more. Relatively few papers addressing these subjects have been published in scientific journals.

Imperfect ash plume simulations alone can as the result, show too large clouds. This has, caused airport closings and economic losses. The accuracy in dispersion models has to improve in order to produce better predictions of ash clouds dangerous for civil aviation. There is a great need for this resilience effort in order to limit the costs of airport closings in the future to a minimum.

Better volcanological data for output rates and grain size distribution are needed for ash plume simulations and prediction.

Tracking volcanic plumes alongside the visible boundary and airport measurements may be a valuable tool in preventing airport closures and mapping volcanic clouds.

A successful model of an eruption where the concentrations are known may be scaled to represent a different event. It can also be scaled to represent the pollution from a plume. This method may be used to construct plume maps for different plume heights and wind velocities. Event scenarios that have occurred in the past or are anticipated to occur sometime in the future may also be established.

Sakurajima in Japan is a good location to develop this science and make the results count in practical disaster prevention effort.

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Appendix A

The danger for civil jetliners and the problem of ash cloud predictions

The most common description of this danger is that the heat in the burning chambers of the jet engine melts the silicon dioxide particles and when they are carried into the exhaust turbine they stick to the blades, solidify, clog the turbine and the engine stops as Fig. A1 explains. This obviously takes some time, so a sharp limit on "safe" ash concentrations does not seem to be applicable as a safety limit, a time limit on the flight in this concentration should also be included. A total ash intake by the engine, i.e. a concentration value multiplied by the flying time in the ash, could be more appropriate. Never the less, today's safety limits prescribe that if the ash concentration is 2 mg/m3 [11] or less, the aircrafts should be safe. It so happens, that this is approximately the concentration limit for visible ash clouds (Elíasson, et al (2010)). This makes dangerous ash clouds easy to detect during daylight hours, but flights at night become more problematic, therefore the predictions are used. However, to issue graphics of ash clouds 40 – 100 times bigger than the actual plumes evokes new problems, unnecessary flight bans, closing of airports, stranded passengers in desperate situations, chaos in air traffic and enormous economic loss because modern society depends so heavily upon air traffic (Perkins 2010).

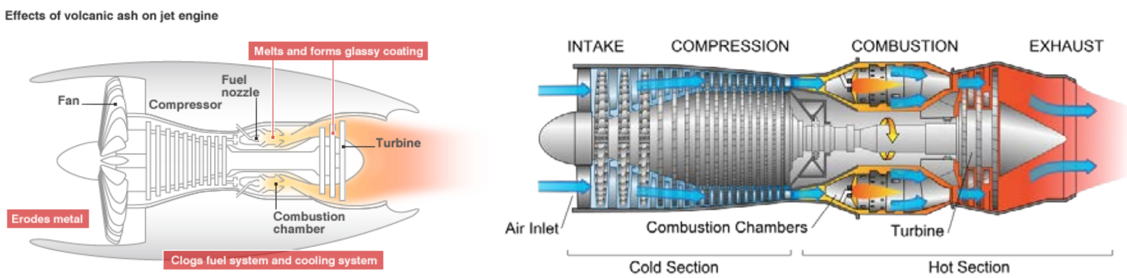

Fig A1 Jet engine. Left: Engine with fan. Right: The engine core and the core flow

At present, the flight danger zone is 2 – 4 mg/m3, but in the future the 4 mg/m3 limit will probably be rescinded. The reason is not because of the problem with the motors; but rather that passengers are endangered if the cabin air contains more volcanic ash dust than 2 mg/m3, as contamination this high is way above all public health limits.

If this rule is adapted passenger aircraft are to be kept out of visible ash clouds (pollution > 2 mg/m3) and that would take care of the engine problem. Civil airliners sometimes fly through air contaminated with dust up to the 2 mg/m3 limit or higher[12] such as fly ash[13], street dust and desert sand. Strictly speaking, jets should also be kept out of this type of dust pollution, as the dust contains sufficient silicon

[11] Announced in the video conference of the European Transport ministers April 19th, 2010.
[12] On June 6th 2010 a concentration 6 mgr/m3 was observed outside University of Iceland laboratory less than 1 km from Reykjavik airport. This was resuspended Eyjafjallajökull ash but the eruption had stopped and no warnings were issued by the VACC. Flights continued in spite of reduced visibility.<http://www.hi.is/sites/default/files/oldSchool/Measurement%20of%20fly%20ash%20June%204th%202010%2015.pdf>
[13] This is the closest relative to volcanic ash with extensively researched properties. It is carried by wind over large distances. Fly ash, a residues of coal combustion contains substantial amounts of silicon dioxide. Two classes of fly ash are defined by ASTM C618: Class F and Class C. They range in size from 0.5 μm to 100 μm. Respective settling velocities in still air are 1.7 and 68.800 meters per day. Fly ash from Iceland volcanoes encountered in Europe will therefore have diameter sizes less than 50 μm.

dioxide to inflict the same damage upon exhaust turbines in jet engines as volcanic ash does.

However, similar rules to flights in dust polluted areas as those valid for flights in volcanic ash clouds have not been implemented. Experience shows that flights in dust pollution means shorter lifetime of the motors, but they don't break down or stop on the spot like the BEA flight in 1982 (British Airways Flight 9 2013). What happened then is probably that the ash load was so heavy that ash sediments in the burning chambers of the engines destroyed the fuel/air ratio, suffocated the flame, and stopped the motors. This cannot be proved, but the motors started again when the plane dived out of the ash plume. The motors would not have started again if the exhaust turbines were destroyed, but the free air flow through the engine core during the descent can clean out ash sediments from the combustion chambers (Fig. A1).

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