International Civil Aviation Organization

WORKING PAPER

INTERNATIONAL VOLCANIC ASH TASK FORCE (IVATF)

FIRST MEETING

Montréal, 27 to 30 July 2010

Agenda Item 7: Improvement and harmonization of dispersion models and their visual presentation (IAVW Coordination Group)
7.1: Need for additional work on dispersion models

EFFECT OF VOLCANIC INPUT ON UNCERTAINTIES IN FORECASTING VOLCANIC ASH CONCENTRATIONS IN THE ATMOSPHERE

(Presented by the United States)

SUMMARY

An analysis is presented of the effect of eruption-source parameters (plume height, mass eruption rate, and particle size/fallout rate) on dispersion-model forecasts of ash-cloud location, concentration, and longevity. To the extent that eruption-source parameters and natural ash removal processes are not well constrained in real situations, considerable uncertainties are introduced into dispersion-model outputs. This topic needs more attention if ash concentration maps are to be used operationally to define fly-through zones.

1.   INTRODUCTION

1.1   As a result of the widespread, week-long closure of airspace over Europe and the North Atlantic during the April 2010 eruption of Eyjafjallajökull volcano in Iceland, new policies are being considered to allow commercial passenger flights in airspace with dilute ash contamination under some circumstances. A key to operational implementation of such policies is the depiction on maps of contoured areas of forecast ash concentrations (in units of grams per cubic meter). Accordingly, it makes sense for the diverse parties involved to be aware of the uncertainties in such forecasts.

1.2   Numerical models of ash-cloud movement can forecast locations of ash clouds and, in principle, can forecast ash concentrations, in a quantitative manner that is not possible through most remote sensing or other observational methods. However, the accuracy of such models hinges in large part their input data, which historically have not been well constrained during eruptions. In this paper, we analyze the effect of eruption source parameters on the uncertainties in modeled forecasts of ash-cloud location, concentration, and longevity.

2.   ANALYSIS

2.1   Several different numerical models are used operationally by Volcanic Ash Advisory Centers (VAAC) to forecast the location and movement of ash clouds as guidance to the preparation of a Volcanic Ash Significant Meteorological Information notice (SIGMET). But regardless of the particular model used, several types of input related to the volcanic source must be known or estimated during an eruption:

> — *Height of the volcanic plume.* This is the most important volcanic input, as it determines whether ash exists at typical jet cruise altitudes and in what wind fields and weather systems it disperses. Plume heights can range from less than a kilometer to nearly 50 km. They can be estimated from several satellite techniques, radar, or observations by ground observers or pilots. All these observations have uncertainties. Where multiple estimates of plume height are available, they commonly vary by several kilometers.
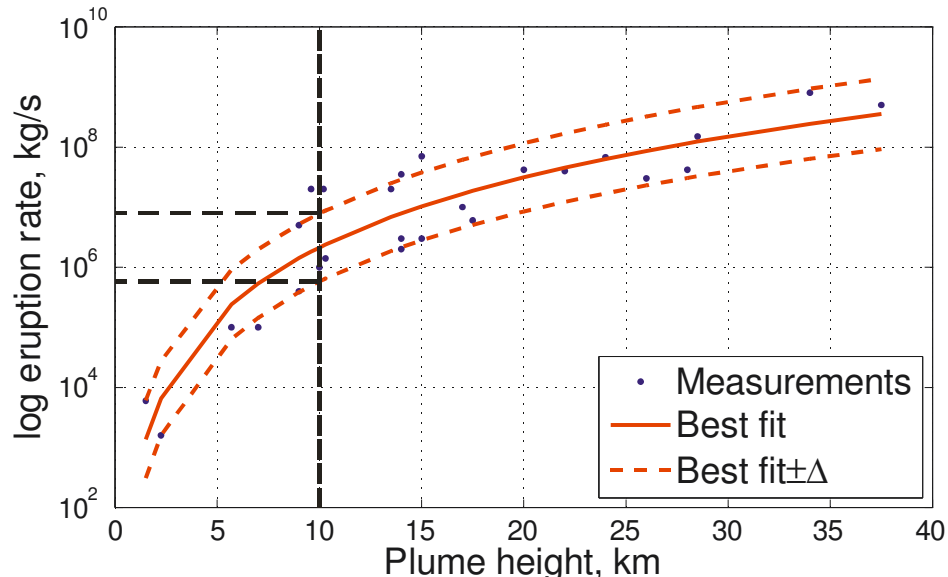
Figure 1: Plot of log eruption rate versus plume height for eruptions in which these quantities have been estimated. Mass eruption rates were was estimated for each eruption by measuring the mass distribution the ash that fell onto the ground surface, integrating to obtain erupted mass, and dividing this mass by the duration of the eruption. Dashed black lines indicate the range of eruption rates that might correspond to a plume height of 10 km.

> — *Mass eruption rate, or rate at which ash is pumped into the atmosphere.* Ash concentration in volcanic clouds is directly related to this rate, which ranges over more than five orders of magnitude for historical events. The mass eruption rate cannot be determined directly during an eruption; it can only be estimated by correlation with plume height (Fig. 1). There is considerable scatter in the relationship of mass eruption rate and plume height, which reflects both real variance and measurement error. A plume height of 10 km correlates best with an eruption rate of about 1.8 million kg/s; but within the 1 standard-deviation

error it could range from ~0.7 million kg/s to 8 million kg/s—more than an order of magnitude (Fig. 1). Deviations from this trend are especially common among small eruptions in tropical regions, where plume height is boosted by the latent heat of rising moist air.
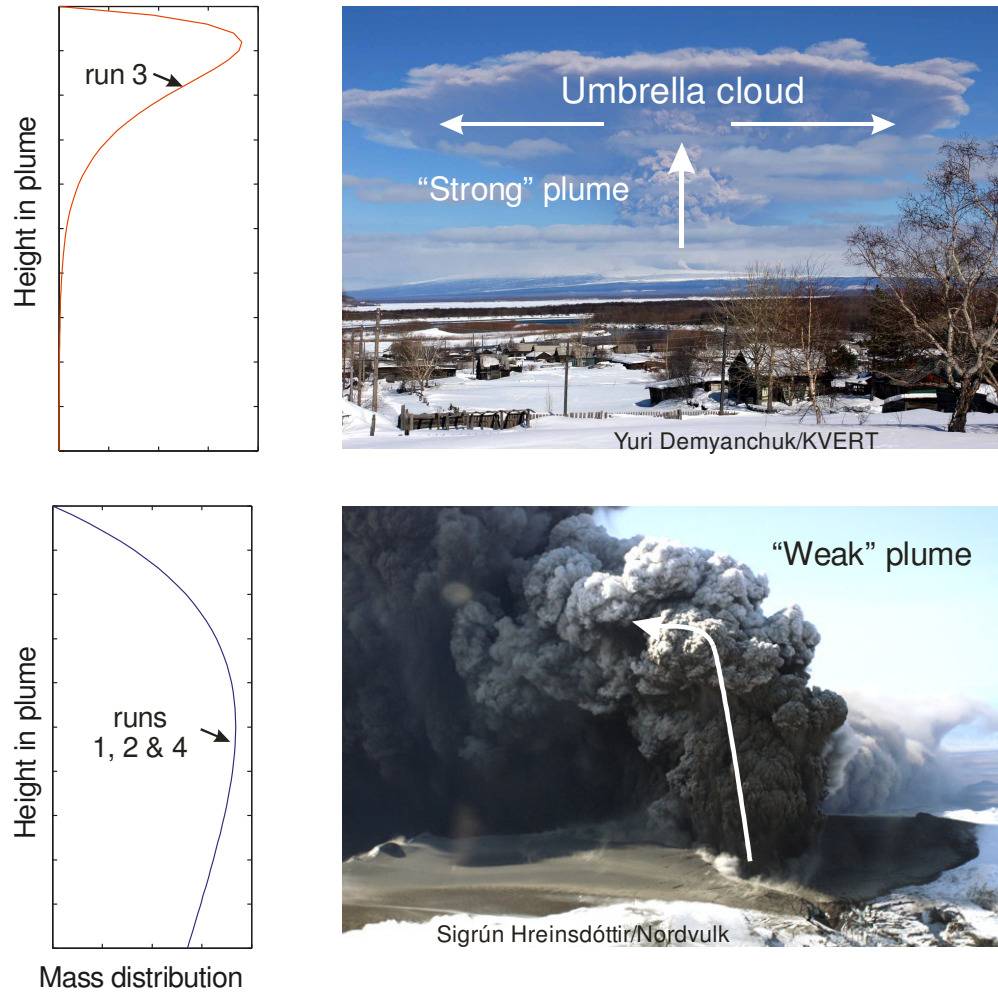
Figure 2: Example of two types of volcanic plumes with different distributions of erupted mass with elevation in the plume. Top: a strong plume ascending from Sheveluch Volcano, March 9, 2009 (photo by Yuri Demyanchuk/KVERT). In strong plumes, tephra rapidly ascends straight up into an umbrella cloud and then spreads out laterally. The left-hand column shows schematically that most erupted mass is concentrated near the top of the plume. This mass distribution curve was used in model run 3 in Fig. 4. Bottom: a weak plume ascending from Eyjafjallajökull volcano, April 17, 2010 (photo by Nordic Volcanological Center). In weak plumes such as this one, tephra ascends slowly and is bent over by wind during ascent. The mass distribution of tephra with elevation is likely more uniform, as illustrated schematically in the plot on the left. This mass distribution plot was used in model runs 1, 2 and 4 in Fig. 4.

— ***Mass distribution of material in the plume by elevation. .*** Volcanic plumes are driven upward by buoyancy of hot gas and air. Large eruptions pump out so much heat that ash columns can ascend over 100 km per hour to an elevation at which their density equals that of the surrounding atmosphere. These rapidly rising columns are unlikely to be bent over by wind, thus forming a straight or "strong" plume that spreads laterally near its top to form an umbrella cloud (Fig. 2, top). Most mass is concentrated at this elevation. In contrast, small eruptions rise slowly and are easily affected by wind (Fig. 2, bottom) to form a bent or "weak plume". Weak plumes distribute mass over a wider range of elevation in the atmosphere. Sometimes it is possible to distinguish these plume types during an eruption and adjust model input.

— ***Fragment size and rate of fallout.*** Erupted fragments, which are known as tephra, range in size from meters to less than a micrometer (micron); ash is tephra that is less than 2 mm (2000 microns) in diameter. Individual fragments may rise to many kilometers and then fall out as they travel downwind. Fragments larger than several tens of microns can fall at a meter per second or faster, reaching the ground within several hours and usually within a few hundred kilometers of the volcano. Micron-sized fragments would theoretically fall at centimeters per second or less, staying in the atmosphere for days. The fraction of the erupted mass that consists of these small particles is not well constrained because most of our knowledge comes from deposits that fall from the ash cloud—not the cloud itself. In a handful of studies, deposits were sampled more than 1000 km from the volcanic source and analyzed for fragment size to the sub-micron range; in those cases, perhaps a tenth of the deposit may have been smaller than several microns. The fraction of fine ash in an eruption likely varies with eruption size and magma chemistry. Fragments larger than several tens of microns tend to fall at the settling velocities predicted for their size, but for smaller particles various processes can occur during transport to accelerate ash removal. Aggregation by electrostatic attraction, scavenging by raindrops, and encasement in ice crystals all increase the fallout rate of fine particles (Fig. 3). How much is removed by these processes is poorly known and probably varies greatly depending on meteorological conditions. None of these processes can be modeled accurately, although several models estimate them using theoretical or semi-empirical relationships.

2.2   Dispersion models use a variety of numerical methods to calculate the location and movement of ash clouds. In Lagrangian models, the geographic location of points (numerical domain) where ash properties are calculated move with the cloud; in Eulerian and semi-Lagrangian models the gridded numerical domain remains stationary as the cloud passes through it. The latter two methods differ in the way that they estimate mass transport through a fixed grid and comprise the majority of techniques used for atmospheric transport. For any of these methods, if the models are well-constructed then the errors in output resulting from numerical solution techniques are small relative to errors resulting from uncertainty in input.

Time (minutes to hours) ⟶

particle aggregation
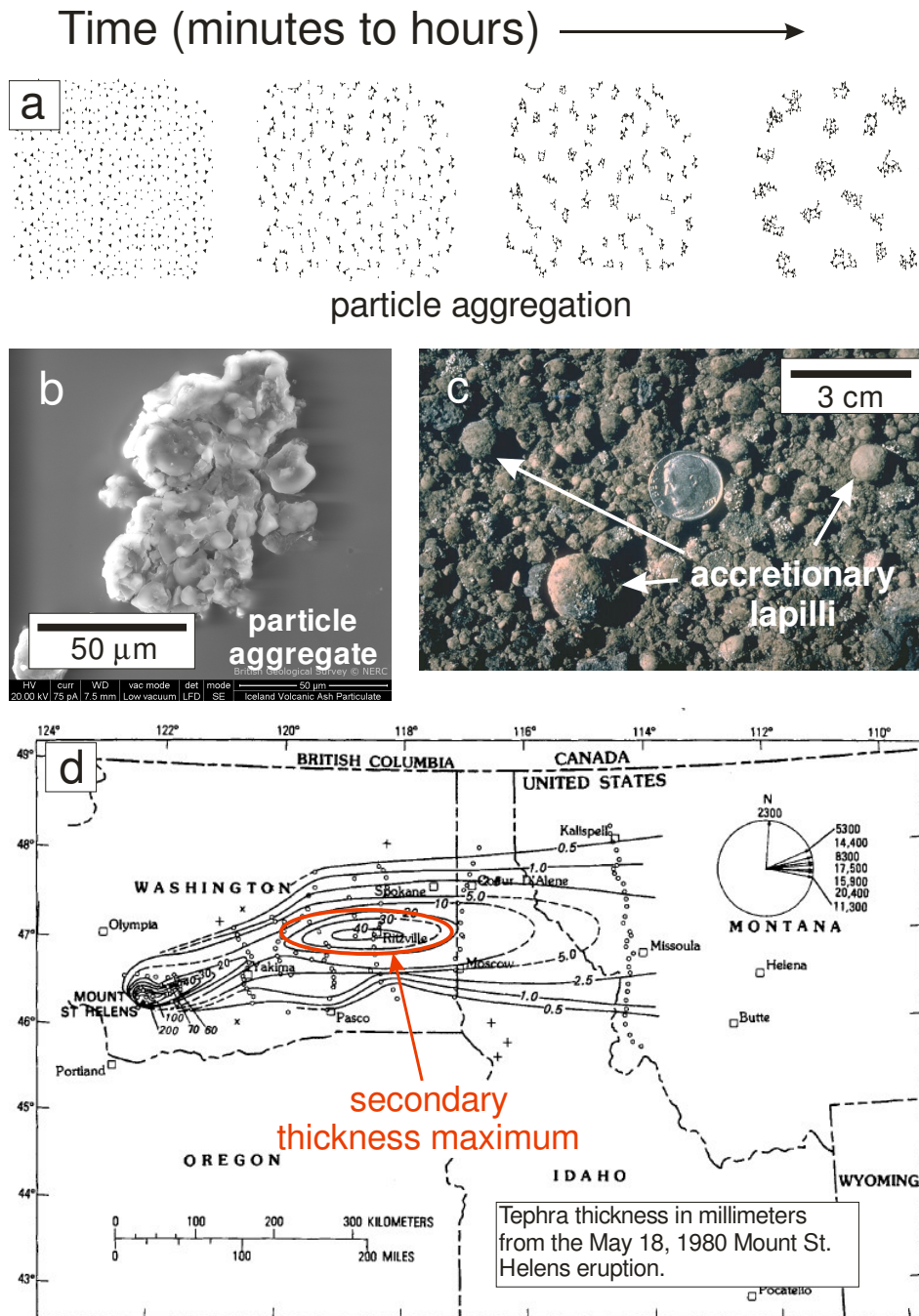
Figure 3: (a) Illustration of the process of particle aggregation, which greatly accelerates the rate of fallout of fine ash from the atmosphere. Evidence for particle aggregation is abundant and includes (b) micrographs of aggregated particles collected downwind, and (c) accretionary lapilli, or balls of aggregated fine ash found in some volcanic deposits. Indirect evidence for particle aggregation is also apparent in the thickness distribution of tephra deposits such at those from May 18, 1980 at Mount St. Helens (d). There, deposit thickness decreases with distance from the volcano, then increases to form a secondary maximum inferred to have formed when particle aggregates began to fall out from the cloud at an accelerated rate. Photo b is of

Eyjafjallajökull tephra collected in Loughborough, England by the British Geological Survey. Photo c is from Kilauea volcano, Hawaii, by the USGS

2.3   Figure 4 shows the effect of varying some of these input parameters on model predictions using a hypothetical, 2-hour-long eruption from Eyjafjallajökull into a randomly chosen but real wind field, using data from the high-resolution (0.5 degree nodal spacing) NOAA Global Forecast Model. Input parameters for the different model runs are given in Table 1. The numerical model used is Ash3d, a finite-volume Eulerian code recently developed by the USGS for research purposes; the model allows for a choice of high-resolution techniques for avoiding numerical artifacts to solve for advective transport of ash.

Table 1. Summary of input parameters for different model runs. All runs use plume height of 10 km and eruption duration of 2 hr.				
Property	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Mass eruption rate	$8 \times 10^{6\dagger}$ kg/s	$7 \times 10^{5*}$ kg/s	7×10^{5} kg/s	7×10^{5} kg/s
Mass distribution by elevation (Fig. 2)	Nearly uniform	Nearly uniform	80% in top 2.5 km	Nearly uniform
Distribution of fallout rates	100% at 0.01 m/s	100% at 0.01 m/s	100% at 0.01 m/s	10% at 0.01 m/s 22.5% at 0.5 m/s 22.5% at 1 m/s 22.5% at 2 m/s 22.5% at 4 m/s

[†] Represents the best-fit eruption rate shown in Fig. 1 for a 10-km plume height, plus 1σ uncertainty.
[*] Represents the best-fit eruption rate shown in Fig. 1 for a 10-km plume height, minus 1σ uncertainty.

2.4   For runs number 1 and 2, we varied the mass eruption rate from 8 million kg/s to 0.7 million kg/s, representing the +/- 1 std. dev. for a 10-km plume height (Fig. 1). Comparison of Runs 1 and 2 shows that an order-of-magnitude decrease in mass eruption rate significantly decreases the areal extent of the higher-concentration ash cloud.

2.5   We also varied the mass distribution in the ash column from that representing a weak plume (run 2) to a strong plume (run 3). Comparison of runs 2 and 3 shows that concentrating ash in the umbrella cloud reduces the areal extent of the ash cloud because ash is transported in a simpler wind regime than exists through the lower elevations.

2.6   Finally, we varied the particle fall rate from 0.01 m/s for all particles (micron-scale individual fall rates) to 0.01-4 m/s for a range of fragment sizes with thorough aggregation of the finest ash. Comparison of run 4 with the other runs demonstrates that the most dramatic effect on model output in terms of longevity of the ash cloud is that of aggregation as it affects fallout rates. Extensive aggregation of ash in run 4 removes it from the atmosphere within several hours, while most ash remains in the atmosphere after 18 hours in other runs.

2.7   We emphasize that these model runs represent a single, illustrative example and that effects at real eruptions will vary depending on the particular conditions at each volcano. The main point is that quantitative values of ash-cloud location, concentration, and longevity depend on input conditions which are not well constrained. These limitations have been long known among ash-cloud modelers and

were formally recognized by the International Airways Volcano Watch Operations Group (IAVWOPSG) as an issue requiring attention.   In 2007, in response to the recomendations of IAVWOPSG, a multidisciplinary working group developed a protocol for assigning source parameters in the absence of observational constraints (Mastin et al., 2009a, b). Additional strategies are also being tested for using ensemble runs that span the range of possible input conditions, and presenting the results as probabilistic maps. In order for future models to accurately consider uncertainty, ensemble techniques will have to be further developed and the uncertainty in source parameters better characterized.
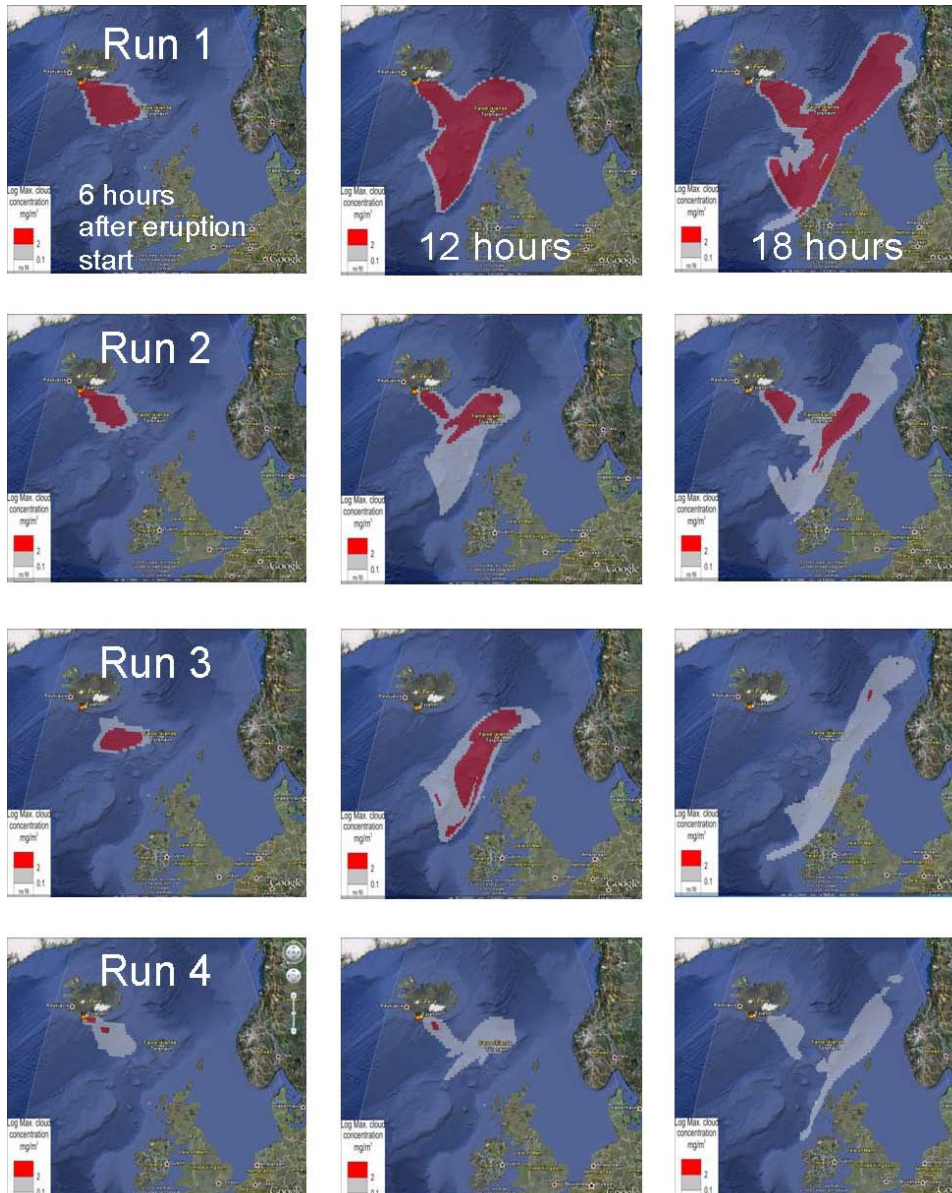
Figure 4: Model runs from a hypothetical two-hour-long eruption from Eyjafjallajökull volcano in an arbitrarily chosen but real wind field, using a range of input values illustrated in Table 1. The maps show the extent of an ash cloud whose

concentration exceeds 1x10$_{-4}$ g/m$_3$ (white). Red portions of the ash cloud contain concentrations exceeding 2x10$_{-3}$ g/m$_3$. The model domain is indicated by the lightly shaded region that extends from southern England to near the top of each figure, and from western Iceland east to near the Norwegian coast. For these runs we solve on a spherical grid with nodal points spaced at 0.2 degree horizontally and 1 km vertically. Diffusion is set to zero. For a wind field we use the high-resolution Global Forecast System model data with horizontal nodal spacing of 0.5 degrees.

2.8   More information on eruption-source parameters is at the IAVWOPSG web site: http://www2.icao.int/en/anb/met-aim/met/iavwopsg/Pages/default.aspx/ and at the Eruption Source Parameters web site: http://esp.images.alaska.edu/ . Results of the Eruption Source Parameters workgroup are published as:

Mastin, L. G., M. Guffanti, R. Servranckx, P. Webley, S. Barsotti, K. Dean, R. Denlinger, A. Durant, J. W. Ewert, A. Neri, W. I. Rose, D. Schneider, L. Siebert, B. Stunder, G. Swanson, A. Tupper, A. Volentik, and C. F. Waythomas (2009), A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions, J. Volcanol. Geotherm. Res., 186, 10-21.
Mastin, L. G., M. Guffanti, J. W. Ewert, and J. Spiegel (2009), Spreadsheet of eruption source parameters for active volcanoes of the world, in U.S. Geological Survey open-file report 2009-1133. Online at http://pubs.usgs.gov/of/2009/1133/

3.   CONCLUSION

3.1   In light of the above material, a draft action is suggested:

Action Agreed 1/… — Work on eruption source parameters

That, the IAVW coordination group be tasked to:

b)   further evaluate the effect of eruption-source parameters on uncertainties in dispersion models with respect to the location, concentration, and longevity of ash clouds and

c)   investigate how to better assess, depict, and reduce such uncertainties.

4.   **ACTION BY THE IVATF**

4.1   The IVATF is invited to:

     a) note the information in this paper, and

     b) decide on the draft action.

— END —