Ash Dispersal Forecast and Civil Aviation Workshop

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Consensual Document

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Executive Summary

As a result of the serious consequences of the 2010 Eyjafjallajökull eruption on civil aviation, more than 50 volcanologists, meteorologists, atmospheric dispersion modellers, and space and ground-based monitoring specialists from 12 different countries (including representatives from 6 Volcanic Ash Advisory Centers and related institutions) gathered at the WMO headquarters in Geneva (for acronym definitions, see Appendix 1) to discuss the needs of the ash-dispersal modelling community, investigate new data-acquisition[1] strategies and discuss how to improve communication between volcanological community and operational agencies. Based on a dedicated benchmark exercise and on three days of in-depth discussion, recommendations have been made for future model improvements, new strategies of ash forecasting, multidisciplinary data acquisition, and more efficient communication amongst different communities. Issues addressed in the Workshop and key findings include:

1. *Ash dispersal modelling*. VATDM developers need to make a significant effort in collaboration with volcanologists and meteorologists to improve the definition of the source term (mainly mass eruption rate, grainsize distribution and mass distribution along the eruption column) and some critical aspects of particle sedimentation (i.e., particle aggregation and wet deposition), particularly if concentration has to be computed.
2. *Uncertainty*. VATDM developers need to make an effort to design models and forecasting strategies that can better characterize uncertainties. In fact, both the intrinsic behaviour of the natural system and input data (i.e., volcanological and meteorological data) are affected by various levels of uncertainties that need to be accounted for in order to compile comprehensive descriptions of particle transport and sedimentation. Stakeholders (e.g., aviation companies, decision makers) need to integrate probabilistic strategies into their processes of decision making.
3. *Ensemble forecasting*. Ash dispersal forecasting could be significantly improved through the implementation of ensemble forecasting strategies, namely: i) ensemble of input variables, ii) ensemble of VATDM (multi model), iii) ensemble on NWP and iv) ensemble on both VATDM and NWP. VATDM developers both from meteorology and volcanology fields need to explore and identify the best ensemble strategies that can be adapted to ash dispersal forecasting.
4. *Combination of VATDM and observations*. Real-time assimilation of observations into VATDM is crucial to model accuracy and hence to aviation safety. VATDM developers and monitoring specialists need to identify optimized strategies for the combination of models and observations.

[1] Data acquisition here is considered in the sense of quantitative measurements and observations

5. *Sensitivity analysis*. VATDM developers need to perform a systematic sensitivity and accuracy analysis of all models in order to assess the effect of different inputs on model outputs and to prioritize data acquisition.

6. *VATDM variability.* Our dedicated benchmark exercise highlighted some discrepancies in output results of the 12 VATDM considered, likely due to different physics, different parameterization of the source term and/or slightly different input choices (e.g., NWP, grainsize classes). VATDM developers need to carry out further studies in order to assess the origin of these discrepancies.

7. *Data acquisition*. Ash dispersal forecasting accuracy relies on a real-time comprehensive definition of the source term (i.e., plume height, mass eruption rate, grainsize distribution, erupted mass and onset/cessation of the eruption), which can only be accomplished through the combination of various measurement techniques with various application limits and assumptions. Space and ground-based monitoring specialists need to find the optimal data integration technique in order to design an optimized strategy for a robust real-time source-term description. Clearly, observers should provide the relevant VAAC with eruption observations.

8. *Pre-eruption forecasting, first simulation and data assimilation*. VAACs need to adopt different forecasting strategies for different phases of volcanic crisis if they are not already doing so. Given that a volcano is forecast to erupt, before eruption onset, VATDM need to be run based on potential activity scenarios associated with a given volcano. Just after eruption onset, VATDM need to be run based on real-time detected plume height and PDFs for erupted mass (and/or eruption duration) and TGSD (specific for a given volcano) if available. Source-term description needs to be improved with time by data assimilation. This is particularly important for long-lasting eruptions.

9. *Research priorities*. Research institutions and operational agencies (e.g., VAACs, Meteorological Offices, Volcano Observatories) need to establish long-lasting collaborations and to join the effort in order to optimize strategies of ash dispersal forecasting. Current research priorities include: i) data assimilation, ii) aggregation processes, iii) plume dynamics (in particular of weak plumes) and better characterization of the source term (e.g. based on validation with 3D models), iv) magma fragmentation, particle characterisation and size distribution from proximal to distal environments, v) separation of SO_2 from ash clouds, vi) chemistry analysis of plumes (particles, sulphuric acid aerosols, H_2S, halogen chemistry) and, vii) aerosol transformations. Implicit is the need for reference observations and corresponding source-term information with which to evaluate the models.

10. *New communication strategies to improve information flow and operational routines*. Operational institutions are often end users of research. They should therefore be closely involved in setting research priorities. Research is essential to develop new methodologies and techniques that are not well enough established to be operational, also to carry out one-off detailed studies. Volcano Observatories and VAACs should be encouraged to agree on mutual expectations and requirements before volcanic crises, if they have not already done so. Volcano Observatories, ICAO, VAACs and Meteorological Offices have the responsibilities to implement new critical

11. *Funding*. Cooperation between research and operational institutions might be fostered or encouraged if it were promoted by institutions that traditionally fund research (e.g., American National Science Foundation, European Science Foundation). A larger involvement of these institutions in volcanological research could more easily result in the funding of more direct operational applications. In addition, new sources beyond the traditional low-level of funding should be also pursued.

Introduction

[1] The regulatory response to the 14 April 2010 Eyjafjallajökull eruption resulted in severe disruption to air traffic. By 21 April, the UK Civil Aviation Authority (CAA) and Eurocontrol had pioneered a new way to manage the crisis based on ash concentration thresholds defined by engine manufacturers. Both the initial zero ash tolerance approach by ICAO and the new ash concentration thresholds, used by the UK MetOffice and currently under discussion within ICAO, require robust ash dispersal forecasting based on the combination of Numerical Weather Prediction (NWP), Volcanic Ash Transport and Dispersal Models (VATDM) and ash cloud data acquisition. The new ash concentration thresholds require more accurate information on the ash mass in the eruption since downwind concentrations depend on the source. The first IAVCEI-WMO Ash Dispersal Forecast and Civil Aviation Workshop (www.unige.ch/hazards/Workshop.html) aimed to produce a consensual document describing the characteristics and range of application of different VATDM, identifying the needs of the modelling community, investigating new data-acquisition strategies and discussing how to improve communication between different disciplines, researchers and operational institutions to improve volcanic ash transport and dispersion model forecasts. The workshop was held at the WMO Geneva headquarters under the sponsorship of the Faculty of Sciences of the University of Geneva, the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), and Canton of Geneva, and organized by scientists from the University of Geneva (Switzerland), the Barcelona Supercomputing Center (Spain), the Aeronautical Meteorology Division of the World Meteorological Organization (WMO), and the British Geological Survey (U.K.). More than 50 volcanologists, meteorologists, atmospheric dispersion modellers, and space and ground-based monitoring specialists from 12 different countries were gathered (attendance by invitation only), including representatives from 6 Volcanic Ash Advisory Centers (VAACs) and related institutions (Appendix 2).

[2] A model benchmark exercise (based on the Hekla 2000 eruption in Iceland) was carried out before the workshop. The defined parameters of the benchmark included erupted mass, plume height, tephra total grain size distribution, particle size-dependent densities, meteorological datasets (ECMWF ERA-40 and NCEP/NCAR reanalysis-1) , and start and end time of the eruption. Model outputs were specified as concentration contour maps

at different flight levels and times, vertical concentration profiles at a given point, and tephra ground load maps. The benchmark exercise was performed by 12 VATDM (ASH3D, ATHAM, FALL3D, FLEXPART, HYSPLIT, JMA, MLDP0, MOCAGE, NAME, PUFF, TEPHRA2, and VOL-CALPUFF). This includes the vast majority of the VATDM in use worldwide and all models currently operative at VAACs. Another model inter-comparison was done by Witham et al. (2007)[2], but a test case involving so many models has never been done before. In addition, two detailed documents have been compiled to define characteristics, application limits and outputs of both the 12 VATDM and selected data-acquisition techniques and instruments associated with ash detection (namely AIRS, ASTER, AVHRR, GOES-11, GOES-12,13,14,15, Grimm EDM 107, Grimm Sky OPC, IASI, IMO-radar, Infrasonic Array, LIDAR, MISR, MODIS, MTSAT, OMI, PLUDIX, SEVIRI, Thermal Camera, UV Camera, VOLDORAD). Associated summary tables are shown in Tables 1 and 2 (see also complementary documents for more details, which can be downloaded from the workshop website: http://www.unige.ch/sciences/terre/mineral/CERG/Workshop/results.html). After three days of dedicated talks, break-out sessions, and extensive plenary discussions (focusing on dispersal modelling, data acquisition, and decision making during volcanic crisis), suggestions have been made for future model improvements, new strategies of ash forecasting, new synergy among different observation techniques and different platforms, and more efficient communication between different disciplines and agents (i.e., volcanology, atmospheric science, remote sensing, meteorology, operational institutions, regulators, government departments, airlines, pilots, aeronautical engineers, engine/plane manufacturers). This consensual document gathers the opinions of scientists and experts who attended the workshop and is intended to highlight key points of our discussions. This workshop focused on dispersion model output, not the forecast information available in the ICAO volcanic ash products: the volcanic ash SIGMET (SIGnificant METeorological information) and the text Volcanic Ash Advisory (VAA, or in graphical format, Volcanic Ash Graphic, VAG). In some instances the forecast information of the VAA has been known to differ from that in the model output.

[2] Witham, C.S., Hort, M.C., Potts, R., Servranckx, R., Husson, P., and Bonnardot, F. 2007. Comparison of VAAC atmospheric dispersion models using the 1 November 2004 Grimsvotn eruption, Meteorological Applications, 14, 27-38.

Issues addressed in the Workshop and recommendations

1. Ash Dispersal Modelling

[3] Ash dispersal models considered during this workshop (see Table 1 and Model Summary Document) have been found to accurately describe important aspects of transport of volcanic particles (e.g. advection and diffusion). However, other aspects, such as the definition of the source term, convective transport, or the removal of airborne ash by specific sedimentation processes, could be better characterized.

[4] Source Term. The Source Term in VATDM is defined by: i) Mass Eruption Rate (MER), ii) vertical distribution of mass and grainsize, iii) column height, iv) Total Grainsize Distribution (TGSD) and particle properties (i.e. density and shape), v) eruption onset and end time, vi) source position, and sometimes vii) the fraction of fine ash. Variations in the description of the source term are probably the main cause of VATDM variability (see section 6 *VATDM variability*).

[5] MER, vertical distribution of mass and vertical distribution of grainsize can be derived from a better description of plume dynamics. First, empirical relationships exist between column height and MER for sustained vertical plumes. However, when volcanic plumes are not sustained and/or are strongly affected by atmospheric conditions (e.g., "bent-over plumes"), different formulations should be used that are more complex: 1D radial-averaged plume models as a first approach or, ideally, more sophisticated 3D numerical models (e.g., ATHAM). Nonetheless, sophisticated 3D numerical models are too computationally expensive to be used operationally and, therefore, 1D models might still be required to describe MER in complex conditions (e.g., "bent-over plumes", crosswind entrainment). As a result, 1D radial-averaged plume models should be further validated with data and/or calibrated against 3D numerical models. Second, time dependency of source parameters, especially MER and column height, should be accounted for in any VATDM (some models still assume steady source conditions). Description of Eruption Source Parameters (ESP) time-dependency can be accomplished in real-time forecasting by data assimilation, given the availability of observations (see sections 4 and 8). Finally, a more accurate parameterization of plume dynamics (i.e., plume velocity and turbulence field) could help

define the distribution of particle sizes within the column and therefore define the vertical distribution of mass that serves as an input to VATDM.

[6] Column height, TGSD, particle properties (i.e. density and shape), eruption start and end time and source position can only be derived from observations and field data (see section 7 *Data Acquisition*). Use of a virtual 'displaced' source, downwind from the original vent based on satellite or other observations of cloud position, could be considered as an alternative initial condition for VATDM to improve forecast accuracy of ash dispersal in medial and distal regions. Virtual-source-term parameters could be measured using a combination of remote sensing techniques (both active, i.e., radar, LIDAR, and passive, i.e., radiometric) and in-situ from different platforms (satellite, aircraft - including UAVs), ground based and drop sondes.

[7] Sedimentation. Some sedimentation processes strongly affect particle transport and deposition and still need to be better parameterized for inclusion in models (i.e., particle aggregation and wet deposition). Currently, some aspects of particle aggregation are described by one VATDM (FALL3D; Table 1) but aggregation has never been considered during real-time ash forecasting because the associated range of processes that can induce particle collision and sticking are extremely complex and are still not fully understood for the specific case of volcanic ash. More experimental studies and field observations should be carried out in order to develop and calibrate both wet and dry ash aggregation models. Wet deposition is accounted for in 7 models (FLEXPART, HYSLPIT, JMA, MLDP0, MOCAGE, NAME, VOLCALPUFF; Table 1), but a better description of specific parameters (e.g. scavenging coefficients) is needed. Moreover, VATDM output needs to be applied cautiously when wet deposition is included, because of typically high uncertainties in NWP precipitation forecasts (rain is amongst the worst predicted variables by NWP models).

[8] On-line solution of VATDM. It was recognized that an on-line approach (i.e. concurrent solution of NWP models and VATDM) could, to some extent, improve specific aspects of VATDM (mainly advection and diffusion). However, the off-line approach (i.e. solve first NWP models and then VATDM) has advantages in the forecast mode for multiple reasons: execution time, logistics, flexibility to deal with eruption variations and uncertainty in the source term (i.e. no need to re-run NWP model each time volcanological inputs vary), etc. Nonetheless, on-line simulations should be considered in the analysis mode for model

testing purposes and/or to investigate the feedback effects that airborne ash may exert on NWP models by modifying the atmospheric fields and the atmospheric radiative balance.

2. Uncertainty

[9] VATDM developers need to make an effort to design models and forecasting strategies that can better deal with uncertainties. In fact, both the observations used to define the source term (e.g., MER, plume height, erupted mass and TGSD) and the meteorological datasets used (global or mesoscale forecasts) are affected by various levels of uncertainties. Uncertainties are of different nature and mainly depend on the random behaviour of natural systems, on random errors in field measurements and on the lack of information of both field data and numerical investigations, i.e. inaccuracy of field techniques, limitations of the geological records and limitations of the physical models (NWP models and VATDM). The random behaviour of the natural system and the random errors associated with field measurements can be classified as aleatoric uncertainties, whereas the lack of information of both field data and numerical investigations can be defined as epistemic uncertainties. Often, treatment of aleatoric uncertainty can be accomplished quantitatively, but realistically epistemic uncertainty may be more important. As an example, uncertainties related to the random behaviour of the natural system (aleatoric) can be dealt with identifying appropriate activity scenarios and Probability Density Functions (PDFs) of input parameters (see section 8 *Pre-eruption forecasting, first simulation and data assimilation*). This is why ash dispersal forecasting may be more accurate if it simply outputs a range of probability values as opposed to absolute values of ash concentration and mass loading on the ground. Probabilistic strategies need to be discussed with stakeholders (see section 3 *Ensemble forecasting*). In contrast, epistemic uncertainties can be reduced by improving the parameterization of the physical processes, the field investigation techniques, and the numerical accuracy.

3. Ensemble forecasting

[10] The experience from modelling atmospheric transport of distinct substances (e.g. radioactive nuclei, aerosols, mineral dust) strongly suggests that ash dispersal forecasting could be largely improved by the implementation of ensemble forecasting on both modelling

and source term conditions (see ENSEMBLE project at http://ensemble.jrc.ec.europa.eu). In particular, four different types of ensemble forecasting could be envisaged: i) ensemble of input variables (according to activity scenarios and data uncertainties), ii) ensemble of VATDM (multi model) (on a single or different NWP), iii) ensemble on NWP and iv) both VATDM and NWP.

[11] Ensemble forecasting should be carried out in order to better characterize uncertainty rather than to hide gaps in our understanding. Ensembles on input variables could be performed by perturbation of source conditions and sampling of PDFs. Ensembles on models could be implemented by running models independently and averaging the outputs (deterministic output) or by assessing the probability of model outputs (probabilistic output). Advantages and disadvantages of deterministic and probabilistic outputs need to be discussed with stakeholders (e.g., aviation companies, regulators). Probabilistic maps better characterize the intrinsic uncertainty of the natural system and model, and would be very useful for pre-flight planning. In either case, models used in ensemble forecasting should use parameterization for different physical processes that cover the uncertainty range. In fact, ensemble forecasting of very similar VATDM would not add any more information to the associated output. There are currently several logistical constraints that need to be resolved if ensemble forecasting is to be operational during volcanic crises. It is responsibility of VATDM developers to identify the best ensemble strategies that could optimize ash forecasting. ICAO should also provide an output format that is immediately understandable and meaningful.

4. Combination of VATDM and observations

[12] Ash dispersal modelling should be coupled as close to real time as possible with observations and measurements in order to reduce uncertainty and improve outputs.

[13] *Data assimilation*. Observations should be assimilated into VATDM from: i) direct measurements and, ii) indirectly through combination with other models (e.g. using models to invert for source vertical mass distribution from satellite images and/or radar information). Numerous techniques are possible, varying in hierarchy from user manually changing inputs, inverse modeling techniques or full variational data assimilation (as done by NWP models). See also section 7 *Data Acquisition*.

[14] *Real-time model validation*. Real-time model validation (e.g., by comparison with satellite and ground-based remote sensing data) should be done, if possible, with Level 1 data (Level 1 data could be made accessible in near real time from many satellites and other platforms).

[15] In addition, pre-eruption model validation should be done on both high quality data of past eruptions and synthetic datasets designed to highlight the role of different aspects in each model.

5. Sensitivity analysis

[16] A systematic sensitivity analysis of all VATDM should be performed in order to assess the effect of different inputs (e.g. MER, plume height, erupted mass, TGSD) on model outputs and therefore to prioritize data acquisition. This is also important for the construction of an ensemble on input variables. In addition, sensitivity of numerical model accuracy on discretization should also be quantified (i.e., mesh resolution in the case of Eulerian models or particle number and resolution of the background averaging mesh in the case of Lagrangian models).

6. VATDM variability (benchmark results)

[17] Several models are designed to compute airborne ash concentration, some of them born in the context of aerosol dispersion; others specifically designed for volcanic ash. The main goal of this workshop was to define model characteristics and application limits rather than to rank or validate VATDMs (e.g., Table 1). The benchmark exercise was used to understand the influence of the parameterization of different sedimentation processes and source term treatments on the model outputs. Comparisons with ash cloud observations were not made. Following our group discussion we can conclude that: i) there are some discrepancies in model outputs (likely due to different model physics, different parameterization of the source term and slightly different input choices, e.g., NWP, grainsize classes), ii) as expected, discrepancies increase with time (i.e., distance from vent) and, for this particular benchmark case, become important and generalized after 36h, iii) discrepancies are also different at different altitudes, iv) models could be clustered in a few groups based on these discrepancies. Discrepancies will need to be analysed in more detail

by the modellers in order to assess their actual origin and to investigate if these discrepancies could eventually be exploited in ensemble forecasting (see also section 3 *Ensemble Forecasting*).

7. Data acquisition

[18] All techniques used to measure/monitor variables furnished as inputs to VATDM have application limits. Ideally, a range of techniques should be used simultaneously and combined to cover all the observation spectra (see Table 2 and Data Acquisition Document for details) and to get as many variables as possible. Key variables to VATDM that characterize the source term are: i) plume height, ii) MER, iii) TGSD, iv) erupted mass and the v) onset and vi) end of an eruption. Particle concentration and SO_2 observations can also be important (e.g., for data assimilation or model validation, provided SO_2 transports similarly as ash). There is the need for a shared high-quality database gathering all critical parameters standardized based on same formats (see also section 10 *New communication strategies to improve information flow and operational routines*).

[19] Plume Height. Plume height is usually the easiest parameter to constrain in real time (e.g. using radar, satellite, LIDAR, ceilometers, PiReps or ground visual observation, infrasound, thermal camera, seismic amplitude, aircraft measurements, dropsondes, ballonsondes, lightning detection). Nevertheless, there are important considerations. First, each technique is associated with a certain measurement uncertainty and, therefore, a range of plume heights should be provided for each technique rather than a single absolute value. Second, the part of the plume/cloud for which the height is derived needs to be specified (e.g., neutral buoyancy level, overshooting, top of umbrella cloud). Third, the distance from the vent at which the height is detected also needs to be specified (in particular for bent-over plumes). Finally, a better standardization among different communities is required for the determination of plume height (e.g., height should always be reported above sea level and consistently relative to the same datum).

[20] Mass Eruption Rate. MER is hard to measure directly and a distinction should be made amongst MER (i.e., at vent), mass transport rate (MTR) in the cloud at the neutral buoyancy level and local mass transport rate (i.e., at a given distance from the vent). A

distinction should also be made between MER/MTR of all particle sizes and MER/MTR of small particles (i.e., particle detected by satellite sensors). Ash dispersal forecasting associated with aviation safety and long-range dispersion mainly requires information on MER of fine particles that enter the horizontally-spreading cloud. If MER is calculated from plume height, then the most appropriate parameterization should be used (see *Source Term* in section 1 *Ash Dispersal Modelling*). Examples of techniques that could help constrain MER/MTR (of selective particle sizes) are: i) Radar, ii) LIDAR, iii) Ground-based IR or UV camera (they can in principle be used to scan an un-obscured ash cloud and obtain 3-D cloud load; if the cloud is moving, the flux through a cross section can be used to obtain mass flux), iv) Satellite, v) Seismic energy release, vi) Infrasound, vii) In situ aircraft for local MER. See Table 2 for more details.

[21] Erupted Mass and TGSD. Unfortunately a comprehensive real-time technique that can provide the erupted mass associated with the whole particle size spectrum does not exists. As an example, satellite retrievals can only determine the effective particle radius of the ash cloud within the field-of-view only if the actual effective radius is <15 μm (with spatial resolution issues), while meteorological Doppler radar (S, C, X and Ka bands) can only detect particles with radius >30 μm. In-situ sampling (e.g., piston engine aircrafts) can detect particles between 250 nm and 32 μm. As a result, TGSD (and the associated mass) can only be derived from the combination of various techniques. Nevertheless, information should also be given on whether the resulting cloud is ash-rich or gas-rich.

[22] Cloud Concentration. The concentration of ash in the cloud can be derived from both remote sensing (e.g., radar, LIDAR and satellites) and in-situ techniques (e.g., dropsondes and research aircraft). In terms of aviation safety, engine manufactures should define weather safety thresholds are to be considered in terms of peak concentrations or in terms of dose (i.e. maximum tolerable engine ingested mass). This is a complex issue and many other aspects such as engine age, type or operating settings (climb, flight level, etc) can play a role.

[23] Aggregation-related observations. For better constraints on aggregation processes, more information should be gathered on: i) particle-number concentration for different sizes, ii) ice vs liquid water content, iii) depolarization ratio of aggregates vs individual

particles (in LIDAR signal), iv) electrical charges through lighting detection, electric field measurement or direct sampling.

[24] Eruption onset. Eruption onset and eruption end are crucial to ash forecasting and for aviation-safety purposes. Various techniques can be used to detect the onset of an eruption. Satellite and seismic analyses, direct personal observation and via webcam, are traditional techniques. Infrasound, radar, LIDAR and lightning analyses are newer techniques. First, infrasound can be used to get both onset and duration, even though the sound speed limits its usability when the volcano is distant. Infrasound data can also provide a proxy for eruption intensity and provide constraints on the size of vortices and the vent diameter (if the infrasound is close enough that atmospheric effects are small). Second, combination of radar and LIDAR can provide onset and duration of eruptions. Finally, WWLN has also been used to detect eruptions (if there is lightning in the cloud). WWLN cannot detect cloud height but a VHF give 3-D location of the lightning and might be able to constrain height. HF systems only detect cloud-to-ground lightning. It is essential that observers notify the relevant VAAC when an ash eruption begins.

[25] Eruption end. Notification of the end of an eruption (or an event) is essential for regulators and decision-makers. A definition is required; a default may be the Smithsonian Institution three months of background monitoring. However most non-scientists will consider an eruption ended when the plume is no longer visible (sulphur dioxide likely to remain elevated but declining even when there's no ash). For aviation safety purposes, the relevant question is whether the volcano is still injecting ash in the atmosphere and if the remaining ash has decreased in concentration to below their threshold levels (VAAC's need to know when any significant emissions have stopped). At U.S. volcanoes, for example, a change in the aviation color code from, say, orange or red to yellow, signals the end of any hazardous activity. But there is a separate notification for ground-based hazards involving, for example, lava flows or lahars (http://volcanoes.usgs.gov/activity/alertsystem/index.php). This has been adopted by the world Organization of Volcano Observatories: http://www.wovo.org/aviation-colour-codes.html

8. Pre-eruption forecasting, first simulation and data assimilation

[26] Various phases of ash dispersal forecasting during volcanic crisis are characterized by a different use of data and modeling strategies. In particular, the pre-eruption forecasting and the first simulation, assuming no observations are available, should be based on a probability assessment of activity scenarios (defining PDFs for possible plume height, erupted mass and TGSD) for each volcano. Activity scenarios and PDFs can be constructed for each volcano through accurate field work and/or through the use of databases (e.g., Smithsonian, VOGRIPA, specific studies). If observations, scenarios and PDFs are not available, standard Eruption Source Parameters may be used accounting for related uncertainties.

[27] Pre-eruption forecasting. Before the onset of an eruption, VATDM should be run to account for potential activity scenarios. This has to be done using short-term weather forecast, and is most useful if statistics are used to assign probabilities to source-term parameters (i.e., plume height, erupted mass, TGD) based on past history (deposits). In case of long-lasting plumes, longer-term weather predictions are also needed (e.g., 1-2 weeks).

[28] First simulation. Just after the onset of an eruption, VATDM models should be run using a real-time detected plume height and PDFs for erupted mass (and/or eruption duration) and TGSD (specific for a given volcano), if available. The difference between this and [27] above is the certainty of the onset of the eruption, as it is unlikely source parameters will be known quickly.

[29] Data assimilation. Information on the source term and ash cloud evolution will usually increase with time. As a result, an effort should be made to systematically assimilate new data (detected both proximally and in the far field) in order to continuously improve the associated ash-forecasting outcome. In particular, during long-lasting eruptions, information on particle size, morphology and density and erupted mass derived from direct ground observations (but time-consuming) can also be integrated. It is essential that observers notify the appropriate VAAC immediately of any change in eruption vigor whether quantified or not. The use of quantitative information to systematically update forecasts is most robust if done within a statistical framework.

9. Research priorities

[30] Research priorities have typically been focused on improvements to volcanic ash dispersion modeling rather than on improving ash cloud data acquisition capabilities. Optimized strategies of operational ash dispersal forecasting can only be developed as a result of a strong link between research institutions and operational agencies. Research priorities include: i) improvement of observation techniques (e.g., real time data and better accuracy, synergy among different platforms and instruments, investigations of new techniques, improvement of geographical gaps), ii) data assimilation, iii) improved quantification on aggregation processes, iv) plume dynamics (in particular of weak plumes) and better characterization of the source term, v) magma fragmentation, particle characterization and size distribution from proximal to distal environments, vi) SO_2 and vapor separation, vii) volcanic aerosol transformations and chemistry analysis of plumes (particles, sulfuric acid aerosols, H_2S). Data assimilation is crucial to the improvement of source-term definition but requires an optimal combination of VATDM and observations. Aggregation processes significantly affect particle sedimentation, and hence ash concentrations aloft, but their current numerical description is computationally expensive and the phenomenon is not well parameterized for the case of volcanic ash. As a result, more field and laboratory observations are needed in order to develop modelling strategies describing particle aggregation that can be used operationally. A better understanding of plume dynamics in various atmospheric (e.g., strong/weak wind, temperature, humidity) and eruptive (sustained/not sustained) conditions is needed for a better description of the source term, which is critical to VATDMs. More studies on separation of SO_2 clouds and vapor from ash clouds need to be undertaken in order to predict better ash vs gas dispersal. Finally, chemical analyses of plumes need to be carried out in order to improve our understanding of dispersal processes. Implicit is that VATDM need to be evaluated against available observations from eruptions with known source term characterization.

10. New communication strategies to improve information flow and operational routines

[31] Ash dispersal forecasting is a multidisciplinary issue that cannot be dealt with by any discipline or institute in isolation. In general, there is still insufficient interaction between the different communities and disciplines concerned with safe aviation operations during

volcanic crises (i.e., volcanology, meteorology, atmospheric science, regulators, airlines, pilots, engineers and manufacturers). There is a need to better understand the effects of ash and other substances from volcanoes on jet engines and other aircraft systems from the engineers and manufacturers before the next significant eruption. Improved interaction is also required when dealing with volcanic eruptions across VAACs and international boundaries. Further, there is a need for a unified effort to improve the efficient flow of information to all of the different communities involved with resolving aviation issues during a volcanic crisis. The ICAO Handbook has a "Sample Letter of Agreement between Air Traffic Services (ATS), Meteorological Authorities and Volcanological Authorities" (ICAO, 2004[3]) for the provision of volcanic ash information. Use of this, or a derivative of it, should be encouraged so mutual expectations and requirements, at least between Volcano Observatories and VAACs, are established before a volcanic crisis. Some key new strategies to improve the information flow and facilitate the decision-making processes include: i) each discipline should facilitate the integration of outside experts from other disciplines in order to facilitate operations (e.g., use and interpretation of data, use of VATDM, interpretation of VATDM outcomes) and to ensure optimum value and outcomes from research; ii) an official database (e.g., information clearinghouse) should be constructed with the objective of sharing high-quality data during a volcanic crisis; iii) a closer link and mutual understanding between research and operational institutions should be fostered by continued and focused interaction, visits, staff exchanges, etc; iv) a coordinated approach to educational information is essential before and during the crisis, to ensure all stakeholders including the public can properly understand the issues. Nonetheless, it is crucial that coordination (e.g., trust building, identification of responsibilities and capabilities) starts before the crisis in order to avoid misunderstanding and decision-making failure.

[32] Points i) to ii) listed above are responsibility of Volcano Observatories, ICAO, VAACs, WOVO and Meteorological Offices. The ICAO International Airways Volcano Watch Operations Group (IAVWOPSG) and the International Volcanic Ash Task Force (IVATF) are tasked with establishing the ground rules for institutional cooperation and communication.

[3] ICAO, 2004: Appendix A, Handbook on the International Airways Volcano Watch (IAVW), ICAO Doc 9766-AN/968 (http://www2.icao.int/en/anb/met-aim/met/iavwopsg/IAV%20Handbook/Forms/AllItems.aspx).

In particular, IVATF, in association with the IAVWOPSG, should play a fundamental role for the construction of a high-quality database (point ii)) and make every effort to ensure that all recommendations indicated in this document are encouraged to be put into action and implemented into ash dispersal forecasting procedures. Points iii) and iv) need to be addressed together by Observatories, VAACs and academic institutions in order to seek common funding and share common goals.

[33] Finally existing networks across Europe (e.g. EARLINET, EUSAAR) are valuable. Coordination, data management and availability are priorities. Some networks currently work well at a national level but need to develop the means to coordinate with European partners. The aim is to make data available as soon as possible to the VAACs.

[34] Cooperation between research and operational institutions might be fostered or encouraged if it were promoted by institutions that traditionally fund research (e.g., American National Science Foundation, European Science Foundation). A larger involvement of these institutions in volcanological research could more easily result in the funding of more direct operational applications. In addition, new sources beyond the traditional low-level of funding should be also pursued.

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	ASH3D	ATHAM	FALL3D	FLEXPART	HYSPLIT	JMA	MLDP0	MOCAGE	NAME	PUFF	TEPHRA2	VOL-CALPUFF
Operational												
Approach (1)	E/H	E	E	L	H	L	L	E	L	L	E	H
Method (2)	N	N	N	N	N	N	N	N	N	N	A	S
Coverage (3)	LRG	L	LR	LRG	LRG	G	LRG	G	LRG	LRG	L	LR
Physics												
Topography												
H wind advection												
V wind advection												
H atm. diffusion								See (5)				
V atm. diffusion												
Particle sed.												
Other dry dep.												
Wet deposition												
Dry part. aggr.												
Wet part. aggr.												
Particle shape												
Gas species												
Chemic. processes												
Granulometry												
Variable size class.												
Variable GS distr.												
Variable size limits												
Source term												
Mass distribution(4)	LN	O	ALL	PS/L/U/P/O	PS/L/U/P/LN	PS/L/U/P/LN	PS/L/U/LN	PS/L	PS/L/O	PS/L/U/P	L/U/LN	PS/BP

(1) L=Lagrangian, E=Eulerian, H=Hybrid
(2) A=Analytical, S=Semi-analytical, N=Numerical
(3) L=Local, R=Regional, G=Global
(4) PS=Point Source, L=Linear, U=Umbrella-type, P=Poisson, LN=Log-normal, BP=Buoyant Plume, O= Other (see Appendix).
(5) Neglected. Diffusion of numerical origin appears to be sufficient, with particularly good results at 0.5°.

Table 1. Main characteristics of VATDM (see Model Summary Document for more details; www.unige.ch/hazards/Workshop.html).

	Eruption start / end	Plume Height	MER/MTR	Mass	Grain size	Cloud Concentration	SO_2
AVHRR		Altitude, Temperature, Pressure	Local MTR	0.1-100μm	Effect. radius: 0.1-15μm	Mass loading	
GOES-11 Imagery		Altitude, Temperature, Pressure	Local MTR	0.1-100μm	Effect. Radius: 0.1-15μm	Mass loading	
GOES-12,13,14,15 Imagery		Altitude, Temperature, Pressure	Local MTR	0.1-100μm	Effective radius 0.1-15μm	Mass loading	
Grimm EDM 107					Size range: 250nm-32μm	Mass/volume Number/volume	
Grimm Sky OPC					Size range: 250nm-32μm	Mass/volume Number/volume	
Doppler radar			Local MTR		Ka band > 30 μm X and C band: > 100 μm S band > 1 mm		
Infrasonic Array		From source MER	Source MER				
ASTER							SO_2 burden
LIDAR		Altitude		Size range: 100nm-2μm	Size range: 100nm-2μm	Mass/volume Number/volume	Possible using DIAL
MISR		Altitude		All particle sizes		Mass Loading	
MODIS		Altitude, Temperature, Pressure	Local MTR	0.1-100μm	Effective radius 0.1-15μm	Mass loading	SO_2 burden
MTSAT		Altitude, Temperature, Pressure	Local MTR	0.1-100μm	Effective radius 0.1-15μm	Mass loading	
OMI							SO_2 burden
AIRS		Altitude, Temperature, Pressure	Local MTR	0.1-100μm	Effective radius 0.1-15μm	Mass loading	SO_2 burden; Vertical distr.
IASI		Altitude, Temperature, Pressure	Local MTR	0.1-100μm	Effective radius 0.1-15μm	Mass Loading	SO_2 burden; Vertical distr.
PLUDIX (X-band)*					Effect. radius >100μm		
Seismic data		From seismic amplitude and reduced displacement					
SEVIRI		Altitude, Temperature, Pressure	Local MTR	0.1-100μm	Effective radius 0.1-15μm	Mass loading	SO_2 burden
Thermal Camera							
UV Camera				Ash Opacity			SO_2 line of sight burden
VOLDORAD* (L-band)	Data acq. rate (10 Hz)	Max detection limit: 12 km	Source MER		~All particle sizes	Pixel size (~150m)	

Table 2: Summary of source-term parameters that can be detected with various techniques (see Data Acquisition Document for more details; www.unige.ch/hazards/Workshop.html). Green cells: direct measurements; Blue cells: derived measurements; Orange cells: experimental.
*, PLUDIX and VOLDORAD are particular cases of Doppler radar discussed during the workshop

Appendix 1: List of acronyms

AIRS	Atmospheric Infrared Sounder
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATHAM	Active Tracer High resolution Atmospheric Model
AVHRR	Advanced Very High Resolution Radiometer
DIAL	Differential absorption lidar technique
ECMWF	European Centre Medium-Range Weather Forecast
EDM	Environmental Dust Monitors
EUSAAR	European Supersites for Atmospheric Aerosol Research
GOES	Geostationary Operational Environmental Satellites
HYSPLIT	HYbrid Single-Particle Lagrangian Integrated Trajectory
IASI	Infrared Atmospheric Sounding Interferometer
IAVCEI	International Association of Volcanology and Chemistry of the Earth Interior
IAVWOPSG	International Airways Volcano Watch Operations Group
ICAO	International Civil Aviation Organization
IMO	Icelandic Meteorological Office
IR-SO2	Infrared Spectroscopy of SO2
IVATF	International Volcanic Ash Task Force
JMA	Japan Meteorological Agency
LIDAR	Light Detection And Ranging
MLDP0	Modèle Lagrangien de Dispersion de Particules d'ordre zéro
MAXDOAS	Multiple Axis Differential Optical Absorption Spectroscopy
MER	Mass Eruption Rate
MISR	Multi-angle Imaging Spectro-Radiometer
MOCAGE	Modélisation de la Chimie Atmosphérique Grande Echelle
MODIS	Moderate Resolution Imaging Spectroradiometer
MTR	Mass Transport Rate in the cloud
MTSAT	Multi-Functional Transport Satellite
NAME	Numerical Atmospheric-dispersion Modelling Environment
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NWP	Numerical Weather Prediction (Models)
OMI	Ozone Monitoring Instrument

OPC	Optical Particle Counter
PDF	Probability Density Functions
SEVIRI	Spinning Enhanced Visible and Infrared Imager
TGSD	Total Grain Size Distribution
VATDM	Volcanic Ash Transport and Dispersal Models
VAA	Volcanic Ash Advisory
VAAC	Volcanic Ash Advisory Center
VAG	Volcanic Ash Graphic
VO	Volcano Observatories
VOGRIPA	Volcano Global Risk Identification and Analysis
VOL-CALPUFF	Volcanic CALifornia PUFF model
VOLDORAD	Volcano Doppler Radar
WMO	World Meteorological Organization
WOVO	World Organization of Volcano Observatories

<u>Appendix 2: List of participants</u>

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