2nd IUGG-WMO Workshop on Ash Dispersal Forecast and Civil Aviation

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Consensual Document

Costanza Bonadonna[1], Peter Webley[2], Matthew Hort[3], Arnau Folch[4],
Susan Loughlin[5], Herbert Puempel[6]

[1]Earth and Environmental Sciences Section, University of Geneva, Switzerland
[2]University of Alaska Fairbanks, USA – World Organization of Volcanic Observatories
[3]UK Met Office – London Volcanic Ash Advisory Centre, UK
[4]Barcelona Supercomputing Centre, Spain
[5]British Geological Survey, UK
[6]World Meteorological Organization, Switzerland

This consensual document has resulted from the contribution
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Executive summary

As a consequence of the severe disruption to air traffic generated by the April-May 2010 eruption of Eyjafjallajökull volcano in Iceland, a new multidisciplinary international community was born whose aim was to better describe the source term for volcanic ash dispersal modelling, the transport of ash in the atmosphere and the removal of volcanic particles from ash clouds. This diverse community gathered at the Geneva Headquarters of the World Meteorological Organization (WMO) on 18 - 20 October 2010 for the 1st IUGG-WMO workshop to promote stronger interactions between the volcanological and the operational forecasting communities. The resulting outcomes served as a road-map for on-going research.

A great deal of scientific progress has been made since 2010 in both the characterisation of volcanic eruptions, and in ash dispersal modelling and forecasting as a result of increased multidisciplinary collaboration. In particular, a large number of projects and consortia have been funded worldwide that cover multiple aspects of ash dispersal. However, more recent volcanic ash crises, such as the eruption of Cordón Caulle (Chile) and Grímsvötn (Iceland) in 2011, have demonstrated that specific needs remain and they have posed new challenges to the community. Three years after our first gathering, the 2nd IUGG-WMO workshop aimed at consolidating the multidisciplinary community established in 2010 and at optimizing the scientific and operational advances. Based on three days of dedicated talks, posters, break-out sessions, and extensive plenary discussions, research priorities were identified, including:

1. Better description of the source term:
    - Advances in the observation and study of particle aggregation focusing on multidisciplinary approaches, e.g. combination of field, modelling, monitoring and experimental strategies;
    - Data assimilation and inversion approaches and possible operational application;
    - Coupled near-source plume-atmosphere interaction;
    - Develop techniques to detect and better understand ash and sulphur dioxide separation;
    - Compilation of dedicated Probability Density Functions of Eruptive Source Parameters for critical volcanoes that could aid rapid initial forecasting during volcanic eruptions;
    - Formulate and validate ash emission source schemes for re-suspension events;
    - Combination of distal clouds measurements from different sensors that have different temporal, spatial and spectral resolutions.
2. Ash modelling:
    - Improvement of model physics, e.g. buoyant plume rise, wind entrainment, magma/water interaction, plume/atmosphere interaction, and particle aggregation;
    - Development of database(s) of eruption observations ranging from near-source to far-field, deposit characterisation and eruption source parameters to enable more systematic and easier model validation;
    - Model inter-comparison studies (including operational models).
3. Quantification of uncertainty and its propagation due to:
    - Proximal observations, e.g. variation and uncertainty of plume height and Mass Eruption Rate with time, total grain size distribution, vertical distribution of erupted products, volcanic plume content, and particle aggregation);
    - Distal observations, e.g. satellite remote sensing (both TIR ash retrievals and LIDAR);
    - Source term modelling (including uncertainty of wind entrainment and implications for the determination of Mass Eruption Rate);

   - Atmospheric transport models, e.g. physics, processes, resolution;
   - Numerical Weather Predictions driving atmospheric transport models;
   - Variability and/or complex eruption characteristics, e.g. rapidly varying intensity, multiple sources, co-Pyroclastic Density Current plumes, cessation;
   - Identification of best ensemble forecasting schemes to better characterize and manage uncertainties.

4. Hazard assessment:
   - Development of hazard assessment to identify critical volcanoes based on impact on aviation, e.g. proximity to flight paths, airports and communities;
   - Implementation and/or enhancement of systematic ground and space-borne monitoring for most critical active volcanoes with potential to impact on aviation routes and neighbouring communities;
   - Quantification and definition of volcanic sulphur dioxide hazards (and its oxidation products, mainly sulphuric acid aerosol particles) to aircraft components and occupants.

In addition to the listed research priorities, the attendees at the 2nd IUGG-WMO workshop also identified specific operational issues/concerns that should to be addressed in the short term. Provided below is a list of the specific items, noting that they are not listed in terms of highest priority first:

- Identification of suitable operational probabilistic modelling strategies to better quantify forecast uncertainty;
- Description and communication of uncertainty;
- Need for improved provision of, and access to, real time observational data for all operational institutions, e.g. Volcanic Ash Advisory Centres (VAACs), Volcano Observatories (VOs);
- Assessment of the feasibility and methodology for a VAAC volcanic sulphur dioxide warning service (at flight levels);
- Better understanding and forecasting of ash re-suspension;
- Improved communication and collaboration activities amongst operational institutions, e.g. VOs, VAACs and Meteorological Watch Offices;
- Develop funding opportunities and pathways for the achievements from the wider scientific community to be pulled through to operations in the operational institutions;
- Harmonisation to minimize the differences between information products of different VAACs, especially where ash clouds cross two or more VAAC areas of responsibility;
- Harmonisation of policy across the different civil aviation regulators and states regarding airspace restrictions during the different phases of probable ash concentrations;
- Implementation of ground-based monitoring systems at critical volcanoes, e.g. proximal to flight paths, airports, and communities, to improve description of source terms;
- Promote competency-based training networks between VAACs and VOs to build the two communities outside eruptive episodes;
- Develop accurate measurements of the impact of volcanic ash on engines in order to define better mitigation strategies.

The work presented and the discussions held at the 2nd IUGG-WMO workshop along with this consensual document show that the whole ash-aviation community, from research to operations, is working together to build the most capable system for aviation safety. The resulting outcomes provide the next steps for the community to move forward.

1 Introduction

[1] Worldwide, there are about 20 volcanoes erupting at any given time (www.volcano.si.edu) and these pose a potential hazard to aviation. Since 1973, there have been 120 reported aviation incidents due to volcanic ash, including 26 cases of very severe engine damage and 9 incidents of in-flight engine failure. Several recent eruptions (such as Eyjafjallajökull 2010, Iceland, and Cordón Caulle 2011, Chile) have been a stark reminder of the need to plan for, and be able to respond effectively to, future eruptions in order to minimize disruption to air transport and protect human safety.

[2] As a consequence of the severe disruption to air traffic generated by the April-May 2010 eruption of Eyjafjallajökull volcano in Iceland, it became clear that the tephra-dispersal community needed to improve monitoring and forecasting methodologies and to provide a more robust and reliable response to societal needs. In particular, an integrated strategy was urgently needed, based on collaboration between the volcanological and meteorological communities and the International Civil Aviation Organization (ICAO) in order to ensure that both the scientific knowledge and aviation safety aspects were considered (please refer to Appendix 1 for a complete list of acronyms). In fact, the zero-ash tolerance approach (i.e. diversion of flights) was shown not to be workable for high capacity European Air Space during a long-lasting eruption and so the ICAO EUR/NAT region amended their volcanic ash contingency plan to an ash mitigation plan based on ash concentration thresholds. This new strategy currently only employed in the ICAO EUR/NAT region clearly requires more accurate information on the ash mass in the erupting ash cloud since downwind concentrations strongly depend on the source strength. As a result, a new multidisciplinary international scientific community able to work together on a better description of both the source term and the transport and sedimentation of volcanic particles naturally developed.

[3] The 1st IUGG-WMO workshop on “Ash dispersal forecast and civil aviation” that took place in Geneva on 18-20 October 2010 promoted stronger interactions between the volcanological and the operational forecasting communities and the resulting outcomes served as a road-map for on-going research. About 50 volcanologists, meteorologists, atmospheric dispersion modellers, and space, air and ground-based monitoring specialists (including representatives from 6 VAACs) gathered to: i) discuss the needs of the ash dispersal modelling community, ii) investigate new data acquisition strategies and, iii) discuss how to improve communication between the research community and operational agencies. A consensual document was produced together with a document summarizing the results of a model-benchmark exercise carried out before the workshop, a document summarizing critical features of the main Volcanic Ash Dispersal and Transport Models (VATDMs) and a document summarizing the main data-acquisition techniques available at that time (http://www.unige.ch/hazards/Workshop/results.html).

[4] The main conclusion of the 1st IUGG-WMO workshop was that model developers, meteorologists, volcanologists and stakeholders (e.g. aviation sector) needed to work more closely together over the long term in order to develop new and improved strategies for ash dispersal forecasting. In particular, this new community had to work together to: i) improve the definition of the source term (mainly Mass Eruption Rate, MER, Total Grain-Size Distribution, TGSD, and mass distribution in the eruption column), and some critical aspects of particle sedimentation (mainly particle aggregation and wet deposition), ii) design models and forecasting strategies that could better characterize uncertainties both in the source term and in the physical description adopted by VATDMs, iii) explore the ensemble strategies for ash dispersal forecasting and, iv) identify optimized strategies for the combined use of models and observations. Research priorities were also identified and mainly included: 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) chemical analysis of plumes (particles, sulphuric acid aerosols, H_2S, halogen chemistry) and, vii) aerosol transformations.

[5] A great deal of scientific progress has been made since 2010 to improve characterisation of volcanic eruptions and to understand sensitivities and uncertainties in ash dispersal modelling and forecasting as a result of increased multidisciplinary collaboration. A large number of projects and consortia were funded worldwide that cover multiple aspects of ash dispersal, ranging from the expansion of ground-based remote sensing networks and capabilities for the characterization of far-field ash clouds to the real-time characterization of the source (see section 2 for more details). In addition, recent volcanic crises (i.e. Grimsvötn 2011, Iceland; Cordón Caulle 2011, Chile) have demonstrated how specific needs remain (e.g. accurate description of the source term) and posed new challenges (e.g. re-suspension of deposited volcanic ash). Finally, a significant challenge in rapid operationalization of scientific achievements is clearly evident.

[6] Three years after our first gathering, the 2nd IUGG-WMO workshop aimed at consolidating the multidisciplinary community established in 2010 and at optimizing the scientific and operational advances under the sponsorship of the World Meteorological Organization (WMO), the University of Geneva, the International Union of Geodesy and Geophysics (IUGG), the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), the British Geological Survey (BGS) and the UK Met Office. In order to facilitate the transfer of knowledge from research to operational products, the organizing committee was enlarged to include representatives of operational institutions worldwide (i.e. Dr. M. Hort, UK Met Office – London VAAC and Dr. P. Webley, University of Alaska Fairbanks, USA and World Organization of Volcanic Observatories).

[7] Ninety-five participants from 18 countries representing various scientific institutions, operational agencies (including all 9 VAACs) and stakeholders gathered at the Geneva Headquarters of the WMO to discuss: i) progress since 2010 and on-going research projects, ii) operational response to recent eruptions: practice and challenges, iii) characterization of Eruption Source Parameters (ESP), and iv) ash and gas dispersal modelling. In total, there were 47 invited talks and 32 posters; see Appendix 2 for list of participants. Specific objectives included: i) to review and institutionalize the interaction between meteorological, atmospheric, volcanological, modelling and remote sensing communities, ii) to develop strategies for a closer working relationship and further collaboration between the aviation industry and the scientific community, iii) to document progress from the 1st IUGG-WMO workshop, iv) to identify best practice modelling strategies to support operational implementation and, v) to identify and develop strategies to address current challenges.

[8] This consensual document attempts to summarize the outcomes of three days of dedicated talks, posters, break-out sessions, and extensive plenary discussions (focusing on operational challenges, characterization of the source term, and ash and gas dispersal modelling) in combination with a document compiled before the workshop gathering the opinions of the participants on the most pressing challenges in our communities and the efforts made across disciplines to overcome them. In addition, Appendix 3 and 4 (with the new Data-Acquisition Summary and Model Summary Documents) provide an update on both data-acquisition techniques and model developments first compiled during the 1st IUGG-WMO workshop (https://vhub.org/resources/503 and http://www.unige.ch/hazards/Workshop/results.html).

2 Current knowledge and capabilities

[9] The research carried out by the communities represented at the 2nd IUGG-WMO workshop has been considerable and has provided some new methods and techniques to improve eruption onset detection, better constrain of initial plume height, MER and TGSD as well as provide improved observations of the downwind plume and clouds for comparison with the VATDM's. There have

been a number of large research projects, mainly in the European region, that have started since the 1st IUGG-WMO workshop in 2010. These can be found in Appendix 5. Two 'Supersite' projects have started under the umbrella of the Group on Earth Observations (GEO) and are funded by the European Commission FP7 programme, namely in Iceland (FUTUTREVOLC) and in Italy (MED-SUV). These involve large groups of researchers from many different European countries, bringing together many different disciplines to observe and better understand volcanic processes. There has been development of the E-profile network, incorporating around 700 ceilometers in Europe as well as the EARLINET system of LIDARS for use in detecting distal volcanic clouds across Europe. A cooperation between E-profile and the more advanced LIDAR community of EARLINET has been established for detecting distal volcanic clouds across Europe. EARLINET stations could be used as "core sites" for the E-profile operational networks based on less advanced LIDAR instruments. The following sections briefly summarize such progress. The European 'drive' behind these projects reflects the degree to which the 2010 crisis affected the region, and should be understood as a continuation of efforts in other regions affected by previous major eruptions, such as the 1982 and 1985 incidents in Indonesia, the 1989 incident in Alaska, and the multiple ash encounters resulting from the eruption of Mt Pinatubo, Philippines, in 1991.

2.1 Characterization of eruption source parameters and ash cloud

[10] In 2010, the 1st IUGG-WMO workshop defined challenges in characterizing the source term as one of the main reasons for VATDM output variability and it was recognized as a research priority. The following section documents the progress made since 2010, in terms of determination of the source term as well as characterization of the volcanic cloud. With regards to characterizing the source term, two approaches have been explored. One, measuring the source parameters directly and the second, using inverse modelling approaches to better characterize the terms.

2.1.1 Plume modelling

[11] Firstly, there has been progress in the use of both three-dimensional (3-D) models and one-dimensional (1-D) models of the eruptive plume (e.g. [10.5047/eps.2013.03.009], [10.1029/2009GL042159], [http://dx.doi.org/10.1016/j.jvolgeores.2013.02.015], [10.1029/2012GL052566], [10.1029/2012JB009592]). 1-D models, even if simplified, do offer a more realistic representation of the erupting plume than can be achieved from just empirical methods, and provide a rapid modelling tool to determine MER from a measured plume top altitude in real time and even in the presence of strong wind. 3-D models, while computationally far more expensive and therefore limited in operational application, have been shown to provide useful information on the entrainment coefficients and interaction with the surrounding atmosphere. While 3D models offer the hope of numerical laboratories in which the detailed processes can be extensively explored, the 1-D models currently offer the best tool for operational use and broad exploratory investigations.

2.1.2 Proximal observations of Eruption Source Parameters

[12] Real-time observations of erupting plumes from ground-based cameras, in ultra-violet (UV), visible (VIS) and infrared (IR) wavelengths, have been collected to better characterize the MER, vertical mass distribution and plume top heights. Plume tracking mechanisms have been developed to map out plume top with time and examine both the thermal flux rise rates as well as map out ejecta both in the VIS and IR. Additionally, there has been development in the use of multispectral ground instruments to examine a wider spectrum of volcanogenic species from erupting volcanoes. Continued research has been performed in the use of ground-based radars to measure grain size and plume top heights. This has included the use of weather radar, permanent C-band radar sites as well as the development of mobile X-band radar stations, such as those in Iceland. All these radar

methods and datasets have been used to map out the top heights from erupting plumes and, given the radar wavelength, the potential particle size ranges derived from the radar retrieved signals. A recent study regarding the 2011 eruption of Kirishimayama volcano also demonstrated the ability of the Japanese weather radar network to measure the height of ash plumes more accurately and to contribute consequently to the improvement of model output. In addition, a ground camera network has potential to increase the accuracy of distal observations. Radar data will be soon put into operation also in Japan to underpin the provision of ash fall forecast and volcanic ash advisories for volcanoes.

[13] Several groups have examined the use of arrays of acoustic sensors to assess various ESPs. One example is the use of infrasound as a tool to detect an event and to assess the rate of eruptive material from the acoustic pressure released (e.g. [http://dx.doi.org/10.1016/j.epsl.2013.02.005]). Other groups have developed tools to make use of lightning detection arrays to assess event start times as well as the size of the eruption (e.g. [http://iopscience.iop.org/1748-9326/5/4/044013], [10.1007/s00445-010-0393-4]).

[14] Multiple groups have worked on mapping of eruptive products from older eruptions to determine the associated ESPs (TGSD, eruption rate and total eruptive mass and volume). These geological field studies provide the ability to define appropriate Probability Density Functions (PDFs) of ESPs for the VATDMs, based upon the past history of eruptions at the volcano.

2.1.3 Distal observations: ground, air and satellite

[15] During the 2010 eruption of Eyjafjallajökull volcano, the European LIDAR network documented the volcanic cloud as it passed across Europe. The analysis of the EARLINET data collected for this event provided the 4D distribution of the volcanic cloud [10.5194/acp-13-4429-2013, 10.5194/acp-12-2229-2012]. A specific relational database available on request through the EARLINET web site collects all information about volcanic aerosol layers observed by EARLINET.

[16] Research has been carried out into how to use these data systematically for operations and provide modellers with validating observations. There has been considerable work on the in-situ measurements of distal volcanic clouds using aircraft: grain size distributions within the dispersing cloud have been made using optical particle counters and ultra-violet DOAS instruments have been used to measure volcanogenic sulphur dioxide (SO_2). Before 2010, there were significant developments in retrieving volcanic cloud properties, such as total column loading, effective particle size and the timing of the eruption onset from satellite remote sensing. This was mainly completed in a research mode. Since 2010, the satellite remote sensing community has moved to developing timely and quantitative products for use in real-time observations of the dispersing cloud. This data can then be used to compare to the VATDM's, but satellite data coverage is not uniform in space or time across the globe.

2.1.4 Inverse modelling of source terms

[17] Along with 3-D modelling to constrain 1-D models of the eruptive column, progress has been made in inverse modelling combining the use of satellite remote sensing observations and transport or chemistry-transport modelling of dispersing ash/SO_2 clouds. Several approaches have been developed which aim at determining MERs, vertical mass distribution at the vent and initial plume top [10.5194/acp-8-3881-2008; 10.1029/2009JD013286; 10.5194/acp-11-4333-2011; 10.5194/acp-13-8569-2013]. Some of the methods require a priori data to constrain the inversion methodology.

2.1.5 Re-suspension of volcanic ash

[18] Re-suspension of fine ash has long been recognized as an issue for aviation and air quality in some regions of the world (e.g. Alaska, Argentina and Iceland). Research groups focusing on re-suspension have aimed to both classify the source of re-suspended material as well as identify methodologies to include it as an area source within the VATDM's. To define the source term, re-

suspension emission schemes for mineral dust have been tested for volcanic ash in Iceland [10.1029/2011JD016802] and Argentina [10.5194/nhess-14-119-2014], showing promising results.

2.1.6 Observatory monitoring

[19] Provision of eruption early warning and identification of eruption onset is often reliant on local monitoring systems maintained by state VO. Since 2010, some specific very active high-risk volcanoes have had improved monitoring capabilities, most notably in Iceland and at Mount Etna, Italy. Elsewhere, some volcanic regions have become less well-monitored and have reduced the communities' capability to detect an event's onset. This reduced capability has been brought on by financial as well as maintenance, technological, and logistical constraints.

2.1.7 Experimental observations

[20] Despite the development of sophisticated numerical models and data-acquisition techniques, we lack knowledge of critical processes, and this is reflected in significant uncertainties in forecasting volcanic ash dispersal and deposition. These uncertainties result in part from lack of understanding of: (i) ash generation processes, (ii) ash aggregation processes, (iii) aggregation rates and timescales, and (iv) the aerodynamic behaviour of ash particles and aggregates. A combination of laboratory simulations, real-time field observations and verified modelling is required to yield powerful tools to forecast: (i) aggregation processes in the volcanic conduit, jet, and column, and (ii) far field processes in dilute volcanic clouds.

[21] Experimental work on sedimentation and aggregation of volcanic ash has been, and is being undertaken by a number of groups using different approaches. Aqueous liquids play a major role in the formation of strongly bound aggregates [10.1007/BF00301467; 10.1007/BF00326465; 10.1007/s00445-005-0430-x] with hygroscopic solutes acting to stabilize liquid layers. Data from these early experiments provide a first-order constraint on recent models of volcanic ash aggregation [10.1029/2009JB007175; 10.1029/2009JB007176]. The role of electrostatic charge in near-field ash aggregation is indicated by the presence of observed vent lightning. Recently, experimental work has given insight into the fluid-dynamic charge separation mechanisms that may generate electrostatic discharges [doi:10.1130/G34802.1] as an explosive volcanic flow exits the conduit. The experimental aggregation of dry, charged ash particles generated by pumice comminution [10.1029/2001JB000950; 10.1029/2002JB002011] produces aggregates with very similar aerodynamic behaviour to those observed in real time falling from a volcanic plume [10.1130/G32016.1]. This suggests that electrostatic charge is a key driver in the near-field aggregation of volcanic ash.

[22] Experimental research is currently being undertaken into the interaction between particles falling in the atmosphere [10.1063/1.4805019], impacting with other particles [10.1016/j.jvolgeores.2011.09.008] and under wet and icy conditions [10.1007/s00445-012-0634-9]. These, and other experimental work, will provide a growing understanding of the richness of aggregation processes as well as data with which to verify numerical simulations and better interpret satellite retrievals.

2.2 Ash dispersal modelling

[23] During the last 3 years there has been a significant collaborative effort between volcanologists, atmospheric dispersion modellers and meteorologists to address some of weaknesses of VATDMs discussed during the 1st IUGG-WMO workshop including: i) the definition of the source term (discussed in section 2.1.1), ii) model physics and iii) model post-process and validation.

2.2.1 Model Physics

[24] There has been little progress in modelling dry/wet ash aggregation phenomena occurring in the volcanic plume or in the atmosphere during transport. Several experimental studies and in-situ field observations have improved the quantification of settling velocities and grain size of aggregates (see for example section 2.1.7), but this does not indicate the process. These data have been included in some VATDMs, which assume aggregation to occur instantaneously in the plume and consider aggregates as another particle class (bin), introduced as a standard source term. The IAVCEI Commission for Tephra Hazard Modelling is creating a database for ash aggregates including not only processes occurring in volcanic clouds, but also interpretation of aggregate structures in the geological record and bringing together ideas from experiments and models.

[25] Some progress has been made to better describe the contribution of the gravity current spreading to the transport of volcanic ash, which can result in: i) more rapid cloud downwind spreading, ii) more significant upwind spreading than predicted by simple advection-diffusion models, iii) cloud thinning downwind.

2.2.2 Model validation

[26] Since the 1st IUGG-WMO workshop in 2010, a significant number of model validation papers have been published. Most of these have focused on the Eyjafjallajökull 2010 eruption due to the extensive observational data gathered during that event and extensive knowledge of the associated ESPs. Far fewer have been published yet for Grimsvötn 2011, Iceland, or Cordón Caulle 2011, Chile. These events were predominantly only monitored via satellite highlighting our dependence on these platforms but also demonstrating the need for more extensive observations for thorough model validation. Similarly, there has been little work done on dispersion of ash from tropical eruptions, such as those from Merapi, Indonesia in 2010, where relevant ground and remote sensing data have tended to be poor. The higher entrained moisture content and the nature of tropical convection and broader circulation also provide different challenges.

[27] There have been efforts to create databases for model validation. In addition to a database for particle aggregation (section 2.2.1), the IAVCEI Commission for Tephra Hazard Modelling is also developing a benchmarking exercise for plume models of both strong and weak plumes and collaborates with the VASAG in building a database including satellite data, NWPM results and ESPs for recent eruptions. This will constitute the first open dataset for VATDM validation.

2.3 Operational forecasting

[28] The presence of representatives from all 9 VAACs and from some VOs provided a valuable opportunity for the workshop to hear of the operational developments and challenges in delivering volcanic ash forecasts. Significant challenges remain, as captured in Section 3.3. However, the workshop heard of encouraging developments particularly in the areas of: i) communication and collaboration, ii) training, iii) use of and access to observational data, iv) modelling enhancements, v) understanding of uncertainty and, vi) new services and operational pull-through.

[29] These developments are however small in comparison to the developments occurring in the research community due to a significant increase in research funding in the past few years. Some operational institutions (many of which are also active in research) may be unable to receive funding as research partners for a variety of reasons (e.g. not in the same country as the funding agency) and the necessary transition from research to operations may also lack funding and can be delayed due to significant bureaucratic processes. These issues can also inhibit the valuable contribution that operational and permanent services can make to on-going scientific investigations.

2.3.1 Communication and Collaboration

[30] VOs, VAACs and MWOs are mutually inter-dependent and also reliant upon others to deliver timely and accurate guidance. The workshop heard of numerous cases of improved communications and collaboration, e.g. in Europe, the Americas and Asia.

[31] Both VAACs and VOs have started programs of "Best Practice" workshops aimed at sharing of experience and enhancement of services/activities. These activities have highlighted needs and in some limited way have started work on: i) collaborative decision making, ii) data/information sharing processes/formats, iii) default assumptions including the use of historic data, iv) communication processes, etc.

[32] The VAAC Best Practice program has been supported by workshops including the WMO "In's and Out's" meeting in Washington 2012 which brought together operational support scientists, in many cases for the first time, to explore and determine the operational modelling gaps and challenges. These efforts are just the start and the need for a continued, sustained and linked effort across the range of operational, applied and academic areas is still very apparent.

2.3.2 Training

[33] Several examples of inter-organisational learning (i.e. Best Practice) and internal institutional training activities were presented. Several centres have established formal training programs and this material is also being shared. In particular, specific attention has been paid to training in the use and interpretation of observational data and products, e.g. radar and satellite data.

2.3.3 Use of and access to observational data

[34] Both proximal and distal observational capability remains highly variable across the globe. Certain volcanoes/volcanic regions (e.g. Iceland and Italy), already starting from a high point continue to develop further observational capabilities. Other regions though have seen a reduction in observations, e.g. the Americas, due to the re-tasking of certain satellite resources.

[35] Proximal observations remain poor or non-existent for many volcanoes. However, the meeting heard of developments at several NMS/VAACs/VOs in the use of radar data. Significantly, much of this focused on the use of existing weather radars, which were identified as an underutilised resource.

[36] Distal observations are dominated by the use of satellite data though currently only Europe and Africa have access to relevant multi-spectral geostationary instruments for quantitative information. Planned launches will fill this particular gap and the meeting heard of work already underway at several VAACs that will enable rapid adoption of products based on the next generation of launches through 2015-2016. Access to relevant satellite data and derived products for many VOs though is still sparse and presents a significant challenge but also an opportunity given how much data exists. With respect to ground based observations, quick looks of LIDAR measurements are typically available in NRT for operational LIDAR networks as ceilometer ones and for the most of EARLINET stations.

2.3.4 Modelling enhancements

[37] Fundamental dispersion model capability has changed little since the 2010 workshop. However effective operational use of models has improved at several VAACs where new and/or improved interfaces have been developed offering forecasters access to a greater range of inputs and model settings, e.g. TGSD, variable vertical mass distribution and MER options, wet deposition. However, real time specification of some of these remains a challenge and can only be addressed through further work with the volcanological community.

[38] Significant model validation has been carried out and several peer-reviewed papers and reports have been published based on many of the VAAC models.

[39] Advancing NWP skills at the VAACs parent NMSs has continued. Access to ensemble NWP data remains very limited with no true operational probabilistic capability as yet.

[40] While data assimilation/inversion activities remain largely research-based there has been some initial important operational progress. VAAC London has deployed a semi-operational inversion technique that will run automatically given an eruption in Iceland. VAAC Darwin has also begun developments in this area. Several VAACs, e.g. Washington, Darwin and Tokyo, have developed the ability to initiate their dispersion models qualitatively from satellite imagery of the distal plume.

2.3.5 Understanding of uncertainty

[41] Through the Best Practice meetings, VAACs and their supporting researchers have begun to explore the inclusion and presentation of uncertainty or forecast confidence. This though is a complex issue with many research questions and progress is very limited.

2.3.6 New services and operational pull-through

[42] Ash deposited during the recent eruptions in Iceland and Chile has raised awareness of the hazard of re-suspended volcanic ash. Measured concentrations at ground level (Air Quality monitoring sites) and satellite observations indicate that re-suspension events present a clear aviation hazard especially at, and in the vicinity of, airports. Both London and Buenos Aries VAAC's have investigated new forecast warning services with London deploying an operational service for Iceland and Buenos Aires developing one for their region. Anchorage VAAC has provided response services as well. Nevertheless, this remains an area needing research and operational development.

2.4 Hazard communication and aviation sector

2.4.1 Harmonisation of procedures

[43] A series of airplane-ash encounters in the 1980s, led to a joint effort by volcanologists, meteorologists and the aviation industry to find ways to avoid future encounters. An international conference was held in Seattle in July 1991 resulting in the establishment of the network of nine Volcanic Ash Advisory Centres (VAACs) which follow clear International Airways Volcano Watch (IAVW) procedures in terms of communication (http://www.icao.int/safety/meteorology/iavwopsg/Pages/default.aspx). Representatives of the VAAC provider states are members of the IAVW Operations Group (IAVWOPSG), which meets regularly to address operational development of the IAVW.

[44] The VOs are expected to issue volcanic ash activity reports to VAACs, MWOs, and area control centres/flight information centres (ACC/FIC) if there is increasing unrest, increasing volcanic activity, a volcanic eruption or cessation of a volcanic event. For many VO this action is on a 'call-down list' activated during any significant change at a volcano. The call-down may include telephone calls, emails, text messages and so on. There is a list of people in VAACs and VO who are contactable 24 hours per day. There may be an "Aviation Colour Code" system in place at a volcano observatory but this is optional and is not used worldwide.

[45] On receiving information, the ACC/FIC responsible issue NOTAMs to aircraft in flight, these are succinct and informative alerts. The MWOs are expected to issue SIGMETs to aircraft including brief information on date/time and location of ash. The VAACs initialise and run dispersal models and review satellite images and other observational data to then issue advisory information on the extent and forecast trajectory of a volcanic ash cloud. This is normally in the form of an 'ash – no ash' chart, effectively denoting an area where there is a significant risk of ash encounters. However, new supplementary ash-concentration based charts were developed for the EUR/NAT region in 2010 to better inform the regulatory safety risk assessment requirements of this densely packed region of airspace.

[46] The hazard to aircrafts is frequently greatest during the first few hours of an eruption so these procedures must be smooth and communication timely and effective. For this reason, many VO, VAACs and stakeholders practice and test the IAVW procedures in formal exercises on a regular basis.

[47] There are many unmonitored volcanoes and many volcanoes with limited monitoring. For this reason, observations from pilots or detection by satellite observation at the VAAC office may be the first indication of an eruption.

[48] When an ash cloud crosses the boundary between different VAAC areas of responsibility, the first VAAC retains responsibility for advisories until an agreed handover. Multiple VAAC's can issue advisories for the same volcano if agreed upon by each VAAC. Most of the time it is only two VAAC doing this. This usually happens during larger eruptions. To implement this in a globally harmonized manner, IAVWOPSG has been considering establishment and enhancement of Collaborative Decision Analysis and Forecasting (CDAF). CDAF process will omprise coordination between two adjacent VAACs on message content, analyzing satellite imagery and other remote sensing data, running models, etc.

2.4.2 VAAC outputs and graphics

[49] As concluded by the ICAO International Volcanic Ash Task Force (http://www.icao.int/safety/meteorology/ivatf/Pages/default.aspx) ash-concentration charts as developed during the 2010 of Eyjafjallajökull are not workable as an operational hazard warning product for aviation, primarily because of the order-of-magnitude uncertainties in dispersion model output (and also because engine tolerances to ash ingestion have not yet been determined). There is a tremendous amount of relevant research underway now that will contribute to improved graphics and visualisations of ash clouds in the future.

2.4.3 Vulnerability of engine and airframe components

[50] There is some damage data available from planes that have interacted with volcanic products (e.g. ash, sulphur dioxide and sulphates) in flight and on the ground but before 2010 there was considered no need to pursue rigorous studies if planes followed procedures and avoided volcanic ash. Given the change in procedures in the ICAO EUR/NAT region and the need for airline Volcanic Ash (VA) Safety Risk Assessments (SRA) to potentially fly in areas of low forecast ash contamination, there are now efforts and a gathering momentum to identify what the vulnerability of engines, airframe components and critical systems may be.

[51] VA SRAs are currently only required in the ICAO EUR/NAT region and are currently largely based on the supplementary ash concentration charts, produced at the request of their respective regulators by the UK Met Office and Meteo-France. The concentration charts are not supported globally potentially leading to issues with harmonisation. However, the updating and new issuance of ICAO guidance documents, such as the *Handbook on the International Airways Volcano Watch (IAVW) — Operational Procedures and Contact List* (Doc 9766) and the *Flight Safety and Volcanic Ash* (Doc 9974) as a result of the work of the IVATF has also provided a much stronger framework behind the IAVW. Document 9974, for example, clearly articulates the responsibility of operators for risk management, and Document 9766 has considerably strengthened the requirement on State VO to provide information on volcanic activity.

3 Challenges and recommendations

[52] The breakout groups and plenary discussions, held at the 2nd IUGG-WMO workshop, defined some of the continuing and new research priorities that need to be approached. Additionally, before the workshop, the attendees had identified the main challenges in their specific areas of expertise

and ways to overcome them. Documented here is their consensus, again defined by the five topics/areas defined earlier for the current knowledge and capabilities in Sections 2.1 – 2.5.

3.1 Characterization of the observations and Eruption Source Parameters

[53] In the inquiry documents compiled by the meeting attendees before the workshop, the term ‘uncertainty’ was prevalent and the need to define the limitations, and/or level of accuracy in recorded observations, was a common trend. Be it from ground based measurements at the source through to satellite remote sensing retrievals of ash and SO_2, knowledge of the measurement accuracy and how to classify the uncertainty were repeatedly raised as a research challenge and a priority in future research ventures. Nevertheless, research priorities and challenges were also identified in various other areas.

3.1.1 Pre-eruptive ESP for scenario planning

[54] Before a volcanic event occurs and also during periods of volcanic unrest, pre-eruptive planning is a critical process for the VAACs and aviation industry. For this, ESPs are needed. A challenge is in defining these for the world’s volcanoes. Some volcanoes are well understood while others may not erupt for thousands of years (such as Chaitén, Chile). Defining the most likely eruption from past event studies is critical to define the pre-event scenarios. For these well-understood volcanoes, examination of past eruptive deposits can provide grain-size distributions, total eruptive mass and possibly potential plume height and duration. For the less active or poorly studied volcanoes, this is a harder task and requires more research. Mastin et al. [http://dx.doi.org/10.1016/j.jvolgeores.2009.01.008] classified the ESP for world’s volcanoes based on 10 types. Several recent eruptions have shown that more work is needed to define pre-event ESP per volcano. More field studies of eruptive deposits are needed to establish the past history of the volcano and build up PDFs for each ESP for the VATDM’s. This would then allow probabilistic modelling based on these pre-event scenarios. The highest priority for such work should be given to those volcanoes most likely to re-awaken.

3.1.2 Measuring Eruption Source Parameters at vent

[55] Proximal observations need to not only record the measured parameters but also the uncertainty or measurement accuracy in the data collected. This includes source terms such as: i) event start and end time, ii) plume top height (with time), iii) MER (with time), iv) TGSD, v) aggregation effects within the near-field plume, vi) volcanic plume content (ash, water and gases), and vii) vertical distribution of the erupted material. Classifying the uncertainty in these terms is a major challenge of the research community, especially in terms of real-time observations as compared to those in post-event analysis. It should be noted that none of the above mentioned parameters should be seen as constant throughout an eruption.

3.1.2.1 Mass Eruption Rate (MER)

[56] MER is necessary to characterize the amount of mass injected into the atmosphere. It is often measured at a defined point in time, usually from one plume height measurement, coupled with empirical methods or 1-D models. However, eruptions have commonly time-varying plume heights. These can come from ground instruments, in-situ, airborne, or satellite measurements as well as pilot reports. Additionally, to providing time-varying plume heights, the different methodologies used to relate plume height to MER require more research. The effort of the IAVCEI Commission on Tephra Hazard Modelling to benchmark different volcanic column models (see section 2.2.2) is a good start to the process. These different models need to be compared to the empirical equations, MER measurements from the ground, and thermal/infrasonic measurements at the source, with more 3-D modelling work and possible look-up tables from 3-D modelling. There is also a need to more accurately quantify rates of air entrainment into plumes, through a combination

of laboratory and field measurements and to improve the formulation by which control volumes are tracked in 1-D models.

[57] Other techniques also require inter-disciplinary inter-comparisons. There are a multitude of different techniques and tools to measure plume heights that are used operationally. As plume heights are often used to assess the MER, then uncertainty estimates need to be included on the measured plume heights. The methodologies used for plume heights (i.e. local X-band radar, seismic and infrasound signals, satellite data, weather C-band radar, pilot reports, and ground based cameras) need to be compared and their differences/similarities understood. Because MER estimates are highly sensitive to slight variations in plume height, resources should be devoted to the purchase and deployment of instruments whose accuracy is high, and installation procedures should be developed for instruments such as mobile radar to maximize measurement accuracy.

3.1.2.2 Event occurrence at remote volcanoes

[58] Many volcanoes worldwide do not have a ground based monitoring system and as such further research is needed to make use of regional/global networks of additional remote-sensing instrumentation. Some of these include using the global infrasound and lightning networks. Significant steps have been made to use these instruments for event detection, but more work can be accomplished. Comparing these datasets to other information from satellite data can help to clarify the occurrence of an eruption at a remote, poorly monitored volcano. Often one method may not be enough to confirm an event, but combined together the different methods and instruments can improve the potential for event detection and for timely information available at the volcano observatory and information flow to the VAAC.

3.1.2.3 Aggregation processes at vent and eruptive plume characteristics

[59] For VATDMs, there is need to define the TGSD of particles that are transported in the atmosphere. Aggregation processes can significantly change the initial erupted TGSD and this and other loss processes need to be considered when determining the most appropriate TGSD for the VATDM's. Being able to fully describe aggregation in VATDMs will be discussed later, but there is also more research needed into how to use ground observations to constrain airborne grain sizes, particle density and the percentage erupted that is ash, ash aggregates or hydrometeors. Research is also needed on fragmentation processes and the influence of external sources, such as meteoric water/ice/steam, on TGSD, vertical plume distribution and the content of the eruptive column. This research will help to define the uncertainty in the TGSD and act as a priori for inverse techniques by providing the most accurate representation of the eruptive material for the VATDM's.

3.1.2.4 Ash and sulphur dioxide separation at vent and SO_2 ESP

[60] With discussions on the potential hazard of SO_2 and its derivatives for the aviation community continuing, SO_2 is also sometimes used as a tracer for volcanic ash or as indicator of an eruption when no ash has been detected, and hence the potential separation of SO_2 from ash requires further study.

3.1.2.5 Re-suspension

[61] Re-suspension events are dependent on a range of parameters. To determine these, field studies to measure and map the volcanic material, including multiple year campaigns are required. Field studies should be able to assess how the volcanic deposit changes in time and provide useful source parameters for re-suspended material.

3.1.2.6 Overall aim

[62] From all of these source parameters, the real need is to be able to provide them in a near real time environment, with defined limitations/uncertainty estimates so one method can be

assessed against another. Defining uncertainty estimates for each of the source parameters can then allow the VATDM's to build probabilistic approaches to forecasting and define confidence levels on the VATDM forecasts.

3.1.3 Distal cloud measurements

[63] For distal clouds, there is a need to be able to obtain real-time observations for the observation section of the VAA and to compare to the VATDMs as well as provide data that can be used for inversion methods to better define the source term. Data can be collected from ground, airborne and satellite methods.

[64] For ground-based observations of the distal cloud, LIDAR data and ceilometers backscatter plots were heavily used in Europe to track the location of the cloud from the Eyjafjallajökull eruption in 2010. The presence of volcanic aerosol and geometrical and optical characterization of the observed layers were obtained processing the collected data with a specific methodology [10.5194/acp-13-4429-2013, 10.5194/acp-12-2229-2012]. A big challenge is how to process this information in near real-time to make it directly useable for the VATDMs. For some specific cases, mass retrieval was possible through the combination of aerosol optical profiles and sun-photometer measurements [10.1029/2010JD015567, 10.5194/acp-11-2209-2011, 10.5194/acp-12-3115-2012]. Further work is required to turn the backscatter data into mass retrievals as well as coupling the data with satellite retrievals for use in determining cloud thickness.

[65] For in-situ airborne measurements, a big challenge is how to make more use of this in a near-real time process. Many airborne measurements, mainly from aircraft, have been ad-hoc or opportunistic. Further research is needed in how to use this data in the VATDMs as well as how to best coordinate the systematic collection. This will require both the VATDM community and the sampling community to define and discuss common practices so that the useful in-situ data can be used for VATDMs.

[66] Satellites offer a suite of opportunities for further research and use. Research is required in defining, quantifying and in minimize the uncertainty in the retrievals and developing the best approaches for comparison to the VATDMs or for use in inverse modelling. There has been some development in reporting of probabilities in ash satellite retrievals for each output parameter (such as cloud top height, optical depth, effective radii, and mass loading) as well as in probability of ash occurrence. Further work is needed to continue this process as well as in reducing the uncertainties in the measurements. For example there is a need for improved refractive indices measurements used in the volcanic ash retrievals as much of the data currently used comes from experiments in the 1970s.

[67] Many satellite retrievals require a defined TGSD, usually a log-normal curve with defined size range. Further research is needed of observations of the TGSD with time-coincident satellite data to reduce potential uncertainty in the retrieved ash cloud masses. To this end, a database of such in-situ measurements would be very useful to the remote sensing community.

[68] There is further work needed in how to fuse together data from different sensors that have different temporal, spatial and spectral resolutions. The goal being to provide a temporally frequent and systematic data set for use in and comparison to VATDM forecasts.

3.2 Ash dispersal modelling

3.2.1 Eruption Source Parameters

[69] To model ash dispersion we need to improve the quantification of the ESPs of VATDMs for a number of key processes, including: i) magma-water interaction, ii) co-PDC plumes, iii) gravity current spreading (which can result in more rapid cloud downwind spreading, more significant

upwind spreading and cloud thinning downwind), iv) re-suspension by wind (depending on meteorological and time-dependent deposit characteristics).

[70] Better understanding and calibration of the wind-affected entrainment parameterization of 1-D plume models is also needed (i.e. turbulent mixing of atmospheric air into the plume). These models are commonly used to derive MER from column height and wind field. However, values for entrainment range between 0.1 and 0.9 depending on different parameterizations and experimental/numerical results. Given the squared dependency of MER on entrainment coefficient, this variation can introduce large variations in the MER estimate. Further laboratory experiments, 3D numerical simulations, comparison of model predictions with observations, and model sensitivity studies could better constrain the range of this parameter.

3.2.2 Model uncertainty

[71] Model uncertainties can arise from multiple paths but mainly depend on the nonlinear behaviour of natural systems, errors in measurements and data acquisition, lack of accuracy of model input data, and/or limitations of the physical models and parameterizations. Model developers should make an effort to quantify uncertainty in model forecasts depending on: i) uncertainty in the source term (including uncertainty on wind entrainment and plume height and implications for the determination of MER), ii) uncertainty in transport models due to physical processes not included in both source and transport (e.g. physics at scales lower than model resolution or ash aggregation or buoyancy effects), iii) uncertainty in transport models due to numerical inaccuracies (e.g. limited model resolution), iv) uncertainty in the driving NWP, v) occurrence of complex events (e.g. rapidly varying intensity of eruptions, possible multiple sources or co-ignimbrite clouds, etc.) and, for longer-lasting eruptions, and vi) changing eruption characteristics, cessation, etc. To this purpose modellers should identify which are the most important input parameters for ash dispersal modelling, how precisely these need to be quantified, and how uncertainties in inputs propagate to model outputs.

3.2.3 Data assimilation

[72] Information on the source term and ash cloud evolution typically increases with time. Systematic assimilation of new data (both in the proximal and far-field) is important to improve ash forecasts. To date, observations assimilated into VATDMs have been limited to model inputs and come directly from measurements of ESPs or indirectly (e.g. using inversion techniques to obtain MER and vertical distribution of fine ash from satellite retrievals). Full data assimilation, as done in NWP, has not been used yet in VATDMs.

3.2.4 Ensemble forecasting

[73] This type of forecasting includes ensembles of model inputs for a given VATDM or ensemble of models (considering different VATDMs, different driving NWP or a combination of both). Ensembles of input variables combine a range of ESPs and associated PDFs, and can be used to quantify forecast uncertainty providing either a deterministic (but with associated uncertainty) or a probabilistic forecast. On the other hand, ensembles of models can potentially improve the accuracy of forecasts. However, previous experience in multi-model ensembles for atmospheric transport of distinct substances (e.g. radioactive nuclei) shows the importance of inspecting the ensemble prior to using it. In the case of VATDMs, it is necessary to identify to which extent the combination of models is meaningful and to determine the number and types of relevant models.

3.2.5 Aggregation

[74] Dry and wet aggregation phenomena, still not fully understood but known to commonly occur, need to be better modelled and aggregation models and/or parameterisations included in

VATDMs in order for the VATDMs to better simulate downwind ash transport and removal. Knowing the TGSD is required for these simulations.

3.2.6 Plume-atmosphere interaction

[75] It is important to investigate the effects of volcanic plumes on near source meso- and microphysics, i.e. to which extent and up to which distance volcanic plumes can affect meteorology. Given that operational VATDMs run off-line, to neglect the influence of the plume on meteorology may affect (near-range) forecasts and this therefore needs to be quantified, particularly for large-magnitude eruptions.

3.3 Operational forecasting

[76] Operational forecasting requires a high standard of underpinning science for observing and modelling volcanic clouds. Furthermore, the large-scale nature of ash events needs efficient inter-agency communication and collaboration in real-time, and these events often occur in a data sparse environment. Due to the safety relevance of the information and the vast economic impact that ash events can have on the aviation industry and, given the reliance of economies on aviation, high standards in accuracy, reliability and coverage of this information are paramount. The flow of information between organizations involved in operational service delivery is critical for a successful service. VOs, VAACs and MWOs are in some cases under-resourced, which may compromise reliable service delivery.

[77] As noted earlier, ICAO has recently strengthened the relevant guidance documents and operational requirements placed on its Member States. It is hoped that these measures, where implemented, will significantly strengthen the operations of the IAVW, but the implementation itself will continue to require the strong support of the scientific and operational community.

[78] The remainder of this section, using the same categories as in Section 2.3, outlines those items identified as representing the focus for operational forecasting. Obviously these are linked with the observational and modelling challenges and advances outlined elsewhere in this document.

3.3.1 Use of and access to observational data

[79] Observational data and its accessibility in real time remain variable, a problem further compounded by a lack of knowledge of the characteristics, e.g. typical eruption type, of volcanoes, their particle size distribution and other features.

[80] Significant effort needs to be directed to improving the consistency and accuracy of near real-time data. This may require new equipment and/or VO resources but it will also include making better use of data already in existence e.g. weather radar, satellite, etc. This later data may be underutilised, as it is ‘owned’ by different organisations or due to limited tele- and data-communication links.

[81] Dispersion models, as used by the VAACs, require as inputs the physical characteristics of the ash and eruption. While real time data of these during an event is ideal, their availability is often limited, especially during the early phase of an eruption. However volcanoes often exhibit characteristic behaviour and, as such, analysis of their historic behaviour can provide information that is significantly better than generic, non-specific ESP. Collection and compilation of such data in an easily accessible form, e.g. online database, to operational organisations would be beneficial. Such data is also valuable in terms of pre-eruption and general hazard assessment both of which are under-utilised activities.

3.3.2 Modelling enhancements

[82] Operational use of numerical modelling continues to be diverse across the VAACs. Efforts to introduce common standards and operating practices have been undertaken, e.g. by holding

workshops on VAAC Best Practice, VAAC "In's and Out's", but further effort in this regard is required and encouraged.

[83] The use of quantitative modelling and observational data is clearly the way forward. In this vein, three specific items were raised repeatedly; model validation, inversion/data assimilation and representation of uncertainty (See section 3.3.3).

[84] VAACs were encouraged to conduct or support more model validation and inter-comparison studies. Acknowledging that this often requires significant effort, the setting up and use of common databases for input and observation data was encouraged. The use of frameworks such as "Ensemble Modelling" in assessing the results was also suggested.

[85] Observations clearly provide a ground truth but obviously are limited to always being "historic" and have a level of uncertainty. Data assimilation and/or inversion provide quantitative and repeatable methods for constraining the source term based on available observations. If produced in near real-time, that source term can be used to produce an enhanced model forecast. Some effort has started at the VAACs on this but it requires both more research (e.g. new techniques, use of multiple observation types) and application. The weather forecast community has demonstrated the benefits that such fused approaches offer but also illustrates the effort that may be required.

3.3.3 Understanding of uncertainty

[86] Forecast uncertainty is a complex issue as it encompasses uncertainties from all components, e.g. source term, aggregation, meteorological advection, wet or dry deposition, and dispersion processes. This is complicated by the fact that some aspects of the resulting errors are non-linearly dependent upon each other. Many challenges clearly exist in terms of quantifying the individual and combined uncertainties of all the separate components, e.g. development of PDFs for source parameters, model uncertainties and the propagation of uncertainties. Communication of uncertainty is also a very complex task. Clearly significant research work is required in this area before the operational adoption of a quantitative approach is possible.

[87] Within the operational community, however there exists a desire to attempt to communicate at least aspects of this issue in a simple and perhaps qualitative way. The use of the term confidence level has been suggested and will be discussed at a VAAC meeting in February 2014. Such a strategy needs to be articulated more clearly if the broader community is to contribute.

3.3.4 Training

[88] The operational VAAC role is becoming more sophisticated. Developments and improvements mean that operational staff are increasingly presented with new and more data from many sources, e.g. satellite, radar, eruptive history and are also simultaneously expected to condense and explain the decision making process to the regulators and operators. Operational staff therefore need training and in some cases support from experts in the interpretation of observational data, limitations/capabilities of models and in communication skills. VAACs are required to address these issues as part of their quality management processes and are increasingly introducing competency-based training frameworks.

3.3.5 Communication and collaboration

[89] Communication and collaboration activities need to be further expanded. VOs, VAACs and MWOs need to develop a better understanding of each other's capacities and requirements outside of the response period. Regular contact, joint projects, and staff exchanges should be part of the duties in delivering a multi-organisation response. This is not always possible due to many challenges, such as financial, technological and linguistic.

[90] Data collection and sharing also form an important aspect of the communications. Certain information can be developed if enough time is available, e.g. typical characteristics of a given

volcano to be used to better inform initial response. Other data needs to flow during the event, e.g. eruption column height. However in both cases, methodologies and details on what is behind the summary/condensed communication can and should be developed as part of business as usual activities. This all requires clear articulation of the needs of each organisation to each other and to the research community.

[91] Communication and collaboration also need to be enhanced between the responding organisations and the customers, i.e. regulators and operators.

3.3.6 New services and operational pull-through

[92] The understanding and forecasting of ash re-suspension needs to be developed. Several regions are now likely to experience regular events and clarity of suitable operational procedures including the roles of the VOs and VAACs, neither of which may be observing the deposit area and/or be able to model the cloud, needs to be established.

[93] Volcanic gases clearly present a potential hazard to humans, airframes and engines through toxicity and corrosive properties, although little work has been done to understand, quantify and articulate the hazard. Currently there exists no forecasting and warning requirement for volcanic gases. In addition the nature of the potential risks is also poorly understood. While research is clearly needed in this area it is felt that enough is known, for some gases, that effort should be expended on assessing the feasibility and methodology for a volcanic gas warning service.

[94] The effort required to pull through science and capability to operations is often greatly under-estimated and underfunded. Delivery of best of breed services remains constrained by this issue and tackling this remains a key operational challenge.

3.4 Hazard communication and aviation sector

[95] Communication can be particularly challenging when multiple VAACs and multiple civil aviation authorities are responding to the same eruption. The Eyjafjallajökull eruption in 2010 demonstrated that even relatively small magnitude eruptions can affect many countries. The following topics were identified as the main challenges for hazard communication and for the aviation sector, primarily from the Eyjafjallajökull eruption.

3.4.1 Coordination of procedures/responses

[96] Despite efforts by Eurocontrol, EU, ANSPs, ICAO and others, the different civil aviation authorities (CAAs) currently apply differing regulatory processes and philosophies to their sovereign airspace for a variety of reasons. Establishing harmonised procedures and common agreements between CAAs regarding airspace management, particularly regarding the response to different forecast levels of ash contamination in Europe and potentially elsewhere (should these forecasts evolve to an operationally mature product) will greatly reduce the current complexity.

[97] Harmonisation to minimize any differences in the information outputs from different VAACs would be valuable, especially in situations where ash clouds are crossing VAAC boundaries and advisory responsibility transfers from one VAAC to the next. The international aviation community needs to receive essentially the same information no matter who is the provider. In particular: i) there may be variations or differences in interpretation among VAAC forecasters on the location of the ash cloud, ii) there has been non-agreement at times between private sector forecasts and the VAAC forecasts, iii) the eruption source parameters and/or other dispersion model inputs need to be included with the model output products to assure appropriate use of the products and are critical to the quality of the model output, iv) to ensure effective implementation of CDAF when more than one VAAC runs its dispersion model for an eruption, particularly when the ash is near a VAAC boundary, the relevant VAACs should have access to each other’s model output, and discuss in real-time, as time permits, the forecast portion of the VAA before it’s issuance. As an example, NOAA Air

Resources Laboratory, through support of the Federal Aviation Administration (FAA), will be leading efforts to i) implement standards for VAAC model output, including a description of the model inputs, ii) develop a common platform for display of VAACs' model output, and iii) institute a series of periodic dispersion model exercises to allow VAACs to become more familiar with each other's models.

3.4.2 VAAC outputs and graphics

[98] While there are currently no quantitative certification criteria for airframe and engines, and consequently no agreed limits of "safe" ash tolerance or even limits that may alter maintenance schedules, it is expected that such criteria may eventually become available, and the scientific community needs to be prepared to answer new and emerging requirements for quantitative predictions of ash. This may require a future new-generation quantitative (e.g. using column loading) forecast graphic that depicts ash clouds three dimensionally (i.e., with tops and bottoms) and with some quantification of the cloud edges. Despite the significant amount of on-going research, the big challenge for researchers and the VAACs is achieving the above in an operational mode on a global scale.

[99] The development and communication of probabilistic forecasts remains a research and operational challenge. While some probabilistic forecasts have been demonstrated, these have only explored very limited aspects of the uncertainty, e.g. just the meteorological uncertainty, and considerable work is required in how to determine and then incorporate the probabilities for source terms etc. Equally challenging is the communication and presentation and use of such products. There is a need for researchers, VAACs, regulators and operators to work on this from both a developer and user perspective that will, if successful, also necessitate a significant training effort to ensure robust operational use.

[100] Definition of the '...agreed in-situ and/or remote sensing techniques' that underpin the following IAVWOPSG-7 approved definition of 'Discernible ash': "Discernible ash - volcanic ash detected by defined impacts on/in aircraft or by agreed in-situ and/or remote sensing techniques." These agreed techniques will be fundamental in underpinning the evolution of improved model-based (validated against observations to better quantify uncertainties) quantitative volcanic ash forecasts that better support airline VA safety risk assessments (SRA). VA SRAs are currently only required in the ICAO EUR/NAT region and are currently largely based on supplementary ash concentration charts, produced at the request of their respective regulators by the UK Met Office and Meteo-France. The concentration charts are not supported globally leading to issues with harmonisation and so initiatives are underway to define a better way of producing agreed quantitative-based products for the purposes of SRAs both in the EUR/NAT region and other parts of the world. An 'agreed techniques' Working Paper is to be presented to the ICAO IAVWOPSG-8 meeting in Melbourne in February 2014.

3.4.3 Vulnerability of engines and airframe components

[101] The most pressing challenge for the aircraft engine manufacturers is whether there is a need to undertake research to further understand and quantify the impact volcanic ash has on engines. There is a view within the engine Original Equipment Manufacturer (OEM) community that there is no need or justification for spending large quantities of money understanding effects that should be avoidable. The counter to this position is that this may not always be possible and that there may be economic, social and safety reasons to attempt to keep aircraft flying in low concentration of ash. Thus a good understanding of the vulnerability of aircraft to various ash concentrations and dosages still need to be developed. It may also need to be considered that as engines become more optimized for fuel efficiency and light weight, they could eventually become vulnerable to non-visible, but discernible, volcanic ash; good communications between OEM's, airspace users and the

science community will thus be essential. Based on such information, a requirement for accurate measurements and predictions of volcanic ash contamination may replace the poorly defined criterion of 'visible ash' in the safety management process.

[102] Development of engine vulnerability curves will, if it happens at all, be a long term undertaking. It is worth note though that some experimental work is being done by some manufacturers, and there is the planned whole-engine NASA lead VIPR experiment. Much effort has also been made to compile details of past encounters, but there is still more to be done.

3.5 Other recommendations

[103] The first is in how the VAACs interact directly with the scientific community. To be able to obtain the support from the scientific community and develop new methods and datasets of greatest use for operations, there is a need for dialogue between the groups. Such a dialogue will benefit both groups and is encouraged. There also needs to be a better understanding by the research community that the VAAC provides information based on the needs and requirements of the aviation community. Communication of the requirements and understanding of this and the frameworks that operational work must conform to would improve operational-research collaboration. A relevant issue is that operational centres often do not have funding to 'play' with the implementation of new techniques, and so research efforts may need to allocate resources towards the engagement with VAACs and their parent organizations.

[104] Secondly, there is a need to develop hazard assessment of the critical volcanoes along flight paths. The GVM is working towards a classification of the different monitoring capabilities at volcanoes worldwide. However, the process for the aviation community would be to develop probabilistic volcanic hazard assessment on the impact to flight operations from volcanic eruptions and tephra dispersal. Rates and styles of volcanic activity vary considerably among volcanically active regions such as arcs, hot spots and areas of distributed volcanism. In the long term, it is practical to prepare volcanic hazard assessments for individual flight paths based on probability estimates of eruption from arc segments, groups, or from individual volcanoes, based on the geological and historical records of activity in these volcanic systems. It is also practical to bound the range of potential eruptive styles for these volcanic systems and to assess the probability of significant tephra concentrations along a given air route given these probable eruption conditions, using VATDMs. The product of such analyses is an estimate of the annual probability of tephra concentrations exceeding some threshold along the flight path. This gives planners the opportunity to assess long-term hazard rates and operational costs associated with specific routes.

4 Acknowledgments

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Appendix 1. List of Acronyms

AIRS	Atmospheric Infrared Sounder
AOD	Aerosol Optical Depth
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATHAM	Active Tracer High resolution Atmospheric Model
AVHRR	Advanced Very High Resolution Radiometer
CDAF	Collaborative Decision Analysis and Forecasting
DIAL	Differential absorption lidar technique
ECMWF	European Centre Medium-Range Weather Forecast
EDM	Environmental Dust Monitors
ESP	Eruption Source Parameter
EUSAAR	European Supersites for Atmospheric Aerosol Research
GOES	Geostationary Operational Environmental Satellites
HYSPLIT	HYbrid Single-Particle Lagrangian Integrated Trajectory
IASI	Infrared Atmospheric Sounding Interferometer
IAVW	International Airways Volcano Watch
IMO	Icelandic Meteorological Office
IR-SO2	Infrared Spectroscopy of SO2
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
MWO	Meteorological Watch Office
NAME	Numerical Atmospheric-dispersion Modelling Environment
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NMS	National Meteorological or Hydrometeorological Service
NOTAM	Notice to Airmen
NWP	Numerical Weather Prediction (Models)
OMI	Ozone Monitoring Instrument
OPC	Optical Particle Counter
PDF	Probability Density Function
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SNR	Signal to Noise Ratio
TGSD	Total Grain Size Distribution
TIR	Thermal InfraRed
VATDM	Volcanic Ash Transport and Dispersal Models
VAA	Volcanic Ash Advisory
VAG	Volcanic Ash Graphic
VO	Volcano Observatory
VOGRIPA	Volcano Global Risk Identification and Analysis
VOL-CALPUFF	Volcanic CALifornia PUFF model
VOLDORAD	Volcano Doppler Radar

Appendix 2. List of Participants

Organizing Committee		
1. Costanza Bonadonna	University of Geneva, Switzerland	costanza.bonadonna@unige.ch
2. Arnau Folch	Barcelona Supercomputing Center, Spain	arnau.folch@bsc.es
3. Sue Loughlin	British Geological Survey, UK	sclou@bgs.ac.uk
4. Matthew Hort	UK MetOffice; VAAC London, UK	matthew.hort@metoffice.gov.uk
5. Peter Webley	University of Alaska Fairbanks, USA; AVO, WOVO	pwebley@gi.alaska.edu
6. Herbert Puempel	World Meteorological Organization	HPuempel@wmo.int
Participants		
7. Varunjay Ahluwalia	Ministry of Defence, UK	vahluwalia@mail.dstl.gov.uk
8. Nicole Asencio	VAAC Toulouse, France	Nicole.Asencio@meteo.fr
9. Gholamhossein Bagheri	University of Geneva, Switzerland	Gholamhossein.Bagheri@unige.ch
10. Sara Barsotti	Icelandic Meteorological Office, Iceland	sara@vedur.is
11. Sebastien Biass	University of Geneva, Switzerland	Sebastien.Biasse@unige.ch
12. Marie Boichu	Lab. de Météorologie Dynamique, IPSL, France	mboichu@lmd.ens.fr
13. Greg Brock	Meteorology Section Air Navigation Bureau, ICAO	gbrock@icao.int
14. Federico Brogi	University of Geneva, Switzerland	Federico.Brogi@unige.ch
15. Marcus Bursik	University at Buffalo, USA	mib@buffalo.edu
16. Elisa Carboni	University of Oxford, UK	elisa@atm.ox.ac.uk
17. Simon Carn	Michigan Technological University, USA	scarn@mtu.edu
18. Katharine Cashman	University of Bristol, UK	glkvc@bristol.ac.uk
19. Rory Clarkson	Rolls-Royce Civil Aerospace, UK	Rory.Clarkson@rolls-royce.com
20. Lieven Clarisse	Université Libre de Bruxelles, Belgium	Lieven.Clarisse@ulb.ac.be
21. Mauro Coltelli	INGV, Sezione di Catania, Italy	Coltelli@ct.ingv.it
22. Chuck Connor	University of South Florida, USA	chuck.connor@gmail.com
23. Stefano Corradini	INGV, Sezione di Roma, Italy	corradini@ingv.it
24. Antonio Costa	INGV, Sezione di Bologna, Italy	antonio.costa@bo.ingv.it
25. Julia Crummy	BGS, Edinburgh, UK	juli@bgs.ac.uk
26. Helen Dacre	University of Reading, UK	h.f.dacre@reading.ac.uk
27. Gabriel Damiani	VAAC Buenos Aires, Argentina	sovaacbue@smn.gov.ar
28. Cory Davis	VAAC Wellington, New Zealand	Cory.davis@metservice.com
29. Wim Degruyter	Georgia Institute of Technology, USA	wim_degruyter@msn.com
30. Jonathan Dehn	University of Alaska Fairbanks	jdehnavo@gmail.com
31. Roger Denlinger	USGS - CVO, USA	roger@usgs.gov
32. Adam Durant	NILU, Norway	Adam.Durant@nilu.no
33. Nils Ek	VAAC Montreal, Canada	Nils.Ek@ec.gc.ca
34. Fabrizio Ferrucci	Open University, Milton Keynes, UK	Fabrizio.Ferrucci@open.ac.uk

35. Stefano Galmarini	EC/DG-JRC/IES	stefano.galmarini@jrc.ec.europa.eu
36. Magnús Guðmundsson	University of Iceland, Iceland	mtg@raunvis.hi.is
37. Marianne Guffanti	USGS, USA	guffanti@usgs.gov
38. Alexander Haefele	Office fédéral de météorologie et de climatologie MétéoSuisse, Switzerland	Alexander.Haefele@meteoswiss.ch
39. Michael Herzog	University of Cambridge, UK	mh526@cam.ac.uk
40. Charles Holliday	Air Force Weather Agency, USA	hollidac@offutt.af.mil
41. Armann Höskuldsson	University of Iceland, Iceland	armh@hi.is
42. Eun-Suk Jang	Hanzhong University, South Korea	breeze@empas.com
43. Sigrún Karlsdóttir	Icelandic Meteorological Office, Iceland	sigk@vedur.is
44. Jamie Kibler	VAAC Washington, USA	jamie.kibler@noaa.gov
45. Stephan Kox	DLR-Institut für Physik der Atmosphäre, Germany	Stephan.Kox@dlr.de
46. Nina Kristiansen	NILU, Norway	Nina.Iren.Kristiansen@nilu.no
47. Ulrich Kueppers	Ludwig-Maximilians-University Munich, Germany	u.kueppers@lmu.de
48. Steve Lane	Lancaster University, UK	s.lane@lancaster.ac.uk
49. Baerbel Langmann	University of Hamburg, Germany	baerbel.langmann@zmaw.de
50. Peter Lechner	CCA, New Zealand; ICAO IAVW SG	Peter.Lechner@caa.govt.nz
51. Ian Lisk	WMO, WEZARD	ian.lisk@metoffice.gov.uk
52. Giovanni Macedonio	Osservatorio Vesuviano, Italy	macedon@ov.ingv.it
53. Alain Malo	VAAC Montreal, Canada	Alain.Malo@ec.gc.ca
54. Emanuele Marchetti	University of Firenze, Italy	emanuele.marchetti@unifi.it
55. Alex Marti	Barcelona Supercomputing Center, Spain	alejandro.marti@bsc.es
56. Frank Marzano	University of Rome, Italy	marzano@diet.uniroma1.it
57. Larry Mastin	USGS - CVO, USA	lgmastin@usgs.gov
58. Ralf Meerkötter	DLR-Institut für Physik der Atmosphäre, Germany	Ralf.Meerkoetter@dlr.de
59. Luca Merucci	INGV, Sezione Roma, Italy	luca.merucci@ingv.it
60. Sarah Millington	Met Office, UK	sarah.millington@metoffice.gov.uk
61. Stephen Mobbs	University of Leeds and NCAS, UK	s.d.mobbs@ncas.ac.uk
62. Lucia Mona	CNR, Potenza, Italy	mona@imaa.cnr.it
63. Augusto Neri	INGV, Sezione di Pisa, Italy	neri@pi.ingv.it
64. Chris Newhall	Earth Observatory, Singapore	cnewhall@ntu.edu.sg
65. Jeff Osiensky	VAAC Anchorage, USA	jeffrey.osiensky@noaa.gov
66. Soledad Osores	Servicio Meteorológico Nacional, Argentina	msosores@smn.gov.ar
67. Thorgeir Palsson	IATA	tpalsson@hr.is
68. Mike Pavolonis	NOAA/NESDIS, USA	mpav@ssec.wisc.edu
69. Melissa Anne Pfeffer	Icelandic Meteorological Office, Iceland	melissa@vedur.is
70. Rodney Potts	Bureau of Meteorology, Australia	r.potts@bom.gov.au
71. Fred Prata	NILU, Norway	Fred.Prata@nilu.no

72. Gloria Pujol	Servicio Meteorologico Nacional, Argentina	gpujol@smn.gov.ar
73. Theo Rindlisbacher	Federal Office of Civil Aviation, Switzerland	Theo.Rindlisbacher@bazl.admin.ch
74. Maurizio Ripepe	Università di Firenze, Italy	maurizio.ripepe@unifi.it
75. Eduardo Rossi	University of Geneva, Switzerland	Eduardo.Rossi@unige.ch
76. Chiara Scaini	Barcelona Supercomputing Center, Spain	saetachiara@gmail.com
77. Hans Schlager	DLR-Institut für Physik der Atmosphäre, Germany	Hans.Schlager@dlr.de
78. Anja Schmidt	University of Leeds, UK	A.Schmidt@Leeds.ac.uk
79. Hans Schwaiger	USGS - CVO, USA	hschwaiger@usgs.gov
80. Simona Scollo	INGV, Sezione Catania, Italy	scollo@ct.ingv.it
81. Birthe Marie Steensen	Norwegian Meteorological Institute, Norway	birthems@met.no
82. Andreas Stohl	NILU, Norway	ast@nilu.no
83. Martin Stuefer	University of Alaska Fairbanks, USA	stuefer@gi.alaska.edu
84. Barbara Stunder	NOAA Air Resources Laboratory, USA	Barbara.Stunder@noaa.gov
85. Yujiro Suzuki	ERI, University of Tokyo, Japan	yujiro@eri.u-tokyo.ac.jp
86. Joerg Thurnheer	Federal Office of Civil Aviation, Switzerland	Joerg.Thurnheer@bazl.admin.ch
87. Andrew Tupper	VAAC Darwin, Australia	A.Tupper@bom.gov.au
88. Tetsuyuki Ueyama	VAAC Tokyo, Japan	tetsu.ueyama@met.kishou.go.jp
89. Sebastien Valade	Università di Firenze, Italy	valade.sebastien@gmail.com
90. Alexa Van Eaton	Arizona State University, USA	alexa.vaneaton@gmail.com
91. Matt Watson	University of Bristol, UK	Matt.Watson@bristol.ac.uk
92. Konradin Weber	Fachhochschule Düsseldorf, Germany	konradin.weber@fh-duesseldorf.de
93. Claire Witham	VAAC London, UK	Claire.witham@metoffice.gov.uk
94. Mark Woodhouse	University of Bristol, UK	mark.woodhouse@bristol.ac.uk
95. Gerhard Wotawa	National Meteorological Centre, Austria	gerhard.wotawa@zamg.ac.at

Appendix 3. Data Acquisition Tables

Table 1a: Summary of source-term parameters that can be detected with various techniques (see Data Acquisition Document for more details). Green cells: direct measurements; Blue cells: derived measurements; Orange cells: experimental. * - given the scattering algorithms used, further discussion needed on the maximum size that can be resolved. LOS = Line of Sight, LL = Low-Light, VIS = Visible

	Eruption start / end	**Plume Height**	**MER/MTR**	**Mass**	**Particle size**	**Airborne Ash Quantity**	**SO_2**
AVHRR		Altitude, Temperature, Pressure	Local MTR	0.1-100μm*	Effect. radius: 0.1-15μm	Mass loading	
GOES Imagery		Altitude, Temperature, Pressure	Local MTR	0.1-100μm*	Effect. Radius: 0.1-15μm	Mass loading	
Infrasound		From source MER	Source MER				
Suomi NPP VIIRS		Altitude, Temperature, Pressure	Local MTR	0.1-100μm*	Effect. radius: 0.1-15μm	Mass loading	SO_2 burden
ASTER							SO_2 burden
LIDAR		Altitude (only optically thin clouds)		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 altitude (not yet operational)		Ash mass loading retrievals possible	Effective radius	Aerosol Index (rel. ash abundance)	SO_2 burden, altitude
Suomi NPP OMPS		SO_2 altitude (not yet operational)		Ash mass loading retrievals possible	Effective radius	Aerosol Index (rel. ash abundance)	SO_2 burden, altitude
AIRS		Altitude, Temperature, Pressure	Local MTR	0.1-100μm*	Effective radius 0.1-15μm	Mass loading	SO_2 burden
IASI		Altitude, Temperature, Pressure	Local MTR	0.1-100μm*	Effect. radius 0.1-15μm	Mass Loading	SO_2 burden
SEVIRI		Altitude, Temperature, Pressure	Local MTR	0.1-100μm*	Effect. radius 0.1-15μm	Mass loading	SO_2 burden
VIS to LL camera		If daytime data available	local MTR				
Thermal Camera			Local MTR	With Filters can measure BTD	Effective radius ~μm – ~mm	Mass loading	
UV Camera		If daytime data available		Ash detection			SO2 LOS
Electric field sensors			Estimated from assumed TGSD				

Table 1b: Summary of source-term parameters that can be detected with various techniques (see Data Acquisition Document for more details). Green cells: direct measurements; Blue cells: derived measurements; Orange cells: experimental. *, PLUDIX and VOLDORAD are particular cases of Doppler radar discussed during the workshop. CAPS-DEPOL=Cloud, Aerosol and Precipitation Spectrometer with Depolarization Measurement. 1 - Discrimination of type of particles like ash, water droplet, soot, sand particles. ** - reference see Wiegner, M. and Geiß, A., 2012. Aerosol profiling with the Jenoptik ceilometer CHM15kx. Atmos. Meas. Tech., 5(8): 1953-1964.

	Eruption start / end	**Plume Height**	**MER/MTR**	**Mass**	**Grain size**	**Cloud Concentration**	**SO_2**
Optical particle counter					<1 – 50/60 microns	Number	
Celiometer**					🟦	🟦	🟩
CAPS-DEPOL					Size Range: 0,51 µm -1,5 mm	Mass/volume Number/volume Depolarization by the particles,[1]	🟩
Zenith view UV-DOAS, based on aircraft					🟦	SO2-column content of plume, SO2-flux of plume, plume mapping	🟦
Ground based Scanning UV-DOAS					🟦		🟦
Airborne scanning UV-DOAS					🟦		🟦
Airborne imaging DOAS					🟦		🟦
Doppler radar	🟩	🟩	Local MTR Source MER (depending on beam occlusions)	0.01-10 mm	> 30 µm (Ka band) > 10 µm (X band) > 100 µm (C band) > 1 mm (S band) Depends on distance and receiver sensitivity	Mass/volume Number/volume	
PLUDIX (X-band)*					Effect. radius >100µm		
Seismic data	🟩	From seismic amplitude and reduced displacement					
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 main detection limits of selected techniques used for the detection of ash particles

Method	Detection limit	Spatial resolution	Nominal particle size sensitivity	Limitations
Optical particle counter		mm	~0.25 – 32 µm	Sampling bias; particle shape effects; uncertainty in particle refractive index; cannot distinguish particle aggregates
LIDAR	AOD < 0.01	m	Sub-microns to tens of microns (but 0.1-2 µm for retrieval of microphysical properties)	Sunlight decreases SNR; complex retrieval; presence of hydrometeors complicates retrieval; Uncertainty in dielectric constant; Signal extinction in presence of thick clouds; cannot distinguish particle aggregates
Radar		m - 10s km	Mean detectable effective radius: > 30 µm (Ka band) > 10-100 µm (X and C band) > 1 mm (S band)	Uncertainty in dielectric constant; presence of hydrometeors causes attenuation and complicates retrieval; particle size detection limit changes with range; cannot distinguish particle aggregates
Satellite-based UV remote sensing	< 0.2 g m^{-2}	10-100s km	tbd; potentially sensitive to smaller particles than IR	Uncertainty in particle refractive index and shape; presence of water clouds and hydrometeor formation on ash may prevent measurement; cannot distinguish particle aggregates
Satellite-based TIR remote sensing	< 0.5 g m^{2}	<100 m – 100s km	Effective radius 0.5 - 15 µm	Uncertainty in particle refractive index; presence of water clouds and hydrometeor formation on ash may prevent measurement; cannot distinguish particle aggregates
Ground-based TIR remote sensing	< 0.2 g m^{2}	<1-10 m	Effective radius 0.5 - 15 µm	Uncertainty in particle refractive index; presence of water clouds and hydrometeor formation on ash may prevent measurement; cannot distinguish particle aggregates

Table 3: Passive remote sensing satellite instruments and products available for detection of volcanic ash clouds

Instrument	Spacecraft	Orbit geometry	Space agency	Spectrum employed	Products	Spatial resolution (FOV size km)	Frequency of data
AIRS	Aqua	Near polar, sun-synchronous orbit; period ~100 minutes	NASA	TIR	SO_2, Ash index	~15	Twice daily (nominally)
GOME-2	MetOp-A	Polar, sun-synchronous orbit; period 101 minutes	ESA EUMETSAT	UV	SO_2, Absorbing aerosol index	40–80	Twice daily (nominally)
IASI	MetOp-A	Polar, sun-synchronous orbit; period 101 minutes	ESA EUMETSAT	TIR	SO_2, Ash index	~15	Twice daily (nominally)
MODIS	Terra/Aqua	Near polar, sun-synchronous orbit; period ~100 minutes	NASA	TIR	SO_2, Ash	~1	Twice daily (nominally)
OMI	Aura	Near polar, sun-synchronous orbit; period ~100 minutes	NASA	UV	SO_2, Aerosol index	~12–48	Twice daily (nominally)
SEVIRI	Meteosat	Geostationary orbit above equator;	EUMETSAT	TIR	SO_2, Ash	~4	15 mins

Appendix 4. Model Definition Table

Table 4. Main characteristics of selected VATDM's

	ASH3D	ATHAM	FALL3D	FLEXPART	HYSPLIT	JMA-GATM JMA-RATM	MLDP0	MOCAGE	NAME	PUFF	TEPHRA2	VOL-CALPUFF
Operational	🟦		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Approach (1)	E/H	E	E	L	H	L	L	E	LH	L	E	H
Method (2)	N	N	N	N	N	N	N	N	N	N	A	S
Coverage (3)	LRG	L	LR	LRG	LRG	RG	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. aggregation												
Wet part. aggregation			🟥									
Variable part. shape	🟥		🟥		🟥	🟥	🟥					🟥
Gas species		🟥	🟥	🟥	🟥			🟥	🟥			🟥
Chemic. processes				🟥	🟥				🟥			🟥
Granulometry												
Variable size class.	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩
Variable GS distr.	🟩		🟩	🟩	🟩				🟩		🟩	🟩
Variable size limits	🟩	🟩	🟩	🟩			🟩		🟩	🟩	🟩	🟩
Source term												
Mass distribution(4)	PS/U/LN	O	ALL	PS/L/U/P/O	PS/L/U/P/LN	PS/L/LN	PS/L/U/P/O	PS/L	PS/L/U/BP/O	PS/L/U/P/O	L/U/LN/O	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 Model Summary Document).
(5) Neglected. Diffusion of numerical origin appears to be sufficient, with particularly good results at 0.5°.

Appendix 5. Ongoing relevant projects

Table 5. Table of recent and ongoing projects relevant to ash dispersal modelling and forecasting. Start and end date format is DD/MM/YY

Acronym	Project name	Funding	Start date	End date	Contact	Website
ARISE	Atmospheric Research InfraStructure in Europe	EC FP7	1/01/2012	31/12/2014	E. Blanc (CEA, France)	http://arise-project.eu/
E-PROFILE	A network for vertical profiling of wind and aerosols	EUMETNET	01/01/13	31/12/17	A. Haefele (MeteoSwiss)	http://www.eumetnet.eu/e-profile
EVOSS	European Volcano Observatory Space Services	EC FP7	01/08/09	31/07/13	F. Ferrucci (Open Univ., UK)	www.evoss-project.eu
FUTUREVOLC	Futurevolc	EC FP7	01/10/12	30/04/16	F. Sigmundsson (Univ. of Iceland)	www.futurevolc.is
MedSUV	MEDiterranean SUpersite Volcanoes	EC FP7	01/06/13	30/05/16	G. Puglisi (INGV Italy)	http://med-suv.eu/
NEMOH	Numerical, Experimental and stochastic Modelling of vOlcanic processes and Hazard	EC FP7 ITN	1/01/12	1/01/16	P. Papale (INGV Italy)	http://www.nemoh-itn.eu/
NNAP	National Norwegian Ash Project	Norw. Ministry of Transport	1/10/12	30/09/15	BM Steensen (Norw. Met. Inst.)	
SACS & SACS2	Support to Aviation Control Service	ESA	SACS 2009 SACS2 2012	SACS 2012 SACS2 2014	Belgian Inst. for Space Aeronomy	http://sacs.aeronomie.be
SHIVA	Spectrally High resolution Infrared measurements for the characterisation of Volcanic Ash	NERC	01/04/13	31/03/16	R. Grainger (Uni. Oxford- UK)	
SMASH	Study on an End-to-End system for volcanic ash plume monitoring and prediction	ESA	13/09/12	31/03/14	M.L. Tampellini (CGS - Italy)	http://www.cgspace.it/download/SMASH_WEB_PAGE.pdf
PURE	Probability, Uncertainty and Risk in the Environment	NERC				http://www.nerc.ac.uk/research/programmes/pure/
VANAHEIM	Volcanic and Atmospheric Near- to far-field Analysis of plumes Helping Interpretation and Modelling	NERC	01/03/11	30/09/13	S. Mobbs (Leeds University, UK)	http://www.ncas.ac.uk/index.php/en/vanaheim-introduction
VAST	Volcanic Ash Strategic-initiative Team	ESA	01/06/12	01/06/15	A.Fahre Vik	http://vast.nilu.no/
VERTIGO	Volcanic ash: FiEld, expeRimenTal and numerIcal investiGations of prOcesses during its lifecycle	EC FP7 ITN	01/01/14	31/12/18	U. Kueppers (LMU, GERMANY)	www.vertigo-itn.eu
VIPR-III	Vehicle Integrated Propulsion	NASA				

Appendix 6. Official Organization and Groups

Acronym	Organization Name	Link	Description
ICAO	International Civil Aviation Organisation	Web Link	A specialized agency of the United Nations, ICAO was created to promote the safe and orderly development of international civil aviation.
WMO	World Meteorological Organisation	Web Link	A specialized agency of the United Nations. WMO is the UN system's authoritative voice on the state and behaviour of the Earth's atmosphere, its interaction with the oceans, the climate it produces and the resulting distribution of water resources.
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior	Web Link	The primary international focus for: (1) research in volcanology, (2) efforts to mitigate volcanic disasters, and (3) research into closely related disciplines, such as igneous geochemistry and petrology, geochronology, volcanogenic mineral deposits, and the physics of the generation and ascent of magmas in the upper mantle and crust. A member Association of the IUGG (see below)
IUGG	International Union of Geodesy and Geophysics	Web Link	The international organization dedicated to advancing, promoting, and communicating knowledge of the Earth system, its space environment, and the dynamical processes causing change.
VAAC	Volcanic Ash Advisor Centre	Anchorage; Buenos Aires; Darwin; London; Montreal; Tokyo; Toulouse; Washington; Wellington	The VAACs are tasked with issuing observational analysis and forecast advisories to the aviation industry on behalf of the WMO and ICAO of the hazard from volcanic ash in the atmosphere. The VAACs as listed are hosted respectively by NOAA, , National Meteorological Service Argentina, BOM, Met Office UK, CMC, JMA, Meto France, NOAA and Met Service New Zealand.
WOVO	World Organization of VO	Web Link	World Organization of VO.
IATA	International Air Transport Association	Web Link	The trade association of the airlines.
IVATF	International Volcanic Ash Task Force	Web Link	Temporary group (2010-2012) formed by ICAO to address immediate issues arising due to the 2010 eruption of Eyjafjallajokull, Iceland. Papers and guidance produced covering science, operations and regulation.
IAVWOPSG	International Airways Volcano Watch Operations Group	Web Link	Standing group consisting of representatives from states, regulators, science community, operational forecasting including VAACs, VO to provide advice and develop capability to meet aviation's evolving safety requirements in relation to volcanic ash, chemical, radioactive contamination and space weather.

VASAG	Volcanic Ash Scientific Advisory Group	Web Link	WMO group tasked with acting as a single, authoritative source of scientific expertise in the field of volcanic ash affecting civil aviation with emphasis both on atmospheric as well as geophysical/volcanological issues. Expertise to be made available to the relevant ICAO IAVWOPS group as a basis for future development of operational procedures, standards and guidance.
IWVA	International Workshop on Volcanic Ash	Web Link	WMO workshop, held every 3 years, focused on applied science relevant to the delivery of the VAAC advisories.

Appendix 7. Table of Online Resources

Name	Link	Details
EARLINET	Web Link	EARLINET, the European Aerosol Research Lidar Network, is the first aerosol lidar network, established in 2000, with the main goal to provide a comprehensive, quantitative, and statistically significant data base for the aerosol distribution on a continental scale. Link to the NRT data images web-page and to the Eyja2010 relational database are available on the EARLINET web-page.
E-PROFILE	Web Link	It continues the operational service of E-WINPROF (former programme) providing vertical profiles on wind measurements from radar wind profilers (vertically pointing radars) and weather radars from a network of locations across Europe.
EVOSS	Web Link	European Volcano Observatory Space Services.
EUMETSAT-RealTime	Web Link	European Organisation for the Exploitation of Meteorological Satellites.
FALL3D-NMMB	Web Link	Free FALL3D software (version 7): an Eulerian model for the transport and deposition of volcanic tephra.
FUTUREVOLC	Web Link	26-partner project funded by FP7 Environment Programme of the European Commission addressing topic “Long-term monitoring experiment in geologically active regions of Europe prone to natural hazards: the Supersite concept”. The supersite concept implies integration of space and ground based observations for improved monitoring and evaluation of volcanic hazards, and open data policy.
GVM	Web Link	The project is developing an integrated global database system on volcanic hazards, vulnerability and exposure, make this globally accessible.
HYSPLIT VA Interface	Web Link	Ability to run HYSPLIT for volcanic eruptions anywhere in the world.
Earth Observatory	Web Link	Collection of NASA imagery.
PlumeRise	Web Link	An online tool for modelling the rise of volcanic plumes in a moist and windy atmosphere.
Smithsonian GVP	Web Link	The mission of GVP is to document, understand, and disseminate information about global volcanic activity.
SACS	Web Link	Near real time SO_2 and ash alert notification and imagery.
VOGRIPA – LaMEVE	Web Link	The Large Magnitude Explosive Volcanic Eruptions database has been a large collaborative effort. This database contains data on eruptions of magnitude 4 or greater, reaching back to the start of the Quaternary.
Volcview	Web Link	Access to a number of satellites in near real time for the North Pacific region.
Volcanic Cloud Monitoring — NOAA/CIMSS	Web Link	NOAA-CIMSS satellite imagery pages. Includes a range of single, two and multi-channel products.
WOVOdat	Web Link	World Organization of VO database (WOVOdat) is a collective record of volcano monitoring, worldwide.