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SHORT SCIENTIFIC COMMUNICATION

Future developments in modelling and monitoring of volcanic ash clouds: outcomes from the first IAVCEI-WMO workshop on Ash Dispersal Forecast and Civil Aviation

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Abstract As a result of the serious consequences of the 2010 Eyjafjallajökull eruption (Iceland) on civil aviation, 52 volcanologists, meteorologists, atmospheric dispersion modellers and space and ground-based monitoring specialists from 12 different countries (including representatives from 6 Volcanic Ash Advisory Centres and related institutions) gathered to discuss the needs of the ash dispersal modelling community, investigate new data-acquisition strategies (i.e. quantitative measurements and observations) and discuss how to improve communication between the research community and institutions with an operational mandate. Based on a dedicated benchmark exercise and on 3 days of in-depth discussion, recommendations have been made for future model improvements, new strategies of ash cloud forecasting, multidisciplinary data acquisition and more efficient communication between different communities. Issues addressed in the workshop include ash dispersal modelling, uncertainty, ensemble forecasting, combining dispersal models and observations, sensitivity analysis, model variability, data acquisition, pre-eruption forecasting, first simulation and data assimilation, research priorities and new communication strategies to improve information flow and operational routines. As a main conclusion, model developers, meteorologists, volcanologists and stakeholders need to work closely together to develop new and improved strategies for ash dispersal forecasting and, in particular, to: (1) improve the definition of the source term, (2) design models and forecasting strategies that can better characterize uncertainties, (3) explore and identify the best ensemble strategies that can be adapted to ash dispersal forecasting, (4) identify optimized strategies for the combination of models and observations and (5) implement new critical operational strategies.

Keywords Explosive volcanism · Volcanic ash cloud · Atmospheric dispersion · Source term parameters · Operational forecasting · Data acquisition

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Introduction

Ash produced during explosive volcanic eruptions can cause serious impacts both close to the volcano and also at great distances (e.g. Blong 1984). Infrastructure and vegetation can be significantly damaged by ash accumulations of only a few millimetres but accumulations of tens of centimetres are not unusual in proximal environments. Significant damage to infrastructure might include collapse of roofs, disruption to lifelines (e.g. water and electricity supplies) and disruption to transport networks (e.g. roads, airports; Spence et al. 2005). Environmental and social impacts might include air-quality deterioration, health hazards (e.g. asthma, silicosis, tuberculosis reactivation and lung cancer), crop pollution and water contamination (e.g. Baxter 1999; Durant et al. 2010). Ash continues to be a hazard long after an eruption due to resuspension by winds and possible generation of lahars (e.g. Lecointre et al. 2004; van Westen and Daag 2005; Alexander et al. 2010). Even small concentrations of ash injected into the atmosphere can lead to widespread disruption to aviation. Turbine engines are particularly threatened by ingestion of airborne ash, and aircraft surfaces may be subject to abrasion and in the longer-term corrosion (e.g. Heiken et al. 1992; Casadevall 1994; Casadevall et al. 1996; Guffanti et al. 2010). The April–May 2010 eruption of Eyjafjallajökull volcano (Iceland) caused an unprecedented closure of the European and North Atlantic airspace with global economic losses of US$5 billion (Oxford-Economics 2010) and was a stark reminder of the vulnerability of our society to explosive eruptions, even those of small-moderate intensity. In fact, this event dramatically demonstrated the limits of the precautionary "zero-ash tolerance" criteria in the case of long-lasting eruptions affecting broad geographic areas with dense air traffic, such as the North Atlantic and Europe. By 21 April 2010, a week after the onset of the explosive phase, the U.K. Civil Aviation Authority and Eurocontrol had introduced a new way to manage the crisis based on ash concentration thresholds defined by engine manufacturers. Both the initial "ash avoidance" approach by International Civil Aviation Organization (ICAO) and the new ash concentration thresholds, used during the crisis and currently under discussion within ICAO, require robust ash dispersal prediction based on a combination of source-term data, ash-cloud observational data, Numerical Weather Prediction Models (NWP) and Volcanic Ash Transport and Dispersal Models (VATDM). This combination demands efforts from many different agencies, from turbine manufacturers (to specify the ash concentrations and doses that engines can tolerate), to volcano observatories (to provide close to real-time data about the source), to dispersal modellers (to improve and optimize modelling strategies of volcanic ash dispersal). Members of the international science community dealing with ash dispersal modelling and characterization have the responsibility to develop targeted research solutions to improve capabilities in modelling global ash dispersal and to better observe and characterize eruption plumes and ash clouds in close to real time leading to robust and reliable model outputs with reasonably low uncertainties.

In this context, 52 volcanologists, meteorologists, atmospheric dispersion modellers and space- and ground-based monitoring specialists from 12 different countries (including representatives from 6 Volcanic Ash Advisory Centres and related institutions) gathered on 18–20 October 2010 at the World Meteorological Organization (WMO) headquarters in Geneva under the auspices of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) for the first IAVCEI-WMO workshop on Ash Dispersal Forecast and Civil Aviation. The objectives of the workshop were to discuss the needs of the ash dispersal modelling community, investigate new data-acquisition strategies (i.e. quantitative measurements and observations) and discuss how to improve communication between the research community and institutions with an operational mandate. A VATDM model benchmark exercise (based on the Hekla 2000 eruption in Iceland; (Hoskuldsson et al. 2007; Smith et al. unpublished data)) was carried out before the workshop to define model characteristics and application limits. The benchmark exercise was performed on 12 VATDMs (ASH3D, ATHAM, FALL3D, FLEXPART, HYSPLIT, JMA, MLDP0, MOCAGE, NAME, PUFF, TEPHRA2 and VOL-CALPUFF). This includes the vast majority of the VATDMs in use worldwide and all models currently operative at VAACs. Another inter-comparison between models used at VAACs was done by Witham et al. (2007), but a test case involving so many models has never been done before. In addition, two detailed documents have been compiled to define characteristics, application limits and outputs of both the 12 VATDMs and selected data-acquisition techniques and instruments that can be used for volcanic ash detection (namely AIRS, ASTER, AVHRR, GOES-11, GOES-12,13,14,15, Grimm EDM 107, Grimm Sky OPC, IASI, IMO-radar, Infrasonic Array, LIDAR, MISR, MODIS, MTSAT, OMI, PLUDIX, SEVIRI, Thermal Camera, UV Camera, VOLDORAD). These include summary tables that provide a broad overview of the situation at the time of the meeting (Tables 1, 2 and 3). Based on the dedicated benchmark exercise and on 3 days of in-depth discussion, recommendations have been made for future model improvements, new strategies of ash dispersal forecasting, multidisciplinary data acquisition and more efficient communication amongst different communities. An extensive workshop Consensual Document (Bonadonna et al. 2011a) and a Benchmark Document (Bonadonna et al. 2011b) have resulted from the team effort of all workshop participants. Complementary materials are also available at the workshop website (www.unige.ch/hazards/Workshop/results.html). In order to summarize the results of our team effort to the international community, we present here the main conclusions and recommendations concerning: (1) ash dispersal modelling, (2) uncertainties and ensemble forecasting, (3) forecasting strategies and the combining of VATDMs with observations, (4) new communication strategies and research priorities.

Ash dispersal modelling

VATDMs considered in the benchmark exercise (see Table 1) have been found to accurately describe some important aspects of the transport of volcanic particles (e.g. advection and diffusion). However, other aspects such as the character-

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

	ASH3D	ATHAM	FALL3D	FLEXPART	HYSPLIT	JMA	MLDP0	MOCAGE	NAME	PUFF	TEPHRA2	VOL-CALPUFF
Operational												
Approach[a]	E/H	E	E	L	H	L	L	E	L	L	E	H
Method[b]	N	N	N	N	N	N	N	N	N	N	A	S
Coverage[c]	LRG	L	LR	LRG	LRG	G	LRG	G	LRG	LRG	L	LR
Physics												
Topography												
H wind advection												
V wind advection												
H atm. diffusion								See[d]				
V atm. diffusion												
Particle sedimentation												
Other dry deposition												
Wet deposition												
Dry particle aggregation												
Wet particle aggregation												
Particle shape												
Gas species												
Chemical processes												
Granulometry												
Variable size classes												
Variable TGSD distribution												
Variable size limits												
Source term												
Mass distribution[e]	LN	O	ALL	PS/L/U/P/O	PS/L/U/P/LN	PS/L/U/P/LN	PS/L/U/LN	PS/L	PS/L/O	PS/L/U/P	L/U/LN	PS/BP

[a] *L* Lagrangian, *E* Eulerian, *H* Hybrid

[b] *A* analytical, *S* semi-analytical, *N* numerical

[c] *L* local, *R* regional, *G* global

[d] Neglected: Diffusion of numerical origin appears to be sufficient, with particularly good results at 0.5°

[e] *PS* point source, *L* linear, *U* umbrella type, *P* Poisson, *LN* log-normal, *BP* buoyant plume, *O* Other (see Model Summary Document)

Table 2 Brief summary of source-term parameters that can be detected with various techniques (see Data Acquisition Document for more details; www.unige.ch/hazards/Workshop.html)

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

Green cells direct measurements, *Blue cells* derived measurements, *Orange cells* experimental

[a] Vertical distribution possible

[b] PLUDIX and VOLDORAD are particular cases of Doppler radar discussed during the workshop

Table 3 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
Radar		m–10s km	Mean detectable effective radius: > 30 μm (Ka band) >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 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

ization of the source term, convective transport or the removal of airborne ash by specific sedimentation processes could be better characterized. The source term in VATDMs is defined by: (1) mass eruption rate (MER), (2) plume height, (3) total grainsize distribution (TGSD) and particle properties (i.e. density and shape), (4) vertical distribution of erupted mass and grainsize, (5) eruption onset and end time, (6) source position (i.e. vent location). MER and vertical distribution of mass and grainsize are very difficult to quantify in real time but can be characterized to some extent by a detailed description of the changing dynamics of the plume. Plume height, TGSD, particle properties, eruption start and end time, and source position can only be derived from observations and field data. Consequently, a good assessment of the source term for ash dispersal modelling requires a time series of observations, rapid data acquisition and data assimilation.

Discrepancies in VATDMs demonstrated by our benchmark exercise are probably due to the use of different physics, different parameterization of the source term and/or slightly different input choices. In order to address these issues, the workshop agreed on the following:

Recommendation 1: VATDM developers to carry out further collaborative studies in order to assess the origin of these discrepancies and, in particular, to seek input from volcanologists and meteorologists in order to improve the definition of the source term and some critical aspects of particle sedimentation (i.e. particle aggregation and wet deposition), particularly if airborne far-field ash concentration is to be computed.

Recommendation 2: A systematic sensitivity analysis of all VATDMs to be performed in order to assess the effect of different inputs (e.g. MER, plume height, erupted mass, TGSD) on model outputs and therefore to prioritize data acquisition. This is also important for the construction of an ensemble on input variables.

Recommendation 3: The sensitivity of numerical model accuracy on model discretization has to be quantified (i.e. mesh resolution in the case of Eulerian models or particle number and resolution of the background averaging mesh in the case of Lagrangian models).

Uncertainty and ensemble model forecasting

Both the observations used to define the source term (e.g. MER, plume height, erupted mass and TGSD) and the meteorological inputs (from either global or mesoscale forecasts) are affected by various levels of uncertainties. The random behaviour of the natural system and the random errors associated with field measurements can be classified as aleatoric uncertainties, whereas the incomplete nature of both field data and numerical investigations can be defined as epistemic uncertainties. Epistemic uncertainties can be reduced by improving the parameterization of the physical processes, the field investigation techniques and the numerical accuracy, whereas aleatoric uncertainties can be dealt with by identifying appropriate activity scenarios and Probability Density Functions (PDFs) of input parameters. This is why ash dispersal forecasting may be more accurate if it simply outputs a range of probability values as opposed to absolute values of ash concentration and mass loading on the ground. It is anticipated therefore that stakeholders (e.g. aviation industry, decision makers) will eventually need to integrate probabilistic strategies into their processes of decision making.

The experience from modelling atmospheric transport of distinct substances (e.g. radioactive nuclei, mineral dust, sea salt, anthropogenic aerosols) strongly suggests that uncertainty could be better characterized by the implementation of ensemble forecasting on both modelling and source-term conditions (see ENSEMBLE project at http://ensemble.jrc.ec.europa.eu). In particular, four different types of ensemble strategies could be envisaged: (1) ensemble of different input conditions (according to eruption scenarios and data uncertainty ranges), (2) ensemble of different VATDMs (multi model) (on a single NWP), (3) ensemble of different NWP forecasts (on a single VATDM) and (4) a combination of one or more strategies above. There are currently several logistical constraints that need to be overcome if ensemble forecasting is to be operational during volcanic crises. The workshop agreed on the following:

Recommendation 4: Volcanologists and volcano observatories to identify appropriate PDFs and activity scenarios for each given volcano.

Recommendation 5: VATDM developers to design models and forecasting strategies that can better deal with uncertainties in model inputs.

Recommendation 6: VATDM developers to identify the best ensemble strategies that could optimize ash forecasting.

Recommendation 7: VATDM modellers to work with ICAO to discuss uncertainty, probabilistic approaches and design a possible output format that is immediately understandable and meaningful to stakeholders.

Forecasting strategies and combining VATDMs with observations

Ash dispersal forecasting during the phases of volcanic crises are characterized by different use of data and modelling strategies. There is likely to be little or no data at the onset of an eruption but the quantity and variety of data on the source term and ash-cloud evolution will usually increase with time. Accuracy of ash dispersal forecasting during a long-lasting volcanic eruption (following the first simulation) relies on effective data assimilation. In order to address these challenges, the workshop agreed on the following:

Recommendation 8: The *pre-eruption forecasting* and the *first simulation*, assuming no observations are available, should be based on a probability assessment of eruption scenarios (defining PDFs for possible plume height, erupted mass and TGSD) for each volcano. Eruptive-activity scenarios and PDFs can be constructed for each volcano through geological field work and/or through the use of historical databases (e.g. Smithsonian Institution, VOGRIPA, specific studies). If observations, scenarios and PDFs are not available, standard Eruption Source Parameters may be used accounting for related uncertainties (e.g. Mastin et al. 2009).

Recommendation 9: A real-time comprehensive definition of the source term can only be accomplished through the combination of various monitoring/measurement techniques, each with different application limits and assumptions (Table 2 and 3). Ideally, a range of techniques should be used simultaneously and in combination to cover the full spectrum of observations and address as many variables as possible. The key VATDM variables that characterize the source term are: (1) plume height, (2) MER, (3) TGSD, (4) erupted mass and the (5) onset and (6) end of an eruption.

Recommendation 10: Plume height is usually the easiest parameter to measure or estimate in real time (e.g. using radar, satellite, lidar, pilot reports or ground visual observation, infrasound, thermal camera, seismic amplitude, aircraft measurements, dropsondes, ballonsondes, lightning detection). Nonetheless, a better standardization of the measurements should be implemented (e.g. specify the horizontal distance from the vent at which the height is measured, specify if height is the maximum plume height or the height of the neutral buoyancy level at which horizontal injection into the atmosphere occurs, ensure that height is always reported above sea level, indicate measurement uncertainty).

Recommendation 11: Mass Eruption Rate is hard to measure directly and a distinction should be made between MER (i.e. at vent), mass transport rate (MTR) in the cloud at the neutral buoyancy level and local MTR (i.e. MTR at a given distance from the vent). A distinction should also be made between MER/MTR of all particle sizes and MER/MTR of small particles (i.e. particles detected by satellite sensors). If MER is calculated from plume height, then the most appropriate parameterization should be used (e.g. strong plume vs weak plume empirical and theoretical relations; Mastin et al. 2009; Sparks 1986; Wilson and Walker 1987). A range of techniques that could help constrain MER/MTR (of selective particle sizes) include radar, lidar, ground-based IR or UV camera, satellite, seismic energy release, infrasound and *in situ* aircraft for local MTR. Unfortunately, a comprehensive real-time technique that can provide the *erupted mass* associated with the *whole particle-size spectrum* does not yet exist; this could only be derived from a combination of various techniques (e.g. satellite retrievals, Doppler radar and aircraft in situ sampling).

Recommendation 12: Ash concentrations measured in the ash cloud can be useful for data assimilation or model validation. They can be derived from both remote sensing (e.g. radar, lidar and satellites) and *in situ* techniques (e.g. dropsondes and research aircraft). Attempts should be made to coordinate whatever resources that are available and ensure data is made available to VATDM modellers for assimilation/validation. SO_2 and aerosols may be a hazard in themselves and should also be monitored and modelled; SO_2 and aerosol observations are also useful for validating ash cloud dispersal (when SO_2 and secondary products are emitted and transported at the same altitude as the ash, although this is not always the case, e.g. Carn et al. 2007).

New communication strategies and research priorities

Institutions with an operational mandate are end-users (and often also developers) of research. They should therefore be closely involved in setting research priorities. Research and operational institutions here refer respectively to institutions that are mainly focused on research (e.g. universities) and institutions that have an operational mandate (e.g. meteorological offices, VAACs, volcano observatories, aviation industry). Clearly, some research institutions also have operational duties and some operational institutions also carry out important research. Research is essential to develop new methodologies and techniques that are not well-enough established to be operational, and to carry out one-off and short-term detailed studies. The workshop agreed on the following:

Recommendation 13: Volcano observatories, air traffic controllers and VAACs are encouraged to agree on mutual expectations and requirements before volcanic crises (e.g. IAVW Handbook 2004).

Recommendation 14: Operational institutions should investigate new critical operational strategies such as: (1) integration of outside experts and strategic research that could facilitate various operational stages; (2) construction of an official database with the objective of sharing high-quality data from multiple sources during a volcanic crisis. This would require consideration of about access and rules of data use, but have the aim of being as open and inclusive as possible to stimulate interdisciplinary collaboration and sharing of expertise/insight.

Recommendation 15: Existing monitoring networks across Europe (e.g. EARLINET, EUSAAR) are valuable but coordination of resources, data management and resource availability can be improved. Some networks currently work well at a national level but need to develop the means to coordinate with European partners. The aim is to make data available as soon as possible to the VAACs. Given that data accuracy might change with time, it is also important to provide qualifying information on the associated uncertainties.

Recommendation 16: Research and operational institutions should establish long-lasting collaborations in order to optimize strategies of ash dispersal forecasting. Current research priorities include: (1) data assimilation, (2) aggregation processes, (3) plume dynamics (in particular of weak plumes) and better characterization of the source term (e.g. based on validation with 3D models), (4) magma fragmentation, particle characterisation and size distribution from proximal to distal environments, (5) separation of SO_2 from ash clouds, (6) chemical analysis of plumes (particles, sulphuric acid aerosols, H_2S, halogen chemistry) and (7) aerosol transformations. Implicit is the need for reference observations and corresponding source-term information with which to evaluate the models.

Cooperation between research and operational institutions is fostered when researchers have to demonstrate to funding bodies the positive impact their science will have and how that impact will be achieved (usually by interaction with operational institutions and other end-users). The workshop has demonstrated that there is abundant volcanological and atmospheric research that can be achieved through partnerships between operational and research institutions that will significantly improve the global response to future volcanic eruptions. Traditionally, volcano research has received only limited funding; it is hoped that this unprecedented international, interdisciplinary, scientific coordination and collaboration will encourage funding bodies to release funding to address these issues and encourage potential new funders of research to come forward.

Concluding remarks

The first IAVCEI-WMO workshop on Ash Dispersal Forecast and Civil Aviation represents a unique effort that brought together volcanologists; meteorologists; atmospheric dispersion modellers; and space-, air- and ground-based monitoring specialists in the common attempt to improve our strategies of ash forecasting and reduce the risk associated with ash dispersal. Such successful team work has highlighted multidisciplinary and interdisciplinary collaboration between various research and operational institutions as the key to sustainable and long-lasting ash-forecasting solutions at the global scale. In fact, effective ash dispersal forecasting can only be achieved by collaboration across scientific disciplines and can be made operational only thanks to cooperation between operational agencies both at the national and international level. In this context, communication and efficient data transfer become crucial to the information flow and operational routines, which underpin any decision-making process. In particular, we have concluded that VATDM developers, meteorologists, volcanologists and stakeholders need to work closely together in order to: (1) improve the definition of the source term, (2) design models and forecasting strategies that can better characterize uncertainties, (3) explore and identify the best ensemble strategies that can be adapted to ash dispersal forecasting, (4) identify optimized strategies for the combination of models and observations and (5) implement new critical operational strategies. Workshops of this sort become necessary when the scientific community is faced with natural phenomena that affect various sectors of our society both at the local and global scale. The resulting enriching interactions, constructive discussions and cooperation are the reminder that when the international scientific community works together on a common problem significant progress can be made. The research and operational effort should continue and keep the momentum going for the long term in order to make all these priorities a reality and ensure we are as prepared as we can be for the next volcanic eruption. With this in mind, we aim to organise a second workshop within the next few years.

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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
DIAL	Differential absorption lidar technique
ECMWF	European Centre Medium-Range Weather Forecast
EDM	Environmental Dust Monitors
EUSAAR	European Supersites for Atmospheric Aerosol Research
GOES	Geostationary Operational Environmental Satellites
HYSPLIT	HYbrid Single-Particle Lagrangian Integrated Trajectory
IASI	Infrared Atmospheric Sounding Interferometer
IAVCEI	International Association of Volcanology and Chemistry of the Earth Interior
IAVWOPSG	International Airways Volcano Watch Operations Group
ICAO	International Civil Aviation Organization
IMO	Icelandic Meteorological Office
IR-SO2	Infrared Spectroscopy of SO_2
IVATF	International Volcanic Ash Task Force
JMA	Japan Meteorological Agency
LIDAR	Light Detection And Ranging
MLDP0	Modèle Lagrangien de Dispersion de Particules d'ordre zéro
MAXDOAS	Multiple Axis Differential Optical Absorption Spectroscopy
MER	Mass Eruption Rate
MISR	Multi-angle Imaging Spectro-Radiometer
MOCAGE	Modélisation de la Chimie Atmosphérique Grande Echelle
MODIS	Moderate-Resolution Imaging Spectroradiometer
MTR	Mass Transport Rate in the cloud
MTSAT	Multi-Functional Transport Satellite
NAME	Numerical Atmospheric-dispersion Modelling Environment
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NWP	Numerical Weather Prediction (Models)
OMI	Ozone Monitoring Instrument
OPC	Optical Particle Counter
PDF	Probability Density 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
VAAC	Volcanic Ash Advisory Centre
VAG	Volcanic Ash Graphic
VO	Volcano Observatories
VOGRIPA	Volcano Global Risk Identification and Analysis project
VOL-CALPUFF	Volcanic CALifornia PUFF model
VOLDORAD	Volcano Doppler Radar
WMO	World Meteorological Organization
WOVO	World Organization of Volcano Observatories

Appendix 2

List of participants

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