
5th INTERNATIONAL WORKSHOP ON VOLCANIC ASH

Report

Santiago, Chile, 22-26 March 2010

Convened by the *World Meteorological Organization*
In collaboration with the *International Civil Aviation Organization*
Hosted by *Dirección General de Aeronautica Civil de Chile*



Eruption of Chaiten volcano, Chile, 2 May 2008 (*Carlos Gutierrez*)

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List of Acronyms

AIRS	Atmospheric Infrared Sounder
ASTER	Advanced Space-borne Thermal Emission And Reflection Radiometer
ATZ	Air Traffic Zone (air traffic management)
AVHRR	Advanced Very High Resolution Radiometer
BTD	Brightness Temperature Difference
CAeM	Commission for Aeronautical Meteorology (WMO)
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
COAMPS	Coupled Ocean Atmosphere Mesoscale Prediction System
CTR	Control Area (air traffic management)
DGAC	Dirección General de Aeronautica Civil de Chile
DOAS	Differential Optical Absorption Spectrometer
ENAC	
ESP	Eruption Source Parameter
EUR/NAT	Europe/North Africa Region (ICAO)
FAA	US Federal Aviation Authority
GOES	Geostationary Operational Environmental Satellite
IACVEI	International Association of Volcanology and Chemistry of the Earth's Interior
IATA	International Airline Transport Association
IAVW	International Airways Volcano Watch system (ICAO)
IAVWOPSG	International Airways Volcano Watch Operations Group (ICAO)
ICAO	International Civil Aviation Organization
IGNS	Institute of Geological and Nuclear Science (New Zealand)
IMS	Infrasound Measuring System
INGV	National Institute Of Geophysics And Volcanology (Italy)
IUGG	International Union of Geophysics and Geodesy
LEO	Low-Earth Orbit
METEOSAT	Meteorological Satellite
MISR	Multi-Angle Imaging Spectroradiometer

MODIS	Moderate Resolution Imaging Spectrometer
MSG	
MWO	Meteorological Watch Office
NAME	Numerical Atmospheric-Dispersion Modeling Environment,
NEXRAD	US Weather Radar network
NEXTGEN	US air traffic management system (in development)
NMHS	National Meteorological And Hydrological Services
NOAA	National Oceanic and Atmospheric Administration
PNG	Papua New Guinea
SARPs	Standard and Recommended Practice
SAVAA	
SERNAGEOMIN	Servicio Nacional De Geologia Y Minería -Chile
SIGMET	Notice of Significant Meteorological Phenomena (ICAO)
SMS	Safety Management Systems (ICAO)
SWOT	Strengths Weaknesses Opportunities and Threats Analysis
UAF	University Of Alaska-Fairbanks
USGS	United States Geological Service
VA	Volcanic Ash
VAAC	Volcanic Ash Advisory Center
VACT	Volcanic Ash Collaboration Tool
VASSG	Volcanic Ash Science Steering Group
VATD	Volcanic Ash Transport And Dispersion Model
VEI	Volcanic Explosivity Index
VHub	
VO	Volcano Observatory
VONA	Volcano Observatory Notice For Aviation
WMO	World Meteorological Organization
WOVO	World Organization Of Volcano Observatories
WRF	Weather Research And Forecasting
WSO	
WWLLN	Worldwide Lightning Network

Notes of Appreciation

The participants in the 5th WMO International Workshop on Volcanic Ash would like to acknowledge the generous hospitality of the Directorate General of Civil Aeronautics of Chile in ably hosting the meeting in Santiago 22-26 March 2010. Given the civil emergency and loss of life and property suffered as a result of the earthquake on 27 February 2010, the participants in the workshop are humbled by the resilience and fortitude of Chile in recovering from the disaster. In particular, the workshop participants are highly appreciative of the perseverance of the Directorate General of Civil Aeronautics in hosting the meeting when, in other countries, the meeting may well have been cancelled in such circumstances.

The participants would also like to thank those responsible for organizing the meeting itself. In particular the great work done by Marianne Guffanti from the USGS in organizing the scientific programme and ensuring the representation at the meeting of key people from all over the world is greatly appreciated. Similarly, the work done by Reinaldo Gutierrez from Dirección General de Aeronautica Civil de Chile working locally to ensure the venue and all related services and programmes were in place.

The participants on the two workshop field trips, with vulcanological (overflight of central Chilean volcanoes) and meteorological (Fidae Air and Space Show with briefing on meteorological services for Chile) foci express their delight and appreciation to the Dirección General de Aeronautica Civil de Chile for the respective arrangements made.

And lastly, the continuing willingness of the WMO to foster and take responsibility for the workshops is recognized and greatly appreciated, as is the confidence and trust of ICAO through the International Airways Volcano Watch (IAVW).

1. General Summary

The 5th International Workshop on Volcanic Ash was held in Santiago, Chile, from 22 to 26 March 2010. The meeting heard of progress in many scientific and operational areas of interest to the International Airways Volcano Watch (IAVW) and international aviation in general.

Over 40 scientists, technologists and operations experts participated in the workshop.

The workshop noted again that, so far, no fatal aircraft encounters with volcanic ash have occurred, arguably as a result of the efforts of the IAVW and its robust support from the scientific community.

The presentations given by the participants helped to identify areas of progress, but also those remaining questions that need to be addressed by both the scientific community and the operational users of the information.

2. Outcomes Summary

- (a) The science behind the IAVW has advanced in many areas, including in satellite remote sensing, cloud height assignment, dispersion modeling, and eruption detection through lightning, infrasound and seismic networks. Two major 'special issues' of academic journals dealing with the volcanic clouds issue have been published since 2007.
- (b) In general, the interaction between all IAVW participants appears to have improved, and this is evident to users of IAVW products. The lack of major safety incidents during the major eruptions of 2007-2010 is seen as a significant testimony to the effectiveness of the IAVW, despite some ongoing concerns.
- (c) There continues to remain no definition of a "safe concentration" of ash for different aircraft, engine types or power settings. In order to give a reliable and justifiable "all clear" once a plume has dispersed enough to be undetectable, clear limits of ash content are required from both the manufacturers and aviation licensing authorities (refer Actions Summary).
- (d) A two-year effort to establish a protocol for assigning eruption source parameters to dispersion models during eruptions, when real-time observations were unavailable, has been completed. The result is a table of values, assigned to each of the world's volcanoes. The main limitation of the protocol is that it does not consider uncertainty at this stage (refer Findings Summary).
- (e) There needs to be a very co-operative and collaborative process in moving the science and new technology into the operational sphere and that management of such transfer needs to work carefully within the constructs of the safety management frameworks of ICAO, WMO and other international organizations (refer Actions Summary).

3. Actions Summary

- (a) Airbus agreed to write to the engine manufacturers asking if an answer is available on the question of safe particle size and concentration of ash that is sustainable by engines on its aircraft. Airbus will respond to IATA who will in turn inform the workshop and IAVWOPSG.
- (b) A subgroup/working group of VAAC members (to be designated by the new Scientific Steering Group) should be formed to examine the use/provision of uncertainty forecasting and probabilistic information. The group should report back to the IAVWOPSG/6 meeting in Dakar in September 2011.

- (c) It was recommended that a Volcanic Ash (VA) Science Steering Group (VASSG) be established under the auspices of the WMO, comprising no more than 5-6 key scientists representing the various science communities involved, and perhaps chaired by the WMO. The workshop agreed that the approach would provide a much more timely and dynamic method of co-ordinating the science developments with the changing needs of international aviation (refer section 5.3 for full details).

4. Findings Summary

- (a) The discussion identified the importance of engaging researchers in the problems of the IAVW, even where direct funding is unavailable. Efforts such as the SAVAA project in the European Union demonstrate that third party funding (in this case from the European Space Agency) can be obtained for assisting in IAVW science problems.
- (b) The integration of data between Volcano Observatories, MWOs, and VAACs was raised as a particularly important area to progress. Discussion on this point also outlined broader information sharing needs between Volcano Observatories and NMHSs for volcanic-related disaster risk reduction.
- (c) It is becoming increasingly important to improve the capability of the Volcano Observatories to produce a standardized pre-eruption probabilistic prediction scale that could be used in a qualitative assessment of the chances of an eruption occurring.
- (d) The VAACs need for more frequent and higher resolution satellite imagery was recognized, with the European MSG being recognized as current best operational source of geostationary data, particularly benefiting Europe and Africa. Analysis of the geostationary meteorological data stream shows that there is significant variation of coverage, with the Pacific Ring of Fire in particular being relatively poorly served. The advent of GOES-R will help answer to these issues for the Americas, however that is not expected until the 2014/2015 timeframe and will not assist all VAACs. Polar orbiting multi-spectral and hyperspectral data is becoming increasingly sophisticated and available.
- (e) Recent work in Europe and the US has shown a greatly enhanced potential for improved volcanic cloud detection using multi-spectral and hyperspectral data, and using improved algorithms for sensing sulphur dioxide and other volcanic gases, volcanic ash, and mixed (ash, gas, water/ice) clouds. Particular improvements have also been made in volcanic cloud height assignment, using remote sensing and blended remote sensing / dispersion model approaches. Within 5 years, VAACs will have access to a new level of best practice techniques, greatly assisting operations.
- (f) The universal implementation of these techniques is very important, noting that some of the improved algorithms for detection and cloud classification are designed to work with existing polar orbiting and geostationary data streams and to be essentially platform independent regardless of the variable quality of input data. The improved techniques will be very useful in addressing specific issues in remote sensing, such as for high altitude, ash-poor, ice-rich clouds in particularly warm and moist areas such as the Maritime Continent north of Australia, and also for reducing water-vapour effects on ash detection.
- (g) The improvements expected for the next decade in satellite detection and tracking methods will require re-training of VAAC staff and users and will offer a prospect of significant immediate improvements in the aviation safety applications. An international workshop especially for remote sensing of volcanic clouds be held to help with this, or possibly this effort could be addressed at regional workshops at several sites around the world.
- (h) There is a need for better ash fall modeling in and around airports in support of improved future warning protocols. This would include better predictive information on timing and amounts of ash fall. Uncertainty forecasting including probabilistic information is needed.

- (i) There is still a requirement for a volcanic ash end-to-end system which includes a capability for VAAC collaboration. It was noted that the Volcanic Ash Collaboration Tool (VACT) project was terminated in the U.S. without the project being completed. The intellectual capital and lessons learned from this effort should not be lost.
- (j) VAACs must share best practices for plume height and volcanic cloud discrimination between them, in support of consistent operational output and consistent competency-based training. In addition to the use of the WSO workshops for this purpose, this may be aided through posting to a common access web site, wiki, or by some other means to be determined.
- (k) A trial of purpose-driven deployment of a portable Doppler radar by the USGS confirmed the system/technology is useful for all-weather confirmation of an event, cloud height estimation, eruption mass rate and proximal fall out characteristics.
- (l) There is a need to encourage more use of radar systems which are near airports, but which are underutilized as volcanic cloud observation tools that could improve aircraft safety.
- (m) Analysis of Worldwide lightning network (WWLLN) data indicates it works best on 'wet' eruptions, and in areas of low ambient noise. This appears to be very useful tool to add to the toolkit for confirming activity has occurred. Unlike most ground-based networks, it is tuned for cloud-cloud lighting and therefore is more likely to pick up volcanic lightning.
- (n) Infrasound, including the IMS Infrasound network, remains another tool that can be adopted to detect an explosive volcanic eruption. Uptake and use of this technique has been low and issues remain with the correlation of plume height with signal amplitude.
- (o) Recent USGS work has further explored the utility of correlating eruption height and seismic wave amplitude for remote eruptions, with promising results.
- (p) There is a need to encourage data sharing especially of the growing variety of potentially useful satellite sensors.
- (q) Remotely sensed ground-based measurements (imaging cameras, radar, scanning DOAS etc.) should be more widely used and better integrated with satellite data.

5. Session Synopses

5.1 Panel – Science challenges in mitigation volcanic risk to aviation

Panel members: *Andrew Tupper (Moderator), David Schneider, Fred Prata, Eliecer Duarte*

The panel considered the key science priorities identified by the 4th WMO workshop in Rotorua, New Zealand, in 2007, and identified areas of major progress and remaining concern:

1. Two major 'special issues' of academic journals dealing with the volcanic clouds issue have been published since 2007¹.
2. There has been some improvement in *close monitoring of known, existing active volcanoes by both local and remote means*. Remote sensing in particular has advanced, and on-site cameras for observatories have also developed significantly, but are not a complete answer in themselves. Many developing countries are still struggling to prioritize volcanic

¹ Prata, A.J. and Tupper, A.C. (Eds.) Natural Hazards: Special Issue on Aviation Hazards from Volcanoes, 51 (2), 2009, Mastin, Larry and Webley, Peter (Eds.), Journal of Volcanology and Geothermal Research: Special Issue on Volcanic Ash Clouds, 186, 2009.

monitoring, particularly where volcanoes are not in eruption or have not recently erupted. Observatories struggle for political support in these circumstances.

3. *Pre-eruption monitoring* is being seen as increasingly important, but the science behind it is still insufficiently resourced. International assistance for monitoring networks largely relies on particular donor States, noting particularly the work of the US Volcano Disaster Assistance Program. Efforts by IAVW participants to implement cost-recovery provisions for designated State Volcano Observatory services to aviation are potentially very important for improvement in this area.
4. The *eruption source parameters* effort has significantly advanced, even though more work is seen as useful for applying the work for improving ash dispersion forecasts;
5. Further work has been done to demonstrate the use of *weather radar* for detecting and monitoring eruption clouds.
6. Little work has apparently been done to further validate *dispersion models*, including comparison to observations as well as between models. No science plan exists for this work, although the advent of new un-manned technology such as video sondes may make direct examination of clouds possible.
7. No progress was made in the 2007-2010 period on defining a “*safe concentration*” of ash for different aircraft, engine types or power settings.

Findings

- (a) In general, the interaction between all IAVW participants is seen to have improved, and this is evident to users of IAVW products. The lack of major safety incidents during the major eruptions of 2007-2010 is seen as a highly significant testimony to the effectiveness of the IAVW, despite our ongoing concerns.
- (b) The discussion also identified the importance of engagement of researchers in the problems of the IAVW, even where direct funding is unavailable. Efforts such as the SAVAA project in the European Union demonstrate that third party funding (in this case from the European Space Agency) can be obtained for assisting in IAVW science problems.
- (c) The integration of data between Volcano Observatories, MWOs, and VAACs was raised as a particularly important area to progress (refer discussion later in report).

5.2 Panel – Industry Perspectives

Panel members: *Graham Rennie (Moderator), and Ignacio Di Prospero, Manfred Birnfeld, Hans-Rudi Sonnabend,*

A series of questions came from the expert group which centred on gaining an improved understanding of aircraft/airline operations, the interaction with VAACs and the role of the Volcano Observatories. The importance of the Volcano Observatories was emphasized as being critical to safe and efficient operations.

The panel asked the expert group “what are the impediments to providing an effective pre-eruption alert?” The responses from the expert group ranged from never being able to do so to being extremely difficult. The follow up questions focussed on the capability of the Volcanic Observatories to produce a pre-eruption probabilistic prediction scale or range of an eruption occurring which could be used in a qualitative assessment of risk. The expert group were concerned with the expected high false alarm rate. It was explained that when probabilistic weather prediction started, the FAR was also high, and still is, but with continuous scientific developments, this has improved. Lengthy debate followed but it ended indecisively. It was noted that the initial eruption phase is the most dangerous phase for aircraft and the idea is worthy of follow up.

Another question from the panel asked about the relationship, governance and regulatory control of the volcanic organizations, WOVO (the World Organization of Volcano Observatories) and IACVEI. WOVO as a Commission of IAVCEI is part of a scientific association (IUGG) and relies on essentially volunteer labour and volunteer protocols – there is no UN Treaty Organization covering international cooperation on volcanic issues, which is a matter of some concern. Nevertheless, a lot has been accomplished for the IAVW through IAVCEI².

A question was put to Airbus regarding the ability of Airbus aircraft to sustain power when encountering an ash cloud. Airbus provided some engineering details on the redundancies installed in engines. Explaining further, the current generation aircraft of jet aircraft engines are protected to some extent against particle ingestion, particularly for low level sand and dust that may be expected to be encountered routinely in operations and which also has a higher melting point than volcanic ash. Engines are proven for sand and dust ingestion during their development process covering the operational environment at Take Off and Landing. But the defences can be brought down depending on particle size, concentration and duration of the exposure. The main threats are understood to be blockage of turbine blade cooling air passes on one side, which ultimately can lead to blade destruction, and erosion of compressor blades and vanes leading to rapid degradation and significant loss of efficiency on the other side. The likely initial effect to be expected is that engine power would be reduced but not fully lost. Further degradation may however lead to full power loss.

Referring to the need to have established alert thresholds, Airbus was then asked what is the safe particle size and concentration of ash that is sustainable by aircraft. Similarly, the same question relating to Sulphurous gas was also asked. Airbus could not provide an answer to either question because this information is not readily available. Airbus highlighted that flight in volcanic ash laden atmosphere is not part of the environmental specifications to which aircraft and engines are built. However, an action item was taken by Airbus to write to the engine manufacturers asking if an answer is available. Airbus will respond to IATA.

A question on exposure with regard to ash particles entering the fuel system was also briefly discussed, in the context of the 2006 all-engine flame-out of a Gulfstream (low bypass type engines) over Papua New Guinea (reported at the previous WMO workshop). Aside from this incident, it is believed that only very small particles and insignificant quantities of such particles could enter the aircraft fuel tanks through the vent system. They would then be retained by the engine fuel filter. It would need larger quantities to block the filter and cause the filter bypass to open. After bypass opening, the continuous fuel flow would depend on the engine's ability to absorb the passing particles through the combustor and maintain the fuel flow regulator system operational.

Findings

- (a) The integration of data between Volcano Observatories, MWOs, and VAACs was raised as a particularly important area to progress (refer discussion later in this report).
- (b) The capability of the Volcanic Observatories to produce a pre-eruption probabilistic prediction scale or range of an eruption occurring which could be used in a qualitative assessment of risk was raised.
- (c) Airbus agreed to write to the engine manufacturers asking if an answer is available on the question of safe particle size and concentration of ash that is sustainable by engines on its aircraft. Airbus will respond to IATA who will in turn inform the workshop and IAVWOPS.

² At the time of the Workshop, the three WOVO co-leaders were employees of three agencies strongly committed to the International Airways Volcano Watch: the Italian Istituto Nazionale di Geofisica e Vulcanologia, the Australian Bureau of Meteorology, and the United States Geological Survey.

5.3 Panel – Science needs of Volcanic Ash Advisory Centres (VAACs)

Panel members: *Jeffrey Osiensky (Moderator), Philippe Husson (Toulouse), Tony Hall (Anchorage), Martina Suaya (Buenos Aires), Andrew Tupper (Darwin), Makoto Saito (Tokyo), Peter Lechner (Wellington)*

Five VAAC managers or their representatives were part of a panel session entitled “Science Needs of the VAACs”. Several themes/topics were presented to the group for discussion. The topic of uncertainty forecasting was discussed and the panel as well as the members of the meeting agreed that the VAACs must pursue uncertainty forecasting and provide probabilistic information to its customers. Airline representatives in the meeting agreed that the provision of probabilistic information is critical to decision making.

ACTION: A subgroup/working group of VAAC members (participants TBD) must be formed to examine the use/provision of uncertainty forecasting and probabilistic information. The group will report back to the IAVOPSG/& meeting in Dakar in September 2011

The panel members also discussed that each of the VAACs have a somewhat different approach in determining ash cloud top heights. These differing height assignments become problematic particularly when VAACs “hand off” plume from one area of responsibility to another. This causes a great inconsistency in service and general confusion to the customer.

ACTION: VAACs must share plume height discrimination techniques best practices amongst one another. In addition to using WMO workshop processes, this may be accomplished through posting to a common access web site, wiki, or by some other means to be determined.

FINDING: The panel discussed the need to have more frequent and higher resolution satellite imagery in the VAACs, although it is understood that ground-based information may often be the only practical way to detect eruptions in cloudy areas. The Darwin VAAC manager mentioned the difficulty in detecting eruptions in a tropical, high moisture environment, a problem also frequently found by VAAC Toulouse for African eruptions. The advent of GOES-R should help address these issues in the United States; however that is not expected until the 2014/2015 timeframe.

FINDING: The panel and members of the group discussed the need for VAACs and VOs to share information. The discussion was centered around the idea of sharing information where it makes sense. There was some disagreement from the VAACs on the utility of seismic data. Some VAACs don't want to see the data, while others use it and coordinate with their VO to discuss various signatures and trends (refer discussion from ‘break-out’ session later).

FINDING: The group also discussed the need for better ash-fall modeling in and around airports. This would include better predictive information on timing and amounts of ash-fall. Again, uncertainty forecasting including probabilistic information is needed.

FINDING: The panel and members of the group discussed the need for better collaboration and sharing of best practices amongst the VAACs. The Volcanic Ash Collaboration Tool (VACT) project was discussed but unfortunately the project was not completed. There is still a requirement for a volcanic ash end to end system which includes a capability for VAAC collaboration.

5.4 Talks – Detection and alerting for volcanic eruptions

Moderator: *Brad Scott*; Talks from: *David Schneider, John Ewert, Andrea Steffke, Larry Mastin, Eliecer Duart, Mauro Coltelli*

This session consisted of 6 talks, four founded on geophysics related to observing or detecting volcanic eruptions, and two from Volcano Observatories: one covering the impacts of recent volcanic unrest and minor activity and other the operations involved in dealing with an active volcano near a busy airport.

Key observations from the talks;

- USGS now has a portable Doppler radar (250W, C-Band, 100km range) that was successfully deployed at the recent eruption of Redoubt in Alaska. The equipment requires a 20' container for shipping but this also doubles as an operations hut. The system is sensitive to particle size, minimum detection is of particles about 0.1mm across. This initial deployment confirmed the system/technology is good for all weather confirmation of an event, cloud height estimation, eruption mass rate and proximal fall out characteristics.
- World-wide lightning network (WWLLN) provides 1 min data updates, of cloud to cloud and cloud to ground strikes. If the strike is recorded on 5 or more stations, activity up to about 10,00km away can be located to within 10km. An analysis of the recorded data for 2008 and 2009 has demonstrated that the network has seen all VEI 4 eruptions, 8/12 VEI 3, and 4/68 VEI 2 eruptions. The analysis indicated it works better on wet eruptions, and in areas of low ambient noise. This appears to be very useful tool to add to the toolkit for confirming activity has occurred.
- The IMS Infrasound network remains another tool that can be adopted to detect an explosive volcanic eruption. It can work at regional scales (<250km) or locally. Analysis has shown well designed networks do work. Uptake and use of this technique has been low and issues remain with low occurrence of highly correlate signals. There can also be an azimuth issues for some areas, but there has also been success at defining plume heights. Local arrays work better.
- Recent USGS work has developed our understanding of the relationship between the height of an eruption column and the amplitude of seismic waves radiated. The waves are generated by the 'downward' force generated as the eruption column accelerates from the active vent (solved via the rocket equation). Analysis of two recent larger eruptions suggests this technique may have useful applications and warrants further work.
- A case study of the recent reawakening (2005-2010) of Turrialba volcano in Costa Rica demonstrated many of the issues related to uncertainty and smaller scale activity from an active volcano. Due to the juxtaposition of the volcano and a significant population and utilized airspace many issues have arisen. This has lead to development of techniques to deal with these by the local aviation authority but little support has followed for more extensive underpinning science.
- In the last 30 years Etna volcano in Italy (Sicily) has produced many small eruptions affecting aviation. This presentation demonstrated the magnitude of the effort involved in providing near real time assessments to maintain an efficient modern aviation capability. Complex interagency relationships and an extensive monitoring capability have been established to achieve this. The presentation outlined how the capability has been established, adoption of aviation procedures, crafted together with research to develop near-real time monitoring and reporting. An enormous commitment to the issues.

Findings

- (a) Initial deployment of portable Doppler radar by the USGS confirmed the system/technology is good for all-weather confirmation of an event, cloud height estimation, eruption mass rate and proximal fall out characteristics.
- (b) Analysis of the World-wide lightning network (WWLLN) data indicates it works better on wet eruptions, and in areas of low ambient noise. This appears to be very useful tool to add to the toolkit for confirming activity has occurred.
- (c) The IMS Infrasound network remains another tool that can be adopted to detect an explosive volcanic eruption. Uptake and use of this technique has been low and issues remain with low occurrence of highly correlated signals.
- (d) Recent USGS work has improved our understanding of the relationship between the height of an eruption column and the amplitude of seismic waves radiated.

5.5 Talks – Detection and tracking of VA and gas clouds

Moderator: *David Schneider*; Talks from: *Andrew Tupper, Vincent Realmuto, Michael Pavolonis, Fred Prata, Matt Watson*

This session consisted of 5 talks, focusing on aspects of remote sensing of volcanic clouds. The first talk summarized all the issues around the height, ash content, and detection of ash clouds in the moist tropics, and the next 4 outlined some exciting remote sensing developments.

Key observations from the talks:

- Observations of tropical volcanic clouds since the previous workshop in 2007 have tended to validate the model proposed then of a tendency towards high, ash-poor clouds that are difficult to explicitly detect ash in. Data-sharing (including for ground-based data) remains a very high priority in cloudy areas.
- A new suite of tools called ‘Plume-tracker’ from a Jet-Propulsion Laboratory-based project will use a principal component style approach for cloud classification, combined with objective ash and SO₂ analysis and data analysis to provide an innovative multi-tool approach within a single environment.
- Extremely promising results in automated volcanic cloud detection are being obtained by NOAA/NESDIS using ratios of effective absorption optical depth as an alternative to ‘split-window’ analysis, and estimating cloud height, effective particle size, and mass loading using multi-spectral techniques. These techniques are being implemented in a platform-independent manner.
- An analytical inverse modeling method has been developed to estimate the vertical emission profile of sulphur dioxide (SO₂) emitted during a volcanic eruption, as part of the Support to Aviation for Volcanic Ash Avoidance (SAVAA) project funded by the European Space Agency (ESA). The eventual goal of this work is to be able to better forecast the movement of hazardous volcanic clouds by using of satellite data together with dispersion modeling.
- The advent of hyperspectral imagery, for example the Atmospheric Infrared Sounder (AIRS), has the capacity to improve our ability to detect and quantify ash – particularly to reduce the effect of multiple interfering species on detection of ash burden.

Findings

- The talks presented showed that remote sensing techniques have been developing swiftly and in a way that will address many (but not all) of the complex challenges of volcanic cloud remote sensing. Each of the new approaches presented showed distinct promise as well as some convergence of thought.
- The increased ability to retrieve quantitative data such as ash height, presence of multiple species etc to compensate for the presence of water vapour, and the increased thought being given to algorithm implementation suggests that within 5 years, VAACs will have access to a new level of best practice techniques, greatly assisting operations.

5.6 Panel – Detection and tracking of VA and gas clouds

Panel members: *Bill Rose (Moderator), Fred Prata, Mike Pavolonis, Matt Watson*

This panel began with a summary presentation by Fred Prata, “New Techniques and technologies for remote sensing of volcanic ash and SO₂ gas”. A highlight of this presentation was an animated false colour series of images representing 36 hrs of geostationary satellite measurements from the SEVIRI sensor of the 11-12 February 2010 eruption of Soufriere Hills, Montserrat. This sequence of views shows the mapped “triple detection” dispersion of SO₂, ash and cloud ice every 15

minutes and dramatically demonstrated the improved capability of satellite data on volcanic clouds that presently covers Europe, Africa, and the Atlantic as far as the Lesser Antilles. Details of Fred's presentation show how improved spectral resolution in the Infrared (800-1150 wavenumber) can differentiate the components of volcanic clouds and also lead to quantitative estimates of burdens.

Although techniques exist to map volcanic ash clouds where the burdens of ash are quantified and plotted (Prata, 1989; Wen & Rose, 1994 and many more research papers thereafter), the operational community in VAACs has used the infrared sensing tools ("split window" on AVHRR, GOES, MODIS) mainly in a brightness temperature difference (BTD) format which can sometimes confuse some users (eg Simpson et al 2000; Prata et al 2001). Moreover the satellite based split window detection mapping method does not directly address the issue of cloud height. As a further problem, the split window method is compromised in the Western Hemisphere by the elimination of a critical spectral band in the 12 micron wavelength region for geostationary satellites in the 2000-2015 period. Thus, while the current state of satellite ash detection uses is challenging, significant improvement in Europe and Africa is already in place and will be shared by the Americas after 2015.

Work by Mike Pavolonis (see presentation: "Advances in Automated Satellite Remote Sensing of Volcanic Ash") anticipates this coming improvement and the desirability for quantitative ash mapping tools including height and ash burden. Importantly, this new effort will work through the meteorological community and its software community (McIDAS-V) by using the advanced IR spectral and spatial techniques of the new GOES-R sensors (ABI) to enable SO₂, Ash, Cloud Ice, and Cloud height maps to be produced at high temporal resolution. Special attention is called to the benefits of the new automated method in addressing problems of water vapor which can obscure BTD based ash detection and the cloud height retrievals. It can be expected that these improvements will expand to include geostationary satellites that will cover the Western Pacific region by 2020 (in addition to current applicability to polar orbiting AVHRR and MODIS data), making the whole effort globally applicable and largely removing the uneven coverage that currently exists.

The improvements coming in the next decade for satellite methodology (discussed above) will require re-training of VAAC staff and users and offer a prospect of significant immediate improvements in the aviation safety applications. It is important that the planned detection/tracking improvements be used intelligently as soon as possible after satellite sensors are operating. The group suggests that an international workshop especially for remote sensing of volcanic clouds be held to help with this, or possibly that this effort could be addressed at regional workshops at several sites around the world.

The value of ground based radar systems to mitigate volcanic cloud hazards was discussed next. Ground based radar provides an important tool to accurately measure eruption cloud height early in eruptions and to map these events dynamically (Lacasse et al 2003; Schneider & Hoblitt, this workshop) especially when the radar is located near airports. It was felt that more and better use of the radar systems which are near airports, but which are currently underutilized as volcanic cloud measurement devices, should be encouraged and could improve aircraft safety.

The group encourages data sharing especially of the growing variety of potentially useful satellite sensors. Such efforts could enhance near-real time access by VAACs and also address research needs post-mortem. The WOVO data and VHub projects are working together to help address the need of a data archive of satellite remote sensing of eruptions. We observed and applauded the MODVOLC website and its pixel-based preservation of thermal IR hotspots. This MODVOLC model could potentially be applied to volcanic cloud sensors and our panel may look into this. Such an archive could lead to more rapid learning of improvements by providing efficient access to widely scattered data sets.

It might be possible to enhance the outreach of workshops like this by using a web-based technology for participants. Currently lecture presentations can be recorded using a software

called “screenflow” either during the workshop or before, and these movie files can be shared via the web or DVDs to capture both the words and complete visual records of the presentations. Discussions can be joined via the internet either live or after the event by using additional software (Adobe Connect Pro) which operates through any browser. For demonstration of these technologies see the Ashfall website of WI Rose (<http://www.geo.mtu.edu/~raman/Ashfall>). Such techniques will be investigated for use at subsequent workshops.

The idea of holding another international workshop on volcanic cloud remote sensing, perhaps located in or near Madison, Wisconsin, was advanced for discussion. Regional workshops with the same objective could lead to attendance by more people with hands-on relationship to operational remote sensing and might also be a vehicle for the generation of lecture movies and hands-on laboratory data. Examples of such events include the recent workshop “Remote Sensing and GIS modeling at Volcanoes” held at the Earth Observatory, Singapore, 3-10 March 2010; and the planned workshop “Volcanic Hazards and Remote Sensing in Pacific Latin America” to be held in Costa Rica in January or February 2011.

Fred Prata’s presentation also included some results from two new ground-based imaging camera systems; one operating at infrared wavelengths and the other at UV wavelengths. Both systems are able to sample plumes at safe distances (up to 10 km, depending on atmospheric conditions) and can detect and quantify both SO₂ gas and ash particles. These systems seem likely to become part of the arsenal of ground-based measurements useful at volcano observatories or at airports and will aid in early warnings of ash hazards. The panel believed remotely sensed ground-based measurements (imaging cameras, radar, scanning DOAS, etc.) should be more widely used and better integrated with satellite data.

References

- Prata, A. J., 1989: *Observations of volcanic ash clouds in the 10-12-micron window using AVHRR/2 Data*. Int.J.Remote Sens., 10, 751-761.
- Wen, S and W I Rose, 1994, *Retrieval of Particle sizes and masses in volcanic clouds using AVHRR bands 4 and 5*, J. Geophys. Res., 99:5421- 5431.
- Pavolonis MJ 2010: *Advances in Extracting Cloud Composition Information from Spaceborne Infrared Radiances: A Robust Alternative to Brightness Temperatures Part I: Theory* Subm to Journal of Applied Meteorology and Climatology
- Simpson, J. J., Hufford, G., Pieri, D., & Berg, J. (2000). Failures in detecting volcanic ash from a satellite-based technique. Remote Sensing of Environment, 72, 191–217.
- Prata, AJ GJS Bluth WI Rose DJ Schneider and A Tupper, 2001, Comments on “Failures in detecting volcanic ash from a satellite-based technique” Remote Sensing of Environment 78 (2001) 341–346
- Lacasse, C, S Karlsdóttir, G Larsen, H Soosalu, W I Rose and G G J Ernst, 2003, Weather radar observations of the Hekla 2000 eruption cloud, Iceland, Bulletin of Volcanology, 66:457-473

Findings

- (a) The current state of satellite ash detection uses is challenging, but there is excellent improvement in Europe and Africa already in place and which will be shared by the Americas after 2015.
- (b) Advances in Automated Satellite Remote Sensing of Volcanic Ash” anticipates a coming improvement and the desirability for quantitative ash mapping tools including height and ash burden.
- (c) Special attention is drawn to the benefits of the new automated method in addressing problems of water vapour which can obscure BTM based ash detection and the cloud height retrievals. There is optimism that these improvements will expand to include geostationary satellites that will cover the Western Pacific region by 2020.

- (d) The improvements coming in the next decade for satellite methodology will require re-training of VAAC staff and users and offer a prospect of significant immediate improvements in the aviation safety applications. An international workshop especially for remote sensing of volcanic clouds to be held to help with this, or possibly that this effort could be addressed at regional workshops at several sites around the world.
- (e) There is a need to encourage more use of radar systems which are near airports, but which are underutilized as volcanic cloud measurement devices could improve aircraft safety.
- (f) There is a need to encourage data sharing especially of the growing variety of potentially useful satellite sensors.
- (g) Remotely sensed ground-based measurements (imaging cameras, radar, scanning DOAS, etc.) should be more widely used and better integrated with satellite data.

5.7 Talks – Atmospheric dispersion modeling

Moderator: *Larry Mastin*, talks from: *Larry Mastin, Arnau Folch, Ted Tsui*

René Servranckx of the Canadian Meteorological Centre, Barbara Stunder of the U.S. National Oceanic and Atmospheric Administration, and Sara Barsotti of the Istituto Nazionale di Geofisica e Vulcanologia Sezione di Pisa, were unable to make it to the meeting.

Larry Mastin summarized a two-year group effort to establish a protocol for assigning eruption source parameters to dispersion models during eruptions, when real-time observations were unavailable. The result is a table of values, assigned to each of the world's volcanoes. The main limitation of the protocol is that it does not consider uncertainty. Arnau Folch described the advanced Fall3d model, which can simulate ash deposition and cloud transport over scales ranging from few kilometers to thousands of kilometers. Ensemble simulations from 730 model runs showed the probability of ash inundation, and ash arrival time at regions surrounding Vesuvius from a hypothetical eruption equal in size to the AD 472 eruption, in a wind field sampled from 2005 model data. Model comparisons with MISR satellite data for ash plumes at Etna were generally favorable but pointed out weaknesses in this and other models that are detailed below. Ted Tsui described the U.S. Naval Research Laboratory's Coupled Ocean Atmosphere Mesoscale Prediction (COAMPS) model, which can ingest data and model results from any section of the globe and use them in a finer-scale Eulerian nested grid simulation of meteorology and ash-cloud movement. Model results from the August 2008 Kasatochi eruption compared well with GOES 11 split window images of ash movement.

Findings

Discussions during the meeting brought out several key issues in models that will likely be the focus of future research. These include the following:

- (a) Uncertainty in plume height, erupted volume, duration, and other source parameters has not been considered adequately, either in the ESP protocol or in some models that are run as forecasts before or during eruptions. Model uncertainty is starting to be addressed through ensemble modeling. Examples from the U.S. National Oceanic and Atmospheric Administration (Barbara Stunder), the Vesuvius hazard forecasts by the Barcelona Supercomputing Center, and incipiently by the USGS Cascades Volcano Observatory were shown.
- (b) Members of the workshop felt that the effort to address eruption source parameters should continue, with improvements focused on addressing issues of uncertainty.

Atmospheric dispersion models were frequently mentioned as producing "conservative" ash clouds that were both wider and extended farther downwind than observed in satellite

images or inferred from mapped deposits. These discrepancies were thought to result from at least two factors:

- (i) Numerical diffusion in ash-cloud models a cloud margin that is more diffuse than is commonly observed. The width of modeled ash clouds depends on the (somewhat arbitrary) concentration assigned to the ash-cloud margin.
- (ii) Downwind extent of ash clouds reflects the rate of tephra fallout from the cloud. It is well known that fine ash falls out much faster than is predicted from the settling velocity of individual particles. Dry ash aggregation, scavenging of ash by raindrops or ice, and wet accumulation all accelerate ash removal. Currently, no model considers these processes using physically based principles, although their inclusion is under development in the Fall3d model with collaboration from atmospheric scientists.

5.8 Seminar – Transferring Science to operations

Moderator: *Peter Lechner*, Talks from; *Mauro Colteli*, *Herbert Puempel*, *Steve Albersheim*, *Andrew Tupper*, *Claudio Pandolfi*

This session consisted of 4 presentations, spanning specialised scientific support for aviation through formal product introduction mechanisms, capability training in VAACs and the key safety management perspectives being progressively applied in the aviation sector.

The speakers recognized that the aviation industry was heavily procedural for safety and operational reasons, and that bringing new systems or procedures into that environment was a complicate but ultimately sure. An appropriate example of such a successful process is the establishment of the IAVW (International Airways Volcano Watch) operations to which this work offers support.

Mauro Colteli explained the extensive local procedures used in the mitigation of ash in aviation as a result of the ongoing activity of Mt Etna, Sicily, with respect to the aviation operations in and around the Catania and Calabria aerodromes, both of which serve international aviation. The procedures involve very close co-ordination and communication between INGV, the air traffic services and the meteorological services. Effectively IGNS is currently providing a graphical volcanic ash advisory product from its own dispersion modeling work using a modified PUFF system.

It was also explained that the engagement of these valuable products and processes with the international ICAO IAVW systems and standard operating procedures and recommended practices (SARPs) was presently the subject of a formal ENAC circular.

Herbert Puempel reported that the training sub-group concepts had effectively been superseded by the agreement to establish a new steering group for the WMO sponsored IWVA – refer section 4.3.

Steve Albersheim presented an important outline of the significant evaluative process new concepts and operations must be subjected to within the US aviation environment regulated by the FAA. The process described was generic for the development and introduction of any new product to be used by controllers, pilots, and dispatchers. The FAA had already defined products for VA, but was in the process of conducting a gap analysis to scrub the existing services to define specific performance parameters that will be required in support of United States NEXTGEN's vision of meteorological services and the nature of the information that will be required for VA decision support tools.

The presentation stressed the need for performance requirements to be specified in all products to ensure their efficacy can be measure and appropriate remedial action taken if necessary. In this light, the importance of the further defining performance parameters to mitigate the costs to industry from ash encounters was stressed.

The FAA plans to share the development of operational requirements for space weather and the gap analysis for volcanic ash with the International Civil Aviation Organization and the World Meteorological Organization for the purpose of improving the quality of information that is currently provided by National Meteorological and Hydrological Service providers and by the World Organization of Volcano Observatories in support of aviation.

Andrew Tupper presented material outlining the operation training and competency measurement of meteorologists at the Darwin VAAC. Such training was implemented in a serious fashion and meteorologists were expected to demonstrate their ongoing competency through rigorous simulation exercises. This fulfilled the widely accepted and mandated requirement in aviation meteorology (under Annex 3 of the Convention on International Civil Aviation) to meet ISO9001:2008 requirement that staff must demonstrably meet preset standards.

The systems for this in the Darwin VAAC included computer based exercises using historical ash events, oral questioning, case studies, quizzes and observation. This approach, referred to as a blended learning perspective was identifying a number of areas where additional training was needed, especially with staff who had not experienced high level eruptions, as well as validating the competence of the great majority of staff. In this regard the approach was seen as a successful one.

It was also noted that under the new ICAO Safety Management System (SMS) requirements, the training and competency system measured up quite well. Its core assessment of internal risk and the mitigation of that risk was well aligned.

Claudio Pandolfi presented an overview of how and why the DGCA of Chile was putting significant effort into the introduction of the ICAO SMS requirements. Chile was acutely aware of the significance of natural events and the risk and consequences imposed on its population. As a result, the DGCA was putting significant effort into the implementation of SMS in the Chilean civil aviation system and the individuals and organizations operating in that system.

The new SMS approach was seen as the natural extension of the reactive and proactive approaches adopted in the history of aviation. SMS is seen as a predictive tool, forecasting risk and consequence and implementing preventative measures on a probabilistic basis; identify the risk potentials, evaluate the most probable scenarios, select the most cost effective mitigation, apply the actions or interventions, and measure the result.

Of importance: the workshop was reminded to never underestimate the value the affected communities can have in assisting and informing these kinds of processes.

Findings

- (a) The general overview of the session was that there needs to be a very co-operative and collaborative process in moving the science and new technology into the operational sphere and that management of such transfer needs to work carefully within the constructs of the IAVW, ICAO and other international organizations.

5.9 Special Lecture - Chilean volcanism and on-going efforts of the Government of Chile to improve volcano monitoring capabilities

Drs Jose Antonio Naranjo and Jorge Munoz of the Servicio Nacional de Geologia y Minería (SERNAGEOMIN)

In addition to sessions that focussed on global aspects of the volcanic ash and aviation safety theme, the workshop heard presentations from Drs Jose Antonio Naranjo and Jorge Munoz of the Servicio Nacional de Geologia y Minería (SERNAGEOMIN) about the 2008 eruption of Chaiten volcano, the scope of Chilean volcanism, and efforts now underway to create a national volcano monitoring network. Chile has within its continental border approximately 122 active or potentially

active volcanoes. Current estimates are that a significant eruption (one with widespread effects, including aviation impacts) occurs in Chile about every 8-10 years,

Dr Naranjo described the highlights of the Chaiten eruption, the hazards, and the Chilean Government's response to the eruption crisis including the evacuation and likely abandonment of the townsite of Chaiten (pop. ~4000). The 2008 VEI 4 eruption of Chaiten was the most significant explosive eruption in southern South America since the 1991 VEI 5 eruption of Mount Hudson. The eruption of Chaiten had a profound effect on air operations in both Chile and Argentina, and this, combined with the effects on nearby population and infrastructure catalysed the Government of Chile into taking a proactive role in volcano hazards monitoring and mitigation.

Dr Munoz described a five-year program now underway in Chile to assess hazards and implement volcano monitoring networks at the 43 most threatening Chilean volcanoes. Called the Red Nacional de Vigilancia Volcanica (National Volcano Monitoring Network; RNVV), the programme will allow the earliest signs of volcanic unrest to be detected and timely alerts about volcanic activity to be issued to at-risk communities, including the aviation sector.

The participants of the workshop applaud this significant development in volcano monitoring and hazards mitigation being undertaken by the Government of Chile, and look forward to learning more about how SERNAGEOMIN and DGAC will apply these new capabilities to increasing aviation safety in this region.

6. Breakout Synopses

6.1 Data-sharing and volcano observatory / NMHS cooperation.

Data-sharing for the International Airways Volcano Watch

Given the good representation of volcano observatories at the Workshop, the opportunity was taken to have discussions on scientific data-sharing needs and related issues required for the purposes of the IAVW.

The group considered that:

- the scientific data that should be shared should be that which helps each agency to reach a professional and consistent analysis of the situation;
- data analysis should be performed by the agency with the appropriate expertise (for example, seismic station data by the Volcano Observatory (VO); and,
- documented data-sharing arrangements between VOs, National Meteorological and Hydrological Services (NMHSs), and Volcanic Ash Advisory Centres (VAACs) should ideally be agreed in advance of a volcanic crisis.

Observatories have been requested to use the Volcano Observatory Notice for Aviation (VONA) format for their analysis of volcanic activity for aviation purposes, including for the critical role of eruption prediction. In general, the data contained in this or equivalent communications should suffice for operational purposes, although there may be occasions where other information might be usefully added by mutual agreement or individual initiative.

An example of this last point might be for information about possible 'remobilised ash', where dry ash can be blown off a deposit for many decades after an event³. These clouds can be seen in remote sensing and pose an aviation hazard, but the events also bear much in common with sandstorms despite the lower melting point of ash and the associated explicit aviation hazard.

In order to produce the analysis contained in a VONA, the data needs of the Volcano Observatories from other IAVW participants will vary according to local arrangements, but may include:

- Pilot, ship, and ground-based meteorological observer observations of volcanic activity, including cloud height;
- Radar observations of a volcanic plume;
- Lightning data indicating the possibility of eruptions at a volcano;
- Satellite-based analysis of volcanic plumes;
- Satellite-derived 'hot spot' observations (noting that many NMHSs and all VAACs are in receipt of meteorological satellite data including 'hot spot' channels in real-time);
- Archived VAAs for post analysis;
- Post event analysis results, including that information sent to the Smithsonian Institution.

Where a volcanic eruption has no ground-based monitoring in place, the above observations tend to take on particular importance, but even with instrumental monitoring, multiple sources of information are often required to establish volcanic plume height, which can significantly affect volcanological assessment of the scale of an eruption as well as the scale of plume dispersion.

³ For example, at Katmai, Alaska in 2003 following the 1912 eruption.

Data-sharing for general disaster risk reduction

The Handbook on the International Airways Volcano Watch, ICAO Doc 9766-AN/968, which sets out communications between Selected State Observatories and other parties for the purposes of aviation safety, suggests that, consistent with the Hyogo Framework for Action 2005-2015, “in order to enhance stronger linkages, coherence and integration with States' disaster risk reduction units, Contracting States are encouraged to send back to States' volcano observatories any relevant information regarding volcanic ash to the extent and in a form agreed between the VAAC and the VO concerned”.

Further to this, the group noted informally that a number of volcanic hazards are closely related to atmospheric processes, and that close cooperation between VO, VAACs and NMHSs would indeed be useful in providing a comprehensive and consistent natural hazards warning system in the States concerned. Areas of interest include:

- 1) *Ashfall modeling and dispersion modeling.* Volcano observatories are becoming increasingly interested and proficient in modeling ashfall using real-time numerical model data and combined dispersion models such as Fall3d & VOL-CALPUFF. Ashfall is an important volcanic hazard because of the immediate risk to life and property close to the source, as well as a disruption to life and to industries such as agriculture further away from the source. Ashfall on airports has caused considerable disruption during many eruptions, and this can have the further effect of inhibiting airborne relief efforts.

Ashfall modeling and long-term dispersion modeling for airborne volcanic cloud warnings are typically conducted on different scales and at different model resolutions (with terrain a particular consideration for mesoscale ashfall patterns), but it would nevertheless be useful to ensure consistent input meteorology to the extent possible, and that, regardless of which agency takes formal responsibility for ashfall, NMHSs, VOs, and VAACs closely coordinate for efficiency of effort, ensure the best possible meteorological and volcanological input, and possibly seek assistance from a WMO Regional Specialized Meteorological Centre in obtaining suitable numerical weather prediction data.

The group also noted that quantitative estimates of ash depth are an important factor in ashfall prediction. Currently, ash concentration is more qualitative for VAAC dispersion modeling, since there is no defined ‘safe’ concentration, but this may change in the future. The group also noted the potential importance of an ensemble approach in future work.

- 2) *Rainfall-triggered volcanic hazards.* Lahars (volcanic mudflows) are a common, highly destructive, and frequently fatal volcanic hazard and are generally rainfall triggered. Rainfall is also known to trigger lava dome collapses in some situations⁴, causing highly dangerous pyroclastic flows. Rainfall intensity and duration forecasting by NMHSs can be highly useful for assisting VOs and disaster mitigation agencies in mitigating these hazards.
- 3) Volcanic landslides, ashfall, submarine eruptions and pyroclastic flows into the sea pose shipping hazards. Landslides and volcanic eruptions may cause localized tsunamis, and major volcanic eruptions or collapses may cause basin or ocean-wide tsunamis. Incorporation of warnings and eruption analysis from VOs will be important in the further development of global tsunami warning systems.

⁴ Most notably at Soufrière Hills, Montserrat

6.2 New Technologies

Summary of Remote Sensing Technology and Algorithm Science Breakout Session

The discussion in this breakout session was focused on two specific topics:

1. The science and technology used to estimate ash cloud heights
2. Geostationary satellite coverage and instrument capabilities relevant to volcanic cloud remote sensing

The science and technology used to estimate ash cloud heights

All of the breakout session participants agreed that ash cloud height information is critical for forecasting the dispersion of ash clouds and determining if ash clouds are at airline cruising altitudes. Three recently developed, and operationally relevant, methods for estimating ash cloud height were identified and discussed. These methods are: weather (or C-band) radar reflectivity (e.g. Schneider et al.), combined satellite/dispersion model technique (e.g. Prata et al.), and multi-spectral infrared retrievals (e.g. Pavolonis et al.).

Weather radars are very useful for monitoring volcanic cloud heights with high temporal resolution, especially in the early stages of the eruption when larger particles are present (the radar is largely insensitive to small particles). For instance, the USGS radar system detected all sixteen major ash-producing events of Redoubt that produced ash clouds at altitudes in excess of 10 km above sea level between March 23 and April 4, 2009. In many cases, it was possible to provide eruption notification while the column was still ascending. Radar estimated cloud heights have an accuracy of ± 1 km. The breakout session participants concluded that weather radar data are underutilized in volcanic cloud remote sensing.

Inverse modeling methods can be used to estimate the emission height profile of volcanic clouds. The inverse modeling method is designed to identify the volcanic cloud emission vertical profile, within an atmospheric transport model, which most accurately reproduces the shape, horizontal position, and total column loading of volcanic material (SO_2 or ash) derived from satellite data. The inverse modeling method has the potential to provide unique information on the vertical structure of volcanic clouds, which will lead to improved dispersion forecasts.

Multi-spectral infrared measurements can be used to retrieve the mean cloud radiative temperature, cloud emissivity, and cloud microphysical parameter. The mean cloud radiative temperature can be converted to a mean cloud radiative height using temperature profiles and/or lapse rate approximations. Unlike single channel cloud height approaches (e.g. 11 μm look-up), no assumptions concerning cloud opacity are made in multi-spectral approaches. Thus, multi-spectral approaches are more accurate. Comparisons to spaceborne lidar data indicate that the three-channel (11, 12, and 13.3 μm) version of the multi-spectral infrared technique of determining ash cloud height has an accuracy of <2 km for tropospheric clouds and <3 km for stratospheric ash clouds. The two channel (11 and 12/13.3 μm) version of the algorithm is less accurate than the three channel (11, 12, and 13.3 μm) version, but still more accurate than the single channel approach. The three-channel approach can be applied to current sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS), the Spinning Enhanced Visible and Infrared Imager (SEVIRI), while the two-channel approach must be used for all other current ash relevant imaging sensors, which lack the necessary channel combination.

The breakout group also recognized the importance of ash cloud height validation and characterization. Space-borne Lidars, such the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), which can detect cloud and aerosol layers with a vertical resolution of 60 m, can be used to validate other methods. Since June 2006, CALIOP has measured at least 10 ash clouds. Stereographically-determined ash cloud height products were also discussed. The Multi-angle

Imaging Spectro-Radiometer (MISR) standard products include cloud top heights at a spatial resolution of 1.1 km, and wind vectors on a mesoscale grid spacing of 70.4 km. The MISR Project has released the MISR Interactive Explorer (MINX) toolkit, which generates height and wind vector estimates at a spatial resolution of 275 m. The Advanced Spaceborne Emission and Reflection Radiometer (ASTER) products include stereo-based DEM's at a spatial resolution on 30 m. The DEM's are generated on-demand at the Land Processes DAAC (LP_DAAC at the USGS-EDC). Cloud shadow-derived heights are also useful for validating and characterizing other ash cloud height products. The breakout group also suggests that caution be used when interpreting direct, ground-based observations of cloud heights, as their accuracy is questionable.

The participants of this breakout session recommend that users should be trained on the use of ash cloud height information prior to operational use. The training should include basic information on the algorithm physical basis, accuracy, and limitations. Without proper training, there is a risk that ash height information may be misinterpreted.

Geostationary satellite coverage and instrument capabilities relevant to volcanic cloud remote sensing

A second topic of concern for the breakout group was the geostationary satellite capabilities available to each Volcanic Ash Advisory Centre (VAAC). An overview of the geostationary satellite capabilities is given in Table 1 as a function of VAAC. The table summarizes the temporal and spectral capabilities (those relevant to volcanic ash remote sensing) of each instrument that covers each VAAC area of responsibility. In addition, future geostationary satellite capabilities are summarized.⁵ The geostationary satellite spectral and temporal capabilities are clearly not homogeneous⁵. The SEVIRI instrument on the European Meteosat Second Generation (MSG) offers superior spectral, spatial, and temporal capabilities compared to the other geostationary instruments currently in orbit. SEVIRI provides full disk imagery every 15 minutes and the spectral measurements can be used to more accurately detect volcanic ash, more accurately retrieve the ash cloud height, mass loading, and ash cloud microphysics, and detect SO₂. Unfortunately, the SEVIRI spatial domain does not include the circum-Pacific "ring of fire."

Three Geostationary Operational Environmental Satellite (GOES) satellites provide coverage that roughly extends from the central Pacific to the eastern Atlantic. While the GOES satellites provide coverage for much of the western hemisphere, the temporal and spectral capabilities vary between satellites and regions. Beginning with GOES-12, the 12 µm channel was replaced with the 13.3 µm channel. This substitution greatly limits the effectiveness of the reverse absorption brightness temperature difference method of ash detection. More complicated and less accurate methodologies must be used to detect volcanic ash with the GOES-12, GOES-13, GOES-14, and GOES-15 satellites. In the traditional operational configuration, the GOES satellites provide coverage of the Southern Hemisphere only every 3 hours, which significantly impacts the operational capabilities of the Buenos Aires VAAC. In general recognition of the operational satellite needs of South American countries, NOAA will begin operating the GOES-12 satellite at 60oW longitude in June 2010. Once GOES-12 is stationed at 60oW, it will provide imagery of South America every 15 minutes. This is the second occasion that NOAA has moved a GOES satellite to 60oW for the benefit of South American countries. In 2007, NOAA positioned GOES-10 at 60oW. Unfortunately, after a long operational lifetime, GOES-10 was retired in December 2009 due to spacecraft problems.

⁵ Many VAACs supplement geostationary data, which has generally high temporal resolution, with multispectral polar orbiting data, such as AVHRR and MODIS data. These data have lower temporal resolution but generally higher spatial and spectral resolution.

The Japanese Multi-Functional Transport Satellite (MTSAT) series provides coverage of the volcanically and meteorologically active western Pacific. MTSAT provides imagery (including split-window information), every 30 minutes over the Northern Hemisphere and hourly in the Southern Hemisphere. While MTSAT does allow for traditional reverse absorption based ash detection (using the split-window brightness temperature difference), the hourly refresh rate for the Southern Hemisphere is not optimal for operational volcanic cloud monitoring. In addition, the interpretation of MTSAT imagery is complicated by instrument calibration uncertainties. The Feng Yun 2 (FY2) geostationary satellites, operated by the China Meteorological Administration (CMA), also provide coverage of the western Pacific and have similar spectral and spatial capabilities as MTSAT. Unfortunately, the utility of FY2D and FY2E is also hampered by instrument calibration and navigation uncertainties.

This overview has shown that current geostationary satellite capabilities vary from VAAC to VAAC. However, based on current plans, the United States, Europe, Japan, and China will be upgrading their geostationary capabilities in the 2015 – 2020 timeframe. The next generation of satellite instruments will offer SEVIRI like or better spatial, spectral, and temporal capabilities, resulting in more homogeneous operational volcanic cloud monitoring capabilities.

Finally, the participants of this breakout group recognize the importance of high spectral resolution infrared measurements in geostationary orbit and recommend that all geostationary satellite operators strongly consider including this capability on future geostationary platforms. Currently, Eumetsat (MTG), CMA (FY4A), and the United States (GOES-T) are **considering** hyperspectral infrared sounding capabilities for future satellites.

VAAC	GEO Satellite(s)	Temporal Refresh	Spectral Capabilities	Next Generation GEO Satellite
Anchorage	GOES-11	30 minutes	Split-window	GOES-R (2015)
Buenos Aires	GOES-12	15 minutes	No split-window	GOES-R (2015) and MTG (~2018)
	GOES-13	180 minutes	No split-window	
	MSG	15 minutes	Advanced	
Darwin	MTSAT	60 minutes	Split-window	GOES-R like from JMA (2020?) and FY4A from China (2014)
	FY2D	60 minutes	Split-window	
	FY2E	60 minutes	Split-window	
London	MSG	15 minutes	Advanced	MTG (~2018)
Montreal	GOES-11	30 minutes	Split-window	GOES-R (2015)
	GOES-13	15 or 30 minutes	No split-window	
Tokyo	MTSAT	30 minutes	Split-window	GOES-R like from JMA (2020?) and FY4A from China (2014)
	FY2D	60 minutes	Split-window	
	FY2E	60 minutes	Split-window	
Toulouse	MSG	5 or 15 minutes	Advanced	MTG (~2018)
Washington	GOES-11	30 minutes	Split-window	GOES-R (2015) and MTG (~2018)
	GOES-12	15 minutes	No split-window	
	GOES-13	15 or 30 minutes	No split-window	
	MSG	15 minutes	Advanced	
Wellington	MTSAT	60 minutes	Split-window	GOES-R like from JMA (2020?) and GOES-R (2015)
	GOES-11	180 minutes	Split-window	

Table: An overview of the geostationary satellite capabilities is shown as a function of Volcanic Ash Advisory Centre (VAAC). The table summarizes the temporal and spectral capabilities (those relevant to volcanic ash remote sensing) of each instrument that covers each VAAC area of responsibility. In addition, future geostationary satellite capabilities are summarized. Next generation satellites that include a hyperspectral sounding capability are shown in bold.

6.3 Science Steering Group Change.

The need for a better co-ordinated, multi-disciplinary research-to-operations implementation

Given the good representation of scientific and operational stakeholders at the meeting, and at the suggestion of Herbert Puempel (WMO), a breakout group explored the overall direction of the intercessional focus and work represented and enabled at the workshop in support of the IAVW operating under the auspices of ICAO.

It was noted that since the inception of the workshop a great deal of progress had been made in the science of identifying eruptions, modeling the ash dispersion and understanding the general dynamics of volcanic ash in the atmosphere. These advances had greatly assisted the VAACs, within the IAVW system, in their operational responsibilities to inform international civil aviation of the likely presence and trajectory of ash plumes and the issue of SIGMET by MWOs.

It was also noted that the amount of science now being done in the area, and represented at the workshop, was of such an extent and pace that the current WMO workshop and IAVW engagement arrangements needed to be reviewed.

In particular, the breakout group noted from Herbert Puempel's presentation that:

- Geophysical and vulcanological information was essential for:
 - Eruption risk assessment and forecast
 - Determining eruption source parameters
 - Estimate of residence time, deposition rates
- Meteorological know-how was necessary for:
 - Transport and dispersion modeling
 - Interaction with water cycle (wash-out, convection)
 - Remote sensing techniques and tools
- Aircraft technology information was necessary for:
 - Impact of different ash types, granularity, density
 - Determining thresholds for operability
- Aircraft Operations information was necessary for:
 - Required lead-times for warnings
 - Accuracy, resolution and reliability requirements

Future deliverables from the scientific community included for example (– not exhaustive):

- Eruption Source Parameters
 - Review of existing VAAC guidance and best practice
 - Gathering, evaluation and communication of emerging data and knowledge
 - Maintenance of web site/discussion forum as an open platform
 - Encouragement of dialogue between in-situ and remote sensing groups and institutions with a view to establish consensus on best (or combination of) techniques

- Ground-based detection methods
 - Establishment of a SWOT analysis for different techniques
 - Determine remaining gap for combined techniques
 - Liaison with Remote Sensing Community for observing /detection system integration
 - Documentation of best practices on web site / forum
- Remote sensing
 - Establish a SWOT analysis for existing sensors and platforms
 - For different regions (availability of geostationary platforms)
 - Timing of LEO overpasses
 - Cloud masking, ice coating of ash, SO₂
 - Formulate a consensus on timelines and expected capabilities of new sensors and platforms
 - Evaluate potential impact of emerging multi-spectral techniques on current gaps
 - Provide remote sensing guidance documentation for IAVWOPS site for VAAC/MWO staff training
- Aviation industry
 - Sharing information with airline operators, regulators and service providers (VAAC, MWO)
- Training
 - Support CAeM Expert Team on Training and Education /Task Team on the Competency Assessment Toolkit to define required competency for
 - Aeronautical meteorological forecasters (AMF) for briefing
 - AMF working in Meteorological Watch Offices with a responsibility to issue VA SIGMET
 - AMF working in a VAAC providing VAA
 - Advice for training institutions on state-of-the art techniques and methods

In light of the breadth of possible work and deliverables, the breakout group discussed at length the best means of steering the science for best efficacy in the aviation community. The science advisory nature of the relationship between ICAO and the WMO was noted and it was agreed that the role of steering the science development remained with WMO.

It was also noted that the operational requirements were set by ICAO, and specifically through the work of the IAVWOPSG. At present, there was a relatively wide request for assistance from the IAVW to the workshop and given the achievements and pace of scientific work as encompassed at the workshop, it was felt that the IAVWOPSG needed to have a more frequent and more detailed engagement with the science community represented at the workshop. It was agreed that under the present structure this could not be achieved with a 3-year meeting cycle of the workshop and the 18-month cycle of the IAVWOPSG.

From discussion earlier at the workshop, the breakout group noted that the view of the scientists was that they needed to focus on their particular area of expertise and development without the encumbrance of having to manage or take part in an overall approach or orchestration of global

scientific efforts in the field. They were otherwise pleased to receive advice on the direction of their work to ensure usefulness to the IAVW system.

After much discussion, the group proposed that:

1. A Volcanic Ash (VA) Science Steering Group (VASSG) be established under the auspices of the WMO, comprising no more than 5-6 key scientists representing the various science communities involved, and perhaps chaired by the WMO;
2. The work of the VASSG would be to receive requests for specific advice or assistance from each IAVWOPSG meeting, or intersessionally, and report to the IAVWOPSG on progress at each meeting or intersessionally as may be appropriate from time to time;
3. The VASSG would use its networks and contacts to allocate the prescribed science work amongst the international science community. That allocation would be documented along with estimates of timescale. This is expected to assist the VASSG ensure timely attention to any requests from the IAVWOPSG;
4. The various scientists would carry out the prescribed and any associated work and report progress and results to the VASSG, continue to meet in the ongoing WMO International Workshop on Volcanic Ash forum held every 3 years, and continue the dynamic global collaboration that is currently the practice;
5. The IAVW would receive the VASSG Report at each of its 18 month meetings and deliver back to the VASSG any requests for specific scientific assistance. The IAVWOPSG may also make requests to the VASSG intersessionally.

The group believed that the approach outlined above would provide a much more timely and dynamic method of co-ordinating the science developments with the changing needs of international aviation. It was also expected to give the scientific effort a level of credibility that would assist in securing funding for the various research and work programmes.

Appendix 1 – Participants

- Alvaro Amigo, Nacional de Geología y Minería de Chile, aamigo@sernageomin.cl
- Andrea Steffke, University of Hawaii at Manoa, steffke@higp.hawaii.edu
- Andrew Tupper, Darwin Volcanic Ash Advisory Center, a.tupper@bom.gov.au
- Arnau Folch, Barcelona Supercomputing Center, arnau.folch@bsc.es
- Bill Rose, Michigan Technological University, raman@mtu.edu
- Brad Scott, New Zealand Geological & Nuclear Sciences, b.scott@gns.cri.nz
- David Schneider, U.S. Geological Survey, djschneider@usgs.gov
- Domenico Patane, Istituto Nazionale di Geofisica e Vulcanologia, patane@ct.ingv.it
- Eliecer Duarte, OVSICORI-UNA, eliecerduarte@una.ac.cr
- Fred Prata, Norwegian Institute for Air Research (NILU), fpr@nilu.org
- Graham Rennie, Qantas Airways, grennie@qantas.com.au
- Herbert Puempel, World Meteorological Organization, hpuempel@wmo.int
- Ignacio Di Prospero, Airbus/LAN Chile, ignacio.di-prospero@airbus.com
- Jeff Osiensky, U.S. National Weather Service, jeffrey.osiensky@noaa.gov
- John Ewert, U.S. Geological Survey, jjewert@usgs.gov
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- Jose Huepe, Dirección General de Aeronautica Civil de Chile
- Jose Naranjo, Servicio Nacional de Geología y Minería de Chile, jnaranjo@sernageomin.cl
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- Mauro Coltelli, Istituto Nazionale di Geofisica e Vulcanologia, coltelli@ct.ingv.it
- Michael Pavolonis, National Oceanic & Atmospheric Administration, mpav@ssec.wisc.edu
- Myrna Araneda Fuentes, Dirección General de Aeronautica Civil de Chile
- Peter Lechner, New Zealand Civil Aviation Authority, lechnerp@caa.govt.nz
- Philippe Husson, Toulouse Volcanic Ash Advisory Center, philippe.husson@meteo.fr
- Raul Romero, International Civil Aviation Organization, rromero@icao.int
- Reinaldo Gutierrez, Dirección General de Aeronautica Civil de Chile, reinaldo@meteochile
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- Steven Albersheim, U.S. Federal Aviation Administration, steven.albersheim@faa.gov
- Ted Tsui, U.S. Naval Research Lab, ted.tsui@nrlmry.navy.mil
- Tony Hall, Anchorage Volcanic Ash Advisory Center, tony.hall@noaa.gov
- Vincent Realmuto, NASA/Jet Propulsion Laboratory, vincent.j.realmuto@jpl.nasa.gov

Appendix 2 – Agenda

MONDAY, 22 MARCH

8:30-9:30

WORKSHOP OPENING

Moderator: Luis Rossi (Directorate General of Civil Aeronautics of Chile)

Expression of Solidarity & Moment of Silence for Victims of the 2010 Chilean Earthquake

Official Welcome

Jose Huepe, Director, Directorate General of Civil Aeronautics of Chile

Volcanic Ash, Space Weather and Sand-and Dust Storm Advisories and Warnings as Scientific Challenges to WMO

Herbert Puempel, World Meteorological Organization

Role of the International Airways Volcano Watch Operations Group

Raul Romero, International Civil Aviation Organization

9:30-10:30

KEYNOTE TALKS

Moderator: Luis Rossi, (Directorate General of Civil Aeronautics of Chile)

An Overview of Chaiten Volcano and Highlights of the 2008 Eruption

Jose Naranjo, Chilean National Service of Geology and Minerals (SERNAGEOMIN)

Overview of Ash/Aircraft Encounter Data

Marianne Guffanti, U.S. Geological Survey and Intl. Union of Geodesy & Geophysics

Airline Costs of Operating in an Active Volcanic Environment

Graham Rennie, Qantas Airways

10:30-11:00 BREAK

11:00-12:00

PANEL: Science Challenges in Mitigating Volcanic-Cloud Risks to Aviation

Moderator: Andrew Tupper (Australian Bureau of Meteorology)

Panelists: David Schneider (USGS), Fred Prata (Norwegian Institute for Air Research)

12:00-1:30 LUNCH

1:30-3:00

PANEL: Industry Perspectives

Moderators: Graham Rennie (Qantas) and Ignacio Di Prospero (Airbus)

Panelists: Manfred Birnfeld (Airbus), Hans-Rudi Sonnabend (Lufthansa), Rafael Latorre (Pratt & Whitney)

3:00-3:30 BREAK

3:30-5:00

PANEL: Science Needs of Volcanic Ash Advisory Centres

Moderator: Jeffrey Osiensky (NOAA/National Weather Service)

Panelists: Philippe Husson (Toulouse), Tony Hall (Anchorage), Martina Suaya (Buenos Aires), Andrew Tupper (Darwin), Makoto Saito (Tokyo), Peter Lechner (Wellington)

TUESDAY, 23 MARCH

8:15-10:15

TALKS: Detection and Alerting For Volcanic Eruptions

Moderator: Brad Scott (New Zealand Geological & Nuclear Sciences)

- *Rapid Eruption Detection & Cloud Height Determination with Transportable Doppler Radar: David Schneider (USGS)*
- *Detecting Eruptions with World Wide Lightning Location Network: John Ewert (USGS)*
- *Detecting Large Volcanic Eruptions with Remote Infrasound Arrays: Andrea Steffke (University of Hawaii)*
- *Volcanic Plume Height Measured by Seismic Waves: Presented for authors by Larry Mastin*
- *Volcanic Ash Hazards at Turrialba Volcano, Costa Rica: Eliecer Duarte (OVSICORI)*
- *Forecasting & Monitoring Etna Volcanic Ash Clouds for Aviation: Mauro Coltelli (Istituto Nazionale di Geosifica e Vulcanologia)*

10:15-10:30 BREAK

10:30-12:00

TALKS: Detection and Tracking of Volcanic Ash & Gas Clouds

Moderator: David Schneider (USGS Alaska Volcano Observatory)

- *Ash Clouds in the Moist Tropics: Andrew Tupper (Darwin VAAC)*
- *Plume Tracker--Multispectral Thermal Infrared Remote Sensing: Vincent Realmuto (NASA/JPL)*
- *Advances in Automated Satellite Remote Sensing of Volcanic Ash: Michael Pavolonis (NOAA)*

- *Improved Forecasting of Transport of Volcanic Clouds Using Dispersion Modeling & Satellite Data: Fred Prata (NILU)*
- *Correcting Ash Retrievals for Presence of Interfering Species: Matt Watson (Univ. of Bristol)*

12:00-1:30 LUNCH

1:30-2:30

PANEL: Detection and Tracking of Volcanic Ash & Gas Clouds

Strengths and weaknesses (gaps), advances and new techniques

Moderator: Bill Rose (Michigan Tech. University)

Panelists: Fred Prata (NILU), Mike Pavolonis (NOAA), Matt Watson (Univ. of Bristol)

2:30-3:00 BREAK

3:00-5:00

TALKS: Atmospheric dispersion modeling

Moderator: Larry Mastin (USGS)

- *Eruption Source Parameters (ESP): Larry Mastin (USGS)*
- *The FALL3D Model: Arnau Folch (Barcelona Supercomputing Center)*
- *Volcanic-Ash Hazard Climatology for Icelandic Eruptions: Susan Leadbetter (UK Met Office)*
- *Size-Resolved Forecasting of Volcanic Ash Plumes: Ted Tsui (Naval Research Laboratory)*

WEDNESDAY, 24 MARCH

9:00-10:30

SCIENTIFIC QUESTION-and-ANSWER SESSION

Opportunity for speakers to present more detailed information & answer questions

10:30-12:00

SEMINAR: Transferring Science to Operations

Moderator: Peter Lechner (New Zealand Civil Aviation Authority)

- *Italian contingency plan for Etna volcanic clouds: Mauro Coltelli, (INGV)*
- *WMO training sub-group on volcanic ash: Herbert Puempel (WMO),*
- *Moving Products & Services from Research Concept into Operations: Steven Albersheim (FAA)*
- *Competency Training in the Darwin VAAC: Andrew Tupper (Australian Bureau of Meteorology)*
- *Management System for Operational Security: Claudio Pandolfi (DGAC)*

12:00-1:30 LUNCH

1:30-2:00

SPECIAL LECTURE: From Chaitén 2008 to the National Volcano Monitoring Network

Jorge Munoz (SERNAGEOMIN)

2:00-5:00

BREAK-OUT SESSIONS

Sessions on major topics identified by workshop participants. Scheduled at staggered times, so that people can participate in more than one. Each session picks a presenter.

THURSDAY, 25 MARCH

- Field trip to the International Air Show in Santiago
- Aerial trip to view Chile's southern volcanoes including Chaiten

FRIDAY, 26 MARCH

9:00-10:30

REPORTS from breakout sessions and discussion

Moderator: Peter Lechner, New Zealand Civil Aviation Authority

10:30-10:45 BREAK

10:45-12:00

WORKSHOP SUMMARY

Recent accomplishments; ongoing scientific efforts; promising new research directions.

Moderators: Raul Romero (ICAO), Herbert Puempel (WMO), and Marianne Guffanti (USGS)

Appendix 3 – Abstracts

1. Overview of Aircraft Encounters with Volcanic-Ash Clouds

Marianne Guffanti, U.S. Geological Survey, Reston, Virginia, USA

Volcanic-ash clouds are a frequent hazard to aviation on a global basis. Volcanic ash is present in the atmosphere at cruise levels virtually every day somewhere around the world because of a few long-lived eruptions (e.g., Tungurahua in Ecuador, Soufriere Hills in the British West Indies, Rabaul in Papua New Guinea) and many shorter-lived ones. An ash cloud eventually dissipates as ash particles settle out of the atmosphere, but the “safe” threshold concentration at which dispersed ash poses no harm to aircraft is not known. Accordingly, the consensus of the aviation community is that if an ash cloud can be discerned, visually by a pilot or on satellite images, it should be avoided. However, ash avoidance works imperfectly, and aircraft do inadvertently fly into ash-contaminated airspace. Based on an updated compilation of information on encounters of aircraft with volcanic-ash clouds, at least 126 incidents from 1953 through 2008 have been documented. Since 1973 when jet travel became prevalent, the annual frequency of encounters ranges from 0 to 21, with an average encounter rate of approximately 3 per year. Thirty-eight source volcanoes for the ash clouds have been identified, with size of the eruptions ranging from small, brief episodes to major, sustained events.

The documented encounters vary greatly in the severity of effects observed by flight crews during the encounters and of damages to the aircraft. A severity index has been developed, with 6 classes, ranging from 0 (minor sulfurous odor) to 5 (crash). Fortunately, no class 5 encounters have occurred; ten class 4 encounters (temporary engine failure) have occurred from 1980-2006. Of the 109 encounters for which a severity class could be assigned, 75 (~70%) were damaging (classes 2-4). Aircraft exposures to ash-cloud hazards (defined by ash concentration and time in cloud) not well constrained by the available data; however, the data do show that most damaging encounters have occurred within two days of ash-producing eruptive activity.

Not flying over volcanic areas is an unrealistic option in this modern, interconnected world, so how can the risk of encounters otherwise be reduced? (1) Improve eruption forecasting and reporting by reducing the number of volcanoes with no real-time, ground-based, geophysical monitoring and by directed research on explosive volcanism. (2) Improve remote-sensing methods to detect and characterize ash clouds more quickly and accurately with new sensors and improved algorithms). (3) Improve the accuracy of dispersion models, so that aircraft diversions and flight plans can be carried out more safely and efficiently. (4) Improve the content and dissemination of warning messages to pilots, dispatchers, and air-traffic controller about the occurrence of explosive eruptions and whereabouts of ash clouds. (5) Be vigilant about communication protocols, training, and hazard education. All of these aspects are being worked on by various groups worldwide, as evidenced by the broad-based participation in this international workshop.

2. Rapid Eruption Detection and Cloud Height Determination: Experience from the Initial Deployment of a Transportable Doppler Radar System for Monitoring the 2009 Eruption of Redoubt Volcano, Alaska

David J. Schneider, U.S. Geological Survey, Alaska Volcano Observatory, Anchorage, Alaska, USA

Richard P. Hoblitt, U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington, USA

The rapid detection of explosive volcanic eruptions and accurate determination of eruption-column altitude and ash-cloud movement are critical factors in the mitigation of volcanic risks to aviation and in the forecasting of ash fall on nearby communities. The U.S. Geological Survey (USGS) deployed a transportable Doppler radar during the precursory stage of the 2009 eruption of Redoubt Volcano, Alaska, and it provided valuable information during subsequent explosive events. We describe the capabilities of this new monitoring tool, present data that it captured during the Redoubt eruption, and compare it to satellite images and dispersion model results.

The volcano-monitoring Doppler radar operates in the C-band (5.36 cm) and has a 2.4-meter parabolic antenna with a beam width of 1.6 degrees, a transmitter power of 330 watts, and a maximum effective range of 240 km (130 nm). The entire disassembled system, including a radome, fits inside a 20-foot steel shipping container that has been modified to serve as base for the antenna/radome, and as a field station for observers and other monitoring equipment. The radar was installed at the Kenai Municipal Airport, 82 km (44 nm) east of Redoubt and controlled remotely from the Alaska Volcano Observatory office in Anchorage. This site is near a NEXRAD Doppler radar operated by the Federal Aviation Administration (FAA) which permitted comparisons with an established weather-monitoring radar system.

The USGS radar system detected all of the sixteen major ash-producing events of Redoubt that produced ash clouds at altitudes in excess of 10 km (32,800 ft) above sea level between March 23 and April 4. The radar system provided the capability to observe the developing eruption columns within minutes of onset. In many cases, it was possible to provide eruption notification to the FAA regional air traffic control center while the column was still ascending. Eruption cloud rise rate determined from the radar data ranged from about 35-40 m/s (~6,900-7,900 ft/min), resulting in ash clouds at aircraft cruise altitudes within approximately 4 minutes of eruption onset. Maximum altitude of the sixteen major events as determined by radar ranged from 12.6-18.9 km (~41,300-62,000 ft) above sea level. The radar data also serve to illustrate the inherent difficulties in accurately determining eruption cloud height using traditional methods such as cloud top temperature, and comparisons between ash dispersion models and observed cloud trajectory.

3. Detecting Explosive Volcanic Eruptions with the World Wide Lightning Location Network (WWLLN)

John W. Ewert, U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington, USA

Robert Holzworth, University of Washington, Seattle, Washington, USA

Angela K. Diefenbach, U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, Washington, USA

We report on correlation of lightning detected by the World Wide Lightning Location Network (WWLLN, see <http://wwlln.net>) with explosive eruptions world wide in 2008 and the 2009 eruption of Redoubt Volcano, Alaska, USA. We compared explosive volcanic activity worldwide compiled using data from the Smithsonian's Global Volcanism Program, volcano observatory reports, Volcanic Ash Advisory Center (VAAC) reports, and ancillary data sources with the entire catalog of WWLLN data for 2008 to determine the eruption-detection capabilities of the system. Duration and number of WWLLN lightning detections is positively correlated with eruption magnitude. Of 45 volcanoes that produced eruptions with Volcanic Explosivity Index (VEI) of 2–5 in 2008, ten volcanoes produced lightning detected by the WWLLN. The WWLLN detected lightning from all eruptions VEI 4 or larger (Chaiten, Chile; Kasatochi and Okmok, Alaska, USA), about half of the ~VEI 3, and a small fraction (two) of ~VEI 2 eruptions. Where eruption-onset times are well determined by seismic or remote sensing data, onset of lightning flashes occurred within 4 to 58 minutes. Lightning was detected from eruptions that produced ash clouds with heights that ranged from approximately 1–14 km above the vent, but most ash clouds were >9 km high. Detected eruptions covered a wide range of eruptive styles and product compositions. At least seven explosive eruptions that were not detected by the WWLLN also produced high ash plumes, but these typically were the result of short-lived discrete explosions. In 2008, the WWLLN consisted of about 35 networked stations that are used to detect and locate lightning in near-real time. Geographic distribution of stations is non-uniform and may account for the inconsistency with which smaller magnitude eruptions were detected.

The well-monitored 2009 eruption of Redoubt Volcano allows comparison of WWLLN data to well-constrained eruptive parameters. From 22 March to 4 April 2009, Redoubt produced a series of explosive eruptive events with a total magnitude of ~VEI 3. 480 flashes were detected by the WWLLN within 112 km of Mt. Redoubt associated with 16 of 19 explosive events. Eruptive column heights that produced lightning ranged from 4.3–16.5 km above the vent, which has an altitude of ~2.4 km a.s.l. The number of lightning detections per explosive event ranged greatly—from single flashes associated with two explosions on March 26 to 173 flashes for the 09:38 UTC explosion on 23 March. The average height of ash plumes associated with WWLLN-detected lightning was 3.6 km higher than plumes without associated lightning, but correlation of flashes with eruption durations measured by seismic or infrasound instruments is more random. Results of our investigation show that when used in conjunction with other monitoring information, the WWLLN can provide valuable corroborative data to aid in rapid detection of larger explosive eruptions globally.

4. Detecting Large Volcanic Eruptions with Remote Infrasound Arrays

Andrea M. Steffke, Infrasound Laboratory, Hawaii Institute of Geophysics and Planetology, SOEST, University of Hawaii at Manoa, Honolulu, USA

Milton A. Garces, Infrasound Laboratory, Hawaii Institute of Geophysics and Planetology, SOEST, University of Hawaii at Manoa, Honolulu, USA

David E. Fee, Infrasound Laboratory, Hawaii Institute of Geophysics and Planetology, SOEST, University of Hawaii at Manoa, Honolulu, USA

Atmospheric transport and dispersion models are routinely coupled with remote sensing techniques to track hazards to the aviation community created by volcanic ash plumes. Satellite remote sensing data is currently analyzed to determine eruption onset, duration and ash plume heights which are in turn used as input to the models. These methods are limited by the temporal resolution of satellite sensors, cloud cover, and large volcanic plumes that may obscure the vent after the eruption onset. Therefore more accurate constraints on the eruption onset and duration of eruptions are necessary for improved forecasting of volcanic plume dispersion. As a result of the Acoustic Surveillance for Hazardous Eruptions (ASHE) project we can now show how properly designed infrasound arrays may be used to detect the onset, duration and, in most cases, estimate the intensity of large volcanic eruptions. We show how infrasound signals collected at regional (<250 km) and teleseismic (>250 km) ranges aid in monitoring and hazard mitigation of volcanic eruptions.

Teleseismic infrasound data from the International Monitoring System (IMS) were acquired for the Kasatochi and Okmok 2008 eruptions. At least six IMS stations clearly recorded the 7-8 August 2008 Kasatochi eruption with IS53 (Fairbanks, AK), IS18 (Greenland), IS59 (Kona, Hawai'i) capturing the clearest signals. Three distinct eruption pulses were detected that correlate with satellite imagery collected during the eruption. Infrasound-derived origin times and durations of the eruption pulses are broadly consistent with those derived from satellite and seismic observations, although some discrepancies exist. Sustained VLP acoustic jetting signals have previously indicated tropospheric to stratospheric ash emissions (Garces et al., 2008; Fee et al., a in press; Steffke et al., in press). Preliminary results indicate the shape of the volcanic jetting spectrum resembles the man-made jet spectrum, and indicates sustained ash emissions into the atmosphere (Matoza et al., 2009). Similar jetting signals were also detected during the 12-13 July 2008 Okmok eruption, but were slightly less energetic and occurred at slightly lower frequencies. Utilizing infrasound-derived eruption onsets, durations and cessations can therefore constrain eruption parameters that are necessary for accurately monitoring and tracking volcanic plumes and therefore aid in hazard mitigation for the aviation community.

Regional infrasound data collected during the July 2006, August 2006 and February 2008 eruptions of Tungurahua Volcano, Ecuador were examined in detail. Satellite data were used to determine ash plume heights and eruption chronologies, and infrasound data accurately derived eruption onsets, durations and cessations. Infrasonic energy from sub-Plinian to Plinian eruptions is shown to correlate well with ash plume heights (as determined from satellite imagery) and indicates changes in eruptive styles. As observed in the Okmok and Kasatochi eruptions, acoustic spectra may be used to identify volcanic jetting and ash injection to aircraft cruising altitudes (Fee et al., b in press).

5. Volcanic Plume Height Measured by Seismic Waves

Stephanie G. Prejean, U.S. Geological Survey, Alaska Volcano Observatory, Anchorage, Alaska, USA

Emily E. Brodsky, University of California, Dept. of Earth & Planetary Sciences, Santa Cruz, California, USA

Volcanic eruptions produce seismic waves as material is ejected into the atmosphere. Empirical studies have suggested that the amplitude of seismic waves radiated during large volcanic eruptions generally scales with the height of an eruption column. Despite this, a direct calculation of the expected seismic wave amplitude based on physical models has not yet been successful. We use seismic data to infer the expected height of large eruptive columns based on a combination of existing fluid and solid mechanical models. In so doing, we introduce a model that connects a common observable, seismic wave amplitude, to the physics of an eruption column. The model performs well for plumes produced by the 2006 eruption of Augustine volcano and the 2008 eruption of Kasatochi volcano. These results are sufficiently encouraging that more work in this field is warranted. Use of the model holds promise for rapidly characterizing plume height and resulting ash hazards to aircraft based on seismic data. It would be a particularly useful tool for exploring eruption characteristics in remote environments where direct observation is often not possible, such as the volcanoes of the northern Pacific Ocean.

6. Volcanic Ash Hazards at Turrialba Volcano, Costa Rica: A Natural Drill That Calls for an Early Warning System

E. Duarte, Volcanological and Seismological Observatory of Costa Rica (OVSICORI), Universidad Nacional, Heredia, Costa Rica

E. Fernández, Volcanological and Seismological Observatory of Costa Rica (OVSICORI), Universidad Nacional, Heredia, Costa Rica

Turrialba (10°02'N, 83°45'W) is a 3,349-m high stratovolcano located at the SE end of the Central Volcanic Range, Costa Rica. The summit shows three EW-oriented craters (East, Central, and West). Since its last eruptive phase (1864–1866), the Central and West craters have displayed minor fumarolic activity, with outlet temperatures around 90°C. After 2001, seismic swarms, minimum ground deformation, and increased fumarolic activity occurred. From 2005 to 2010, new fumarolic vents opened between and within the Central and West craters, and along the western and southwestern outer flanks of the volcanic edifice. On January 5-6th, 2010 a phreatic episode produced several eruptions that opened a 60x20m wide vent on the SW inner side of the W crater. Fine particles were dispersed from the summit, along a narrow belt to the SW, some 40kms reaching the most populated area of the country: Central Valley.

Erupted material consisted of: submetric preexistent heavily altered blocks that stayed not far from the summit (less than 300m), decimetric pieces of similar material lie among the coarse blocks and large quantities of fine particles and sediments associated to the last phreato-magmatic period. Such particles (old ashes) carpeted natural forest patches, agricultural and dairy land up to urban areas.

Raised concern provoked rapid actions from the National Emergency Commission to the point of evacuation of people, cattle and domestic animals in a radius of 5kms around the volcano. A mixture of sandy and powdery tall plumes, also raised concern on the Civil Aviation authorities to the point of issuing several ashtams in order to avoid the affected aerial space. Although no incidents or encounters were reported this phreatic episode put into the national palette the almost forgotten topic of volcanic ash and aviation.

For at least 3 years personnel from OVSICORI-UNA has shown interest to local Civil Aviation authorities to carry out a formal agreement in order to provide rapid and valid information on the importance of volcanic ashes and their risk to aviation. In fact a punctual proposal was handed to some high rank officials with no success.

It is timely, after the January phreatic eruptions, to call the attention within the Civil Aviation International community to create conditions that promote preparedness and safety in Costa Rica. A (low cost) cuasi-early system was presented to Civil Aviation Authorities by the middle of year 2009 with no positive results. Despite the need of information about volcanic ash during and after the phreatic episode, Civil Aviation authorities do not show interest to coordinate and support valid academic and monitoring initiatives.

Recent volcanic ash near our International Airport requires interest and attention. January, modest ash plumes must be taken as a natural drill that can easily change into worst scenarios; any time, from any volcano.

7. The System of Forecasting and Monitoring of Etna Volcanic-Ash Clouds Aimed at Alerting and Minimizing the Hazard to Aviation

Mauro Coltelli, Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Catania, Catania, Italy

In the last 30 years Etna volcano produced many short-lived and two long-lived ash plume-forming eruptions that disrupted the operations of Catania and Reggio Calabria airports and caused severe problems to the air traffic in the central Mediterranean region. National Institute of Geophysics and Volcanology (INGV) is charged of the monitoring of Etna eruptive phenomena. It cooperates with the National Civil Protection Department, the National Agency for Civil Aviation (ENAC), the Air Traffic Control Company (ENAV) and the Italian Air Force for warning continuously the aviation authorities about the occurring of the ash cloud on Sicilian airspace and the ash fallout on Catania and Reggio Calabria airports. Starting from the ICAO-IAVW documents that prescribe a set of procedures for volcanic ash avoidance, a commission formed by the previous and other aviation organizations had developed a Contingency Plan for Catania and Reggio Calabria ATZ, CTR and airports named "Procedures for Flight Operations in presence of volcanic ash cloud". The INGV duty is to promptly alert the air traffic control for a correct management of the incoming and outgoing flights from the two airports near the volcano in case of a new explosive eruption or the detection of any precursor that may herald an ash plume-forming eruption. INGV is also engaged to forecast daily the ash cloud dispersal, in case of eruptions, on the base of some numerical models for two more likely eruptive scenarios.

In the last five years INGV develop and implement a system for forecasting and monitoring volcanic plumes of Etna. Monitoring is based at present on multispectral infrared satellite imagery received at high-rate from METEOSAT, ground-based visual and thermal cameras, a Doppler Radar for volcanic-jet monitoring and some ash fallout detectors. Forecasting is using a multi-model approach that is performed every day through a fully automatic procedures for: i) downloading weather forecast data from meteorological mesoscale models; ii) running models of tephra dispersal, iii) plotting hazard maps of volcanic ash dispersal and deposition for certain scenarios and, iv) publishing the results on a web-site dedicated to the Civil Protection. Simulations are based on eruptive scenarios obtained by analysing of field data collected from recent Etna eruptions. Forecasting is, hence, supported by plume observations carried out by the monitoring network. The forecasting and monitoring system was tested successfully on some explosive events occurred during 2006 and 2007, and during the Volcanic Ash Exercise of ICAO EUR/NAT in November 2009. Another test of the general organization and procedures reliability will be performed during this year after the Contingency Plan for Catania and Reggio Calabria ATZ, CTR and airports will be formalized by ENAC.

8. Ash Clouds in the Moist Tropics

Andrew Tupper, Bureau of Meteorology, Darwin, Australia
Rebecca Patrick, Bureau of Meteorology, Darwin, Australia

At the 4th International workshop on volcanic ash (Rotorua, New Zealand, 2007), comments made from Darwin VAAC included:

- relatively weak volcanic eruptions in the tropics can trigger deep tropospheric convection that transports volcanic material to 15-20 km
- relatively few mid-troposphere (~10 km) cloud heights are observed
- many of these clouds have a relatively small proportion of fine ash in the cloud (due to entrained water vapour enhancing ice content, the small size of many of these eruptions, the role of ice and liquid water in removing ash from the cloud)
- remote sensing of ash can be very challenging in these situations, although SO₂ can often be used as a cloud ‘tracer’.
- remote sensing and ground and pilot observation conditions demand a high level of cooperative data sharing to derive both good height estimates and estimates of the ash ejected during an eruption (which, by the logic above, will not correlate well with eruption height in the moist tropics).

The 2007-2010 period has been relatively quiet volcanically, but the events that have occurred have tended to reinforce the points above. Eruptions from Soputan, Indonesia, for the 2005-08, for example, have demonstrated each point, including large differences in ground and satellite height reports. A suspected high level plume from Karkar (PNG) volcano in November 2009 is thought to most likely have been meteorological convection aided by volcanic activity, and further Karkar activity early in 2010 reinforced the pressing need for reliable, systematic observations from the ground (in this case when a negative helicopter report was compared with visual villager observations). The next step towards IAVW reliability in the region will be detailed standard operating procedures that ensure all possible information is captured and shared to best advantage (also consistent with the Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters).

A definition of hazardous ash concentration and consistent standard operating procedures around high altitude, low ash content cloud also remains a very high priority, although the growing aviation industry concern about high Ice Water Content clouds as well as any SO₂ content might suggest that an ice-rich volcanic cloud should in any case be avoided.

9. Plume Tracker: A System for the Detection and Mapping of Volcanic Plumes with Multispectral Thermal Infrared Remote Sensing

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The Plume Tracker project is a collaboration between the Jet Propulsion Laboratory (JPL) and Geophysical Institute of the University of Alaska-Fairbanks (UAF). Plume Tracker will integrate tools for the detection and mapping of volcanic plumes behind a single user interface, with on-demand delivery of the image and ancillary data necessary to accomplish these tasks. The prototype version of this system will focus on MODIS data acquired for the Northern Pacific volcanoes monitored by the Alaska Volcano Observatory (AVO).

Plume Tracker will have three main components. The first component will feature automated plume detection based on Machine-Learning technology. The plume detection algorithm will exploit unique features in thermal infrared (TIR) spectra of plume constituents. We will enhance these spectral features through the application of the decorrelation stretch, which is based on a Principal Components analysis of scene statistics. The output from the plume detection component will be a map showing the locations of plume candidates, coded to indicate the confidence in the identification as a plume.

The second component will feature interactive tools for the evaluation of the candidate plumes via radiative transfer (RT) modeling. The presence of SO₂ in a plume, as detected in the TIR, will be taken as a confirmation of the volcanic origin of the plume. This component will be patterned after the MAP_SO₂ toolkit, which provides an interface to the MODTRAN RT model, together with tools for the visualization of the data input to MODTRAN and the resulting output.

The use of RT modeling to detect SO₂ requires knowledge of several environmental factors, including the plume height and profiles of atmospheric temperature and humidity. The third component of Plume Tracker will be a server that locates these data products automatically, based on the time and geographic location of the satellite scene under consideration. The source of atmospheric profiles will be the Weather Research and Forecasting (WRF) model, which is run twice per day at the UAF's Arctic Region Supercomputer Center. Each WRF run provides 100 to 120 hours of numerical weather forecast over the western Arctic at 18km grid spacing, with higher resolution over select forecast areas. The plume heights will be inferred through comparison of the MODIS imagery to the output from Puff, the UAF's volcanic ash tracking model. The Puff model is run every 3 hours for 14 volcanoes in Kamchatka, Alaska, and the Cascades (Mount St. Helens), using the most recent wind field predictions from WRF. We will set up custom runs of Puff for eruptions of volcanoes not on the current watch list.

We will illustrate the concepts behind Plume Tracker using data acquired during the recent eruptions of Sarychev and Augustine volcanoes. The sources of our TIR image data are the Moderate Resolution Imaging Spectrometer (MODIS) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). We will compare Puff model results to plume height estimates derived from Multi-angle Imaging Spectroradiometer (MISR) data. In addition, we will compare the WRF atmospheric profiles to those derived from Atmospheric Infrared Sounder (AIRS) data.

10. Advances in Automated Satellite Remote Sensing of Volcanic Ash

Michael J. Pavolonis, NOAA/NESDIS/STAR, Madison, WI, USA

Operational volcanic ash detection techniques used at the various Volcanic Ash Advisory Centers (VAACs) are generally qualitative and require manual analysis. Reliable, and automated, satellite-based ash detection techniques are few and far between due to the difficult nature of separating volcanic clouds from meteorological clouds and other non-volcanic features on a global basis. As such, globally applicable automated volcanic ash detection requires a combination of advanced spectral and spatial techniques. The spectral sensitivity to volcanic ash is improved by utilizing effective absorption optical depth ratios in lieu of brightness temperature differences. Further, volcanic ash clouds are composed of pixels of varying spectral uniqueness. A cloud object based ash detection approach allows pixels, within an ash cloud, that have the strongest spectral signature (e.g. the most spectrally unique pixels) to be used to detect the entire ash cloud. It will be shown that cloud object based volcanic ash detection can be used to issue accurate automated ash cloud alerts to VAAC meteorologists. In addition, an objective estimate of the cloud height, effective particle size, and mass loading is needed to help forecast ash cloud dispersion. These parameters can be retrieved using infrared radiances and volcanic ash microphysical models. We will present results from a fully automated, and globally applicable, optimal estimation technique used to retrieve these important parameters. All of the techniques described in this talk are utilized in an automated ash detection, retrieval, and alert system currently being transitioned to NOAA operations.

11. Improved Forecasting of the Transport of Volcanic Clouds Using Dispersion Modeling and Satellite Data

Nina Kristiansen, Norwegian Institute for Air Research, Kjeller, Norway

Fabrizia Buongiorno, Istituto Nazionale di Geosifica e Vulcanologia, Rome, Italy

Sabine Eckhardt, Norwegian Institute for Air Research, Kjeller, Norway

Fred Prata, Norwegian Institute for Air Research, Kjeller, Norway

Andreas Richter, University of Bremen, Bremen, Germany.

Petra Seibert, Inst. of Meteorology, Univ. of Natural Resources and Applied Life Science, Vienna, Austria

Andreas Stohl, Norwegian Institute for Air Research, Kjeller, Norway

To accurately predict the transport and fate of volcanic emissions, the vertical profile of the emissions is essential. An analytical inverse modeling method has been developed to estimate the vertical emission profile of sulphur dioxide (SO₂) emitted during a volcanic eruption. The method has been applied to the eruption of Jebel at Tair (Red Sea) in September 2007 and the eruption of Kasatochi (Alaska) in August 2008.

An analytical inversion method used to estimate the emission height profile makes use of satellite-observed SO₂ columns from various satellite instruments (e.g., AIRS, OMI) together with modelled SO₂ columns from the atmospheric transport model FLEXPART, which is based on Lagrangian physics. On the basis that particles are transported to different directions due to vertical wind shear, the modelled emissions from certain height levels will give a best match to the satellite observations, thus the method finds the emission profile with which the model can optimally reproduce the shape and horizontal position of the observed SO₂ plume. By minimizing the total difference between the simulated and observed SO₂ columns and also consider a priori information, the inversion method estimates the vertical emission profile.

The eventual goal of this work is to be able to better forecast the movement of hazardous volcanic clouds by using of satellite data together with dispersion modeling. Once the optimally estimated emission height profile has been obtained, there will be better accuracy in the vertical distribution and horizontal movement of the clouds forecast by the dispersion model. The combined use of a Lagrangian model with satellite data will also lead to improved products for VAACs. This work is part of a larger project – Support to Aviation for Volcanic Ash Avoidance (SAVAA) funded by the European Space Agency (ESA) – that is aimed at providing new data products to VAACs and other users.

12. Correcting Ash Retrievals for Presence of Interfering Species

I. Matthew Watson, University of Bristol, Bristol, UK

The inversion of satellite imagery, to retrieve burdens, masses and optical properties of volcanic emissions to the atmosphere, is confounded by the inevitable presence of multiple attenuating species. Spectral interference can come from either (i) other volcanogenics or (ii) ambient atmospheric constituents, or, most likely both. Most retrievals, until recently at least, consider only the presence of the single target species. This can lead to large errors when delimiting the burden and location of volcanic cloud componentry, and has been the subject of much discussion, particularly infrared retrievals of volcanic ash. The split window algorithm, or more accurately its application to volcanic ash cloud detection, was twenty years old last year. Often applied, and much maligned, the split-window algorithm has changed little since its first application, due primarily to radiometric limits on infrared satellite sensors. However, the advent of hyperspectral imagery, for example the Atmospheric Infrared Sounder (AIRS), has the capacity to improve our ability to detect and quantify ash. Although the trade off between spectral and spatio-temporal resolution is far too high a cost to make AIRS directly useful to aircraft hazard managers, it has the capacity to illuminate the validity of the multispectral split-window algorithm. In concert with a coupled plume-atmosphere radiative transfer model, hyperspectral data can be used to delimit failings in high temporal resolution retrievals. This can be done in three ways: (i) validation of multispectral data using near-coincident AIRS images, (ii) forward modeling of detection sensitivities to ash including composition, size and number density and (iii) quantifying the effects of environmental variables including background surface temperature and atmospheric water vapour content. The research can be used to provide insights into best practice for application of the split-window algorithm and to look forward to the next generation of IR-enabled research and meteorological platforms.

13. New Techniques and Technologies for Remote Sensing of Volcanic Ash and SO₂ Gas

Dr Fred Prata, Norwegian Institute for Air Research, Kjeller, Norway

Remote sensing is a valuable technology for monitoring volcanic hazards because it can be used at a safe distance and can provide quantitative information on the constituents of volcanic emissions. In recent years new sensors have become available that make real-time use of remote sensing data from satellites and from ground-based systems viable and affordable for use in operational monitoring and for research applications. When these data are combined with predictive models, new products can be generated and disseminated to users for use in forecasting the fate of hazardous volcanic clouds.

New techniques for measuring volcanic emissions from satellites and from a new range of imaging camera technologies are described. These include a new algorithm for detecting volcanic ash from satellite based high-resolution spectral measurements, and a new method for detecting boundary layer SO₂ from infrared satellite measurements. Two new imaging camera systems are also described. EnviCam is a multi-filter imaging SO₂ camera utilising UV light and is suitable for use during the daytime for monitoring emissions from volcanoes from distances of up to 5-10 km, depending on visibility. CyClops is a multi-filter imaging infrared camera that can measure both ash and SO₂ during the day or night and from distances of 10-20 km, depending on the water vapour structure and clouds. Both systems employ rapid sampling (1 Hz or greater), fast communications and can be operated from 12V low power supplies for field deployment or from a volcano observatory using mains power. The advantages and disadvantages of the two systems are compared and contrasted and the use of ground-based systems in conjunction with satellite-based information is emphasised.

14. Constraining Eruption Source Parameters to Improve the Accuracy of Ash-Cloud Model Forecasts

Larry G. Mastin, U.S. Geological Survey, Vancouver, Washington, USA

John Ewert, U.S. Geological Survey, Vancouver, Washington, USA

Marianne Guffanti, U.S. Geological Survey, Reston, Virginia, USA

René Servranckx, Canadian Meteorological Centre, Québec, Canada

Peter Webley, Geophysical Institute, University of Alaska, Fairbanks, Alaska

During eruptions, volcanic ash transport and dispersion models (VATDs) are used to forecast the location and movement of ash clouds in order to define hazards to aircraft and to communities downwind. Those models use input parameters, called “eruption source parameters” (ESPs) such as plume height H , mass eruption rate M , duration D , and the mass fraction m_{63} of erupted debris finer than about 63 μm , which can remain in the cloud for hours to days. Observational constraints on the value of such parameters are frequently unavailable in the first minutes or hours after an eruption is detected. Moreover, observed plume height may change during an eruption, requiring rapid assignment of new parameters. In the late 1990s, the International Airways Volcano Watch Operations Group (IAVWOPSG), a branch of the International Civil Aviation Organization, noted that limitations in our ability to constrain ESPs during an eruption limited the accuracy of VATDs as a hazard forecasting tool. In March 2007, the U.S. Geological Survey (USGS) convened a working group of about 20 participants in Vancouver, Washington (USA), to identify a method to improve the accuracy of real-time ESPs. Members included representatives of Volcanic Ash and Advisory Centers in Washington, D.C., Montreal, and Anchorage; the Air Force Weather Agency; and scientists with expertise in eruptive processes. As part of this effort, the group compiled observed parameters from three dozen or so of the world’s best documented historical eruptions, and examined relationships between ESPs as a function of the volcano type and magma chemistry (Mastin et al., *JVGR* 186:10-21, 2009; <http://esp.images.alaska.edu/index.php>). From this we classified eleven eruption types: four each for different sizes of silicic and mafic eruptions; submarine eruptions; “brief” or Vulcanian eruptions; and eruptions that generate co-ignimbrite or co-pyroclastic flow plumes. For each type we assigned source parameters. We then assigned a characteristic eruption type to each of the world’s 1500 Holocene volcanoes. These parameters can be used for real-time simulations in the event that no observational constraints are available. The product of this work (Mastin et al., USGS Open-File Report 2009-1133, 2009) was delivered to IAVWOPSG in September 2009. In October 2009, a committee of the working group met in Vancouver, Washington to assess the utility of this protocol in real-world situations and to identify improvements. The group concluded that, in order to be useful during eruptions, uncertainty in ESPs would have to be incorporated through, for example, modeling an ensemble of parameters. Changes in parameter values and uncertainty would also have to be modified as observations are acquired during an eruption. The ESP working group officially dissolved following delivery of the ESP product to IAVWOPSG; however, members continue to collaborate informally through development of ensemble models and improvement of assigned ESPs at particular volcanoes. The ESP effort also has been integrated into the work of the Tephra Commission of the International Association of Volcanology and Chemistry of the Earth’s Interior.

15. Modeling Volcanic Ash Transport Using FALL3D: Model Description, Validation Results and Future Perspectives

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Antonio Costa, Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy

FALL3D is a multipurpose and multiscale model for the dispersion of atmospheric particles based on an Eulerian formulation of the advection-diffusion-sedimentation equation. Time-dependent 3D wind fields and atmospheric variables are furnished by coupling off-line the model with prognostic, diagnostic or re-analysis meteorological data. Depending on the considered resolution, coupling can be with global (e.g. GFS, NMM-b) or mesoscale (e.g. NMM-b, WRF, ETA) meteorological models or with local-scale mass-consistent interpolators (e.g. CALMET). Different options exist for describing the source term (volcanic column), including a numerical solution of the equations based on the buoyant plume theory that allows for estimating the eruption rate from the observed eruption column height. The model can deal simultaneously with a wide spectrum of particle sizes (from lapilli to very fine ash) and inert gas aerosol components (e.g. H₂O or SO₂). Aggregation of fine ash during the transport, due to the presence of both ice and liquid water, can be also considered. This versatility allows the model to be applied for describing different processes as the proximal deposit or the features and the temporal evolution of volcanic ash clouds. Model outputs include ground load (deposit thickness), airborne concentration, ash concentration at selected flight levels, column mass and Aerosol Optical Depth (AOD). Model outputs are written in NetCDF format, which allows subsequent automatic map production in multiple formats, including GIS layers and GoogleEarth overlays.

Here we focus on the use of FALL3D to forecast volcanic ash clouds and fine ash fallout at large distances (relevant to airport disruption), including expected thickness and accumulation rates. We also present a comparison between model results and Multi-angle Imaging SpectroRadiometer (MISR) data and Moderate Resolution Imaging Spectroradiometer (MODIS) retrievals for the 2001 and 2002 Mt Etna plumes. MISR allows a 3D reconstruction of the cloud geometry. MODIS retrievals give volcanic ash cloud mass and AOD. Finally, we overview the use of FALL3D in different on-going research projects which involve its implementation at the VAAC of Buenos Aires (Argentina), in the CYTED Latin-American Network, and as part of ATMOST, a Spanish national research project on massive parallelism.

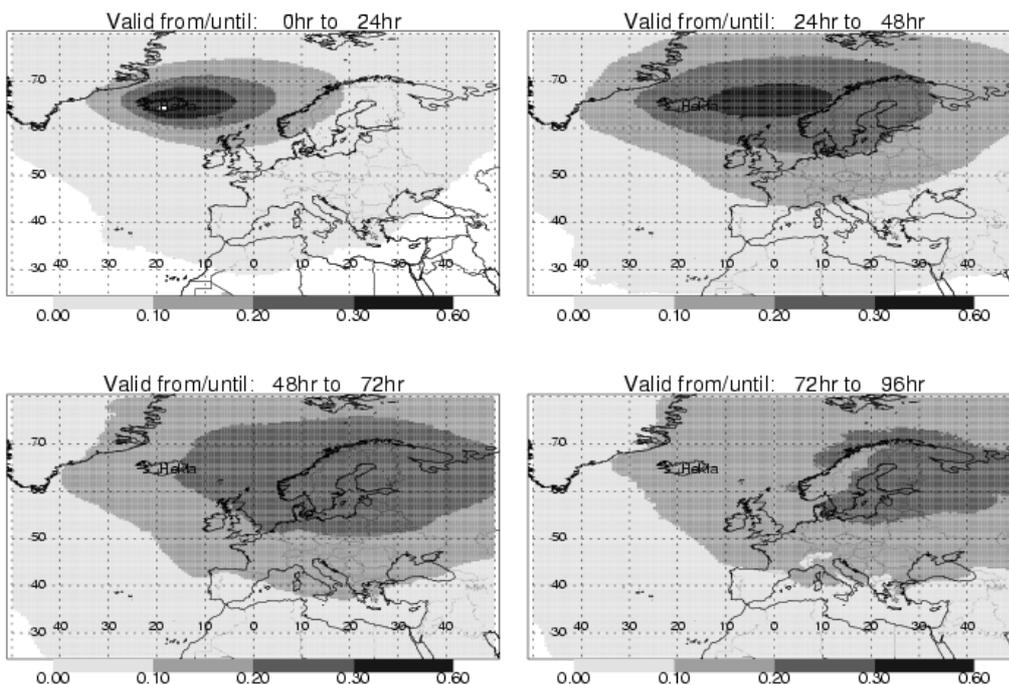
16. A Volcanic Ash Hazard Climatology for Icelandic Volcanic Eruptions

Susan Leadbetter, Met Office, Exeter, United Kingdom

Matthew Hort, Met Office, Exeter, United Kingdom

Ash produced by a volcanic eruption on Iceland can be hazardous for both the transatlantic flight paths and European airports and airspace. In order to begin to quantify the risk to aircraft, this study explored the probability of ash from the eruption of a typical Icelandic volcano (Hekla, 63.98°N, 19.7°W) reaching European airspace. Transport and dispersion of the ash cloud from a three hour 'explosive' eruption with an initial plume height of 12km was simulated using the Met Office's Numerical Atmospheric-dispersion Modeling Environment, NAME III, the model used operationally by the London Volcanic Ash Advisory Centre. Eruptions were simulated over a six year period, from 2003 until 2008, and ash clouds were tracked for four days following each eruption.

Results showed that a rapid spread of volcanic ash is possible, with all countries in Europe facing the possibility of a significant air concentration of ash within 24 hours of an eruption. An additional high impact, low probability event which could occur is the southward spread of the ash cloud which could block transatlantic flights returning to Europe. Probabilities of significant concentrations of ash are highest to the east of Iceland, with probabilities exceeding 20% in most countries north of 50°N (see figure below which shows the probability of significant ash concentrations between surface and FL550 in the four days following an eruption in Iceland). There is some seasonal variability in the probabilities. Ash is more likely to reach southern Europe in winter when there are stronger northerly winds across the continent. In summer, ash concentrations over Europe remain high for longer because the mean zonal wind speeds are lower. Although limited to one eruption type and size, this study provides a benchmark for the probability of ash incursions to European airspace.



17. Size-Resolved Forecasting of Volcanic Ash Plumes

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Ted Tsuii, and Naval Research Laboratory, Monterey, CA, USA

Hway-Jen Chen, Naval Postgraduate School, Monterey, CA, USA

The Naval Research Laboratory has adapted the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) to model the transport of volcanic ash and sulfur dioxide emitted from volcanoes. The model is applied to the Kasatochi eruption of August 7, 2008 as a test of the model's ability to forecast ash transport, to understand the injection scenario, and to help explain the complicated transport pattern that developed downwind.

COAMPS has a fully embedded aerosol microphysical module (i.e. it has an in-line module that uses the exact modeled meteorological fields at each time step and grid point.) It solves the mass conservation equation including the effects of production, transport, sedimentation, coagulation, and wet and dry deposition. In this application, the model has two nested grids with 5 and 15 km horizontal resolution with the domains centered just east of Kasatochi. The model is initialized with global weather data on 0000 UTC, Aug. 5 and run 60 hours with data assimilation every 12 hours to develop realistic mesoscale features.

Infrasound data from Alaska, Hawaii, and Japan suggests there were four separate eruptions between 2214 UTC, Aug. 7 and 0902 UTC, Aug. 8, with a possible fifth eruption at 1200 UTC, Aug. 8. Pilot reports, satellite imagery, and other information are gathered and processed by the AVO, Anchorage VAAC, and the NWS and reported by the NWS to the aviation community as SIGMETs. For Kasatochi, the SIGMETs reported the ash top at 39,000 ft with the base at the surface or, in some areas, unknown. Following the eruption, the data from the ground-based MPL and spaceborne CALIPSO lidar show the volcanic ash between 5 km and 18 km. It is likely the injection penetrated the stratosphere since the tropopause height was 12.3 km at Cold Bay. During the 36-h forecast cycle beginning at 1200Z Aug. 7 ash is injected at each model level between 300 m and 20 km for the four periods identified by the infrasound data.

At 17:09 UTC on Aug 8, the ash cloud is clearly evident in the split window analysis of the AVHRR scene. A low pressure system was located just east of Kasatochi at the time of the eruptions and the ash is transported cyclonically around the low during the first 12 to 18 hours. The diameter of the arc is 450 km, travelled in 20 hours, for an approximate transport speed of 10 m/s, in agreement with tropospheric winds of 9 to 15 m/s at nearby Cold Bay. Stratospheric winds are weak and generally below 3 m/s.

The COAMPS simulation of total ash mass load shows good agreement with this cyclonic pattern. In particular, the four injections produce four discrete maxima in the simulated mass load that possibly explain the local maxima observed in the split window imagery. We note, however, that in the split window imagery, the ash plume reaches back to Kasatochi at 1700 UTC, Aug. 8, whereas in the simulation the head of the ash plume is some 100 km downwind of Kasatochi. This suggests that a fifth injection at 1200 UTC, as suggested by the infrasound data, is likely.

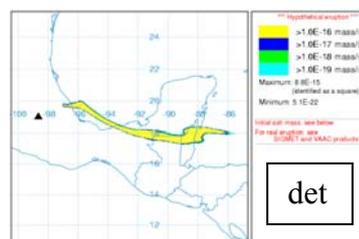
http://www.nrlmry.navy.mil/aerosol/Case_studies/20080807_kasatochi/

18. Ensemble Dispersion Modeling

Barbara J.B. Stunder, NOAA Air Resources Laboratory, Silver Spring, MD, USA

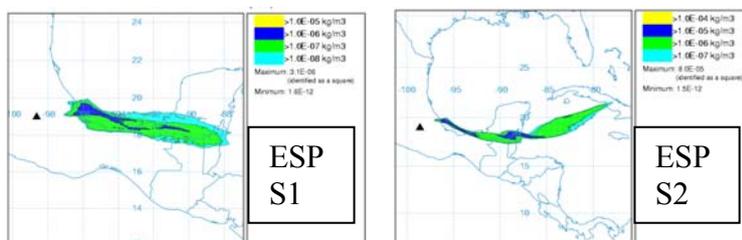
The NOAA Air Resources Laboratory has modified its “Volcanic ash cloud forecasts for hypothetical eruptions” web site <http://ready.arl.noaa.gov/ready2-bin/ashhypo.pl> to include ensemble forecasts using (a) the eruption source parameters (ESP, Mastin et al., 2009), and (b) a meteorological offset (Draxler, 2003). Ensembles are used in weather forecasting to assess some of the meteorological model uncertainty. The ensemble concept can be applied to dispersion – here specifically (a) through the ESP, and (b) through the meteorological model. Dispersion model output from these ensemble simulations can be used for planning purposes to estimate the effect of various model inputs compared to the output from the traditional deterministic simulation. These products are intended for meteorological forecasters (e.g. at the Volcanic Ash Advisory Centers) rather than end-users.

At the above web site, “Run 1” is the traditional deterministic (det) run using a unit source of mass (e.g. 1 kg), a 12-km high initial eruption column, and a 1-hour eruption duration. The contours correspond to the large-medium-small-default ash reduction levels in the NOAA HYSPLIT volcanic ash dispersion model output product. If the mass of the eruption of the ash particle sizes modeled is known, the forecast concentration can be computed by multiplying the given output concentration by the eruption mass. The example to the right is the 18-h forecast from a hypothetical eruption of Popocatepetl, Mexico, 00 UTC March 4, 2010.

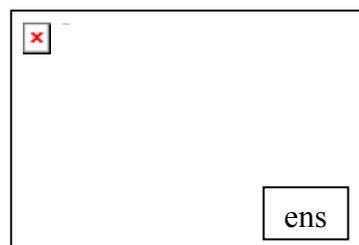


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“Run 2” is the ESP ensemble, showing output from the small (S1, assigned for Popocatepetl, shown), medium (S2, shown), large, and as appropriate brief, eruption types. The title at the top of each plot online states the assigned ESP for the volcano. The ESP mass is used and so the forecast concentration values differ from the non-ESP runs, which use a unit mass. For the medium scale Popocatepetl case shown, the ash plume goes much farther downwind compared to the small scale case.



“Run 3” is the meteorological offset ensemble (ens) in which data from one meteorology model are used for all 27 members of the ensemble. The “control” run uses the meteorology as provided, but for the other 26 members, the meteorology is offset in the horizontal and/or vertical to test the sensitivity of the calculation spatially varying meteorological conditions. Other model inputs are the same as for “Run 1”. Statistical plots from the ensemble are provided on the web page as a means to more readily interpret output from 27 simulations. For example the plot to the right shows the number of ensemble members. A forecaster would be more confident of ash occurring in the small, inner region (>15 members) than the outer region (1-5 members).



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19. Competency Training and Assessment at Darwin VAAC

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Michelle Hollister, Bureau of Meteorology, Melbourne, Australia

Andrew Tupper, Bureau of Meteorology, Darwin, Australia

Following steady progress in developing training materials and a sharper focus on well-defined operational procedures during the period 2002-09, an intensive competency training project was conducted during December 2009 to February 2010. Key motivations for this were:

1. Saving lives: Adequately trained forecasters are more likely to detect volcanic clouds and follow the appropriate procedures to provide timely warnings to aviation
2. Progress towards ISO 9001:2008. ISO requires that staff be competent (performing to an agreed standard) “on the basis of education, training, skills and experience”, and we need to have documented proof of their level of competence.
3. Assessment allows management to determine whether current training methods are adequate

The usual method of training in the VAAC has been on-the-job (‘dualling’) training in public weather, marine and aviation forecasting which incorporates work in the VAAC. This dualling period is usually 4-5 months for new meteorologists, or may be as little as one month for an experienced meteorologist that is new to the Darwin office. This training is supplemented by annual Volcanic Ash refresher training provided by the VAAC Manager.

In the new ‘Blended Learning’ paradigm, a key consideration was ‘Authenticity in Assessment’ (ensuring the method used for assessment gives an accurate reflection of the knowledge and abilities the candidate would demonstrate in an operational environment). The strategies used were:

1. Self-learning by reading resources (e.g. procedural Directive)
2. Written quiz questions (to assess knowledge, and allow identification and self-awareness of any training gaps)
3. Short training sessions on satellite detection techniques (NIR, Split Window, SO₂)
4. Workplace observation (to assess satellite monitoring ability, attention to alerts)
5. Partly timed case study exercise for a real high-level ash cloud event (to assess speed of reaction to information, correct process in an event)
6. Exercises on satellite detection and issuing SIGMET
7. Oral questioning (to confirm critical knowledge without access to written resources)

The results were revealing and in some cases challenging. Difficulties encountered included developing the training resources to a sufficient standard, defining appropriate standards to assess against, consideration of how forecasters who didn’t attain the required statement should be treated, considering the standard to which supervisors should be assessed, and dealing with the considerable logistical challenges of the exercise. In general, the best performed forecasters were those who had several years experience, and therefore greater likelihood of having been exposed to a *high level* event in operations, and those who had benefited from a longer dualling period.

20. Desafíos en la Aplicación de un Sistema de Gestión de Seguridad Operacional (SMS-SSP)

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En la actualidad estamos un punto de inflexión operacional, que junto a la aplicación de herramientas de las tecnologías de la información y comunicación (TIC's) y que bajo una estrategia de seguridad operacional *del tipo Predictiva* permitirá gestionar de modo más eficiente nuestros niveles de seguridad Operacional, logrando un nivel aceptable de riesgos operacionales o ALoS y con ello un nuevo estándar de aplicación para un Sistema de Gestión de Seguridad Operacional (SMS) en cada uno de los niveles operacionales en el cual tenemos un grado de responsabilidad. Esta es la experiencia en la introducción del SMS en un sistema aeronáutico de regional, el cual opere bajo la interacción del Programa de Seguridad Operacional del estado o SSP. Este desafío va transitando desde el modelo tradicional hacia una visión sistémica en la aplicación de las herramientas requeridas para la aplicación del SMS y su interacción con el programa de seguridad operacional de Estado o SSP, el cual esté en concordancia a las exigencias del siglo XXI, donde los fenómenos naturales nos sorprenden y nos invitan a meditar, una respuesta a estas inquietudes es actuar en forma coordinada ante las acciones de una erupción Volcánica, en especial en nuestro país con una gran plataforma en este sentido.

21. Federal Aviation Administration Examination of Space Weather and Volcanic Ash for Aviation

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Briefing is provided on the process that the Federal Aviation Administration follows to bring research into operations. The process described is generic for the development and introduction of any new product to be used by controllers, pilots, and dispatchers. In particular this paper will illustrate the work underway within the FAA for volcanic ash and space weather. Development of operational requirements for space weather is new to the National Airspace System and follows a different path than operational products for volcanic ash (VA). The FAA has already defined products for VA, but is in the process of conducting a gap analysis to scrub the existing services to define specific performance parameters that will be required in support of NEXTGEN's vision of meteorological services and the information that will be required for decision support tools. The briefing also makes comment of the importance of the further defining performance parameters to mitigate the costs to industry from ash encounters. The FAA plans to share the development of operational requirements for space weather and the gap analysis for volcanic ash with the International Civil Aviation Organization and the World Meteorological Organization for the purpose of improving the quality of information that is currently provided by National Meteorological and Hydrological Service providers and by the World Organization of Volcano Observatories in support of aviation.