
7th INTERNATIONAL WORKSHOP ON VOLCANIC ASH

“Science into operations, now and into the future”

Anchorage, Alaska, USA, 19-23 October 2015

Convened by the World Meteorological Organization,

in collaboration with the International Civil Aviation Organization

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Workshop report



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1. INTRODUCTION

The workshop, 'Science into Operations, Now and into the Future' was opened at 09.00 at the Atwood Center, Alaska Pacific University, Anchorage, Alaska, United States. The nearly 100 delegates were informed that the aim of the workshop was the improvement of the scientific aspects of the International Airways Volcano Watch including:

- The understanding and use of ground-based volcanic monitoring;
- Detecting, analysing and tracking volcanic clouds;
- Forecasting ash cloud dispersion.

The workshop was pleased to recognize the long and distinguished service of Grace Swanson, VAAC Washington, on the occasion of her imminent retirement. As Washington VAAC manager and a long-time satellite analyst, Ms Swanson has made an immense contribution to volcanic ash and aviation safety.

2. DAY 1: "THE PARTNERSHIP BETWEEN SCIENCE AND AVIATION"

The first day of the workshop was devoted to overview presentations and panel discussions that focussed on perspectives of different players, in particular members of the aviation industry, and VAACs.

2.1 Overview Presentations

Following introductions, the day began with three overview presentations. Andrew Tupper, head of the Australian Bureau of Meteorology's National Operations Centre, gave an overview talk entitled "[Case Studies that Illustrate the Hazard](#)", in which he described some critical, well-studied aircraft encounters, where they occurred, what damage was sustained, and the circumstances that brought the aircraft and ash cloud together. Andrew Tupper emphasized the twin motivations of safety and efficiency in the development of the International Airways Volcano Watch, and cautioned the volcanic ash community to not rest on its laurels despite the successful avoidance of catastrophic encounters so far.



This was followed by the presentation "[A History of Ash Avoidance](#)", by Thomas J. Casadevall, U.S. Geological Survey (emeritus), who investigated the early, well-documented encounters, including the KLM 4-engine flameout near Redoubt volcano in 1989, and who helped establish the International Airways Volcano Watch as well as the VAAC infrastructure. Thomas Casadevall explained the development of our understanding of how ash damages aircraft, the database of historical encounters, and photos of damage to aircraft and engines following encounters of the past half century.

Figure 1 - The Crew of KL 867 inspecting the damage of their Boeing 747-406M (Registration PH-BFC) which encountered the ash cloud from Mt Redoubt in Alaska in December 1989 (source: wiki-commons)

The final talk was given by Matthew Hort, head of the dispersion modeling group at the U.K. Met Office. Entitled "[How the Eyjafjallajökull crisis influenced developments in volcanic ash forecasting science](#)", Matthew Hort explained how the Eyjafjallajökull crisis radically altered the European aviation regulatory framework; caused EU states to reconsider their assessment of volcanic hazards; and arguably 'kick started' a resurgence in research, development and services linked to monitoring and predicting volcanic ash and gas hazard forecasting for aviation. That brought together diverse communities to address this multi-disciplinary challenge, with several workshops aimed at joining research with operations, and numerous dedicated conference sessions.

2.2 Aviation Industry Perspectives: Challenges in managing aviation risk from ash hazards

This session consisted of a panel discussion involving expert representatives from United, Delta, Pratt & Whitney, Rolls Royce, Qantas, Boeing and Alaskan Airlines. During their discussion they highlighted the following main points:

- a) New two-engine aircraft types mean that there are now flight times of up to 19-hours that require rapid harmonization of diverse information about changing volcanic activity.
- b) The burden on airline operators is to perform dynamic risk assessments, including during the pre-eruptive phase.
- c) Finding the right balance between ensuring safety of flight (recognizing and avoiding hazardous airspace) and implementing efficiency of flight (minimizing unnecessary diversions and re-routing) is an ongoing challenge.
- d) More funding is needed to better support volcano monitoring activities and associated pre-eruption risk assessments. More engine testing (actual and with model simulation) is required to better characterize the hazard posed to jet engines by ash.

2.3 VAAC Perspective: How the VAACs are working together to better meet the aviation industry expectations

During this session, the 9 VAAC representatives collectively delivered an overview of their collaborative activities. The VAACs had a major Best Practice meeting earlier during 2015, and a shorter meeting immediately prior to the Workshop, which had been hosted by VAAC Anchorage. Short presentations were given on the following topics:

- a) VAAC collaboration activities including the development of a common website;
- b) Volcanic Ash Advisories – How the VAACs use the 'Discernible Ash' definition to draw their lines now and in the future;
- c) Volcanic Ash Advisories – Introducing confidence assessments;
- d) Monitoring volcanic ash with the next generation of satellite platforms;
- e) Future priorities and plans for VAAC best practice.

It was reaffirmed that VAAC best practice is, as previously defined by the International Volcanic Ash Task Force, the "expert evaluation of the best available sources of meteorological and volcanological information i.e. qualitative and quantitative satellite data, model output, ground and airborne based in-situ and remotely sensed observations and pilot reports using collaborative approaches to derive authoritative, high quality, evidence-based and globally consistent analysis and forecasts".

To support the implementation of best practice, a set of priority activities was agreed and these can be found in the meeting report at https://www.wmo.int/aemp/sites/default/files/VAAC_BP_Report_FINAL.pdf.

3. DAYS 2-5: SCIENTIFIC AND TECHNICAL THEME SESSIONS.

Tuesday through Friday, the meeting focussed on four scientific themes: (1) modeling; (2) remote sensing; (3) engine tests and aircraft encounters; and (4) new methods to detect and measure eruptions. For each theme, part of a day was devoted to scientific presentations, followed by a one-hour panel discussion. At the conclusion of the meeting, breakout groups met for 1.5 hours to discuss and list the five greatest advances in these themes since 2010, and the five biggest challenges. The main findings of each theme are given below. In addition, a very successful poster session was held on the Wednesday night, covering all the science themes and giving attendees the chance to discuss topics at depth. Tours were also held of the Alaska Volcano Observatory and (virtually) of the Anchorage VAAC, which enabled participants to examine and discuss operational practices.

3.1 Modeling

Modeling talks focussed on modeling advances since the 2010 Eyjafjallajökull eruption and the challenges of moving those advances into the operational realm. Matthew Hort of the U.K. Met Office presented "[Modeling innovations at the London VAAC](#)", emphasizing changes to modeling techniques and practices at that key VAAC since that eruption. Talks by Barbara Stunder (NOAA), Sara Barsotti (IMO), Arnau Folch (Barcelona Supercomputing Centre), Dov Bensimon (Montreal VAAC), and Hans Schwaiger (USGS Alaska Volcano Observatory) followed with advances to modeling and its operational implementation at the Washington VAAC, Icelandic Met. Office, Buenos Aires VAAC, Montreal VAAC, and Alaska Volcano Observatory. Yujiro Suzuki of the Earthquake Research Institute of Tokyo followed with results of a worldwide Intercomparison of volcanic plume models. Meelis Zidikheri introduced an inversion technique that relies only on 'binary' (presence or not of ash) input from the satellite analyst. Finally, Nina Iren Kristiansen of the Norwegian Institute for Air Research presented results of model simulations that constrain the concentration of volcanic ash encountered by a passenger jet during the February 2014 eruption of Kelud Volcano, Indonesia.

The following table summarizes results of the breakout session, listing the biggest modeling advances since 2010, and the biggest challenges. Items in bold are among the top five:

ADVANCES SINCE 2010	CHALLENGES
TOPIC 1: Plume (source term) characterization	
<ul style="list-style-type: none"> • Inverse modelling for source term (fine ash only) • Use of pre-defined ESPs • TOTAL Mass eruption Rate (MER) characterization from plume height and wind 	<ul style="list-style-type: none"> • Quantify entrainment coefficients for 1D buoyant plume theory models • Gravity current modelling (umbrella cloud)
TOPIC 2: Model physics, performance and accuracy	
<ul style="list-style-type: none"> • Inter-comparison exercises of plume and dispersal models • Increased use of multiple models (small ensembles) to characterize forecast uncertainty • Modelling volcanic SO₂ 	<ul style="list-style-type: none"> • Data assimilation/inverse modelling for plume (ESPs) and virtual sources (far-range) • More validation and model sensitivity studies • Near-source processes including ash aggregation and turbulence in the plume • Development of and access to well-characterized datasets for model validation

TOPIC 3: Operations	
<ul style="list-style-type: none"> • Quantitative operational outputs and model validation 	<ul style="list-style-type: none"> • Bring probabilistic forecasts into operations and communication of probabilistic products • Determination of PDFs for ESPs. • Bring scientific advances into operations (VAACs)
TOPIC 4: NWP and dispersal coupling	
<ul style="list-style-type: none"> • On-line modelling, e.g. explore coupling and feedback effects 	<ul style="list-style-type: none"> • On-line coupling of plume/cloud with atmospheric processes • Utilizing NWP to its full resolution (i.e. increase dispersal model resolution)
TOPIC 5: Ash re-suspension	
<ul style="list-style-type: none"> • Experimental operational setups 	<ul style="list-style-type: none"> • Develop ash re-suspension emission schemes (currently we use dust schemes)
TOPIC 6: Others	
<ul style="list-style-type: none"> • Improved links across different communities 	<ul style="list-style-type: none"> • Training for VAAC and VO staff

It was suggested that two working groups could be established to: (i) To develop better model validation datasets and (ii) further explore probabilistic modeling and communicating probabilistic model output

3.2 Remote Sensing

The first talk of this session, given by Mike Pavolonis (NOAA/NESDIS), described results of the first worldwide intercomparison of satellite-derived volcanic ash retrieval algorithms. The WMO [Sustained Coordinated Processing of Environmental Satellite Data for Nowcasting](#) (SCOPE)-Nowcasting group lead the intercomparison activity. This intercomparison of 22 different ash-detection and characterization algorithms found that estimates of mass loading from the various algorithms generally agreed to within about a factor of four. However, ash detection capabilities varied significantly, where only a few approaches were shown to automatically detect ash consistent with a human expert analysis. Most detection algorithms had a detection threshold of about 0.2 g/m² or lower and all algorithms performed worse in scenes containing two or more cloud layers. The intercomparison presentation was followed by presentations by Kenneth Holmlund (standing in for Rosemary Munro) and Peter Francis, describing satellite-based, ash detection and characterization algorithms developed by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) and the U.K. Met. Office respectively. These talks illustrated that EUMETSAT and the U.K. Met. Office have made significant progress over the last several years on developing satellite-based volcanic ash products for operational applications, and additional developments are expected in the coming years. Dirk Engelbart of the German Federal Ministry of Transport described efforts in Germany to derive unique information on volcanic ash layers using a combination of ground-based measurements and modeling. Dirk Engelbart also emphasized how the combination of ground-based observations and modelling can enhance VAAC operations. The next presentation was given by Yuta Hayashi of the Japanese Meteorological Agency (JMA), who described how the new Himawari-8 geostationary satellite is enhancing volcanic cloud tracking and characterization. Himawari-8 is the first in a series of next generation geostationary satellites that will be launched by operational agencies in the next 5 years. Next, Estela Collini (Servicio Meteorologico Nacional) showed that high-level volcanic ash re-suspension events are common within the Buenos Aires VAAC region of responsibility. The re-suspension events are sometimes difficult to distinguish from new eruptive activity and must be modelled differently in order to produce a reasonable dispersion forecast. Simon Carn

(Michigan Technological University) then described how ultra-violet sensors on the *Aqua*, Suomi National Polar-orbiting Partnership (NPP), and Deep Space Climate Observatory (DSCOVR) satellites provide unique quantitative information on SO₂ and volcanic aerosols. Finally, Mike Fromm of the U.S. Naval Research Laboratory described some case studies that illustrate the challenge of using lidar alone to distinguish between dispersed volcanic ash and other aerosol types.

The following table summarizes the main outcomes of the remote sensing panel session and breakout discussion:

ADVANCES SINCE 2010	CHALLENGES
<ul style="list-style-type: none"> • Advanced usage of hyperspectral satellite measurements for volcanic cloud monitoring (e.g. more detailed information on cloud composition) • Improved (more accurate and timely) volcanic cloud detection utilizing pattern recognition techniques in combination with spectral methods • Development of eruption alerting applications (e.g. ESA and NOAA) • Integration of satellite observations and dispersion models (additional development for operational applications and broader utilization are needed) • International collaboration on inter-comparing different satellite-based methodologies 	<ul style="list-style-type: none"> • Ensuring consistent geostationary satellite capabilities and continuation of space-based lidar measurements • Developing methods to integrate different satellite measurements into quantitative products that mitigate limitations of single sensor approaches and benchmark performance (validation) • More advanced integration of satellite data with non-satellite data and models (cross-cutting goal) • Developing policies on information flow from advanced applications such as satellite-based eruption alerting • Continued international collaboration to integrate best remote sensing practices into real-time applications that are sustained and contribute to the global harmonization of operational capabilities (cross-cutting goal) • Sustained commitment to user training (cross-cutting goal) • Managing “Big Data” • Overall: Generation of coherent information in support of decision making

3.3 Engine Testing and Encounters

The Workshop heard introductory presentations on the volcanic ash hazard, including on the nature of some of the encounters, and the early history of the International Airways Volcano Watch. It was noted that, prior to 2010, there had been 79 known *damaging* encounters, and a large number of encounters where no damage was recorded. 9 incidents have resulted in engine failure in flight, with the most recent of these in 2006 involving a Gulfstream business-style jet in very diffuse ash (due to a particular design feature of the low-bypass engines). Since 2010, there have been a large number of further encounters, most of which were associated with the 2010 Eyjafjallajökull eruptions, although fortunately only a handful involved any damage and no more engines were shut down in flight. One recent event, a 2014 encounter with the extensive ash cloud from an eruption of Kelut, Indonesia, attracted much discussion in several sessions, with the workshop noting that communication and warning receipt issues, rather than eruption/cloud detection as such, had most likely contributed to the event. The aircraft involved in that event landed safely with ash deposited in the engine but without significant engine degradation, following

prompt action by the crew. The operator and other associated airlines have since taken action to improve procedures and information flows, although other known International Airways Volcano Watch issues such as SIGMET issuance remain imperfectly addressed.

3.3.1 Updating the Encounters Database

Since the last WMO Workshop on volcanic ash and aviation, a major effort has been underway, led by Carsten Christmann of DLR (Germany) in collaboration with Marianne Guffanti of the USGS (USA) and other partners, to update the international aircraft encounter database and also the classification scheme for encounters. This work was presented by Carsten Christmann. It has proceeded extremely well, and is expected to result in a significant expansion of our knowledge of the hazard. Discussion on this issue highlighted the importance of a comprehensive database of encounters, particularly the more serious ones (airlines are not always aware of when they have flown through diffuse ash clouds), and of further developing rigorous procedures for ensuring that relevant data are captured and analysed. In this connection, the importance of engagement with the insurance, and reinsurance industries was recognized, in addition to strong internal procedures. The meeting emphasized that full and frank exchange of data, together with continued respect for the long standing practice of not identifying airline operators was fundamentally important for driving our appreciation of the risks and costs of volcanic ash to aviation and our potential means of reducing them.

3.3.2 Engine Tests and Volcanic Ash Experimentation

The Workshop was excited to hear a presentation by John Lekki (NASA Glen Research Center) about the recent experiments to ingest low concentrations of ash into a jet engine, organized within the US under the VIPR programme and led by NASA with active participation by many agencies. In these tests, representative volcanic ash at well-defined concentrations had been ingested under controlled conditions, with the results currently being analysed for expected release during 2016. The preliminary results discussed at the workshop indicated that the tests would significantly advance our knowledge of the actual effects of ash on engines at the concentrations used. This work is the first such work since the 1980s, and represents a very welcome response to previous calls for more work in this area. Participants at the Workshop expressed warm appreciation for the efforts of all involved.

The meeting was also very pleased to hear of work to document and systematize critical aviation encounters in a way that allows us to further understand the effects of varying *concentrations* and total *dosages* of ash on aircraft. Whilst it is important to not jump to conclusions at this stage about refinements to threat levels and ash management strategies, it is clear that there is significant potential for us to further clarify the threat posed by volcanic ash low to medium concentrations.

A stimulating presentation by Ulrich Kueppers (Ludwig Maximilians University, Munich) showed the value and application of investigating fundamental ash and eruption properties with the laboratory, using compressed 'cool' chambers and other experimental techniques.

In discussion, a broad group of stakeholders, including representatives of IATA and individual operators, and other International Airways Volcano Watch participants, urged that relevant work of this nature continue in order to better understand and define the ash hazard, to improve safety, and to develop strategies to reduce the economic cost of volcanic ash avoidance, which is borne by operators, OEMs (who would prefer their aircraft to be used), and the wider transport-dependent sectors of the economy. The cost of large disruptive events such as the 2010 Eyjafjallajökull has been estimated at several billions of dollars, but even 'small' scale events such as the 2015 Raung eruption can cost even a single group of carriers tens of millions of dollars in ash-avoidance costs.

3.3.3 Improving Operator Risk Management

Graham Rennie of Qantas Airlines, presented to the Workshop some considerations on 'best practice' issues of volcanic ash management from the operational perspective. Effective management of the volcanic ash hazard requires a considered process that is understood by Flight Dispatch and the flight crews. In order to address the challenges posed by volcanic ash, a sophisticated risk assessment approach is needed. The process is supported by the airline's meteorological team, extensive ground supporting systems and flight monitoring, evidence based assessment, strong links to the VAACs and understanding of International Airways Volcanic Watch processes, and strong internal management through the airline's Critical Event Operations Group. Other investments include our participation in industry and government working groups, and an extensive Volcanic Ash Operations Manual grounded in international best practice.

The challenges ahead include seamless development of good processes at ICAO level, managing the pre-eruption information challenges, engine certification for volcanic ash, more exact volcanic ash forecasts, better knowledge of the hazard to hone an appropriate risk level, improved collaboration, better management of airport closures, better ash encounter reporting, post-event reviews, and better cost reporting. All of these are essential for the continued development of the IAVW. Science and operational communities must continue to work together to continue to ensure aviation safety around volcanic ash while considering economic efficiency of operations.

In discussion of these points, the Workshop was reminded of the need to ensure consistent and detailed pre-eruption procedures, including detailed information from the volcano observatories. Further discussion of this area is included in the volcanic monitoring section, which follows.

During the breakout session, the following were identified as the biggest advances since 2010 and the greatest challenges:

ADVANCES SINCE 2010	CHALLENGES
<ul style="list-style-type: none"> • Engine tests • Encounter understandings • Relationships revitalized between industry and the scientific community, as evidenced by this workshop • VAAC best practice (eg collaboration, consistency distribution) • WMO science & training support for volcanic ash has markedly improved. 	<ul style="list-style-type: none"> • Future engine-test matrix that identifies key volcanological parameters of the ash used (eg viscosity, gas content, glass/crystal proportions, etc.) • Improving reporting – systems & procedures • ICAO management structure & impacts to the science enterprise – manage risks well • Involving airports in discussion – having ashfall forecasts used well • Understanding and responding to operator needs for good risk- based management

3.4 New Methods of Detecting and Measuring Eruptions

Presentations on this theme concentrated on ground-based methods to detect eruptions or to measure their properties. The session began with a talk by Sigrun Karlsdottir, Director of Natural Hazards at the Icelandic Met. Office, describing improvements in volcano monitoring in Iceland over the past three to four years. Some key improvements include addition of portable ground-based radar systems to measure plume height, and expanded GPS stations to better track uplift or subsidence of volcanoes or glaciers. This was followed by talks by David Fee (University of Alaska, Fairbanks) and Pierrick Mialle (Comprehensive

Test-ban Treaty Organization) describing the maturing of infrasound as a capability to detect atmospheric waves produced by eruptions or explosions. Matt Haney (USGS, Alaska Volcano Observatory) followed with a talk explaining the possibilities and challenges of estimating volcanic plume height from seismic data. David Schneider (USGS, Alaska Volcano Observatory) explained current capabilities of weather radar systems in detecting eruptions and characterizing volcanic plumes and clouds. A talk by Konradin Weber (Duesseldorf University of Applied Sciences) on in-situ ash-cloud measurement was unfortunately cancelled due to injury, and replaced with a talk by Mike Pavolonis (NOAA/NESDIS) on new capabilities and challenges associated with utilizing the next generation of weather satellites for operational volcanic cloud applications. For the final talk, Alvaro Amigo (Servicio Nacional de Geología y Minería, Chile) gave a stimulating presentation on the spectacular eruption of Calbuco Volcano in April, 2015.

The following table summarizes the main outcomes of the volcano monitoring sessions and discussions:

ADVANCES SINCE 2010	CHALLENGES
<ul style="list-style-type: none"> • Development of new techniques for eruption detection of volcanoes (satellite, local infrasound, Comprehensive Test-Ban Treaty Organization (CTBTO) infrasound, GPS), in some cases using data for uses beyond their original intent. • Real-time, continuous multi-parametric data for monitoring subsurface magmatic/volcanic processes (e.g., real-time seismic, multi-gas, webcams, tilt/gps/deformation). • Increased communication among VAAC meteorologists, observatory volcanologists, and the research community, facilitated by meetings like this workshop, that help inform the community on needs and capabilities. • Improved geological understanding and threat-ranking for volcanoes; more is needed; threats and eruptive scenarios; improving the source term databases. • New ways of thinking about eruption monitoring parameters in eruption forecasting to include databases of previous eruptions and construction of event-trees to guide discussion on eruption scenarios. 	<ul style="list-style-type: none"> • Improvements in the science of “forecasting” eruptions have been made (at least advance warning), but the specific time, duration and intensity is unknown. • Interpreting and communicating processed products to the VAACs quickly. Better, multidisciplinary instruments exist, but the challenge remains how to extract the relevant information and products for source terms quickly. • The level of monitoring and available resources for improvement is inconsistent around the world with associated opportunities to plug some of the gaps with improved satellite imagery and other capabilities e.g. infrasound. It was also recognized that greater efforts should be made to better communicate how and where volcano monitoring capabilities vary worldwide e.g. graphically through a map. • Availability, accessibility, consistency, interoperability and oversight of diverse datasets (satellite, radar, in-situ monitoring data) accessible in near real time globally. • Volcano Observatories need input from aviation users about what products are required. • Integration of different data streams based on Iceland best practice example where data streams are being effectively integrated between meteorological and geophysical data. There is also a need to get the meteorological and volcano observatory data more closely aligned. The use of satellite data is one data stream that unites the two groups.

4. CLOSING REMARKS

Mr Ian Lisk, vice-president of the WMO Commission for Aeronautical Meteorology (CAeM) thanked the USGS and NOAA co-hosts for hosting what had proved to be a very successful, interactive and productive event. He also thanked the organizing committee, in particular Larry Mastin as the scientific organizing committee chair and Dave Schneider as the local organizing committee lead for their hard work over the last 9-months. Mr Lisk concluded by thanking the delegates for their contributions and encouraged them to maintain the links and collaborations made during the event.

The workshop then closed at 11:30 on Friday 23 October 2015, and was immediately followed by a meeting of the WMO-IUGG Volcanic Ash Science Advisory Group (VASAG-6, reported separately)

5. ANNEXES

The meeting agenda, along with all available presentations, abstracts, and summaries of the breakout sessions, are posted at the meeting web site,

<https://www.wmo.int/aemp/iwva-7>
