COMMISSION FOR BASIC SYSTEMS
OPEN PROGRAMME AREA GROUP ON INTEGRATED OBSERVING SYSTEMS
INTER-PROGRAMME EXPERT TEAM ON SATELLITE UTILIZATION AND PRODUCTS
SCOPE-Nowcasting Pilot Project 2: Globally consistent Volcanic Ash Products

Meeting on the Intercomparison of Satellite-based Volcanic Ash Retrieval Algorithms

Madison WI, USA
29 June – 2 July 2015
FINAL REPORT
Regulation 42

Recommendations of working groups shall have no status within the Organization until they have been approved by the responsible constituent body. In the case of joint working groups the recommendations must be concurred with by the presidents of the constituent bodies concerned before being submitted to the designated constituent body.

Regulation 43

In the case of a recommendation made by a working group between sessions of the responsible constituent body, either in a session of a working group or by correspondence, the president of the body may, as an exceptional measure, approve the recommendation of behalf of the constituent body when the matter is, in his opinion, urgent and does not appear to imply new obligations for Members. He may then submit this recommendation for adoption by the Executive Council or to the President of the Organization for action in accordance with Regulation 9(5).
EXECUTIVE SUMMARY

The volcanic ash cloud satellite-based retrieval intercomparison activity contributes to improved knowledge of satellite-based detection and quantification of volcanic ash. The activity aims to provide consistent ash products for aviation services, inform the international regulations established by ICAO (Annex 3 of its regulation, and the International Airways Volcano Watch Roadmap) and WMO. Its results are expected beneficial to other meteorological applications such as nowcasting and air quality forecasting. The activity has been established as part of WMO SCOPE-Nowcasting (as Pilot Project 2, reporting to the WMO Commission for Basic Systems), and is contributing to the WMO/IUGG Volcanic Ash Scientific Advisory Group (VASAG; reporting to the Commission for Aeronautical Meteorology and ICAO), the ICAO MET Panel and its Working Group on Meteorological Information and Service Development (with sub-group on volcanic ash), and the WMO Global Atmosphere Watch (GAW) and World Weather Research Programmes.

Objectives of the intercomparison are to (i) establish a basic validation protocol for satellite-based volcanic ash products, (ii) quantify and understand differences in products for the selected six volcanic eruptions with the aim to extract best practices, (iii) standardize volcanic cloud geophysical parameters contributing to the context of WMO and ICAO. The performance of algorithms should also be seen in view of the sensors to be available in the 2015-2020 timeframe on the next generation of meteorological satellites.

22 algorithms from institutions and groups all over the world using passive satellite imagery were considered in the intercomparison; reference data were used from the CALIPSO CALIOP space-borne lidar instrument, the United Kingdom FAAM research aircraft, and EARLINET ground-based lidar data. The six volcanic eruption cases considered in the intercomparison were Eyjafallajökull (2010), Grimsvötn (2011), Sarychev Peak (2009), Kelut (2014), Puyehue-Cordón Caulle (2011) and Kirishimayama (2011).

Conclusions

In summary, the results from the intercomparison show related to detecting volcanic ash clouds:

1. Only well-dispersed ash clouds, with mass loadings that are generally less than 1 g/m², have been evaluated so far, as dictated by sampled reference data. The consensus lower limit of detection for passive IR techniques under suitable conditions (fine grained ash is the highest cloud layer and is sufficiently colder than the background) is 0.1 g/m², which is in very close agreement with previously established thresholds.

2. The sensitivity of passive satellite measurements can be divided into two categories. As VAACs routinely demonstrate through manual analysis of multi-spectral imagery, passive satellite measurements are most sensitive to the general presence of volcanic ash (discernable ash/no discernable ash). The sensitivity of passive satellite measurements to ash cloud properties (height and loading) is less than the sensitivity to ash detection because more assumptions are required to retrieve ash cloud properties. Thus, at a given location, the confidence in the discernable ash/no discernable ash classification will be greater than the confidence in the retrieved ash cloud properties.

3. Human expert analysis of the areal extent of volcanic ash within a given passive meteorological satellite image should be regarded as the upper limit of detection sensitivity. A consensus based ash detection analysis derived from the inter-comparison datasets contains very few false alarms, but has a detection sensitivity that is well below the upper limit. However, a few algorithms approached this upper limit without introducing a significant number of false alarms.
4. R&D satellites provide a useful contribution to advance the state of knowledge in volcanic ash cloud retrievals.

Related to quantifying volcanic ash clouds, the intercomparison showed that:

5. Best estimates of mass concentration from aircraft campaigns have uncertainties of a factor ~2 for <4mg/m3 (mainly due to uncertainty in composition/refractive index).

6. Mass loading values from passive satellite retrievals were validated in the range 0.1 - 1 g/m2 with FAAM airborne lidar measurements, and were shown to be capable of agreement with the aircraft data, given the uncertainties noted in item #1 above.

7. Pending further analysis, mass loadings compared between different schemes were in general in agreement to within a factor of between 2 and 4.

8. There was an observed tendency for mass loadings and effective radius retrievals from hyperspectral sounders to be smaller than their imager counterparts.

9. Passive retrievals of ash layer height show variable agreement with airborne- and space-borne lidar validation data, depending upon the scene conditions. Single-layer ash cases were shown to provide reasonable agreement (within ~2 km in general), with multi-layer cases proving more problematic for retrievals and for the current validation strategy.

10. Different retrievals of ash effective radius showed generally low correlations (0.2-0.5), although some well-correlated results were also noted. No in situ validation data were analysed as part of this inter-comparison.

11. Optical thickness correlations were somewhat higher (0.4-0.6) than for the effective radius comparisons noted in item #6 above (»Different retrievals…«). However, some distributions showed unexplained characteristics.

12. Retrievals of optical thickness from schemes using visible reflectances yielded consistently higher values than for the IR-only schemes.

13. Spectrum-based discrimination between ash and dust only seemed possible from the use of hyperspectral sounder data - otherwise contextual information (e.g. back trajectories, etc.) were required.

14. More detailed analysis of the intercomparison results is necessary (see Recommendations)

**Recommendations**

In the intercomparison, the following steps to improve satellite-based volcanic ash detection and quantification in the future were identified:

1. Full exploitation (spectral, spatial, temporal) of the space-based Global Observing System, including the next generation of sensors (e.g. new GEO imagers)

2. Expert analysis is important in determining a best-estimate of the spatial extent for volcanic ash (e.g., through consensus)
3. Acceptable false alarms rates need to be determined with users (VAACs, modellers)

4. Attach confidence levels to detection products to fulfil the needs of the VAACs (e.g., ‘low, medium, high’, or probabilities)

5. VAACs, VOs, and the remote sensing research community are encouraged to form collaborative links for training and interpretation of events. The VAACs recognize the value of satellite retrievals and indicate that most efficient use of these data sets are when they are within their operational analysis platforms. The research and operational communities are encouraged to work together on data format standards for ingest into their systems, as appropriate.

6. In-situ and ground-based remote sensing data can add value to near-source volcanic cloud detection and characterization, as many satellite-based techniques have difficulty in detecting this region.

7. Flag areas where ash can be reasonably expected (due to spatio-temporal context) but cannot be directly detected

8. Systematic analysis of CALIOP and possibly MISR reference data for volcanic eruptions is required

9. Better NRT access to ground-based lidar data, and better temporal/spatial network coverage is required

10. Provision of airborne ash measurements during future eruptions, plus resources for associated scientific analysis

11. In-situ and remotely-sensed particle size distribution (PSD) measurements are required more broadly. Using a log-normal size distribution of volcanic ash may be a recommended best practice for the dispersed ash cloud.

12. Ash cloud sensitivity studies using models and observation operators should be carried out

13. Optical ash properties should be revisited in laboratory experiments (main references from 1970s)

14. Encourage VAACs and other users and to share products and visualization tools

15. Since human expert analysis of the horizontal extent of volcanic ash represents the upper limit of detection within a given satellite image, which may be greater than 0.1 g/m² if difficult background conditions are present, quantitative volcanic ash products should be presented to users in tandem with multi-spectral imagery.

16. Further analysis should include breaking down mass loading intercomparisons into constituent components – e.g. optical thickness, effective radius, extinction efficiency, bulk density, etc.

17. Further analysis should include widening the scope of the validation data (e.g. including in situ PSD information)

18. Research groups should fill in gaps in the validation data for the current intercomparison case studies, where possible, for subsequent intercomparisons.
19. The volcano ash community is encouraged to formulate requirements (parameters, data formats, latency, possibly sites) to the GALION (WMO Global Atmosphere Watch Lidar Observation Network) and the ground-based aerosol network should also be considered.

20. The providers of volcanic ash detection and retrieval products should liaise with data assimilation centres to foster modelling and forecasting capabilities.

21. The intercomparison data and related processing and analysis code should be made available to the community, to support further analyses. Published work using the intercomparison data and code should provide appropriate references.

22. Pending final analysis of results, a second intercomparison is recommended, using more focused, in-depth comparisons of algorithms, using well-understood case studies, with additional validation data/scenes available (including expert ash analyses, aircraft data, CALIOP analyses), and using the next-generation imagers/sounders.
FULL REPORT

1. Background, overview of goals and user perspectives

1.1 Welcome and practical information

Mike Pavolonis welcomed participants to the Pyle Center of the University of Madison-Wisconsin, thanked everyone for having travelled to attend this meeting, and stressed the global nature of the group (participants coming from five out of six WMO Regions) as an indication that volcanic ash cloud detection and quantification is an issue of global interest. He highlighted the importance of the volcanic ash retrieval algorithm intercomparison activity, aimed to advance science in support of applications promoted by WMO and ICAO.

Mike provided practical information for participants about Madison and expressed thanks to the University of Wisconsin Space Science and Engineering Center (SSEC), and local staff for their support in organizing the meeting.

Participants introduced themselves in a tour-de-table (see Annex II for list) - present were 38 participants from ten countries, EUMETSAT, and ESA.

Further links related to the meeting:

Resources related to the intercomparison activity:
http://cimss.ssec.wisc.edu/meetings/vol_ash15/program.html
(including: Intercomparison Work Plan, Algorithm Table, Scene Selection)

Meeting presentations:
https://www.dropbox.com/sh/9u5fc49d80y76s9/AAB0L79_8x6jl2mERX-FjRQRa?dl=0

WMO SCOPE-Nowcasting:

Raw Intercomparison results (password-protected):
ftp://ftp.rsg.rl.ac.uk/

1.2 Background and objectives in the context of ICAO, WMO, and SCOPE-Nowcasting (Stephan Bojinski)

Stephan Bojinski briefed on background to the volcanic ash cloud retrieval intercomparison activity, and the context of WMO and ICAO to which it contributes: to WMO SCOPE-Nowcasting (as one pilot project, reporting to the WMO Commission for Basic Systems), the WMO/IUGG Volcanic Ash Scientific Advisory Group (VASAG; reporting to the Commission for Aeronautical Meteorology and ICAO), the ICAO MET Panel and its Working Group on Meteorological Information and Service Development (with sub-group on volcanic ash), and the WMO Global Atmosphere Watch (GAW) and World Weather Research Programmes.

He thanked the intercomparison organizing committee for its work to prepare the activity and the meeting, in particular Marianne Koenig (EUMETSAT), Pete Francis (UK Met Office), Hiroaki Tsuchiyama (JMA), Dave Schneider (USGS), Elisa Carboni (Oxford University), and Mike Pavolonis (NOAA/NESDIS).
He pointed out the three main goals of the intercomparison: (i) establish a basic validation protocol for satellite-based volcanic ash products, (ii) quantify and understand differences in products for the selected six volcanic eruptions with the aim to extract best practices, (iii) standardize volcanic cloud geophysical parameters. The current state of science should be assessed in the meeting. The performance of algorithms should also be seen in view of the sensors to be available in the 2015-2020 timeframe on the next generation of meteorological satellites, e.g. by geostationary imagers with up to 16 channels on JMA Himawari-8 (entered operations on 7 July 2015), NOAA GOES-R, CMA FY-4A and others.

The six volcanic eruption cases considered in the intercomparison are:

- Eyjafallajökull (2010)
- Grimsvötn (2011)
- Sarychev Peak (2009)
- Kelut (2014)
- Puyehue-Cordón Caulle (2011)
- Kirishimayama (2011)

In total, **22 algorithms took part in the intercomparison** (see Annex III for list), and reference data from CALIOP, the lidar on board the United Kingdom FAAM research aircraft, EARLINET lidar data. DLR Falcon and ground-based MW radar for validation were discussed under item 2 of the meeting, but not used in the present state of the intercomparison.

The intercomparison results will feed into the ICAO Roadmap for International Airways Volcano Watch (IAVW), which defines improved services including the integration of volcanic meteorological information into decision support systems for trajectory based aircraft operations. Volcanic ash cloud monitoring is one of the four service categories (eruption monitoring, volcanic ash cloud monitoring, volcanic ash forecasts, communication of volcanic ash information to users).

The Roadmap anticipates changes over the period 2018-2028: until 2018, “improved ground-based, air-based and space-based observing networks to determine Eruption Source Parameters and existing ash loading (N.B. this includes methods, algorithms)” are expected and need to be specified in this living document. By 2018, this material or a subset thereof will be considered for inclusion into internationally binding ICAO regulation (i.e., within an amendment to Annex 3 – Meteorological Service for International Air Navigation), through an Aviation System Block Upgrade. Depending on the maturity of volcanic ash detection and quantification practices, such upgrades can also be done later.

To inform the ICAO process, consolidating the satellite-based volcanic ash retrieval algorithm intercomparison results by November 2015 is necessary. He stressed that recommendations could be formulated in a staggered manner, e.g., satellite-based volcanic ash detection capabilities available by 2018, by 2022 etc.

Stephan presented a timeline of post-meeting activities:

- 6 Jul 2015: Preliminary results, to inform WMO-led plans for lidar-based intercomparison (CIMO)
- 31 Aug 2015: Finalize Meeting Report
- By Sep 2015: Communicate recommended practices to VAACs and define steps to improve their capacity in using satellite-derived VA products
- Report to EUMETSAT Meteorological Satellite Conference 21-25 Sep 2015
• By 31 Oct 2015: Report to ICAO MET Panel and Commission for Aeronautical Meteorology for further development of Int’l Airways Volcano Watch Roadmap

He raised the possibility of compiling a peer-reviewed publication; a writing team initially consisting of the intercomparison activity organizing committee, would be needed for this purpose.

1.3 Volcanic ash information for the WMO Global Atmosphere Watch (GAW) and World Weather Research Project (WWRP) (Alexander Baklanov)

Alexander Baklanov described the structure of research programmes at WMO (WCRP, WWRP, and GAW). A nowcasting for aviation project in WWRP is underway, to eventually include volcanic ash. He described the structure of GAW and the aerosol variables measured. He pointed out the importance of the GAW Aerosol Lidar Observation Network (GALION), co-led by Gelsomina Pappalardo (CNR Italy) and Ellsworth Judd Welton (NASA), and the EARLINET which is further developed under ACTRIS-2. The Nabro 2011 and Eyjafjallajökull 2010 eruptions were captured by several components of GALION. A key objective of GAW and GALION is data provision in NRT to support data assimilation. He suggested an intercomparison activity among VAACs related to volcanic ash modeling and assimilation.

1.4 CREW Cloud Intercomparison (Andy Heidinger)

The Cloud Retrieval Evaluation Workshops (CREW) were started by EUMETSAT, driven by MSG SEVIRI, with initially 23 and a maximum of >70 participants, initially one day for intercomparison, later over five days. Agreement was found on a set of cloud parameters. EUMETSAT visiting scientists (A. Walther, U. Hamann) provided analyses ahead of meeting, such that algorithm providers would know these before the meeting. He showed the 11 algorithm providers, and an example for a Cloud Top Pressure matrix showing product and one-by-one comparisons. Only A-train instruments were used for validation purposes. CREW did not pursue common algorithms, but instead looked at multiple algorithm ensembles and other comparisons. The organization of workshops evolved around four topical groups (retrievals, evaluation, research), and results were published in a BAMS article. CREW has now morphed into the CGMS International Cloud Working Group.

Comparing CREW to the intercomparison at hand, Andy noted that in contrast to meteorological clouds for which there are many opportunities to observe, volcanic ash clouds are much rarer and sensor overlap is less likely, hence it is inherently more challenging to perform an algorithm intercomparison.

1.5 ESA Volcanic Cloud Intercomparison Activity (Claus Zehner)

He presented the ESA projects Volcanic Ash Strategic Initiative Team (VAST) and Support to Aviation Control Service (SACS), which have the aim to enhance the use of EO satellite data for volcanic ash monitoring, for demonstration purposes. He also presented some early findings from VAST related to validation datasets (aircraft, lidar, ceilometers, ground-based sun photometry). Such data should span the full range of realistic quantities (e.g., mass loading) describing an ash cloud, and be used for validating both detection and retrievals. Validation in VAST focussed on the eruptions of the Eyjafjallajökull and Grimsvötn volcanos where sufficient, high-quality and published validation data were available. The report Validation Dataset for Satellite-based Volcanic Ash Retrievals would be made available soon.
Participants remarked that the tolerance limit for false alarms (detection of volcanic ash from satellite in areas where none can be otherwise detected) was dependent on the user and application, e.g., whether an operator or other filter mechanism was involved to discard obvious cases of false alarms.

Claus also informed about the ESA Living Planet Symposium planned on 9-13 May 2016 in Prague, Czech Republic, and encouraged participants to submit papers, with the possibility of organizing a separate volcanic ash session (abstracts are due on 16 Oct 2015).

1.6 Overview of Anchorage VAAC operations with focus on use of satellite data (Don Moore)

Don Moore provided an overview of VAAC operations, with e.g., 130 advisories issued in 2014 (80 for below FL290, 50 for above FL290). Challenges to volcanic ash characterization are mainly (i) meteorological clouds obscuring eruptions (particularly eruptions with clouds below 8500 metres), (ii) identification of the edge of ash clouds or when ash clouds dissipate, and (iii) handover and collaboration with other VAACs (Tokyo). He showed the VolcView (volcview.wr.usgs.gov) collaborative interface used, inter alia, to compare retrieved ash cloud height with results obtained from backward trajectories using the HYSPLIT model. Since 2014 automated satellite-detected volcanic ash alerts from the NOAA/CIMSS system have been routinely provided. He stressed that collaboration of the VAAC with the Alaska Volcano Observatory and the weather service was key to its success. Himawari-8 is expected to lead to improved monitoring of ash and SO2; SO2 alerts are being considered since there is high demand by VAACs and airlines to use it as a proxy for volcanic ash.

1.7 Overview of Washington VAAC operations with focus on use of satellite data (Jamie Kibler)

VAAC Washington has been using GOES-13/15, MTSAT, Meteosat, and also MODIS Aqua, Terra, and for SO2/aerosol detection OMI and OMPS in its operations. In 2014, the VAAC issued 933 advisories and 241 graphical advisories for its area of responsibility. He illustrated the difficulty in detecting ash from a complex eruption (Soufriere Hills, 2010) where the cloud spread in multiple directions at low altitude (3000-5000 m). Satellites were useful in detecting hotspots as a precursor of a possible activity, such as from volcanos in El Salvador and Guatemala. Direct readout from polar satellites would overcome some of the data latency issues. The NOAA/CIMSS-developed automated volcanic ash alert system was available at the VAAC, and it was making use of other sources of information, such from Volcano Observatories, social media, and web cameras.

1.8 Overview of operations at the Alaska Volcano Observatory with a focus on use of satellite data (Dave Schneider)

Dave Schneider presented the Alaska Volcano Observatory hazard warning programme, to which the value of satellites is obvious given the length of the Aleutian arc (2500 km). Satellites allow determination of whether an eruption is occurring (to confirm seismic networks that monitor 60% of the volcanos), to see whether ash is being emitted, to provide a scale of the eruption size, and to track ash clouds. The key questions to be addressed by any volcano monitoring system are: timing of the event, height of the ash cloud (no correlation between tremor and plume height), length of the event, area of dispersed ash. USGS uses the NOAA/CIMSS volcanic ash alert system, and in addition, data from OMI and IASI for analyses of trace gases and aerosols. There is successful collaboration with Anchorage VAAC in coordinating information statements and other technical support.
1.9 Dispersion modelling needs for satellite data (Larry Mastin)

In this talk, Larry Mastin concentrated on operational dispersion models: both Lagrangian and Eulerian models place ash into the atmosphere above the volcano, then downwind advection, crosswind diffusion and gravitational settling are calculated. In Lagrange models, forward modelling of ash occurs along trajectories, and gridding needs to be added to calculate concentrations. In Eulerian models, the atmosphere is divided into 3D cells, and the model calculates fluxes among cells, which allows direct calculation of concentration.

In the Anchorage VAAC, forecasters combine model output, observations, and other sources, whereby model forecasts provide a qualitative, but useful predictor of location and extent of the cloud. Quantitative Bayesian methods are under development, which would allow for NRT assimilation of satellite data into model runs (at different heights).

With the Eyjafjallajökull eruption in 2010, significant progress was made in quantitative validation of model, leading to best practices and focus on challenges: (i) ash resuspension is difficult to model (e.g., in case of Puyehue Cordon-Caulle in 2011), and satellite imagery could assist there; (ii) better modelling of the injection of ash into atmosphere: some large eruptions eject umbrella ash clouds even upwind and change wind field (Pinatubo 1991).

1.10 Potential impacts of the next generation of meteorological satellites (Mike Pavolonis)

A VAAC best practices meeting in May 2015 identified high demands of Centres including for:

- Developing confidence levels in graphical product output
- Contamination advisory products, based on quantitative ash mass column loading thresholds
- Jet engine damage impact incurred by the presence of ash

Major impacts of satellites were identified:

- Better ash detection is expected from new-generation geostationary (GEO) imagers due to higher spatio-temporal resolution than current imagers (demonstrated by Himawari-8 capturing the ash cloud of a Kamchatka volcano that was indistinguishable using MTSAT-2); for example, a 10-minute image scan cycle leads to higher sensitivity in detecting brightness temperature changes of rapidly changing objects such as near-source ash plumes than a 30-minute cycle
- Imagery from low-Earth orbit (LEO) is important, e.g., for high-resolution imagery or for correcting parallax effects in high latitudes
- The spatial continuity of spectral signatures can be exploited when cloud signatures are fading

Challenges:

- “Big Data” (increase in data rate by factor of 100 from next-generation satellites)
- Multi-sensor analyses, and data fusion
- User readiness

1.11 Group discussion on user needs

The discussion focussed on the needs of VAACs and other users for volcanic ash cloud information. For VAACs and airlines, provision of volcanic ash information in real time is very important. For VAACs, provision of a cascade of products may be an option, consisting of near real-time, simple, robust nowcasting products (e.g., ash/no ash) of reasonable accuracy and for which little training is required; and in a second, delayed stage provision of more sophisticated products (e.g., mass loading) that require more analysis, training and possibly interaction with an expert. Consideration of the cascade would depend on the significance of the event. Merged products can simplify analysis by VAAC operators and foster uptake in operational forecasting.
Another issue is communication of uncertainty and other product features to users. Some aircraft operators (e.g., Lufthansa) require a product identifying a mass concentration of 4 mg/m³. The uncertainty associated with such a product (estimated at an order of magnitude for mass concentration) needs to be understood by users. Airlines also request products allowing hazard assessment of aircraft engines, e.g., to discern between a risk of engine failure vs a risk of engine degradation.

Participants agreed that user training is needed, for example to explain that uncertainty in satellite-based volcanic ash products is a function of retrieval conditions. VAAC representatives confirmed that such training has increased confidence levels of forecasters in satellite-based products. It remains to be seen how to increase the uptake of all 9 VAACs of volcanic ash products derived from satellites.

2. Validation sources, intercomparison results

2.1 Space-based lidar as a validation source (Anne Garnier)

Anne Garnier presented on the Cloud-Aerosol Lidar with Orthogonal Polarisation (CALIOP) onboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite which is flying in low-Earth orbit as part of the A-Train. CALIPSO also carries an Imaging Infrared Radiometer (IIR) and a Wide-Field Camera (WFC). In expedited mode, CALIOP data processing latency is 12h, and 3 days in standard mode. The instrument measures attenuated backscatter and depolarization at 532nm, and backscatter at 1064nm. Analyzing the depolarization ratio allows discriminating ash from sulphates. Ice clouds are identifiable using the IIR.

CALIOP directly measures altitude and layer thickness of aerosols and clouds, at vertical resolution of 30-60m up to 20km altitude. Retrievals of optical depth and mass concentration are possible, with assumptions on the lidar ratio (extinction/ backscatter ratio). The IIR can identify ice clouds. Although CALIOP is very useful for measuring volcanic ash cloud properties, and for validating results obtained using passive IR/MW instruments, the layer classification algorithm is not specifically designed for volcanic ash; ash layers are sometimes identified as aerosol or ice cloud. In such cases, ice cloud information from the IIR, or contextual information, e.g., using backward trajectories is required. Ash can be discriminated from SO2 aerosols using the depolarization signature.

She also introduced the CATS (Cloud-Aerosol Transport System) deployed on the International Space Station, which is a lidar measuring the depolarization ratio at 1064nm, between 51S and 51N.

In the discussion participants remarked that it is difficult to discriminate volcanic ash from all other particulate matter using lidar alone. It was also mentioned that CALIOP data are under-utilized regarding volcanic ash, and more attention should be put on specific studies. A catalogue of volcanic ash clouds observed by CALIOP would be beneficial to researchers and potentially VAACs.

2.2 Airborne lidar measurements of volcanic ash: A validation source (Franco Marenco)

Franco Marenco described the FAAM Atmospheric Research Aircraft operated by the UK MetOffice and NERC, with 4t scientific payload, which was used during flights in volcanic ash clouds over the UK during the Eyjafjallajökull event in 2010. Based mainly on remote sensing (lidar), ash concentration estimates were obtained along flight paths over the UK and adjacent areas, at an
uncertainty of around a factor 2, with assumptions on the particle size distribution and lidar ratio (60). These aircraft measurements were compared to results from SEVIRI, IASI, and the NAME model, showing varying degrees of agreement. He then showed comparisons of FAAM results and retrievals (of cloud top height, optical thickness, from SEVIRI_NOAA, AVHRR_MO, IASI_OXFORD algorithms) obtained within the WMO intercomparison for the Eyjafjallajökull event, showing overall reasonable agreement.

He also introduced the London VAAC hosted by UK MetOffice which in 2010 was producing threshold-based Volcanic Advisory Graphics, using 200-2000, 2000-4000, and >4000 µg/m³ ash mass concentration thresholds. The Eyjafjallajökull event triggered development of competence and infrastructure volcanic ash remote sensing in the MetOffice. As emerging capabilities, he pointed out the emerging CAA lidar and sun photometer network for volcanic ash detection over the UK, and the MOCCA aircraft for volcanic ash, SO2, and optical property studies.

2.3 Aircraft measurements as a validation source (Hans Schlager)

Hans Schlager showed measurement results during the Eyjafjallajökull event in 2010 obtained from the DLR Falcon aircraft, using a range of aerosol and trace gas instruments (remote sensing and in-situ) on its payload. During the event, 12 aircraft from across Europe were taking measurements, but many did not have specific equipment and did not cover all layers of ash. Particle counters were used to measure number and volumetric ash size distributions, and thus allowing inferences on mass concentration. Size distributions mostly follow log-normal functions. Chemical composition of ash and its change over time was measured, as well as physical quantities (refractive index, aspect ratio, density) and ash layer profiles. He reported on the overall good collocation of SO2 and ash measurements.

Based on a comparison of aircraft, ground-based lidar and satellite analyses on 19 Apr 2010 over the Leipzig area, he suggested an uncertainty of a factor of 2 for ash mass concentration derived from aircraft observations (in agreement with UKMO in item 2.2).

The discussion concluded that, given that airborne measurements of volcanic ash are considered the most accurate, the uncertainty in satellite retrievals of mass loading and concentration must be larger than a factor of 2 since more a priori assumptions are required for the retrieval, introducing additional uncertainty.

2.4 Microwave measurements as validation source (space and ground-based) (Frank Marzano)

Frank Marzano explained the use of passive and active microwave instruments, both satellite (e.g., ATMS, SSMIS) and ground-based, for retrieving volcanic ash parameters. Microwaves penetrate meteorological clouds and therefore allow for an all-weather view on ash plumes and a physics-based inversion on the plume interior (especially when IR brightness temperature saturates). Various modelling and retrieval methods have been studied. Ground-based MW radars have been used as a near-source probe of ash plumes. The spatial resolution of satellite MW radiometry is currently inadequate for optically thin plumes. Case studies looked at Grimsvötn and Etna 2013, and Calbuco 2015, for the retrieval of ash concentration, orientation, particle size distribution.

Satellite retrievals require assumptions on size distribution (Gamma distribution used here, and may be appropriate for the core cloud, not necessarily for the dispersed part of the cloud).

In the discussion, participants suggested that a log-normal size distribution of volcanic ash may be a recommended best practice for the dispersed ash cloud.
2.5 Introduction to intercomparison results (Mike Pavolonis)

A total of 22 algorithms were submitted to the intercomparison, and statistics on the algorithms, sensor types, limitations, and mathematical techniques were provided. Products are publicly available in near real-time from 4 algorithms, products are generated in near real-time for internal (non-public) distribution from 6 algorithms, and 12 algorithms are run in an R&D mode. Optimal estimation and a look-up-table (LUT) approach are the dominant mathematical techniques. He acknowledged the EUMETSAT support for the contractor RAL to carry out the synthesis and analysis of the intercomparison results.

2.6 Intercomparison results and discussion (Richard Siddans)

Richard Siddans presented and discussed results of the intercomparison of satellite-based volcanic ash detection and retrieval algorithms. The work was carried out under a EUMETSAT contract, following earlier EUMETSAT studies on the retrieval of cloud and ash properties from MSG SEVIRI. He explained the approach taken and showed results for ash detection and comparisons of quantitative ash cloud properties. He stressed the preliminary status of results due to the short period available for synthesis and analysis and indicated that RAL could only do limited additional analysis work after the workshop. EUMETSAT confirmed that the RAL contractor’s report, due in September 2015, could be made publicly available.

For the six case studies, the submitted 22 algorithms (see Annex III) were compared with four “validation sources”:

- Space-based lidar on NASA/CNES CALIPSO mission (CALIOP)
- UKMO airborne lidar (FAAM)
- Ground-based lidar (EARLINET_IMAA), and
- Expert evaluation of ash extent for Eyjafjallajökull (SEVIRI_VOLCAT)

The retrieved parameters considered in the study were:

- Ash cloud top height [km]
- Ash mass loading (ash column mass density) [g/m2]
- Ash effective radius [µm]
- Ash optical depth at two wavelengths, expressed in terms of effective emissivity \[1 - \exp(-\tau(0.55\mu m, 1.1\mu m)),\] with optical depth \(\tau\)

The overall intercomparison approach is depicted in Figure 1. Details on processing of validation data, collocation criteria, gridding rules are given in the presentation available online (dropbox).
Figure 1: Intercomparison approach

Figure 2 provides an overview of the number of data files (satellite products and “validation” datasets) available per day for each of the six Case Studies.
Comparisons among pairs of algorithms and against validation data were made for areas where both algorithms agreed on the presence of ash. The extent to which algorithm pairs agree on the presence of ash was quantified, taking into account regions where both instruments sample. Figure 3 shows an example for ash co-detection by two algorithms (MODIS_NOAA and SEVIRI_MO, for the Eyjafjallajökull Case Study on 7 May 2010).

Comparisons between algorithms of retrieved values were then made using pixels where both algorithms had detected ash, and after re-gridding; the following figures illustrate comparisons for mass loading (Figure 4), cloud top height (Figure 5), effective radius (Figure 6).
Figure 3: Co-detection of ash by two algorithms for the Eyjafjallajökull Case Study.

Figure 4: Eyjafjallajökull Case Study: Intercomparison of mass loading [g/m²], with overall reasonable agreement (top left panel); reference values from FAAM range from 0.1-1 g/m². Consistency is generally lower for the Grimsvötn and Puyehue Cordon-Caulle Case Studies.
It should be noted that large differences prevail in the number of comparison match-ups (see Figure 4 lower right panel, and Figure 5), leading to sampling issues that affect comparisons between different pairs.

Figure 5: Eyjafjallajökull Case Study: Comparison of ash cloud top height [km] between algorithms and CALIOP. There is overall reasonable agreement, and particularly good agreement for the MODIS_NOAA, SEVIRI_NOAA and SEVIRI_MO algorithms (which all have large numbers of match-ups). Note the large spread in the number of match-ups (from 3 to 1956) due to variability in spatial collocations and/or ash detection sensitivity.

Figure 6: Grimsvötn Case Study: Comparison of MODIS_RAL with other algorithms of effective radius [µm], with reasonable agreement except for SEVIRI_EUMOP with consistently higher.
We use the Puyehue Cordon-Caulle Case Study to illustrate some of the complexities in detecting ash clouds in multiple layers (Figure 7), and the issue of false positives over areas where ash is likely confounded with desert land surfaces (Figure 8).

Figure 7: Puyehue Cordon-Caulle Case Study: Differences in determining ash cloud top height in the presence of multiple cloud layers, along CALIPSO flight path (bottom right insert map), between CALIOP (attenuated backscatter profiles, and cloud top height estimate in black), the MODIS ORAC algorithm (middle) and MODIS_NOAA (top). Ash altitude is indicated as red crosses over the CALIPSO backscatter profiles. Bottom two panels show “dust” RGB false colour image and 11-12 micron brightness temperature differences derived from the thermal imager flown with CALIPSO. Both schemes detect ash around 45S, but provide different heights, corresponding to different layers seen by CALIPSO. The ash height derived from CALIPSO is indicated by the black line, which agrees better with MODIS ORAC, however it is not clear if this really corresponds to the layer containing ash.
Figure 8: Puyehue Cordon-Caulle Case Study, illustrating the problem of false positive detection of volcanic ash over Southern Africa (red circles), likely due to the presence of desert land surfaces. Panels are based on products regridded on a 0.5° grid and show the number of products detecting ash (top) and mean fraction of ash per grid cell (bottom). These issues affect comparisons as multiple schemes have false ash detections in the same area.
The discussion identified the following points:

i. Overall results are most consistent for the Eyjafjallajökull Case Study, mostly due to a large number of intercomparable pixels, the availability of validation data and relatively simple meteorological conditions. Puyehue was also very valuable as there was a high volume of results, enabling algorithms to be intercompared for a distinct eruption type. However, there was limited independent validation data for this eruption and use of CALIPSO was complicated by the frequent occurrence of high-altitude ice cloud layers. Less data was generally available for the other eruptions selected.

ii. Ash cloud height and mass loading tend to agree relatively well between different algorithms. Larger differences could be noted in optical depth and effective radius.

iii. Only limited “validation” data are generally available, making solid conclusions difficult; additional data (e.g., from DLR Falcon, FAAM in-situ size distributions) should be included in the future.

iv. While no scheme clearly performed “better” overall, special mention could be made of the NOAA MODIS/SEVIRI algorithms which were provided for a comprehensive set of cases and seemed to have a good level of consistency with each other. These had a relatively large number of co-locations with validation data and most other products. Comparisons with NOAA products could then be used to give an indication of performance for algorithms which had few co-locations with validation data. E.g. AATSR had few matches with validation data, but its retrieved height could be inferred to be performing well based on its good agreement with MODIS-NOAA. The consistency of the NOAA results between SEVIRI and MODIS also provided a useful link between the other SEVIRI and MODIS products, which tended to be only available from distinct algorithms. The use of spatial and temporal context in the NOAA algorithm was seen to lead to robust detection with relatively few clearly false detections. IASI schemes were also seen to give highly sensitive, robust detection, due to the use of more IR channels, sensitive to ash spectral signature. Most algorithms perform well in some situations, though it was not always straightforward to focus the comparison on these (beyond drilling down to specific days/scenes) due mainly to the limited time to carry out the intercomparisons. Given more time, it would be desirable to focus on ranges of different conditions more explicitly (over land / sea, day / night, in presence of cloud or not, selection of single-layer ash etc).

v. Simpler algorithms tend to produce more consistent results; more ambitious algorithms (which attempt to recover more parameters) show promise but some of them need further development to reduce product artefacts.

vi. Retrievals require assumptions on ash physical properties, such as shape, size distribution, refractive index; better validation sources and laboratory studies are suggested to better constrain these properties. It was also noted that some insight might be gained by comparing retrievals deliberately performed with common assumptions for ash optical properties, to eliminate this source of discrepancy.

vii. Datasets generated using a radiative transfer model could be used to assess the sensitivity of the intercomparison retrieval algorithms to various ash cloud properties and background parameters.

viii. The tolerance to false alarms is dependent on the size of the eruption, and on the application – a forecaster may easily filter these out whereas dispersion modellers may face issues.

ix. Context, e.g., provided by a multispectral satellite image or a sequence of images, improves interpretation of derived products; this underscores the benefit of using spatial and temporal information (in addition to spectral) in ash detection algorithms. This information can also be used effectively in ash detection algorithms.
It was recognised that retrievals may not be as important (from the VAAC point of view) for small eruptions.

An attempt was made to form a consensus detection, using results from multiple schemes. This was not successful due largely to common tendencies to generate false detections, in similar regions (e.g. over desert) – consensus of a majority of schemes could not necessarily be relied upon to remove such false detections. An approach based on selecting scenes where all schemes agree on ash would be overly conservative, missing much of the discernible ash.

In order for VAACs to utilize quantitative satellite products, latency must be low and the products should be easy to interpret; VAAC Anchorage and Washington indicate that ash cloud height is the critical parameter, mass loading secondary, effective radius third.

Conveying product uncertainty is recognized as important, but remains a challenge given that the uncertainty at a given location depends on many factors.

Further conclusions and recommendations are provided in section 5.

3. Algorithm overviews

(See Annex III for a summary overview)

3.1 INGV (Stefano Corradini, Luca Merucci)

(MODIS_LUT, MODIS_VPR)

He described two multispectral-based algorithms for the ash retrievals, and a neural network-based approach for ash detection. All the procedures have been applied to MODIS data considering the Eyjafjallajökull case study. The first retrieval algorithm shown is based on look-up tables, while the second uses a simplified procedure named volcanic plume removal (VPR). VPR is based on the removal of the plume from the satellite image, by substituting the radiance values in the plume region with the interpolated values found in region surrounding the plume. From the original and the interpolated images, transmittances are computed. All ash parameters (mass, effective radius and aerosol optical depth) are retrieved from the computed transmittances by only knowing the volcanic cloud altitude. Intercomparison results show general underestimation of cloud top height and a general agreement for the other ash products. The spin-up of a neural network is specific to volcano context and has to be generalized to be used globally.

3.2 DLR (Kaspar Graf)

(SEVIRI_VADUGS)

The Volcanic Ash Detection using GEO satellites (VADUGS) algorithm was presented, using simulated SEVIRI radiances with and without ash. Training datasets are generated using ECMWF fields and forward modelling for a range of atmospheric conditions and ash types. Then, a neural network was trained to yield ash column concentration and ash top height using real SEVIRI imagery for the Eyjafjallajökull, Grimsvötn, and Puyehue Case Study. He further discussed retrievals of cirrus cloud optical properties using CALIOP and SEVIRI. Intercomparison showed reasonable results for mass loading, and less consistent results for ash cloud top height.

Other related DLR projects are VolcATS (on nowcasting of ash-free and ash-contaminated areas) and TeFiS investigate the “grey” zone of German volcanic ash mass concentration regulation (2-4mg/m3).
3.3 Argentine Met Service (Guillermo Toyos)  
(MODIS_CENIZARG)  

Satellite-based volcanic ash detection and retrieval activities started after the Puyehue Cordon Caulle Volcanic Complex eruption in 2011. SMN Argentina use MODIS-based reverse absorption concept implemented at CONAE’s Ground Segment. He showed some preliminary results on a statistical approach for ash detection exploiting 11-12 μm brightness temperature differences and other portions of the electromagnetic spectrum (e.g. 8.5 μm, 6.7 μm, etc.), which is under development and will also use data from other sensors (e.g. VIIRS, etc.). The Prata LUT matching approach, which was used for the intercomparison exercise on PCCVC, is currently offline and being explored. Current and future work includes (i) sensitivity analysis of this approach to boundary conditions (Ts and Tc) and development of LUTs from optical properties of ash of Andean volcanoes, (ii) comparison with numerical models; work on MODIS-based retrievals vs. Fall-3D has started recently and (iii) look into resuspension of ash due to high winds. Collaboration with ground-based lidar sites in Bariloche and Buenos Aires is expected.

3.4 CMA Volcanic Ash Retrievals (Zhu Lin)  
(SEVIRI_CMA)  

She provided an introduction to the CMA satellite programme, described the improvements of FY-3 capabilities over time, and described the next generation of geostationary satellites FY-4 and the imager and sounder instruments on board. CMA investigated eruptions since 2010 to test FY-3 MERSI instrument (PCC, Etna, Sangeang (Indonesia)). Quantitative ash product has been developed for the FY-4A AGRI imager using SEVIRI as proxy. A forward model uses the Pavolonis approach, retrieval method, and validation using independent samples. She showed comparisons of the CMA product with CALIOP and the SEVIRI_NOAA, with good agreement in height retrieval above 5 km.

3.5 Development of Volcanic Ash Products for Korea Satellite Missions (Kwon-Ho Lee)  

In view of the upcoming GEOKOMPSAT-2A geostationary mission by the Republic of Korea, developing volcanic ash product as part of a dust product development. Motivation is the suspicion that North Korean nuclear tests may trigger volcanic eruption of Mt Baedu on the North Korean/Chinese border, and the vicinity of the country to many volcanos on the Pacific Ring of Fire. Himawari-8 AHI is used as the example for developing an ATBD for GEOKOMPSAT-2A/AMI. The commonality among new-generation imagers will be exploited to develop consistent products, and KMA will seek guidance on this development. A look-up table is under development of brightness temperature differences for different heights, r_eff, etc. Tests of ash retrieval algorithms with test cases using MODIS and COMS are underway. Distinction of ash and dust is an issue – there are attempts to use 1.64/0.87 ratio >0.9 to screen out dust. Korea maintains lidar network to validate ash.

CALIOP cannot distinguish ash and dust (the difference in dust properties from Western Sahara and East Sahara is larger than the difference of either to ash).

3.6 EUMETSAT (Phil Watts)  
(SEVIRI_EUMOP)  

Phil Watts presented the operational EUMETSAT Prata algorithm based on MSG SEVIRI IR imagery and a look-up table, and plans for replacing it in a more versatile optimal estimation cloud processor. RAL are currently leading an intercomparison-evaluating study to this effect (comparing
the Prata, OE (RAL ORAC and MET Office methods both presented at this meeting). The final report from this study is available from EUMETSAT. The OE cloud processor uses a physical inversion model and allows for retrievals of ash height, effective radius, ash type, and multiple (two) layer properties. It uses priors such as ECMWF model forecast fields. Testing of the OE scheme with regard to ash retrievals is ongoing.

3.7 UK MetOffice (Pete Francis and Mike Cooke)

(SEVIRI_MO, AVHRR_MO)
He described detection and retrieval of ash pressure, column mass loading and effective radius using SEVIRI IR imagery in a 1D-Var analysis, using background NWP profiles calculated with RTTOV. With Metop-A/AVHRR data, ash detection is based on a simple brightness temperature difference. He pointed out the importance of refractive index data needed to calculate mass absorption coefficients, and limitations of the Pollack et al. (1973) reference.

3.8 Australian Bureau of Meteorology (Chris Lucas)

(MODIS_BOM, MTSAT2_BOM)
Chris Lucas described the role of the Darwin VAAC; its area of responsibility comprises around 130 active volcanos. BOM uses the Hysplit dispersion model, and has installed the NOAA VOLCAT algorithm (MODIS_BOM). The MTSAT2_BOM algorithm uses the water vapour and IR channels of MTSAT2. For the 2014 eruption of Sangeang Api (Indonesia), he compared results for mass loading and \( r_{\text{eff}} \) for MODIS_BOM and MTSAT2_BOM, showing good consistency. He informed about the plans to include imagery from JMA Himawari-8 in the analyses. The VAAC is moving from Darwin to Melbourne. Main issues raised were (i) the seasonal variability in detection skill, and related management of user expectations, (ii) training of forecasters, especially when new products are introduced, (iii) what does \( r_{\text{eff}} \) mean in terms of ash size distribution.

3.9 Japan Meteorological Agency (Daisaku Uesawa)

(MTSAT2_JMA, MTSATIR_JMA)
He described the MTSAT-based JMA algorithm, which uses the water vapour and IR channels of MTSAT-1R/2, and ancillary data from JMA forecasts (LST, atmospheric profiles) and SST analysis. This look-up table approach was developed as prototype at JMA/MSC to determine AOD and \( r_{\text{eff}} \). The algorithm will not be further developed for use with the new-generation Himawari-8 imager (JMA is introducing the NOAA VOLCAT scheme for this purpose). It was applied to the Sarychev Peak, Kirishimayama and Kelut Case Studies. Preliminary analysis identified some issues with detecting high optically-thick ash clouds, and with false alarms.

Daisaku Uesawa mentioned the JMA testbed to support the intercomparison of ash retrieval algorithms; the testbed will be useful for hosting and testing operational codes based on common ancillary data. For inclusion in the testbed, the codes may only require minimum maintenance by JMA.

Furthermore, he showed results by JMA for estimating ash refractive index for a range of eruptions (including Puyehue Cordon-Caulle) using the AIRS sounder. The index could be useful input to the Himawari-8-based and other types of volcanic ash algorithms.
3.10 Oxford University (Imager-based) (Greg McGarragh)

(AQUA_MODIS_ORAC, TERRA_MODIS_ORAC)
He presented the Optimal Retrieval of Aerosol and Cloud (ORAC) algorithm applied to volcanic ash, applicable as a general physics-based retrieval code for multispectral imagery, based on the optimal estimation method. The code is available as a community code and used in a number of ash and cloud retrieval projects, such as ESA Climate Change Initiative Cloud_cci. The code distinguishes between a pre-processor, and a main processor doing the actual retrieval. It makes use of all imager channels for daytime retrievals of ash parameters. The forward model uses RTTOV (for radiative transfer in gas), DISORT (radiative transfer in the presence of particles/ash), assumptions about ash (refractive index, size distribution) and about the surface bi-directional reflectance distribution function (BRDF). Post-processing is applied using retrieval cost and brightness temperature differences.

He then discussed intercomparison results, comparing ORAC to other retrievals of ash cloud top height, \( r_{\text{eff}} \), ash fraction, and \( em_{550}/em_{10} \).

3.11 NOAA (Mike Pavolonis)

(SEVIRI_NOAA, MODIS_NOAA)
He explained components of the NOAA VOLCAT scheme, merging a range of LEO and GEO imagers for alerts of volcanic unrest and eruption, tracking and characterizing volcanic ash clouds, and dispersion forecasting. Sensitivity of the algorithm to detect ash is, in a first approximation, a function of cloud optical depth and cloud height. He argued that imagers generally have good sensitivity for semi-transparent clouds at mid- to high altitudes, and less in other cases. The intercomparison indicates 0.1 g/m² mass loading as the lower limit where ash can be detected. He stressed the value of using correlated spectro-temporal information in imagery loops for tracking ash as “spectral cloud objects”. Spatio-temporal resolution is also used for detecting puffs or explosions, based on temporal trends in brightness temperature, and growth rate anomalies. Complexities in detection arise due to the presence of meteorological clouds that underlie or obscure ash clouds.

3.12 University of Bristol (Luke Western)

(BRISTOL_IASI)
He described the probabilistic ash detection and optimal estimation-based retrieval algorithm using IASI. Probabilistic ash detection is NWP-dependent using a Bayesian approach. Classification is based on probability (clear, cloud, ash). Particle size distributions are assumed as gamma or log normal, since this has not been confirmed in the literature. FAAM airborne lidar and algorithm retrievals were compared during the Eyjafjallajökull event. Advantages of the approach are that it returns uncertainties and is reliable in many volcanic scenarios.

It was noted that none of the retrieval schemes work well for low ash clouds.

3.13 RAL (Richard Siddans)

(MODIS_RAL, SEVIRI_ORAC_RAL)
The MODIS_RAL algorithm was originally produced for the ESA SACS-2 project, SEVIRI_ORAC_RAL is part of the EUMETSAT study to use an optimal estimation-type volcanic ash retrieval (see 3.1). Both schemes include column SO₂ as a retrieved parameter, and utilize Bayes theorem applied to retrieval output to improve ash detection. He explained pros and cons of the ORAC approach (e.g., minimizing cost function in the retrieval using all channels has advantages,
but can mislead in case of multi-layer clouds). Forward modelling of multiple cloud layers is applied and has shown to improve retrievals (but also increase random error). He also discussed the addition of SO2 in the state vector, leading to reasonable SO2 retrievals in the case of Grimsvötn, but can over-determine ash retrievals (slower convergence).

3.14 Oxford University (Sounder-based) (Elisa Carboni)

(ISI_OXFORD)
She presented the ash detection and quantitative iterative retrieval scheme using IASI, based on optimal estimation, along with required assumptions and ancillary data. The error covariance matrix used in the retrieval is constructed from differences between forward-modelling calculation for clear sky, and IASI observations with no ash. This results in a covariance which allows deviations due to cloud, other aerosols and trace-gases but still enables the ash signature to be detected. Optimal estimation provides a full pixel-based error budget (not used in this intercomparison). To derive ash mass loading, assumptions on density, size distribution and refractive index are needed. She discussed false detections of ash over Africa caused by dust; retrieved cloud height compares well with CALIOP (both for the Eyjafjallajökull Case Study). Retrievals fail for high, cold plumes (Kelut) due to errors in the a priori altitude. Future work should assess the ability of retrievals to determine ash type (using improved refractive indices, ozone ECMWF profiles), and the effect of different IASI channel selections on the retrieval.

In the discussion, participants pointed out the prevailing large uncertainties of ash optical properties and size distribution. They suggested launching tethered balloons in thick ash plumes to better quantify its optical properties, such as refractive index. Dedicated campaigns are difficult to plan due to the nature of volcanic eruptions.

3.15 Université Libre de Bruxelles (Lieven Clarisse)

(ULB_IASI)
He described the “uniform aerosol detection” approach, consisting of spatially dependent covariance matrices, K-means clustering to discern representative ash classes, the Mahalanobis distance criterion, and linear discrimination analysis. Confidence levels are attached to ash detection results (low, medium, high) and detection algorithms classified in a range from robust, conservative to sensitive, with more false alarms. He discussed the signature of retrieval parameters (altitude, r_eff etc) in IASI spectra. Particle size distribution is the single biggest source of uncertainty in retrievals (of mass loading, for example) using the IR spectrum. For the Eyjafjallajökull Case Study, the intercomparison showed overall good agreement of algorithms for r_eff. Future work addresses combined ash/dust retrievals using neural networks.

In the discussion, Lieven Clarisse expressed the view that overall uncertainties of volcanic ash retrievals are estimated too low.

3.16 Support to Aviation Control Service (SACS) (Claus Zehner)

He described the SACS service which currently has 250 users and uses a range of LEO satellites to issue notifications on SO2 and ash indicators. Collaboration with several VAACs has been established. The system is conservative to avoid false alerts. Confidence levels in alerts are also provided. SO2 is often useful as a proxy for the occurrence of volcanic ash, and useful information in its own right (corrosive effect on aircraft, noxious impact on cabin air).
3.17 NASA MISR Retrievals (Ralph Kahn)

(MISR_RA)
He provided an overview of ash parameter retrievals using multi-angle multispectral imagery from MISR instrument-based algorithms that can be used as “validation” source in the intercomparison. Plume height can be estimated from the parallax in stereo imagery which is retrieved at 1.1 km horizontal resolution and about 500 m vertical resolution, along with the wind vectors associated with the plume elements. MISR has also been used to differentiate aerosol types based on particle size and shape constraints, using single-scattering phase functions derived from the multi-angular imagery. MISR thus allows retrieval of aerosol optical depth and distinction between non-spherical ash and spherical sulfate/water particles. It provides approximately weekly global coverage and is operated as a research mission, with support to some near-real-time operational applications such as cloud-tracked winds [1]. The MISR Standard aerosol product is available operationally [2], and plume heights are derived from the MISR Interactive Explorer (MINX) software on a case-by-case basis [3]. The issue of discerning ash from smoke and dust was discussed.

References:

3.18 Polar Multi-sensor Aerosol product (Rüdiger Lang)

(METOPB_PMAP, METOPA_PMAP)
Using the PMAp algorithm, he described retrievals of AOD with volcanic ash flag using the GOME sensor on Metop-A and B, over oceans only. No other parameters are provided. The algorithm is based on a look-up table. The AVHRR channels collocated with GOME on Metop-A/B are used for aerosol type pre-classification and derivation of the ash flag. PMAp AOD has been favourably compared with AERONET AOD data. He showed preliminary results of the intercomparison, indicating that PMAp tends to over-estimate AOD (probably due to residual cloud contamination) and has highest correlation with sensors from the same platform (probably due to accurate time matching). There is low correlation with CALIOP. The algorithm has been tuned to robustness (low false alarm rate). Further developments, e.g., retrievals over land, build on using IASI and tandem operations of Metop-A and –B. Smooth ocean-land transitions of products are a challenge. Further comparisons with results from the European Copernicus Atmospheric Monitoring Service, and AERONET, are planned.

3.19 UV absorbing aerosol index (Kai Yang)

He explained the physical basis for aerosol remote sensing in the UV, and contributions by the different components (surface, aerosols, Rayleigh scattering). UV aerosol index is defined as the spectral slope of reflectivity, determined from satellite spectral radiance by its deviation from Rayleigh scattering. There is demonstrated use of the aerosol index using OMPS on SNPP, and plans for the same instruments on JPSS-1 and 2. The DSCOVR L1 mission will provide additional functionality. Detection of ash using the UV aerosol index is independent of ice and liquid contents of clouds, and possible down to the lower atmosphere. UV imagery has helped operations in detecting ash in difficult conditions. Quantification of volcanic ash is accomplished by direct fitting of radiance spectra using radiative transfer modelling, performed with independent assumptions on refractive index and size distribution of ash cloud particles. There is potential synergy with IR-based
retrievals.

Remark:
No briefings were made describing the following algorithms that were part of the intercomparison:
AATSR_FMI
METOP_PLANETA

4. Validation and intercomparison, and next steps

Participants discussed in two groups conclusions from the meeting, and recommendations. These are summarized in section 5.

In addition:

- Participants highlighted the ash and dust products provided operationally and on a global scale by the European Copernicus Atmospheric Monitoring Service (CAMS).
- Upcoming conferences (EUMETSAT Meteorological Satellite Conference 2015 Toulouse (France), AGU December Conference San Francisco (USA), EGU (European Geosciences Union) April 2016 Conference in Vienna (Austria), ESA Living Planet Symposium 2016 Prague (Czech Republic) are opportunities to discuss volcanic ash matters and feature the intercomparison results
- WMO is planning an intercomparison and validation study for volcanic ash forecasting (including VAACs and research) which should be considered by the VASAG.
- RAL are to investigate the possibility of long-term storage of the intercomparison data and code; establishing a mirror site, possibly at the University of Madison-Wisconsin CIMSS, is an option to be further discussed.
- Participants generally supported the idea of preparing a peer-reviewed publication based on the intercomparison results. Richard Siddans, Mike Pavolonis, Pete Francis, Dave Schneider and Stephan Bojinski agreed to be part of an initial writing team.
- Proper credit is to be given to the author of datasets shared within this intercomparison, if used in a publication or presentation. Please mention always: name of instrument and platform; institution; principal investigator.

5. Conclusions from the Intercomparison, and Recommendations

In summary, the results from the intercomparison show related to detecting volcanic ash clouds:

1. Only well-dispersed ash clouds, with mass loadings that are generally less than 1 g/m², have been evaluated so far, as dictated by sampled reference data. The consensus lower limit of detection for passive IR techniques under suitable conditions (fine grained ash is the highest cloud layer and is sufficiently colder than the background) is 0.1 g/m², which is in very close agreement with previously established thresholds.
2. The sensitivity of passive satellite measurements can be divided into two categories. As VAACs routinely demonstrate through manual analysis of multi-spectral imagery, passive satellite measurements are most sensitive to the general presence of volcanic ash (discernable ash/no discernable ash). The sensitivity of passive satellite measurements to ash cloud properties (height and loading) is less than the sensitivity to ash detection because more assumptions are required to retrieve ash cloud properties. Thus, at a given location, the confidence in the discernable ash/no discernable ash classification will be greater than the confidence in the retrieved ash cloud properties.

3. Human expert analysis of the areal extent of volcanic ash within a given passive meteorological satellite image should be regarded as the upper limit of detection sensitivity. A consensus based ash detection analysis derived from the inter-comparison datasets contains very few false alarms, but has a detection sensitivity that is well below the upper limit. However, a few algorithms approached this upper limit without introducing a significant number of false alarms.

4. R&D satellites provide a useful contribution to advance the state of knowledge in volcanic ash cloud retrievals.

Related to quantifying volcanic ash clouds, the intercomparison showed that:

5. Best estimates of mass concentration from aircraft campaigns have uncertainties of a factor ~2 for <4mg/m3 (mainly due to uncertainty in composition/refractive index).

6. Mass loading values from passive satellite retrievals were validated in the range 0.1 - 1 g/m2 with FAAM airborne lidar measurements, and were shown to be capable of agreement with the aircraft data, given the uncertainties noted in item #1 above.

7. Pending further analysis, mass loadings compared between different schemes were in general in agreement to within a factor of between 2 and 4.

8. There was an observed tendency for mass loadings and effective radius retrievals from hyperspectral sounders to be smaller than their imager counterparts.

9. Passive retrievals of ash layer height show variable agreement with airborne- and space-borne lidar validation data, depending upon the scene conditions. Single-layer ash cases were shown to provide reasonable agreement (within ~2 km in general), with multi-layer cases proving more problematic for retrievals and for the current validation strategy.

10. Different retrievals of ash effective radius showed generally low correlations (0.2-0.5), although some well-correlated results were also noted. No in situ validation data were analysed as part of this inter-comparison.

11. Optical thickness correlations were somewhat higher (0.4-0.6) than for the effective radius comparisons noted in item #6 above («Different retrievals...»). However, some distributions showed unexplained characteristics.

12. Retrievals of optical thickness from schemes using visible reflectances yielded consistently higher values than for the IR-only schemes.

13. Spectrum-based discrimination between ash and dust only seemed possible from the use of hyperspectral sounder data - otherwise contextual information (e.g. back trajectories, etc.) were
required.

14. More detailed analysis of the intercomparison results is necessary (see Recommendations)

**Recommendations**

In the intercomparison, the following steps to improve satellite-based volcanic ash detection and quantification in the future were identified:

1. Full exploitation (spectral, spatial, temporal) of the space-based Global Observing System, including the next generation of sensors (e.g. new GEO imagers)

2. Expert analysis is important in determining a best-estimate of the spatial extent for volcanic ash (e.g., through consensus)

3. Acceptable false alarms rates need to be determined with users (VAACs, modellers)

4. Attach confidence levels to detection products to fulfil the needs of the VAACs (e.g., ‘low, medium, high’, or probabilities)

5. VAACs, VOs, and the remote sensing research community are encouraged to form collaborative links for training and interpretation of events. The VAACs recognize the value of satellite retrievals and indicate that most efficient use of these data sets are when they are within their operational analysis platforms. The research and operational communities are encouraged to work together on data format standards for ingest into their systems, as appropriate.

6. In-situ and ground-based remote sensing data can add value to near-source volcanic cloud detection and characterization, as many satellite-based techniques have difficulty in detecting this region.

7. Flag areas where ash can be reasonably expected (due to spatio-temporal context) but cannot be directly detected

8. Systematic analysis of CALIOP and possibly MISR reference data for volcanic eruptions is required

9. Better NRT access to ground-based lidar data, and better temporal/spatial network coverage is required

10. Provision of airborne ash measurements during future eruptions, plus resources for associated scientific analysis

11. In-situ and remotely-sensed particle size distribution (PSD) measurements are required more broadly. Using a log-normal size distribution of volcanic ash may be a recommended best practice for the dispersed ash cloud.

12. Ash cloud sensitivity studies using models and observation operators should be carried out

13. Optical ash properties should be revisited in laboratory experiments (main references from 1970s)

14. Encourage VAACs and other users and to share products and visualization tools
15. Since human expert analysis of the horizontal extent of volcanic ash represents the upper limit of detection within a given satellite image, which may be greater than 0.1 g/m² if difficult background conditions are present, quantitative volcanic ash products should be presented to users in tandem with multi-spectral imagery.

16. Further analysis should include breaking down mass loading intercomparisons into constituent components – e.g. optical thickness, effective radius, extinction efficiency, bulk density, etc.

17. Further analysis should include widening the scope of the validation data (e.g. including in situ PSD information)

18. Research groups should fill in gaps in the validation data for the current intercomparison case studies, where possible, for subsequent intercomparisons.

19. The volcano ash community is encouraged to formulate requirements (parameters, data formats, latency, possibly sites) to the GALION (WMO Global Atmosphere Watch Lidar Observation Network) and the ground-based aerosol network should also be considered.

20. The providers of volcanic ash detection and retrieval products should liaise with data assimilation centres to foster modelling and forecasting capabilities.

21. The intercomparison data and related processing and analysis code should be made available to the community, to support further analyses. Published work using the intercomparison data and code should provide appropriate references.

22. Pending final analysis of results, a second intercomparison is recommended, using more focused, in-depth comparisons of algorithms, using well-understood case studies, with additional validation data/scenes available (including expert ash analyses, aircraft data, CALIOP analyses), and using the next-generation imagers/sounders.
ANNEX I: Meeting agenda

MEETING ON THE INTERCOMPARISON OF SATELLITE-BASED VOLCANIC ASH RETRIEVAL ALGORITHMS WITHIN WMO SCOPE-NOWCASTING

29 June - 2 July 2015

Pyle Center, Madison, WI, USA

MONDAY, 29 JUNE

1. Background, overview of goals and user perspectives
(Chair: Mike Pavolonis)

13:00-13:20: Registration
13:20-13:30: 1.1 Welcome and practical information (Mike Pavolonis)
13:30-13:55: 1.2 Background and objectives in the context of ICAO and WMO SCOPE-Nowcasting (Stephan Bojinski)
13:55-14:10: 1.3 Volcanic ash information for the WMO Global Atmosphere Watch (GAW) and World Weather Research Project (WWRP) (Alexander Baklanov)
14:10-14:30: 1.4 Overview of CREW cloud intercomparison (Andy Heidinger and Bryan Baum)
14:30-14:50: 1.5 Overview of ESA volcanic cloud intercomparison activity (Claus Zehner)
14:50-15:10: Coffee break (included in registration fee)
15:10-15:30: 1.6 Overview of Anchorage VAAC operations with focus on use of satellite data (Don Moore)
15:30-15:50: 1.7 Overview of Washington VAAC operations with a focus on use of satellite data (Jamie Kibler)
15:50-16:10: 1.8 Overview of operations at the Alaska Volcano Observatory with a focus on use of satellite data (Dave Schneider)
16:10-16:30: 1.9 Dispersion modeling needs for satellite data (Larry Mastin)
16:30-16:50: 1.10 Potential impacts of the next generation of meteorological satellites (Mike Pavolonis)
16:50-17:30: 1.11 Group discussions on user needs (Moderator: Mike Pavolonis)

Topics for discussion (preliminary):
- Real-time volcanic ash applications desired by VAAC’s
- Real-time volcanic ash applications desired by modelers
- Ideas for operational applications from the research community
- Communicating uncertainty
- Role of research community in user training
- Blending automated satellite techniques with existing VAAC analysis techniques
- Impact of new sensors on eruption identification and ash cloud tracking
- Multi-sensor fusion

17:30-18:30: Cash bar at Pyle Center
18:00: Group dinner at Pyle Center (included in registration fee)
TUESDAY, 30 JUNE

2. Validation sources, intercomparison results, and algorithm overviews (Chair: Dave Schneider)

09:00-09:20: 2.1 Space-based lidar as a validation source (Anne Garnier)
09:20-09:40: 2.2 Airborne lidar measurements of volcanic ash: A validation source (Franco Marenco)
09:40-10:00: 2.3 Aircraft measurements as a validation source (Hans Schlager)
10:00-10:20: Coffee break (included in registration)
10:20-10:40: 2.4 Microwave measurements (space and ground based) as a validation source (Frank Marzano)
10:40-10:45: 2.5 Introduction to intercomparison results (Mike Pavolonis)
10:45-12:00: 2.6 Intercomparison results and discussion (Richard Siddens)
12:00-13:00: Lunch at Pyle Center (included in registration fee)
13:00-14:00: 2.7 Discussions on intercomparison results with focus on key questions (Moderator: Dave Schneider)

Key Questions (preliminary):

- How do the ash detection results vary as a function of satellite sensor(s) and technique?
- Which cases and scene types produced the most consistent and inconsistent ash detection results?
- What are the best methods for validating volcanic ash detection techniques (e.g. quantifying detection and false alarms)?
- How do the ash cloud property retrieval results vary as a function of satellite sensor(s) and technique?
- Which cases and scene types produced the most consistent and inconsistent ash cloud property retrieval results?
- Which ash cloud parameters are the most relevant and can be validated with sufficient accuracy?
- What are the best methods for validating volcanic ash cloud property retrieval techniques?

Satellite Algorithm Overviews

14:00-14:20: 2.8 INGV (Stefano Corradini and Luca Merucci)
14:20-14:30: 2.9 Discussion
14:30-14:50: 2.10 DLR (Kasper Graf)
14:50-15:00: 2.11 Discussion
15:00-15:20: Coffee break (included in registration fee)
15:20-15:40: 2.12 Argentine Met Service (Guillermo Toyos)
15:40-15:50: 2.13 Discussion
15:50-16:10: 2.14 CMA (Zhu Lin)
16:10-16:20: 2.15 Discussion
16:20-16:40: 2.16 KMA (Kwon-Ho Lee)
16:40-16:50: 2.17 Discussion
16:50-17:00: 2.18 End of day summary

WEDNESDAY, 01 JULY

3. Algorithm Overviews (continued) (Chair: Justin Sieglaflf)

09:00-09:20: 3.1 EUMETSAT (Phil Watts)
09:20-09:30: 3.2 Discussion
09:30-09:50: 3.3 UK Met Office (Pete Francis and Mike Cooke)
09:50-10:00: 3.4 Discussion
10:00-10:30: Coffee break (included in registration fee)
10:30-10:50: 3.5 Australian Bureau of Meteorology (Chris Lucas)
10:50-11:00: 3.6 Discussion
11:00-11:20: 3.7 JMA (Daisaku Uesawa)
11:20-11:30: 3.8 Discussion
11:30-11:50: 3.9 Oxford Imager Based (Greg McGarragh)
11:50-12:00: 3.10 Discussion
12:00-13:00: Lunch at Pyle Center (included in registration fee)
13:00-13:20: 3.11 NOAA (Mike Pavoloni)
13:20-13:30: 3.12 Discussion
13:30-13:50: 3.13 University of Bristol (Luke Western)
13:50-14:00: 3.14 Discussion
14:00-14:20: 3.15 RAL (Richard Siddens)
14:20-14:30: 3.16 Discussion
14:30-14:50: 3.17 Oxford Sounder Based (Elisa Carboni)
14:50-15:00: 3.18 Discussion
15:00-15:20: Coffee break (included in registration fee)
15:20-15:40: 3.19 Universite Libre de Bruxelles (Lieven Clarisse)
15:40-15:50: 3.20 Discussion
15:50-16:10: 3.21 SACS (Claus Zehner and Lieven Clarisse)
16:10-16:20: 3.22 Discussion
16:20-16:40: 3.23 NASA MISR retrievals (Ralph Kahn)
16:40-16:50: 3.24 Discussion
16:50-17:00: 3.25 End of day summary

THURSDAY, 02 JULY

4. Validation and intercomparisons (continued) and next steps (Chair: Dave Schneider)

09:00-09:20: 4.1 EUMETSAT PMAp Aerosol Retrievals (Ruediger Lang)
09:20-09:30: 4.2 Discussion
09:30-09:50: 4.3 UV absorbing aerosol index (Kai Yang)
09:50-10:00: 4.4 Discussion
10:00-10:30: Coffee break (included in registration)
10:30-12:00: 4.5 Discussions on intercomparison results (ash detection focus) (Moderator: Dave Schneider)

Discussion Topics (preliminary):
- For each sensor type, identify key attributes of ash detection algorithms that were shown to most consistently define the spatial bounds of the volcanic ash
- “Best practices” for ash detection algorithms.

12:00-13:00: Lunch at Pyle Center (included in registration fee)
13:00-14:30: 4.6 Discussions on intercomparison results (ash retrieval focus) (Moderator: Dave Schneider)

Discussion Topics (preliminary):
- For each sensor type, identify key attributes of ash cloud property retrieval algorithms that were shown to be most consistent with independent data (e.g., lidar and aircraft).
- “Best practices” for ash cloud property retrieval algorithms.
- Should an ensemble approach (merging results from several different methods) be strongly pursued?
- Should multi-sensor fusion approaches (within a common algorithm framework) be strongly pursued?
- Standard units and quality flags for volcanic cloud geophysical parameters
- Recommendations to Volcanic Ash Advisory Centres (VAACs) and other users on how to best to utilize quantitative satellite products in operations

14:30-15:00: 4.7 Discussions on next steps (Moderators: Stephan Bojinski and Alexander Baklanov)

Discussion Topics (preliminary):
- “Road map” for future volcanic ash related scientific developments and intercomparison/validation activities that can also be applied to SO2 clouds and emergent volcanic clouds
- Intercomparison report

15:00-15:20: Coffee break (included in registration fee)
15:20-16:00: 4.8 Continued discussions on next steps (Moderators: Stephan Bojinski and Alexander Baklanov)

16:00: Meeting concludes (in the event that the discussion sessions take less time than scheduled, the meeting will conclude earlier)
ANNEX II: List of Participants

Alexander Baklanov  
WMO, Research department  
7 bis, Avenue de la Paix, BP2300  
Geneva, 1211 Switzerland  
abaklanov@wmo.int

Bryan Baum  
SSEC  
1225 W. Dayton St  
Madison, WI 53706 USA  
bryan.baum@ssec.wisc.edu

Stephan Bojinski  
World Meteorological Organization  
7bis Avenue de la Paix  
Geneva, 1211 Switzerland  
sbojinski@wmo.int

Elisa Carboni  
University of Oxford  
AOPP, Clarendon Laboratory, Parks Road  
Oxford, UK OX1 3PU UK  
elisa@atm.ox.ac.uk

John Cintineo  
University of Wisconsin -- Madison  
1225 W. Dayton St.  
Madison, WI 53706 USA  
john.cintineo@ssec.wisc.edu

Lieven Clarisse  
Université Libre de Bruxelles  
Av. F.D. Roosevelt 50, CP 160/09  
Brussels, 1050 Belgium  
lclarisse@ulb.ac.be

Michael Cooke  
Met Office  
Fitzroy Road  
Exeter, Devon EX1 3PB United Kingdom  
michael.c.cooke@metoffice.gov.uk

Stefano Corradini  
Istituto Nazionale di Geofisica e Vulcanologia  
via di vigna murata, 605  
Rome, 143 Italy  
stefano.corradini@ingv.it

Frank S. Marzano  
Sapienza University of Rome  
Via Eudossiana 18  
Rome, Not U.S. 184 Italy  
frank.marzano@diet.uniroma1.it

Larry Mastin  
U.S. Geological Survey  
1300 SE Cardinal Court  
Bdlg. 10, Suite 100  
Vancouver, WA 98683 USA  
lgmastin@usgs.gov

Greg McGarragh  
University of Oxford, Department of Physics  
Clarendon Laboratory  
Parks Road  
Oxford, England OX1 3PU UK  
g.mcgarragh1@physics.ox.ac.uk

Luca Merucci  
INGV  
Via di Vigna Murata, 605  
Rome, Italy 143 Italy  
luca.merucci@ingv.it

Don Moore  
NOAA/NWS VAAC Anchorage  
6930 Sand Lake Road  
Anchorage, AK 99502 USA  
donald.moore@noaa.gov

Rosemary Munro  
EUMETSAT  
Eumetsat-Allee 1  
Darmstadt, Hessen 64295 Germany  
rosemary.munro@eumetsat.int

Mike Pavolonis  
NOAA/NESDIS/STAR  
1225 West Dayton Street  
Madison, WI 53706 USA  
mpav@ssec.wisc.edu

Hans Schlager  
Deutsches Zentrum für Luft- und Raumfahrt  
Institute of Atmospheric Physics  
Oberpfaffenhofen  
Wessling, Bavaria 82234 Germany  
hans.schlager@dlr.de
Alice Crawford  
NOAA Air Resources Laboratory  
NOAA NCWCP building.  
5830 University Research Ct.  
College Park, Md  20740 USA  
alice.crawford@noaa.gov

Pete Francis  
Met Office (UK)  
FitzRoy Road  
Exeter, Devon  EX1 3PB United Kingdom  
pete.francis@metoffice.gov.uk

Anne Garnier  
SSAI/LaRC  
1 Enterprise Parkway Suite 200  
Hampton, VA  23666 USA  
anne.garnier@latmos.ipsl.fr

Kaspar Graf  
German Aerospace Center (DLR)  
Institute of Atmospheric Physics  
Muenchner Str. 20  
Wessling, Bavaria  82234 Germany  
kaspar.graf@dlr.de

Andrew Heidinger  
NOAA/NESDIS/STAR  
1225 West Dayton Street  
Madison, WI  53706 USA  
andrew.heidinger@noaa.gov

Ralph Kahn  
NASA Goddard Space Flight Center  
Code 613  
Greenbelt, MD  20771 USA  
ralph.kahn@nasa.gov

Jamie Kibler  
NESDIS/OSPO/SPSD/SAB-Washington VAAC  
5830 University Research Court  
College Park, MD  20740 USA  
Jamie.Kibler@noaa.gov

Ruediger Lang  
EUMETSAT  
EUMETSAT Allee 1  
Darmstadt, Hessen  64295 Germany  
ruediger.lang@eumetsat.int

David Schneider  
USGS Alaska Volcano Observatory  
4230 University Dr  
Anchorage, Alaska  99508 USA  
djschneider@usgs.gov

Sung-Kyun Shin  
Gangneung-Wonju National University  
#415 Life Science building 7 Juk-Heon st.  
Gangneung, Gangwon  210702 South Korea  
skyun2011@gmail.com

Richard Siddans  
STFC Rutherford Appleton Lab  
Chilton  
Didcot, Oxon.  OX11 0QX UK  
richard.siddans@stfc.ac.uk

Justin Sieglaff  
UW/CIMSS  
1225 W. Dayton St  
Madison, WI  53706 USA  
justins@ssec.wisc.edu

Guillermo Toyos  
Servicio Meteorológico Nacional (SMN) /  
Comisión Nacional de Actividades Espaciales (CONAE)  
Av. Paseo Colon 751  
Buenos Aires,  1063 Argentina  
gtoyos@conae.gov.ar

Daisaku Uesawa  
Japan Meteorological Agency  
3-235 Nakakiyoto  
Kiyose, Tokyo  Japan  
d-uesawa@met.kishou.go.jp

Philip Watts  
EUMETSAT  
Eumetsat Allee 1  
Darmstadt, Hessen 64295 Germany  
philip.watts@eumetsat.int

Luke Western  
University of Bristol  
School of Earth Sciences  
Wills Memorial Building, Queen’s Rd  
Bristol, England  BS8 1RJ United Kingdom  
luke.western@bristol.ac.uk
Kwonho Lee
Gangneung-Wonju National University
7, Jukheon-gil
Gangneung, Gangwon-do 210-702 KOREA
kwonho.lee@gmail.com

Chris Lucas
Bureau of Meteorology
700 Collins St
Docklands, VIC 3008 Australia
c.lucas@bom.gov.au

Franco Marenco
Met Office
Fitzroy Road
Exeter, Devon EX1 3PB United Kingdom
franco.marenco@metoffice.gov.uk

Kai Yang
University of Maryland College Park
Dept. of Atmospheric and Oceanic Science
Computer and Space Science Building
College Park, MD 20742-2425 USA
kaiyang@umd.edu

Claus Zehner
European Space Agency
Via Galileo Galilei CP64
Frascati, Rome 00044 Italy
Claus.Zehner@esa.int

Lin Zhu
National Satellite Meteorological Center, China
Meteorological Administration
46 Zhongguancun south street, Haidian District
Beijing, 100081 China
zhulin@cma.gov.cn
Annex III: Algorithms considered in the intercomparison (22)

- Products that are publicly available in near-real time (NRT) are highlighted in green
- Products that are available in near-real time (NRT) are highlighted in yellow
- Products run in a research and development (R&D) mode are not highlighted

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<tr>
<th>Acronym</th>
<th>Dataset name</th>
<th>POC name</th>
<th>POC Email</th>
<th>Primary retrieved parameters and units</th>
<th>Applicable sensors and spatial resolution of retrieval output at nadir (only sensors that software can currently process)</th>
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<tbody>
<tr>
<td>1 SEVIRI_NOAA</td>
<td>NOAA</td>
<td>Mike Pavolonis</td>
<td><a href="mailto:Mike_Pavolonis@noaa.gov">Mike_Pavolonis@noaa.gov</a></td>
<td>Ash probability (%) Ash top height (km, AMSL) Ash top pressure (hPa) Ash mass loading (g/m²) Ash effective radius (μm) Ash optical depth at 11 μm Ash emissivity at 11 μm Ash 12/11 μm B ratio 1-sigma retrieval uncertainty estimates for state vector variables * retrieval state vector</td>
<td>SEVIRI (3 km) MODIS (1 km)</td>
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<td>2 IASI_OXFORD</td>
<td>Oxford IASI</td>
<td>Lucy Ventress</td>
<td><a href="mailto:Ventress@atm.ox.ac.uk">Ventress@atm.ox.ac.uk</a></td>
<td>Log 10 Ash optical depth at 550nm* Ash top pressure (hPa)* Ash effective radius (μm)* Ash mass loading (g/m²)</td>
<td>IASI-A, IASI-B (FOV circle of 12 km diameter)</td>
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<tr>
<td>3 METOP-A_PMAP</td>
<td>EUMETSAT</td>
<td>Michael Grzegorski / Ruediger Lang</td>
<td><a href="mailto:ruediger.lang@eumetsat.int">ruediger.lang@eumetsat.int</a></td>
<td>Ash optical depth at 550nm Ash top altitude (km)</td>
<td>GOME-2A (40 km ACT / 5 km ACT) GOMES-2B (40 km ACT / 10 km ACT)</td>
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<td>4 MTSAT2_BOM</td>
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<td>Chris Lucas</td>
<td><a href="mailto:c.lucas@bom.gov.au">c.lucas@bom.gov.au</a></td>
<td>Ash probability (%) Ash top height (km, AMSL) Ash top temperature (K)* Ash mass loading (g/m²) Ash effective radius (μm) Ash optical depth at 11 μm Ash emissivity at 11 μm Ash 12/11 μm B ratio 1-sigma retrieval uncertainty estimates Ash top height * retrieval state vector</td>
<td>MTSAT (4 km)</td>
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<td>5 MODIS_BOM</td>
<td>BOM (2)</td>
<td>Chris Lucas</td>
<td><a href="mailto:c.lucas@bom.gov.au">c.lucas@bom.gov.au</a></td>
<td>Ash probability (%) Ash top height (km, AMSL) Ash top temperature (K)* Ash mass loading (g/m²) Ash effective radius (μm) Ash optical depth at 11 μm Ash emissivity at 11 μm Ash 12/11 μm B ratio 1-sigma retrieval uncertainty estimates Ash top height * retrieval state vector</td>
<td>MODIS (1 km), Himawari-8 (when it becomes available)</td>
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<td>6 IASI_ULB</td>
<td>Université Libre de Bruxelles IASI</td>
<td>Lieven Clarisse</td>
<td><a href="mailto:lclariss@ulb.ac.be">lclariss@ulb.ac.be</a></td>
<td>Ash detection Ash mass loading (g/m²) Ash effective radius (μm) Ash optical depth at 10 μm Uncertainties</td>
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<td>7 SEVIRI_VADUGS</td>
<td>DLR_VADUGS</td>
<td>Kaspar Graf</td>
<td><a href="mailto:kaspar.graf@dlr.de">kaspar.graf@dlr.de</a></td>
<td>Ash mass loading (g/m²) * Ash top altitude (km)</td>
<td>SEVIRI (3 km)</td>
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<td>Argentine Met Service</td>
<td>Guillermo Toyo</td>
<td><a href="mailto:gtoyos@conae.gov.ar">gtoyos@conae.gov.ar</a></td>
<td>Ash mask Ash optical depth at 11 μm Ash effective radius (μm) Ash mass loading (g/m²)</td>
<td>MODIS (1 km), SEVIRI (3 km)</td>
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<td>9 MODIS_LUT</td>
<td>INGV (1)</td>
<td>Stefano Corradini and Luca Merucci</td>
<td><a href="mailto:stefano.corradini@ingv.it">stefano.corradini@ingv.it</a>, <a href="mailto:luca.merucci@ingv.it">luca.merucci@ingv.it</a></td>
<td>Ash top height (km, AMSL) Ash top temperature (K)* Ash mass loading (g/m²) Ash effective radius (μm) Ash optical depth at 11 μm Ash optical depth at 0.55 μm</td>
<td>MODIS (1km)</td>
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<td>10 MODIS_VPR</td>
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<td>Ash top height (km, AMSL) Ash top temperature (K)* Ash mass loading (g/m²) Ash effective radius (μm) Ash optical depth at 11 μm Ash optical depth at 0.55 μm</td>
<td>MODIS (1km)</td>
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<td>11 BRISTOL_IASI</td>
<td>University</td>
<td>Luke Western</td>
<td><a href="mailto:luke.western@bristol.ac.uk">luke.western@bristol.ac.uk</a></td>
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<td>No.</td>
<td>Instrument</td>
<td>Organization</td>
<td>Contact Person(s)</td>
<td>Retrieved State Variables</td>
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<td>Pete Francis/ Mike Cooke</td>
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<td>Ash top pressure (hPa)</td>
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<td>Alex Rublev</td>
<td>Ash mask*</td>
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<td>Ash mass loading (g/m^2)</td>
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<td>Ash optical depth at 0.55μm</td>
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<td>Ash optical depth at 550nm*</td>
<td>Ash top height (km)</td>
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<td>Ash top pressure (hPa)</td>
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<td>Ralph Kahn / Jim Limbacher</td>
<td>Total Column Aerosol Optical Depth (AOD; 550 nm); Total Column Aerosol Effective Radius (micron); stereo-derived plume height (km)</td>
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To: Dr Anthony Rea,

Chair, SCOPE-Nowcasting group

Dear Anthony,

Many thanks for today's joint session, which from our side was warmly received. In our discussion following the session, we noted that, from the point of view of the States involved, this initiative to propose volcanic ash as a SCOPE-nowcasting trial project, amongst other things, represents part of a proactive response to the Joint ICAO/WMO State Letter AN 10/18.3-13/53 of May this year (copy attached). We are also enthusiastic about the proposed intercomparison work, in support of continuous improvement of techniques and their implementation. Having better, efficiently implemented, and global volcanic cloud products (including ash and SO2) would certainly support the joint aims of ICAO and WMO in this area and particularly support VAAC operation, and therefore support the quality of information available for ash risk management for aviation.

We look forward to continued active dialogue in this regard, and we propose Dr Michael Pavolonis as the key contact for the WMO-IUGG Volcanic Ash Science Advisory Group

Kind regards,

Dr Larry Mastin & Dr Andrew Tupper

Co-chairs, WMO-IUGG Volcanic Ash Science Advisory Group

22 November 2013
Ref.: ICAO AN 10/18.3-13/53 31 May 2013

WMO WDS/AN/VA

Subject: Detection of volcanic ash in the atmosphere

Action required: Support activities to improve the availability of, and access to, satellite-based, ground-based and airborne volcanic ash detection data

Sir/Madam,

1. We have the honour to inform you that the International Volcanic Ash Task Force (IVATF), which was established by the International Civil Aviation Organization (ICAO) in close coordination with the World Meteorological Organization (WMO), has completed its work in respect of the response to the disruption caused to civil aviation by the eruption of the Eyjafjallajökull volcano in Iceland in April 2010.

2. One of the most important considerations of the IVATF was flight planning to avoid volcanic ash in the atmosphere that poses a significant hazard to flight safety and efficiency. During a volcanic eruption, flights will be planned on the basis of forecasts, prepared to internationally agreed standards, of the location and extent of volcanic ash clouds.

3. To ensure that data on the location and extent of volcanic ash clouds are made available to States that maintain volcanic ash advisory centres and/or meteorological watch office(s) within the framework of the ICAO international airways volcano watch, we kindly urge you to encourage and support necessary activities within your State to improve the availability of, and access to, satellite-based, ground-based and airborne volcanic ash detection data, taking into account where there is a need to establish a bilateral agreement as described in the attachment.

Accept, Sir/Madam, the assurances of our highest consideration.

Raymond Benjamin
Secretary General
ICAO

Michel Jarraud
Secretary-General
WMO

Enclosure:
Background on detection of volcanic ash in the atmosphere
ATTACHMENT to State letter AN 10/18.3-13/53

BACKGROUND ON DETECTION OF VOLCANIC ASH IN THE ATMOSPHERE

1. One of the most important considerations of the International Volcanic Ash Task Force (IVATF) was flight planning to avoid volcanic ash in the atmosphere that poses a significant hazard to flight safety and efficiency. During a volcanic eruption, flights will be planned on the basis of forecasts, prepared to internationally agreed Standards, of the location and extent of volcanic ash clouds. These are issued by volcanic ash advisory centres (VAACs) and/or meteorological watch offices (MWOs) within the framework of the international airways volcano watch (IAVW). Improved availability and access to volcanic ash observational data, including eruption source parameters, by the VAACs and the MWOs from satellite-based, ground-based and airborne detection systems, will lead to enhanced knowledge about the presence of volcanic ash in the atmosphere. The result of this will be increased observational capability and forecast accuracy, which in turn will lead not only to economic benefits for civil aviation through more efficient flight profiles, but also safety benefits through increased common situational awareness and user confidence.

2. Detection of volcanic ash in the atmosphere is currently possible through satellite-based remote-sensing technologies and ground-based and airborne detection systems. However, Eyjafjallajökull and similar eruptions, before and since, have demonstrated that observational data from such systems available at the VAACs and MWOs was often insufficient to enable these meteorological service providers to issue forecasts with a high level of confidence to the users. The issuance of forecasts uncorroborated by observations may have resulted in cancellations or deviations of scheduled flights which might otherwise have been conducted safely had better information been available.

3. Occasionally, observing networks used for the detection of volcanic ash in the atmosphere are maintained by a State only for non-operational, research-oriented purposes rather than for 24/7 operational decision-support purposes. Nevertheless, collaboration between non-operational and operational communities can often prove mutually beneficial. Where research-oriented resources are made available to assist the operational response, a bilateral agreement between the parties concerned may be necessary to ensure that requirements for the level of services and any associated costs are clearly specified.

— END —