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# Volcanic Ash Algorithm Intercomparison (SCOPE-Nowcasting PP2)

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## Summary and Purpose of Document

The volcanic ash cloud satellite-based retrieval intercomparison activity in SCOPE-Nowcasting 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. It contributes to improved knowledge of satellite-based detection and quantification of volcanic ash. The results are also expected to benefit other meteorological applications such as nowcasting and air quality forecasting.

The intercomparison (organization of which started in late 2014 and results were discussed at a workshop in July 2015) considered more than 20 passive satellite sensor algorithms from institutions and groups all over the world; reference data were used from the CALIPSO CALIOP spaceborne 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).

Results of the intercomparison are summarized in this paper. In general, for reasons of scientific understanding and utility of its results for operational volcanic ash services, the intercomparison revealed the need for additional scientific development of algorithms and more detailed comparisons between datasets within an organized international framework. Thus, a continuation of the intercomparison over a period of 12-18 months is recommended, for which dedicated resources would be required. The proposed next steps are outlined in this document.

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## ACTION PROPOSED

The second session is invited to note the information and recommendations contained in this paper, and comment on the proposed way forward with this Pilot Project;

**Appendices**: A. International Participation
B. Intercomparison Case Studies
C. Intercomparison Recommendations

# DISCUSSION

## 1. Background and Introduction

High quality quantitative volcanic ash cloud products are needed to improve the volcanic ash cloud analyses and dispersion forecasts provided to aviation users. Quantitative satellite remote sensing of volcanic ash clouds has evolved significantly over the last decade with the advent of new sensors and techniques. In order to document the current state of satellite-based volcanic ash cloud retrieval science and to determine how best to evolve the science within the context of meeting end-user needs, several actions must be taken by the international research community.

1. Using pre-selected cases, quantify the differences between satellite-derived volcanic ash cloud properties derived from different techniques and sensors.
2. Establish a basic validation protocol for satellite-derived volcanic ash cloud properties
3. Document the strengths and weaknesses of different remote sensing approaches as a function of satellite sensor
4. Standardize the units and quality flags associated with volcanic cloud geophysical parameters
5. Provide recommendations to Volcanic Ash Advisory Centers (VAACs) and other users on how to best to utilize quantitative satellite products in operations
6. Create a "roadmap" for future volcanic ash-related scientific developments and intercomparison/ validation activities that can also be applied to $SO_2$ clouds and emergent volcanic clouds

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.

The above activities, which were first informally discussed by an international contingent of scientists in Geneva, Switzerland in November 2013, are succinctly referred to as the "international volcanic ash intercomparison." In recognition of its importance, the World Meteorological Organisation (WMO) has provided an organized forum for the international volcanic ash intercomparison under the Sustained, Coordinated Processing of Environmental Satellite Data for Nowcasting (SCOPE-Nowcasting) initiative (http://www.wmo.int/pages/prog/sat/scope-nowcasting_en.php) as Pilot Project 2.

This Pilot Project reports 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.

Results from the intercomparison activity were presented and discussed at the WMO International Volcanic Ash Intercomparison Meeting held 29 June – 2 July 2015 in Madison, WI, USA. All of the presentations from the Madison meeting are available on the web at: http://cimss.ssec.wisc.edu/meetings/vol_ash15. Volcanic ash satellite remote sensing experts from operational and research organizations participated in the intercomparison activity (see Appendix A). The intercomparison focused on volcanic ash cloud properties for several pre-selected cases that span a wide range of background conditions and ash cloud properties (see Appendix B). While volcanic sulphur dioxide satellite remote sensing is also a very important topic, this study was focused solely on volcanic ash due to time and resource constraints. A WMO report that documents the intercomparison results and recommendations is available at:
http://www.wmo.int/pages/prog/sat/documents/SCOPE-NWC-PP2_VAIntercompWSReport2015.pdf

## 2. Primary Conclusions of Intercomparison (as of July 2015)

The primary conclusions of the intercomparison activity can be summarized as follows:

1. The primary sensitivity of passive satellite measurements is to the presence or, lack thereof, of detectable volcanic ash.

2. Only a couple of automated ash detection methods were able to approach the skill of a human analyst.

3. The lower detection limit of the most sensitive algorithm/sensor combinations was between 0.01 and 0.1 g/m$^2$.

4. Given the uncertainty of aircraft based estimates of mass loading, the uncertainty in satellite based assessments is greater than a factor of 2 and most satellite derived mass loadings differed from aircraft assessments by a factor of 4 or more. The uncertainty in concentration will be greater.

5. Complicated backgrounds are common and further increase uncertainty in all satellite-derived products.

6. High spectral resolution measurements while currently spatially and temporally limited, help to mitigate some issues with complicated scenes.

## 3. Proposed Next Steps

Relative to satellite-derived meteorological cloud properties, quantitative satellite-derived volcanic ash cloud properties do not have a long heritage in operational applications. To facilitate operational readiness, in response to the demand for quantitative ash cloud products from the aviation user community, an organized international effort is needed to benchmark the accuracy of various satellite products under a large variety of conditions and establish best scientific practices for operational applications. Under SCOPE-Nowcasting, the first component of an international effort to benchmark and inter-compare volcanic ash products derived from satellite measurements has been completed.

The successful WMO Intercomparison of Satellite-based Volcanic Ash Retrieval Algorithms activity broadly revealed that the accuracy of satellite-based volcanic ash products is a strong function of the retrieval methodology, satellite sensor capability, and scene complexity. In order to benchmark the various retrieval methodologies and satellite sensors as a function of the scene attributes (e.g. number of cloud layers, type of underlying surface, ash composition, etc.) and ascertain which methodologies and scientific practices are best suited for operational applications, the intercomparison activity needs to be advanced further using the recommendations from the 2015 intercomparison report as a guide (see Appendix C).

Given the significant effort required to advance the inter-comparison and benchmarking exercise, this activity can only be completed as a formal effort, with dedicated resources. The proposed additional intercomparison activities are well aligned with a recommendation from IWVA/7 (“Continued international collaboration to integrate best remote sensing practices into real-time applications that are sustained and contribute to the global harmonization of operational capabilities”) and outcomes from the VAAC Best Practices Workshop in May 2015. The following actions should be completed within a 12-18 month period.

- Generate additional human expert analysis, from multiple analysts, and compare to the ash detected by the satellite algorithms over the course of an event (ensure that GEO and LEO comparisons can be made)
- Acquire DLR aircraft data and compare to satellite products in a manner that is analogous to the UK-FAAM analysis
- Where possible, acquire independent estimates of ash optical depth and mass loading from space-based lidar (CALIOP), ground-based lidar (EARLINET), and sun photometers and compare to passive satellite retrievals
- *Gain detailed insight into differences:* Compare all retrieval inputs (satellite measurements and

ancillary data) for a select number of common pixels, co-located with validation data, with different background conditions (water background, land background, meteorological cloud background, etc.). For the same common pixels, analyze all retrieval outputs.

- Where practical, partition validation data according to certain scene attributes (underlying cloud layers, land surface, water surface) and compare to satellite retrievals
- Assess the impact of viewing angle on the accuracy of satellite retrievals through comparisons to CALIOP and analysis of internally generated uncertainty estimates
- Inter-compare volcanic ash products derived from the first of the next generation geostationary satellites (Himawari-8 AHI) to volcanic ash products derived from heritage LEO and GEO sensors
- Develop a database of existing “state of the art” volcanic ash optical and microphysical properties
- *If resources allow a more detailed understanding of differences in satellite retrieval methodologies and sensor capabilities should be extracted using model simulated satellite data sets. More specifically, simulated satellite data sets with volcanic ash need to be generated. Each relevant satellite sensor (LEO/GEO and imager/sounder) would need to be simulated. Each retrieval methodology would then be applied to the simulated data and compared to the known solution. A 2-dimensional simulated data set is needed in ensure that algorithms with spatial dependencies are applicable. This action requires significant effort and close collaboration between the algorithm providers, the modeling community, and the group performing the inter-comparison analyses.*

Regarding the necessary resources, a first estimate of needed man-months has been made. Upon completion of the above actions, a second intercomparison meeting should be held to discuss the results in detail and report back to the international user and scientific communities.

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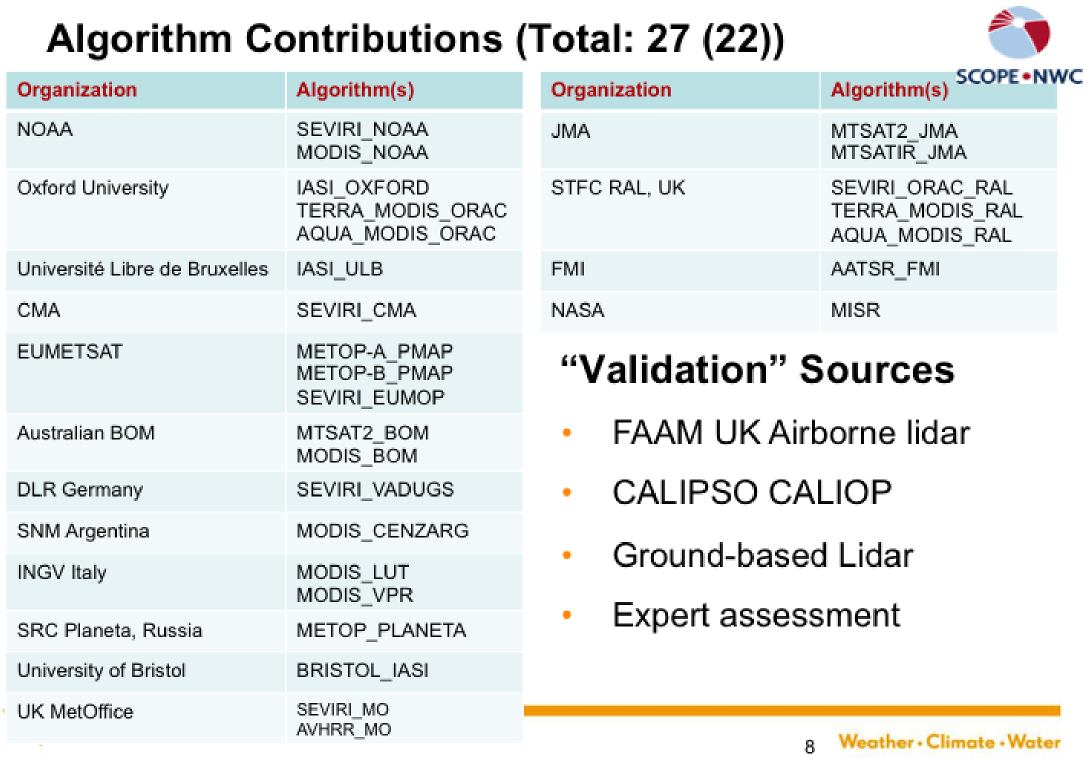
## Appendix A

### International Participation in the Intercomparison

A total of 27 passive satellite-derived volcanic ash data sets, produced by 22 different retrieval methodologies, were intercompared and all passive satellite products were compared to 4 sources of validation data (see below).



## Algorithm Contributions (Total: 27 (22))

SCOPE•NWC

| Organization | Algorithm(s) |
|---|---|
| NOAA | SEVIRI_NOAA<br>MODIS_NOAA |
| Oxford University | IASI_OXFORD<br>TERRA_MODIS_ORAC<br>AQUA_MODIS_ORAC |
| Université Libre de Bruxelles | IASI_ULB |
| CMA | SEVIRI_CMA |
| EUMETSAT | METOP-A_PMAP<br>METOP-B_PMAP<br>SEVIRI_EUMOP |
| Australian BOM | MTSAT2_BOM<br>MODIS_BOM |
| DLR Germany | SEVIRI_VADUGS |
| SNM Argentina | MODIS_CENZARG |
| INGV Italy | MODIS_LUT<br>MODIS_VPR |
| SRC Planeta, Russia | METOP_PLANETA |
| University of Bristol | BRISTOL_IASI |
| UK MetOffice | SEVIRI_MO<br>AVHRR_MO |

| Organization | Algorithm(s) |
|---|---|
| JMA | MTSAT2_JMA<br>MTSATIR_JMA |
| STFC RAL, UK | SEVIRI_ORAC_RAL<br>TERRA_MODIS_RAL<br>AQUA_MODIS_RAL |
| FMI | AATSR_FMI |
| NASA | MISR |

## “Validation” Sources

- FAAM UK Airborne lidar
- CALIPSO CALIOP
- Ground-based Lidar
- Expert assessment

8 Weather • Climate • Water

## Appendix B

## Intercomparison Case Studies

The cases utilized in the intercomparison study were chosen to coincide with independent measurements that can serve as "truth" for at least some retrieved parameters (e.g. ash cloud height). In addition, an effort was made to cover a broad range of ash cloud properties and background conditions within different geostationary satellite coverage areas and Volcanic Ash Advisory Center (VAAC) regions. All of the selected cases produced large ash clouds with large-scale (e.g. regional and greater) impacts on aviation. The larger scale events allow for more robust intercomparison/validation statistics to be computed (e.g. many pixels can be analyzed). Smaller eruptions are also important and far more common than eruptions that produce large amounts of ash. The tools developed for the intercomparison can be applied to ash eruptions that produce more localized impacts at a later time through collaborations brought about by the intercomparison exercise or as a possible organized follow-on activity. The following cases were evaluated: Eyjafallajökull (2010), Grimsvötn (2011), Sarychev Peak (2009), Kelut (2014), Puyehue-Cordón Caulle (2011), and Kirishimayama (2011). Algorithm providers provided data as described in the intercomparisn work plan (http://cimss.ssec.wisc.edu/meetings/vol_ash15/wmo_satellite_ash_retv_intercomparison_plan.pdf). The rational for selecting each case is as follows:

*Eyjafallajökull (2010)* – This long-duration, high impact, event is well captured by a modern geostationary satellite sensor and "validation" data (ground, aircraft, and space-based) are plentiful. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, IASI, MISR, MODIS, and SEVIRI.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=372020

*Grimsvötn (2011)* – This eruption is well captured by a modern geostationary sensor and the emergent, ash-rich, cloud provides an opportunity to assess retrieval performance in a high mass loading scenario. A fair amount of "validation" data (ground and space-based) is also available for this event. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, IASI, MISR, MODIS, SEVIRI, and SSMIS.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=373010

*Sarychev Peak (2009)* – This event allows for algorithm comparisons over a broad range of ash optical depth and background meteorological conditions. In addition, ash from this eruption was tracked by three VAACs (Tokyo, Anchorage, and Washington). Many CALIOP overpasses are available to serve as "validation" data. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, IASI, MODIS, and MTSAT.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=290240

*Kelut (2014)* – Large amounts of ash were produced by a highly explosive eruption in a very moist tropical environment where satellite remote sensing methods sometimes struggle. A jet aircraft encounter also occurred a few hours after the start of the eruption. Some CALIOP overpasses are available to serve as "validation" data. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, CrIS, IASI, MODIS, MTSAT, and VIIRS.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=263280

*Puyehue-Cordón Caulle (2011)* – This is the most silicic major eruption of the satellite era so it provides an unprecedented opportunity to assess the sensitivity of satellite retrieval algorithms to the composition of the ash. Many CALIOP overpasses are available to serve as "validation" data. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, IASI, MODIS, and SEVIRI.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=357150

*Kirishimayama (2011)* – This case allows for intercomparisons within a sub topical environment with plentiful background boundary layer liquid water cloud cover, which sometimes severely impacts the retrieval of the overlying ash cloud properties. The analysis for this case will be centered around a single CALIPSO overpass. Anticipated satellite sensors of relevance: AIRS, AVHRR, CALIOP, IASI, MODIS, and MTSAT.
Volcano information: http://www.volcano.si.edu/volcano.cfm?vn=282090

## Appendix C

## Intercomparison Recommendations

In the 2015 intercomparison activity, 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

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

10. 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.

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

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

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

14. 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.

15. Further analysis should include breaking down mass loading intercomparisons into constituent

components – e.g. optical thickness, effective radius, extinction efficiency, bulk density, etc.

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

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

18. 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.

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

20. 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.

21. 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