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WMO AEROSOL BULLETIN

INTEGRATED OBSERVATIONS OF ATMOSPHERIC AEROSOLS

Volcanic Aerosols

Volcanic aerosols are a specific kind of atmospheric particles that are important for aviation safety and climate modelling. On one hand, the volcanic eruption in Iceland (Figure 1) demonstrated a need for better knowledge of volcanic ash dispersion in the atmosphere to ensure security of air traffic. In this respect, delivery of warnings of volcanic ash is important. On the other hand, the success in implementation of the Paris Agreement on climate change depends to a certain extent on improved knowledge of the climate system. Estimates of aerosol impacts on climate are largely uncertain. Volcanic aerosols are one of the sources of sulphur in the upper troposphere and may have a cooling effect on climate that needs to be quantified. This third issue of the WMO Aerosol Bulletin focuses on recent advances in monitoring and modelling volcanic ash and other related aerosols. The points discussed in this issue draw on the work of the WMO Global Atmosphere Watch (GAW) Programme, which collaborates closely on volcanic aerosols with the International Civil Aviation Organization (ICAO), the International Union of Geodesy and Geophysics (IUGG) and other partners. The issue explores ongoing progress on light detection and ranging ("lidar") instruments, the GAW Aerosol Lidar Observation Network (GALION) alerting system, a new initiative on intercomparison of volcanic ash forecasting products, and the International Airways Volcano Watch.

Introduction to volcanic aerosols

Aerosols – small particles suspended in the atmosphere – are an important part of the composition of the atmosphere. They affect climate, human health and many economic sectors. While climate change research has focused on anthropogenic aerosols (mainly released via fossil fuel burning), the subject should also be considered in the context of natural aerosols (such as dust, sea salt, and ash from volcanoes and wild fires), which are usually released in greater quantities.

Volcanic eruptions contribute to natural aerosols directly, via emissions of ash and other particulates, or indirectly, through the release of sulphur gases that

Figure 1. *Eyjafjallajökull volcanic eruption, Iceland, 16 April 2010.*

subsequently condense to form sulphate aerosols. While ash particles are quickly removed from the atmosphere due to their relatively large size, smaller sulphate particles can cause substantial climate cooling, especially if released volcanic gases travel up to the lower stratosphere. There, in the absence of clouds and associated removal processes, the lifetime of sulphate aerosols is extended and can reach the order of years at lower latitudes.

Thus, major volcanic eruptions may contribute to significant climate cooling for two to three years – for example, as occurred in 1992 and 1993 following the Mount Pinatubo eruption of 1991 (Robock, 2000). In the troposphere, continuous degassing by volcanoes leads to regional cooling through direct and indirect effects (as sulphate aerosols act as efficient cloud condensation nuclei). This reduces air quality and visibility and also poses dangers to air traffic.

Use of lidar techniques for volcanic aerosol observations

Lidar techniques

Ground-based lidar techniques represent a powerful method for monitoring the dispersion of a volcanic cloud in the atmosphere. Lidar instruments use ultraviolet, visible or near-infrared light to image aerosols. They can be used at different locations: close to the source for monitoring mainly the volcanic plume height, or a long distance away to provide data on the atmospheric dispersion of the volcanic cloud. Lidar observations can be much more powerful if coordinated across monitoring networks. Lidar monitoring networks are fundamental for the study of aerosols on a large spatial scale, including the processes of their transport and transformation. Coordinated lidar ground-based observations are valuable when integrated with satellite data to show the evolution of the event over space and time.

The first aerosol measurements by lidar were recorded in late 1966. However, the technique was not widely used in research until the 1990s. It was not until after the eruption of Mount Pinatubo in the Philippines in 1991 that the scientific community started to explore the possibility of using lidar techniques for the investigation of stratospheric volcanic clouds. There was a large increase in the number of published papers and citations on aerosol lidar methods after the first studies on the Pinatubo eruption were published. This event triggered the augmentation in use of aerosol lidar methods and data.

In a similar way, the air traffic crisis caused by the eruption of Eyjafjallajökull in Iceland in 2010 can be considered as the starting point of a new era for aerosol lidars. The event coincided with the achievement of a level of maturity of aerosol lidar methods that enabled the research community to provide almost continuous lidar measurements over Europe (technical maturity), to translate near-real-time measurements into information useful to decision-makers (communication maturity) and to develop ad hoc products for other scientific users (scientific maturity).

Nowadays, there are different lidar techniques for the investigation of aerosol properties spanning from the simplest elastic backscatter lidar to others that are more complex and advanced, such as the multi-wavelength Raman lidar and the high spectral resolution lidar (HSRL). All of these techniques are suitable for monitoring the spatial and temporal distribution of volcano-emitted particles up to the upper troposphere and lower stratosphere regions. They can characterize these particles from a dynamical and in some cases microphysical point of view.

The more complex the lidar technique is, the more information it can deliver. The simplest lidar provides the geometrical properties (top and bottom) of the aerosol layers and some aerosol optical properties; more advanced lidar techniques (that is, Raman or HSRL) provide more quantitative data about aerosol optical properties (such as lidar ratio and aerosol backscatter and extinction coefficient profiles). Multi-wavelength Raman lidar and HSRL provide spectral aerosol optical properties that could be used to derive microphysical properties (shape, size and refractive index) using appropriate numerical algorithms.

In this way, lidar techniques provide valuable information about aerosol optical and microphysical properties, which are relevant for both climate and air-quality research.

One of the objectives of the WMO GAW Programme is to study the four-dimensional space–time distribution of aerosols. A strong effort to determine the spatio-temporal distribution of aerosol properties related to climate forcing and air quality up to multi-decadal time scales is underway within the Programme, where the establishment of a global lidar observation network has been considered of strategic importance. While within GAW an observing network for aerosol properties at ground level is well established, and a programme has been initiated for the coordination of sun-photometer networks for measuring column-integrated aerosol optical properties, the vertical component is not yet covered.

The mission of GALION is to organize the capability to observe the four-dimensional distribution of key aerosol parameters on a global scale (GAW Report No. 178, see WMO, 2007).

The vertical component of this distribution will be provided by GALION through advanced laser remote sensing from a network of globally distributed ground-based stations. GALION is a federated network of existing lidar networks that contribute data to GAW: Asian Dust and Aerosol Lidar Observation Network, Latin American Lidar Network, Atmosphere Aerosol and Ozone Monitoring in CIS Regions through Lidar Stations Network, European Aerosol Research Lidar Network (EARLINET), Micro-pulse Lidar Network, Network for the Detection of Atmospheric Composition Change, National Oceanic and Atmospheric Administration (NOAA) Cooperative Remote Sensing Science and Technology Lidar Network and Canadian Operational Aerosol Lidar Network.

GALION observations of volcanic particles

Because explosive volcanic eruptions are sudden and unforecastable events that can affect the upper troposphere and lower stratosphere regions at a global scale, an alerting system has been set up for this kind of event within GALION. This alerting system notifies the lidar stations about specific events such as explosive volcanic eruptions. It also provides notifications about other events, such as intense dust outbreaks and large forest fires, in order to perform coordinated observations of the specific event. In 2011, the Nabro eruption in Eritrea resulted in the first GALION-coordinated effort for the monitoring of a specific single event at the global scale. The result was the observation and characterization of the volcanic plume as it moved around the globe, with a detailed analysis of extensive (such as aerosol optical depth (AOD)) and intensive (mainly lidar ratio) properties (Figure 2). GALION observations were complemented by CALIPSO satellite measurements, showing the advantages of the synergistic use of ground-based global observations and satellite data.

The role of lidar and GALION during a volcanic crisis

In 2010, Europe was hit by a volcanic crisis that caused the closure of air space over the European continent. This had economic and social impacts and affected air quality over north-western Europe. The Eyjafjallajökull volcano in Iceland started its explosive eruptive phase on 14 April 2010, injecting large amounts of ash and sulphates into the troposphere (Stohl et al., 2011). By the following day, European society had discovered it was not prepared for this kind of event. Since then, the European Union has supported many initiatives for improving resilience to volcanic events. At the time, however, the only routine observational data available for supporting the forecasting and management of the crisis was certain satellite products.

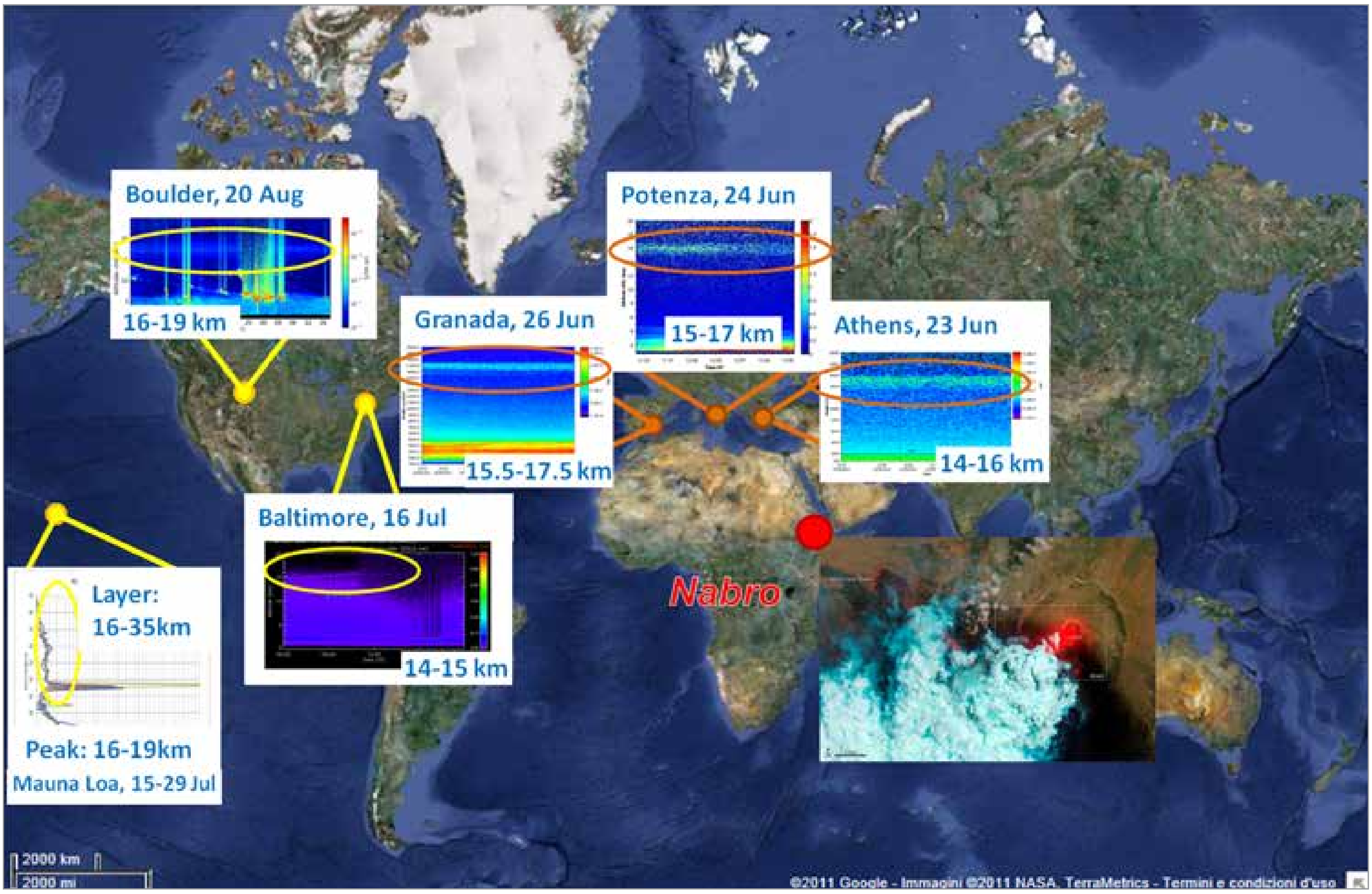

Figure 2. *GALION lidar network observations of the Nabro eruption plume in summer 2011. This event was the first example of GALION-coordinated observations worldwide (Sawamura et al., 2013).*

Policymakers and agencies reached out to state-of-the-art research communities to acquire further knowledge about the volcanic cloud distribution over Europe. EARLINET, the European component of GALION, performed lidar aerosol observations whenever weather conditions permitted to support decision-makers during the entire event until 21 May. A report of the observations of the volcanic cloud at EARLINET stations was sent daily to the Volcanic Ash Advisory Centre (VAAC) and WMO containing information about the altitude at which volcanic particles were observed (Figure 3).

Once the crisis period ended, a methodology was specifically designed by EARLINET for this event. It provided a detailed description in four-dimensions of the distribution of the volcanic cloud over Europe for the whole period. Geometrical properties of the volcanic cloud over Europe were provided with high vertical resolution (typically 60–180 m) in terms of base, top and centre of mass of the volcanic layer. Any mixing of volcanic particles with other kinds of aerosol (e.g., continental and local dust) was identified. Mixing with Saharan dust was observed mainly during May 2010 at all Southern Europe stations. Quantitative optical data collected by EARLINET during this event, including a specific relational database of parameters describing the geometrical properties of the volcanic cloud, were used for model evaluation, satellite-data validation, and integration.

Lidar for resilience

The 2010 volcanic crisis showed the need for near-real-time monitoring of volcanic clouds for air traffic safety. It also confirmed the benefits of having operational lidars to detect a volcanic plume and describe its spatio-temporal distribution as an integral part of these observations. Information obtained close to the source is very valuable for the initialization of plume-transport models, while information about the global distribution of the ash vertical layering, in combination with satellite and aircraft observations, is fundamental for early warning activities.

In this sense, many initiatives are operating worldwide. Meteorological services recognize the importance of working towards a better standardization of commercial automatic systems for aerosol vertical

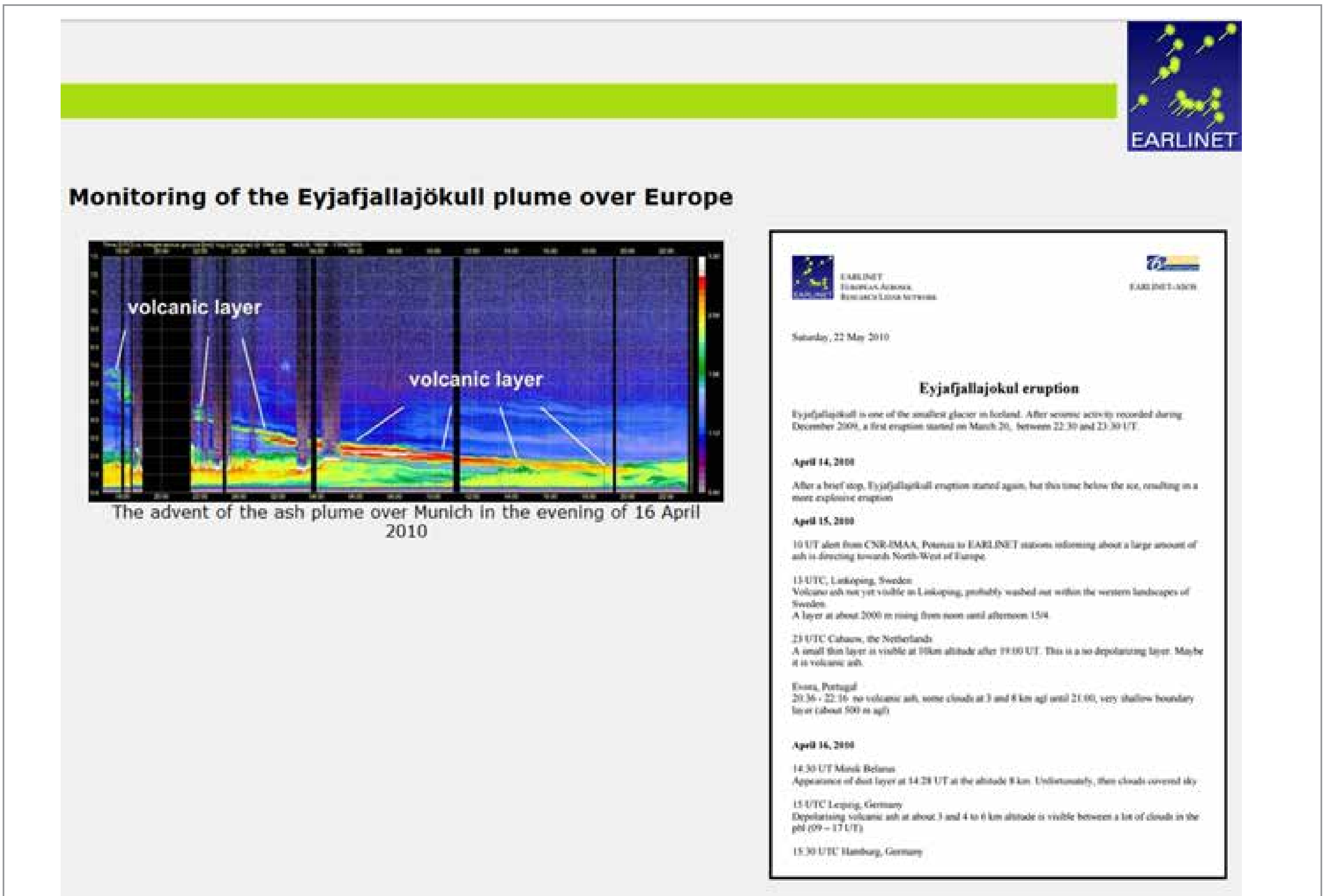

Figure 3. *EARLINET performed measurements intensively during the volcanic crisis that affected Europe in 2010. Although not an operational network, fast analysis was performed to provide valuable information to public services. A report on the observation and no observation of volcanic cloud over EARLINET stations was sent daily to VAAC and WMO. Quick Look images were promptly made available through the EARLINET web page (Pappalardo et al., 2013).*

profiling. The ceilometer lidar is the easiest to use and cheapest instrument for this application. It has been demonstrated that even under certain limits and assumptions, ceilometers are effective for the detection of intense aerosol plumes, and in some cases also for their quantitative characterization.

Within GALION, the linking of research lidar networks and operational ceilometers is in progress. Cooperation between the operational and research communities is the best approach for providing comprehensive information to decision-makers during crisis situations. Operational networks rely on advanced research lidar systems for the calibration of their own lidar systems. This is important, for example, for improving the retrieval of profiles of optical properties and for understanding the reliability of the necessary assumptions in their retrieval.

Nowadays, the geographical distribution of operational lidar systems (ceilometer and commercial) is such that they are able to provide a good coverage over Europe and North America, and partially over Japan and South America (Figure 4). The coverage over Africa, Asia, Australia and the polar regions is sparse. The high number of ceilometer and automatic lidar systems available today can provide a better spatial coverage of vertical profile measurements of aerosols for tracking ash and dust plumes, and for monitoring long-range transport. This is supported by research lidar systems used as anchor stations to provide reference bias-free data.

International inter-comparison of satellite-based volcanic ash products

High-quality, quantitative volcanic ash-cloud products are needed to meet the evolving needs of users, especially those in aviation. Quantitative satellite remote sensing of volcanic ash clouds has evolved significantly over the last decade with the advent of new sensors and techniques. Models that forecast the dispersion and transport of volcanic ash clouds have also evolved, and satellite products have been shown to improve forecasts.

To document the state of satellite-based volcanic ash cloud retrieval science and improve international coordination on research and operational activities related to satellite remote sensing of volcanic ash, a product inter-comparison initiative has been created. This initiative was established by an international contingent of scientists attending the second IUGG–WMO Workshop on Ash Dispersal Forecast and Civil Aviation, held in Geneva, 18–20 November 2013. The inter-comparison activity was subsequently formalized through the creation of a pilot project under the WMO Sustained, Coordinated Processing of Environmental Satellite Data for Nowcasting (SCOPE-Nowcasting) initiative. The goal of the WMO SCOPE-Nowcasting initiative, which is led by the WMO Space Programme, is to demonstrate continuous and sustained provision of consistent, well-characterized satellite products for nowcasting and severe-weather risk reduction.

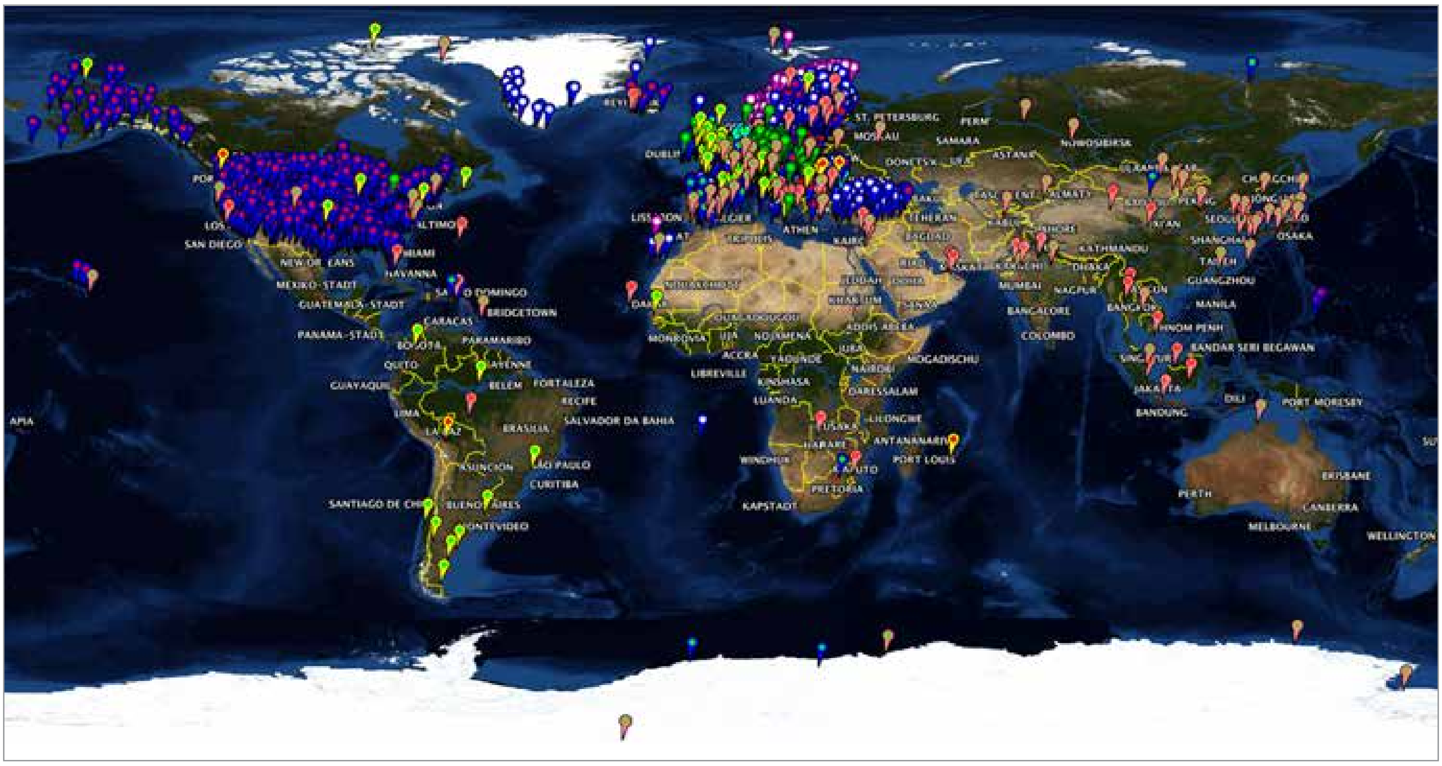

Figure 4. Global map of operational ceilometers (October 2017) as reported at http://www.dwd.de/ceilomap. Different colours represent different manufacturers.

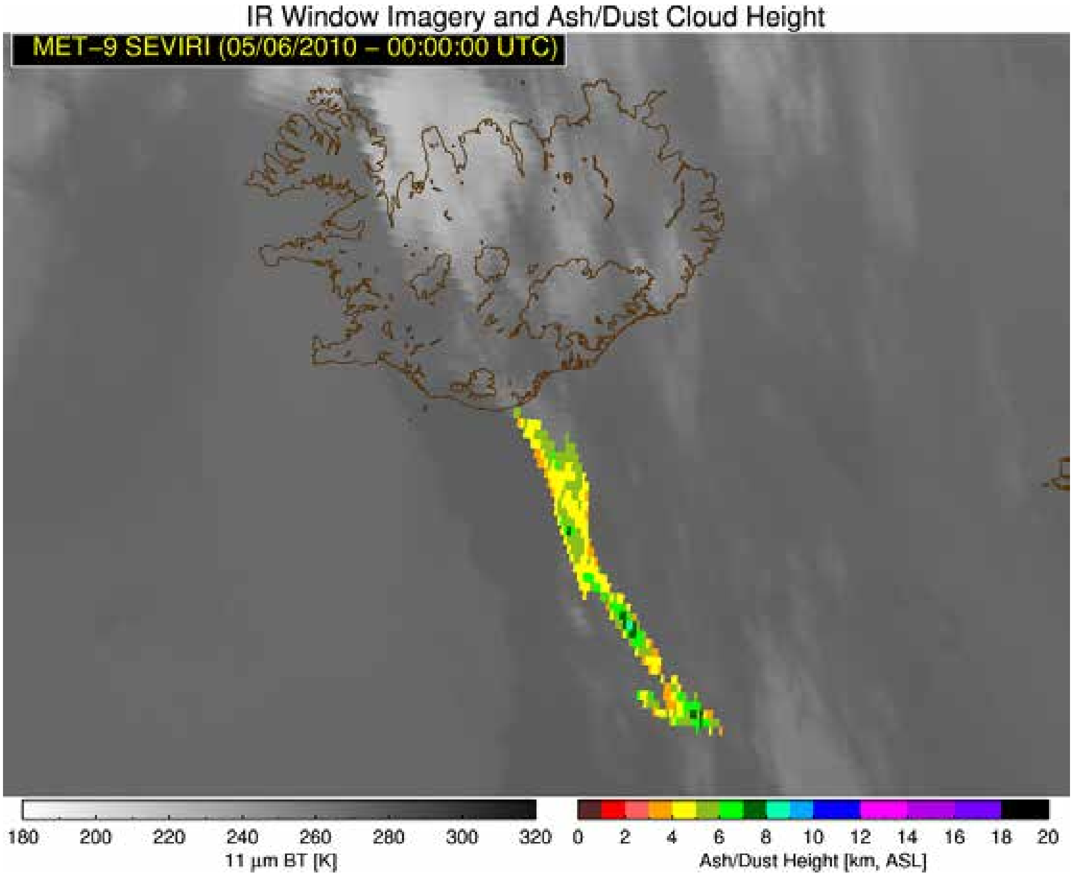

Figure 5. *Meteorological satellite data can be used to estimate critical volcanic ash cloud parameters such as ash cloud top height, an example of which is shown for ash emissions from the Eyjafjallajokull volcano in Iceland on May 6, 2010. Such products, derived using numerous satellite sensors and computer algorithms, were assessed and validated as part of a WMO SCOPE-Nowcasting pilot project.*

The SCOPE-Nowcasting volcanic ash inter-comparison pilot project consists of two phases. The first, which was completed in 2015, aimed to document the strengths and limitations of satellite algorithms that detect and characterize volcanic ash clouds. The characterization component of the algorithms generally includes the determination of ash cloud top height (Figure 5) and mass loading (total column mass per unit area). A total of 27 passive satellite-derived volcanic ash datasets, produced by 22 different retrieval methodologies, were inter-compared and all passive satellite products were compared to independent "validation data". With support from the European Organization for the Exploitation of Meteorological Satellites, scientists at the Rutherford Appleton Laboratory in the United Kingdom performed the inter-comparison analysis and the results were discussed at a workshop held in Madison, Wisconsin, 29 June–2 July 2015. The first phase of the inter-comparison analysis revealed that the accuracy of satellite-based volcanic ash products is a strong function of the retrieval methodology, satellite sensor capability and scene complexity. While areas of general agreement were found for the three major eruptions that were analysed,[1] there are differences in capabilities that need to be better understood.

The primary objective of the second phase of the inter-comparison activity, which will be completed in 2018, is to better characterize and understand product differences. The impact of new satellite capabilities that were not available for use in the first phase of the inter-comparison will also be assessed.[2] Upon completion of the second phase of the analysis, a workshop will be held to report on the results and formulate recommendations for improving volcanic ash satellite remote sensing capabilities. The inter-comparison activity will continue to encourage participation from related groups such as the WMO–IUGG Volcanic Ash Science Advisory Group (VASAG), WMO GAW and VAACs. With sustained international coordination, operational satellite remote sensing capabilities for volcanic ash will continue to mature at an accelerated pace.

The International Airways Volcano Watch

Following the near-disastrous encounters of aircraft with volcanic clouds during the eruptions of Galunggung (Indonesia, 1982), Redoubt (United States of America, 1989), and Pinatubo (Philippines, 1991),

1 Eyjafjallajökull (Iceland) 2010, Grimsvötn (Iceland) 2011 and Puyehue-Cordón Caulle (Chile) 2011.

2 The Himawari-8 satellite was launched by the Japanese Meteorological Agency on 7 October 2014. NOAA launched the first next generation Geostationary Operational Environmental Satellite (GOES-16) on 19 November 2015.

and many other encounters of significance, a new warning system was created, the International Airways Volcano Watch (IAVW). Creation of the system involved intense collaboration between WMO, ICAO and the volcanological community, represented principally by the International Association for Volcanology and Chemistry of the Earth's Interior, a member association of IUGG. Once the first VAACs started operating in the 1990s, IAVW was in existence and the real operational work could begin.

To provide accurate information to the aviation industry on volcanic ash matters, the most accurate knowledge possible of several elements is required:

- Elemental carbon (EC) to be used instead of BC for data derived from methods that are specific to the carbon content of carbonaceous matter.
- When a volcano will erupt, preferably to the hour;
- What the composition of the eruption cloud is (preferably in advance), and how much mass is in the cloud;
- How the constituents of the cloud are vertically distributed;
- How the ash particles will aggregate and fall out, and how the gas constituents will evolve over time;
- How all of the above might best be measured through remote sensing and then forecast using modelling processes.

Uncertainties related to the listed factors play out during a real-time event that might have large safety and economic implications.

Certain progress has been made to date, but a brief consideration of the points detailed above shows that much more effort is required. Volcanic eruption prediction is itself a large field of endeavour. Volcanic clouds can vary hugely in composition, can have extremely complex vertical and horizontal distribution, as shown following the eruption of Eyjafjallajökull, and can also interact with the meteorological environment in various interesting ways.

Generally, during an event operational staff utilize information from all sources, including operational and research-focused satellites, ground-based and space-based lidar systems, radars, and ground and airborne observers. An operations officer rarely says "no" to information, particularly if its provenance is well known.

Following an event, lessons are best learned through collaboration. For example, the VAACs will have created a real-time record of their analysed cloud heights and extent. They would usually be delighted to have discussions around the post-analysis, and to participate in studies of the event. In many cases, the operational research divide can be one of the hardest to cross, to the detriment of the quality of publications and of operational improvement.

In the bigger picture, IAVW creates one necessary element of a grand, real-time connection between the monitoring of the solid earth and the atmosphere, and the management of hazards and phenomena that cross between the two. Volcanoes affect atmospheric composition, cause tsunamis, lahars (volcanic mudslides), pyroclastic flows, agricultural and health problems, and much more besides. The work to describe the emission and movement of volcanic ash in the service of aviation security is one part of a wider effort to understand Earth's atmosphere. To be successful, such effort requires much closer collaboration between different groups and players in the field.

GAW products and services

Observations, such as those made by ground-based and mobile platforms (for example, aircraft), and satellites are vital to monitor and understand atmospheric composition. Atmospheric models also have a critical role in analysing and investigating the transport of pollutants, their interaction, evolution and removal. Models are also vital in being able to explore the "entire" current environment and also as they can be used for forecasting the future atmospheric state. Such forecasts can span hours to decades and include both actual and possible man-made and natural changes in emissions, processes, environmental factors, and the like.

A common requirement for all modelling is the need for observations that guide model development and that can be used to validate and verify model results. In addition, the fusion of observations and models is the best and most robust way to understand and predict the evolution and composition of the atmosphere.

Society is impacted by both long-term and short-term changes to atmospheric composition. Volcanic ash and gas emissions are good examples demonstrating both immediate impacts – for example on aviation and human health – and longer-term, including climate forcing and impacts from the changing atmospheric composition. While both present a range of challenges, the former places considerable additional demands in terms of data timeliness and temporal and spatial resolution. This near-real-time need for observations is indeed a common requirement across a range of impacts, but one that is not always conducive to the significant processing involved in producing fully assured atmospheric composition data. However, timely data can be produced and has the potential to be of considerable use for a wide range of applications.

In recognition of this the GAW Programme has identified the need for increased support for the development and expanded use of services and research activities concerning the forecasting of atmospheric composition and its induced environmental phenomena. As part of this activity the GAW Scientific Advisory Group on

Modelling Applications (SAG-APPs) was established in 2016 to enhance the exchange between the GAW observational community, the modelling communities and end users of atmospheric composition data. The expertise of SAG-APPs covers a broad range of disciplines and includes representatives of a number of research and user communities. SAG-APPs is a collaborative effort of GAW together with the World Weather Research Programme and the World Climate Research Programme.

The main objective of SAG-APPs is to further develop a portfolio of modelling products and services related to atmospheric composition, and more specifically to demonstrate the usefulness of exchanging chemical observational data in near-real time in support of monitoring and forecasting applications. As such, monitoring and modelling activities related to air quality and emergency response atmospheric forecasting, such as that performed for volcanic eruptions, are key areas of interest and challenge. To this end SAG-APPs is coordinating with existing groups, such as VASAG on volcanic forecasting and the GAW Urban Research Meteorology and Environment project on air quality to identify possible demonstration projects and knowledge exchange opportunities.

Acknowledgements

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Questions and answers

What is the Aerosol Bulletin?	The *WMO Aerosol Bulletin* provides general information on the aerosol component of GAW and focuses on specific components or applications of GAW aerosol observations and process studies.
How do I join GAW?	The procedure is described at http://www.wmo.int/pages/prog/arep/gaw/join_GAW.html
How do I access data?	Download ground-based in-situ, lidar and AOD data from http://www.gaw-wdca.org/, and satellite data from http://wdc.dlr.de/data_products/AEROSOLS/
How should I make measurements?	Follow the measurement guidelines and standard operating procedures described in *GAW Report No. 227. WMO/GAW Aerosol Measurement Procedures, Guidelines and Recommendations*, https://library.wmo.int/opac/doc_num.php?explnum_id=3073.
Where can I find more information?	Information about GAW is available at http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html, about the GAW Station Information System at https://gawsis.meteoswiss.ch/, and about SAG-Aerosol at http://gaw.tropos.de/index.html. Questions regarding the content of this bulletin should be addressed to Alexander Baklanov, abaklanov@wmo.int.

World Meteorological Organization
Atmospheric Environment Research Division, Research Department, Geneva
E-mail: AREP-MAIL@wmo.int | Website: public.wmo.int/gaw

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