Earth Observations and Volcanic Ash

A report from the ESA/Eumetsat Dublin workshop, 4–7 March, 2013.

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FOREWORD

The Eyjafjallajökull eruption in spring 2010 found the European air transportation system unprepared to deal effectively with such a large-scale event. At that time the European Space Agency and Eumetsat convened a two-day meeting in Frascati, Italy, with specialists in space-based observations of volcanic emissions, to consider if best possible use was being made of observing systems, along with models, to inform management of the situation. The workshop demonstrated that the research community across Europe had responded extensively to the crisis on a best-effort basis, and their results offered significant promise for more effective future management of such events. A comprehensive set of recommendations was made for work to realize this research potential as operational tools that could better inform the response to any similar future situations. The present report summarizes the outcome of a follow-on workshop in March 2013, also convened by ESA and EUMETSAT, in Dublin, Ireland. This brought together representatives of the research community along with aircraft manufacturing industry, airline operators, regulators and meteorological offices, to review progress and guide on-going work within the ESA "Volcanic Ash Strategic Initiative Team" project, led by the Norwegian Institute for Air Research (NILU). This report summarizes the workshop findings on progress made in the intervening three years on observations and models, as well as on the regulatory side. It shows that, while a similar event would today be met with a more adaptive and economically effective response, there remains significant opportunity to optimize the operational use of satellite, ground and airborne observations during such situations.

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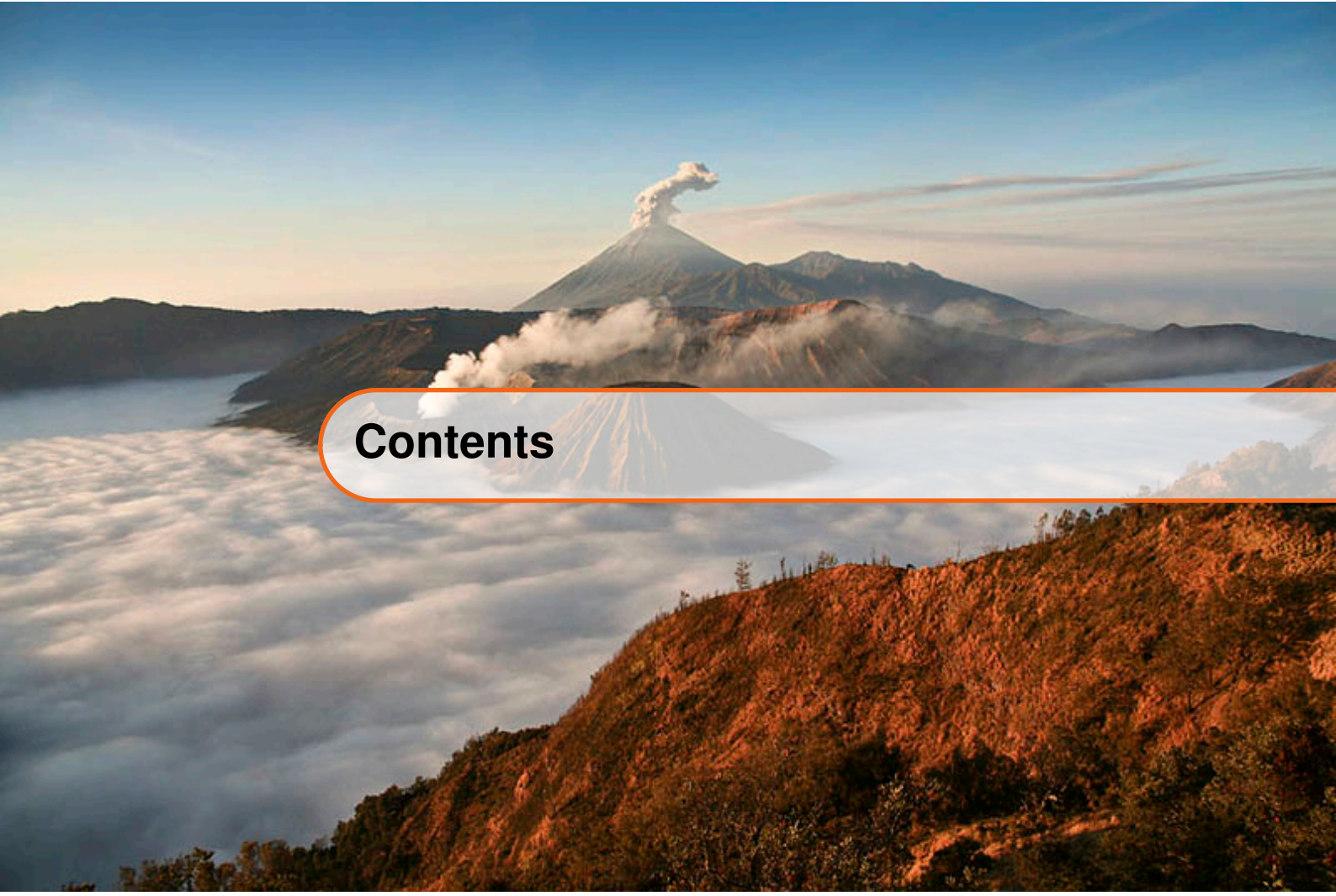

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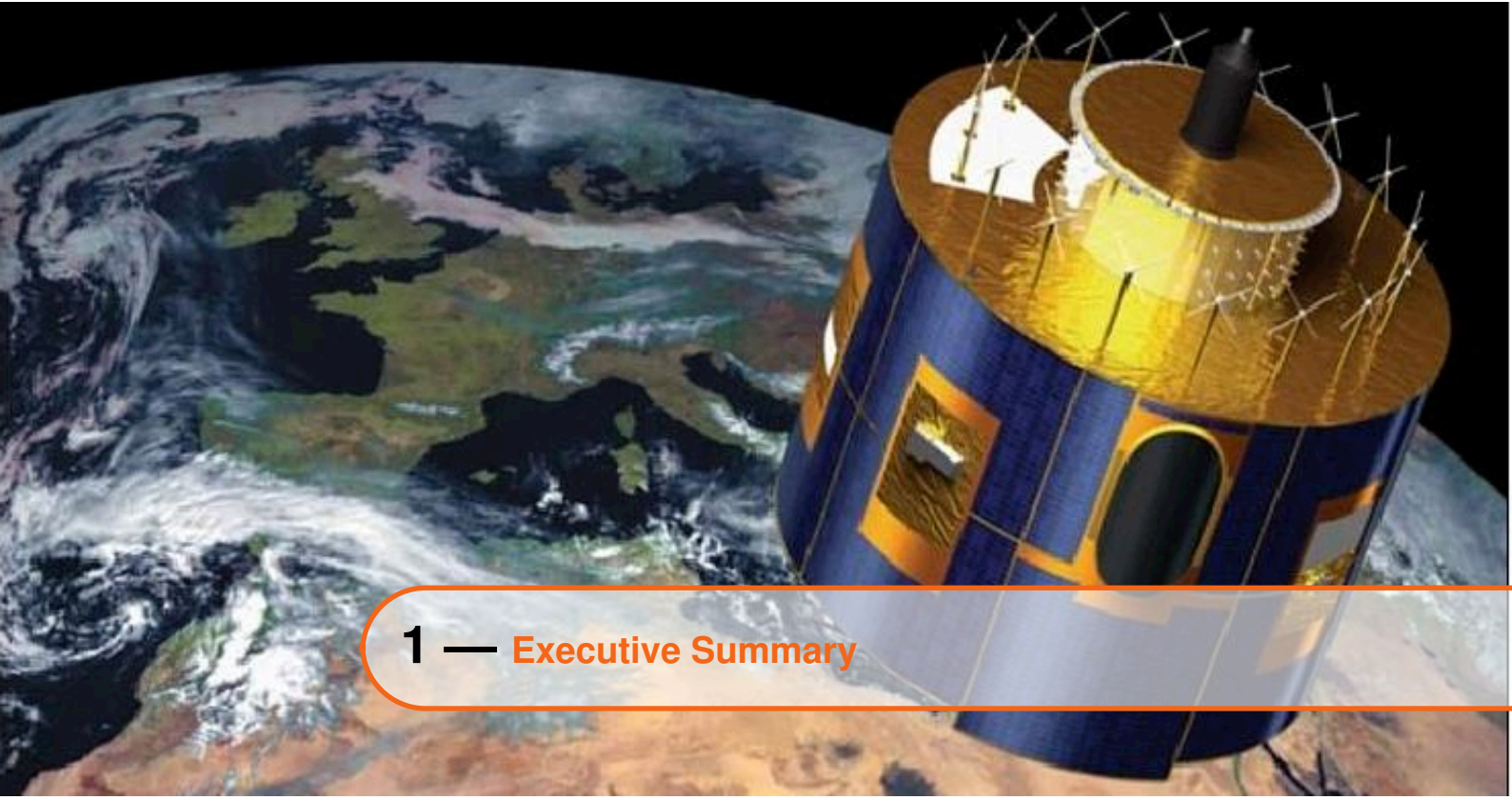


1 — Executive Summary

The Eyjafjallajökull eruptions of AprilMay 2010 represent a step change in the approach taken by industry, regulators, data providers and academia to the problem of mitigating the hazardous effects of volcanic ash on the aviation industry. More than 100 papers have been published on scientific and phenomenological aspects of the eruption, and dozens of national and international projects have been or are being undertaken to address various issues associated with the problem. Prior to the Eyjafjallajökull eruptions, there had been two international symposia on Volcanic Ash and Aviation Safety. These took place 1991 [1] and 2003 [2]. In May 2010, the European Space Agency (ESA) and Eumetsat held a dedicated workshop in Frascati to discuss lessons learned as a result of the Eyjafjallajökull event and to examine the use of satellite data to improve aviation safety. A set of recommendations were outlined at the workshop and are summarised in an ESA report by Zehner *et al.*, [3]. The report also proposed follow-up meetings to review progress on these recommendations. In March 2013 a workshop was held in Dublin, Ireland which successfully brought together aviation industry stakeholders, regulatory bodies, EO data providers, end-users and academic researchers. It provided a unique forum to discuss the considerable progress made on the problem of ash and aviation and demonstrated the responsiveness of the scientific community in meeting industry needs. Participation included experts from airlines, civil aviation authorities, volcanic ash advisory centres, end-users (pilots), data providers (ESA, Eumetsat, NASA) and academic researchers with expertise in atmospheric science, meteorology, transport modelling, volcanology and aerosol science. The meeting was co-sponsored by ESA and Eumetsat and included a visit and demonstration at the operations centre of Aer Lingus at Dublin airport. This report provides a summary of the outcomes of the Dublin meeting under the following topics:

- Dispersion and transport modelling of volcanic ash
- User requirements
- Best end-to-end system for volcanic ash forecasting
- Evolution of the European aviation response to volcanic cloud hazards
- Future response–the role of satellites

Highlights of the Report are provided in the Key Points extracted from each of the following chapters and includes a summary table highlighting the progress made on the main recommendations from the Zehner report [3]. A comprehensive bibliography of reports and articles relating to volcanic ash and aviation completes this report.

2 — Key Points

Transport modelling of volcanic ash *(Chapter 3)*

- *Integrated, flexible, data assimilating models are being developed to improve operational forecasting of volcanic ash*
- *Satellite data are key ingredients, but the lack of real-time availability of specific volcanic ash products is a limiting factor*
- *Improved parametrisations of volcanic processes, especially to constrain the eruption source parameters (e.g. water entrainment) are needed*
- *Improved coordination to ensure qualitative agreement among models being used at the VAACs, other European Met Offices and Research Institutes are needed*

User needs *(Chapter 4)*

- *Operators need more frequent forecast information, longer advanced warnings (5–6 hours) and longer validity times (24–36 hours)*
- *Users need volcanic ash data products, especially from Geostationary instruments as quickly as possible and ideally in real-time*
- *Users would like standardised EO products, with quality assurance and traceability*
- *Spatial and temporal resolution of EO data are able to meet the current user requirements*

Optimal observing system for volcanic ash monitoring in Europe *(Chapter 5)*

- *Current satellite systems provide good global coverage for volcanic ash and SO_2 observations*
- *Improved exploitation of geostationary sensor data in order to provide high temporal resolution information is a high priority*
- *Improved satellite-based detection of 'volcanic ice' and hydrometeor-rich volcanic clouds*
- *Timing, spatial resolution, both horizontal and vertical, are prerequisites for an optimal observing system*
- *The planned ESA Sentinels will enhance the observing system for volcanic ash, but an optimal system will need to make use of other EO systems and include ground-based measurements*

Evolution of the European aviation response *(Chapter 6)*

- *Difficulty in implementing zero tolerance to quantitative thresholds*
- *Need for clarity on standard definition of what constitutes 'visible' and 'discernible' ash*
- *Introduction of Airline operator safety cases allow operators greater freedom to operate in ash-affected airspace*

Future response–the role of satellites *(Chapter 7)*

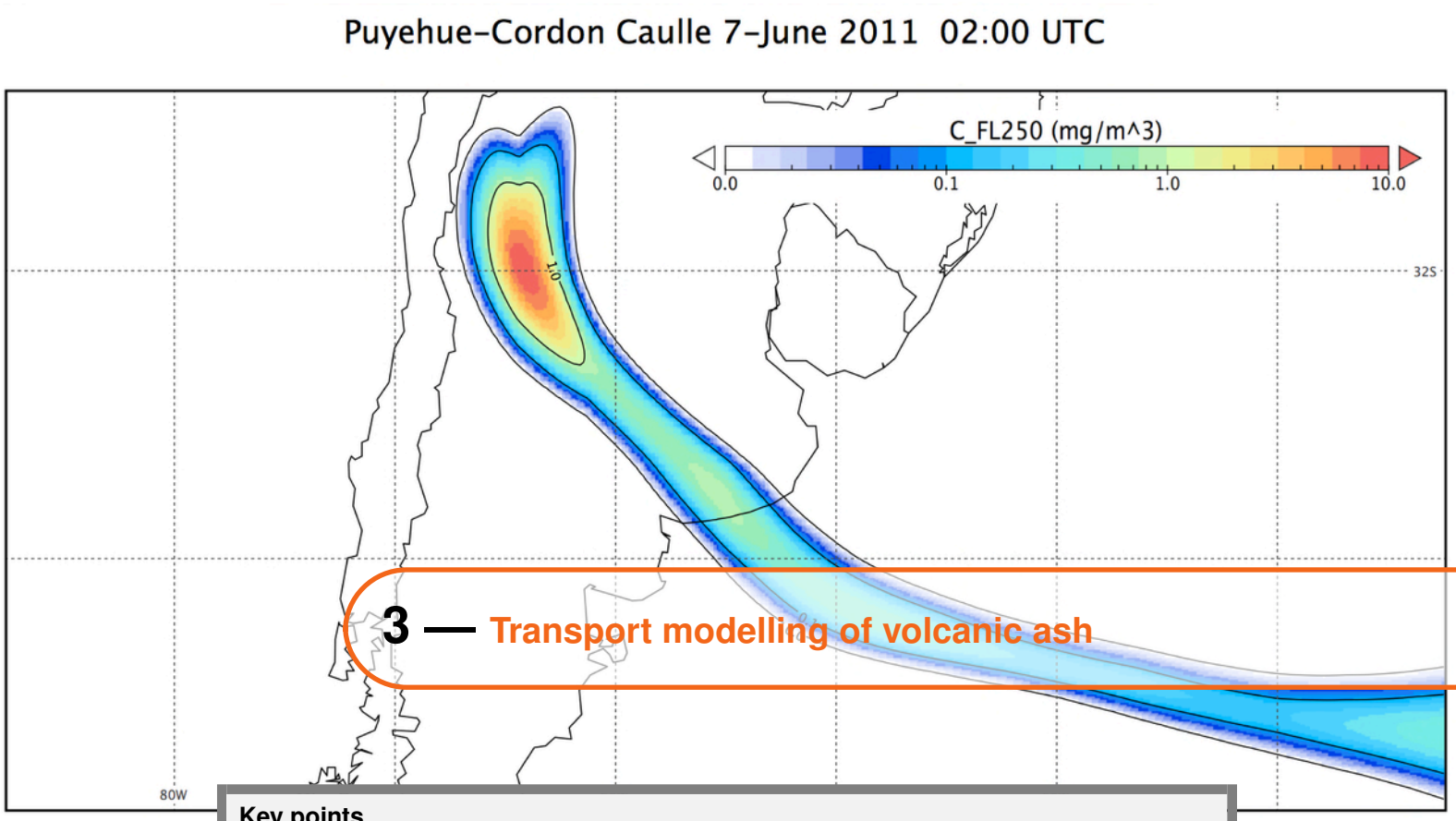
- *Satellite data will be increasingly important for ash forecasting*
- *Satellite data will be increasingly important for monitoring volcanic activity (ash and SO_2 clouds and thermal anomalies)*
- *Provision of new satellite data products from the EO system*
- *Improved coordination between satellite agencies for standardised ash products*

2.1 Progress on recommendations

Here we summarise the progress made on the main recommendations of the Zehner report *See Zehner [3]*

Recommendation	Progress
R1 Access to all data sources of volcanic plume observations in Europe should be accelerated, improved and open.	Some progress made with a new database of all satellite observations, model simulations, validation data and source parameters being developed within VAST (Volcanic Ash Strategic Team). A similar database is being developed by the USGS.
R2 Existing observing capabilities within Europe should be further consolidated and enhanced by combining satellite, airborne and ground-based systems for detecting and characterising volcanic ash clouds.	Several European projects addressing this. New lidar systems are being installed at key European volcanic regions. There is a continued need for better coordination between satellite data product providers, ground-based networks and airborne observation systems.
R3 Actions should be taken to ensure that accurate and timely data are available from volcano observatories or monitoring stations situated near to volcanoes.	Progress has been made at critical European volcanic regions: two new mobile radar systems and a lidar have been installed in Iceland. The FP7 FUTUREVOLC project will provide a Supersite laboratory for Icelandic volcanology.
R4 Concerted developments should be undertaken to integrate existing advanced retrieval methods into operational systems.	Eumetsat has established a new operational satellite ash product. Several institutions and meteorological agencies are taking advantage of this to ingest data into their VATD models. Further validation, testing and improvements are needed.

Recommendation	Progress
R5 Techniques for assimilation and inversion of satellite data in dispersion models should be further developed and applied to provide quantified ash cloud advisory information.	The London and Darwin VAACs have established research and development programs to address this topic. Other research organisations are conducting similar projects.
R6 Relevant satellite observation systems and data products should be formally validated with observations from other sources and should, where appropriate, be certified with respect to quantitative requirements for volcanic plume monitoring.	Some validation has been done [24], but more is needed. The VAST and SMASH/SCAS-2 projects include work packages on validation and a new database is being developed. At CGMS-41 (Tsukuba, July 2013) it was agreed that the JMA would lead an inter-comparison of ash retrieval algorithms.
R7 Actions should be taken to ensure that planned future European satellites will provide more efficient guaranteed support for ash cloud related crises; both operational systems (MTG, Sentinels) and research missions.	Several studies/projects are ongoing (e.g. usage of CALIOP, IASI measurements) preparing optimal usage of future research and operational satellite instruments (e.g. EARTHCARE, MTG-IRS) for volcanic eruption detection and emission monitoring.
R8 Studies should be made of potential new satellites and instruments dedicated to monitoring volcanic ash plumes and eruptions.	It has been found that the existing and medium term planned European space segment and data distribution infrastructure is adequate for the European Aviation Safety application sector.
R9 Intensive basic research should be conducted on the physical, chemical and radiative properties of volcanic ash, from crater to aged clouds.	At least two new European projects addressing this, including FUTUREVOLC and VANAHEIM. Theoretical work at NASA/GSFC and the University of Maryland (N. Krotkov, K.Yang and A. Rocha Lima) has improved retrievals of SO_2 and absorbing aerosols using UV satellite measurements, notably from OMI (See list of references for papers on this topic), and there is a project to measure the optical, microphysical and compositional properties of Eyjafjallajökull ash.
R10 European recommendations and actions should be coordinated with International Civil Aviation Organization (ICAO), as the global presiding aviation regulatory authority, and with World Meteorological Organization (WMO), as coordinator of the global system of VAACs See references [4–7].	Establishment of the VASAG and IVATF have been very effective in getting research results into operational use. ICAO and WMO have been very active and willing to act WMO/ICAO organise ash workshops approximately every 2 years; see [8–12] for information on the first 5 workshops.
R11 A follow-up workshop should be organised to review progress on these recommendations after one year.	Several workshops have occurred including the WMO/IAVCEI sponsored Geneva meeting (November 2011 [13]) and in Washington DC, (November 2012 [14]); the VASAG meetings; the IUGG Melbourne Workshop (July, 2011) and the Dublin VAST workshop (March, 2013).



3 — Transport modelling of volcanic ash

Key points

- *Integrated, flexible, inverse modeling and data assimilation tools are being developed to improve operational forecasting of volcanic ash*
- *Satellite data are key ingredients, but the lack of real-time availability of specific volcanic ash products is still a limiting factor*
- *Improved parametrisations of volcanic processes , especially to constrain the eruption source parameters (e.g. water entrainment) are needed*
- *Need for improved coordination to ensure qualitative agreement among models being used at the VAACs, other European Met Offices and Research Institutes*

3.1 Introduction

The aim of this section is to review the current roles, capabilities and limitations of volcanic ash transport and dispersion (VATD) models. VATD models are used operationally by Volcanic Ash Advisory Centres as well as a number of National Meteorological Services (NMS), to produce forecasts of ash distribution in the atmosphere and on the Earths surface. They are also used as a research tool to understand the physical processes controlling the transport and dispersion of volcanic ash clouds. VATD model capabilities, limitations and future developments are dependent on their role.

3.2 Operations

3.2.1 Current operational role and capabilities

VAACs provide ICAO-approved volcanic ash forecasts for civil aviation during eruptions. These are volcanic ash advisories (VAA) and volcanic ash graphics (VAG). Currently the pre-approved hazard maps consist of instantaneous horizontal ash coverage in three vertically integrated layers of the atmosphere at 6-hourly intervals. The ash boundaries signify the furthest extent of ash dispersion. The VAAs provide one snapshot of the ash location and then a forecast at +6, +12 and+18 hours from the time of the VAA. At national level several NMSs provide their own nationally mandated VA forecasts. The NMS products are typically customised to the needs of the respective country or region. They provide guidance and advice to the national authorities

in charge of aviation as well as public health. NMS products are frequently used for aviation planning together with the VAAC products. Only NMS products are offered for public health as there are no VAAC products currently available. All operational VATD models produce an estimate of the future distribution of volcanic ash following an eruption and are therefore essential for planning purposes >6 hours ahead.

3.2.2 Current operational limitations

The accuracy of any VATD model forecast largely depends on the accuracy of the volcanic eruption source parameters (ESPs). These include the height of the volcanic ash plume above the volcano event, the mass eruption rate, the vertical distribution of ash in the plume and the particle size distribution. Since the VATD model forecasts are usually produced before observational data become available, predefined ESPs need to be used. For example, these might include a uniform vertical distribution of ash from the volcano vent to a predefined height, and a particle size distribution based on historical data. As soon as observational data become available, these ESPs are refined and updated forecasts are produced. However, these refinements are subjective, currently prepared manually and subjectively by the forecasters, and cannot make optimal use of all the data typically available, especially satellite remote sensing data. Inverse modelling techniques have recently been developed that combine a priori information about on the source term (e.g., eruption column height), a large number of sensitivity calculations with a VATD model and satellite retrievals of total ash (or SO_2) column, to produce an optimized optimised source term. This source term allows the best possible fit of the model, while keeping it within the uncertainty bounds given by the a priori data. The inverse modelling techniques have been proven to work in research mode and are now being tested at several operational centres, including NMSs and VAACs. Further improvement can be expected from data assimilation methods, which also allow for correction of model errors with origins other than the source term (e.g., errors in the modelled wind fields). Different VATD models can produce quite different model forecasts and even forecasts from a single VATD model can differ substantially when different meteorological input data sets are used. Potential differences between the designated VAAC models and the regional NMS models pose a certain challenge, which needs to be addressed by coordination. Technically, ensemble forecasting methods should be used to address such differences and deviations, which reflect the current range of uncertainties rather than deficiencies of single models.

3.2.3 Future operational capabilities

Potential operational capabilities are currently being investigated by running VATD models in research mode. New operational capabilities will be available in the future, provided they do not decrease the speed at which forecasts are produced. These new capabilities require integrated, flexible approaches enabling predictions to be fine-tuned based on the arrival of new measurements as the event evolves. As well as the integration of models, another important future operational aspect is the direct transfer of VATD results, including their uncertainties, into adequate decision support systems, which could take into account flight routes and air traffic situation. Sveinbjörnsson [15] addressed this topic for the Icelandic air traffic situation.

3.3 Research

3.3.1 Current research capabilities

In response to the severe impact of the 2010 Eyjafjallaökull eruption, VATD models were run in research mode and simple parametrisations of near-source plume dynamics and microphysical processes were developed. These parametrisations allowed quantitative estimates of volcanic

ash concentrations to be produced (supplementary to the ICAO official products). Following Eyjafjallajökull new capabilities are being developed. These include:

(1) Improvements to existing simple parametrisations of physical processes. For example, aggregation, interaction of the plume with the environment, sedimentation rates and wet deposition.
(2) Integration of observational data and model forecasts to better constrain ESPs. For example, inverse modelling and data assimilation techniques.
(3) Quantification of uncertainties associated with VATD model inputs (ESPs, meteorological fields) and modelled physical processes.
(4) Ensemble forecasting using different VATD models or the one VATD model run with different ESP's or parameter assumptions.
(5) Ensemble forecasting using the Ensemble Prediction Systems (EPS) of major meteorological centres.

3.3.2 Current research limitations

Currently, the factors limiting our ability to implement these research capabilities into operationally running VATD models include:

(1) Reliable availability and quality of routine monitoring data (especially from satellites) to enable automated integration of observations and modelling data in near real-time.
(2) Extensive evaluation of newly developed parametrisation schemes in a wide range of meteorological situations and eruption types.
(3) The availability and communication of detailed (volcano specific) ESP's from volcanic observatories to the VAAC's to be used as pre- or post-eruption model inputs.
(4) Lack of resources to develop new observational techniques (for example to measure particle size distribution) or to run computationally expensive ensembles of model simulations.
(5) Lack of resources to run computationally demanding inverse modelling or data assimilation systems close to real time

Much work is still to be done by the scientific community to overcome these challenges and to provide the end-user communities with a reliable, robust and easily understandable communication of volcanic ash hazards.

4 — User requirements review

Key points

- *Operators need more frequent forecast information, longer advanced warnings (5–6 hours) and longer validity times (24–36 hours)*
- *Users need volcanic ash data products, especially from Geostationary instruments as quickly as possible and ideally in real-time*
- *Users would like standardised EO products, with quality assurance and traceability*
- *Spatial and temporal resolution of EO data are able to meet the current user requirements*

4.1 Introduction

The User Workshop attracted 57 participants from a wide range of end-users; including one engine manufacturer, three airlines and one pilot, as well as three regulatory authorities, ESA, NASA, EUMETSAT, eight weather service providers, seven research institutes, 2 VAAC representatives, ten universities and two corporations. In particular the requirements of key end-users such as the VAACs, meteorological offices, airlines and aviation regulatory bodies of satellite-based data products for volcanic ash monitoring and forecasting were discussed. It is not possible to include all of the requirements and discussions of the varied user groups in this report, which is limited to the key user requirements and some of the important findings from the VAST User Survey. The results of the VAST User Survey results (published in December 2012) were presented at the workshop (see VAST http://vast.nilu.no/media/documents/2013/09/03/nilu-esa-vast-urd-v0.4.pdf User Requirement Document for details). This User Survey relied on the SAVAA projects requirements dating from April, 2009 and focussed especially on the needs of the London and Toulouse VAACs, as these were key stakeholder users of the SAVAA project. The recommendations from ESA-EUMETSAT workshop, May, 2010 and other VAAC requirements were also considered. There were 74 respondents; 29 operational, 45 research 7of the 9 VAACs, 3 airlines (KLM, Icelandair, Qantas airways), regulatory authorities (EASA, Irish Aviation Authority, CAA-ICAO), air traffic services operators, pilots, and practising meteorologists. The importance of detecting and tracking sulfur dioxide (beside ash) was highlighted during the workshop. Although Sulfur dioxide does not pose immediate danger to airline operations, it affects the engine lifetime,

cabin air quality and possibly has some repercussions on health of airline passengers and staff. The chemical composition of the cloud also appears to be important for engine manufacturers. SO_2 is relatively straightforward to detect from space; indeed it appears to be easier to measure than ash. In many circumstances the transport modelling of SO_2 is also easier than for ash. For passive degassing volcanoes that emit S02, the gas seldom reaches flight levels and therefore does not pose a significant hazard to aviation. On the other hand, explosive eruptions tend to emit SO_2 to the tropopause (or higher) and transport at these levels is less affected by the more complex processes that dominate in the lower troposphere (eg wet and dry deposition, cloud cycling, turbulent mixing). Users of volcanic ash information include:

- Airlines
- Air Navigation Services Providers
- Regulatory bodies (e.g. VAAC, CAA, IATA, etc.)
- Meteorological institutes
- Volcano observatories
- R&D institutes (academic, engine & air frame)
- Governmental
- Media outlets
- Military
- Public health institutes
- Private/commercial industry

The VAST User Survey relied on the SAVAA projects requirements dating from April, 2009 and focussed especially on the needs of the London and Toulouse VAACs, as these were key stakeholder users of the SAVAA project. The recommendations from ESA-EUMETSAT workshop, May, 2010 and other VAAC requirements were also considered. There were 74 respondents; 29 operational, 45 research 7of the 9 VAACs, 3 airlines (KLM, Icelandair, Qantas airways), regulatory authorities (EASA, Irish Aviation Authority, CAA-ICAO), air traffic services operators, pilots, and practising meteorologists.

4.2 Key user requirements

The results of the user survey were presented at the Workshop and discussed. The main questions included in the survey are shown below:

- Which volcanic hazard products or services do you regularly use (select all that apply)?
- What would be the main obstacles to adopting the use of new/additional EO products?
- What is your preferred product delivery mechanism?
- What is your preferred data format for receiving volcanic satellite products?
- What is the minimum (not optimum) spatial resolution required for forecast products?
- What is the minimum acceptable vertical resolution of volcanic aviation hazard observation products?
- For both observation and forecast products, what is your preferred coordinate system?
- Do you want an error characterisation with the product?
- What is the minimum acceptable spatial accuracy of these satellite-based products?
- What is the required update frequencies for satellite-based products?
- What is the required update frequencies for model forecast products?
- In terms of ash cloud forecasting, what is your preferred modelling approach (singe or ensemble)?

There were also questions concerning the relevance of the VAST project and an invitation for comment. The complete User Report and Power Point Presentation are available on the VAST website. For the purposes of this report, only the difference in response from *operational* users and *research* users for two of the questions regarding alerts and standards are highlighted.

4.2.1 Alert services

ESA has invested considerable effort into making EO data available in a convenient format for its users. For volcanic SO_2 and ash these are provided in the form of alerts from the SACS, SACS2, and VAST projects. The alerts are not formalised nor do they require a compulsory reaction, however the general feedback has been that these alert services are used and welcome. Figure 4.1 shows the survey results for both category of users. The majority of operational users use the *official* VAAC advisories, as wold be expected, but also make considerable use of the SACS alerts. The picture for research users is quite similar, with a greater emphasis on research products and less on VAAC advisories; also as expected.

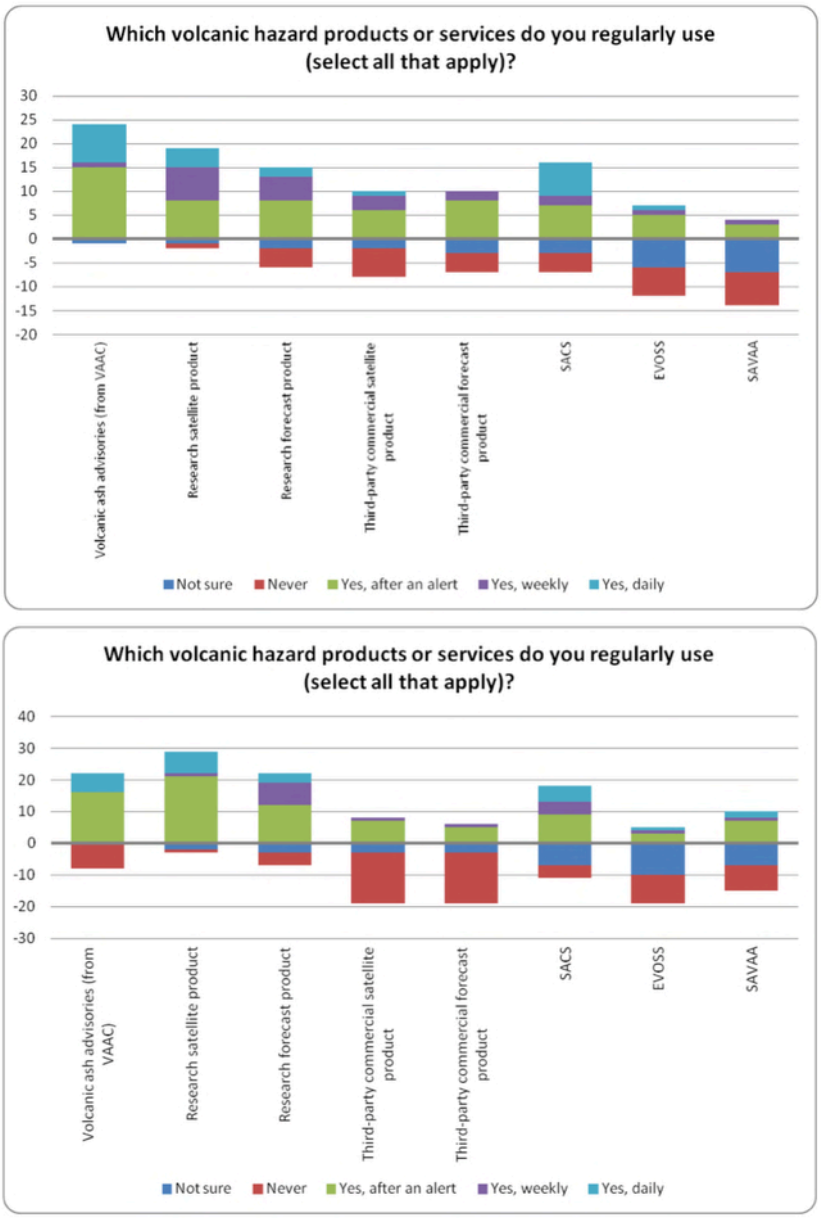


Figure 4.1: Results of the survey concerning use of current alert services by *operational* (top) and *research* (bottom) user categories.

4.2.2 Monitoring services

Satellite data play a key role in alerting the community when an eruption cloud is observed. However, they can also play a role in on-going monitoring of activity on a global scale. In the European domain, the MSG-2/3 satellites also have an excellent view of volcanoes in Africa and recent activity in the Rift Zone has been the site of several eruptions affecting aviation. Beyond the impact on aviation, volcanoes also affect communities and infrastructure in the vicinity of the active volcano. The EVOSS project has been very successful in utilising space-based assets, particularly from the geostationary instrument SEVIRI, to provide continuous monitoring services for communities in Africa vulnerable to volcanic activity. Funding for the service has officially ended but the webpage is still active (password protected for specific users only) and there are steps in place to seek further funding to continue the service. In the longterm, mechanisms to permit a sustainable monitoring service are needed.

4.2.3 Spatial resolutions

The resolution of data required by users is of key interest to satellite instrument providers. The survey results for the horizontal spatial resolution show a strong dichotomy between operations and research needs. (Fig. 4.2). Operational users are content with spatial resolutions of $<$10 km, while research users prefer 1 km resolution data. Fortunately, the current status is that both of these requirements are met by existing satellite instruments. These conclusions are valid for both ash and SO_2 sensing. The survey did not go into detail regarding spectral requirements and the link between wavelength interval and resolution. Passive microwave data could provide extremely valuable information in the early stages of volcanic cloud evolution , when it is opaque, small and rapidly developing. Capturing the developing ash column would require a passive microwave sensor in geo orbit with spatial resolutions of $\sim$1 km or less.

4.2.4 Forecast frequency

The frequency of updated forecasts and the length of time of their validity is of vital importance to airline operators. The survey found that operational users wanted forecast updates within15 minutes, but that within 1 hour was also acceptable. 10 respondents indicated that within 6 hours was acceptable as a minimum requirement. Research users showed no clear preference, probably reflecting the way the forecast data are used by various research groups. Note that some of the research respondents are suppliers of forecast information.

4.2.5 Standards and traceability

Industry demands standards and traceability when dealing with operational situations, especially when safety is involved [16–19]. The increasing use of EO data to inform decisions requires data products with some measure of their accuracy, the methodology used to derive the products and an audit trail. Currently there are no standards for ash and SO_2 satellite data products. As a first step there are strong efforts to provide error characterisation with the data product, derived from systematic validation campaigns. Generally the Algorithm Theoretical Basis Document (ATBD) details the algorithms and lists the caveats and theoretical performance. In order to establish a system of standards for ash and SO_2 products, a further step is required to inter-compare data products from various research groups (and some meteorological agencies. A new activity has started under the auspices of WMO for an inter-comparison workshop to be held in mid-2014.

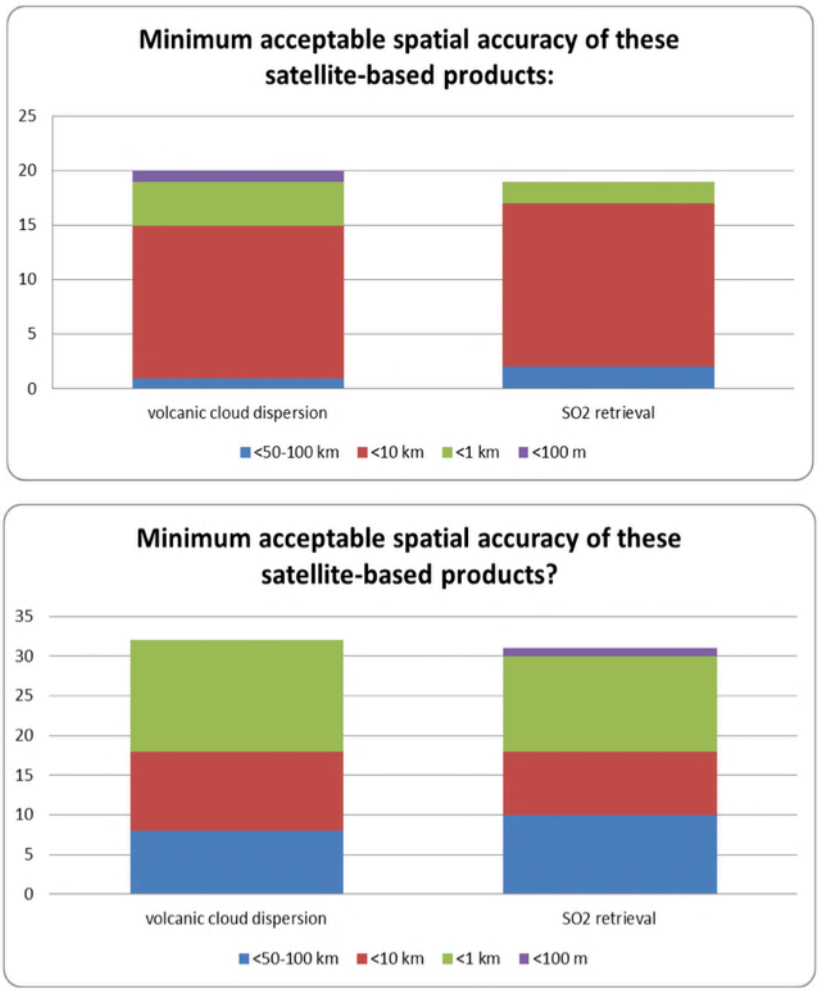


Figure 4.2: Results of the survey concerning horizontal spatial resolution of satellite products by *operational* (top) and *research* (bottom) user categories.

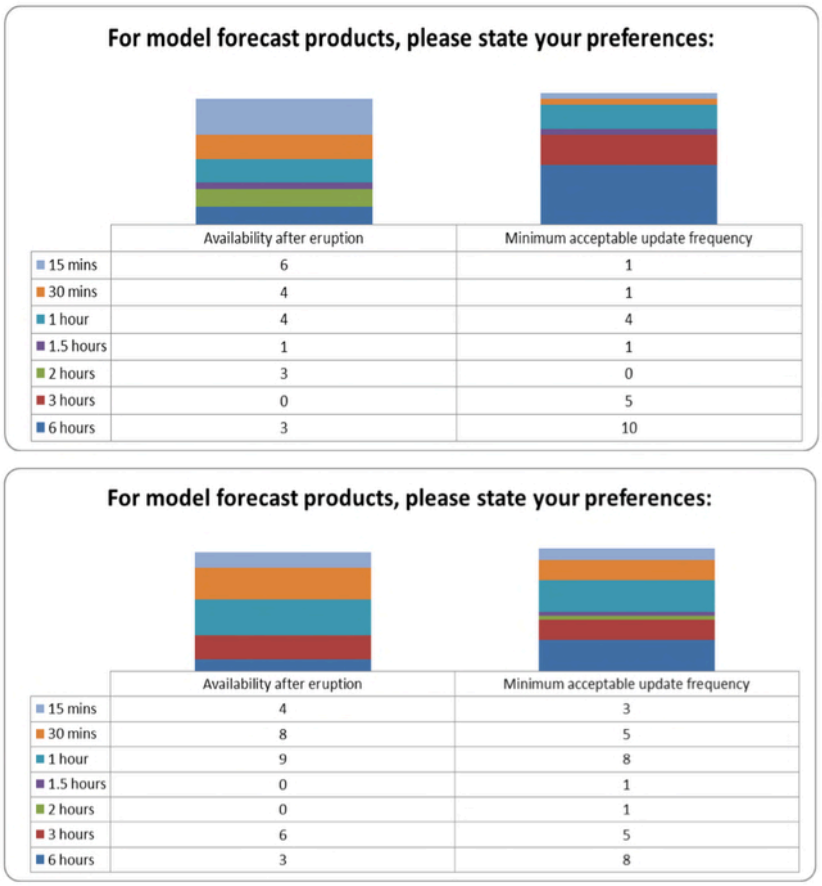


Figure 4.3: Results of the survey concerning forecast frequency by *operational* (top) and *research* (bottom) user categories.

5 — Optimal observing system for Europe

Key points

- *Current satellite systems provide good global coverage for volcanic ash and SO_2 observations*
- *High priority for improved exploitation of geostationary sensor data providing high temporal resolution*
- *There is a need for standardisation of EO volcanic products*
- *Timing, spatial resolution, both horizontal and vertical, are prerequisites for an optimal observing system*
- *Improved satellite-based detection of volcanic ice and hydrometeor-rich volcanic clouds*
- *The planned ESA Sentinels will enhance the observing system for volcanic ash, but an optimal system will need to make use of other EO systems and include ground-based measurements*

5.1 Introduction

The 2010 Eyjafjallajökull eruption showed that real-time detection and tracking of volcanic clouds based on satellite, aircraft and ground data plays a key role in the management of aviation crises. At the time of the eruption satellite data were not assimilated into ash forecasting models and much comment was made on this by industry; likewise actual observations of ash in the atmosphere from aircraft and ground-based lidars clearly demonstrated their importance.

Three years on from the eruption and after significant aviation impacts from Eyjafjallajökull [21], the May 2011 Grímsvötn event, the eruptions of Puyhue-Cordon Caulle and the SO_2-rich eruption of Nabro in Eritrea, satellite data are now seen as a vital part of the ash-observing system and national meteorological agencies and some research institutes are engaged in developing satellite data assimilation systems for the purpose of improving ash forecasts. This progress is discussed here.

5.2 Satellites

The main requirements for an optimal volcanic ash satellite monitoring system are high temporal resolution (minutes), high spatial resolution (∼1–10 km^2) and vertical resolution (∼100–

300 m), and a spectral range that permits detection and quantification of ash (mass loadings) and gas, principally SO_2. As volcanic activity tends to be sporadic and highly unpredictable, a high revisit time is required in order to follow the continuity of the volcanic eruption process. High spatial resolution allows better characterisation of the volcanic clouds near the vent where determination of the source term is an essential input for initialising VATDs. The wide spectral range from UV to TIR is exploited to retrieve the volcanic ash particle from fine (0.05 μm) to coarse (15 μm) and SO_2. The latter it is often used as proxy for volcanic ash, and proved to be important for flight safety because of long term effects on aircraft engines. The high sensitivity is also essential to guarantee the possibility to detect and retrieve also small quantities of volcanic ash and SO_2. Moreover, an optimal satellite system should also be able to deal with the criticalities still present in the ash and SO_2 estimations due to the ash type (i.e. the ash optical properties), problems associated with very thin ash clouds [22], problems associated with distant-source eruptions [23], and volcanic cloud altitude and thickness uncertainties. In particular, the latter influences ash concentration estimation.

5.2.1 State of the art

Current satellites provide excellent spatial, temporal and spectral coverage for passive measurements. The Meteosat Second Generation (MSG) platform that carries the SEVIRI [24] is of particular value for ash detection and quantification over the European region. This instrument has 12 spectral channels spanning the visible to infrared wavelengths and providing 1 x 1 km^2 to 3 x 3 km^2 resolution data every 15 minutes, continuously. Two channels situated near 11 and 12 μm are needed for ash detection; a third or fourth channel, also in the infrared, is useful for constraining the height of the ash cloud, needed for ash quantification. Both polar and geostationary systems have these capabilities, exploiting other regions of the EM spectrum to determine parameters such as the aerosol optical depth (AOD) at 05 μm (e.g. AATSR), an aerosol absorbing index (AAI) from ultraviolet measurements (e.g. OMI, GOME-2) and utilising the near infrared region to distinguish ice and water clouds from ash clouds. A challenging aspect of using satellite data is to design algorithms that make use of the spectral, temporal (especially for geo sensors) and spatial information. Thus, the hyper spectral sensors IASI and AIRS use a kind of 'fingerprinting' to identify specific molecules from their spectral signatures (e.g. for SO_2) and the shapes of the absorption curves to ascertain the microphysics of particles (e.g. size and composition). This kind of information is not available on all sensors, but by combining temporal and spatial information together with broadband spatial coverage from polar and geo sensors (e.g. MODIS and SEVIRI) retrievals can be made. For example, repeat coverage of a particular area using geostationary data can reveal 'climatological' behaviour of broadband channels. Departures from these climatological signatures can be assigned to the presence of an anomalous aerosol (ash) in the atmosphere. Once ash-affected pixels are identified a retrieval is undertaken. In many instances the major challenge is to identify the nature of a pixel (clear, cloud, ash etc.) is the major challenge. Sophisticated cloud detection schemes have been developed that utilise statistical measures, physical models and temporal variation to classify pixels. The state of the art on cloud detection is good, but improvements are always needed. Physical retrieval schemes applied to ash detected pixels suffer from a lack of knowledge of some basic microphysical and optical parameters needed to run the retrieval models. In particular there is a lack of accurate spectral refractive index information for ash particles. The size distribution of fine ash (1–63 μm, diameter) is poorly constrained and more measurements are needed, particularly for ash that is airborne. Lack of information on important source and sink (fallout through aggregation) processes is also hindering progress. The importance of water in volcanic clouds is emphasised here because of the vital nature these processes play in the development and transport of volcanic clouds. Much more work is required in trying to identify

ice-coated ash particles, and it is suggested that a class of ice-rich volcanic cloud be recognised and termed 'volcanic ice' cloud. Such clouds are frequently observed in tropical eruptions of great vertical extent (e.g. 8 km or higher) and are often not identified correctly by traditional IR methods (e.g. reverse absorption). Passive (and active) microwave data may play a role in detection improvements.

The situation for active sensors for measuring gases and particles is much less satisfactory. The passive microwave sensors (e.g. MLS, AMSU-1, AMSU-B, SSMI) may be able to provide information on the early evolution of volcanic plumes, especially at the stage of column development when the clouds have high numbers of large particles ($\sim$ mm size) and/or there is an abundance of hydrometeors. The Caliop instrument on board the CALIPSO platform (part of the A-train constellation) is proven to be extremely useful for measuring the vertical structure of volcanic plumes. Identification of both volcanic aerosol (sulphates) and particles has been possible because of the dual wavelength polarisation capability of Caliop. When used in combination with infrared imaging instruments, the full 3D structure can be accessed. Unfortunately, Caliop has a narrow swath ($\sim$90 m) and long repeat time ($\sim$16 days) which makes use of the data for operational purposes problematic. Radar sensors (e.g. CloudSat) have not yet been fully investigated for use with volcanic eruptions, but there is some potential in the early stages of column development.

5.2.2 Future systems

The operational use of geostationary (GEO) EO data at the Volcanic Ash Advisory Centres (VAACs) for the current and near-future (next 10 years) is shown in Table 5.2.1 which lists capabilities at all VAACs The European VAACs (London and Toulouse) are in a relatively good situation with geo seniors. This will continue and improve with the launch of the MTG (Meteosat Third Generation) geo carrying a hyperspectral sensor. The VAACs covering the Americas and Pacific basin are less well served and will lose the split window capability by 2015. Some research has been done to assess the impact of this and there is the possibility of using a longer wavelength channel, but the loss of the split-window capability is regarded as having serious implications for volcanic ash monitoring. The Chinese FY4A will also have hyperspectral capability covering ash monitoring in the western pacific, Indonesian archipelago, Philippines, Japan and Kamchatka. Polar orbiters cover the whole globe and wide swath imaging instruments (e.g. MODIS) can provide 2 or more coincidences per day depending on latitude for any given point on Earths surface. With several polar orbiters carrying split-window capability (or hyperspectral sensors) the coverage is generally very good. Thus, sensors such as the MODIS-Terra, MODIS-Aqua, AVHRRs, NPP, AIRS, IASI and the Sentinel-3 instruments (SLSTR and OLCI), together with similar sensors from the Japanese, Chinese, Russian, Korean and Indian space agencies will provide excellent global monitoring for volcanic ash for the next 10–20 years. Coupled with the use of the UV polar orbiters (Sentinel-4 will carry a UV geo sensor) for monitoring SO_2 (daytime) there will be adequate EO resources available to the research, commercial and operational communities for the near future (next 10 years).

Some of the new sensors useful for volcanic ash and SO_2 monitoring are listed below:

New sensors 1 *European region*

- FCI (GEO VIS/TIR multispectral, MTG-S). FCI will be capable of providing additional channels with better spatial, temporal and radiometric resolution, compared to MSG-SEVIRI instrument.
- IRS (GEO IR hyperspectral, MTG-S). It will deliver over the Full Disk data every 60 minutes, with a spatial resolution of 4 km, increasing the capability of the IASI ash and SO_2 retrieval schemes.
- Sentinel 4 (GEO UV/NIR hyperspectral, MTG-S). It will deliver over the Full disk data every 60 minutes, with a spatial resolution of better than 10 km, increasing the capability of the OMI, GOME-2 and SCIAMACHY SO_2 retrieval schemes.
- NPP
- OLCI and SLSTR (LEO VIS/TIR multispectral, Sentinel 3). Covering VIS to TIR with high signal to noise ratio and spatial resolution. Increasing the capability of MODIS, AVHRR, MERIS and AATSR ash and SO_2 retrieval schemes, and SLSTR dual view will permit stereo matching retrieval of volcanic plume altitude.
- Backscatter Lidar (ATLID), aboard the EARTHCARE mission, should be use to improve the volcanic ash thickness retrieval needed for a precise estimation of the ash concentration.

New sensors 2 *Global*

- Includes all polar orbiters for the European region, e.g. Sentinel-3 and EPS MetOP-SG/MODIS/AVHRR/NPP (OMPS, VIIRS), TROPOMI (UV/SWIR) on Sentinel 5P, VNS Sentinel 5, IASI-NG, 3MI and METOP-C sensors: IASI and GOME-2
- MTG-FCI (GEO VIS/TIR multispectral, Sentinel 4). FCI will be capable of providing additional channels with better spatial, temporal and radiometric resolution, compared to MSG-SEVIRI instrument.
- MTG-IRS (GEO IR hyperspectral, Sentinel 4). It will deliver over the Full Disk data every 60 minutes, with a spatial resolution of 4 km, increasing the capability of the IASI ash and SO_2 retrieval schemes.
- MTG-UVN (GEO UV/NIR hyperspectral, Sentinel 4). It will deliver over the Full Disk data every 60 minutes, with a spatial resolution of better than 10 km, increasing the capability of the OMI, GOME-2 and SCIAMACHY SO_2 retrieval schemes.
- OLCI and SLSTR (LEO VIS/TIR multispectral, Sentinel 3). They will cover all the spectral range from VIS to TIR with high signal to noise ratio and spatial resolution. They will increase the capability of MODIS, AVHRR, MERIS and AATSR ash and SO_2 retrieval schemes, and SLSTR dual view will permit stereo matching retrieval of volcanic plume altitude.
- Backscatter Lidar (ATLID), aboard the EARTHCARE mission, should be use to improve the volcanic ash thickness retrieval needed for a precise estimation of the ash concentration.

High resolution (spatial) commercial satellites (e.g. SPOT, Pleiades) have not been exploited as much as their lower resolution cousins, but this situation could change with the much greater availability of commercial satellite data and the concomitant cost reduction. With sev-

eral constellations now flying the opportunity to acquire good high resolution (visible) imagery of a volcanic event has greatly improved. The data can be used to infer cloud heights (from shadow) or parallax (stereo-viewing) and it is also possible to do some quantitative aerosol retrievals of a similar kind to this done for MODIS; although the poorer spectral coverage (usually only RGB data are available) is a limitation.

The large amount of similar data from a variety of space agencies and platforms suggest the need for standardisation of ash and SO_2 products and agreement on uncertainties, traceability and product definitions. Such activities have started but it is unlikely that standardised products will be available within the next 3 years.

Table 5.2.1 An overview of the geostationary satellite capabilities is shown as a function of Volcanic Ash Advisory Centre (VAAC). The table summarises the temporal and spectral capabilities (those relevant to volcanic ash remote sensing) of each instrument that covers each VAAC area of responsibility. In addition, future geostationary satellite capabilities are summarised. Next generation satellites that include a hyperspectral sounding capability are shown in orange.

VAAC	Geo satellite(s)	Temporal refresh	Spectral capabilities	Next generation Geo satellite
Anchorage	GOES-11	30 min	Split-window	GOES-R (2015)
Buenos Aires	GOES-12	15 mins	No split-window	GOES-R (2015) and
	GOES-13	180 mins	No split-window	**MTG (∼2018)**
	MSG	15 mins	Advanced	
Darwin	MTSAT	60 mins	Split-window	GOES-R like from
	FY2D	60 mins	Split-window	JMA (2020?) and
	FY2E	60 mins	Split-window	**FY4A (2014)**
London	MSG	5 or 15 mins	Advanced	**MTG (∼2018)**
Montreal	GOES-11	30 mins	Split-window	GOES-R (2015)
	GOES-13	15 or 30 mins	No split-window	
Tokyo	MTSAT	60 mins	Split-window	GOES-R like from
	FY2D	60 mins	Split-window	JMA (2020?) and
	FY2E	60 mins	Split-window	**FY4A (2014)**
Toulouse	MSG	5 or 15 mins	Advanced	**MTG (∼2018)**
Washington	GOES-11	30 min	Split-window	GOES-R (2015)
	GOES-12	15 mins	No split-window	GOES-R (2015) and
	GOES-13	15 or 30 mins	No split-window	**MTG (∼2018)**
	MSG	15 mins	Advanced	
Wellington	MTSAT	60 mins	Split-window	GOES-R like from
	GOES-11	180 mins	Split-window	JMA (2020?) and GOES-R (2015)

5.2.3 Optimal future system

An ideal instrument and satellite configuration for global ash monitoring requires a constellation of five geo satellites and at least 4 polar orbiters. Each platform should house a hyper spectral infrared imaging sensor and UV imager with 1–10 km spatial resolution, 30 mins refresh rate and adequate signal to noise to resolve temperature changes of 0.2 K at 270 K. In the ultra-violet, the measurement requirement should be the same or better than that for OMI, which has proved

useful for both explosive and passively degassing volcanoes. To better constrain the volcanic cloud thickness and height, essential parameters for a reliable ash concentration estimation, lidar satellite systems are needed to complement the Caliop measurements. These systems should provide global coverage on a twice daily basis. Since many of these requirements fit well with those for other applications, the goal of such a system is not unreasonable, although still requires a large and on-going funding commitment from space agencies. Given that the community is moving quickly towards data assimilation, some of the missing information not measured well by satellite instrument will be provided by numerical models (e.g. cloud top height, atmospheric structure, winds). The optimal system then consists of constellations of satellites, numerical data assimilation models, validation systems and standardised products, some of which can be tailored to the specific needs of the aviation industry.

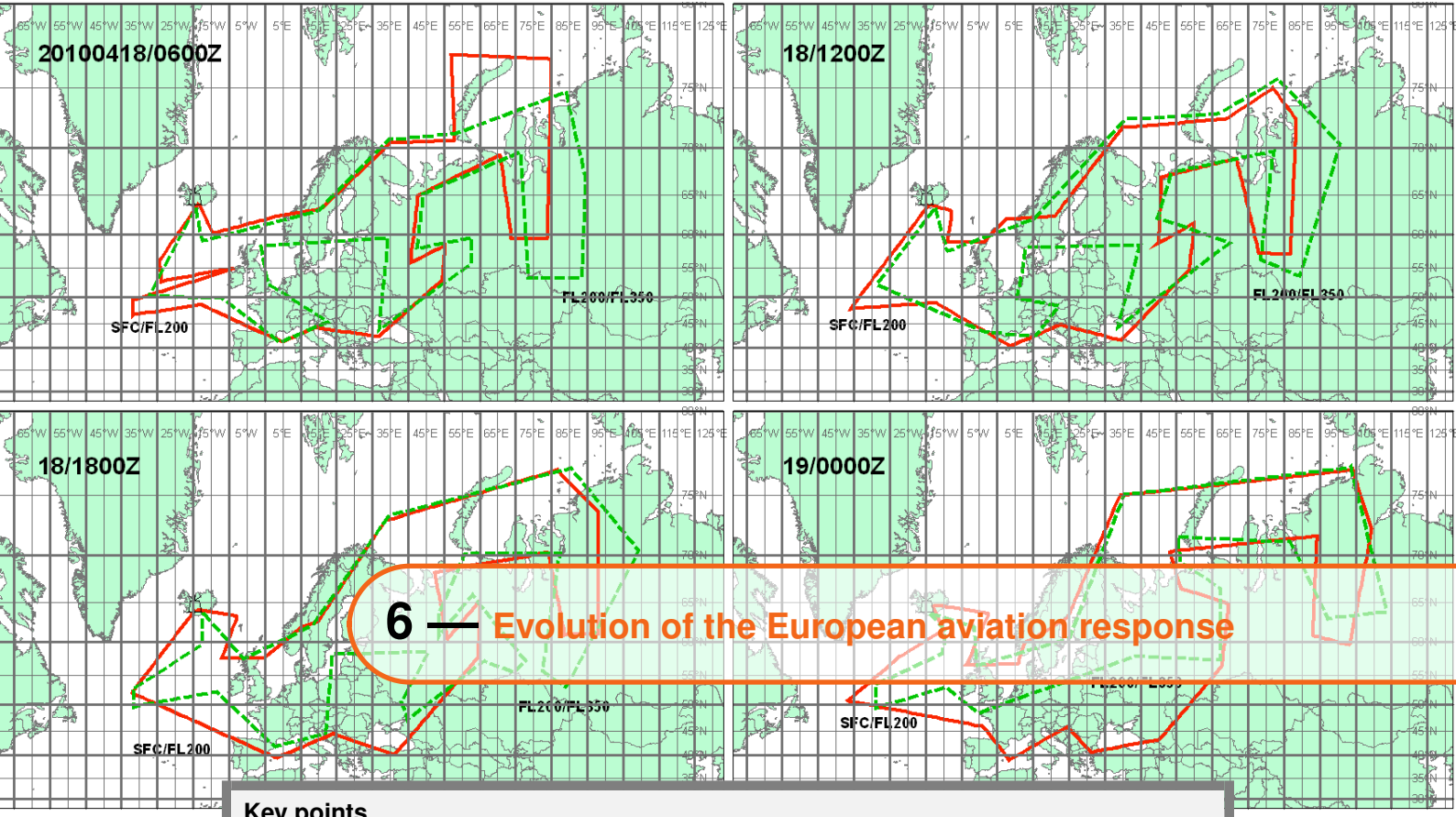
5.3 Ground-based and airborne platforms

The ash products will also be significantly improved by means of ground-based instruments (UV and TIR cameras, lidar and radar systems) that can be used either for the products validation or for the source terms estimation. This latter is needed as input to the ash dispersion models with a significant impact on precision and accuracy of model forecasts, and their reliability as a decision support to the VAAC during volcanic crisis management. Moreover, improved ash retrievals can be obtained by combining satellite and ground measurements.

The role of the Observatories is fundamental to give continuous and high quality measurements from standardized instruments and procedures. To improve the exploitation of the valuable ground-based datasets routinely collected, a great effort should be addressed to make them freely accessible to the whole scientific community.

5.4 Integration

The satellite systems provide global coverage of Earth observation data, but there is no single space-borne platform that can carry all the instruments suitable to ensure a comprehensive description of a given phenomenon. Each geosynchronous Earth orbit (GEO) platform can ensure the Earth hemisphere data collection with a high temporal sampling, while low Earth orbit (LEO) satellites sensors provide global coverage with higher spatial resolution and sensitivity. Therefore, the integration of all the different instrument retrievals available is key to obtaining more reliable and effective results. The general idea behind an improved ideal European volcanic ash and SO_2 monitoring system is the combination of the rapid temporal sampling of GEO sensors, the higher spatial resolution and sensitivity of LEO sensors with ground-based observations.



6 — Evolution of the European aviation response

Key points

- *Difficulty in implementing zero tolerance to quantitative thresholds*
- *Need for clarity on standard definition of what constitutes 'visible' and 'discernible' ash*
- *Introduction of Airline operator safety cases allow operators greater freedom to operate in ash-affected airspace*

6.1 Introduction

Prior to the April–May, 2010 Eyjafjallajökull eruptions, Europe had not experienced any significant aviation disruptions from volcanic ash. The Grimsvotn 2004 eruption had caused some minor flight disruptions in northern Europe, but this cloud was predominantly composed of SO_2 and caused no actual problems. The global community involved in this problem had been meeting regularly (every 3 years) to discuss all aspects of monitoring and forecasting volcanic ash movement–the 6th meeting of this group was held in Citeko, Indonesia in March, 2013 and the 5th meeting was held in Santiago, Chile in March 2010, just prior to the Eyjafjallajökull eruptions. It is generally agreed in hindsight that the closure of European airspace during April and May 2010 was an overreaction. It can be argued that for safety concerns and because the London VAAC relied on a model that did not utilise observations, a highly conservative approach was necessary and the airspace closures justified. Indeed Prata and Prata (2012) show that satellite observations suggest that the ash cloud over parts of Europe were highly heterogeneous and although mean concentrations were relatively low (<2 mg m^{-3}), maximum concentrations exceeded 4 mg m^{-3} in patches. Models are unlikely to be able to forecast and pin-point in space and time these small, highly concentrated patches. The general guidance for aircraft operating in ash affected airspace is that if the ash is visible then it should be avoided [4]. This guidance is flawed for two reasons: it is unclear what concentration of ash is actually visible (to the human eye) because of variations in illumination and viewing geometry, and it is unclear what level of ash concentration is dangerous (causes an unacceptable safety risk). In the congested European airways, therefore, the approach taken was to designate large areas of the atmosphere ash-contaminated as the amount of ash erupted was uncertain and hence the amount dispersed across Europe also uncertain. In the three years since the Eyjafjallajökull event, much has been

learned and there have been further eruptions to study and practice exercises have been undertaken. The evolution of the European response is discussed here with an emphasis on how things have improved and how the next large event will most likely be handled.

6.2 Eyjafjallajökull

6.2.1 Before Eyjafjallajökull

During the satellite earth observation era (∼1970s onwards) there have been several significant volcanic eruptions within Europe. Overwhelmingly the volcanic activity has been either in Italy (notably Etna) or in Iceland. Significant periods of activity, including ash emissions that affected Catania airport have occurred many times and on several occasions the airport has been closed. Ash emissions have been reported in satellite imagery in October 1981 (AVHRR, first launched in 1979) and it is likely that activity in the 1970s (notably 1975, 1977 and 1978) would have been observed by earth observing satellites. Periods of stronger activity occurred in 1991–1993 and 2002–2003; an international space station photograph of one of the eruptions in October 2002 is shown in Figure 1. It is reported that ash from this plume reached Libya and SO_2 satellite retrievals from the AIRS sensor (Prata and Bernardo,) support this conclusion

Figure 6.1: International Space Station at image, showing an ash-rich plume from Mt. Etna, first blowing SE, and then blowing S towards Africa at higher altitudes on 30 October 2002. Ashfall was reported in Libya, more than 560 km distance from Etna. *Courtesy of Earth Sciences and Image Analysis, NASA-Johnson Space Center – Image ISS005-E-19016.*

6.2.2 During Eyjafjallajökull

A list (not comprehensive) of the important events (regulatory and scientific) is provided below, showing the evolution of factors affecting the ash/aviation problem in Europe and the response from the scientific and regulatory communities.

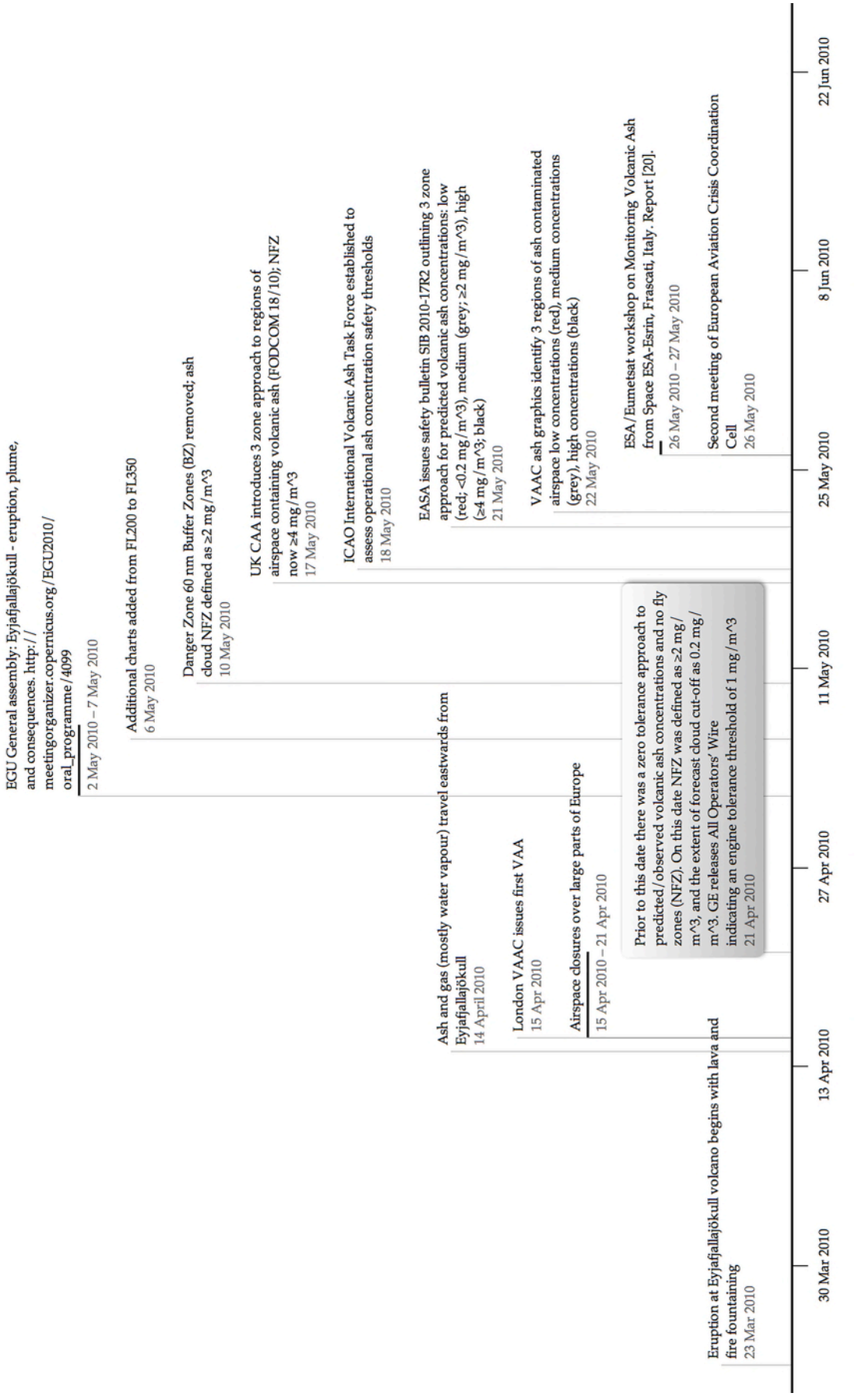


Figure 6.2: Timeline of some important events during the Eyjafjallajökull volcanic ash crisis in Europe. March–June, 2010.

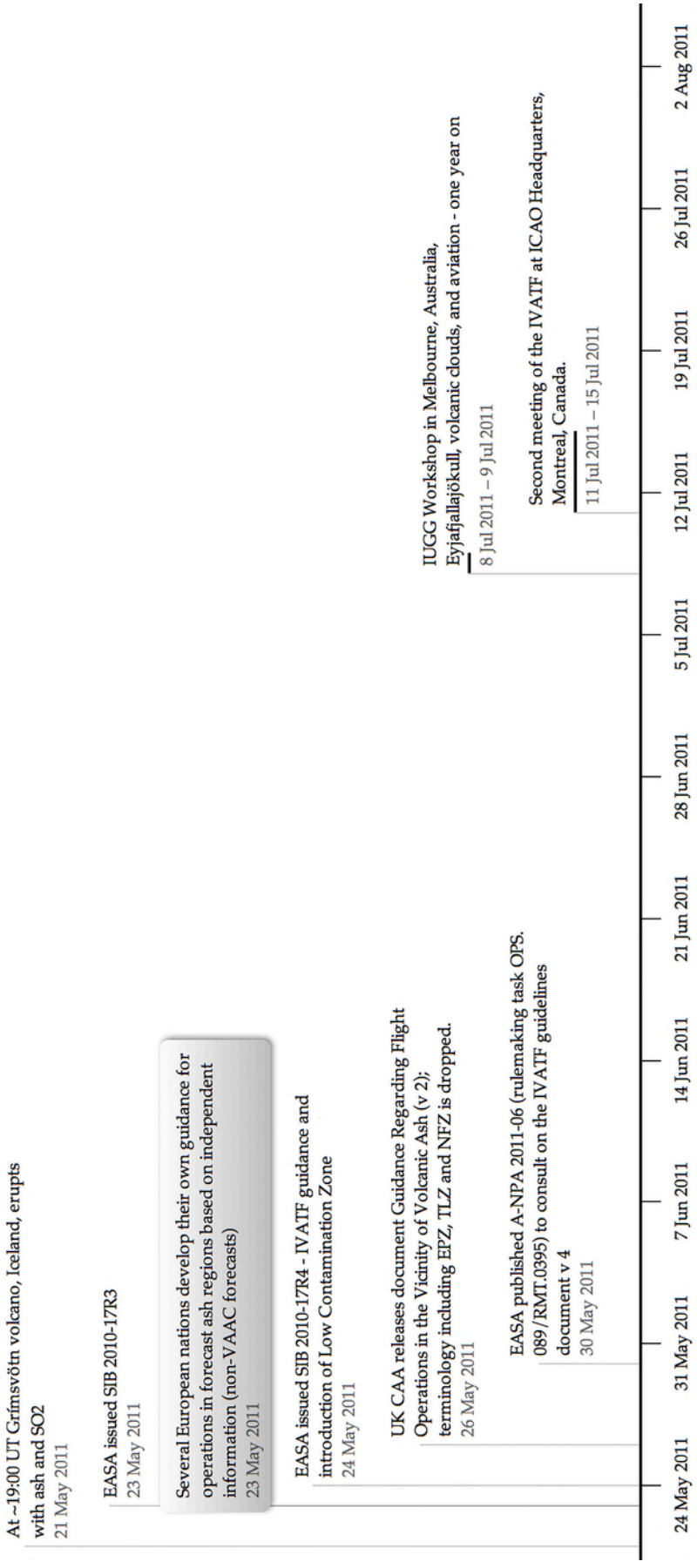


Figure 6.3: Timeline of some important events during the Grímsvötn volcanic ash eruption in Europe. May–August, 2011.

6.2.3 After Eyjafjallajökull–Grímsvötn

At about 19:00 UTC on 22 May 2011, the subglacial volcano Grímsvötn began an eruption. Despite all of the progress made on improving the forecast of volcanic emissions, errors were made in estimating the amount of ash transported towards European airspace. The UK national press noted the change in forecast emissions from one day to the next and confidence in model forecasts diminished. This led to some European nations developing and using their own guidance, while acknowledging the London VAACs authority on the issuance of VAAs. Once again it appears that not enough attention was given to satellite observations which clearly showed a large separation of SO_2 emissions travelling northwards at high altitude (>10 km) and ash emissions, of low concentration travelling southwards and then eastwards at altitudes lower than 5 km. The ash concentrations reaching southern Scandanavia were measured to be less than 1 mg m^{-3} and agreed well with the satellite observations. The problematic forecasts were based on a relationship between eruptive column height and mass eruption rate which breaks down when there are strong winds (bent-over plumes) or weak winds and column collapse, as appeared to have happened in the case of Grímsvötn. The significant separation of SO_2 and ash also contributed to the errors as the models treat all emissions in the same way and make no distinction between volcanic constituents. Figure 2 shows satellite-based retrievals of SO_2 and ash integrated over the period 22–25 May 2011; clearly showing the separation and giving an indication of the mass loadings.

6.3 Responses

6.3.1 UK and Iceland response

The UK has the responsibility for the London VAAC (operated by the Met, Office). The UK Government activated a SAGE team during the crisis and enlisted the support of academic experts from Universities (the University of Bristol in particular), from the British Geological Survey (BGS), the Met. Office and invited experts from Iceland. The Met. Office has been very active since the eruptions of Eyjafjallajökull and Grímsvötn with involvement in several large projects, through ICAO and WMO and by strengthening its own resources in modelling and satellite data analysis. The Met. Office has invested in a new aircraft (MOCCA) for the purpose of providing airborne platform measurements during another event and also in several new ground-based lidars.

The Icelandic response has been equally strong. Two new radars have been acquired and a new mobile lidar placed at Keflavik. Icelandic scientists are heavily involved in many European initiatives and projects and the Icelandic Met Office (IMO) conducts regular volcano exercises (VOLCEX). The London VAAC and IMO have regular conference calls and the communication links are now very robust and active. These developments are very encouraging and positive, but the airline industry still feels a certain amount of disconnect with what they perceive as largely academic activities with little relevance to the industry needs. In a critical submission to the UK government (http://www.publications.parliament.uk/pa/cm201011/cmselect/cmsctech/498/498we21.htm) British Airways highlighted the over reliance on modelling that they believed informed the decision to close airspace.

6.3.2 The rest of Europe

Although the London and Toulouse VAACs retain the primary responsibility for advising aviation of the potential hazards from airborne volcanic ash, it has become clear that several European national meteorological services have developed their own capabilities and advisory networks. Airspace closure is the responsibility of the national authority and it is thus natural that European governments might wish to enhance their capabilities. The largest investments

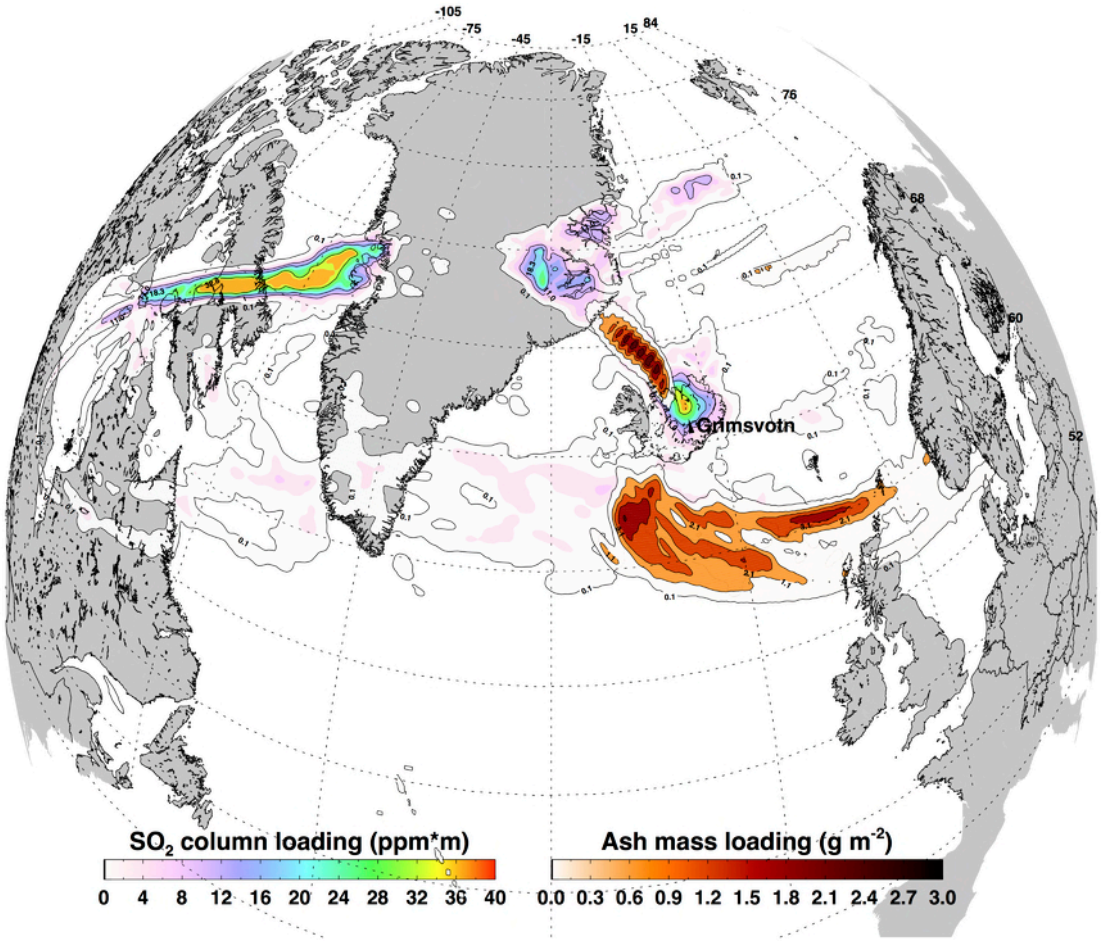


Figure 6.4: Ash and SO_2 column loadings for the period 22–25 May, 2011 derived from AIRS (SO_2) and SEVIRI (ash). After, Prata *et al.* (2014).

have been in developing VATD models and in some cases in infrastructure; for example, the lidar networks have been improved in France and Germany. The Norwegian response has been to instigate a national project to develop capabilities in modelling and to consider expansion of the ceilometer network. The Italian response has been more considered, partly because of funding limitations but also because Italy already has a very strong capacity in volcanological research and observations. Many European countries have invested national funds towards research projects aimed at improving knowledge of volcanic ash and the European Union has invested in various new projects, including WEZARD (see project list) which has a component on volcanic ash. More resources from the EU are expected in the 2020 funding scheme with funding priorities to be announced in late 2013.

6.3.3 The rest of the world

The effect of volcanic ash on the aviation industry is a global problem [25]. The major impact of the Eyjafjallajökull eruption was felt in Europe. Similar sized eruptions have occurred in other parts of the world without a similar paralysis of the aviation industry. There has been speculation that this was because of the infrequency of ash events over Europe coupled with the highly congested skies. The existence of many different aviation authorities with national

sovereingty over their skies also makes for a highly complex and difficult management problem. While the rest of the world took note, very little has changed in the operational environment for volcanic ash advisories in the rest of the world. The idea of using concentrations has not been adopted and has in fact been replaced with various ideas of *visible* and *discernible* ash. Neither of these descriptive terms have good definitions and it is likely that there will be confusion in the future. The USA have sufficiently advanced systems and significant resources that it is likely they would cope with an event over the US similar to Eyjafjallajökull – indeed the 1992 Mt Spurr eruption that brought ash and SO_2 over the whole of the northern USA may be considered as similar. Other parts of the world may not fare so well. Of greatest concern is SE Asia, where there are many active volcanoes (Philippines, Indonesia, PNG, and Japan) and where air traffic is growing fastest. Transfer of knowledge, experience and systems to less developed parts of the world will go some way to help mitigate the effects of dispersing volcanic ash on global air transport.

6.4 Safety cases

In the rest of the world airspace closures due to volcanic ash are quite rare. Often decisions are taken by the operators rather than by the regulators and the system appears to be working as there have been no known fatalities or loss of aircraft due to volcanic ash. To facilitate this within European airspace it was decided that operators could submit Safety Cases to their relevant aviation authority which would allow them to fly in conditions where forecast ash concentrations were below 2 mg $m^{?3}$. Safety cases must include information sources and pathways that help the operator decide whether or not they can fly safely through a forecast area of ash contaminated airspace. Third party data (i.e. not source form a VAAC) may be used. The case must also outline inspection and maintenance procedures to be followed and a risk analysis. To date it is known that at least 5 European carriers have approved safety cases. This is a significant change to the situation that existed prior to April 2010 and the industry appears to be strongly supportive of the procedure.

6.5 IVATF and VASAG

The 1st international volcanic ash and aviation meeting was held in Darwin, Australia in 2003 and there have since been five further meetings, the last (the 6th) was held in Citeko, Bogor, Indonesia in March 2013. This group was established to bring together meteorologists, atmospheric scientists, volcanologists and aviation stakeholders together on a regular base ($\sim$3 years) to discuss the issues and advances in volcanic ash and aviation safety. The meetings are sponsored by ICAO and more recently by WMO. At the 5th meeting held in Santiago, Chile, in March 2010 [12] it was proposed that a new group be established the Volcanic Ash Scientific Advisory Group (VASAG) to report directly to WMO. Following the April 2010 event, the International Volcanic Ash Task Force (IVATF) was established under the auspices of ICAO, and the VASAG was requested to provide scientific information to the IVATF as one of four subgroups. The IVATF whose membership includes national representatives and organisational members (ESA is a member) was expected to complete its work by July 2012 and any remaining tasks assigned to the International Airways Volcano Watch Operations Group (IAVWOPSG). The VASAG has held three meetings and will convene again in November 2013 in Geneva. The achievements of IVATF have been summarised in a report [6] and were presented at the recent IAVCEI meeting in Kagoshima, Japan.

Perhaps the most important development arising from the deliberations of the IVATF is the recognition of the need for clarity on the term visible ash. This term is used by ICAO in advice to aviation for avoidance of areas of airspace contaminated with ash [4]. To circumvent the need

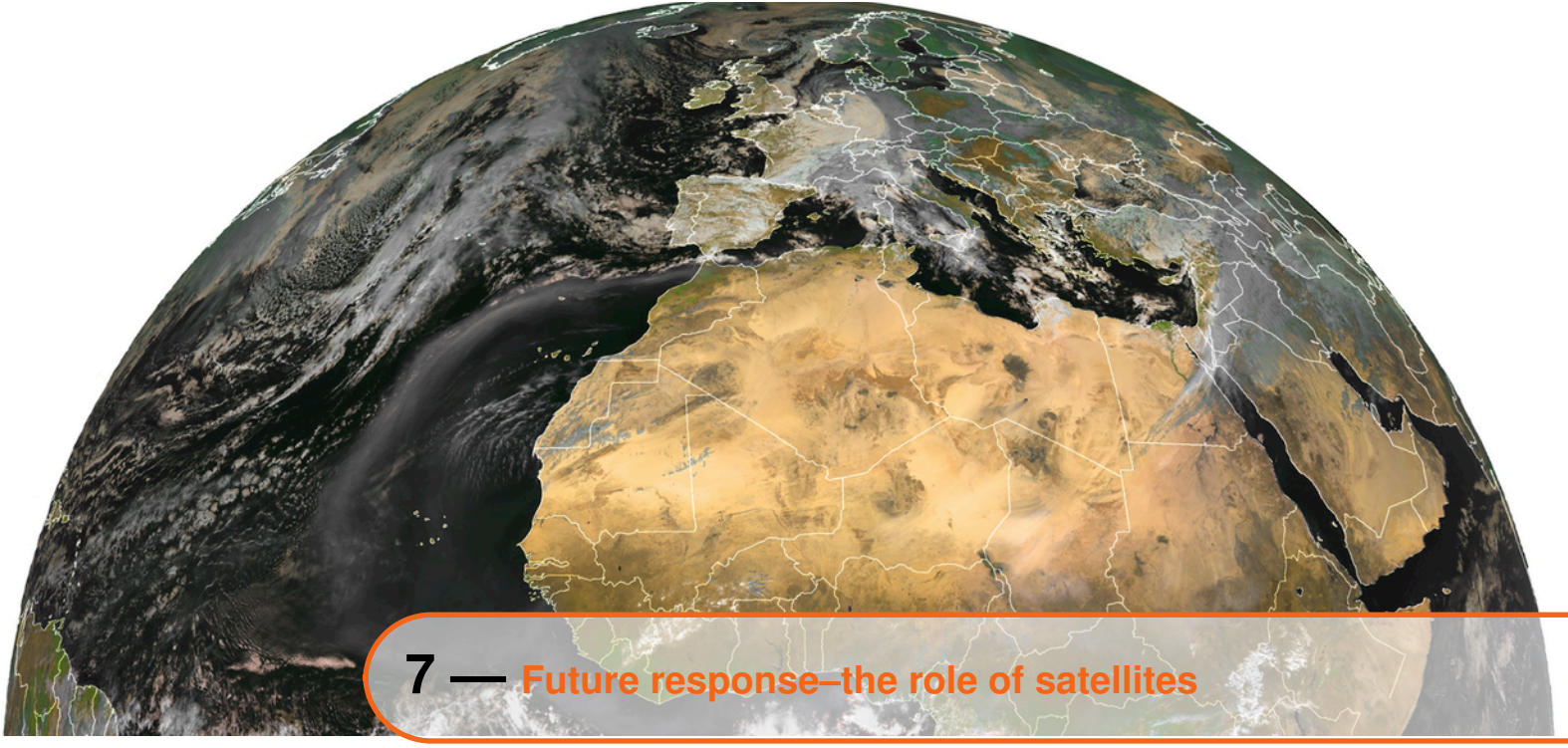
to specify ash concentrations and provide ash tolerances for engines, aviation is able to fly as long as ash is not visible. There are obvious problems with this definition, not least what to do at night? Disregarding the scientific advice of the VASAG to drop this terminology altogether, the IVATF adopted a compromise approach by providing a new term and clarifying definitions for both. The 4th (and final) report of the IVATF [6] states:

The task force agreed to take the following initial definitions forward to the IAVWOPSG:
a) Visible ash–volcanic ash that can be observed by the human eye; and
b) Discernible ash–volcanic ash that can be detected by defined impacts on the aircraft or defined in-situ and/or using remote-sensing techniques.

These definitions are too imprecise. The human eye is an uncalibrated measuring device that includes a highly subjective interpretation method. Exactly what is meant by *defined impacts* is unclear and the comments later just confuse matters further by noting that *discernible* ash may include crew-sensed ash (how would they know?) The report does provide a recommendation based on scientific studies that asserts:

"...the current best estimate of the minimum satellite detection threshold for ash mass loading is 0.2 g m^{-2}*, with a standard error of* ± 0.15 *g* m^{-2} *under favourable conditions using the most advanced retrieval methodologies ..."*

Whether these new definitions and recommendations will be adopted and be useful is yet to be determined. Perhaps, the next large volcanic cloud reaching continental Europe will provide the answer.



7 — Future response–the role of satellites

Key points

- *Satellite data will be an important input for ash forecasting*
- *Satellite data will be an important input for monitoring volcanic activity (ash and SO_2 clouds and thermal anomalies)*
- *New satellite data products from the EO system are emerging*
- *Coordination between satellite agencies for standardised ash products is occurring*

Much has changed since the events of April 2010, especially in competency and capacity to respond to dispersing volcanic ash. Progress in VATD models has been particularly marked (see Chapter 3) and several European institutes and agencies now have in-house capability to run volcanic ash forecasts. Progress on observational systems has also been good, with at least 4 European countries investing in new ground-based lidar systems aimed at measuring volcanic ash concentrations. Developments in radar technology for near-source plume height monitoring, novel radiosonde equipment and unmanned aerial systems (UAV) are also being made.

Satellite data, and in particular satellite ash products, have seen much less investment and this is surprising given the lessons learned concerning the use of models unconstrained by observations. Teams at some institutes (e.g. ZAMG) and at the Met Office and NASA are now developing systems that can assimilate satellite data into VATD models, and to some degree reconstruct the ESP. Still there remain many questions about the validity of satellite retrievals, the error characteristics, the timeliness and paucity of validation data with which to corroborate and validate the satellite estimates. The lack of frequent space-borne lidar measurements is a serious gap in the satellite observing network. There may now be a false sense of security with regard to ash forecasting as there is still too much reliance on VATD and the hit-and-miss approach of using ground-based lidars, which depend on the ash cloud passing over the lidar at a convenient time of day (there are no automated ash-detecting lidar systems in 24/7 operation). The experience of just one or two (including Grímsvötn) eruption events is not sufficient to validate the robustness of VATD models. The ash concentration forecast failures for Grímsvötn and the overreaction of VAACs in other jurisdictions (e.g. the Toulouse VAAC for the June 2011 Nabro event, and the Darwin and Wellington VAACs for the June 2011 PCC events) suggest that, while identification of ash and SO_2 by satellite sensors is improving, the interpretation, use and timeliness in an operational environment still poses problems.

There are some *ad hoc* approaches to improving the situation with regard to the availability of

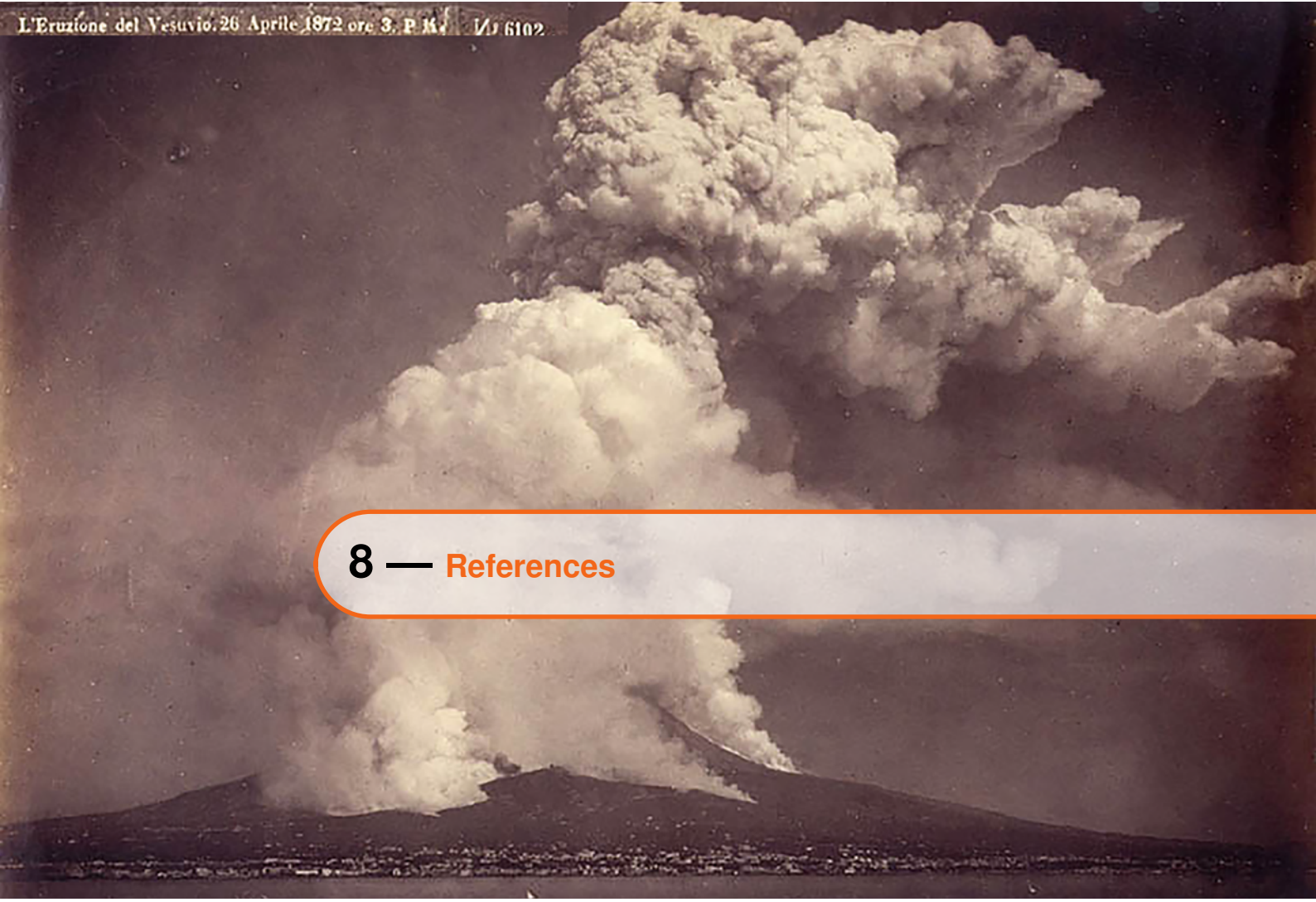
satellite-based volcanic products, including:

- the ESA-sponsored sites at SACS http://sacs.aeronomie.be, IASI alerts http://cpm-ws4.ulb.ac.be/Alerts/index.php and VAST http://fred.nilu.no/sat/,
- NASAs near real-time AIRS products http://disc.sci.gsfc.nasa.gov/nrt/data-holdings/airs-nrt-products/airs-nrt-products#Data, and OMI products http://so2.gsfc.nasa.gov/)
- NOAAs OMI information service http://satepsanone.nesdis.noaa.gov/pub/OMI/OMISO2/index.html and,
- FMIs fast delivery OMI SO_2 volcanic products http://omivfd.fmi.fi/volcanic.html.

Ash is the main hazard to safe operation of aircraft in flight, but SO_2 which often accompanies ash (but not always) is much easier to identify and quantify in satellite data. Some discussions have been held with regard to the health impacts of volcanic SO_2 on passengers and on aircraft parts. There is no consensus on the impact that SO_2 presents to aviation and the Volcanic Ash Manual [4] provides only precautionary advice. Here we see that the satellite products are in advance of the models and the regulatory regime. Current models do not distinguish volcanic SO_2 from volcanic ash and most (not all) VATDs treat volcanic emissions as passive tracers.

Important volcanic processes are still not being included in the operational dispersion models and also in many research-mode models. Some of these processes are complex and difficult to parametrize, for example, ash aggregation and only limited progress has been made. Alarmingly, perhaps the most important aspect of developing and dispersing volcanic clouds, the entrainment of water, has hardly been considered by models. There are at least two important aspects for volcanic clouds that contain large amounts of water. First, it is likely that the ash fragmentation process results in more fine ash (e.g in phreatomagmatic events) and secondly, the presence of hydrometeors in the cloud promotes aggregation (and hence removal of ash) and can often result in large amounts of ice particle formation on ash nuclei. The May 2011 Grímsvötn eruption is known to have had large amounts of water, both glacial and from atmospheric entrainment, resulting in hydrometeor-rich columns which collapsed, removing large amounts of fine ash that subsequently did not suffer transport. Ice in volcanic clouds masks ash from detection by IR methods. The large ice-rich cloud observed during the 1996 Rabaul eruption prevented detection of the ash within and below the cloud. Likewise, the 19 May 1985 Soputan eruption that caused an aircraft encounter could not be detected by the IR methods other than through an ice-particle signature.

Little use has been made of the high resolution (mostly commercial) LEO sensors, such as Quickbird, Pleiades, and SPOT. These sensors have a role and when used in conjunction with more operational assets (e.g. IASI, AIRS, MODIS and OMI), could provide much needed information on height (using stereoscopy or shadows), location (some sensors have better than 5 m pixels), and AOD. Passive microwave data (e.g. from AMSU-A/B) may also be useful during the optically dense phase of eruption cloud development. Passive microwave energy can penetrate deep into optically thick clouds and the brightness temperatures can reveal information on cloud undercooling and ultimately assist in estimating cloud top height. The Suomi National Polar-orbiting partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) will also play an increasing role in quantitative ash remote sensing together with the SLSTR on Sentinel-3, TropOMI on board Sentinel-5 precursor and the eagerly awaited Sentinel-4 mission which will include an infrared sounder and UV instrument in geostationary orbit.



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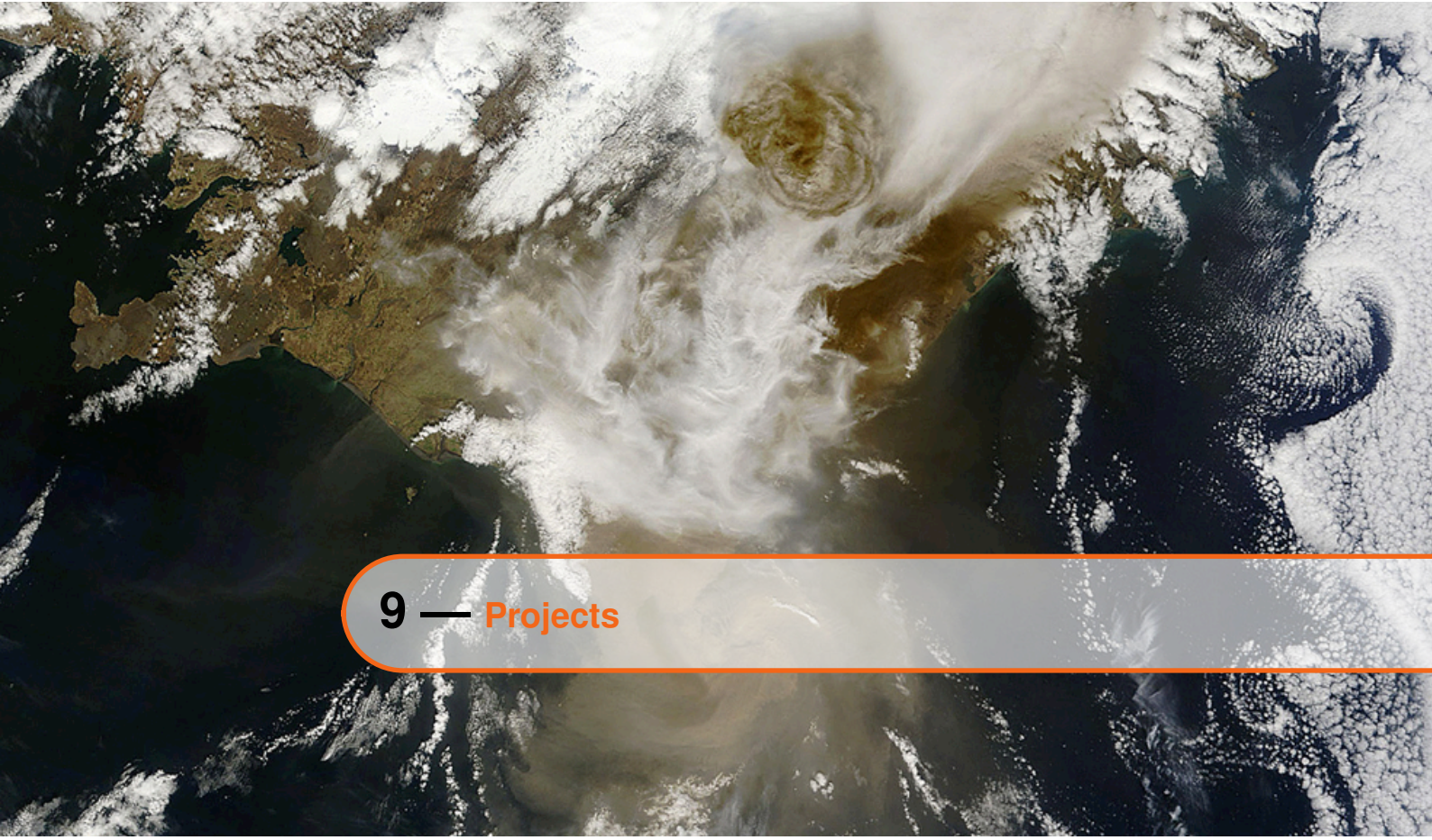
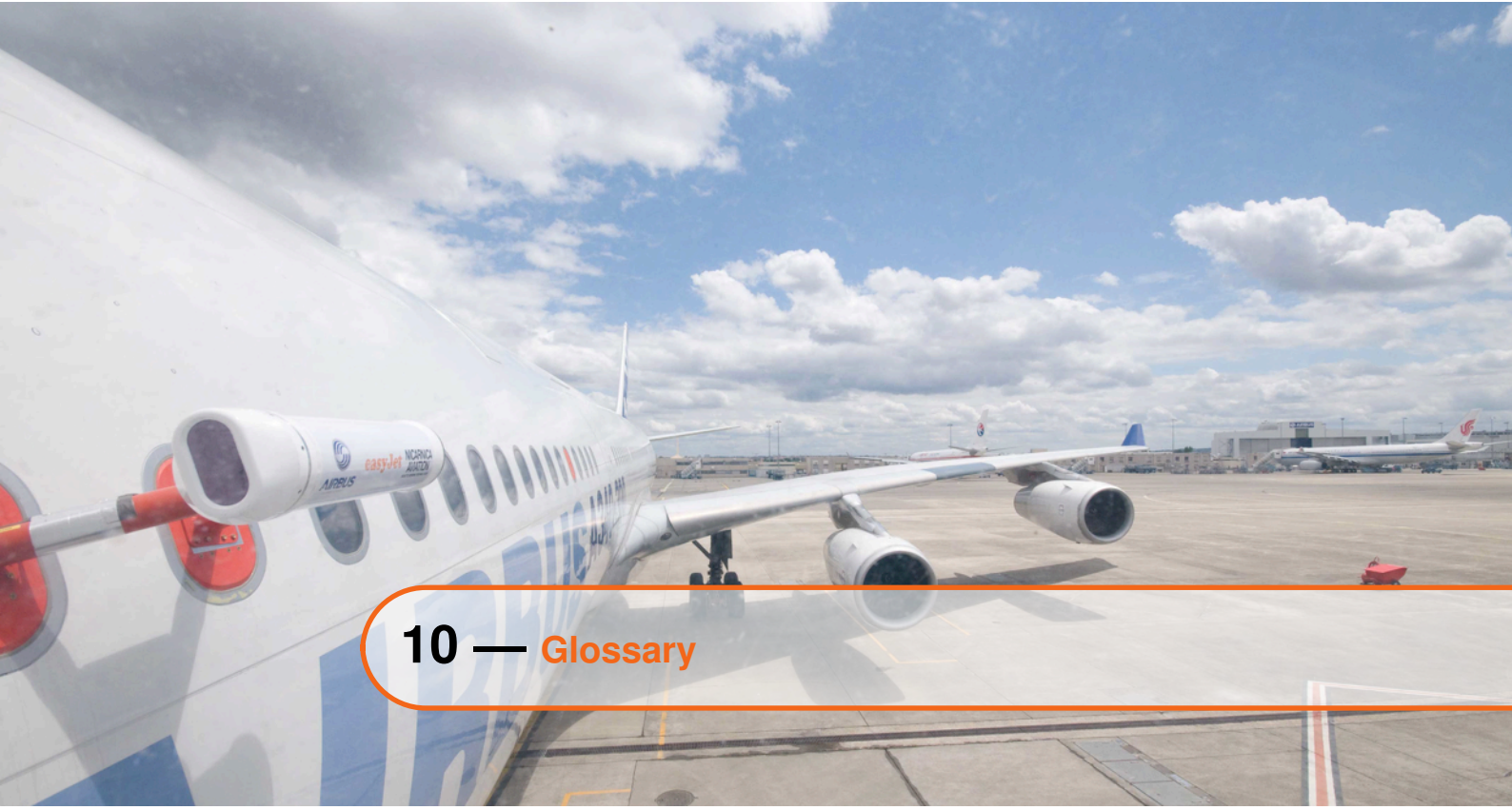


9 — Projects

Project acronym	Description/Website
AphORISM	Advanced PRocedures for volcanIc and Seismic Monitoring.
EPOS	European Plate Observing System. [www.epos-eu.org]
EVOSS	European Volcano Observatory Space Services. [www.evoss.eu]
EXUPERY	Managing volcanic unrest. [www.exupery-vfrs.de]
FUTUREVOLC	FP7 Icelandic volcano super site. [futurevolc.hi.is]
IVATF	International Volcanic Ash Task Force. [www.icao.int/saefty/meteorology/ivatf/]
MACC	Monitoring Atmospheric Composition and Climate. [http://www.gmes-atmosphere.eu/]
MEMOVOLC	ESF funded networking. [www.esf.org/index.php?id=9263]
NOVAC	Network for observation of Volcanic and Atmospheric Change. [www.novac-project.eu]
SAVAA	Support to Aviation for Volcanic Ash Avoidance. [savaa.nilu.no]
SACS-2	Support to Aviation Control Service. [sacs.aeronomie.be]
SMASH	Study on volcanic ash monitoring and prediction. [http://www.cgspace.it/download/SMASH_WEB_PAGE.pdf]
VANAHEIM	NERC/UK Atmospheric/earth science consortium. [www.ncas.ac.uk/index.php/en/vanaheim-introduction]
VAST	Volcanic Ash Strategic Team. [vast.nilu.no]
VOGRIPA	Volcano Global Risk Identification and Analysis Project. [www.bgs.ac.uk/vogripa/]
WEZARD	Weather Hazards for Aeronautics. [www.wezard.eu]



10 — Glossary

AATSR	Advanced Along-Track Scanning Radiometer
AIRS	Atmospheric Infrared Sounder
AOD	Aerosol Optical Depth
ASTER	Advanced Space-borne Thermal Emission And Reflection Radiometer
ATZ	Air Traffic Zone (air traffic management)
AVHRR	Advanced Very High Resolution Radiometer
BTD	Brightness Temperature Difference
CAA	Civil Aviation Authority
CAeM	Commission for Aeronautical Meteorology (WMO)
Caliop	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CTR	Control Area (air traffic management)
DGAC	Dirección General de Aeronautica Civil de Chile
DOAS	Differential Optical Absorption Spectrometer
ESA	European Space Agency
ESP	Eruption Source Parameter
EPS	Ensemble Prediction Scheme
EUR/NAT	Europe/North Africa Region (ICAO)
FAA	US Federal Aviation Authority
GEO	Geostationary Earth Orbit
GOES	Geostationary Operational Environmental Satellite
GOME	Global Ozone Monitoring Experiment
IACVEI	International Association of Volcanology
	and Chemistry of the Earth's Interior
IATA	International Airline Transport Association
IASI	Infrared Atmospheric Sounding Interferometer
IAVW	International Airways Volcano Watch system (ICAO)
IAVWOPSG	International Airways Volcano Watch Operations Group (ICAO)
ICAO	International Civil Aviation Organisation
IGNS	Institute of Geological and Nuclear Science (New Zealand)
IMS	Infrasound Measuring System

INGV	.....	**National Institute Of Geophysics And Volcanology (Italy)**
IUGG	.....	**International Union of Geophysics and Geodesy**
LEO	.....	**Low Earth Orbit**
MERIS	.....	**Medium Resolution Imaging Spectrometer**
MISR	.....	**Multi-Angle Imaging Spectroradiometer**
MODIS	.....	**MODerate resolution Imaging Spectroradiomer**
MSG	.....	**Meteosat Second Generation**
MTG	.....	**Meteosat Third Generation**
MWO	.....	**Meteorological Watch Office**
NAME	.....	**Numerical Atmospheric-Dispersion Modelling Environment**
NEXRAD	.....	**US Weather Radar network**
NEXTGEN	.....	**US air traffic management system (in development)**
NMHS	.....	**National Meteorological And Hydrological Services**
NOAA	.....	**National Oceanic and Atmospheric Administration**
OCLI	.....	**Ocean Colour Light Imager**
OMI	.....	**Ozone Monitoring Instrument**
OMPS	.....	**Ozone Mapping Profiler Suite**
SCIAMACHY	.....	**SCanning Imaging Absorption spectroMeter**
	.....	**for Atmospheric CHartographY**
SEVIRI	.....	**Spin-stabilised Enhanced Visible and Infrared Imager**
SLSTR	.....	**Sea and Land Surface Temperature Radiometer**
SIGMET	.....	**Notice of Significant Meteorological Phenomena (ICAO)**
SMS	.....	**Safety Management Systems (ICAO)**
TIR	.....	**Thermal Infrared**
UV	.....	**Ultra-violet**
USGS	.....	**United States Geological Service**
VAAC	.....	**Volcanic Ash Advisory Centre**
VASAG	.....	**Volcanic Ash Science Advisory Group**
VATD	.....	**Volcanic Ash Transport And Dispersion Model**
VEI	.....	**Volcanic Explosivity Index**
VONA	.....	**Volcano Observatory Notice For Aviation**
WMO	.....	**World Meteorological Organisation**
WOVO	.....	**World Organisation Of Volcano Observatories**
WRF	.....	**Weather Research And Forecasting**
WWLLN	.....	**Worldwide Lightning Network**

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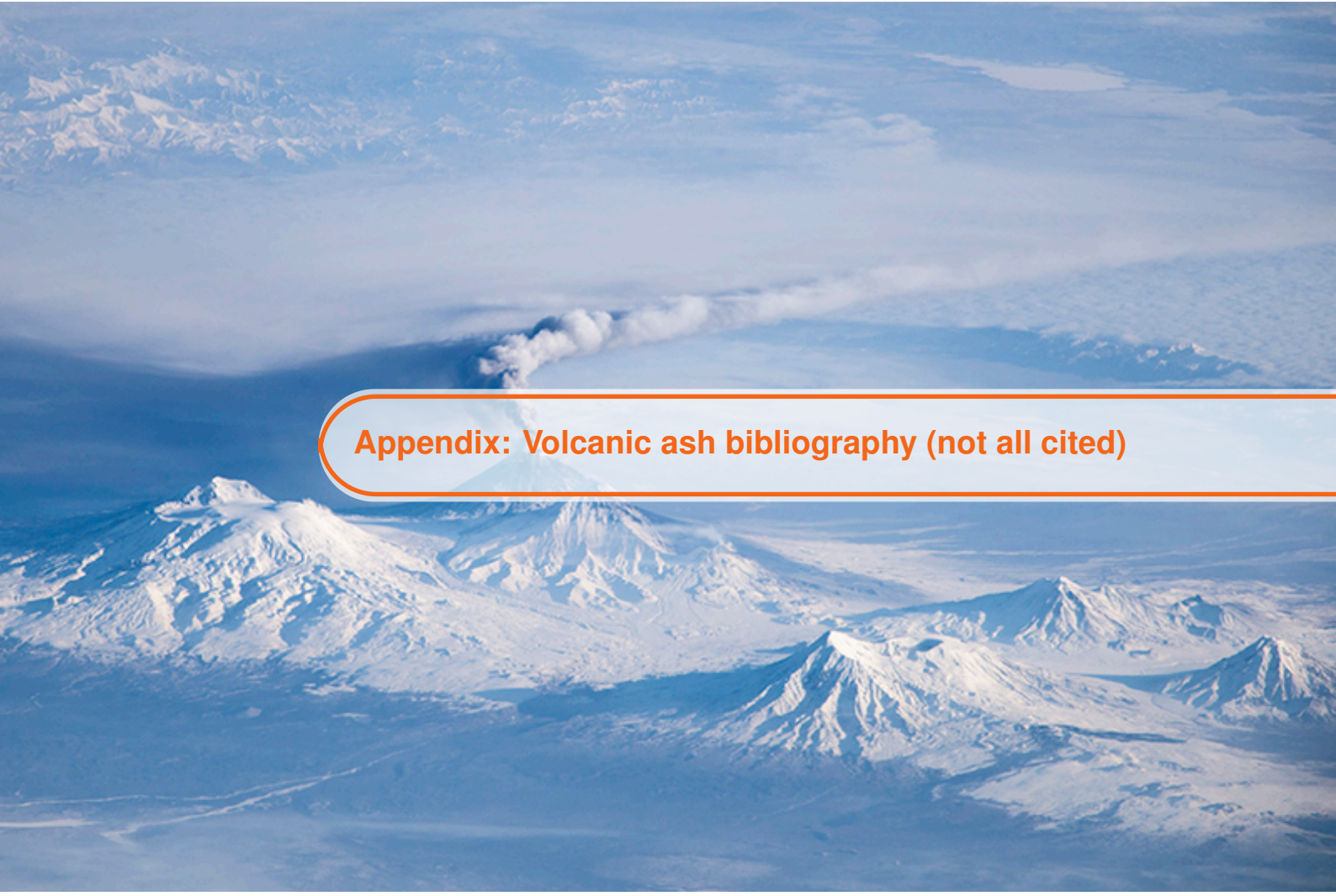

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