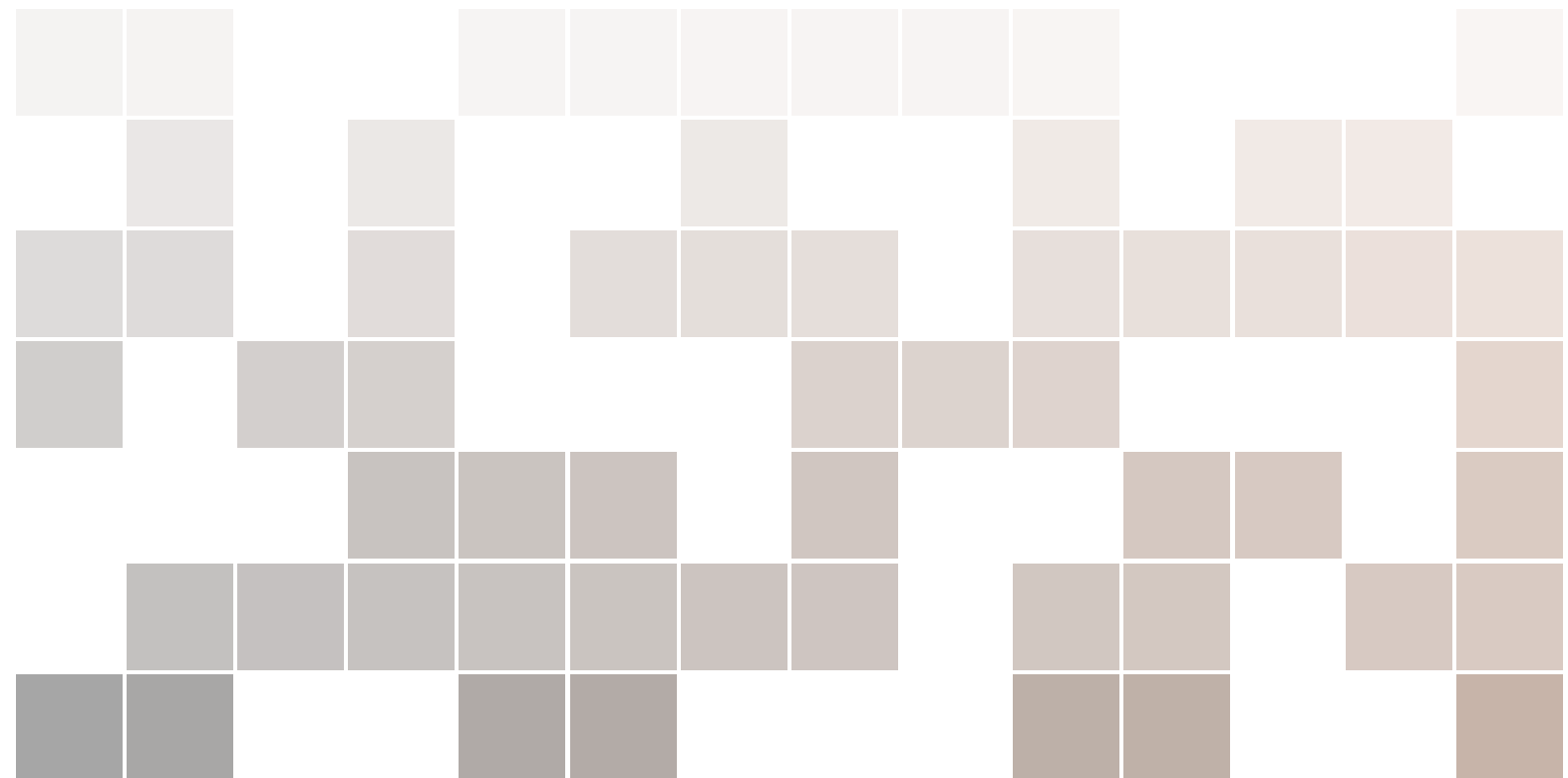


Earth Observations and Volcanic Ash

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

Fred Prata, Claus Zehner and Kerstin Stebel



PUBLISHED BY THE EUROPEAN SPACE AGENCY

Principal authors:

Dr Fred Prata, Senior scientist, Norwegian Institute for Air Research, Kjeller, Norway and Chief Technical Officer, Nicarnica Aviation, Kjeller, Norway. fp@nicarnicaaviation.com

Dr Claus Zehner, Project officer, Earth Observation, ESA, Esrin, Italy. claus.zehner@esa.int

Dr Kerstin Stebel, VAST Project Manager, Senior scientist, Norwegian Institute for Air Research, Kjeller, Norway. kerstin.stebel@nilu.no

Contributing authors: Fred Prata, Kerstin Stebel, NILU, Claus Zehner, ESA (Introduction and Key Points); Gerhard Wotawa, ZAMG, Andreas Stohl, NILU, Helen Dacre, University of Reading, (Chapter 3); Christina Aas, S&T, Fred Prata, NILU, (Chapter 4); Fred Prata, NILU, Nicolas Theys, BIRA/IASB, Stefano Corradini, INGV, (Chapter 5); Fred Prata, Kerstin Stebel, NILU, Claus Zehner, ESA (Chapter 6); Kerstin Stebel, Fred Prata, NILU (Bibliography). Additional comments from: Gerrit de Leeuw and Mikhail Sofiev, (FMI, Finland), Colin O'Dowd, (NUIG, Ireland) and members of the VAST team. Reviewed by: Lucia Maria Tampellini (CGS, Space, Italy), Nina Kristiansen (NILU, Norway), Stefano Corradini (INGV, Italy), and Julie Oakley on behalf of the European Space Agency.

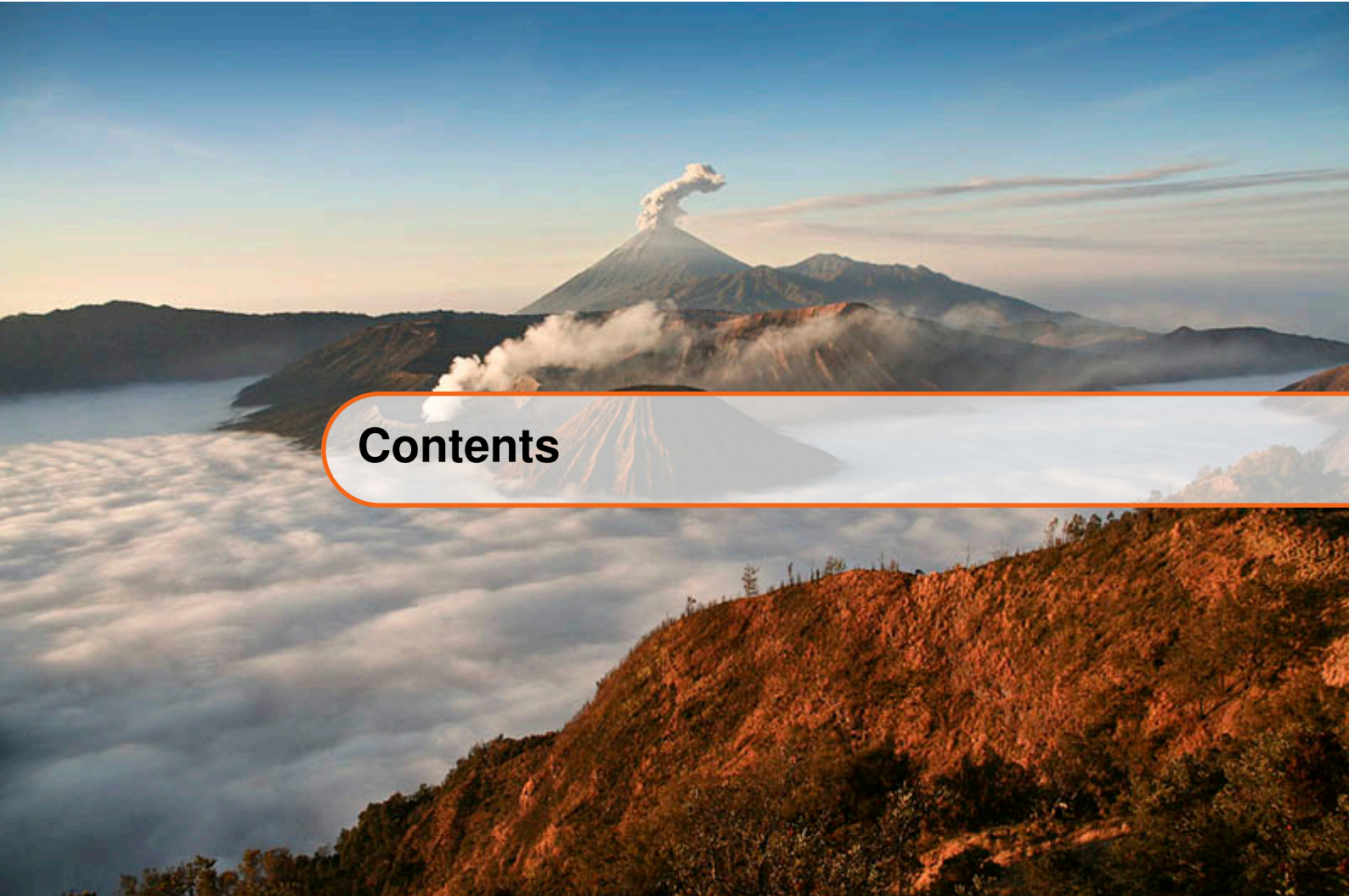
How to cite this document: Prata, A. J., Zehner, C. and K. Stebel, “*Earth Observations and Volcanic Ash: A report of the ESA/Eumesat Workshop, 4–7 March, 2013.*”, doi:10.5270/atmva-14-04, 48pp. (2014).

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.

Dr Mark Doherty

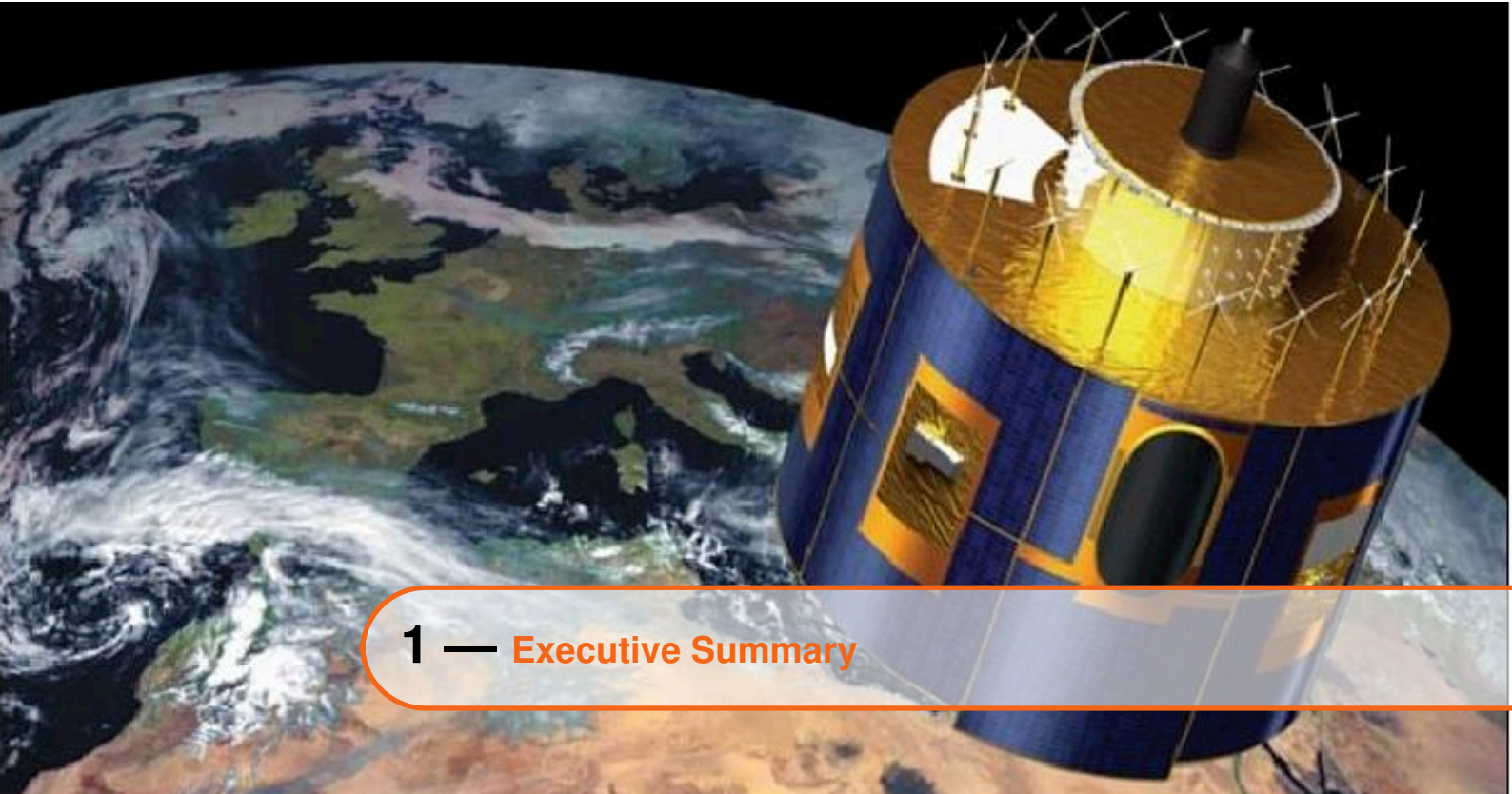
Head of Earth Observation Programmes Exploitation and Services Division,
European Space Agency, ESRIN, Via Galileo Galilei,
00044 Frascati, Italy,
mark.doherty@esa.int



Contents

| | | |
|----------|--|-----------|
| 1 | Executive Summary | 7 |
| 2 | Key Points | 9 |
| 2.1 | Progress on recommendations | 10 |
| 3 | Transport modelling of volcanic ash | 13 |
| 3.1 | Introduction | 13 |
| 3.2 | Operations | 13 |
| 3.2.1 | Current operational role and capabilities | 13 |
| 3.2.2 | Current operational limitations | 14 |
| 3.2.3 | Future operational capabilities | 14 |
| 3.3 | Research | 14 |
| 3.3.1 | Current research capabilities | 14 |
| 3.3.2 | Current research limitations | 15 |
| 4 | User requirements review | 17 |
| 4.1 | Introduction | 17 |
| 4.2 | Key user requirements | 18 |
| 4.2.1 | Alert services | 19 |
| 4.2.2 | Monitoring services | 20 |

| | | |
|------------|--|-----------|
| 4.2.3 | Spatial resolutions | 20 |
| 4.2.4 | Forecast frequency | 20 |
| 4.2.5 | Standards and traceability | 20 |
| 5 | Optimal observing system for Europe | 23 |
| 5.1 | Introduction | 23 |
| 5.2 | Satellites | 23 |
| 5.2.1 | State of the art | 24 |
| 5.2.2 | Future systems | 25 |
| 5.2.3 | Optimal future system | 27 |
| 5.3 | Ground-based and airborne platforms | 28 |
| 5.4 | Integration | 28 |
| 6 | Evolution of the European aviation response | 29 |
| 6.1 | Introduction | 29 |
| 6.2 | Eyjafjallajökull | 30 |
| 6.2.1 | Before Eyjafjallajökull | 30 |
| 6.2.2 | During Eyjafjallajökull | 30 |
| 6.2.3 | After Eyjafjallajökull–Grímsvötn | 33 |
| 6.3 | Responses | 33 |
| 6.3.1 | UK and Iceland response | 33 |
| 6.3.2 | The rest of Europe | 33 |
| 6.3.3 | The rest of the world | 34 |
| 6.4 | Safety cases | 35 |
| 6.5 | IVATF and VASAG | 35 |
| 7 | Future response—the role of satellites | 37 |
| 8 | References | 39 |
| 9 | Projects | 41 |
| 10 | Glossary | 43 |
| | Index | 45 |
| | Bibliography (not all cited) | 47 |




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 SO₂ 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)

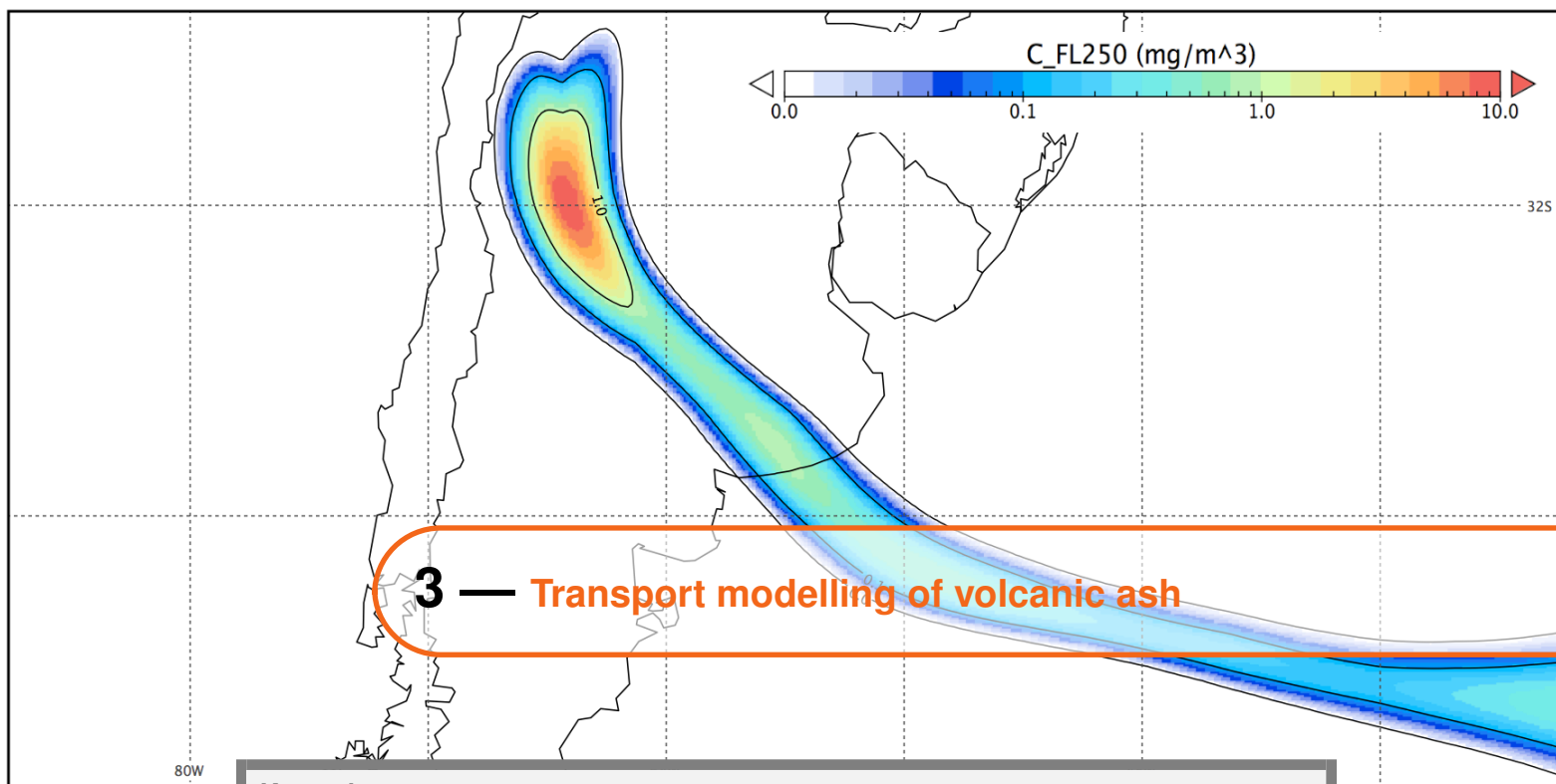
- *Satellite data will be increasingly important for ash forecasting*
- *Satellite data will be increasingly important for monitoring volcanic activity (ash and SO₂ clouds and thermal anomalies)*
- *Provision of new satellite data products from the EO system*
- *Improved coordination between satellite 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 |
|--|---|
| <p>R1 Access to all data sources of volcanic plume observations in Europe should be accelerated, improved and open.</p> | <p>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.</p> |
| <p>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.</p> | <p>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.</p> |
| <p>R3 Actions should be taken to ensure that accurate and timely data are available from volcano observatories or monitoring stations situated near to volcanoes.</p> | <p>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.</p> |
| <p>R4 Concerted developments should be undertaken to integrate existing advanced retrieval methods into operational systems.</p> | <p>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.</p> |

| Recommendation | Progress |
|---|---|
| <p>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.</p> | <p>The London and Darwin VAACs have established research and development programs to address this topic. Other research organisations are conducting similar projects.</p> |
| <p>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.</p> | <p>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.</p> |
| <p>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.</p> | <p>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.</p> |
| <p>R8 Studies should be made of potential new satellites and instruments dedicated to monitoring volcanic ash plumes and eruptions.</p> | <p>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.</p> |
| <p>R9 Intensive basic research should be conducted on the physical, chemical and radiative properties of volcanic ash, from crater to aged clouds.</p> | <p>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 SO₂ 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.</p> |
| <p>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].</p> | <p>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.</p> |
| <p>R11 A follow-up workshop should be organised to review progress on these recommendations after one year.</p> | <p>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).</p> |



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 Earth's 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 SO₂) 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. SO₂ is relatively straightforward to detect from space; indeed it appears to be easier to measure than ash. In many circumstances the transport modelling of SO₂ is also easier than for ash. For passive degassing volcanoes that emit SO₂, 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 SO₂ 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 7 of 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 (single 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 SO₂ 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 would 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.

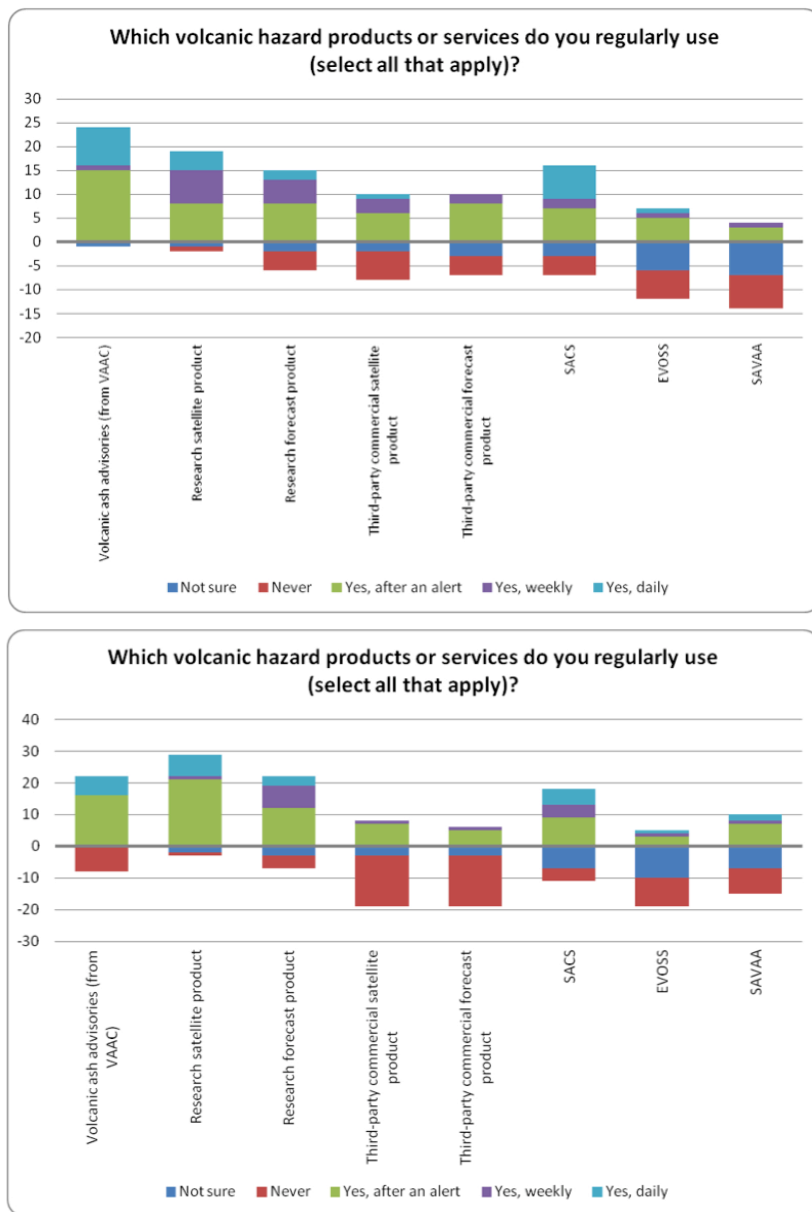


Figure 4.1: Results of the survey concerning use of current alert services by *operational* (top) and *research* (bottom) user categories.

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 SO₂ 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 ~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 within 15 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 SO₂ 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 SO₂ 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.

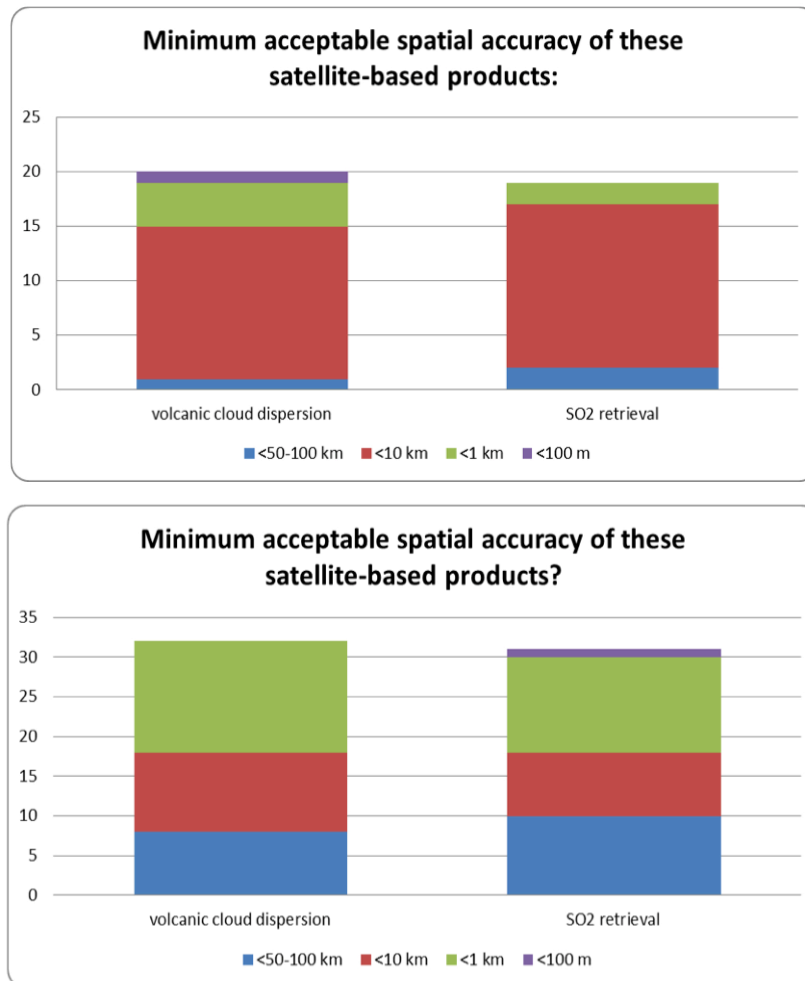


Figure 4.2: Results of the survey concerning horizontal spatial resolution of satellite products by *operational* (top) and *research* (bottom) user categories.

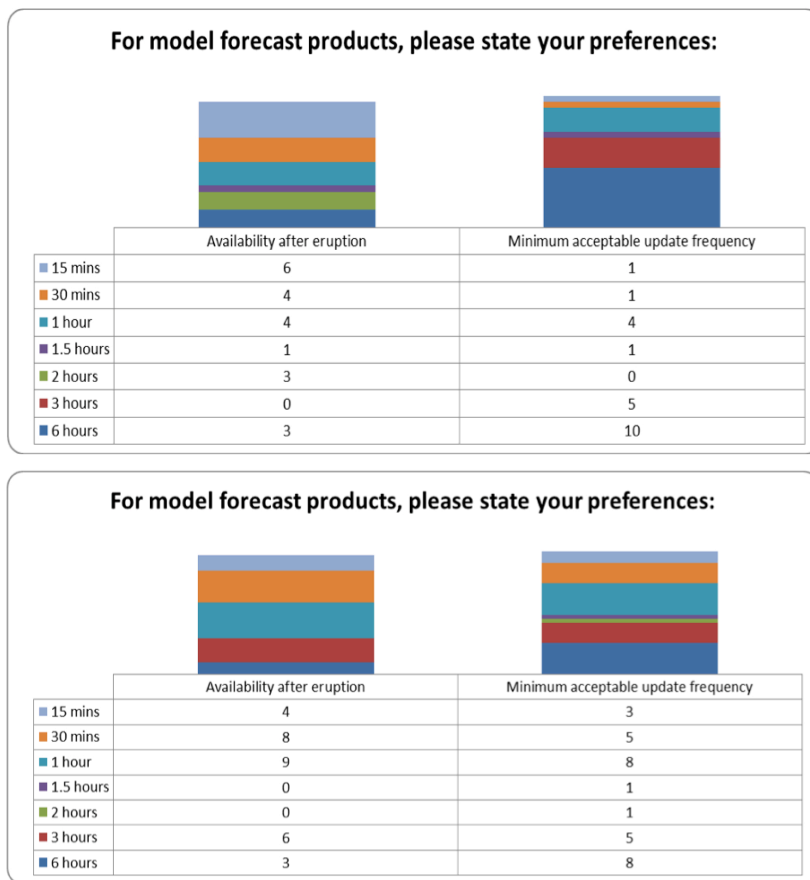


Figure 4.3: Results of the survey concerning forecast frequency by *operational* (top) and *re-search* (bottom) user categories.



5 — Optimal observing system for Europe

Key points

- *Current satellite systems provide good global coverage for volcanic ash and SO₂ 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 SO₂-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 ($\sim 1\text{--}10\text{ km}^2$) and vertical resolution ($\sim 100\text{--}$

300 m), and a spectral range that permits detection and quantification of ash (mass loadings) and gas, principally SO₂. 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 SO₂. 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 SO₂. Moreover, an optimal satellite system should also be able to deal with the criticalities still present in the ash and SO₂ 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 km² to 3 x 3 km² 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 SO₂) 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 Earth's 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 SO₂ (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 SO₂ 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 SO₂ 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 SO₂ 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 SO₂ 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 SO₂ 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 SO₂ 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 SO₂ 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 SO₂ 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) |
| Darwin | MSG | 15 mins | Advanced | |
| | MTSAT | 60 mins | Split-window | GOES-R like from |
| | FY2D | 60 mins | Split-window | JMA (2020?) and |
| London | FY2E | 60 mins | Split-window | FY4A (2014) |
| | 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 Calipso 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.

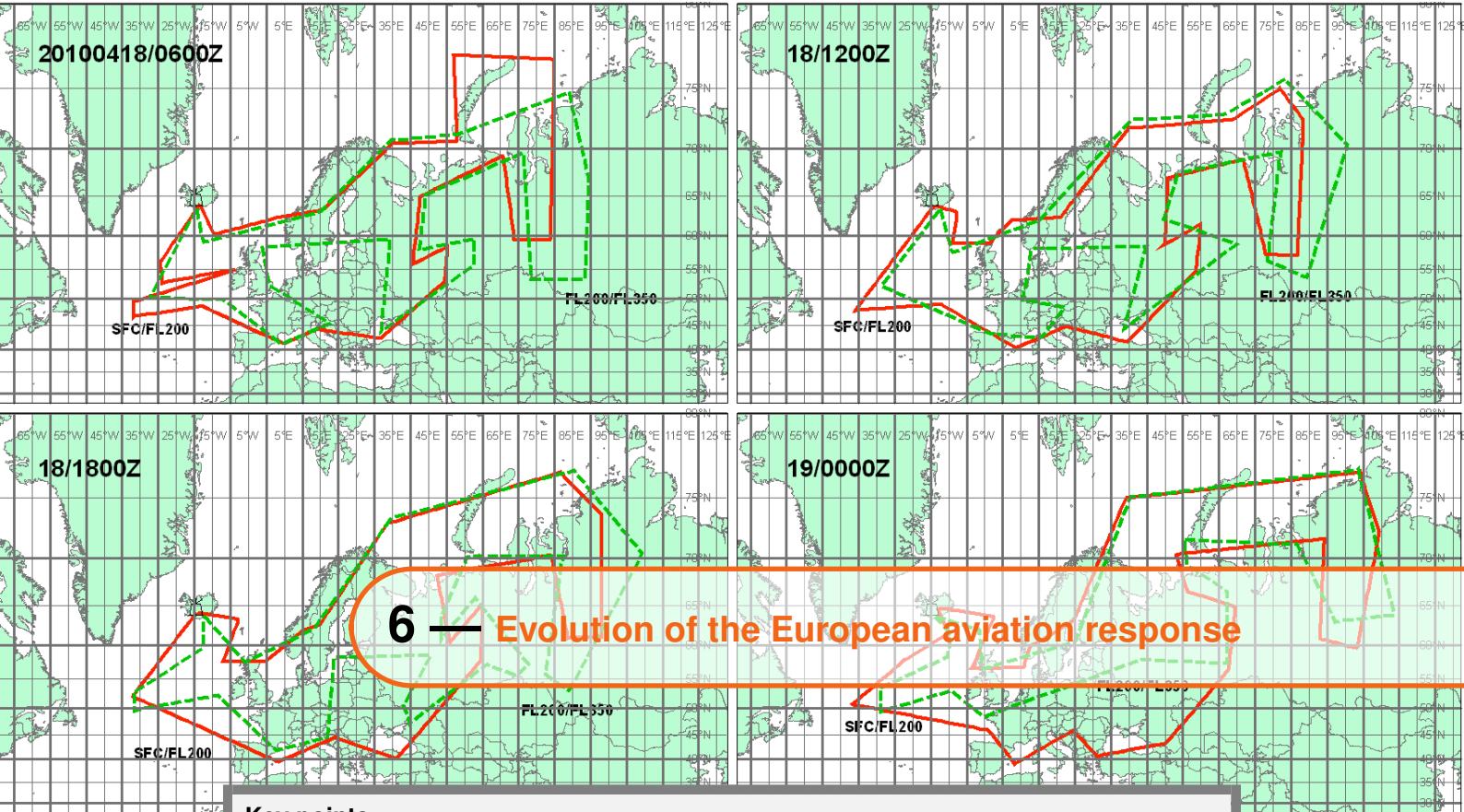
5.3 Ground-based and airborne platforms

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 SO₂ 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.



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 SO₂ 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 ($<2 \text{ mg m}^{-3}$), 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 SO₂ 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.

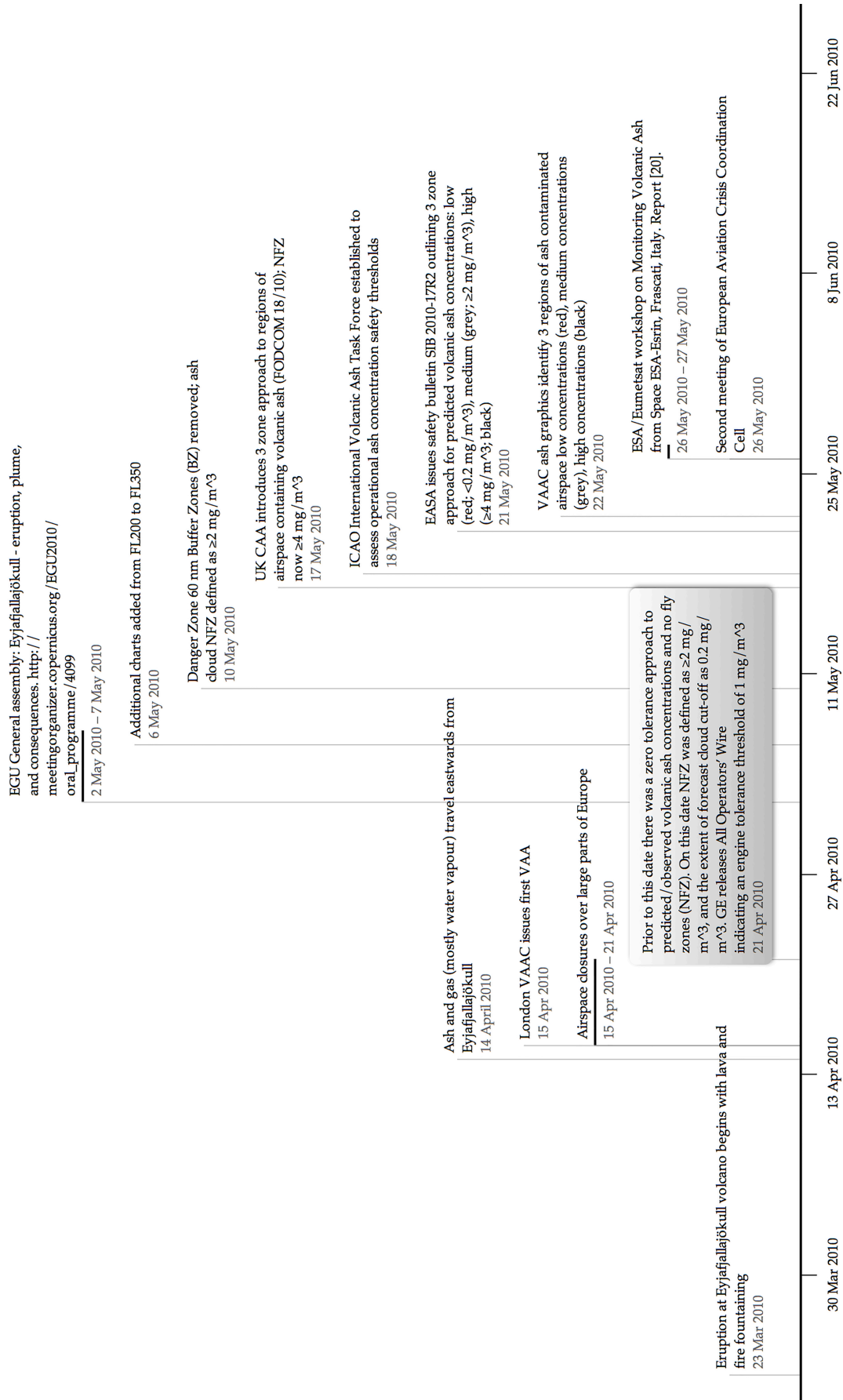


Figure 6.2: Timeline of some important events during the Eyjafjallajökull volcanic ash crisis in Europe. March–June, 2010.

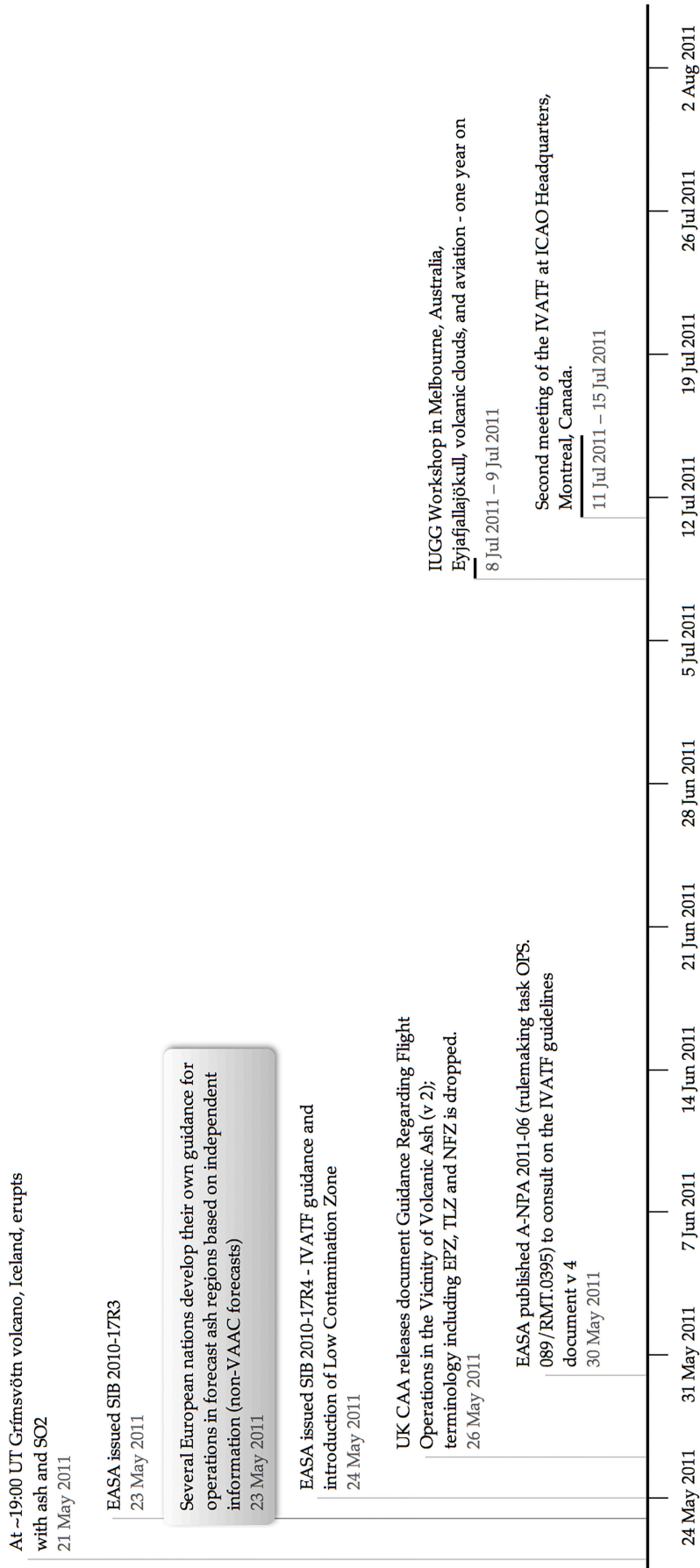


Figure 6.3: Timeline of some important events during the Grímsvötn volcanic ash eruption in Europe. May–August, 2011.

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 SO₂ 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 Scandinavia 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 SO₂ 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 SO₂ 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

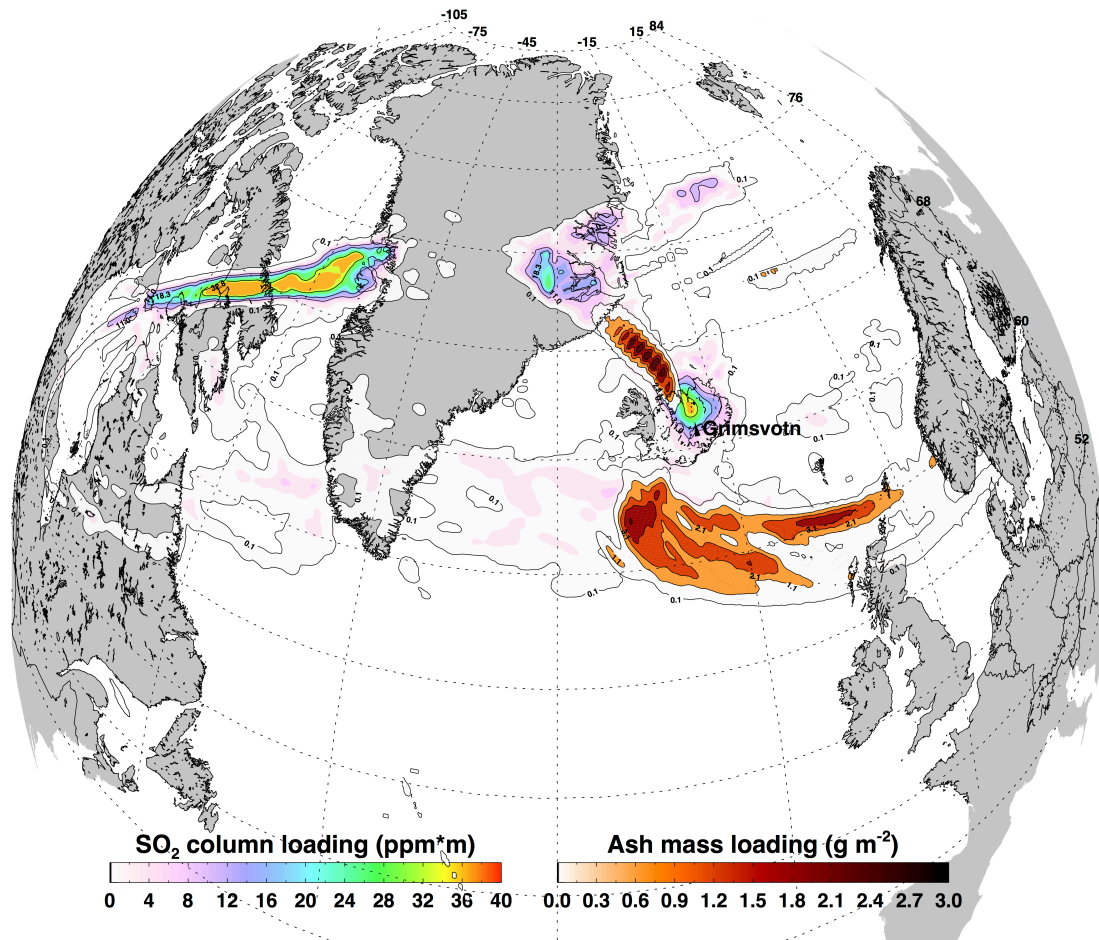


Figure 6.4: Ash and SO₂ column loadings for the period 22–25 May, 2011 derived from AIRS (SO₂) and SEVIRI (ash). After, Prata *et al.* (2014).

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

sovereignty 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 SO₂ 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 (~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 $\pm 0.15 \text{ g m}^{-2}$ 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 SO₂ 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 SO₂ 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 SO₂ volcanic products <http://omivfd.fmi.fi/volcanic.html>.

Ash is the main hazard to safe operation of aircraft in flight, but SO₂ 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 SO₂ on passengers and on aircraft parts. There is no consensus on the impact that SO₂ 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 SO₂ 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.

8 — References

- [1] Csadevall, T. (Ed.), *Proc. of the 1st International Symposium on Volcanic Ash and Aviation Safety*, **USGS Bulletin 2047**, US Govt. Printing Service, 1994.
- [2] OFCM, *Proc. of the 2nd International Symposium on Volcanic Ash and Aviation Safety, 21–24 June, Alexandria, Virginia, USA*, www.ofcm.gov, 2004.
- [3] Zehner, C. (Ed.), *Monitoring volcanic ash from space, ESA-EUMETSAT workshop on the 14 April to 23 May 2010 eruption at the Eyjafjöll volcano, South Iceland*, **STM-280**, 58pp,
- [4] ICAO, *Manual on Volcanic Ash, Radioactive Material and Toxic Chemical Clouds*, , **Doc 9691, ANC/954**, 2nd Edition, 159pp, 2007.
- [5] ICAO, *Handbook on the international airways volcano watch (IAVW), Operational procedures and contact list*, *ICAO/WMO*, **Doc 9766-AN/968**, 2nd Edition, 128pp, 2004.
- [6] ICAO, *Report on the 4th meeting of the international volcanic ash task force (IVATF/4)*, (Montréal, Canada, 13–15 June, 2012, 70pp. URL: <http://www.icao.int/safety/meteorology/ivatf/Meeting%20MetaData/IVATF-4.Final%20Report.pdf>
- [7] ICAO/NATSPG, *Temporary Addendum to NAT Doc 006*, *Nat. Ops. Bulletin*, **Serial number: 2010-009**, 12pp, 14 May, 2010.
- [8] WMO/ICAO, *1st International workshop on volcanic ash and aviation Report*, Darwin, Australia, September, 1995, *ICAO/WMO*, 55pp, 1995.
- [9] WMO/ICAO, *2nd International workshop on volcanic ash and aviation Report*, Toulouse, France, 22–26 March 2010, *ICAO/WMO*, 55pp, 1998.
- [10] WMO/ICAO, *3rd International workshop on volcanic ash and aviation Report*, Toulouse, France, 29 September–3 October 2003, *ICAO/WMO*, 25pp, 2003.
- [11] WMO/ICAO, *4th International workshop on volcanic ash and aviation Report*, Rotorua, New Zealand, *ICAO/WMO*, 55pp, 2010.

- [12] WMO/ICAO, 5th International workshop on volcanic ash and aviation Report, Santiago, Chile, 22–26 March 2010, *ICAO/WMO*, 55pp, 2010.
- [13] Bonadonaa, C. *et al.*, Consensual Document, *WMO/IAVCEI Ash Dispersal Forecast and Civil Aviation Workshop*, Geneva, Switzerland, 25pp. 18–20 October, 2010. See also *Bulletin of volcanology*, **74**(1), 1–10, 2012.
- [14] Puempl, H., Report on VAAC 'Inputs and Outputs' (Ins and Outs) Dispersion Modelling Workshop, *WMO CAeM*, NOAA, Washinhgton DC, 27pp., 5–9 November, 2012.
- [15] Sveinbjörnsson, M., Volcanic eruptions in Iceland: Potential hazards and aviation safety, *Tern Systems Inc.*, **Rep# TERN-20010315-02**, 71pp, 2001.
- [16] Boeing Volcanic Ash Advice, **11ADOBL02**, *IFALPA*, 13pp, May, 2010.
- [17] Pleter, O. T. (Ed.), Volcanic Ash Safety in Air Traffic Management: A White Paper, *European Safety Programme*, **ATM 2010-2014 (ESP+), Edition 1.0**, 44pp, June 2011.
- [18] Klatt, P. (Ed.), Recommendations for the improvement of volcanic ash cloud crisis prevention and management, *European Volcanic Ash Cloud Experts Group (EVACEG)*, 27pp, June, 2010.
- [19] CAA, Rationale for the removal of the current volcanic ash buffer zone, *Civil Aviation Authority, UK*, 19pp, 10 May 2010.
- [20] EU Commission, Report on the actions undertaken in the context of the impact of the volcanic ash cloud crisis on the air transport industry, *European Union*, 11pp, 30 June 2010.
- [21] Oxford Economics, The Economic Impacts of Air Travel Restrictions Due to Volcanic Ash, *Oxford Economics*, Oxford, England, www.oxfordeconomics.com, 15pp, undated.
- [22] Grindle, T. J. and F. W. Burcham, Engine Damage to a NASA DC-8-72 Airplane From a High-Altitude Encounter With a Diffuse Volcanic Ash Cloud, **NASA/TM-2003-212030**, 2003.
- [23] Civil Defence (NZ), Distant-Source Volcanic Ash Response Plan, *New Zealand Civil Defence Publication*, **2012/02**, ISSN: 1179 9560 (online), ISSN: 1175 8902 (print) Bay of Plenty Civil Defence Emergency, Management Group, New Zealand, 47pp. November, 2012
- [24] Prata, A. J., and A. T. Prata, Eyjafjallajökull volcanic ash concentrations determined using Spin Enhanced Visible and Infrared Imager measurements, *J. Geophys. Res.*, *117*(D00U23), doi:10.1029/2011JD016800, 2012.
- [25] Guffanti, Marianne, Casadevall, T.J., and Budding, Karin, Encounters of aircraft with volcanic ash clouds; A compilation of known incidents, 1953–2009: **U.S. Geological Survey Data Series 545, ver. 1.0**, 12 pp., plus 4 appendixes including the compilation database, available only at <http://pubs.usgs.gov/ds/545>, 2010.



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/safety/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 Spectroradiometer |
| 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 |



Index

A

| | |
|--------------------------|----|
| Airborne platforms | 28 |
| Alert services | 19 |

B

| | |
|-------------------------------|----|
| Before Eyjafjallajökull | 30 |
| Bibliography | 47 |

C

| | |
|---------------------------------------|----|
| Current operational limitations | 14 |
| Current research capabilities | 14 |
| Current research limitations | 15 |

D

| | |
|-------------------------------|----|
| During Eyjafjallajökull | 30 |
|-------------------------------|----|

E

| | |
|-------------------------|----|
| Evolution | 29 |
| Executive summary | 7 |
| Eyjafjallajökull | 30 |

F

| | |
|--------------------------|----|
| Forecast frequency | 20 |
| Foreword | 3 |
| Future response | 37 |
| Future systems | 25 |

G

| | |
|------------------------------|----|
| Glossary | 43 |
| Grímsvötn | 33 |
| Ground-based platforms | 28 |

I

| | |
|--------------------|----|
| Integration | 28 |
| Introduction | 13 |
| IVATF | 35 |

K

| | |
|-----------------------------|----|
| Key points | 9 |
| Key user requirements | 18 |

M

| | |
|---------------------------|----|
| Monitoring services | 20 |
|---------------------------|----|

O

| | |
|--------------------------------|----|
| Operations | 13 |
| Optimal future system | 27 |
| Optimal observing system | 23 |

P

| | |
|-----------------------------------|----|
| Progress on recommendations | 10 |
| Projects | 41 |

R

| | |
|------------------|----|
| References | 39 |
| Research | 14 |
| Responses | 33 |

S

| | |
|----------------------------------|----|
| Safety cases | 35 |
| Satellites | 23 |
| Spatial resolutions | 20 |
| Standards and traceability | 20 |
| State of the art | 24 |

T

| | |
|--------------------------|----|
| The rest of Europe | 33 |
|--------------------------|----|

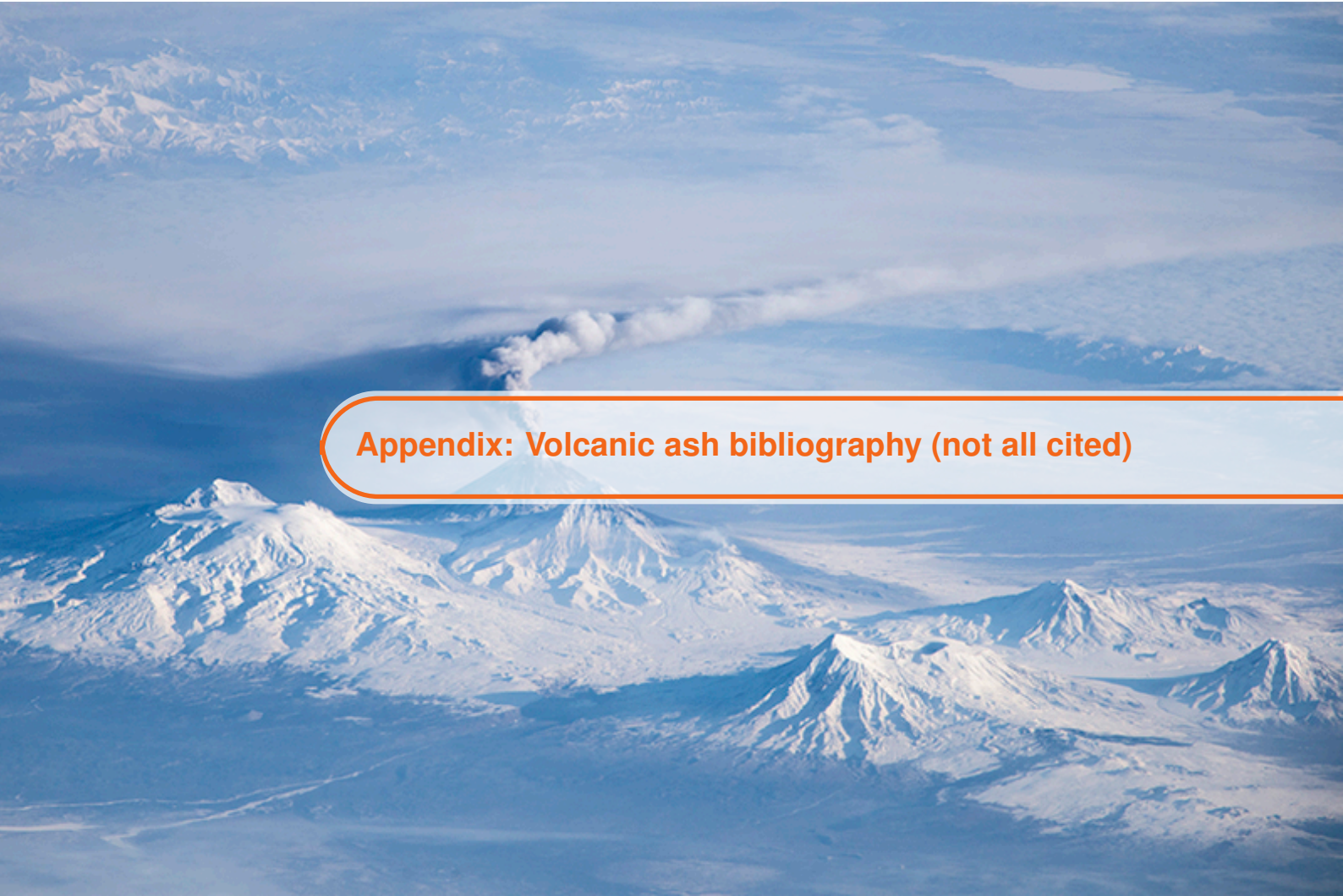
| | |
|-----------------------------|----|
| The rest of the world | 34 |
| Transport modelling | 13 |

U

| | |
|-------------------------------|----|
| UK and Iceland response | 33 |
| User needs | 17 |

V

| | |
|-------------|----|
| VASAG | 35 |
|-------------|----|



Appendix: Volcanic ash bibliography (not all cited)

Bibliography

Volcanic hazards to aviation

- [1] S. Albersheim and M. Guffanti. The United States national volcanic ash operations plan for aviation. *Nat. Hazards*, 51(2):275–285, 2009. doi: 10.1007/s11069-008-9247-1.
- [2] A.I. Bernard and W.I. Rose Jr. The injection of sulfuric acid aerosols in the stratosphere by the El Chichon volcano and its related hazards to the international air traffic. *Nat. Hazards*, 3(1):59–67, 1990.
- [3] Vincent M Brannigan. Alice’s adventures in volcano land: The use and abuse of expert knowledge in safety regulation. *Eur. J. Risk Reg.*, 1:107, 2010. ISSN 1867-299X.
- [4] P. Brooker. Fear in a handful of dust: aviation and the Icelandic volcano. *Significance*, 7(3):112–115, 2010. ISSN 1740-9713. doi: 10.1111/j.1740-9713.2010.00436.x.
- [5] T.J. Casadevall. The 1989–1990 eruption of Redoubt Volcano, Alaska: impacts on aircraft operations. *J. Volcanol. Geotherm. Res.*, 62(14):301 – 316, 1994. ISSN 0377-0273. doi: 10.1016/0377-0273(94)90038-8. The 1989-1990 Eruptions of Redoubt Volcano, Alaska.
- [6] T.J. Casadevall, P.J. Delos Reyes, and D.J. Schneider. The 1991 Pinatubo eruptions and their effects on aircraft operations. In C.G. Newhall and R.S. Punongbayan, editors, *Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines*, pages 625–636. Philippines Institute of Volcanology and Seismology, Quezon City, University of Washington Press, Seattle, 1996.
- [7] A.R. Donovan and C. Oppenheimer. The 2010 Eyjafjallajökull eruption and the reconstruction of geography. *The Geographical Journal*, 177(1):4–11, 2011. doi: 10.1111/j.1475-4959.2010.00379.x.
- [8] J. Dopagne. The European air traffic management response to volcanic ash crises: Towards institutionalised aviation crisis management. *Journal of Business Continuity & Emergency Planning*, 5(2):103–117, 2011.
- [9] G. Fiocco, D. Fuà, G. Visconti, and North Atlantic Treaty Organization. Scientific Affairs Division. The Mount Pinatubo eruption: effects on the atmosphere and climate. *NATO ASI series: Global environmental change*, 1996.
- [10] M. Guffanti and T. P. Miller. A volcanic activity alert-level system for aviation: review of its development and application in Alaska. *Nat. Hazards*, 69(3):1519 – 1533, 2013. ISSN 0921 - 030X. doi: 10.1007/s11069-013-0761-4.
- [11] M. Guffanti, G.C. Mayberry, T.J. Casadevall, and R. Wunderman. Volcanic hazards to airports. *Nat. hazards*, 51(2):287–302, 2009. doi: 10.1007/s11069-008-9254-2.
- [12] M. Guffanti, D.J. Schneider, K.L. Wallace, T. Hall, D.R. Bensimon, and L.J. Salinas. Aviation response to a widely dispersed volcanic ash and gas cloud from the August 2008 eruption of Kasatochi, Alaska, USA. *J. Geophys. Res.*, 115(D00L19), 2010. ISSN 2156-2202. doi: 10.1029/2010JD013868.
- [13] A.J. L. Harris, L. Gurioli, E.E. Hughes, and S. Lagreulet. Impact of the Eyjafjallajökull ash cloud: A newspaper perspective. *J. Geophys. Res.*, 117(B00C08), 2012. ISSN 2156-2202. doi: 10.1029/2011JB008735.
- [14] T.P. Miller and T.J. Casadevall. Volcanic ash hazards to aviation. In: *Sigurdsson H., Houghton B., McNutt S.R., Ryman H., Stix J. (eds) Encyclopedia of volcanoes*, Academic Press, San Diego, pages 915–930, 1999.
- [15] C. Neal, O. Girina, S. Senyukov, A. Rybin, J. Osiensky, P. Izbekov, and G. Ferguson. Russian eruption warning systems for aviation. *Nat. hazards*, 51(2):245–262, 2009. doi: 10.1007/s11069-009-9347-6.

- [16] A. Picquout, F. Lavigne, E.T.W. Mei, D. Grancher, Cholik Noer, C.M. Vidal, and D.S. Hadmoko. Air traffic disturbance due to the 2010 Merapi volcano eruption. *J. Volcanol. Geotherm. Res.*, 261(0):366 – 375, 2013. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2013.04.005.
- [17] A.J. Prata. Satellite detection of hazardous volcanic clouds and the risk to global air traffic. *Nat. hazards*, 51(2): 303–324, 2009. ISSN 0921-030X. doi: 10.1007/s11069-008-9273-z.
- [18] A.J. Prata and A. Tupper. Aviation hazards from volcanoes: The state of the science. *Nat. Hazards*, 51(2): 239–244, 2009. doi: 10.1007/s11069-009-9415-y.
- [19] A.J. Prata, I.J. Barton, R.W. Johnson, K. Kamo, and J. Kingwell. Hazard from volcanic ash. *Nature*, 354(6348): 25–25, 1991. doi: 10.1038/354025a0.
- [20] B.J. Scott and J. Travers. Volcano monitoring in NZ and links to SW Pacific via the Wellington VAAC. *Nat. hazards*, 51(2):263–273, 2009. doi: 10.1007/s11069-009-9354-7.
- [21] S. Self and P.J. Mougini-Mark. Volcanic eruptions, prediction, hazard assessment, remote sensing, and societal implications. *Reviews of Geophysics*, 33(S1):257–262, 1995. doi: 10.1029/95RG00556.
- [22] J. J. Simpson, J.S. Berg, G. L. Hufford, C. Bauer, D. Pieri, and Re. Servranckx. The February 2001 eruption of Mount Cleveland, Alaska: Case study of an aviation hazard. *Wea. Forecasting*, 17(4):691–704, 2002. doi: 10.1175/1520-0434(2002)017<0691:TFEOMC>2.0.CO;2.
- [23] A. Tupper, S. Carn, J. Davey, Y. Kamada, R. Potts, F. Prata, and M. Tokuno. An evaluation of volcanic cloud detection techniques during recent significant eruptions in the western Ring of Fire. *Remote Sensing of Environment*, 91(1):27–46, 2004.
- [24] A. Tupper, I. Itikarai, M. Richards, F. Prata, S. Carn, and D. Rosenfeld. Facing the challenges of the international airways volcano watch: the 2004/05 eruptions of Manam, Papua New Guinea. *Wea. Forecasting*, 22(1):175–191, 2007. doi: 10.1175/WAF974.1.
- [25] C. Witham, H. Webster, M. Hort, A. Jones, and D. Thomson. Modelling concentrations of volcanic ash encountered by aircraft in past eruptions. *Atmos. Environ.*, 48:219–229, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.06.073.
- [26] A. Witze. Volcanic-ash sensor to take flight. *Nature*, 502(7472):422–423, OCT 24 2013. ISSN 0028-0836.

Ash, plume, and transport modeling

- [27] D. Andronico, S. Scollo, S. Caruso, and A. Cristaldi. The 2002-03 Etna explosive activity: Tephra dispersal and features of the deposits. *J. Geophys. Res.*, B4(113), 2008. doi: 10.1029/2007JB005126.
- [28] S. Barsotti, A. Neri, and J.S. Scire. The VOL-CALPUFF model for atmospheric ash dispersal: 1. Approach and physical formulation,. *J. Geophys. Res.*, B03208(113), 2008. doi: 10.1029/2006JB004623.
- [29] M. Boichu, L. Menut, D. Khvorostyanov, L. Clarisse, C. Clerbaux, S. Turquety, and P.-F. Coheur. Inverting for volcanic SO₂ flux at high temporal resolution using spaceborne plume imagery and chemistry-transport modelling: the 2010 Eyjafjallajkull eruption case study. *Atmos. Chem. Phys.*, 13(17):8569–8584, 2013. doi: 10.5194/acp-13-8569-2013.
- [30] C. Bonadonna and J.C Phillips. Sedimentation from strong volcanic plumes. *J. Geophys. Res.*, 108(B7):2340, 2003. doi: 10.1029/2002JB002034.
- [31] C. Bonadonna, J.C. Phillips, and B.F. Houghton. Modeling tephra sedimentation from a Ruapehu weak plume eruption. *J. Geophys. Res.*, 110(B08209), 2005. doi: 10.1029/2004JB003515.
- [32] C. Bonadonna, A. Folch, and S. Loughlin. Future Developments in Modeling and Monitoring of Volcanic Ash Clouds. *Eos Trans. AGU*, 92(10):85–85, 2011.
- [33] C. Bonadonna, A. Folch, S. Loughlin, and H. Puempel. Future developments in modelling and monitoring of volcanic ash clouds: outcomes from the first IAVCEI-WMO workshop on Ash Dispersal Forecast and Civil Aviation. *Bulletin of volcanology*, 74(1):1–10, 2012. doi: 10.1007/s00445-011-0508-6.

- [34] M. Bursik. Effect of wind on the rise height of volcanic plumes. *Geophys. Res. Lett.*, 28(18):3621–3624, 2001. ISSN 1944-8007. doi: 10.1029/2001GL013393.
- [35] M. Bursik, M. Jones, S. Carn, K. Dean, A. Patra, M.I Pavolonis, E.B. Pitman, T.j Singh, P. Singla, P. Webley, H. Bjornsson, and M. Ripepe. Estimation and propagation of volcanic source parameter uncertainty in an ash transport and dispersal model: application to the Eyjafjallajökull plume of 14–16 April 2010. *Bull. Volcanol.*, 74(10):2321–2338, 2012. doi: 10.1007/s00445-012-0665-2.
- [36] M. I. Bursik, S. E. Kobs, A. Burns, O. A. Braitseva, L. I. Bazanova, I. V. Melekestsev, A. Kurbatov, and D. C. Pieri. Volcanic plumes and wind: Jetstream interaction examples and implications for air traffic. *J. Volcanol. Geotherm. Res.*, 186(1 - 2):60 – 67, 2009. ISSN 0377 - 0273. doi: 10.1016/j.jvolgeores.2009.01.021.
- [37] M.I. Bursik, S.N. Carey, and R.S.J. Sparks. A gravity current model for the May 18, 1980 Mount-St.Helens plume. *Geophys. Res. Lett.*, 19(16):1663 – 1666, 1992. ISSN 0094 - 8276. doi: 10.1029/92GL01639.
- [38] G. Carazzo and A. M. Jellinek. Particle sedimentation and diffusive convection in volcanic ash-clouds. *J. of Geophys. Res. Solid Earth*, 118(4):1420 – 1437, 2013. ISSN 0148 - 0227. doi: 10.1002/jgrb.50155.
- [39] R. Cioni, A. Longo, G. Macedonio, R. Santacroce, and A. Sbrana. Assessing pyroclastic fall hazard through field data and numerical simulations: Example from Vesuvio. *J. Geophys. Res.*, B2(108):2063, 2003. doi: 10.1029/2001JB000642.
- [40] E. Collini, Soledad O. M., A. Folch, J.G. Viramonte, G. Villarosa, and G. Salmuni. Volcanic ash forecast during the June 2011 Cordon Caulle eruption. *Natural Hazards*, 66(2):389 – 412, 2013. ISSN 0921 - 030X. doi: 10.1007/s11069-012-0492-y.
- [41] A. Costa, G. Macedonio, and A. Folch. A three-dimensional Eulerian model for transport and deposition of volcanic ashes. *Earth and Planetary Science Letters*, 241(34):634 – 647, 2006. ISSN 0012-821X. doi: 10.1016/j.epsl.2005.11.019.
- [42] A. Costa, A. Folch, and G. Macedonio. A Model for Wet Aggregation of Ash Particles in Volcanic Plumes and Clouds: I. Theoretical Formulation. *J. Geophys. Res.*, B09201(115), 2010. doi: 10.1029/2009JB007175.
- [43] A. Costa, A. Folch, and G. Macedonio. Density-driven transport in the umbrella region of volcanic clouds: Implications for tephra dispersion models. *Geophys. Res. Lett.*, 40(18):4823–4827, 2013. ISSN 1944-8007. doi: 10.1002/grl.50942.
- [44] H.F. Dacre, A.L.M. Grant, R.J. Hogan, S.E. Belcher, D.J. Thomson, B.J. Devenish, F. Marengo, M.C. Hort, J.M. Haywood, A. Ansmann, I. Mattis, and L. Clarisse. Evaluating the structure and magnitude of the ash plume during the initial phase of the 2010 Eyjafjallajökull eruption using lidar observations and NAME simulations. *J. Geophys. Res.*, 116(D00U03), 2011. ISSN 2156-2202. doi: 10.1029/2011JD015608.
- [45] Réal D’Amours, Alain Malo, René Servranckx, Dov Bensimon, Serge Trudel, and Jean-Philippe Gauthier-Bilodeau. Application of the atmospheric Lagrangian particle dispersion model MLDP0 to the 2008 eruptions of Okmok and Kasatochi volcanoes. *J. Geophys. Res.*, 115(D00L11), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013602.
- [46] W. Degruyter and C. Bonadonna. Improving on mass flow rate estimates of volcanic eruptions. *Geophys. Res. Lett.*, 39, AUG 29 2012. ISSN 0094-8276. doi: 10.1029/2012GL052566.
- [47] W. Degruyter and C. Bonadonna. Impact of wind on the condition for column collapse of volcanic plumes. *Earth and Planetary Science Letters*, 377378(0):218 – 226, 2013. ISSN 0012-821X. doi: 10.1016/j.epsl.2013.06.041.
- [48] M. Denlinger, R. P. Pavolonis and J. Sieglaff. A robust method to forecast volcanic ash clouds. *J. Geophys. Res.*, 117(D13208), 2012. doi: 10.1029/2012JD017732.
- [49] B. J. Devenish, P. N. Francis, B. T. Johnson, R. S. J. Sparks, and D. J. Thomson. Sensitivity analysis of dispersion modeling of volcanic ash from Eyjafjallajökull in May 2010. *J. Geophys. Res.*, 117(D00U21), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016782.
- [50] B.J. Devenish. Using simple plume models to refine the source mass flux of volcanic eruptions according to atmospheric conditions. *J. Volcanol. Geotherm. Res.*, 256(0):118 – 127, 2013. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2013.02.015.

- [51] B.J. Devenish, D.J. Thomson, F. Marengo, S.J. Leadbetter, H. Ricketts, and H.F. Dacre. A study of the arrival over the United Kingdom in April 2010 of the Eyjafjallajökull ash cloud using ground-based lidar and numerical simulations. *Atmos. Environ.*, 48:152 – 164, 2012. ISSN 1352-2310. doi: j.atmosenv.2011.06.033.
- [52] S. Eckhardt, A.J. Prata, P. Seibert, K. Stebel, and A. Stohl. Estimation of the vertical profile of sulfur dioxide injection into the atmosphere by a volcanic eruption using satellite column measurements and inverse transport modeling. *Atmos. Chem. Phys.*, 8(14):3881–3897, 2008.
- [53] G.G.J. Ernst, J.P. Davis, and R.S. J. Sparks. Bifurcation of volcanic plumes in a crosswind. *Bulletin of Volcanology*, 56(3):159–169, 1994. doi: 10.1007/BF00279601.
- [54] J. Fero, S.N. Carey, and J.T. Merrill. Simulation of the 1980 eruption of Mount St. Helens using the ash-tracking model PUFF. *J. Volcanol. Geotherm. Res.*, 175(3):355–366, 2008. doi: 10.1016/j.jvolgeores.2008.03.029.
- [55] J. Fero, S.N. Carey, and J.T. Merrill. Simulating the dispersal of tephra from the 1991 Pinatubo eruption: Implications for the formation of widespread ash layers. *Journal of Volcanology and Geothermal Research*, 186(12):120–131, 2009. doi: 10.1016/j.jvolgeores.2009.03.011.
- [56] J. Flemming and A. Inness. Volcanic sulfur dioxide plume forecasts based on UV satellite retrievals for the 2011 Grmsvtn and the 2010 Eyjafjallajökull eruption. *J. Geophys. Res. Atmos.*, 118(17):10172–10189, 2013. ISSN 2169-8996. doi: 10.1002/jgrd.50753.
- [57] A. Folch. A review of tephra transport and dispersal models: Evolution, current status, and future perspectives. *J. Volcanol. Geotherm. Res.*, 235236(0):96 – 115, 2012. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2012.05.020.
- [58] A. Folch, A. Costa, and G. Macedonio. FALL3D: A computational model for transport and deposition of volcanic ash. *Comput. Geosci.*, 35(6):1334 – 1342, 2009. ISSN 0098-3004. doi: 10.1016/j.cageo.2008.08.008.
- [59] A. Folch, A. Costa, and S. Basart. Validation of the FALL3D ash dispersion model using observations of the 2010 Eyjafjallajökull volcanic ash clouds. *Atmos. Environ.*, 48:165 – 183, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.06.072.
- [60] I.P.C. Heard, A.J. Manning, J.M. Haywood, C. Witham, A. Redington, A. Jones, L. Clarisse, and A. Bourassa. A comparison of atmospheric dispersion model predictions with observations of SO₂ and sulphate aerosol from volcanic eruptions. *J. Geophys. Res.*, 117(D00U22), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016791.
- [61] J.L. Heffter. Volcanic ash model verification using a Klyuchevskoi eruption. *Geophys. Res. Lett.*, 23(12):1489–1492, 1996. ISSN 1944-8007. doi: 10.1029/96GL01270.
- [62] B. Heinold, I. Tegen, R. Wolke, A. Ansmann, I. Mattis, A. Minikin, U. Schumann, and B. Weinzierl. Simulations of the 2010 Eyjafjallajökull volcanic ash dispersal over Europe using COSMO/MUSCAT. *Atmos. Environ.*, 48: 195 – 204, 2012. ISSN 1352-2310. doi: <http://dx.doi.org/10.1016/j.atmosenv.2011.05.021>.
- [63] R.E. Holasek, A.W. Woods, and S. Self. Experiments on gas-ash separation processes in volcanic umbrella plumes. *J. Volcanol. Geotherm. Res.*, 70(3):169–181, 1996. doi: 10.1016/0377-0273(95)00054-2.
- [64] E. J. Hughes, L. C. Sparling, S. A. Carn, and A. J. Krueger. Using horizontal transport characteristics to infer an emission height time series of volcanic SO₂. *J. Geophys. Res.*, 117(D18), 2012. ISSN 2156 - 2202. doi: 10.1029/2012JD017957.
- [65] E. Kaminski, S. Tait, F. Ferrucci, M. Martet, B. Hirn, and P. Husson. Estimation of ash injection in the atmosphere by basaltic volcanic plumes: The case of the Eyjafjallajökull 2010 eruption. *J. Geophys. Res.*, 116(B00C02), 2011. ISSN 2156-2202. doi: 10.1029/2011JB008297.
- [66] N. I. Kristiansen, A. Stohl, A. J. Prata, A. Richter, S. Eckhardt, P. Seibert, A. Hoffmann, C. Ritter, L. Bitar, T. J. Duck, and K. Stebel. Remote sensing and inverse transport modeling of the Kasatochi eruption sulfur dioxide cloud. *J. Geophys. Res.*, 115(D00L16), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013286. URL 10.1029/2009JD013286.
- [67] N. I. Kristiansen, A. Stohl, A. J. Prata, N. Bukowiecki, H. Dacre, S. Eckhardt, S. Henne, M. C. Hort, B. T. Johnson, F. Marengo, B. Neining, O. Reitebuch, P. Seibert, D. J. Thomson, H. N. Webster, and B. Weinzierl. Performance assessment of a volcanic ash transport model mini-ensemble used for inverse modeling of the 2010 Eyjafjallajökull eruption. *J. Geophys. Res.*, 117(D00U11), 2012. doi: 10.1029/2011JD016844.

- [68] B. Langmann, K. Zakšek, and M. Hort. Atmospheric distribution and removal of volcanic ash after the eruption of Kasatochi volcano: A regional model study. *J. Geophys. Res.*, 115(D00L06), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013298.
- [69] S.J. Leadbetter, M. C. Hort, S. von Löwis, K. Weber, and C. S. Witham. Modeling the resuspension of ash deposited during the eruption of Eyjafjallajökull in spring 2010. *J. Geophys. Res.*, 117(D00U10), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016802.
- [70] L.G. Mastin. A user-friendly one-dimensional model for wet volcanic plumes. *Geochemistry Geophysics Geosystems*, 8, 2007. ISSN 1525 - 2027. doi: 10.1029/2006GC001455.
- [71] L.G. Mastin, M. Guffanti, J.E. Ewert, and J. Spiegel. Preliminary spreadsheet of eruption source parameters for volcanoes of the world. *Open-File Report, U.S. Geological Survey*, page 1133, 2009. URL <http://pubs.usgs.gov/of/2009/1133/>.
- [72] L.G. Mastin, M. Guffanti, R. Servranckx, P. Webley, S. Barsotti, K. Dean, A. Durant, J.W. Ewert, A. Neri, W.I. Rose, D. Schneider, L. Siebert, B. Stunder, G. Swanson, A. Tupper, A. Volentik, and C.F. Waythomas. A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions. *J. Volcanol. Geotherm. Res.*, 186(1):10–21, 2009. doi: 10.1016/j.jvolgeores.2009.01.008.
- [73] L.G. Mastin, M. Guffanti, R. Servranckx, P. Webley, S. Barsotti, K. Dean, A. Durant, J.W. Ewert, A. Neri, W.I. Rose, D. Schneider, L. Siebert, B. Stunder, G. Swanson, A. Tupper, A. Volentik, and C.F. Waythomas. Erratum to - A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions - by Mastin et al. [J. Volcanol. Geotherm. Res. 188(2009)1–21]. *J. Volcanol. Geotherm. Res.*, 191(34):245 –, 2010. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2009.10.013.
- [74] V. Matthias, A. Aulinger, J. Bieser, J. Custa, B. Geyer, B. Langmann, I. Serikov, I. Mattis, A. Minikin, L. Mona, M. Quante, U. Schumann, and B. Weinzierl. The ash dispersion over Europe during the Eyjafjallajökull eruption – Comparison of CMAQ simulations to remote sensing and air-borne in-situ observations. *Atmos. Environ.*, 48: 184 – 194, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.06.077.
- [75] S. C. Millington, R. W. Saunders, P. N. Francis, and H. N. Webster. Simulated volcanic ash imagery: A method to compare NAME ash concentration forecasts with SEVIRI imagery for the Eyjafjallajökull eruption in 2010. *J. Geophys. Res.*, 117(D00U17), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016770.
- [76] J.M. Oberhuber, M. Herzog, Graf H.F., and Schwanke K. Volcanic plume simulation on large scales. *J. Volcanol. Geotherm. Res.*, 87:2953, 1998.
- [77] C. O’Dowd, S. Varghese, D. Martin, R. Flanagan, A. McKinsty, D. Ceburnis, J. Ovadnevaite, G. Martucci, J. Bialek, C. Monahan, H. Berresheim, A. Vaishya, T. Grigas, Z. McGraw, S.G. Jennings, B. Langmann, T. Semmler, and R. McGrath. The Eyjafjallajökull ash plume Part 2: Simulating ash cloud dispersion with {REMOTE}. *Atmos. Environ.*, 48:143 – 151, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.10.037.
- [78] J. Peng and R. Peterson. Attracting structures in volcanic ash transport. *Atmos. Environ.*, 48:230 – 239, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.05.053.
- [79] S. Pouget, . Bursik, P. Webley, J. Dehn, and M. Pavolonis. Estimation of eruption source parameters from umbrella cloud or downwind plume growth rate. *J. Volcanol. Geotherm. Res.*, 258:100 – 112, 2013. ISSN 0377 - 0273. doi: 10.1016/j.jvolgeores.2013.04.002.
- [80] H. F. Schwaiger, R. P. Denlinger, and L.G. Mastin. Ash3d: A finite-volume, conservative numerical model for ash transport and tephra deposition. *J. Geophys. Res.*, 117(B04204), 2012. doi: 10.1029/2011JB008968.
- [81] C. Searcy, K. Dean, and W. Stringer. PUFF: A high-resolution volcanic ash tracking model. *Journal of Volcanology and Geothermal Research*, 80(1):1–16, 1998.
- [82] P. Seibert, N. I. Kristiansen, S. Eckhardt, A. J. Prata, A. Richter, and A. Stohl. Uncertainties in the inverse modelling of sulphur dioxide eruption profiles. *Geomat. Nat. Haz. Risk*, 2:201 – 216, 2011. doi: 10.1080/19475705.2011.590533.
- [83] C. Spinetti, S. Barsotti, A. Neri, M. F. Buongiorno, F. Doumaz, and L. Nannipieri. Investigation of the complex dynamics and structure of the 2010 Eyjafjallajökull volcanic ash cloud using multispectral images and numerical simulations. *J. Geophys. Res.*, 118(10):4729–4747, 2013. ISSN 2169-8996. doi: 10.1002/jgrd.50328.

- [84] V. Spiridonov and M. Curic. Evaluation of the Physical and Chemical Properties of Eyjafjallajökull Volcanic Plume Using a Cloud-Resolving Model. *Pure and Applied Geophysics*, 170(11):1729–1750, NOV 2013. ISSN 0033-4553. doi: 10.1007/s00024-012-0607-0.
- [85] A. Stohl, A. J. Prata, S. Eckhardt, L. Clarisse, A. Durant, S. Henne, N. I. Kristiansen, A. Minikin, U. Schumann, P. Seibert, K. Stebel, H. E. Thomas, T. Thorsteinsson, K. Tørseth, and B. Weinzierl. Determination of time- and height-resolved volcanic ash emissions and their use for quantitative ash dispersion modeling: the 2010 Eyjafjallajökull eruption. *Atmos. Chem. Phys.*, 11(9):4333–4351, 2011. doi: 10.5194/acp-11-4333-2011.
- [86] C. Textor, H.-F. Graf, M. Herzog, J.M. Oberhuber, W.I. Rose, and G.G.J. Ernst. Volcanic particle aggregation in explosive eruption columns. Part I: Parameterization of the microphysics of hydrometeors and ash. *J. Volcanol. Geotherm. Res.*, 150(4):359–377, 2006. doi: 10.1016/j.jvolgeores.2005.09.007.
- [87] P.W. Webley and T. Steensen. Operational Volcanic Ash Cloud Modeling: Discussion on Model Inputs, Products, and the Application of Real-Time Probabilistic Forecasting. *Lagrangian Modeling of the Atmosphere*, pages 271–298, 2013. doi: 10.1029/2012GM001271.
- [88] P.W. Webley, D. Atkinson, R.L. Collins, J. Fochesatto, K. Sassen, C.F. Cahill, .K Dean, A. Prata, C.J. Flynn, and K. Mizutani. Predicting and Validating the Tracking of a Volcanic Ash Cloud during the 2006 Eruption of Mt. Augustine Volcano. *Bulletin of the American Meteorological Society*, 89(11):1647–1658, 2008. doi: 10.1175/2008BAMS2579.1.
- [89] P.W. Webley, K. Dean, J.E. Bailey, Dehn J., and Peterson R. Automated forecasting of volcanic ash dispersion utilizing virtual globes. *Nat. Hazards*, 51:345361, 2009. doi: 10.1007/s11069-008-9246-2.
- [90] P.W. Webley, K. Dean, R. Peterson, A. Steffke, M. Harrild, and J. Groves. Dispersion modeling of volcanic ash clouds: North Pacific eruptions, the past 40 years: 1970-2010. *Nat. Hazards*, 61(2):661 – 671, 2012. ISSN 0921 - 030X. doi: 10.1007/s11069-011-0053-9.
- [91] P.W. Webley, T. Steensen, M. Stuefer, G. Grell, S. Freitas, and M. Pavolonis. Analyzing the Eyjafjallajökull 2010 eruption using satellite remote sensing, lidar and WRF-Chem dispersion and tracking model. *J. Geophys. Res.*, 117(D00U26), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016817.
- [92] H.N. Webster, D.J. Thomson, B.T. Johnson, I.P.C. Heard, K. Turnbull, F. Marengo, N.I. Kristiansen, J. Dorsey, A. Minikin, B. Weinzierl, U. Schumann, R.S.J. Sparks, S.C. Loughlin, M.C. Hort, S.J. Leadbetter, B.J. Devenish, A.J. Manning, C.S. Witham, J.M. Haywood, and B.W. Golding. Operational prediction of ash concentrations in the distal volcanic cloud from the 2010 Eyjafjallajökull eruption. *J. Geophys. Res.*, 117(D00U08), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016790.
- [93] C.S. Witham, M.C. Hort, R. Potts, R. Servranckx, P. Husson, and F. Bonnardot. Comparison of VAAC atmospheric dispersion models using the 1 November 2004 Grímsvötn eruption. *Meteorol. Appl.*, 14:2738, 2007. doi: 10.1002/met.3.
- [94] M. J. Woodhouse, A. J. Hogg, J. C. Phillips, and R. S. J. Sparks. Interaction between volcanic plumes and wind during the 2010 Eyjafjallajökull eruption, Iceland. *J. Geophys. Res.*, 118(1):92–109, JAN 2013. ISSN 0148-0227. doi: 10.1029/2012JB009592.
- [95] A.W. Woods, R.E. Holasek, and S. Self. Wind-driven dispersal of volcanic ash plumes and its control on the thermal structure of the plume-top. *Bull. Volcanol.*, 57(5):283–292, 1995. doi: 10.1007/BF00301288.

Satellite remote sensing of volcanic ash and SO₂

- [96] I.J. Barton and A..J. Prata. Detection and discrimination of volcanic ash clouds by infrared radiometry: experimental. In *Volcanic Ash and aviation safety: proceedings of the first International Symposium on Volcanic Ash and Aviation Safety*, volume 2047, page 313. DIANE Publishing, 1994.
- [97] I.J. Barton, A.J. Prata, I.G. Watterson, and S.A. Young. Identification of the Mount Hudson volcanic cloud over SE Australia. *Geophys. Res. Lett.*, 19(12):1211–1214, 1992. doi: 10.1029/92GL01122.
- [98] G. J. S. Bluth and S. A. Carn. Exceptional sulfur degassing from Nyamuragira volcano, 1979 - 2005. *Int. J. Remote Sens.*, 29:6667 – 6685, 2008. doi: 10.1080/01431160802168434.

- [99] G.J.S. Bluth, W.I. Rose, I.E. Sprod, and A.J. Krueger. Stratospheric loading of sulfur from explosive volcanic eruptions. *The Journal of Geology*, 105(6):671–684, 1997.
- [100] A.E. Bourassa, D.A. Degenstein, B.J. Elash, and E.J. Llewellyn. Evolution of the stratospheric aerosol enhancement following the eruptions of Okmok and Kasatochi: Odin-OSIRIS measurements. *J. Geophys. Res.*, 115(D00L03), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013274.
- [101] A.E. Bourassa, A. Robock, W.J. Randel, T. Deshler, L.A. Rieger, N.D. Lloyd, E. J. (Ted) Llewellyn, and D.A. Degenstein. Large Volcanic Aerosol Load in the Stratosphere Linked to Asian Monsoon Transport. *Science*, 337(6090):78–81, JUL 6 2012. ISSN 0036-8075. doi: 10.1126/science.1219371.
- [102] A.E. Bourassa, A. Robock, W..J. Randel, T. Deshler, L.A. Rieger, N.D. Lloyd, E.J. Llewellyn, and D.A. Degenstein. Response to Comments on "Large Volcanic Aerosol Load in the Stratosphere Linked to Asian Monsoon Transport". *Science*, 339(6120), FEB 8 2013. ISSN 0036-8075. doi: 10.1126/science.1227961.
- [103] H. Brenot, N. Theys, L. Clarisse, J. van Geffen, J. van Gent, M. Van Roozendael, R. van der A, D. Hurtmans, P.-F. Coheur, C. Clerbaux, P. Valks, P. Hedelt, F. Prata, O. Rasson, K. Sievers, and C. Zehner. Support to Aviation Control Service (SACS): an online service for near real-time satellite monitoring of volcanic plumes. *Natural Hazards and Earth System Sciences Discussions*, 1(5):5935–6000, 2013. doi: 10.5194/nhessd-1-5935-2013.
- [104] R. Champion, G.G. Salerno, P.-F. Coheur, D. Hurtmans, L. Clarisse, K. Kazahaya, M.I. Burton, T. Caltabiano, C. Clerbaux, and A. Bernard. Measuring volcanic degassing of SO₂ in the lower troposphere with ASTER band ratios. *J. Volcanol. Geotherm. Res.*, 194(1-3):42–54, JUL 10 2010. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2010.04.010.
- [105] R. Champion, M. Martinez-Cruz, T. Lecocq, C. Caudron, J. Pacheco, G. Pinardi, C. Hermans, S. Carn, and A. Bernard. Space- and ground-based measurements of sulphur dioxide emissions from Turrialba Volcano (Costa Rica). *Bulletin of Volcanology*, 74(7):1757–1770, SEP 2012. ISSN 0258-8900. doi: 10.1007/s00445-012-0631-z.
- [106] E. Carboni, R. Grainger, J. Walker, A. Dudhia, and R. Siddans. A new scheme for sulphur dioxide retrieval from IASI measurements: application to the Eyjafjallajökull eruption of April and May 2010. *Atmos. Chem. Phys.*, 12(23):11417–11434, 2012. doi: 10.5194/acp-12-11417-2012.
- [107] S.A. Carn and T.M. Lopez. Opportunistic validation of sulfur dioxide in the Sarychev Peak volcanic eruption cloud. *Atmos. Meas. Tech.*, 4(9):1705–1712, 2011. doi: 10.5194/amt-4-1705-2011.
- [108] S.A. Carn, A.J. Krueger, G.J.S. Bluth, S.J. Schaefer, N.A. Krotkov, I.M. Watson, and S. Datta. Volcanic eruption detection by the Total Ozone Mapping Spectrometer (TOMS) instruments: A 22-year record of sulphur dioxide and ash emissions. *Geological Society, London, Special Publications*, 213(1):177–202, 2003.
- [109] S.A. Carn, L.L. Strow, S. de Souza-Machado, Y. Edmonds, and S. Hannon. Quantifying tropospheric volcanic emissions with AIRS: The 2002 eruption of Mt. Etna (Italy). *Geophys. Res. Lett.*, 32(L02301), 2005. ISSN 1944-8007. doi: 10.1029/2004GL021034.
- [110] S.A. Carn, N.A. Krotkov, K. Yang, R.M. Hoff, A.J. Prata, A.J. Krueger, S.C. Loughlin, P.F. Levelt, et al. Extended observations of volcanic SO₂ and sulfate aerosol in the stratosphere. *Atmo. Chem. Phys. Discuss.*, 7(1):2857–2871, 2007. doi: 10.5194/acpd-7-2857-2007.
- [111] S.A. Carn, A..J. Krueger, S. Arellano, N.A. Krotkov, and K. Yang. Daily monitoring of Ecuadorian volcanic degassing from space. *J. Volcanol. Geotherm. Res.*, 176(1):141 – 150, 2008. ISSN 0377 - 0273. doi: 10.1016/j.jvolgeores.2008.01.029. Recent and active volcanism in the Ecuadorian Andes.
- [112] S.A. Carn, A.J. Prata, and S. Karlsdottir. Circumpolar transport of a volcanic cloud from Hekla (Iceland). *J. Geophys. Res.*, 113(D14311), 2008. doi: 10.1029/2008JD009878.
- [113] S.A. Carn, A. J. Krueger, N. A. Krotkov, K. Yang, and K. Evans. Tracking volcanic sulfur dioxide clouds for aviation hazard mitigation. *Nat. Hazards*, 51(2):325–343, 2009. doi: 10.1007/s11069-008-9228-4.
- [114] S.A. Carn, J.S. Pallister, L. Lara, J.W. Ewert, S. Watt, A.J. Prata, R.J. Thomas, and G. Villarosa. The unexpected awakening of Chaitén volcano, Chile. *Eos, Transactions American Geophysical Union*, 90(24): 205–206, 2009.
- [115] S.A. Carn, N.A. Krotkov, K. Yang, and A.J. Krueger. Measuring global volcanic degassing with the Ozone Monitoring Instrument (OMI). *Geological Society, London, Special Publications*, 380(1):229–257, 2013. doi: 10.1144/SP380.12.

- [116] S.A. Christopher, N. Feng, A. Naeger, B. Johnson, and F. Marenco. Satellite remote sensing analysis of the 2010 Eyjafjallajökull volcanic ash cloud over the North Sea during 18 May 2010. *J. Geophys. Res.*, 117(D00U20), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016850.
- [117] L. Clarisse, P.-F. Coheur, A. J. Prata, D. Hurtmans, A. Razavi, T. Phulpin, J. Hadji-Lazaro, and C. Clerbaux. Tracking and quantifying volcanic SO₂ with IASI, the September 2007 eruption at Jebel at Tair. *Atmos. Chem. Phys.*, 8(24):7723–7734, 2008. doi: 10.5194/acp-8-7723-2008.
- [118] L. Clarisse, D. Hurtmans, A. J. Prata, F. Karagulian, C. Clerbaux, M. De Maziere, and P.-F. Coheur. Retrieving radius, concentration, optical depth, and mass of different types of aerosols from high-resolution infrared nadir spectra. *Appl. Optics*, 49(19):3713–3722, JUL 1 2010. ISSN 1559-128X.
- [119] L. Clarisse, F. Prata, J.-L. Lacour, D. Hurtmans, C. Clerbaux, and P.-F. Coheur. A correlation method for volcanic ash detection using hyperspectral infrared measurements. *Geophys. Res. Lett.*, 37(L19806), 2010. doi: 10.1029/2010GL044828.
- [120] L. Clarisse, D. Hurtmans, C. Clerbaux, J. Hadji-Lazaro, Y. Ngadi, and P. F. Coheur. Retrieval of sulphur dioxide from the infrared atmospheric sounding interferometer (IASI). *Atmos. Meas. Tech.*, 5(3):581–594, 2012. ISSN 1867-1381. doi: 10.5194/amt-5-581-2012.
- [121] L. Clarisse, P.-F. Coheur, F. Prata, J. Hadji-Lazaro, D. Hurtmans, and C. Clerbaux. A unified approach to infrared aerosol remote sensing and type specification. *Atmos. Chem. Phys.*, 13(4):2195–2221, 2013. doi: 10.5194/acp-13-2195-2013.
- [122] C. Clerbaux, P.-F. Coheur, L. Clarisse, J. Hadji-Lazaro, D. Hurtmans, S. Turquety, K. Bowman, H. Worden, and S. A. Carn. Measurements of SO₂ profiles in volcanic plumes from the NASA Tropospheric Emission Spectrometer (TES). *Geophys. Res. Lett.*, 35(22), 2008. ISSN 1944-8007. doi: 10.1029/2008GL035566.
- [123] E.K. Constantine, G. J.S. Bluth, and W.I. Rose. TOMS and AVHRR observations of drifting volcanic clouds from the August 1991 eruptions of Cerro Hudson. *Remote sensing of active volcanism*, pages 45–64, 2000.
- [124] S. Corradini, C. Spinetti, E. Carboni, C. Tirelli, M. F. Buongiorno, S. Pugnaghi, G. Gangale, et al. Mt. Etna tropospheric ash retrieval and sensitivity analysis using Moderate Resolution Imaging Spectroradiometer measurements. *J. Appl. Remote Sens.*, 2(023):550–023, 2008. doi: 10.1117/1.3046674.
- [125] S. Corradini, L. Merucci, and A.J. Prata. Retrieval of SO₂ from thermal infrared satellite measurements: Correction procedures for the effects of volcanic ash. *Atmos. Meas. Tech.*, 2(1):303–342, 2009. doi: 10.5194/amt-2-177-2009.
- [126] S. Corradini, L. Merucci, A.J. Prata, and A. Piscini. Volcanic ash and SO₂ in the 2008 Kasatochi eruption: Retrievals comparison from different IR satellite sensors. *J. Geophys. Res.*, 115(D00L21), 2010. doi: 10.1029/2009JD013634.
- [127] S. Corradini, L. Merucci, and A. Folch. Volcanic ash cloud properties: comparison between MODIS satellite retrievals and FALL3D transport model. *Geoscience and Remote Sensing Letters, IEEE*, 8(2):248–252, 2011.
- [128] K. Dean, S.A. Bowling, G. Shaw, and H. Tanaka. Satellite analyses of movement and characteristics of the Redoubt Volcano plume, January 8, 1990. *Journal of volcanology and geothermal research*, 62(1):339–352, 1994. doi: 10.1016/0377-0273(94)90040-X.
- [129] D. Doeringer, A. Eldering, C. D. Boone, G. González Abad, and P.F. Bernath. Observation of sulfate aerosols and SO₂ from the Sarychev volcanic eruption using data from the Atmospheric Chemistry Experiment (ACE). *J. Geophys. Res.*, 117(D3), 2012. ISSN 2156 - 2202. doi: 10.1029/2011JD016556.
- [130] M. Doutriaux-Boucher and P. Dubuisson. Detection of volcanic SO₂ by spaceborne infrared radiometers. *Atmos. Res.*, 92(1):69–79, MAR 2009. ISSN 0169-8095. doi: 10.1016/j.atmosres.2008.08.009.
- [131] G.P. Ellrod. Impact on volcanic ash detection caused by the loss of the 12.0 μm Split Window band on GOES Imagers. *J. Volcanol. Geotherm. Res.*, 135(1):91–103, 2004.
- [132] G.P. Ellrod, B.H. Connell, and Hillger D.W. Improved detection of airborne volcanic ash using multispectral infrared satellite data. *J. Geophys. Res.*, D12(108):4356, 2003. doi: 10.1029/2002JD002802.

- [133] P.N. Francis, M.C. Cooke, and R.W. Saunders. Retrieval of physical properties of volcanic ash using Meteosat: A case study from the 2010 Eyjafjallajökull eruption. *J. Geophys. Res.*, 117(D00U09), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016788.
- [134] M. Fromm, G. Nedoluha, and Z. Charvat. Comment on "Large Volcanic Aerosol Load in the Stratosphere Linked to Asian Monsoon Transport". *Science*, 339(6120), FEB 8 2013. ISSN 0036-8075. doi: 10.1126/science.1228605.
- [135] G. Gangale, A. J. Prata, and L. Clarisse. The infrared spectral signature of volcanic ash determined from high-spectral resolution satellite measurements. *Remote sensing of environment*, 114(2):414–425, 2010. ISSN 0034-4257. doi: 10.1016/j.rse.2009.09.007.
- [136] R.G. Grainger, D.M. Peters, G.E. Thomas, A.J.A. Smith, R. Siddans, E. Carboni, and A. Dudhia. Measuring Volcanic Plume and Ash Properties from Space. *Remote-sensing of Volcanoes and Volcanic Processes: Integrating Observation and Modelling*, edited by: Pyle, D.M., Mather, T.A., and Biggs, J., *The Geological Society Special Publication*, 380, 2013.
- [137] S. Guo, G.J.S. Bluth, W.I. Rose, I.M. Watson, and A.J. Prata. Re-evaluation of SO₂ release of the 15 June 1991 Pinatubo eruption using ultraviolet and infrared satellite sensors. *Geochemistry, Geophysics, Geosystems*, 5(4), 2004. ISSN 1525-2027. doi: 10.1029/2003GC000654.
- [138] J.M. Haywood, A. Jones, L. Clarisse, A. Bourassa, J. Barnes, P.I. Telford, N.s Bellouin, O. Boucher, P. Agnew, C. Clerbaux, P. Coheur, D. Degenstein, and P. Braesicke. Observations of the eruption of the Sarychev volcano and simulations using the HadGEM2 climate model. *J. Geophys. Res.*, 115, NOV 13 2010. ISSN 2169-897X. doi: 10.1029/2010JD014447.
- [139] D.W. Hillger and James D.C. Principal component image analysis of MODIS for volcanic ash. Part I: most important bands and implications for future GOES imagers. *J. Appl. Meteor.*, 41(10):1003–1010, 2002.
- [140] D.W. Hillger and James D.C. Principal component image analysis of MODIS for volcanic ash. Part II: simulation of current goes and goes-m imagers. *J. Appl. Meteor.*, 41(10):1003–1010, 2002. doi: 10.1175/1520-0450(2002)041<1003:PCIAOM>2.0.CO;2.
- [141] R.E. Holasek and W.I. Rose. Anatomy of 1986 Augustine volcano eruptions as recorded by multispectral image processing of digital AVHRR weather satellite data. *Bull. Volcanol.*, 53(6):420–435, 1991. doi: 10.1007/BF00258183.
- [142] R.E. Holasek and S. Self. GOES weather satellite observations and measurements of the May 18, 1980, Mount St. Helens eruption. *J. Geophys. Res.*, B5(100):8469–8487, 1995. doi: 10.1029/94JB03137.
- [143] R.E. Holasek, S. Self, and A.W. Woods. Satellite observations and interpretation of the 1991 Mount Pinatubo eruption plumes. *J. Geophys. Res.*, 101(B12):27635–27, 1996. doi: 10.1029/96JB01179.
- [144] R.A. Kahn and J. Limbacher. Eyjafjallajökull volcano plume particle-type characterization from space-based multi-angle imaging. *Atmos. Chem. Phys.*, 12(20):9459–9477, 2012. doi: 10.5194/acp-12-9459-2012.
- [145] R.A. Kahn, W.-H. Li, C. Moroney, D.J. Diner, J.V. Martonchik, and E. Fishbein. Aerosol source plume physical characteristics from space-based multiangle imaging. *J. Geophys. Res.*, 112(D11), 2007. ISSN 2156-2202. doi: 10.1029/2006JD007647.
- [146] F. Karagulian, L. Clarisse, C. Clerbaux, A. J. Prata, D. Hurtmans, and P. F. Coheur. Detection of volcanic SO₂, ash, and H₂SO₄ using the Infrared Atmospheric Sounding Interferometer (IASI). *J. Geophys. Res.*, 115 (D00L02), 2010. ISSN 2156-2202. doi: 10.1029/2009JD012786.
- [147] C.S. Kearney, K. Dean, V.J. Realmuto, I.M. Watson, J. Dehn, and F. Prata. Observations of SO₂ production and transport from Bezymianny volcano, Kamchatka using the MODerate resolution Infrared Spectroradiometer (MODIS). *International Journal of Remote Sensing*, 29(22):6647–6665, 2008. doi: 10.1080/01431160802168392.
- [148] M.F. Khokhar, C. Frankenberg, M. Van Roozendaal, S. Beirle, S. Khl, A. Richter, U. Platt, and T. Wagner. Satellite observations of atmospheric SO₂ from volcanic eruptions during the time-period of 1996–2002. *Advances in Space Research*, 36(5):879 – 887, 2005. ISSN 0273-1177. doi: 10.1016/j.asr.2005.04.114. Atmospheric Remote Sensing: Earth's Surface, Troposphere, Stratosphere and Mesosphere- I.
- [149] K. Kinoshita, C. Kanagaki, A. Minaka, S. Tsuchida, T. Matsui, A. Tupper, H. Yakiwara, and N. Iino. Ground and satellite monitoring of volcanic aerosols in visible and infrared bands. In *Proc. CEReS Int. Symp. Remote Sensing, Chiba, Japan*, pages 187–196, 2003.

- [150] L. Klüser, T. Erbertseder, and J. Meyer-Arne. Observation of volcanic ash from Puyehue-Cordón Caulle with IASI. *Atmos. Meas. Tech.*, 6(3):35–46, 2013. doi: 10.5194/amt-6-35-2013.
- [151] B. Kravitz, A. Robock, and A. Bourassa. Negligible climatic effects from the 2008 Okmok and Kasatochi volcanic eruptions. *J. Geophys. Res.*, 115, 2010. ISSN 2156-2202. doi: 10.1029/2009JD013525.
- [152] N.A. Krotkov, O. Torres, C. Seftor, A.J. Krueger, A. Kostinski, W.I. Rose, G.J.S. Bluth, D. Schneider, and S.J. Schaefer. Comparison of TOMS and AVHRR volcanic ash retrievals from the August 1992 eruption of Mt. Spurr. *Geophys. Res. Lett.*, 26(4):455–458, 1999. doi: 10.1029/1998GL900278.
- [153] N.A. Krotkov, S.A. Carn, A.J. Kyueger, P.K. Bhartia, and K. Yang. Band residual difference algorithm for retrieval of SO₂ from the Aura Ozone Monitoring Instrument (OMI). *IEEE transactions on geoscience and remote sensing*, 44, 2006. doi: 10.1109/TGRS.2005.861932. 5.
- [154] N.A. Krotkov, M.R. Schoeberl, G.A. Morris, S. Carn, and K. Yang. Dispersion and lifetime of the SO₂ cloud from the August 2008 Kasatochi eruption. *J. Geophys. Res.*, 115(D00L20), 2010. ISSN 2156-2202. doi: 10.1029/2010JD013984.
- [155] A. Krueger, N. Krotkov, and S. Carn. El Chichon: The genesis of volcanic sulfur dioxide monitoring from space. *J. Volcanol. Geotherm. Res.*, 175(4):408–414, 2008. doi: 10.1016/j.jvolgeores.2008.02.026.
- [156] A. J. Krueger, C. C. Schnetzler, and L. S. Walter. The December 1981 eruption of Nyamuragira Volcano (Zaire), and the origin of the mystery cloud of early 1982. *J. Geophys. Res. Atmos.*, 101(D10):15191–15196, 1996. ISSN 2156-2202. doi: 10.1029/96JD00221. URL 10.1029/96JD00221.
- [157] A.J. Krueger. Sighting of El Chichon sulfur dioxide clouds with the nimbus 7 total ozone mapping spectrometer. *Science*, 220:13771379, 1983.
- [158] A.J. Krueger, L.S. Walter, P.K. Bhartia, C.C. Schnetzler, N.A. Krotkov, I. Sprod, and G.J.S. Bluth. Volcanic sulfur dioxide measurements from the total ozone mapping spectrometer instruments. *J. Geophys. Res.*, 100 (D7):1405714076, 1995.
- [159] A.J. Krueger, N. A. Krotkov, K. Yang, S. Carn, G. Vicente, and W. Schroeder. Applications of satellite-based sulfur dioxide monitoring. *Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of*, 2(4):293–298, 2009.
- [160] T. Lopez, S. Carn, C. Werner, D. Fee, P. Kelly, M. Doukas, M. Pfeffer, P. Webley, C. Cahill, and D. Schneider. Evaluation of Redoubt Volcano’s sulfur dioxide emissions by the Ozone Monitoring Instrument. *J. Volcanol. Geotherm. Res.*, 259(0):290 – 307, 2013. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2012.03.002.
- [161] J. Malingreau and Kaswanda P. Monitoring volcanic eruptions in Indonesia using weather satellite data: the Colo eruption of July 28, 1983. *J. Volcanol. Geotherm. Res.*, 27(1-2):179 – 194, 1986. ISSN 0377-0273. doi: 10.1016/0377-0273(86)90085-5.
- [162] F. Marchese, G. Malvasi, M. Ciampa, C. Filizzola, N. Pergola, and V. Tramutoli. A robust multitemporal satellite technique for volcanic activity monitoring: possible impacts on volcanic hazard mitigation. In *Analysis of Multi-temporal Remote Sensing Images, 2007. MultiTemp 2007. International Workshop on the*, pages 1–5. IEEE, 2007. doi: 10.1109/MULTITEMP.2007.4293056.
- [163] F. Marchese, C. Filizzola, G. Mazzeo, R. Paciello, N. Pergola, and Va. Tramutoli. Robust Satellite Techniques (RST) for active volcanoes monitoring. In *Geoscience and Remote Sensing Symposium (IGARSS), 2010 IEEE International*, pages 773–776. IEEE, 2010. doi: 10.1109/IGARSS.2010.5651576.
- [164] M. Matson. The 1982 El Chichón volcano eruptions—a satellite perspective. *J. Volcanol. Geotherm. Res.*, 23 (12):1–10, 1984. ISSN 0377-0273. doi: 10.1016/0377-0273(84)90054-4.
- [165] L. Merucci, M. Burton, S. Corradini, and G.G. Salerno. Reconstruction of SO₂ flux emission chronology from space-based measurements. *J. Volcanol. Geotherm. Res.*, 206(34):80 – 87, 2011. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2011.07.002.
- [166] F.R. Mosher. Four channel volcanic ash detection algorithm. *Conference on Satellite Meteorology and Oceanography, 10 th, Long Beach, CA*, pages 457–460, 2000.

- [167] M.A.M. Novak, I.M. Watson, H. Delgado-Granados, W.I. Rose, L. Cárdenas-González, and V.J. Realmuto. Volcanic emissions from Popocatepetl volcano, Mexico, quantified using Moderate Resolution Imaging Spectroradiometer (MODIS) infrared data: A case study of the December 2000/January 2001 emissions. *J. Volcanol. Geotherm. Res.*, 170(12):76 – 85, 2008. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2007.09.010. The 1994-Present eruption of Popocatepetl: Background, current activity, and impacts.
- [168] E. Ortore, G. Laneve, and G. Bernini. Detection of volcanic gases and particles by satellite. *Acta Astronautica*, 93(0):304 – 316, 2014. ISSN 0094-5765. doi: 10.1016/j.actaastro.2013.07.025.
- [169] M.J. Pavolonis. Advances in Extracting Cloud Composition Information from Spaceborne Infrared Radiances-A Robust Alternative to Brightness Temperatures. Part I: Theory. *Journal of Applied Meteorology and Climatology*, 49(9):1992–2012, SEP 2010. ISSN 1558-8424. doi: 10.1175/2010JAMC2433.1.
- [170] M.J. Pavolonis, W.F. Feltz, A. K. Heidinger, and G.M. Gallina. A daytime complement to the reverse absorption technique for improved automated detection of volcanic ash. *Journal of Atmospheric & Oceanic Technology*, 23(11), 2006. doi: 10.1175/JTECH1926.1.
- [171] M.J. Pavolonis, A.K. Heidinger, and J. Sieglaff. Automated retrievals of volcanic ash and dust cloud. *J. Geophys. Res. Atmos.*, 118:1436–1458, 2013. doi: doi:10.1002/jgrd.50173.
- [172] N. Pergola, V. Tramutoli, F. Marchese, I. Scaffidi, and T. Lacava. Improving volcanic ash cloud detection by a robust satellite technique. *Remote Sensing of Environment*, 90(1):1 – 22, 2004. ISSN 0034-4257. doi: 10.1016/j.rse.2003.11.014.
- [173] M. Picchiani, M. Chini, S. Corradini, L. Merucci, P. Sellitto, F. Del Frate, and S. Stramondo. Volcanic ash detection and retrievals from MODIS data by means of Neural Networks. *Atmos. Meas. Tech.*, 4(12):2619–2631, 2011. doi: 10.5194/amt-4-2619-2011.
- [174] D. Pieri and M. Abrams. ASTER watches the world’s volcanoes: a new paradigm for volcanological observations from orbit. *J. Volcanol. Geotherm. Res.*, 135(1):13–28, 2004. doi: 10.1016/j.jvolgeores.2003.12.018.
- [175] A. Piscini, S. Corradini, F. Marchese, L. Merucci, N. Pergola, and V. Tramutoli. Volcanic ash cloud detection from space: a comparison between the RSTASH technique and the water vapour corrected BTD procedure. *Geomatics, Natural Hazards and Risk*, 2(3):263–277, 2011. doi: 10.1080/19475705.2011.568069.
- [176] A.J. Prata. Infrared radiative transfer calculations for volcanic ash clouds. *Geophys. Res. Lett.*, 16(11):1293–1296, 1989. doi: 10.1029/GL016i011p01293.
- [177] A.J. Prata. Observations of volcanic ash clouds in the 10-12 μm window using AVHRR/2 data. *International Journal of Remote Sensing*, 10(4-5):751–761, 1989. doi: 10.1080/01431168908903916.
- [178] A.J. Prata and I.J. Barton. Detection and discrimination of volcanic ash clouds by infrared radiometry: theory. In *Volcanic Ash and aviation safety: Proceedings of the first International Symposium on Volcanic Ash and Aviation Safety*, page 305. DIANE Publishing, 1994.
- [179] A.J. Prata and C. Bernardo. Retrieval of volcanic SO₂ column abundance from Atmospheric Infrared Sounder data. *J. Geophys. Res.*, 112(D20204), 2007. ISSN 2156-2202. doi: 10.1029/2006JD007955.
- [180] A.J. Prata and I.F. Grant. *Determination of mass loadings and plume heights of volcanic ash clouds from satellite data*. CSIRO Atmospheric Research, 2001.
- [181] A.J. Prata and I.F. Grant. Retrieval of microphysical and morphological properties of volcanic ash plumes from satellite data: Application to Mt Ruapehu, New Zealand. *Q.J.R. Meteorol. Soc.*, 127(576):2153–2179, 2001. doi: 10.1002/qj.49712757615.
- [182] A.J. Prata and J. Kerkmann. Simultaneous retrieval of volcanic ash and SO₂ using MSG-SEVIRI measurements. *Geophys. Res. Lett.*, 34(5):L05813, 2007. doi: 10.1029/2006GL028691.
- [183] A.J. Prata and A.T. Prata. Eyjafjallajökull volcanic ash concentrations determined using Spin Enhanced Visible and Infrared Imager measurements. *J. Geophys. Res.*, 117(D00U23), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016800.
- [184] A.J. Prata, J.B. Wells, and M.W. Ivanac. A satellite’s-eye view of volcanoes on the Lesser Sunda Island. *Weather*, 40(8):245–250, 1985. doi: 10.1002/j.1477-8696.1985.tb06886.x.

- [185] A.J. Prata, W.I. Rose, S. Self, and D.M. O'Brien. Global, long-term sulphur dioxide measurements from TOVS data: A new tool for studying explosive volcanism and climate. *Volcanism and the Earth's Atmosphere*, pages 75–92, 2003. doi: 10.1029/139GM05.
- [186] A.J. Prata, S.A. Carn, A. Stohl, and J. Kerkmann. Long range transport and fate of a stratospheric volcanic cloud from Soufriere Hills volcano, Montserrat. *Atmos. Chem. Phys.*, 7(19):5093–5103, 2007. doi: 10.5194/acp-7-5093-2007.
- [187] A.J. Prata, G. Gangale, L. Clarisse, and F. Karagulian. Ash and sulfur dioxide in the 2008 eruptions of Okmok and Kasatochi: Insights from high spectral resolution satellite measurements. *J. Geophys. Res.*, 115(D00L18), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013556.
- [188] F. Prata, G. Bluth, B. Rose, D. Schneider, and A. Tupper. Comments on Failures in detecting volcanic ash from a satellite-based technique. *Remote Sensing of Environment*, 78(3):341–346, 2001. doi: 10.1016/S0034-4257(01)00231-0.
- [189] P.J. Prata, A.J. and Turner. Cloud-top height determination using ATSR data. *Remote sensing of environment*, 59(1):1–13, 1997. doi: 10.1016/S0034-4257(96)00071-5.
- [190] S. Pugnaghi, G. Gangale, S. Corradini, and M.F. Buongiorno. Mt. Etna sulfur dioxide flux monitoring using ASTER-TIR data and atmospheric observations. *J. Volcanol. Geotherm. Res.*, 152(1-2):4–90, APR 1 2006. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2005.10.004.
- [191] M. Rix, P. Valks, N. Hao, J. van Geffen, C. Clerbaux, L. Clarisse, P.-F. Coheur, R. Loyola, T. Erbertseder, W. Zimmer, and Sunil E. Satellite monitoring of volcanic sulfur dioxide emissions for early warning of volcanic hazards. *Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of*, 2(3):196–206, 2009.
- [192] M. Rix, P. Valks, N. Hao, D. Loyola, H. Schlager, H. Huntrieser, J. Flemming, U. Koehler, U. Schumann, and A. Inness. Volcanic SO₂, BrO and plume height estimations using GOME-2 satellite measurements during the eruption of Eyjafjallajökull in May 2010. *J. Geophys. Res.*, 117(D00U19), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016718.
- [193] A. Robock and M. Matson. Circumglobal transport of the El Chichón volcanic dust cloud. *Science*, 221(4606):195–197, 1983. doi: 10.1126/science.221.4606.195.
- [194] W.I. Rose, D.J. Delene, D.J. Schneider, G.J.S. Bluth, A.J. Krueger, I. Sprod, C. McKee, H.L. Davies, and G.G.J. Ernst. Ice in the 1994 Rabaul eruption cloud: implications for volcano hazard and atmospheric effects. *Nature*, 375(6531):477–479, 1995.
- [195] W.I. Rose, G.J.S. Bluth, and G.G.J. Ernst. Integrating retrievals of volcanic cloud characteristics from satellite remote sensors: a summary. *Phil. Trans. R. Soc. Lond. A*, 358(1770):1585–1606, 2000. doi: 10.1098/rsta.2000.0605.
- [196] W.I. Rose, G.J.S. Bluth, D. J. Schneider, G.G.J. Ernst, C.M. Riley, L.J. Henderson, and R.G. McGimsey. Observations of volcanic clouds in their first few days of atmospheric residence: The 1992 eruptions of Crater Peak, Mount Spurr volcano, Alaska. *The Journal of Geology*, 109(6):677–694, 2001.
- [197] W.I. Rose, Y. Gu, I.M. Watson, T. Yu, G.J.S. Bluth, A.J. Prata, A.J. Krueger, N. Krotkov, S. Carn, M.D. Fromm, D.E. Hunton, G.G.J. Ernst, A.A. Viggiano, T.M. Miller, J.O. Ballenthin, J.M. Reeves, J.C. Wilson, B.E. Anderson, and D.E. Flittner. The February–March 2000 eruption of Hekla, Iceland from a satellite perspective. *Volcanism and the Earth's Atmosphere*, pages 107–132, 2003. doi: 10.1029/139GM07.
- [198] A. Rybin, M. Chibisova, P. Webley, T. Steensen, P. Izbekov, C. Neal, and V. Realmuto. Satellite and ground observations of the June 2009 eruption of Sarychev Peak volcano, Matua Island, Central Kuriles. *Bulletin of Volcanology*, 73(9):1377–1392, NOV 2011. ISSN 0258-8900. doi: 10.1007/s00445-011-0481-0.
- [199] D.J. Schneider, W. I. Rose, and L. Kelley. Tracking of 1992 eruption clouds from Crater Peak vent of Mount Spurr Volcano, Alaska, using AVHRR. *The 1992 Eruptions of Crater Peak Vent, Mount Spurr Volcano, Alaska*, pages 27–36, 1995.
- [200] D.J. Schneider, W. I. Rose, L.R. Coke, G. J.S. Bluth, I.E. Sprod, and A.J. Krueger. Early evolution of a stratospheric volcanic eruption cloud as observed with TOMS and AVHRR. *J. Geophys. Res.*, 104(D4):4037–4050, 1999. doi: 10.1029/1998JD200073.

- [201] T.M. Sears, G.E. Thomas, E. Carboni, A.J.A. Smith, and R.G. Grainger. SO₂ as a possible proxy for volcanic ash in aviation hazard avoidance. *J. Geophys. Res. Atmos.*, 118(11):5698 – 5709, 2013. ISSN 2169 - 897X. doi: 10.1002/jgrd.50505.
- [202] C.J. Seftor, N.C. Hsu, J.R. Herman, P.K. Bhartia, O. Torres, W.I. Rose, D.J. Schneider, and N. Krotkov. Detection of volcanic ash clouds from Nimbus 7/total ozone mapping spectrometer. *J. Geophys. Res.*, 102(D14):16749–16759, 1997. doi: 10.1029/97JD00925.
- [203] S. Self, J.-X. Zhao, R.E. Holasek, R.C. Torres, and A.J. King. The atmospheric impact of the 1991 Mount Pinatubo eruption. *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines. Quezon City: Philippine Institute of Volcanology and Seismology*, pages 1098–1115, 1996.
- [204] J.J. Simpson, G.Hufford, D. Pieri, and J. Berg. Failures in Detecting Volcanic Ash from a Satellite-Based Technique. *Remote Sensing of Environment*, 72(2):191 – 217, 2000. ISSN 0034-4257. doi: 10.1016/S0034-4257(99)00103-0.
- [205] C.E. Sioris, C.D. Boone, P.F. Bernath, J. Zou, C.T. McElroy, and C.A. McLinden. Atmospheric Chemistry Experiment (ACE) observations of aerosol in the upper troposphere and lower stratosphere from the Kasatochi volcanic eruption. *J. Geophys. Res.*, 115(D00L14), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013469.
- [206] E. Spinei, S.A. Carn, N.A. Krotkov, G.H. Mount, K. Yang, and A. Krueger. Validation of ozone monitoring instrument SO₂ measurements in the Okmok volcanic cloud over Pullman, WA, July 2008. *J. Geophys. Res.*, 115(D00L08), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013492.
- [207] C. Spinetti, S. Barsotti, A. Neri, M. F. Buongiorno, F. Doumaz, and L. Nannipieri. Investigation of the complex dynamics and structure of the 2010 Eyjafjallajökull volcanic ash cloud using multispectral images and numerical simulations. *J. Geophys. Res.*, 118(10):4729–4747, 2013. ISSN 2169-8996. doi: 10.1002/jgrd.50328.
- [208] N. Theys, R. Campion, L. Clarisse, H. Brenot, J. van Gent, B. Dils, S. Corradini, L. Merucci, P. F. Coheur, M. Van Roozendael, D. Hurtmans, C. Clerbaux, S. Tait, and F. Ferrucci. Volcanic SO₂ fluxes derived from satellite data: a survey using OMI, GOME-2, IASI and MODIS. *Atm. Chem. Phys.*, 13(12):5945–5968, 2013. ISSN 1680-7316. doi: 10.5194/acp-13-5945-2013.
- [209] H.E. Thomas and A. J. Prata. Sulphur dioxide as a volcanic ash proxy during the April and May 2010 eruption of Eyjafjallajökull Volcano, Iceland. *Atmos. Chem. Phys.*, 11(14):6871–6880, 2011. doi: 10.5194/acp-11-6871-2011.
- [210] H.E. Thomas and I.M. Watson. Observations of volcanic emissions from space: current and future perspectives. *Nat. hazards*, 54(2):323–354, 2010. doi: 10.1007/s11069-009-9471-3.
- [211] H.E. Thomas, I.M. Watson, C. Kearney, S.A. Carn, and S.J. Murray. A multi-sensor comparison of sulphur dioxide emissions from the 2005 eruption of Sierra Negra volcano, Galápagos Islands. *Remote Sensing of Environment*, 113(6):1331–1342, 2009. doi: 10.1016/j.rse.2009.02.019.
- [212] H.E. Thomas, I.M. Watson, S.A. Carn, A.J. Prata, and V.J. Realmuto. A comparison of AIRS, MODIS and OMI sulphur dioxide retrievals in volcanic clouds. *Geomatics, Natural Hazards and Risk*, 2(3):217–232, 2011. doi: 10.1080/19475705.2011.564212.
- [213] W.T. Thomas, T. Erbertseder, M. Ruppert, Van Roozendael, J. Verdebout, D. Balis, C. Meleti, and C. Zerefos. On the Retrieval of Volcanic Sulfur Dioxide Emissions from GOME Backscatter Measurements. *J. Atmos. Chem.*, 50:295–320, 2005. doi: 10.1007/s10874-005-5544-1. 3.
- [214] V. Tramutoli. Robust satellite techniques (RST) for natural and environmental hazards monitoring and mitigation: Theory and applications. In *Analysis of Multi-temporal Remote Sensing Images, 2007. MultiTemp 2007. International Workshop on the*, pages 1–6. IEEE, 2007. doi: 10.1109/MULTITEMP.2007.4293057.
- [215] A. Tupper, J.S. Oswald, and D. Rosenfeld. Satellite and radar analysis of the volcanic-cumulonimbi at Mount Pinatubo, Philippines, 1991. *J. Geophys. Res.*, 110(D09204), 2005. doi: 10.1029/2004JD005499.
- [216] M. Urai. Sulfur dioxide flux estimation from volcanoes using advanced spaceborne thermal emission and reflection radiometer case study of Miyakejima volcano, Japan. *Volcanol Geotherm Res.*, 134(1-2):1 – 13, 2004. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2003.11.008.

- [217] J. P. Vernier, T. D. Fairlie, J.J. Murray, A. Tupper, C. Treppe, D. Winker, J. Pelon, A. Garnier, J. Jumelet, M. Pavolonis, A. H. Omar, and K. A. Powell. An Advanced System to Monitor the 3D Structure of Diffuse Volcanic Ash Clouds. *Journal of Applied Meteorology and Climatology*, 52(9):2125–2138, SEP 2013. ISSN 1558-8424. doi: 10.1175/JAMC-D-12-0279.1.
- [218] J. P. Vernier, L. W. Thomason, T. D. Fairlie, P. Minnis, R. Palikonda, and K. M. Bedka. Comment on "Large Volcanic Aerosol Load in the Stratosphere Linked to Asian Monsoon Transport". *Science*, 339(6120), FEB 8 2013. ISSN 0036-8075. doi: 10.1126/science.1227817.
- [219] J. C. Walker, E. Carboni, A. Dudhia, and R. G. Grainger. Improved detection of sulphur dioxide in volcanic plumes using satellite-based hyperspectral infrared measurements: Application to the Eyjafjallajökull 2010 eruption. *J. Geophys. Res.*, 117(D00U16), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016810.
- [220] S.C. Watkin. The application of AVHRR data for the detection of volcanic ash in a volcanic ash advisory centre. *Meteorol. Appl.*, 10:301311, 2003.
- [221] I.M. Watson, V.J. Realmuto, W.I. Rose, A.J. Prata, G.J.S. Bluth, Y. Gu, C.E. Bader, and T. Yu. Thermal infrared remote sensing of volcanic emissions using the moderate resolution imaging spectroradiometer. *J. Volcanol. Geotherm. Res.*, 135(1):75–89, 2004. doi: 10.1016/j.jvolgeores.2003.12.017.
- [222] P.W. Webley, J. Dehn, J. Lovick, K.G. Dean, J.E. Bailey, and L. Valcic. Near-real-time volcanic ash cloud detection: Experiences from the Alaska Volcano Observatory. *J. Volcanol. Geotherm. Res.*, 186(12):79 – 90, 2009. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2009.02.010.
- [223] S. Wen and W. I. Rose. Retrieval of sizes and total masses of particles in volcanic clouds using AVHRR bands 4 and 5. *J. Geophys. Res.*, 99(D3):5421–5431, 1994. doi: 10.1029/93JD03340.
- [224] D.M. Winker, Z. Liu, A. Omar, J. Tackett, and D. Fairlie. CALIOP observations of the transport of ash from the Eyjafjallajökull volcano in April 2010. *J. Geophys. Res.*, 117(D00U15), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016499.
- [225] R. Wright, S.A. Carn, and L.P. Flynn. A satellite chronology of the May–June 2003 eruption of Anatahan volcano. *J. Volcanol. Geotherm. Res.*, 146(13):102–116, 2005. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2004.10.021.
- [226] K. Yang, N.A. Krotkov, A.J. Krueger, S.A. Carn, P.K. Bhartia, and P. F. Levelt. Retrieval of large volcanic SO₂ columns from the Aura Ozone Monitoring Instrument: Comparison and limitations. *J. Geophys. Res.*, 112 (D24S43), 2007. doi: 10.1029/2007JD008825.
- [227] K. Yang, N.A. Krotkov, A.J. Krueger, S.A. Carn, P.K. Bhartia, and P.F. Levelt. Improving retrieval of volcanic sulfur dioxide from backscattered UV satellite observations. *Geophys. Res. Lett.*, 36(L03102), 2009. doi: 10.1029/2008GL036036.
- [228] K. Yang, X. Liu, P.K. Bhartia, N.A. Krotkov, S. A. Carn, E.J. Hughes, A.J. Krueger, R.J.D. Spurr, and S.G. Trahan. Direct retrieval of sulfur dioxide amount and altitude from spaceborne hyperspectral UV measurements: Theory and application. *J. Geophys. Res.*, 115(D00L09), 2010. doi: 10.1029/2010JD013982.
- [229] T. Yu, W.I. Rose, and A.J. Prata. Atmospheric correction for satellite-based volcanic ash mapping and retrievals using "split window" IR data from GOES and AVHRR. *J. Geophys. Res.*, 107(D16):AAC 10–1–AAC 10–19, 2002. ISSN 2156-2202. doi: 10.1029/2001JD000706.
- [230] K. Zakšek, M. Hort, J. Zaletelj, and B. Langmann. Monitoring volcanic ash cloud top height through simultaneous retrieval of optical data from polar orbiting and geostationary satellites. *Atmos. Chem. Phys.*, 13(5): 2589–2606, 2013. doi: 10.5194/acp-13-2589-2013.
- [231] C. (Ed.) Zehner. Monitoring Volcanic Ash from Space. *in: Proceedings of the ESA-EUMETSAT workshop on the 14 April to 23 May 2010 eruption at the Eyjafjoll volcano, South Iceland, ESA-Publication STM-280*, 2014. doi: 10.5270/atmch-10-01.

Ground-based remote sensing

- [232] D. Andronico, C. Spinetti, A. Cristaldi, and M.F. Buongiorno. Observations of Mt. Etna volcanic ash plumes in 2006: An integrated approach from ground-based and polar satellite NOAA–AVHRR monitoring system. *J. Volcanol. Geotherm. Res.*, 180(2):135–147, 2009. doi: 10.1016/j.jvolgeores.2008.11.013.
- [233] A. Ansmann, M. Tesche, S. Gross, V. Freudenthaler, P. Seifert, A. Hiebsch, J. Schmidt, U. Wandinger, I. Mattis, D. Müller, and M. Wiegner. The 16 April 2010 major volcanic ash plume over central Europe: EARLINET lidar and AERONET photometer observations at Leipzig and Munich, Germany. *Geophys. Res. Lett.*, 37(L13810), 2010. doi: doi:10.1029/2010GL043809.
- [234] A. Ansmann, M. Tesche, P. Seifert, S. Groß, V. Freudenthaler, A. Apituley, K. M. Wilson, I. Serikov, H. Linné, B. Heinold, A. Hiebsch, F. Schnell, J. Schmidt, I. Mattis, U. Wandinger, and M. Wiegner. Ash and fine-mode particle mass profiles from EARLINET-AERONET observations over central Europe after the eruptions of the Eyjafjallajökull volcano in 2010. *J. Geophys. Res.*, 116(D00U02), 2011. ISSN 2156-2202. doi: 10.1029/2010JD015567.
- [235] A. Ansmann, P. Seifert, M. Tesche, and U. Wandinger. Profiling of fine and coarse particle mass: case studies of Saharan dust and Eyjafjallajökull/Grímsvötn volcanic plumes. *Atmos. Chem. Phys.*, 12(20):9399–9415, 2012. doi: 10.5194/acp-12-9399-2012.
- [236] P. Arason, A.J. Bennett, and L.E. Burgin. Charge mechanism of volcanic lightning revealed during the 2010 eruption of Eyjafjallajökull. *J. Geophys. Res.*, 116(B00C03), 2011. ISSN 2156-2202. doi: 10.1029/2011JB008651.
- [237] K.M. Arnoult, J.V. Olson, C.A. L. Szuberla, S. R. McNutt, M.A. Garcés, D. Fee, and M. A. H. Hedlin. Infrasonic observations of the 2008 explosive eruptions of Okmok and Kasatochi volcanoes, Alaska. *J. Geophys. Res.*, 115(D00L15), 2010. ISSN 2156-2202. doi: 10.1029/2010JD013987.
- [238] I.J. Barton, A.J. Prata, I.G. Watterson, and S.A. Young. Identification of the Mount Hudson volcanic cloud over SE Australia. *Geophys. Res. Lett.*, 19(12):1211–1214, 1992. doi: 10.1029/92GL01122.
- [239] L. Bitar, T. J. Duck, N. I. Kristiansen, A. Stohl, and S. Beauchamp. Lidar observations of Kasatochi volcano aerosols in the troposphere and stratosphere. *J. Geophys. Res.*, 115(D00L13), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013650.
- [240] G.J.S. Bluth, J.M. Shannon, I.M. Watson, A.J. Prata, and V.J. Realmuto. Development of an ultra-violet digital camera for volcanic SO₂ imaging. *J. Volcanol. Geotherm. Res.*, 161(12):47–56, 2007. doi: 10.1016/j.jvolgeores.2006.11.004.
- [241] M. Campanelli, V. Estelles, T. Smyth, C. Tomasi, M.P. Martínez-Lozano, B. Claxton, P. Muller, G. Pappalardo, A. Pietruczuk, J. Shanklin, S. Colwell, C. Wrench, A. Lupi, M. Mazzola, C. Lanconelli, V. Vitale, F. Congeduti, D. Dionisi, F. Cardillo, M. Cacciani, G. Casasanta, and T. Nakajima. Monitoring of Eyjafjallajökull volcanic aerosol by the new European Skynet Radiometers (ESR) network. *Atmos. Environ.*, 48:33 – 45, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.09.070.
- [242] P. Chazette, M. Bocquet, P. Royer, V. Winiarek, J.-C. Raut, P. Labazuy, M. Gouhier, M. Lardier, and J.-P. Cariou. Eyjafjallajökull ash concentrations derived from both lidar and modeling. *J. Geophys. Res.*, 117(D00U14), 2012. ISSN 2156-2202. doi: 10.1029/2011JD015755.
- [243] Y. Derimian, O. Dubovik, D. Tanre, P. Goloub, T. Lapyonok, and A. Mortier. Optical properties and radiative forcing of the Eyjafjallajökull volcanic ash layer observed over Lille, France, in 2010. *J. Geophys. Res.*, 117(D00U25), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016815.
- [244] G. Dubosclard, F. Donnadieu, P. Allard, R. Cordesses, C. Hervier, M. Coltelli, E. Privitera, and J. Kornprobst. Doppler radar sounding of volcanic eruption dynamics at Mount Etna. *Bull. Volcanol.*, 56:398411, 2004. doi: 0.1007/s00445-003-0324-8.
- [245] S. Emeis, R. Forkel, W. Junkermann, K. Schäfer, H. Flentje, S. Gilge, W. Fricke, M. Wiegner, V. Freudenthaler, S. Groß, L. Ries, F. Meinhardt, W. Birmili, C. Münkel, F. Obleitner, and P. Suppan. Measurement and simulation of the 16/17 April 2010 Eyjafjallajökull volcanic ash layer dispersion in the northern Alpine region. *Atmos. Chem. Phys.*, 11(6):2689–2701, 2011. doi: 10.5194/acp-11-2689-2011.
- [246] D. Fee, A. Steffke, and M. Garces. Characterization of the 2008 Kasatochi and Okmok eruptions using remote infrasonic arrays. *J. Geophys. Res.*, 115(D00L10), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013621.

- [247] B. Galle, C. Oppenheimer, A. Geyer, A.J.S. McGonigle, M. Edmonds, and L. Horrocks. A miniaturised ultra-violet spectrometer for remote sensing of SO₂ fluxes: a new tool for volcano surveillance. *J. Volcanol. Geotherm. Res.*, 119:241–254, 2003. doi: 10.1016/S0377-0273(02)00356-6.
- [248] B. Galle, M. Johansson, C. Rivera, Y. Zhang, M. Kihlman, C. Kern, T. Lehmann, U. Platt, S. Arellano, and S. Hidalgo. Network for Observation of Volcanic and Atmospheric Change NOVAC A global network for volcanic gas monitoring: Network layout and instrument description. *J. Geophys. Res.*, 115(D5), 2010. ISSN 2156-2202. doi: 10.1029/2009JD011823.
- [249] J. Gasteiger, S. Groß, V. Freudenthaler, and M. Wiegner. Volcanic ash from Iceland over Munich: mass concentration retrieved from ground-based remote sensing measurements. *Atmos. Chem. Phys.*, 11(5):2209–2223, 2011. doi: 10.5194/acp-11-2209-2011.
- [250] S. Groß, V. Freudenthaler, M. Wiegner, J. Gasteiger, A. Geiß, and F. Schnell. Dual-wavelength linear depolarization ratio of volcanic aerosols: Lidar measurements of the Eyjafjallajökull plume over Maisach, Germany. *Atmos. Environ.*, 48:85 – 96, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.06.017.
- [251] M. Grutter, R. Basaldud, C. Rivera, R. Harig, W. Junkerman, E. Caetano, and H. Delgado-Granados. SO₂ emissions from Popocatepetl volcano: emission rates and plume imaging using optical remote sensing techniques. *Atmos. Chem. Phys.*, 8(22):6655 – 6663, 2008. ISSN 1680-7316.
- [252] D.M. Harris and W.I. Rose. Estimating particle sizes, concentrations, and total mass of ash in volcanic clouds using weather radar. *J. Geophys. Res.*, 88(C15):10969–10983, 1983. doi: 10.1029/JC088iC15p10969.
- [253] M. Hervo, B. Quennehen, N. I. Kristiansen, J. Boulon, A. Stohl, P. Fréville, J.-M. Pichon, D. Picard, P. Labazuy, M. Gouhier, J.-C. Roger, A. Colomb, A. Schwarzenboeck, and K. Sellegri. Physical and optical properties of 2010 Eyjafjallajökull volcanic eruption aerosol: ground-based, Lidar and airborne measurements in France. *Atmos. Chem. Phys.*, 12(4):1721–1736, 2012. doi: 10.5194/acp-12-1721-2012.
- [254] A. Hoffmann, C. Ritter, M. Stock, M. Maturilli, S. Eckhardt, A. Herber, and R. Neuber. Lidar measurements of the Kasatochi aerosol plume in August and September 2008 in Ny-Ålesund, Spitsbergen. *J. Geophys. Res.*, 115(D00L12), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013039.
- [255] K.A. Horton, G. Williams-Jones, H. Garbeil, T. Elias, A.J. Sutton, P. Mouginiis-Mark, J.N. Porter, and S. Clegg. Real-time measurement of volcanic SO₂ emissions: validation of a new UV correlation spectrometer (FLYSPEC). *Bulletin of Volcanology*, 68(4):323–327, 2006. ISSN 0258-8900. doi: 10.1007/s00445-005-0014-9.
- [256] P. Jousset, J. Pallister, M. Boichu, M.F. Buongiorno, A. Budisantoso, F. Costa, S. Andreastuti, D. Prata, F. and Schneider, and L. and others Clarisse. The 2010 explosive eruption of Java’s Merapi volcano: 100-year event. *J. Volcanol. Geotherm. Res.*, 241:121–135, 2012.
- [257] E.P. Kantzas, A.J.S. McGonigle, G. Tamburello, A. Aiuppa, and R.G. Bryant. Protocols for UV camera volcanic SO₂ measurements. *J. Volcanol. Geotherm. Res.*, 194(13):55 – 60, 2010. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2010.05.003.
- [258] C. Kern, F. Kick, P. Lübcke, L. Vogel, M. Wöhrbach, and U. Platt. Theoretical description of functionality, applications, and limitations of SO₂ cameras for the remote sensing of volcanic plumes. *Atmos. Meas. Tech.*, 3(3):733–749, 2010. doi: 10.5194/amt-3-733-2010.
- [259] C. Kern, T. Deutschmann, C. Werner, A.J. Sutton, T. Elias, and P.J. Kelly. Improving the accuracy of SO₂ column densities and emission rates obtained from upward-looking UV-spectroscopic measurements of volcanic plumes by taking realistic radiative transfer into account. *J. Geophys. Res.*, 117(D20), 2012. ISSN 2156-2202. doi: 10.1029/2012JD017936.
- [260] C. Kern, C. Werner, T. Elias, A.J. Sutton, and P. Lübcke. Applying UV cameras for SO₂ detection to distant or optically thick volcanic plumes. *J. Volcanol. Geotherm. Res.*, 262(0):80 – 89, 2013. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2013.06.009.
- [261] P. Kokkalis, A. Papayannis, V. Amiridis, R. E. Mamouri, I. Veselovskii, A. Kolgotin, G. Tsaknakis, N. I. Kristiansen, A. Stohl, and L. Mona. Optical, microphysical, mass and geometrical properties of aged volcanic particles observed over Athens, Greece, during the Eyjafjallajökull eruption in April 2010 through synergy of Raman lidar and sunphotometer measurements. *Atmos. Chem. Phys.*, 13(18):9303–9320, 2013. doi: 10.5194/acp-13-9303-2013.

- [262] A. Krueger, W. Stremme, R. Harig, and M. Grutter. Volcanic SO₂ and SiF₄ visualization using 2-D thermal emission spectroscopy - Part 2: Wind propagation and emission rates. *Atmos. Meas. Techn.*, 6(1):47–61, 2013. doi: 10.5194/amt-6-47-2013.
- [263] C. Lacasse, S. Karlsdóttir, G. Larsen, H. Soosalu, W.I. Rose, and G.G.J. Ernst. Weather radar observations of the Hekla 2000 eruption cloud, Iceland. *Bull. Volcanol.*, 66(5):457–473, 2004. doi: 10.1007/s00445-003-0329-3.
- [264] F. Marengo and R.J. Hogan. Determining the contribution of volcanic ash and boundary layer aerosol in backscatter lidar returns: A three-component atmosphere approach. *J. Geophys. Res.*, 116(D00U06), 2011. ISSN 2156-2202. doi: 10.1029/2010JD015415.
- [265] K.M. Markowicz, T. Zielinski, A. Pietruczuk, M. Posyniak, O. Zawadzka, P. Makuch, I.S. Stachlewska, A.K. Jagodnicka, T. Petelski, W. Kumala, P. Sobolewski, and T. Stacewicz. Remote sensing measurements of the volcanic ash plume over Poland in April 2010. *Atmos. Environ.*, 48:66 – 75, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.07.015.
- [266] G. Martucci, J. Ovadnevaite, D. Ceburnis, H. Berresheim, S. Varghese, D. Martin, R. Flanagan, and C.D. O’Dowd. Impact of volcanic ash plume aerosol on cloud microphysics. *Atmos. Environ.*, 48:205 – 218, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.12.033.
- [267] F. S. Marzano, S. Barbieri, G. Vulpiani, and W.I. Rose. Volcanic ash cloud retrieval by ground-based microwave weather radar. *Geoscience and Remote Sensing, IEEE Transactions on*, 44(11):3235–3246, 2006.
- [268] F. S. Marzano, M. Lamantea, M. Montopoli, S. Di Fabio, and E. Picciotti. The Eyjafjöll explosive volcanic eruption from a microwave weather radar perspective. *Atmos. Chem. Phys.*, 11(18):9503–9518, 2011. doi: 10.5194/acp-11-9503-2011.
- [269] F.S. Marzano, G. Vulpiani, and W. I. Rose. Microphysical characterization of microwave radar reflectivity due to volcanic ash clouds. *Geoscience and Remote Sensing, IEEE Transactions on*, 44(2):313–327, 2006.
- [270] F.S. Marzano, M. Lamantea, M. Montopoli, M. Herzog, H. Graf, and D. Cimini. Microwave remote sensing of the 2011 Plinian eruption of the Grímsvötn Icelandic volcano. *Remote Sensing of Environment*, 129(0):168 – 184, 2013. ISSN 0034-4257. doi: 10.1016/j.rse.2012.11.005.
- [271] F.S. Marzano, E. Picciotti, M. Montopoli, and G. Vulpiani. Inside Volcanic Clouds- Remote Sensing of Ash Plumes Using Microwave Weather Radars. *Bulletin of the American Meteorological Society*, 94(10):1567–1586, OCT 2013. ISSN 0003-0007. doi: 10.1175/BAMS-D-11-00160.1.
- [272] T.A. Mather and R.G. Harrison. Electrification of volcanic plumes. *Surv. Geophys.*, 27(4):387–432, 2006. doi: 10.1007/s10712-006-9007-2.
- [273] V. Matthias, A. Aulinger, J. Bieser, J. Custa, B. Geyer, B. Langmann, I. Serikov, I. Mattis, A. Minikin, L. Mona, M. Quante, U. Schumann, and B. Weinzierl. The ash dispersion over Europe during the Eyjafjallajökull eruption – Comparison of CMAQ simulations to remote sensing and air-borne in-situ observations. *Atmos. Environ.*, 48: 184 – 194, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.06.077.
- [274] I. Mattis, P. Seifert, D. Müller, M. Tesche, A. Hiebsch, T.s Kanitz, J. Schmidt, F. Finger, U. Wandinger, and A. Ansmann. Correction to "Volcanic aerosol layers observed with multiwavelength Raman lidar over central Europe in 2008–2009". *J. Geophys. Res.*, 115(D00L99), 2010. ISSN 2156-2202. doi: 10.1029/2010JD014895.
- [275] I. Mattis, P. Siefert, D. Müller, M. Tesche, A. Hiebsch, T.s Kanitz, J. Schmidt, F. Finger, U. Wandinger, and A. Ansmann. Volcanic aerosol layers observed with multiwavelength Raman lidar over central Europe in 2008–2009. *J. Geophys. Res.*, 115(D00L04), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013472.
- [276] A.J.S. McGonigle. Measurement of volcanic SO₂ fluxes with differential optical absorption spectroscopy. *J. Volcanol. Geotherm. Res.*, 162(3–4):111 – 122, 2007. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2007.02.001.
- [277] S.R. McNutt and E.R. Williams. Volcanic lightning: global observations and constraints on source mechanisms. *Bull. Volcanol.*, 72(10):1153–1167, 2010. doi: 10.1007/s00445-010-0393-4.
- [278] A. Miffre, G. David, B. Thomas, P. Rairoux, A.M. Fjaeraa, N.I. Kristiansen, and A. Stohl. Volcanic aerosol optical properties and phase partitioning behavior after long-range advection characterized by UV-Lidar measurements. *Atmo. Environ.*, 48:76 – 84, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.03.057.

- [279] L. Mona, A. Amodeo, G. D'Amico, A. Giunta, F. Madonna, and G. Pappalardo. Multi-wavelength Raman lidar observations of the Eyjafjallajökull volcanic cloud over Potenza, southern Italy. *Atmos. Chem. Phys.*, 12(4):2229–2244, 2012. doi: 10.5194/acp-12-2229-2012.
- [280] M. Montopoli, G. Vulpiani, D. Cimini, E. Picciotti, and F. S. Marzano. Interpretation of observed microwave signatures from ground dual polarization radar and space multi frequency radiometer for the 2011 Grmsvötn volcanic eruption. *Atmos. Meas. Techn. Disc.*, 6(4):6215–6248, 2013. doi: 10.5194/amtd-6-6215-2013.
- [281] T. Mori and M. Burton. The SO₂ camera: A simple, fast and cheap method for ground-based imaging. *Geophys. Res. Lett.*, 33, 2006. doi: 10.1029/2006GL027916,2006.
- [282] N.T. O'Neill, C. Perro, A. Saha, G. Lesins, T.J. Duck, E.W. Eloranta, G.J. Nott, A. Hoffman, M.L. Karumudi, C. Ritter, A. Bourassa, I. Abboud, S.A. Carn, and V. Savastouk. Properties of Sarychev sulphate aerosols over the Arctic. *J. Geophys. Res.*, 117(D4), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016838.
- [283] C. Oppenheimer. Ultraviolet Sensing of Volcanic Sulfur Emissions. *Elements*, 6(2):87–92, APR 2010. ISSN 1811-5209. doi: {10.2113/gselements.6.2.87}.
- [284] A. Papayannis, R.E. Mamouri, V. Amiridis, E. Giannakaki, I. Veselovskii, P. Kokkalis, G. Tsaknakis, D. Balis, N.I. Kristiansen, A. Stohl, M. Korenskiy, K. Allakhverdiev, M.F. Huseyinoglu, and T. Baykara. Optical properties and vertical extension of aged ash layers over the Eastern Mediterranean as observed by Raman lidars during the Eyjafjallajökull eruption in May 2010. *Atmos. Environ.*, 48:56–65, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.08.037.
- [285] G. Pappalardo, L. Mona, G. D'Amico, U. Wandinger, M. Adam, A. Amodeo, A. Ansmann, A. Apituley, L. Alados Arboledas, D. Balis, A. Boselli, J. A. Bravo-Aranda, A. Chaikovskiy, A. Comeron, J. Cuesta, F. De Tomasi, V. Freudenthaler, M. Gausa, E. Giannakaki, H. Giehl, A. Giunta, I. Grigorov, S. Groß, M. Haeffelin, A. Hiebsch, M. Iarlori, D. Lange, H. Linné, F. Madonna, I. Mattis, R.-E. Mamouri, M. A. P. McAuliffe, V. Mitev, F. Molero, F. Navas-Guzman, D. Nicolae, A. Papayannis, M. R. Perrone, C. Pietras, A. Pietruczuk, G. Pisani, J. Preißler, M. Pujadas, V. Rizi, A. A. Ruth, J. Schmidt, F. Schnell, P. Seifert, I. Serikov, M. Sicard, V. Simeonov, N. Spinelli, K. Stebel, M. Tesche, T. Trickl, X. Wang, F. Wagner, M. Wiegner, and K. M. Wilson. Four-dimensional distribution of the 2010 Eyjafjallajökull volcanic cloud over Europe observed by EARLINET. *Atmos. Chem. Phys.*, 13(8):4429–4450, 2013. doi: 10.5194/acp-13-4429-2013.
- [286] M.R. Perrone, F. De Tomasi, A. Stohl, and N.I. Kristiansen. Integration of measurements and model simulations to characterize Eyjafjallajökull volcanic aerosols over south-eastern Italy. *Atmos. Chem. Phys.*, 12(20):10001–10013, 2012. doi: 10.5194/acp-12-10001-2012.
- [287] G.N. Petersen, H. Björnsson, and P. Arason. The impact of the atmosphere on the Eyjafjallajökull 2010 eruption plume. *J. Geophys. Res.*, 117(D00U07), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016762.
- [288] G.N. Petersen, H. Björnsson, P. Arason, and S. von Löwis. Two weather radar time series of the altitude of the volcanic plume during the May 2011 eruption of Grmsvötn, Iceland. *Earth System Science Data*, 4(1):121–127, 2012. doi: 10.5194/essd-4-121-2012.
- [289] G.N. Petersen, S. von Löwis, B. Brooks, J. Groves, and S. Mobbs. Utilising a LIDAR to detect volcanic ash in the near-field. *Weather*, 67(6):149–153, 2012. ISSN 1477-8696. doi: 10.1002/wea.1911.
- [290] A. J. Prata and C. Bernardo. Retrieval of sulphur dioxide from a ground-based thermal infrared imaging camera. *Atmos. Meas. Tech. Disc.*, 7(2):1153–1211, 2014. doi: 10.5194/amtd-7-1153-2014.
- [291] A.J. Prata and C. Bernardo. Retrieval of volcanic ash particle size, mass and optical depth from a ground-based thermal infrared camera. *J. Volcanol. Geotherm. Res.*, 186(1-2):91–107, 2009. doi: 10.1016/j.jvolgeores.2009.02.007.
- [292] M. Ripepe, C. Bonadonna, A. Folch, D. Delle Donne, G. Lacanna, E. Marchetti, and A. Hskuldsson. Ash-plume dynamics and eruption source parameters by infrasound and thermal imagery: The 2010 Eyjafjallajökull eruption. *Earth and Planetary Science Letters*, 366(0):112 – 121, 2013. ISSN 0012-821X. doi: 10.1016/j.epsl.2013.02.005.
- [293] C. Rolf, M. Krämer, C. Schiller, M. Hildebrandt, and M. Riese. Lidar observation and model simulation of a volcanic-ash-induced cirrus cloud during the Eyjafjallajökull eruption. *Atmos. Chem. Phys.*, 12(21):10281–10294, 2012. doi: 10.5194/acp-12-10281-2012.

- [294] W.I. Rose, A.B. Kostinski, and L. Kelley. Real-time C-band radar observations of 1992 eruption clouds from Crater Peak, Mount Spurr volcano, Alaska. *US Geol. Surv. Bull.*, 2139:19–26, 1995.
- [295] G.G. Salerno, M.R. Burton, C. Oppenheimer, T. Caltabiano, D. Randazzo, N. Bruno, and V. Longo. Three-years of SO₂ flux measurements of Mt. Etna using an automated UV scanner array: Comparison with conventional traverses and uncertainties in flux retrieval. *J. Volcanol. Geotherm. Res.*, 183(1–2):76 – 83, 2009. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2009.02.013.
- [296] P. Sawamura, J. P. Vernier, J. E. Barnes, T. A. Berkoff, E. J. Welton, L. Alados-Arboledas, F. Navas-Guzman, G. Pappalardo, L. Mona, F. Madonna, D. Lange, M. Sicard, S. Godin-Beekmann, G. Payen, Z. Wang, S. Hu, S. N. Tripathi, C. Cordoba-Jabonero, and R. M. Hoff. Stratospheric AOD after the 2011 eruption of Nabro volcano measured by lidars over the Northern Hemisphere. *Environ. Res. Lett.*, 7(3), JUL-SEP 2012. ISSN 1748-9326. doi: 10.1088/1748-9326/7/3/034013.
- [297] P. Seifert, A. Ansmann, S. Groß, V. Freudenthaler, B. Heinold, A. Hiebsch, I. Mattis, J. Schmidt, F. Schnell, M. Tesche, U. Wandinger, and M. Wiegner. Ice formation in ash-influenced clouds after the eruption of the Eyjafjallajökull volcano in April 2010. *J. Geophys. Res.*, 116(D00U04), 2011. ISSN 2156-2202. doi: 10.1029/2011JD015702.
- [298] M. Sicard, J. L. Guerrero-Rascado, F. Navas-Guzmán, J. Preißler, F. Molero, S. Tomás, J. A. Bravo-Aranda, A. Comerón, F. Rocadenbosch, F. Wagner, M. Pujadas, and L. Alados-Arboledas. Monitoring of the Eyjafjallajökull volcanic aerosol plume over the Iberian Peninsula by means of four EARLINET lidar stations. *Atmos. Chem. and Phys.*, 12(6):3115–3130, 2012. doi: 10.5194/acp-12-3115-2012.
- [299] W. Stremme, A. Krueger, R. Harig, and M. Grutter. Volcanic SO₂ and SiF₄ visualization using 2-D thermal emission spectroscopy - Part 1: Slant-columns and their ratios. *Atmos. Meas. Tech.*, 5(2):275 – 288, 2012. ISSN 1867 - 1381. doi: 10.5194/amt-5-275-2012.
- [300] G. Tamburello, A.J.S. McGonigle, E.P. Kantzas, and A. Aiuppa. Recent advances in ground-based ultraviolet remote sensing of volcanic SO₂ fluxes. *Annals of Geophysics*, 54(2), 2011. doi: 10.4401/ag-5179.
- [301] M. Tesche, P. Glantz, C. Johansson, M. Norman, A. Hiebsch, A. Ansmann, D. Althausen, R. Engelmann, and P. Seifert. Volcanic ash over Scandinavia originating from the Grímsvötn eruptions in May 2011. *J. Geophys. Res.*, 117, MAY 2 2012. ISSN 2169-897X. doi: 10.1029/2011JD017090.
- [302] C. Toledano, Y. Bennouna, V. Cachorro, J.P. Ortiz de Galisteo, A. Stohl, K. Stebel, N.I. Kristiansen, F.J. Olmo, H. Lyamani, M.A. Obregón, V. Estellés, F. Wagner, J.M. Baldasano, Y. González-Castanedo, L. Clarisse, and A.M. de Frutos. Aerosol properties of the Eyjafjallajökull ash derived from sun photometer and satellite observations over the Iberian Peninsula. *Atmos. Environ.*, 48:22 – 32, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.09.072.
- [303] T. Trickl, H. Giehl, H. Jäger, and H. Vogelmann. 35 yr of stratospheric aerosol measurements at Garmisch-Partenkirchen: from Fuego to Eyjafjallajökull, and beyond. *Atmos. Chem. Phys.*, 13(10):5205–5225, 2013. doi: 10.5194/acp-13-5205-2013.
- [304] O. Uchino, T. Sakai, T. Nagai, K. Nakamae, I. Morino, K. Arai, H. Okumura, S. Takubo, T. Kawasaki, Y. Mano, T. Matsunaga, and T. Yokota. On recent (2008-2012) stratospheric aerosols observed by lidar over Japan. *Atmos. Chem. Phys.*, 12(24):11975–11984, 2012. ISSN 1680-7316. doi: 10.5194/acp-12-11975-2012.
- [305] X. Wang, A. Boselli, L. D’Àvino, G. Pisani, N. Spinelli, A. Amodeo, A. Chaikovsky, M. Wiegner, S. Nickovic, A. Papayannis, M.R. Perrone, V. Rizi, L. Sauvage, and A. Stohl. Volcanic dust characterization by EARLINET during Etna’s eruptions in 2001–2002. *Atmos. Environ.*, 42(5):893 – 905, 2008. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2007.10.020.
- [306] T.E. Wright, M. Burton, D.M. Pyle, and T. Caltabiano. Scanning tomography of SO₂ distribution in a volcanic gas plume. *Geophys. Res. Lett.*, 35(17), 2008. ISSN 1944-8007. doi: 10.1029/2008GL034640.

Aircraft and balloon measurements

- [307] S.M. Andersson, B.G. Martinsson, J. Friberg, C.A.M. Brenninkmeijer, A. Rauthe-Schöch, M. Hermann, P.F.J. van Velthoven, and A. Zahn. Composition and evolution of volcanic aerosol from eruptions of Kasatochi, Sarychev and Eyjafjallajökull in 2008–2010 based on CARIBIC observations. *Atmos. Chem. Phys.*, 13(4):1781–1796, 2013. doi: 10.5194/acp-13-1781-2013.
- [308] A.J. Baran. A new application of a multifrequency submillimeter radiometer in determining the microphysical and macrophysical properties of volcanic plumes: A sensitivity study. *J. Geophys. Res.*, 117(D00U18), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016781.
- [309] N. Bukowiecki, P. Zieger, E. Weingartner, Z. Jurányi, M. Gysel, B. Neiningner, B. Schneider, C. Hueglin, A. Ulrich, A. Wichser, S. Henne, D. Brunner, R. Kaegi, M. Schwikowski, L. Tobler, F. G. Wienhold, I. Engel, B. Buchmann, T. Peter, and U. Baltensperger. Ground-based and airborne in-situ measurements of the Eyjafjallajökull volcanic aerosol plume in Switzerland in spring 2010. *Atmos. Chem. Phys.*, 11(19):10011–10030, 2011. doi: 10.5194/acp-11-10011-2011.
- [310] P. Chazette, A. Dabas, J. Sanak, M. Lardier, and P. Royer. French airborne lidar measurements for Eyjafjallajökull ash plume survey. *Atmos. Chem. Phys.*, 12(15):7059–7072, 2012. doi: 10.5194/acp-12-7059-2012.
- [311] H. F. Dacre, A. L. M. Grant, and B. T. Johnson. Aircraft observations and model simulations of concentration and particle size distribution in the Eyjafjallajökull volcanic ash cloud. *Atmos. Chem. Phys.*, 13(3):1277–1291, 2013. doi: 10.5194/acp-13-1277-2013.
- [312] A.L.M. Grant, H. F. Dacre, D. J. Thomson, and F. Marengo. Horizontal and vertical structure of the Eyjafjallajökull ash cloud over the UK: a comparison of airborne lidar observations and simulations. *Atmos. Chem. Phys.*, 12(21):10145–10159, 2012. doi: 10.5194/acp-12-10145-2012.
- [313] K. Heue, C.A.M. Brenninkmeijer, T. Wagner, K. Mies, B. Dix, U. Frieß, B.G. Martinsson, F. Slemr, and P.F.J. van Velthoven. Observations of the 2008 Kasatochi volcanic SO₂ plume by CARIBIC aircraft DOAS and the GOME-2 satellite. *Atmos. Chem. Phys.*, 10:4699–4713, 2010. ISSN 1680-7324. doi: 10.5194/acp-10-4699-2010.
- [314] K.-P. Heue, C. A. M. Brenninkmeijer, A. K. Baker, A. Rauthe-Schöch, D. Walter, T. Wagner, C. Hörmann, H. Sihler, B. Dix, U. Frieß, U. Platt, B. G. Martinsson, P. F. J. van Velthoven, A. Zahn, and R. Ebinghaus. SO₂ and BrO observation in the plume of the Eyjafjallajökull volcano 2010: CARIBIC and GOME-2 retrievals. *Atmos. Chem. Phys.*, 11(6):2973–2989, 2011. doi: 10.5194/acp-11-2973-2011.
- [315] N. Ivleva, S. Huckele, R. Niessner, C. Haisch, and T. Baumann. Identification and characterization of individual airborne volcanic ash particles by Raman microspectroscopy. *Analytical and Bioanalytical Chemistry*, 405(28): 9071 – 9084, 2013. doi: 10.1007/s00216-013-7328-9.
- [316] B. Johnson, K. Turnbull, P. Brown, R. Burgess, J. Dorsey, A.J. Baran, H. Webster, J. Haywood, R. Cotton, Z. Ulanowski, E. Hesse, A. Woolley, and P. Rosenberg. In situ observations of volcanic ash clouds from the FAAM aircraft during the eruption of Eyjafjallajökull in 2010. *J. Geophys. Res.*, 117(D00U24), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016760.
- [317] T. Jurkat, C. Voigt, F. Arnold, H. Schlager, H. Aufmhoff, J. Schmale, J. Schneider, M. Lichtenstern, and A. Dörnbrack. Airborne stratospheric ITCIMS measurements of SO₂, HCl, and HNO₃ in the aged plume of volcano Kasatochi. *J. Geophys. Res.*, 115(D00L17), 2010. ISSN 2156-2202. doi: 10.1029/2010JD013890.
- [318] F. Marengo, B. Johnson, K. Turnbull, S. Newman, J. Haywood, H. Webster, and H. Ricketts. Airborne lidar observations of the 2010 Eyjafjallajökull volcanic ash plume. *J. Geophys. Res.*, 116(D00U05), 2011. ISSN 2156-2202. doi: 10.1029/2011JD016396.
- [319] S.M. Newman, L. Clarisse, D. I. Hurtmans, F. Marengo, B. Johnson, K. Turnbull, S. Havemann, A.J. Baran, D. O’Sullivan, and J. Haywood. A case study of observations of volcanic ash from the Eyjafjallajökull eruption: 2. Airborne and satellite radiative measurements. *J. Geophys. Res.*, 117(D00U13), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016780.
- [320] T. Petäjä, L. Laakso, T. Grönholm, S. Launiainen, I. Ebele-Peltoniemi, A. Virkkula, A. Leskinen, J. Backman, H.E. Manninen, M. Sipilä, S. Haapanala, K. Hämeri, E. Vanhala, T. Tuomi, J. Paatero, M. Aurela, H. Hakola, U. Makkonen, H. Hellén, R. Hillamo, J. Vira, M. Prank, M. Sofiev, M. Siitari-Kauppi, A. Laaksonen, K.E.J. Lehtinen, M. Kulmala, Y. Viisanen, and V.-M. Kerminen. In-situ observations of Eyjafjallajökull ash particles by hot-air balloon. *Atmos. Environ.*, 48:104 – 112, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.08.046.

- [321] D. Pieri, C. Ma, J.J. Simpson, T. Hufford, G. and Grindle, and C. Grove. Analyses of in-situ airborne ash from the February 2000 eruption of Hekla volcano, Iceland. *Geophys. Res. Lett.*, 29(16), 2002. doi: 10.1029/2001GL013688.
- [322] A. Rauthe-Schöch, A. Weigelt, M. Hermann, B. G. Martinsson, A. K. Baker, K.-P. Heue, C. A. M. Breninkmeijer, A. Zahn, D. Scharffe, S. Eckhardt, A. Stohl, and P. F. J. van Velthoven. CARIBIC aircraft measurements of Eyjafjallajökull volcanic clouds in April/May 2010. *Atmos. Chem. Phys.*, 12(2):879–902, 2012. doi: 10.5194/acp-12-879-2012.
- [323] W.I. Rose, R.L. Chuan, and D.C. Woods. Small particles in plumes of Mount St. Helens. *J. Geophys. Res.*, 87(C7):4956–4962, 1982. doi: 10.1029/JC087iC07p04956.
- [324] W.I. Rose, G.A. Millard, T.A. Mather, D. E. Hunton, B. Anderson, C. Oppenheimer, B.F. Thornton, T.M. Gerlach, A.A. Viggiano, Y. Kondo, et al. Atmospheric chemistry of a 33–34 hour old volcanic cloud from Hekla Volcano (Iceland): Insights from direct sampling and the application of chemical box modeling. *J. Geophys. Res.*, 111(D20206), 2006. ISSN 2156-2202. doi: 10.1029/2005JD006872.
- [325] J. Schmale, J. Schneider, T. Jurkat, C. Voigt, H. Kalesse, M. Rautenhaus, M. Lichtenstern, H. Schlager, G. Ancellet, F. Arnold, M. Gerding, I. Mattis, M. Wendisch, and S. Borrmann. Aerosol layers from the 2008 eruptions of Mount Okmok and Mount Kasatochi: In situ upper troposphere and lower stratosphere measurements of sulfate and organics over Europe. *J. Geophys. Res.*, 115(D00L07), 2010. ISSN 2156-2202. doi: 10.1029/2009JD013628.
- [326] U. Schumann, B. Weinzierl, O. Reitebuch, H. Schlager, A. Minikin, C. Forster, R. Baumann, T. Sailer, K. Graf, H. Mannstein, C. Voigt, S. Rahm, R. Simmet, M. Scheibe, M. Lichtenstern, P. Stock, H. Rüba, D. Schäuble, A. Tafferner, M. Rautenhaus, T. Gerz, H. Ziereis, M. Krautstrunk, C. Mallaun, J.-F. Gayet, K. Lieke, K. Kandler, M. Ebert, S. Weinbruch, A. Stohl, J. Gasteiger, S. Groß, V. Freudenthaler, M. Wiegner, A. Ansmann, M. Tesche, H. Olafsson, and K. Sturm. Airborne observations of the Eyjafjalla volcano ash cloud over Europe during air space closure in April and May 2010. *Atmos. Chem. Phys.*, 11(5):2245–2279, 2011. doi: 10.5194/acp-11-2245-2011.
- [327] K. Turnbull, B. Johnson, F. Marenco, J. Haywood, A. Minikin, B. Weinzierl, H. Schlager, U. Schumann, S. Leadbetter, and A. Woolley. A case study of observations of volcanic ash from the Eyjafjallajökull eruption: 1. In situ airborne observations. *J. Geophys. Res.*, 117(D00U12), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016688.
- [328] L. Vogel, B. Galle, C. Kern, H. Delgado Granados, V. Conde, P. Norman, S. Arellano, O. Landgren, P. Lübcke, J. M. Alvarez Nieves, L. Cárdenas Gonzáles, and U. Platt. Early in-flight detection of SO₂ via Differential Optical Absorption Spectroscopy: a feasible aviation safety measure to prevent potential encounters with volcanic plumes. *Atmos. Meas. Tech.*, 4(9):1785–1804, 2011. doi: 10.5194/amt-4-1785-2011.
- [329] K. Weber, J. Eliasson, A. Vogel, C. Fischer, T. Pohl, G. van Haren, M. Meier, B. Grobéty, and D. Dahmann. Airborne in-situ investigations of the Eyjafjallajökull volcanic ash plume on Iceland and over north-western Germany with light aircrafts and optical particle counters. *Atmos. Environ.*, 48:9 – 21, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.10.030.
- [330] B. Weinzierl, D. Sauer, A. Minikin, O. Reitebuch, F. Dahlkoetter, B. Mayer, C. Emde, I. Tegen, J. Gasteiger, A. Petzold, A. Veira, U. Kueppers, and U. Schumann. On the visibility of airborne volcanic ash and mineral dust from the pilot’s perspective in flight. *Physics and Chemistry of the Earth*, 45 - 46:87– 102, 2012. ISSN 1474 - 7065. doi: 10.1016/j.pce.2012.04.003.

Ground-based in-situ observations - ash characterization

- [331] F. Alfano, C. Bonadonna, A.C.M. Volentik, C.B. Connor, S. F.L. Watt, D. M. Pyle, and L.J. Connor. Tephra stratigraphy and eruptive volume of the May, 2008, Chaitén eruption, Chile. *Bull. Volcanol.*, 73(5):613–630, 2011. doi: 10.1007/s00445-010-0428-x.
- [332] F. Belosi, G. Santachiara, and F. Prodi. Eyjafjallajökull volcanic eruption: Ice nuclei and particle characterization. *Atmos. Clim. Sci.*, 1:34–40, 2011. doi: 10.4236/acs.2011.12005.
- [333] H. Bingemer, H. Klein, M. Ebert, W. Haunold, U. Bundke, T. Herrmann, K. Kandler, D. Müller-Ebert, S. Weinbruch, A. Judt, A. Weber, B. Nillius, K. Ardon-Dryer, Z. Levin, and J. Curtius. Atmospheric ice nuclei in the Eyjafjallajökull volcanic ash plume. *Atmos. Chem. Phys.*, 12(2):857–867, 2012. doi: 10.5194/acp-12-857-2012.

- [334] C. Bonadonna, G.C. Mayberry, E.S. Calder, R.S.J. Sparks, C. Choux, P. Jackson, A.M. Lejeune, S.C. Loughlin, G.E. Norton, W.I. Rose, et al. Tephra fallout in the eruption of Soufrière Hills Volcano, Montserrat. *Geological Society, London, Memoirs*, 21(1):483–516, 2002. doi: 10.1144/GSL.MEM.2002.021.01.22.
- [335] C. Bonadonna, R. Genco, M. Gouhier, M. Pistolesi, R. Cioni, F. Alfano, A. Hoskuldsson, and M. Ripepe. Tephra sedimentation during the 2010 Eyjafjallajökull eruption (Iceland) from deposit, radar, and satellite observations. *J. Geophys. Res.*, 116(B12202), 2011. doi: 10.1029/2011JB008462.
- [336] R.J. Brown, C. Bonadonna, and A.J. Durant. A review of volcanic ash aggregation. *Physics and Chemistry of the Earth, Parts A/B/C*, 45:65–78, 2012. doi: 10.1016/j.pce.2011.11.001.
- [337] N. Bukowiecki, P. Zieger, E. Weingartner, Z. Jurányi, M. Gysel, B. Neining, B. Schneider, C. Hueglin, A. Ulrich, A. Wichser, S. Henne, D. Brunner, R. Kaegi, M. Schwikowski, L. Tobler, F. G. Wienhold, I. Engel, B. Buchmann, T. Peter, and U. Baltensperger. Ground-based and airborne in-situ measurements of the Eyjafjallajökull volcanic aerosol plume in Switzerland in spring 2010. *Atmos. Chem. Phys.*, 11(19):10011–10030, 2011. doi: 10.5194/acp-11-10011-2011.
- [338] P. Dellino, M. T. Gudmundsson, G. Larsen, D. Mele, J. A. Stevenson, T. Thordarson, and B. Zimanowski. Ash from the Eyjafjallajökull eruption (Iceland): Fragmentation processes and aerodynamic behavior. *J. Geophys. Res.*, 117(B00C04), 2012. ISSN 2156-2202. doi: 10.1029/2011JB008726.
- [339] A.J. Durant, R.A. Shaw, W.I. Rose, Y. Mi, and G.G.J. Ernst. Ice nucleation and overseeding of ice in volcanic clouds. *J. Geophys. Res.*, 113(D09206), 2008. ISSN 2156-2202. doi: 10.1029/2007JD009064.
- [340] A.J. Durant, C. Bonadonna, and C.J. Horwell. Atmospheric and environmental impacts of volcanic particulates. *Elements*, 6(4):235–240, 2010.
- [341] A.J. Durant, G. Villarosa, W.I. Rose, P. Delmelle, A.J. Prata, and J. Viramonte. Long-range volcanic ash transport and fallout during the 2008 eruption of Chaitén volcano, Chile. *Physics and Chemistry of the Earth*, 45:50–64, 2012. doi: 10.1016/j.pce.2011.09.004.
- [342] T.K. Flaathen and S.R. Gislason. The effect of volcanic eruptions on the chemistry of surface waters: The 1991 and 2000 eruptions of Mt. Hekla, Iceland. *J. Volcanol. Geotherm. Res.*, 164(4):293–316, 2007. doi: 10.1016/j.jvolgeores.2007.05.014.
- [343] H. Flentje, H. Claude, T. Elste, S. Gilge, U. Köhler, C. Plass-Dülmer, W. Steinbrecht, W. Thomas, A. Werner, and W. Fricke. The Eyjafjallajökull eruption in April 2010: detection of volcanic plume using in-situ measurements, ozone sondes and lidar-ceilometer profiles. *Atmos. Chem. Phys.*, 10(20):10085–10092, 2010. doi: 10.5194/acp-10-10085-2010.
- [344] S.R. Gislason, H.A. Alfredsson, E.S. Eiríksdóttir, T. Hassenkam, and S.L.S. Stipp. Volcanic ash from the 2010 Eyjafjallajökull eruption. *Applied Geochemistry*, 26:S188–S190, 2011. doi: 10.1016/j.apgeochem.2011.03.100.
- [345] S.R. Gislason, T. Hassenkam, S. Nedel, N. Bovet, E.S. Eiríksdóttir, H.A. Alfredsson, C.P. Hem, Z. I. Balogh, K. Dideriksen, N. Oskarsson, et al. Characterization of Eyjafjallajökull volcanic ash particles and a protocol for rapid risk assessment. *Proceedings of the National Academy of Sciences*, 108(18):7307–7312, 2011. doi: 10.1073/pnas.1015053108.
- [346] A. Gudmundsson, N. Oskarsson, K. Gronvold, K. Saemundsson, O.r Sigurdsson, R.r Stefansson, S.R. Gislason, P. Einarsson, B.s Brandsdóttir, G. Larsen, et al. The 1991 eruption of Hekla, Iceland. *Bull. Volcanol.*, 54(3): 238–246, 1992. doi: 10.1007/BF00278391.
- [347] M.T. Gudmundsson, T. Thordarson, Á. Höskuldsson, G. Larsen, H. Björnsson, F.J. Prata, B. Oddsson, E. Magnússon, T. Högnadóttir, G. N. Petersen, C.L. Hayward, J.A. Stevenson, and I. Jnsdttir. Ash generation and distribution from the April-May 2010 eruption of Eyjafjallajökull, Iceland. *Scientific reports*, 2, 2012. doi: 10.1038/srep00572.
- [348] C.R. Hoyle, V. Pinti, A. Welti, B. Zobrist, C. Marcolli, B. Luo, Á. Höskuldsson, H. B. Mattsson, O. Stetzer, T. Thorsteinsson, G. Larsen, and T. Peter. Ice nucleation properties of volcanic ash from Eyjafjallajökull. *Atmos. Chem. Phys.*, 11(18):9911–9926, 2011. doi: 10.5194/acp-11-9911-2011.
- [349] E. Ilyinskaya, R.S. Martin, and C. Oppenheimer. Aerosol formation in basaltic lava fountaining: Eyjafjallajökull volcano, Iceland. *J. Geophys. Res.*, 117(D00U27), 2012. ISSN 2156-2202. doi: 10.1029/2011JD016811.

- [350] J.K. Keiding and O. Sigmarsson. Geothermobarometry of the 2010 Eyjafjallajökull eruption: New constraints on Icelandic magma plumbing systems. *J. Geophys. Res.*, 117(B00C09), 2012. ISSN 2156-2202. doi: 10.1029/2011JB008829.
- [351] V.-M. Kerminen, J. V. Niemi, H. Timonen, M. Aurela, A. Frey, S. Carbone, S. Saarikoski, K. Teinilä, J. Hakkarainen, J. Tamminen, J. Vira, M. Prank, M. Sofiev, and R. Hillamo. Characterization of a volcanic ash episode in southern Finland caused by the Grímsvötn eruption in Iceland in May 2011. *Atmos. Chem. Phys.*, 11(23):12227–12239, 2011. doi: 10.5194/acp-11-12227-2011.
- [352] K. Kvietkus, J. Šakalys, J. Didžbalis, I. Garbariene, N. Špirkauskaitė, and V. Remeikis. Atmospheric aerosol episodes over Lithuania after the May 2011 volcano eruption at Grímsvötn, Iceland. *Atmos. Res.*, 122(0):93 – 101, 2013. ISSN 0169-8095. doi: 10.1016/j.atmosres.2012.10.014.
- [353] B. Langmann, A. Folch, M. Hensch, and V. Matthias. Volcanic ash over Europe during the eruption of Eyjafjallajökull on Iceland, April–May 2010. *Atmos. Environ.*, 48:1– 8, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.03.054.
- [354] A. Lettino, R. Caggiano, S. Fiore, M. Macchiato, S. Sabia, and S. Trippetta. Eyjafjallajökull volcanic ash in southern Italy. *Atmos. Environ.*, 48:97 – 103, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.05.037.
- [355] K.I. Lieke, T.B. Kristensen, U.S. Korsholm, J.H. Srensen, K. Kandler, S. Weinbruch, D. Ceburnis, J. Ovadnevaite, C.D. O’Dowd, and M. Bilde. Characterization of volcanic ash from the 2011 Grímsvötn eruption by means of single-particle analysis. *Atmos. Environ.*, 79(0):411 – 420, 2013. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2013.06.044.
- [356] G. Martucci, J. Ovadnevaite, D. Ceburnis, H. Berresheim, S. Varghese, D. Martin, R. Flanagan, and C.D. O’Dowd. Impact of volcanic ash plume aerosol on cloud microphysics. *Atmos. Environ.*, 48:205 – 218, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.12.033.
- [357] S. Moune, O. Sigmarsson, P. Schiano, T. Thordarson, and J. K. Keiding. Melt inclusion constraints on the magma source of Eyjafjallajökull 2010 flank eruption. *J. Geophys. Res.*, 117(B00C07), 2012. ISSN 2156-2202. doi: 10.1029/2011JB008718.
- [358] O. Munoz, H. Volten, J.W. Hovenier, B. Veihelmann, W.J. van der Zande, L.B.F.M. Waters, and W.I. Rose. Scattering matrices of volcanic ash particles of Mount St. Helens, Redoubt, and Mount Spurr volcanoes. *J. Geophys. Res.*, 109(D16201), 2004. ISSN 2156-2202. doi: 10.1029/2004JD004684.
- [359] J. Naranjo, H.M. Roa, C. Fuentealba, P. Rizzo, P.R. Bitschene, N. Banks, S. Doiron, B. Presgrave, C. Stern, and A.J. Prata. Major eruption reported in Chile. *EOS Transactions of the American Geophysical Union*, 72: 393–394, 1991. doi: 10.1029/90EO00291.
- [360] C. O’Dowd, D. Ceburnis, J. Ovadnevaite, G. Martucci, Jakub Bialek, C. Monahan, H. Berresheim, A. Vaishya, T. Grigas, S. Gerard Jennings, P. McVeigh, S. Varghese, R. Flanagan, D. Martin, E. Moran, K. Lambkin, T. Semmler, C. Perrino, and R. McGrath. The Eyjafjallajökull ash plume Part I: Physical, chemical and optical characteristics. *Atmos. Environ.*, 48:129 – 142, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.07.004.
- [361] M. Pitz, J. Gu, J. Soentgen, A. Peters, and J. Cyrys. Particle size distribution factor as an indicator for the impact of the Eyjafjallajökull ash plume at ground level in Augsburg, Germany. *Atmos. Chem. Phys.*, 11(17): 9367–9374, 2011. doi: 10.5194/acp-11-9367-2011.
- [362] M.A. Revuelta, M. Sastre, A.J. Fernández, L. Martín, R. García, F.J. Gómez-Moreno, B. Artíñano, M. Pujadas, and F. Molero. Characterization of the Eyjafjallajökull volcanic plume over the Iberian Peninsula by lidar remote sensing and ground-level data collection. *Atmos. Environ.*, 48:46 – 55, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.05.033.
- [363] C.M. Riley, W.I. Rose, and G.J.S. Bluth. Quantitative shape measurements of distal volcanic ash. *J. Geophys. Res.*, 108(B10), 2003. doi: 10.1029/2001JB000818.
- [364] W.I. Rose. Scavenging of volcanic aerosol by ash: atmospheric and volcanologic implications. *Geology*, 5(10): 621–624, 1977. doi: 10.1130/0091-7613(1977)5(621:SOVABA)2.0.CO;2.
- [365] W.I. Rose and C.A. Chesner. Dispersal of ash in the great Toba eruption, 75 ka. *Geology*, 15(10):913–917, 1987. doi: 10.1130/0091-7613(1987)15(913:DOAITG)2.0.CO;2.

- [366] W.I. Rose and C.A. Chesner. Worldwide dispersal of ash and gases from earth's largest known eruption: Toba, Sumatra, 75 ka. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 89(3):269–275, 1990. doi: 10.1016/0921-8181(90)90023-6.
- [367] W.I. Rose and A.J. Durant. Fine ash content of explosive eruptions. *J. Volcanol. Geotherm. Res.*, 186(12): 32–39, 2009. ISSN 0377-0273. doi: 10.1016/j.jvolgeores.2009.01.010.
- [368] W.I. Rose, R.L. Wunderman, M.F. Hoffman, and L. Gale. A volcanologist's review of atmospheric hazards of volcanic activity: Fuego and Mount St. Helens. *J. Volcanol. Geotherm. Res.*, 17(1):133–157, 1983. doi: 10.1016/0921-8181(90)90023-6. Explosive Volcanism.
- [369] W.I. Rose Jr, S. Bonis, R.E. Stoiber, M. Keller, and T. Bickford. Studies of volcanic ash from two recent Central American eruptions. *Bulletin Volcanologique*, 37(3):338–364, 1973. doi: 10.1007/BF02597633.
- [370] P. Rossini, E. Molinaroli, G. De Falco, F. Fiesoletti, S. Papa, E. Pari, A. Renzulli, P. Tentoni, A. Testoni, L. Valentini, and G. Matteucci. April–May 2010 Eyjafjallajökull volcanic fallout over Rimini, Italy. *Atmos. Environ.*, 48:122 – 128, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.05.018.
- [371] K. Schäfer, W. Thomas, A. Peters, L. Ries, F. Obleitner, J. Schnelle-Kreis, W. Birmili, J. Diemer, W. Fricke, W. Junkermann, M. Pitz, S. Emeis, R. Forkel, P. Suppan, H. Flentje, S. Gilge, H. E. Wichmann, F. Meinhardt, R. Zimmermann, K. Weinhold, J. Soentgen, C. Münkel, C. Freuer, and J. Cyrus. Influences of the 2010 Eyjafjallajökull volcanic plume on air quality in the northern Alpine region. *Atmos. Chem. Phys.*, 11(16):8555–8575, 2011. doi: 10.5194/acp-11-8555-2011.
- [372] N. Schleicher, U. Kramar, V. Dietze, U. Kaminski, and S. Norra. Geochemical characterization of single atmospheric particles from the Eyjafjallajökull volcano eruption event collected at ground-based sampling sites in Germany. *Atmos. Environ.*, 48:113 – 121, 2012. ISSN 1352-2310. doi: 10.1016/j.atmosenv.2011.05.034.
- [373] I. Steinke, O. Möhler, A. Kiselev, M. Niemand, H. Saathoff, M. Schnaiter, J. Skrotzki, C. Hoose, and T. Leisner. Ice nucleation properties of fine ash particles from the Eyjafjallajökull eruption in April 2010. *Atmos. Chem. Phys.*, 11(24):12945–12958, 2011. doi: 10.5194/acp-11-12945-2011.
- [374] J.A. Stevenson, S. Loughlin, C. Rae, T. Thordarson, A.E. Milodowski, J. S. Gilbert, S. Harangi, R. Lukács, B. Højgaard, U. Árting, S. Pyne-O'Donnell, A. MacLeod, B. Whitney, and M. Cassidy. Distal deposition of tephra from the Eyjafjallajökull 2010 summit eruption. *J. Geophys. Res.*, 117(B00C10), 2012. ISSN 2156-2202. doi: 10.1029/2011JB008904.
- [375] T. Thorsteinsson, T. Jóhannsson, A. Stohl, and N.I. Kristiansen. High levels of particulate matter in Iceland due to direct ash emissions by the Eyjafjallajökull eruption and resuspension of deposited ash. *J. Geophys. Res.*, 117(B00C05), 2012. ISSN 2156-2202. doi: 10.1029/2011JB008756.
- [376] C.F. Waythomas, W. E. Scott, S.G. Prejean, D. J. Schneider, P. Izbekov, and C. J. Nye. The 7–8 August 2008 eruption of Kasatochi Volcano, central Aleutian Islands, Alaska. *J. Geophys. Res.*, 115(B00B06), 2010. ISSN 2156-2202. doi: 10.1029/2010JB007437.