

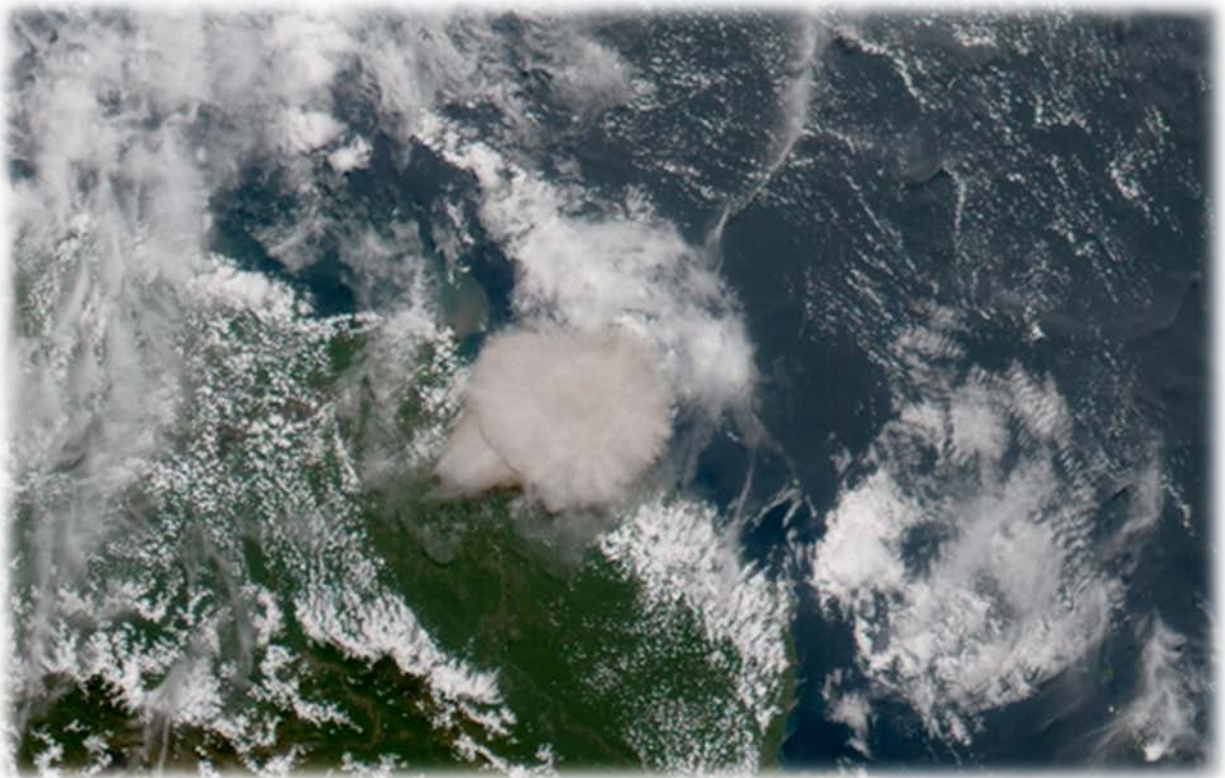
GLOBAL DEVELOPMENT AND USE OF QUANTITATIVE VOLCANIC ASH CONTAMINATION INFORMATION AND FORECASTS

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Geophysics and Geodesy (WMO/IUGG)
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*with input from the
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(ICCAIA)*

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[Source: Japan Meteorological Agency]

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Summary

The 2010 eruption of the Eyjafjallajökull volcano in Iceland prompted a sustained effort to improve the accuracy of ash-cloud forecasts. In this paper we describe progress toward this goal, through (1) quantitative characterization of observations, (2) improving the accuracy of model inputs, and (3) strategies to automatically integrate observations with models. Progress has been made on all three fronts. A key lesson is that accuracy can only be quantified by comparison with reliable observations, which are often elusive. Model improvements must be made in tandem with new technologies to observe and measure.

1. Introduction

In the era of modern air travel, the hazards of volcanic ash to aircraft are well known. More than 250 reported ash encounters with aircraft have clogged pitot tubes, frosted windshields, damaged instruments, sickened crew, and in some cases led to complete engine failure. From the establishment of the volcanic ash advisory centres (VAACs) in the early 1990s through to 2009, the annual number of damaging encounters decreased, leading many to believe that global efforts to reduce risk were working. However, in 2010, the ash cloud from the Eyjafjallajökull volcano in Iceland encountered more aircraft than any other historical event. Also, the combination of location over Europe and the lack of an industry-defined acceptable ash concentration meant that the strong measures required to avoid the possibility of ash encounters caused billions of dollars of economic loss.

That experience prompted a profound rethinking of strategies within Europe. VAAC practices had focused on delineating and forecasting the location of any ash. New strategies focused on quantifying properties such as ash concentration and using them to delineate areas of contamination that were safe versus unsafe for flight. Regulators, VAACs and the aviation community in general migrated toward the view that quantitative information contributed to forecast accuracy, which was needed to both maximize safety and minimize disruption.

Following the Eyjafjallajökull crisis, ICAO assembled an International Volcanic Ash Task Force (IVATF) to expedite a review of the procedures for avoiding ash clouds¹. The IVATF was complementary to an ICAO International Airways Volcano Watch Operations Group (IAVWOPSG), which had existed for almost a decade at that point. Scientific questions raised by the IVATF such as “what is the detection threshold of space-based sensors?”, “what is the uncertainty in ash model forecasts?”, and “at what ash concentration does a cloud become visible?”, were addressed in IVATF Working Papers written by leading scientists². These documents

identified fundamental weaknesses as well as future directions for research. Critically, the IVATF determined that work on developing modelled volcanic ash concentrations as an operational product would be discontinued, but they did strongly encourage more sophisticated risk management, for which the confidence in whether discernable volcanic ash would be present is required³. The IVATF also made specific tasking recommendations for further research to be coordinated by the World Meteorological Organization – International Union of Geodesy and Geophysics (WMO-IUGG) Volcanic Ash Scientific Advisory Group (VASAG), including:

- The establishment of a validation data-set for benchmarking current and future satellite-based retrieval schemes and encouragement of national and international space-based earth observation programmes to maintain and improve the level of coverage based on the current and future global coverage at infrared wavelengths;
- Further scientific investigations into volcanic-cloud thickness and stratification and to engage with the wider scientific community in pursuit of the research topics related to volcanic-cloud hazards respectively;
- Continued efforts to improve eruption detection and measurement capability, improve knowledge and use of eruption source parameters (ESPs), characterize uncertainty, improve a global ESP database, and develop probability density functions for ESPs at individual volcanoes, with special attention to the most active ones;
- Work towards improvements in dispersion modelling and to explore the development of near-real-time ensemble capabilities and prototype probabilistic products;

Effectively, these IVATF recommendations encouraged the research work essential for an eventual mature introduction of quantitative information on volcanic ash clouds.

Since then, work by Rolls-Royce on engine tolerance has provided quantitative limits on the concentrations and dosages of volcanic ash that are hazardous to aircraft engines (which, although not the only part of an airframe susceptible to volcanic ash, are critically important). New ways to quantify the ash have been developed. Some volcano observatories have added mobile radar and webcams to their monitoring capabilities; modellers have developed techniques to quantify uncertainty; new observations are available from lightning detectors, infrasound arrays, satellite platforms, and UAV measurement platforms. A review of the status of quantitative prediction is therefore timely.

2. Satellite Characterization

Volcanic eruptions are most hazardous when undetected. For this reason, volcano observatories have been established in most parts of the world to monitor and communicate unrest. However, this said, two thirds of the world's volcanoes are not monitored by any conventional equipment, such as nearby seismometers. All volcanoes, even remote ones, may pose a hazard to aircraft if they send ash into the air.

To detect eruptions from unmonitored volcanoes, VAAC forecasters can regularly examine satellite images for clouds whose evolution, location, and/or spectral properties are consistent with volcanic activity. Manual examination of satellite imagery, while a critical component of VAAC operations, has important limitations. Satellite data volumes have increased significantly over the years and it is challenging to manually examine every image, over every volcano, in near real-time. Clouds produced by volcanic eruptions are sometimes difficult to distinguish from meteorological clouds³, and meteorological clouds may also obscure ash. As such, and particularly in the absence of eruption reports, clouds may occasionally travel undetected for hours - or not be detected at all.

Fundamental limitations aside, meteorological satellite measurements are the primary observational tool utilized by VAACs, so recent improvements in meteorological satellite capabilities are extremely relevant to operational volcanic cloud monitoring. Compared to the previous generation of satellites, next generation satellites provide much more frequent imagery, with improved spatial detail, and better sampling of regions of the electromagnetic spectrum that are key for volcanic cloud detection and characterization. Every VAAC is now supported, at least in part, by a meteorological satellite that provides high quality images at least every 15 minutes. Several volcanic arcs are routinely imaged every 2.5 or 5 minutes. Next-generation satellite coverage and capabilities will continue to improve. For information on past, current, and future satellite missions, see the WMO Observing Systems Capability Analysis and Review (OSCAR) databaseⁱ.

Prior to discussing the operational impacts of next-generation satellites, some key background information is highlighted. Since volcanic ash emissions can occur at any time of the day, VAAC forecasters rely heavily on thermal infrared imagery, which often allows ash containing clouds to be identified by knowledgeable analysts at all times of the day. During the daytime, VAAC forecasters supplement infrared imagery with satellite-based measurements of reflected sunlight at ultra violet, visible and near-infrared wavelengths. Non-satellite data sources (e.g. web cams,

ⁱ <https://www.wmo-sat.info/oscar/>

volcano observatory reports, pilot reports, social media, etc.) are also utilized when available to build as complete a picture of the situation as is feasible in real time. In addition to providing qualitative imagery, satellite data has quantitative value. Satellite measurements have been used to estimate the height of ash clouds, determine the horizontal extent of ash, and estimate the amount of ash present in each satellite pixel. Quantitative ash cloud properties are largely derived from infrared satellite measurements, although reflected sunlight and microwave-based methods have also been prototyped. The infrared-based techniques, which can be utilized under a broad range of conditions at all times of the day, are most relevant to operations. Non-infrared based techniques provide valuable supplemental information. The strengths, limitations, and future outlook of quantitative satellite products are discussed in the sections that follow.

2.1 Current Capabilities

Here we focus on recent operational improvements due to improved satellite capabilities. Recent improvements are primarily the result of qualitative use of new satellite measurement capabilities (manual analysis of satellite imagery by human experts). Since 2015, when the upgrade to the meteorological satellite constellation began in earnest, and in combination with a continuing increase in ground-reports that can influence satellite analyses, the following impacts have been noted:

- Volcanic ash and/or Sulphur dioxide (SO₂) emissions are detected in a more timely manner (result of more frequent, higher quality satellite images).
- Smaller ash emissions are more likely to be detected.
- Ash and SO₂ tracking are generally improved. The improvement, relative to the previous generation of satellites, varies from incremental to significant depending on the properties of the volcanic cloud and the background conditions. With next-generation satellites, VAAC analysts are generally more confident in determining where discernible ash is located at a given time.

The number of volcanic ash advisories has grown significantly in recent years (Figure 1), reflecting, among other things, the growing VAAC analysis capability, particularly for smaller volcanic clouds that may not have been observed with less satellite capability. This does not necessarily imply increased disruption to industry, providing that VAAC advisories are used to inform a mature risk assessment (for example, recognizing that a volcano continuously emitting ash at low altitudes is principally a local issue).

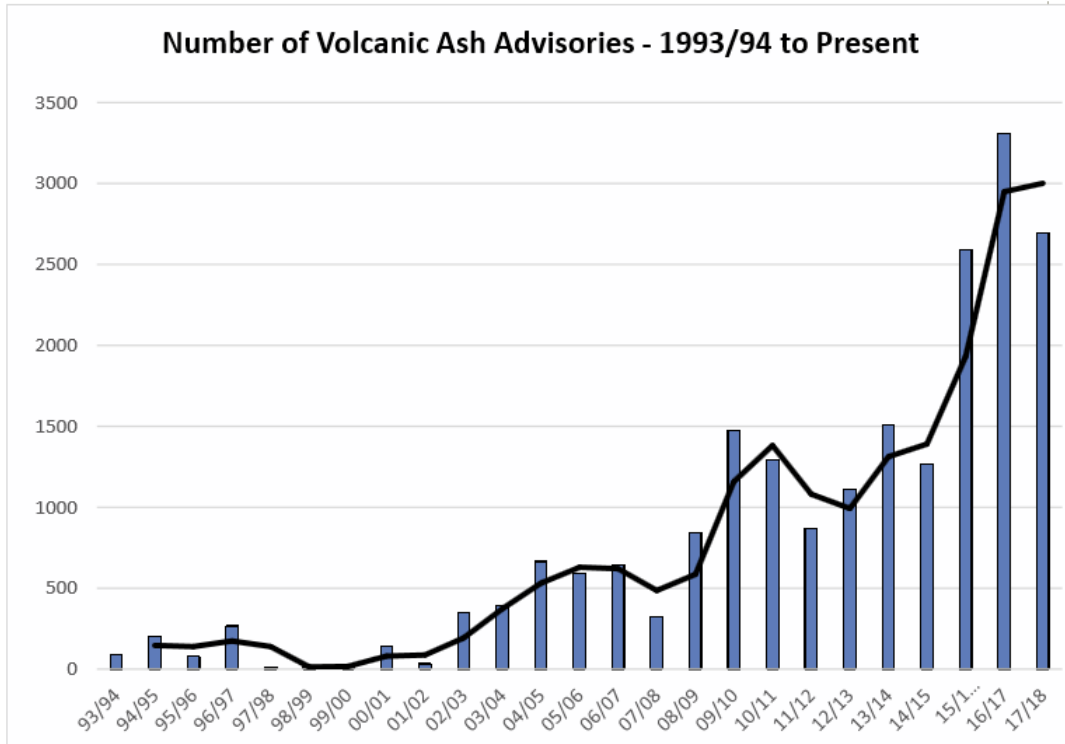


Figure 1. Increase in Volcanic Ash Advisory issuance over period of operation of VAAC Darwin (Bureau of Meteorology, Australia), for July-June periods. Solid line indicates running mean.

2.2 Future Capability Outlook

With the deployment of new satellite capabilities, there is always a significant time lag between initial deployment (launch and commissioning) and *full* utilization of the measurement capabilities. The time lag occurs because, although existing and accepted techniques can usually be implemented quickly with new data sources, longer-term data collection and scientific research are needed to develop more sophisticated practical applications, such as reliable quantitative tools for tracking and charactering volcanic ash clouds. There is also necessarily a significant amount of work to go from cutting edge research, the discernment of the correct way forward, and its implementation as a 24/7 process supported by procedures, training competencies, and operational technical support.

Qualitative volcanic cloud identification techniques are relatively mature from the research perspective, although improved techniques continue to be explored⁴, but are still being implemented consistently in the world's VAACs, in combination with improved procedures for integrating satellite and other data and communicating insights.

Major future improvements in satellite products will largely be associated with quantitative applications, such as ash property mapping, eruption alerting, automated integration of satellite-derived products, and operational dispersion models. Ash-cloud property mapping often consists of estimates of ash altitude, mass loading (i.e. mass of ash per unit area), and the effective grain size. The cloud altitude information is generally limited to the highest ash cloud layer in a given location. In addition, the estimated altitude will correspond to the cloud top for freshly erupted material and the middle of the cloud layer for dispersed ash. The ash mass loading is an estimate of the amount of ash in a given satellite pixel. In order to convert the mass loading to mass concentration, an estimate of the geometric thickness of the ash layer is needed. The geometric thickness is generally unknown, so ash concentration is rarely derived from meteorological satellite data. The effective grain size product, which must be retrieved in tandem with mass loading, provides information that may be related to the residence time of ash in the atmosphere, but more research is needed to establish an operationally relevant relationship. Given that many terabytes of meteorological satellite data are collected every day, automated volcanic eruption alerting has proven to be a useful complement to human expert analysis of satellite imagery. Further, several research studies have shown that the integration of high-quality satellite-derived information and dispersion models improves ash cloud forecasts.

Computer algorithms that map ash-cloud properties must first accurately determine which satellite pixels actually contain volcanic ash. Automated volcanic ash detection is very challenging for the same reasons that human expert identification is sometimes difficult. The additional challenge is that computer algorithms struggle to replicate the feature identification skill of human experts, especially when the attributes of the feature of interest and background are highly variable, as is the case with volcanic clouds. Eruption alerting dispersion modelling applications also require skilled automated ash detection. Transforming satellite measurements into estimates of ash cloud properties, such as altitude and loading, is also exceptionally challenging because the satellite measurements are influenced by so many factors, including background conditions (e.g. meteorological cloud cover, surface temperature, atmospheric moisture, etc.). Thus, while ash cloud property mapping was first introduced in the scientific literature in 1994⁵, such products have largely been used in research studies.

Usage of quantitative satellite products in VAAC operations has been very limited for various reasons. From a scientific perspective, high quality mapping of ash cloud properties, from eruption start until ash is no longer discernable in satellite imagery, has yet to be demonstrated across a broad range of conditions due to the aforementioned complexities. In addition, 24/7 support for the generation of satellite-derived volcanic ash products only recently began in a few meteorological and satellite agencies.

A more detailed assessment of the current and future state of satellite-based volcanic ash products will be available by the end of 2018, when a WMO Sustained Coordinated Processing of Environmental Satellite Records for Nowcasting (SCOPE-Nowcasting) initiative on volcanic ash products has concluded (<http://www.wmo.int/pages/prog/sat/meetings/SCOPE-Nowcasting-EP-1.php>).

Transitioning satellite products from an experimental (i.e. without 24/7 support) to an operational environment (with 24/7 support) generally requires one year or more of effort. In addition, when quantitative satellite products are formally introduced to VAACs, sufficient time will be required for VAAC analysts to become proficient in using them for operational decision-making within a quality managed environment. In addition to the research timeline, all planning for future ICAO requirements should take these factors into account.

3. Advances in Modelling

Atmospheric dispersion models are an essential tool in forecasting ash-cloud movement and contamination. Challenges to quantitative forecast accuracy come from limitations in model input parameters related to the eruptive source of ash plumes and, to a lesser extent, in the accuracy of the driving numerical weather prediction (NWP) data. Much of the recent framework for improving model accuracy took place in meetings that followed the Eyjafjallajökull crisis⁶. For example, in 2012, a WMO “inputs and outputs” workshop considered best practices for VAAC ash-cloud models⁷. Participants ranked the importance and level of knowledge of inputs such as plume height, mass eruption rate, particle-size distribution, vertical distribution of mass, and particle density (Table 1). Much work has since focused on improving knowledge and understanding of these eruption source parameters (ESP).

Data for model validation has been challenging to acquire. Prior to 2010, studies compared model results primarily with the outline of ash clouds⁸⁻¹². A new European requirement for concentration charts spurred an effort to compare modelled quantities with measured values, such as concentration from airborne in-situ measurements, or column mass load (g m^{-2}) from a satellite image¹³⁻¹⁷. Many such data were acquired during the Eyjafjallajökull eruption^{18, 19}, but data of this quality are scarce for other eruptions. A priority was set on developing a database of well-documented eruptions that could be used to validate models²⁰.

Table 1. The inputs for dispersion modelling of volcanic ash, ordered by significance, together with the perceived state of knowledge of these from low (1) to high (5) as of Nov 2012⁷.

Eruption Source Parameter	Current level of suitability
Eruptive plume height	4 (1 in certain locations)
NWP	4 (tropics worse)
Mass eruption rate (MER)	2
Onset and duration	5 (as low as 1 for poorly monitored volcanoes)
Vertical and horizontal distribution of the erupted plume near the source	2
Particle size distribution	2
Ash density	5
Ash sphericity	3

3.1 Improvements to Source Parameters

Among the eruption source parameters (Table 1), the eruption start time, plume height, and duration come from observations. Others must typically be inferred based on knowledge of similar events. To enable quantitative forecasting, data on all these parameters is required. We describe progress against each next.

3.1.1 More and Better Observations

New technologies have helped improve early eruption detection. Alert systems now automatically warn of possible eruptions through satellite detection of anomalous Sulphur dioxide²¹ or objects with characteristics of ash clouds²¹⁻²³. Global networks send automatic warnings of anomalous lightning near volcanoes²⁴, and regional infrasound arrays detect remote atmospheric disturbances²⁵.

Well-placed webcams^{26, 27} (Figure 2a), and images spread through social media²⁸ are helping detect and characterize volcanic plumes, particularly in conditions of good visibility. Mobile radar systems, ground and space-based Lidar, particularly when combined with satellite data, are improving the ability to constrain plume height^{29, 30}. VAACs and volcano observatories are developing computer tools, such as VolcViewⁱⁱ and VESPAⁱⁱⁱ, to speed analysis and rapidly assign ESPs.

ⁱⁱ <https://volcview.usgs.gov>

ⁱⁱⁱ <http://brunnur.vedur.is/radar/vespa/>

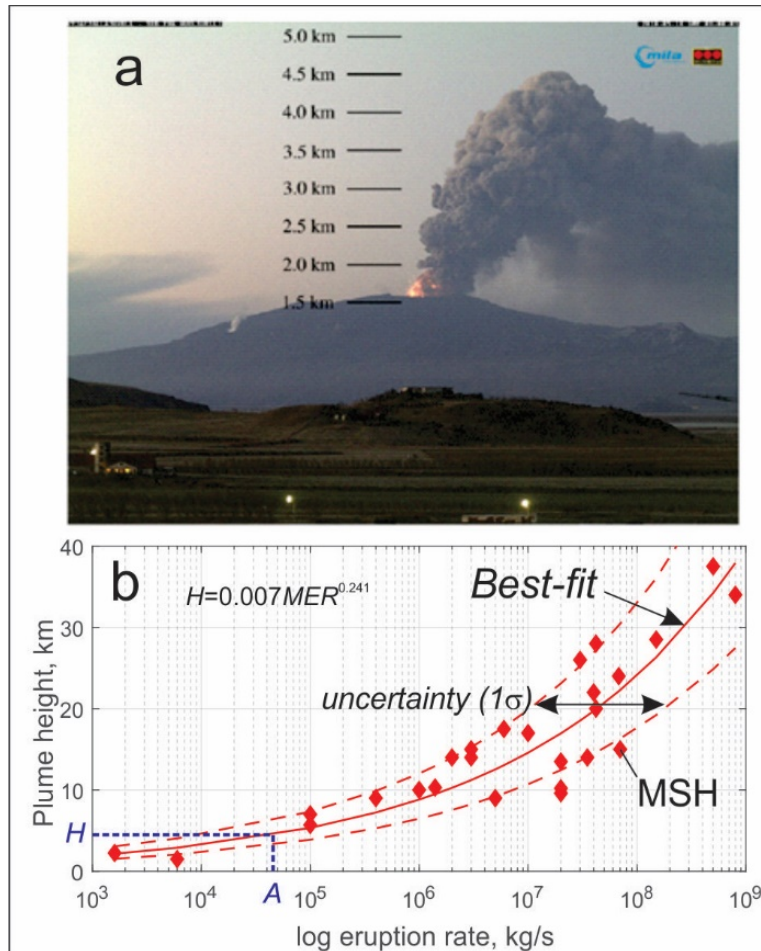


Figure 2. (a) Web-cam image of Eyjafjallajökull, 10 May at 03:00UTC²⁷. Markings on the image are used to determine plume height. (b) Plume height versus eruption rate for eruptions in which plume height and duration were well observed, and where deposits were mapped to obtain erupted mass (e.g., “MSH” is Mount St. Helens, 1980). Red solid line is the best-fit curve, $H = 0.3MER^{0.241}$ ³¹. Using this relation, the 4.5-km height in Fig. 1a implies $MER = 7 \times 10^4 \text{ kg s}^{-1}$ (“A”, Fig. 1b), but the $\pm 1\sigma$ uncertainty, given by the dashed lines, ranges from about $1\text{--}10 \times 10^4 \text{ kg s}^{-1}$. For this eruption, 1-D plume models typically gave MER several times higher than predicted by this curve, due to the effects of wind³².

3.1.2 Constraining Mass Eruption Rate

Mass eruption rate (MER) has received wide attention due to its leading-order effect on ash-cloud concentration. MER is generally inferred from plume height (H) above the vent. Theory suggests that $H \propto MER^{1/4}$, and this proportionality, is borne out by correlations^{31, 33, 34} using data from historical eruptions in which plume height and duration were well observed, and where deposits were mapped to obtain erupted mass (Figure 2b). The most widely used empirical correlation³¹ gives

$H=0.3 \cdot MER^{0.241}$, where H is in km above the vent, and MER is in kg s^{-1} . But there is much scatter in the data, which translates into an uncertainty of roughly an order of magnitude in modelled ash-cloud concentration. The large uncertainty results from inaccurate measurements of H and MER , from the physical effects of atmospheric conditions such as wind, from tropospheric instability and tropopause height, and from plume properties such as grain-size distribution, which can raise or lower H for a given MER ^{35, 36}. Meteorological arguments, observations and modelling also suggest that, in highly convective unstable atmospheres such as in the deep tropics, volcanic plumes can easily attain altitudes of 17-18 km for relatively weak eruptions, just as normal meteorological convection reaches these altitudes without volcanological triggers³⁷.

Measured plume-height accuracy will significantly improve with better satellite data, ground-based, and radar-based observations, but MER accuracy depends on classic field mapping, where the number and distribution of sample locations is key. New techniques are available to extrapolate erupted mass beyond the mapped area^{38, 39}, but they do not substitute for better data. And data points come only once every few years, when a new eruption spreads ash over accessible land and well-trained geologists are available to quickly sample it. Significant improvements to the dataset could therefore take decades.

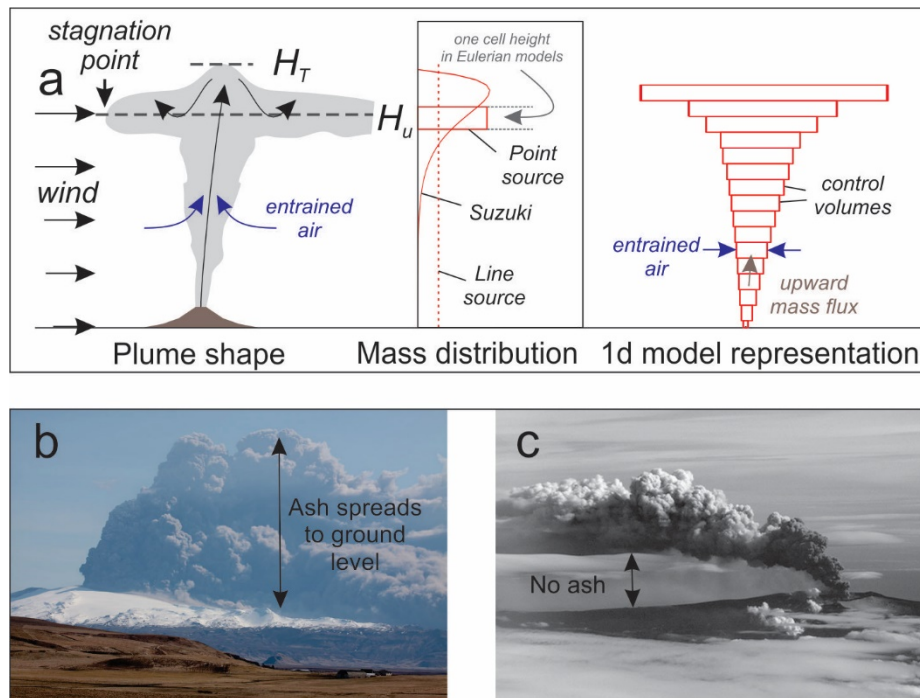


Figure 3. (a) Idealized volcanic plume showing plume-top height (H_T) and umbrella-cloud height (H_u) (left). At center are three mass distributions with height that are commonly used by models (center). In Eulerian models such as Fall3-D and Ash3-D, point sources are distributed within the height of one cell,

illustrated here. At right is an illustration showing that the plume is discretized into a series of control volumes in 1-d plume models. Each control volume tracks the flux of mass, momentum and energy into it from below, and from the sides as air is entrained. (b) and (c): Photos of the Eyjafjallajökull plume, taken on different days, illustrating different distributions of ash with vertical elevation in the downwind direction. Photo at left taken April 17, 2010 by Henrik Thorburn (Wikimedia Commons photo). Photo at right taken by Thorstein Jonsson, Icelandic Meteorological Office, May 4, 2010.

By contrast, tools that consider atmospheric effects on plumes have proliferated. Since 2010, new analytical equations that consider wind and atmospheric stability can relate MER and H ^{32, 40, 41}. Nearly a dozen one-dimensional plume models are now available that calculate effects of wind and moisture on the rising plume. These models discretize the plume into a series of control volumes, and tracks the flux of mass, momentum and energy into each control volume as the plume ascends (Figure 3a, right side). Some are used operationally, to derive MER during eruptions^{42, 43}. Three-dimensional models have also been developed, which provide useful and more realistic information on plume dynamics (see below). These are still too slow to be used in an operational setting^{44, 45}, but they can help calibrate key parameters such as the rate of air entrainment, which affects plume height in 1-D models.

Currently, uncertainties between 1-D plume models are high. In 2016, nine 1-D models were compared for calculating plume height for a given MER , and vice versa. Given the same MER for a weak plume under windy conditions, all 1-D models calculated the same H to within +/-20%. But given H for the same plume and asked to calculate MER , these same models ranged over 1.4 orders of magnitude. This reflects the high sensitivity of MER to H , as well as different assumptions and parameter values set in each model. These models have generally not been validated by comparing them with real, observed plumes. Further, as volcanic plumes are most easily observed in dry environments of high visibility, it is likely that such validations would cover a subset of dynamical situations. The limited accuracy of H and MER measured during real eruptions make such validations a challenge. A promising new technique uses the observed radial growth rate (R) of umbrella clouds in satellite images to estimate MER ^{28, 46}. This technique is especially suited to new-generation geostationary satellites, which can deliver high-resolution images every few minutes. Moreover, unlike H , R is proportional to the first power of MER . Hence factor-of-two variations in MER should be readily distinguishable. The disadvantage is that, globally, eruptions large enough to produce umbrella clouds are usually VEI 4 or larger, which occur less than once a year on average⁴⁷.

Near real-time techniques for measuring MER such as local infrasound arrays and X-band radar show some promise, but have limited testing (due to the infrequency of eruptions) and are deployed in only a few locations.

3.1.3 Better Constraints on Other Parameters

The rate of settling and deposition of volcanic ash depends upon its size and, to a lesser extent, its shape and density^{48, 49}. Ash concentration forecasts are particularly sensitive to the input total grain size distribution (TGSD)⁵⁰⁻⁵² (Figure 4). Aggregation (clumping) of fine ash can strongly control the grain size in the dispersing ash cloud, but the physics are not well understood. Although one model (Fall3-D) calculates aggregation from first principles for research purposes^{53, 54}, the very large computational costs associated with the scheme mean that currently the process of aggregation can only be included in operational models by adjusting the input grain-size or fall velocity to accelerate deposition^{55, 56}. Progress has been made through systematic testing of potential adjustment schemes⁵⁷, demonstrating that the same scheme can match observations for a surprisingly large range of eruption types, but further research is needed.

TGSDs from past eruptions provide a means to define distributions for future eruptions. Efforts to compile TGSDs have been boosted by several international projects. In Iceland, for example, TGSDs have been produced for 15 historical eruptions and the results are open to public through the Catalogue of Icelandic Volcanoes^{iv}.

^{iv} <http://icelandicvolcanos.is/>

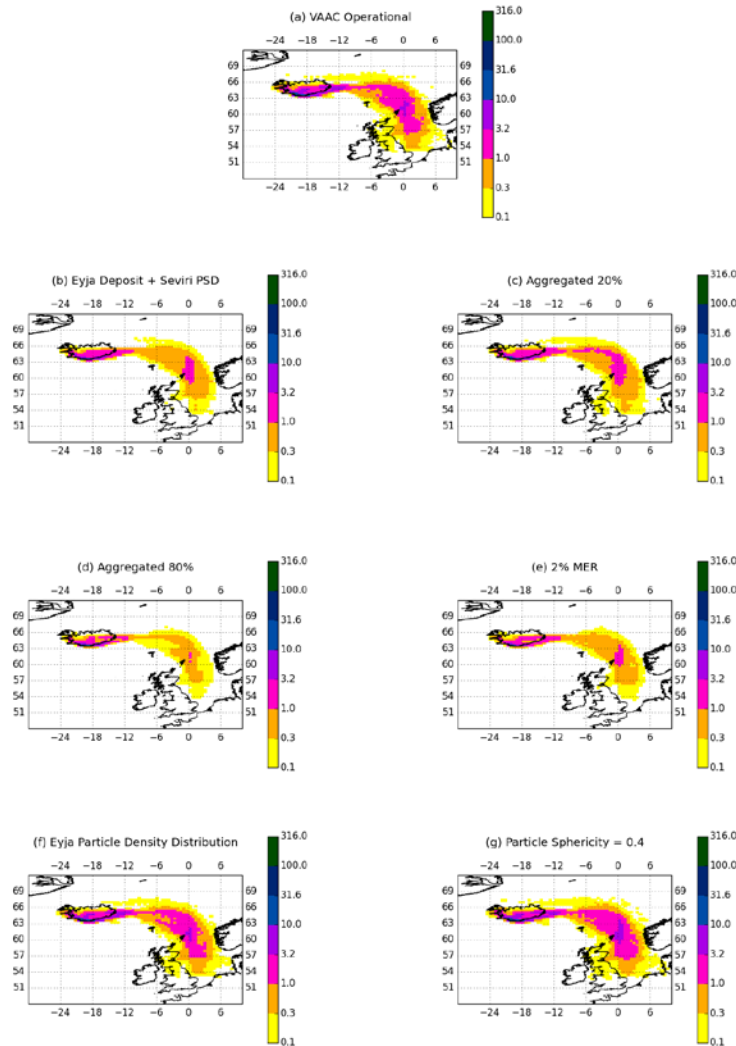


Figure 4. The impact of changing grain-size distribution and MER on modelled ash concentration. Compared to the control (a), changes to the particle size distribution (b), (c) and (d) show a similar impact to a 60% reduction in the MER (e). Changes to the particle density (f) and shape (g) have a negligible impact. From Beckett et al. [2015]⁵⁵. Reprinted with permission from the U.K. Met. Office.

The vertical distribution of mass defines how the erupted mass is distributed with elevation in the atmosphere (Figure 3a, center). This property is neglected in most source parameter discussions^{6, 31}, and there is no conventional way to assign it. Some operational VAAC models use a uniform line source⁷, others use a point source¹⁰ or Suzuki distribution⁵⁸ (Figure 3a). Visual observations (Figure 3b, c) demonstrate that the distribution can vary during eruptions, and model sensitivity studies¹⁰ show it can strongly affect results, especially when wind shear is present. Conventional scientific wisdom suggests that most of the mass of fine ash (tens of microns or smaller) is concentrated towards the zone of peak detrainment near the

top of the column. This is supported by inversion studies¹⁷ and space-borne Lidar data from recent eruptions. However, in larger eruptions, for example at Pinatubo in 1991⁵⁹, ash in the overshooting top was known to collapse into the main umbrella cloud at heights 25-45% below the plume top. Unusual column processes during the Grímsvötn 2011 eruption led to the bulk of the ash cloud being at very low altitudes⁶⁰. Useful insights on the complex distribution of these parameters have been also derived from three-dimensional numerical simulations⁶¹. Quantifying the distribution of ash based on such observations is a challenge and even more so in real-time.

3.1.4 Integrating Observations with Models

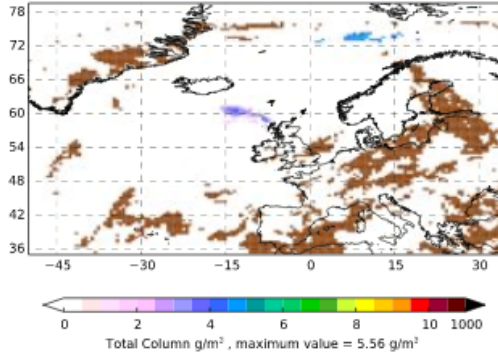
Several strategies for incorporating observations to automatically improve model accuracy have been developed. One involves initiating a model simulation using the location and height of a cloud in a satellite retrieval⁶². Retrieved quantities such as the amount of ash, ash-cloud top height, and ash particle size can all be used in the model⁶³.

Another strategy is to use an inversion scheme that compares model calculations with satellite observations with the aim of optimizing emission parameters at the eruption source for use with the dispersion model (Figure 5). This method uses data on ash cloud location, as well as retrieved properties such as ash mass loading to provide quantitative information on the source strengths at various heights above the vent^{13, 17, 64-66}.

A third technique, which resembles the traditional data assimilation methods used in numerical weather prediction, involves updating a previous model simulation with new observational data and initializing a subsequent model forecast⁶⁷⁻⁷⁰. This method assimilates observations regardless of the emissions at the source.

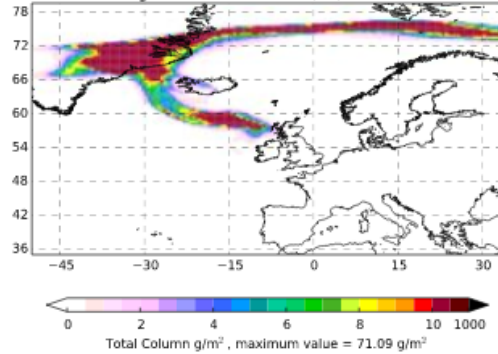
A final technique involves initiating an ensemble of model runs, then automatically comparing results to a satellite retrieval, and dismissing or down-weighting those with a poor match⁷¹⁻⁷³ (Figure 6).

Satellite Retrievals
Ash total column average from 2300 23/05/2011 until 0000 24/05/2011



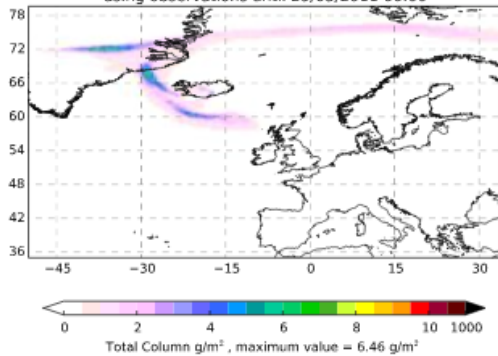
(a) ash and clear sky satellite retrievals
23:00 UTC 23/05/2011 to 00:00 UTC 24/05/2011

Plume from a priori source term
Ash total column average from 2300 23/05/2011 until 0000 24/05/2011
using observations until 29/05/2011 00:00



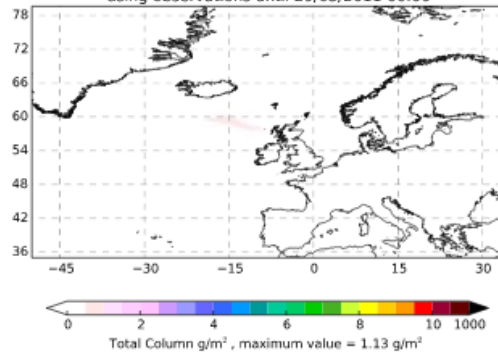
(b) a priori plume
23:00 UTC 23/05/2011 to 00:00 UTC 24/05/2011

Plume from inversion source term
Ash total column average from 2300 23/05/2011 until 0000 24/05/2011
using observations until 29/05/2011 00:00



(c) a posteriori plume using ash-only retrievals
23:00 UTC 23/05/2011 to 00:00 UTC 24/05/2011

Plume from inversion source term
Ash total column average from 2300 23/05/2011 until 0000 24/05/2011
using observations until 29/05/2011 00:00



(d) a posteriori plume using ash and clear sky retrievals
23:00 UTC 23/05/2011 to 00:00 UTC 24/05/2011

Figure 5. The Grímsvötn ash plume between 23:00 UTC on 23/05/2011 and 00:00 UTC on 24/05/2011 as (a) observed by satellite (ash and clear skies, with clear skies shown in brown). (b) The plume as predicted by NAME with a priori emissions based on radar observations of height and (c,d) the plume as predicted by NAME with emissions determined using the InTEM inversion scheme using (c) ash-only and (d) both ash and clear sky satellite observations. The inversions used satellite retrievals up to 00:00 UTC 29/05/2011 [Webster et al, 2017]⁷⁴. Reprinted with permission from the U.K. Met. Office.

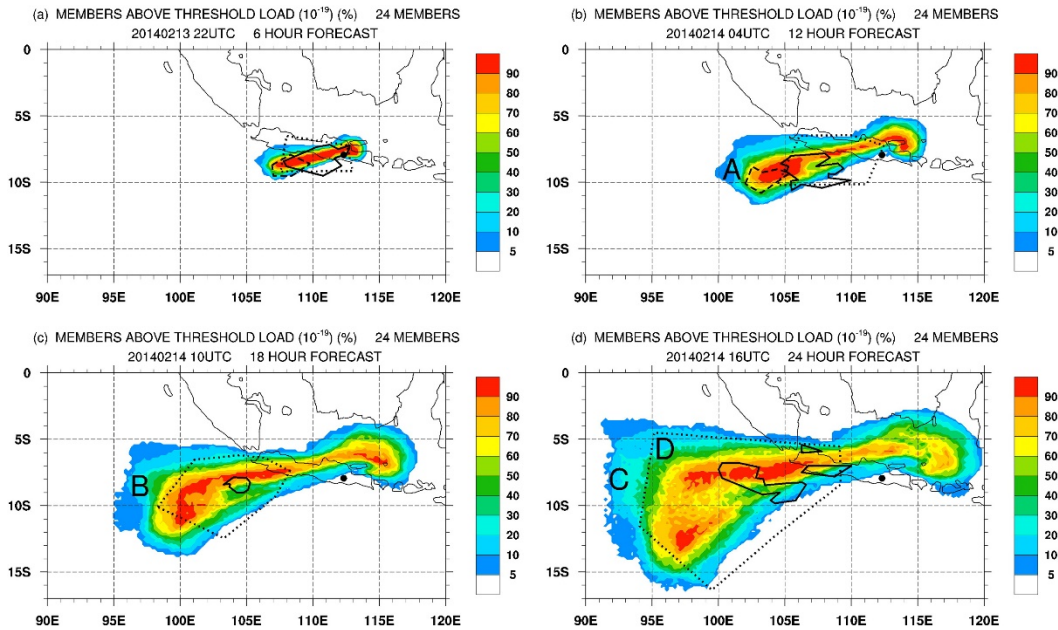


Figure 6. The use of ensembles to provide information on the likelihood of exceeding a quantitative threshold. [Dare et al 2016]⁷⁵. The images show the number of ensemble members (as a percentage) that had an ash column load above a selected threshold for (a) 6, (b) 12, (c) 18, and (d) 24 hours after the eruption of Kelut in 2014, based on a 24-member ensemble. The location of Kelut is shown by the black dot. Dashed, solid, and dotted polygons represent observations.

The satellite data used in these approaches are generally gridded ash-column mass loads derived from infrared (IR) geostationary satellites, which contain their own assumptions and uncertainties. One of the limitations with all these techniques is that the ash cloud thickness is not a retrieved quantity and, unless lidar or specially deployed radiosonde data are available, needs to be assumed. The model forecasts are therefore strongly dependent on the quality of the observations and assumptions made. Uncertainties in the retrieved properties will be carried through to the model forecast.

Strategies like these may be the key to improving both qualitative and quantitative ash-cloud model forecasts and are areas of active research and development. But many hurdles presently block their implementation. One is that few VAACs have the resources to operationalize them. A second is that they require retrievals from geostationary satellites with low latency and high frame rates. Such data were not available for many parts of the world until the recent launches of the Himawari and GOES-R satellites, and some VAACs may still not be able to process this data. A third is that real-world complications, such as the presence of meteorological clouds obscuring the detection of ash, introduce uncertainty and errors, which can limit the applicability of these techniques.

Progress in this area may rest on working with these uncertainties in a way that allows certainty of action where the available data justifies it, meaning that areas with high confidence in observations can, whilst using the same advisory system, respond in a way that maximizes the benefit to users. Compare, for example, typical volcanic plumes from Mt Etna, Italy, and Manam, Papua New Guinea. Mt Etna plumes are much more likely to occur in a dry atmosphere, contain clearly discernable ash, be observed by satellite, meteorological radar and many ground observers, and therefore to be well constrained. By contrast, ash has never been explicitly detected above freezing level from Manam volcano (primarily due to the presence of ice in the cloud) despite its obvious presence in the eruption column, the eruption columns are generally poorly observed from the ground and are often obscured from view by satellite, and there is no radar coverage. Future advisory system design needs to encompass the realities of both situations, in the knowledge that the uncertainties associated with the remote tropical volcano will always likely be much higher. This could, for example, involve assigning a much lower native confidence to any quantitative analysis, and therefore a more conservative risk management strategy, and including the confidence measure in the native design of the system.

3.2 Improved Model Physics

The knowledge of the nature and evolution of the volcanic source and associated dispersal processes, such as the dynamics of the volcanic column and the growth of umbrella cloud, have been also recently improved through the development of several new models with advanced physics^{44, 45, 76, 77}. In particular, 3-D numerical plume models which elucidated some key complexities of the volcanic plume. Such models used the Large Eddy Simulation (LES) approach that not only describes the physics of the erupting gas–particle mixture but also resolves the relevant scales of turbulence. This is critical in the LES of volcanic plumes because the large-eddy scales controlling the entrainment rate are usually at the threshold between grid-resolved and subgrid scales.

The models developed⁴⁴ were able to accurately reproduce the turbulent spectrum in both Direct and Large-Eddy simulations. In particular, the models reproduced not only the averaged dynamics of a laboratory forced plume but also the statistics of turbulent fluctuations, controlling the mixing rate. Sensitivity studies also showed that low and mid-resolution LES were able to capture the essential features of high-resolution simulations, predicting consistent averaged flow fields. In particular, the uncertainty in the averaged flow fields associated with the adopted grid resolutions and subgrid models were significantly lower than that related to the choice of the entrainment coefficient in integral models. The net effect of the gas-pyroclast non-equilibrium on the mean flow profiles was also investigated by switching on and off the kinematic decoupling terms in the transport equations. Such an effect is larger

for weak plumes than for strong plumes; it is worth mentioning that for weak plumes, this decoupling effect can be significantly larger than the effect of the mesh resolution.

Such models have also allowed us to better understand the limitations and uncertainties of 1-D integral models of volcanic plume and to calibrate their key parameters⁴⁴. For instance, comparison of the averaged plume variables from the LES models and results of integral 1-D models allowed us to quantitatively estimate the quality of the 1-D approximation. For weak plumes, 3-D results are consistent with the predictions of integral models in the jet and plume regions, with an entrainment coefficient around 0.10 in the plume region below the Neutral Buoyancy Level (NBL). Vice versa, for strong plumes, the 1-D approximation resulted less appropriate and the computed entrainment coefficient in the plume region more unstable, with a higher average value of 0.24. However, in both cases, predictions from integral models diverge from the 3-D plume behavior in the umbrella region, where the entrainment coefficient assumes negative values. Such outcomes, and associated uncertainties, need to be properly considered when adopting integral models for the description of the volcanic source.

Similarly, models have been improved that forecast *resuspended ash*, which has been a chronic hazard in South America⁷⁸, Alaska^{78, 79} and elsewhere following large-scale ash deposition. Forecasts of relative amounts of resuspended ash for Iceland have been produced operationally since the Grímsvötn 2011 eruption, and satellite data show promise for their ongoing calibration^{80, 81}. Capabilities in Argentina and Alaska will likely soon become operational. Whilst modelling these well-understood deposits is possible, the challenge for quantitative modelling of new deposits is the need for a rapid understanding of the extent of the deposit and its particle-size distribution. Both of which directly impact the concentrations of resuspended material.

3.3 Better Weather Prediction Models, and Better Coupling with Dispersal Models

The skill of NWP models has significantly advanced in recent years. On the global scale, forecasts out to five days ahead are now as accurate as those for two days 20-years ago (Figure 7). Predictive skill in the Northern and Southern hemispheres is now almost equal, thanks to the effective use of observational information from satellite data providing global coverage⁸². Increases in the temporal and spatial resolutions of NWP models have led to better representation of the atmosphere and consequently the weather that affects volcanic ash. The development of higher-resolution regional models, now brings better (although still imperfect) representation of convection, particularly in the tropics where convection is the

dominant method of generating precipitation, and more realistic wind fields around volcanoes, which improve dispersion model predictions.

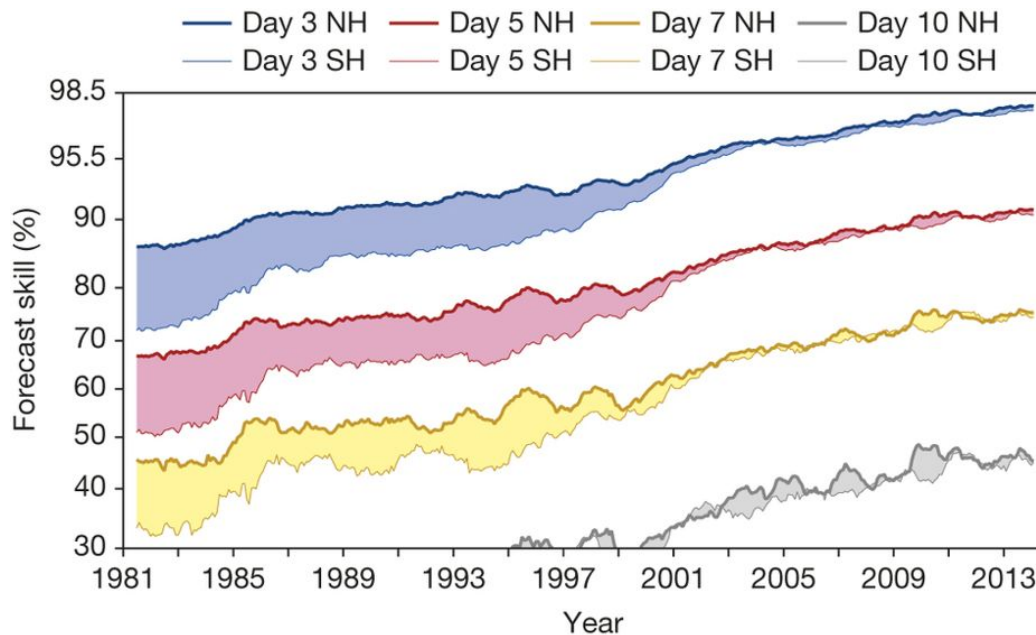


Figure 7. The evolving forecast skill of NWP models since 1981 for both the Northern (NH) and Southern (SH) Hemispheres. Values greater than 60% indicate useful forecasts, while those greater than 80% represent a high degree of accuracy. The convergence of the curves for Northern Hemisphere and Southern Hemisphere after 1999 indicates the breakthrough in exploiting satellite data through the use of variational data⁸². Copied with permission from Nature.

Experiments in coupling dispersal models with NWP models⁸³, show advantages from updating the wind field in the model every time step (every minute or so) rather than every few hours⁸⁴. Recent advances in computer power offer the future potential of making these models operational, with improvements in forecast accuracy.

4. State of Engine Susceptibility Science

In response to the recognition that volcanic ash represented a threat to gas turbine based aero engines, the engine manufacturers' historical operational recommendation was essentially a "total avoidance" strategy. The limitations of this strategy were clearly illustrated during the 2010 Eyjafjallajökull eruption. In response to the problems highlighted by the events of 2010, the European Aviation Safety Agency (EASA) introduced a change to their aircraft level and engine level

certification specifications, requiring original equipment manufacturers (OEMs) to explicitly declare the susceptibility of aircraft and engines to volcanic cloud hazards (EASA CS-25 1593 and CS-E 1050). Some engine OEMs have elected to comply with EASA's new regulations by reiterating the position that aircraft engines are susceptible (i.e. vulnerable) to essentially any volcanic ash exposure.

One engine OEM – Rolls-Royce – primarily in response to operator input has elected to respond to EASA's new regulations by declaring engine susceptibility using explicit ash concentration values. More specifically, their declaration reflects the realization that engine damage from volcanic ash is predominantly driven by the ash dose; that is the product of the exposure time and the exposure concentration. Such a position was supported using in-service and test bed engine exposure data, combined with a phenomenologically based mathematical model of engine core compressor operability loss due to ash exposure.

Consequently, in May 2017, Rolls-Royce declared an acceptable operational envelope in volcanic ash for its RB211 and Trent engine types based on three concentration ranges; namely, actual ash concentrations less than 0.2 mg/m^3 , actual ash concentrations between 0.2 mg/m^3 and 4 mg/m^3 and actual ash concentrations greater than 4 mg/m^3 . From a flight safety perspective, ash concentrations below 0.2 mg/m^3 can be treated as benign, i.e. in effect, the acceptable exposure dose is infinite.

Between concentrations of 0.2 mg/m^3 and 4 mg/m^3 a constant exposure dose applies. For Rolls-Royce RB211 and Trent engine types the acceptable dose from a flight safety perspective is 14.4 g s/m^3 (i.e. equivalent to 4 mg/m^3 for 1 hour or 0.2 mg/m^3 for 20 hours). It is possible that for other engine types the applicable dose is greater or smaller than this number.

Due to a condition set by EASA, that engine susceptibilities based on concentrations above 4 mg/m^3 must be backed up with an engine test, Rolls-Royce has elected not to declare an acceptable dose above 4 mg/m^3 . However, there is increasing evidence that an operationally useful dose exists at ash concentrations greater than 4 mg/m^3 , even if it is slightly less than 14.4 g s/m^3 . At the time of writing, negotiations with regulators and operators are ongoing to explore the need for and ways to clear acceptable exposure doses at concentrations above 4 mg/m^3 .

Rolls-Royce is in the progress of rolling out the above approach across the rest of its engine types. Discussions have also taken place between Rolls-Royce and the other OEMs over whether the Rolls-Royce intellectual property (IP) used to underwrite their approach could be licensed to other OEMs; in principle Rolls-Royce is willing to give the other OEMs access to the IP.

Figure 8, Figure 9, Figure 10, and Figure 11 show the Rolls-Royce Duration of Exposure versus Ash Concentration (DEvAC) chart, with different features emphasized. Figure 8 for example emphasizes various exposure events and the estimated concentrations and durations of exposure. Figure 9 illustrates regions of

the chart where an exposure could lead to engine related flight safety implications. Figure 10 illustrates regions indicating where long term or exigent economic damage is likely to occur. Figure 11 illustrates acceptable operational envelopes for Rolls-Royce RB211 and Trent engine types.

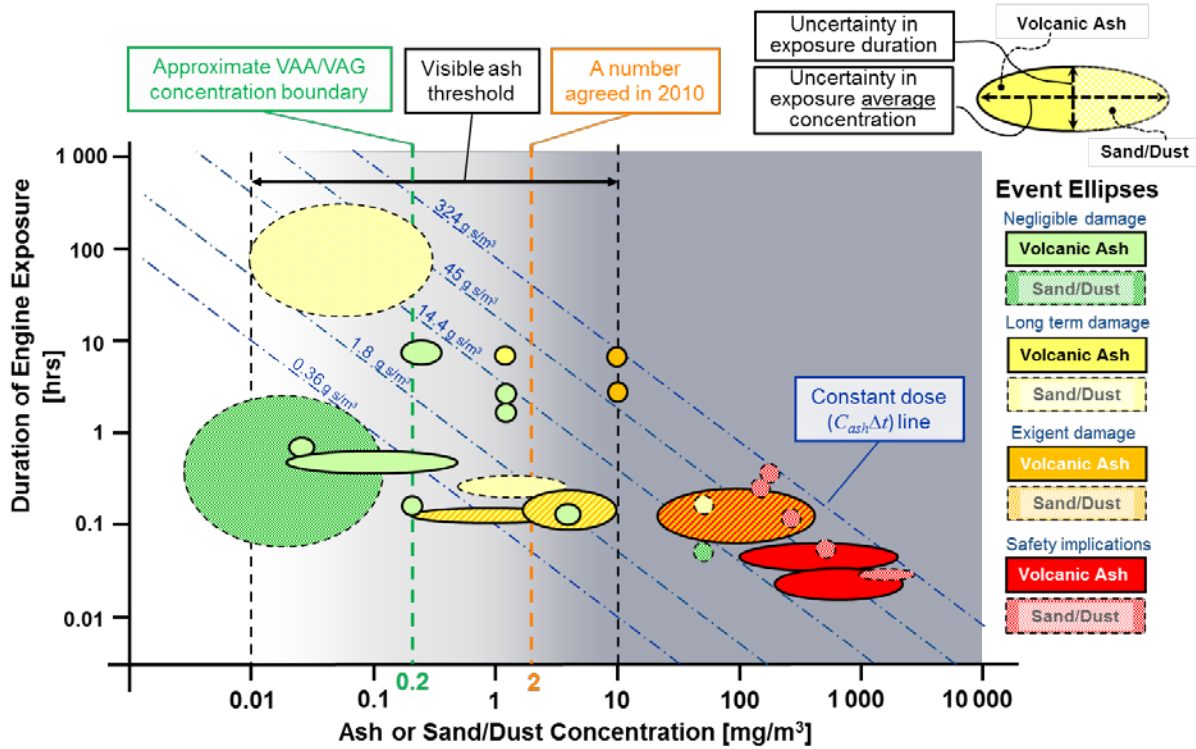


Figure 8. Rolls-Royce Duration of Exposure versus Ash Concentration (DEvAC) chart. Various engine exposure events are plotted, covering a range of engine types, ash (and relevant sand/dust) types, flight phases, etc. The uncertainties in the exposure average concentrations and durations are illustrated using ellipses (see key at top right). The different ellipse colors represent different exposure outcomes, noting that a hatched ellipse indicates some uncertainty over the level of damage. The blue diagonal broken lines on the chart are lines of constant exposure dose, expressed as the product of the concentration and the duration. The background shading on the chart illustrates where ash clouds are generally not visible (white), increasingly visible (increasing grey shading) and always visible (dark grey) in good ambient light.

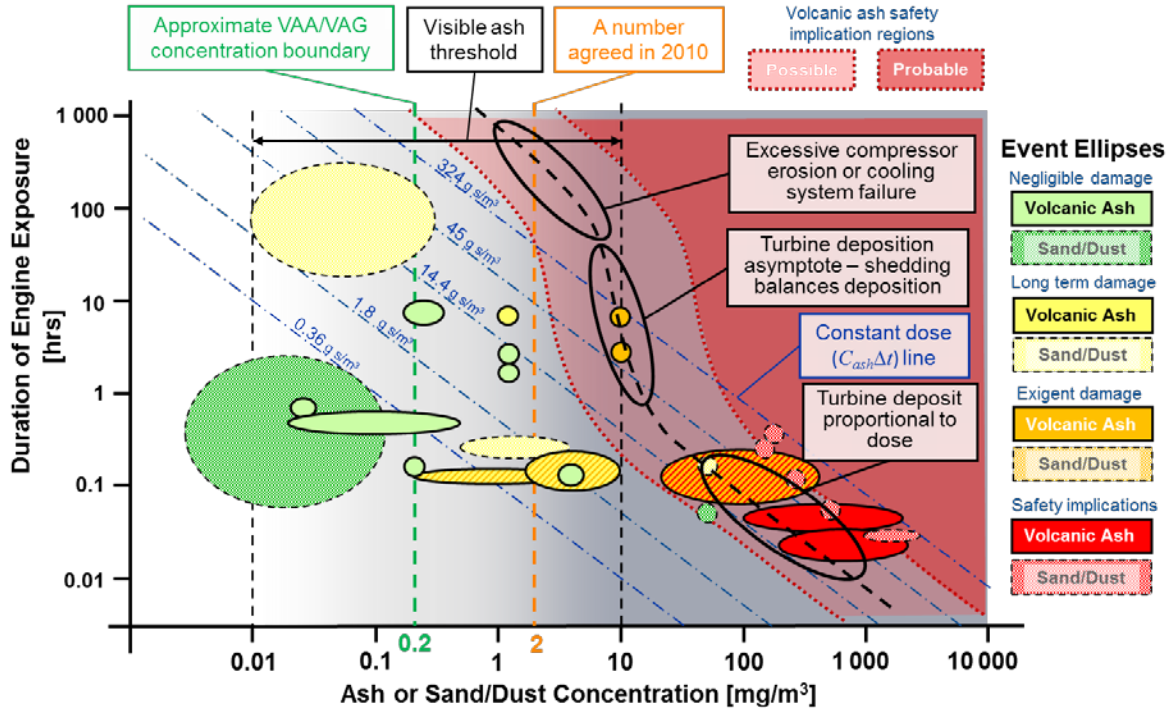


Figure 9. The DEvAC chart from Figure 8 with the regions of the chart (red and pink) where an exposure could lead to engine related flight safety implications. The lower dose boundary of the red and pink regions – a reverse ‘S’ shape – are based on the engine exposure events plotted and a mathematical model which calculates the reduction in core compressor surge margin, the most vulnerable system in an engine. Also shown are indications of the physical effects driving the three sections of the reverse ‘S’ boundary.

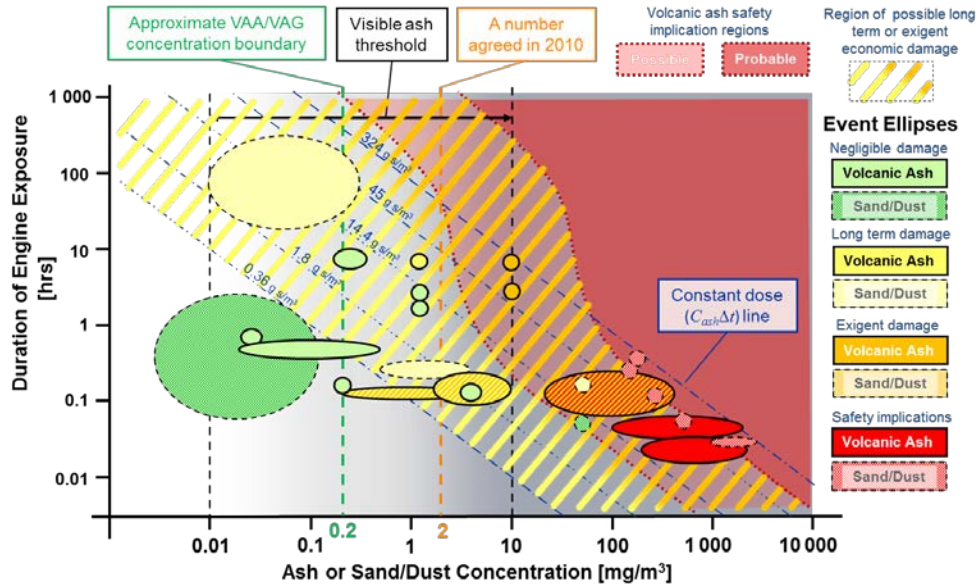


Figure 10. The DEvAC chart from Figure 9 with a hatched region added to indicate where long term or more pressing – exigent – economic damage is likely to occur; such damage does not have immediate flight safety implications.

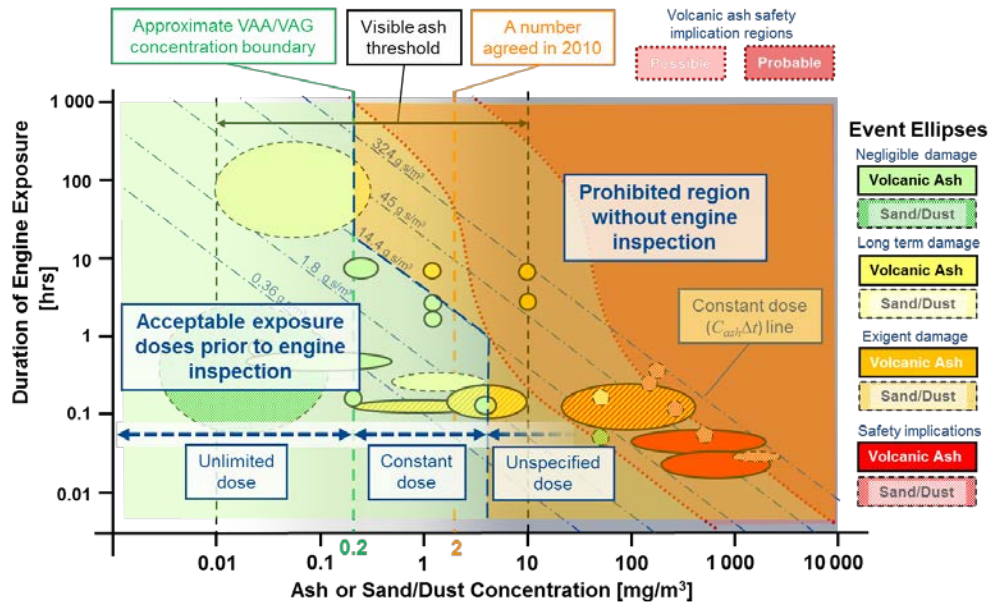


Figure 11. The DEvAC chart from Figure 9 with the acceptable operational envelopes for Rolls-Royce RB211 and Trent engine types added. In addition to the acceptable exposure dose envelope, three concentration ranges are highlighted; $< 0.2 \text{ mg/m}^3$, where there is no limit on exposure dose with regard to deterioration in safety margins (noting that there is still the potential for economic damage to engines); 0.2 mg/m^3 to 4 mg/m^3 , where a constant exposure dose is appropriate; $> 4 \text{ mg/m}^3$, where the acceptable exposure dose is unspecified, due a regulator's current position on engine testing.

5. Discussion and Conclusions

Since the conclusion of the IVATF in 2012, continued intense research has produced new instruments and techniques to measure and forecast the height, mass load, speed, and trajectories of ash clouds. And research by at least one OEM has provided better constraints on how much ash certain jet engines can tolerate. Validation data to measure this progress is rare, and it is important to continue to investigate every significant eruption and incident. New and improved tools will continue to transition into operations to be used and weighted accordingly within an expert analysis and forecasting process.

New monitoring techniques bring promise for improved quantitative information, but there is a global disparity in the availability of equipment. Financial, accessibility and safety issues all impact the ability of volcano observatories to monitor their volcanoes. This presents a quandary for the global use of contamination forecasts. Maintaining the current approach to volcanic-ash forecasting means ignoring the valuable quantitative information that is already available. Conversely, requiring all forecasts to be quantitative will introduce huge challenges and uncertainty for poorly monitored volcanoes. Future advisory system design will need to account for this by allowing for the expression of uncertainty within the warning framework, whilst we continue to work on the global implementation of IVATF arrangements and address the scientific challenges.

Contoured concentration maps have the potential to provide useful guidance on the relative hazards to aircraft and on regions of sharp gradients in concentration, however the magnitude of the contours depicted should be appropriate to the data available. As already noted during the IVATF discussions, given the uncertainties and limitations addressed here, particularly in defining the MER, the distinction between 2 and 4 mg/m³ as used in the European products is not appropriate and meaningful. Rather, an order of magnitude scale, for example 0.2, 2 and 20 mg/m³ would provide a more illustrative depiction of the relative hazard.

If one considers a dose-based threshold, the calculation of dose requires high-resolution 4-D model output of ash concentration, combined with flight-routing software. These data sets can only be produced by models and human forecaster intervention will be difficult. With uncertainties in both the modelled cloud and the flight track, a probabilistic approach may be required.

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