Ongoing Efforts to Make Ash-Cloud Model Forecasts More Accurate

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ABSTRACT

The 2010 eruption of Eyjafjallajökull volcano in Iceland changed the rules for air travel in Europe and introduced the use of restricted fly zones based on ash-cloud concentrations calculated by dispersion models. This change prompted a sustained effort to improve the accuracy of ash-cloud model forecasts. In this paper we describe how this goal is being advanced on three fronts: (1) assessing current capabilities and establishing best practices; (2) improving the accuracy of model inputs; and (3) developing strategies to automatically compare model output with observations and adjust inputs to produce the best match. 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 will have to be made in tandem with new technologies to observe and measure.

1.0 INTRODUCTION

In the modern era of air travel, the hazards of volcanic ash to aviation are well known. Some key events that illustrate the hazard involved military operations. In March 1944 for example, eruption of Mount Vesuvius disrupted the Allied campaign on the Apennine Peninsula during World War II and damaged dozens of aircraft on the ground. On March 25, 1980, a Lockheed L100 Hercules suffered the first documented incident of in-flight engine damage when entering an ash cloud from Mount St. Helens [1]. In the Philippines, U.S. Military aircraft in the air and on the ground were heavily impacted by the June 15, 1991 eruption of Pinatubo [2].

Institutional steps to mitigate the risk to aviation from volcanic-ash clouds followed well-documented encounters in the 1980s [3, 4]. By 1997, ICAO had established nine Volcanic Ash Advisory Centers (VAACs) to detect, track, and forecast ash-cloud hazards in their geographic regions [5]. The most widely used formal product of VAACs is the Volcanic Ash Advisory.

Atmospheric dispersion models are an essential tool in forecasting ash-cloud movement. Originating from relatively simple tools that used wind soundings to calculate the movement of radionuclide clouds or smoke plumes [6, 7], dispersion models now use 3-D wind and other meteorology from advanced, high-resolution, numerical weather prediction models (NWPs). Many dispersion models exist, but only a handful are used operationally by VAACs to forecast ash-cloud movement (Table 1).

Table 1-1: List of atmospheric dispersion models used operationally by Volcanic Ash Advisory Centers

Model	VAACs that use it
Hysplit [6]	Washington, Anchorage, Wellington, Darwin
NAME III [7]	London
Fall3d [8]	Buenos Aires
MLDP0 [9]	Montreal
Mocage Accident [10]	Toulouse
JMA-GATM [11]	Tokyo

Limits in model accuracy reflect both limitations in accuracy of the NWPs and in model input parameters related to the eruptive source of ash plumes (such as plume height, eruption start time, duration, erupted mass, grain-size distribution, etc.). VAACs for example issue official Volcanic Ash Advisories only 18-24 hours into the future due to concerns that more distant future times could not be accurately forecast.

The primary limits to model accuracy are the eruption source parameters (ESPs). Starting in 2006, VAACs [5] led a multidisciplinary effort to improve methods of estimating ESPs [12]. This included an effort to assign ESPs to each of the world's volcanoes based on past behavior, that could be used to initialize runs quickly [13] in cases where no observations are available.

The 2010 eruption of Eyjafjallajökull Volcano, Iceland, focused attention on the accuracy of ash-cloud models. Billions of dollars of economic loss resulted from extensive airspace closures that were based on VAAC Advisories derived from modelling that predicted ash clouds covering most of Europe between April 16 and 19 [14]. Throughout most of this region, no ash clouds were visible. To end the widespread travel disruption, European regulators changed long-standing protocols and allowed flights through "dilute" ash. They also required that Volcanic Ash Advisories produce model-derived maps of ash-cloud concentration. Regions bounded by concentrations of 0.2, 2, and 4 mg m^{-3} would be subject to different flight restrictions [14]. The new requirement raised questions such as "how accurately can models forecast ash-cloud concentration", "how accurately can concentration be measured in a cloud", and even "can a cloud with 0.2, 2, or 4 mg/m^3 ash concentration be seen, by eye or by instruments?" Modelling specialists strongly recommended against the use of direct model output for air-traffic management decisions [15], and ICAO, the United Nations governing organization that writes the rules for flight, chose not to adopt this procedure outside Europe [16]. But it remains in effect in Europe. In the scientific community, the Eyjafjallajökull experience focused efforts to more systematically test and improve model accuracy.

These efforts have been pursued on three fronts: (1) by assessing modelling capabilities through inter-comparison, validation, and establishment of "best practice" standards; (2) through use of more accurate ESPs; and (3) through modelling strategies that automatically compare model results with real-time measurements, then adjust model input to optimize the agreement. Below we briefly discuss each of these.

2.0 Assessing modelling capabilities

Much of the framework for improving model accuracy took form in meetings that followed the Eyjafjallajökull crisis. Weeks before the crisis began, representatives at the World Meteorological Organization's (WMO's) 5th International Volcanic Ash Workshop recommended formation of a Volcanic Ash Scientific Advisory Group (VASAG), sponsored by WMO, to advise ICAO and the aviation community on the science of characterizing ash-cloud hazards [14]. Following the Eyjafjallajökull crisis, ICAO assembled an International Volcanic Ash Task Force (IVATF) to review procedures for avoiding ash clouds.

The IVATF was large (~100 members), multi-disciplinary, and temporary, holding four meetings between 2010 and 2012. It included representatives from VAACs, engine and airframe manufacturers, regulatory agencies, airline associations, pilots, dispatchers, air traffic controllers, and certain science and meteorological organizations. The IVATF considered topics including airworthiness effects, prioritizing volcanoes by risk, health effects to passengers, and model improvements.

By contrast, the WMO VASAG is small (about a dozen prominent scientists) and permanent. From 2010 to 2012, the VASAG played a critical role with the IVATF. 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 referred as written recommendations to the VASAG, which addressed them in IVATF Working Papers written by leading scientists. These documents identified critical weaknesses as well as future directions for research.

The crisis also prompted a WMO-sponsored workshop to compare the world's most widely used ash-cloud models [17]. Participants used 12 separate models to calculate ash-cloud evolution and properties using identical inputs, based on the February 2000 eruption of Hekla, Iceland [18]. The exercise showed that previously overlooked inputs, like vertical distribution of mass in the column, can account for differences in model output. A follow-up meeting in 2013 documented progress and identified best practices for operational use of dispersion models [19].

Best Practices became a new focal point. Could crises be less disruptive if forecasters were better trained? Could lessons learned by one VAAC be transferred to others? Such questions were raised in VAAC best practices meetings, held regularly since 2010. In 2012, a WMO "inputs and outputs" workshop considered best practices for VAAC ash-cloud models [20]. Participants ranked our level of knowledge of inputs such as plume height (4 on a scale of 1 to 5), mass eruption rate (2), particle-size distribution (2), vertical distribution of mass (2), and particle density (5). A priority was set on developing a database of well-documented eruptions that could be used to validate models.

Data for model validation has been challenging to acquire. Prior to 2010, studies compared model results primarily with the outline of ash clouds [21-25]. The new European requirement for concentration charts spurred an effort to compare modeled quantities with measured values, such as concentration from airborne in-situ measurements, or column mass load (g m^{-2}) from a satellite image [26-30]. Many such data were acquired during the Eyjafjallajökull eruption [31, 32]. Data of this quality are scarce for other eruptions.

3.0 Improving source parameters

Among source parameters, the eruption start time, plume height, and duration come from observations. Others must be inferred based on knowledge of similar events. Below, we describe progress in each of these.

3.1 More and better observations

Rapid eruption detection facilitates timely and accurate model forecasts. Countries with financial means install seismic networks around restless volcanoes, especially those near population centers, to ensure timely warnings of activity. However most of the world's volcanoes are not monitored seismically even though they threaten aviation routes. Eruptions at those volcanoes historically have been detected by periodic checking of satellite images by VAACs, or from pilot reports. Some remote eruptions have been detected hours after they start [33]. New technologies have helped reduce this time. Alert systems now automatically warn of possible eruptions through anomalous SO_2 [34] or satellite objects with characteristics of ash clouds [34-36]. Global networks send automatic warnings of anomalous lightning near volcanoes [37] (Fig. 1-1), and regional infrasound arrays detect remote atmospheric disturbances [38]. Well-placed webcams [39, 40], and images spread through social media [41] are also helping detect or characterize volcanic plumes. And VAACs and volcano observatories are developing computer tools like the Alaska Volcano Observatory's VolcView (https://volcview.usgs.gov), to speed ash-cloud detection and analysis.

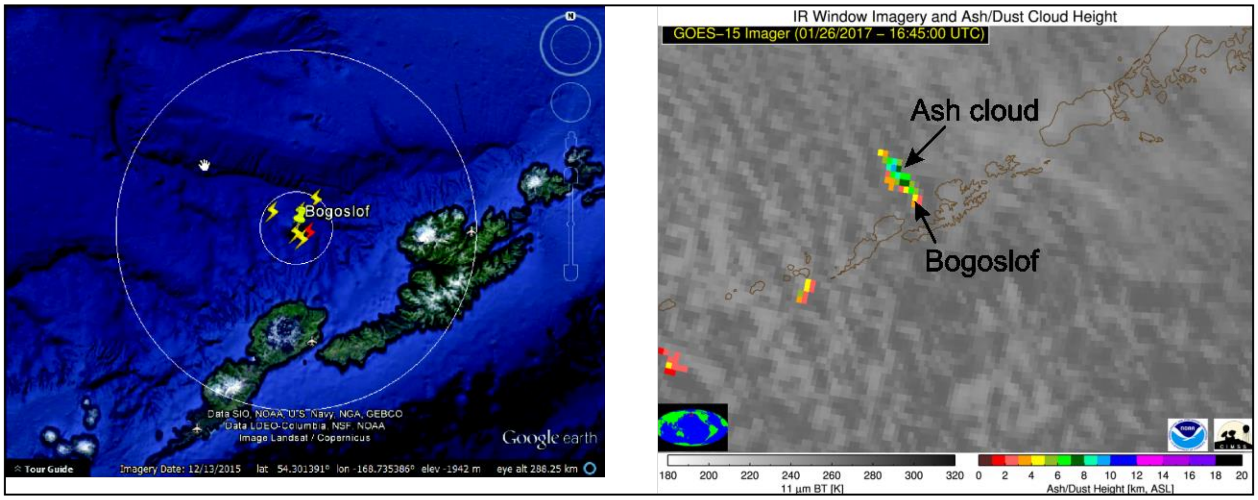

Figure 1-1: (left) Google Earth screenshot showing lightning flashes (yellow and red bolts) detected during an eruption by the Worldwide Lightning Location Network (WWLN) [37] at Bogoslof Volcano, Aleutian Islands, January 26, 2016, 1551-1613UTC. (right) NOAA GOES-15 Imager view of the ash-cloud height from this eruption (bright colors). This eruption was detected by lightning and infrasound, both of which were unavailable in the North Pacific several years ago.

In recent years, our ability to constrain plume height has also improved through greater use of space-based Lidar [42] and mobile radar systems [43].

3.2 Constraining non-observable parameters

Grain-size distribution, vertical distribution of mass in the column, and mass eruption rate must be assigned from knowledge of similar eruptions. Improvements in our understanding of them has been variable.

The first of these, grain-size distribution, is a subset of the factors that control rate of settling and deposition. Other factors include particle shape, density, and, most importantly, the aggregation (clumping) of fine ash as the cloud disperses. The physics of aggregation are not well understood and thus are not included in operational models except by adjusting the input grain-size or fall velocity to accelerate deposition. Short-term progress has been made by systematic testing of adjustment schemes [44], finding for example that the same scheme can match observations for a surprisingly large range of eruption types. Recent, innovative experiments [45, 46] and field observations [47] highlight water-ash interactions that may eventually be coded into improved models.

The vertical distribution of mass in the plume is neglected in most source parameter discussions [12, 17], and there is no conventional way to assign it. Some operational VAAC models use a uniform line source [20], others use a Gaussian or Suzuki [48] distribution [20]. Visual observations (Fig. 1-2) suggest that the distribution could vary significantly between eruptions, and model sensitivity studies [23] show it can strongly affect results, especially when wind shear is present. Model inversions from Eyjafjallajökull [30] suggest a concentration of mass toward the top of the column. In larger eruptions, for example at Pinatubo in 1991 [49], ash in the overshooting top was known to collapse into the main umbrella cloud at heights 25-45% below the plume top. But quantifying the distribution based on such observations has been a challenge.

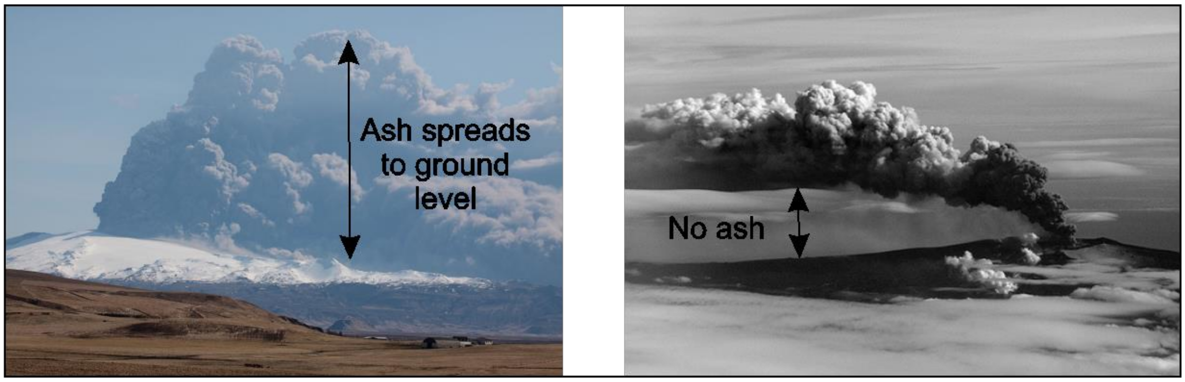

Figure 1-2: Photos of the Eyjafjallajökull plume, taken on different days, illustrating different distributions of ash with vertical elevation in the downwind direction. Photo at left taken April 17, 2010 by Henrik Thorburn (Wikimedia Commons photo). Photo at right taken by Thorstein Jonsson, Icelandic Meteorological Office, May 4, 2010.

3.2.1 Mass Eruption Rate

Mass eruption rate (M) has received wide attention due to its effect on ash-cloud concentration. M is generally inferred from plume height (H) above the vent. Theory [50] suggests that $H \propto M^{1/4}$, and this quarter-root proportionality is borne out by correlations [12, 51, 52] using data from historical eruptions in which plume height and duration were well observed and where deposits were mapped in detail to obtain erupted mass. The most widely used empirical correlation [12] for example gives $H=0.007*M^{0.241}$, where H is in km and M is in kg s^{-1}. But there is much scatter in the data. The correlation has a standard error in M of about a half a log unit [53], which translates into an uncertainty of nearly an order of magnitude in modeled ash-cloud concentration.

The high standard error results from both inaccurate measurements of H and M, as well as atmospheric conditions like wind or humidity which can raise or lower *H* for a given *M* [54] [55]. Plume-height accuracy may gradually improve, but *M* 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 [56, 57], but they do not substitute for better data. And data points come only once every few years, when a new eruption spreads ash over dry, accessible land masses where ready, well-trained geologists can quickly sample it. Significant improvements to the dataset could therefore take decades.

By contrast, tools that consider atmospheric effects have proliferated. Since 2010, new analytical equations that consider wind and atmospheric stability can now relate *M* and *H* [58-60]. Nearly a dozen one-dimensional plume models are now available that calculate effects of wind and moisture on the rising plume [54] [55]. Some are used operationally, to derive *M* during eruptions [61].

In 2016, Costa et al. [62] compared the performance of nine 1-D models in calculating plume height for a given *M*, or vice versa. Given the same *M* for a weak plume under windy conditions, all 1-D models calculated the same *H* to within +/-10%. But given *H* for the same weak, windy plume and asked to calculate *M*, these same models ranged over 1.4 orders of magnitude. This reflects the high sensitivity of *M* to *H*, as well as different assumptions and parameter values set in each model. Except for one study [53], these models have not been validated by comparing them with observations of real eruptive plumes. The limited accuracy of *H* and *M* measured from real eruptions make such validations a challenge.

For large eruptions (Volcanic Explosivity Index>=4), we have made much progress estimating *M* through the growth of umbrella clouds. These clouds form a circular shape in satellite images, unlike the fan shape of downwind-spreading clouds from small eruptions. Modern geostationary satellites with rapid repeat times show these clouds growing in near-real time. By comparing their growth rate with theoretical predictions [51, 63], the *M* of several large, recent eruptions has been estimated [41, 64].

4.0 Adjusting the model to the observations

Several groups are experimenting with strategies that incorporate observations to automatically improve model accuracy. One involves initiating a simulation based on the location and height of a cloud in a satellite retrieval [65]. Another uses a Bayesian inversion scheme that compares model calculations with satellite retrievals to obtain a best-fit time series of source strengths at various heights above the vent [26, 30]. A third involves initiating an ensemble of runs, then automatically comparing results to a satellite retrieval, and dismissing or down-weighting those with a poor match [66, 67] (Fig. 1-3).

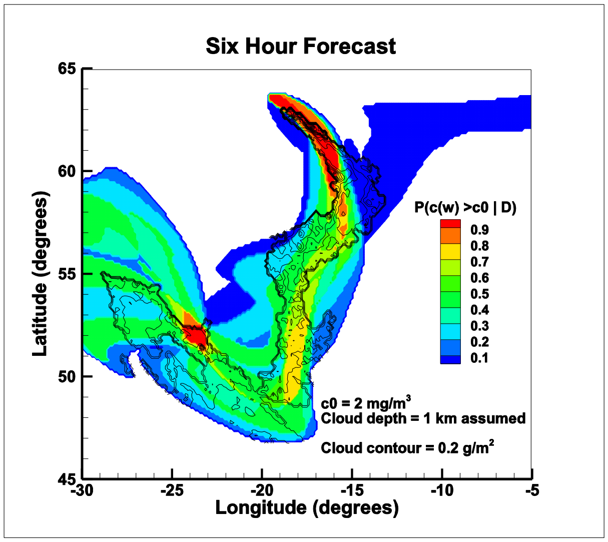

Figure 1-3: Posterior probability P that forecast ash concentrations (c) will exceed the threshold of c_0, which here is 2 mg m^{-3}. Posterior probability distribution is determined by how well the modeled ash distribution matches the actual ash distribution observed by satellites. The comparison is done once a cloud has developed at some later time after the onset of an eruption column. The observations of the ash cloud at this target time are used to build the posterior distribution. The forecast in this figure is 6 hours after that target time. The method is described in Denlinger et al. [66]. Details on the satellite retrieval methodology and comparison are provided in that paper.

The satellite retrievals used for comparison are generally maps of ash column mass load derived from 2- or 3-channel infrared (IR) geostationary satellites [68-70].

Strategies like these may be the key to improving ash-cloud model forecasts. But many hurdles presently block their implementation. One is that few VAACs have the modelling expertise to operationalize them. A second is that they require retrievals from 3-channel IR geostationary satellites with low latency and high frame rates. Such data are not available in many parts of the world, and (or) cannot be processed by some VAACs. A third is that real-world complications, such as the presence of meteorological clouds obscuring the ash, have not been fully worked through.

5.0 Discussion and Conclusions

A concerted effort to improve the accuracy of ash-cloud model forecasts has been made by the modelling community since 2010. After several years of intense research, model comparisons, reviews of procedures, and prioritizing, we have a better understanding of what's necessary to move forward. Improving model accuracy requires the collection of reliable data against which to compare models. Such data are frequently elusive, making progress hard to measure. Thus for the foreseeable future, model results will continue to be a tool, whose utility will be judged in each case by the final arbiter, a trained human forecaster.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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