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Comparison of VAAC atmospheric dispersion models using the 1 November 2004 Grimsvötn eruption

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ABSTRACT: The robustness of the Numerical Atmospheric-dispersion Modelling Environment (NAME) for forecasting the dispersion of volcanic ash clouds is investigated by comparing the output from different Volcanic Ash Advisory Centre (VAAC) models initialised using the parameters for the 2004 Grimsvötn, Iceland, volcanic eruption. London, Darwin, Washington, Montreal and Toulouse VAAC dispersion models are all run operationally as if responding to the eruption. Comparison of the model set-ups reveals differing approaches between the VAACs for model averaging times, ash release rates, and thresholds for defining the ash cloud, amongst others. The importance of these factors is considered in detail. Despite using different weather conditions and having different structures, the models all demonstrate strong similarities for forecasting regional ash cloud transport. The dispersal of volcanic ash is simulated over Scandinavia and as far as Eastern Europe in all cases. Greater variations are seen between the forecast ash concentrations for different aircraft flight levels. The model forecasts are highly dependent on the amount of eruption information available at the time.

KEY WORDS dispersion modelling; volcanic ash; model comparison; volcano; forecasting

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1. Introduction

Grimsvötn volcano, Iceland, erupted on 1 November 2004. During the eruption, London Volcanic Ash Advisory Centre (VAAC) forecasters issued volcanic ash advisory statements using information supplied by the Icelandic Meteorological Office and output from the UK Met Office's Numerical Atmospheric-dispersion Modelling Environment (NAME). These statements led to the diversion of aircraft flight paths and the grounding of some aircraft in Europe, with consequent economic losses. Lack of good satellite data during the eruption hindered real-time verification of model outputs and, following the eruption, prompted discussion of the accuracy of the forecast.

NAME (Ryall and Maryon, 1998) and other aviation-safety ash models such as PUFF (Searcy *et al.*, 1998), HYSPLIT (Draxler and Hess, 1998), MEDIA (Sandu *et al.*, 2003), CANERM (D'Amours, 1998) and VAFTAD (Heffter, 1996) are vital in efforts to prevent aircraft flying into ash plumes with potentially catastrophic results (e.g. Miller and Casadevall, 2000). Validation of individual models requires good observational data for multiple eruptions, but these data can be scarce, particularly given the low frequency of volcanic eruptions. The unique nature of different eruptions also introduces complications in assessing the capabilities and weaknesses of individual models. Where observational data are unavailable, comparison of forecasts from multiple models provides an alternative approach for validation.

To investigate the validity of the NAME Grimsvötn forecast, a comparison of the output from other VAAC models was conducted based on the eruption parameters supplied to the London VAAC at the time of the eruption. The participant VAACs were London, Darwin, Washington, Montreal and Toulouse. The models used by each VAAC are summarised in Table I. Models were run as if responding to the eruption operationally. The information received by London for the Grimsvötn eruption was provided to each VAAC, but the model set-up was left as it would be if the request were real. To help understand the differences in the model outputs, details of the models, including how the volcanic ash concentration thresholds were defined, met data provenance and resolution (spatial and temporal), output resolution and source-term definitions, were requested.

The aim of this comparison was to test whether volcanic ash forecasts similar to those issued at the time would have been made by other VAACs during the Grimsvötn eruption. The long-term goal is to improve and potentially standardise the parameters and thresholds

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Table I. Summary of the different VAAC models used in the comparison.

VAAC	Model	Model type	Default ash release rate per eruption source	Output average time
London	NAME	Lagrangian	0.16667 g h^{-1} (equivalent to 1 g/6 h)	6-h (re-run with 1 h in this comparison)
Toulouse	MEDIA	Eulerian	1.0×10^{10} g h^{-1}	Instantaneous at the forecast time
Montreal	CANERM	Eulerian	Determined here from a total ash emission of 3.9172×10^{13} g	1-h
Washington	HYSPLIT	Lagrangian	Unit mass	1-h (6-h used for this comparison)
Darwin	HYSPLIT	Lagrangian	Unit mass per hour	Instantaneous at the forecast time (6-h used for this comparison)

used by all the VAAC models by promoting discussion of the modelling approaches used by the different VAACs.

1.1. The Grimsvötn eruption

At approximately 2250 UTC on 1 November 2004, Grimsvötn volcano, Iceland, erupted through the Vatnajokull ice cap, forming an eruption column up to 12–14 km. This vigorous stage of the eruption continued until the morning of 3 November, during which time a continuous plume rose to an elevation of about 9 km (Sigmundsson *et al*., 2004a). All of the erupted magma fragmented into tephra (volcanic ejecta) that accumulated at the eruptive site or was carried by the eruption plume (Sigmundsson *et al*., 2004b). Strong southerly winds meant that deposition of tephra was restricted to north-northeast of the vent.

On 3 November, the eruption column was replaced by a low-intensity phase of activity that continued until the evening of 4 November 2004. By 4 November, the eruption plume was greatly reduced, consisting mostly of steam, although intermittent explosions were observed, sending jets of ash and fragmented ice about 1 km above the crater. The corresponding eruption plume rose to a height of 2–4 km (Sigmundsson *et al*., 2004a).

The interaction of water with magma in this type of eruption (known as a *phreatomagmatic eruption*) results in much finer-grained tephra than other explosive eruptions (Morrissey *et al*., 2000). This has implications for ash dispersion, remote ash detection and the hazard to aviation. During this eruption, ash drifted over large parts of the North Atlantic and reached Scandinavia and an area of 311 000 km^2 was closed to aviation until the morning of 4 November, causing disruption to air traffic (Sigmundsson *et al*., 2004a).

Satellite images of the eruption plume were few because detection of plume constituents was limited by the large amount of cloud overlying the area. This lack of data hindered real-time evaluation of the model output. During the eruption, information on eruption plume heights was available from ground-based radar data from Iceland and pilot observations. Later in the eruption, information was also available from observers on the ground. Radar data (Figure 1) show that the maximum height of the plume top during the vigorous phase was 13–14 km asl, although at this altitude and range from the radar station the estimation in height can vary as much as 1–2 km (S. Karlsdöttir pers. comm.). The signal detected by the radar is a combination of the backscatter from all particles in the plume (including hydrometeors, ash and ash encased in ice/snow). Different combinations of particles can give the same signal, so the exact composition of the plume is difficult to ascertain and estimation of ash-particle size by radar measurements is very difficult (Lacasse *et al*., 2004). Additionally, radar systems generally detect larger ash particles than those modelled, so the data does not directly reflect the modelled particle sizes.

The only satellite data that appear to show long-range transport of the Grimsvötn plume come from the SCanning Imaging Absorption spectroMeter for Atmospheric ChartograpHY (SCIAMACHY) sensor on the ESA Envisat satellite. Using this data, a group working on the TEMIS project have tracked what they assume to be sulphur dioxide (SO_2) erupted by Grimsvötn over northern Europe and then Russia (images and explanation are available on the TEMIS Volcanic SO_2 Service website www.temis.nl/aviation/so2.php). Separation of volcanic SO_2 plumes and ash plumes may occur, but it is not known whether this occurred during this eruption. Encouragingly for the model, the dispersion of the SO_2

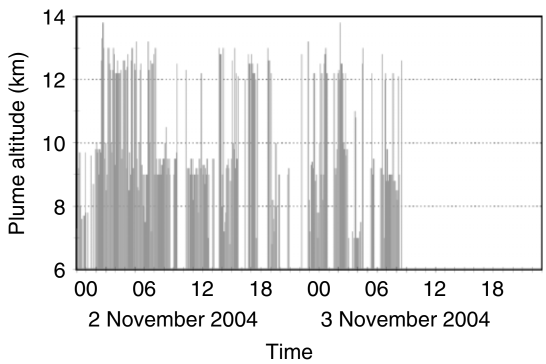

Figure 1. The altitude (in km) of the Grimsvötn eruption plume, was monitored at approximately 5-min intervals by the C-band weather radar in Iceland, located 260 km from Grimsvötn. Owing to the distance between the radar station and the eruption site, the variation in the height measurements can be 1–2 km. (Data courtesy of the Icelandic Meteorological Office).

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anomaly corresponds to the original NAME prediction for the Grimsvötn ash cloud (see Section 4).

Similar eruptions have occurred at Grimsvötn in 1983 and 1998. These eruptions, together with the 1996 Gjalp eruption north of Grimsvötn, reveal much higher activity at Grimsvötn in the last 25 years than during the middle of the twentieth century, and may indicate that the volcano is entering into a new period of high volcanic activity that could last for decades (Sigmundsson *et al.*, 2004a). Improving forecasting skill for ash plumes from Grimsvötn should therefore be a priority for the London VAAC.

2. Comparison of models

Langragian and Eulerian dispersion models were used in the comparison (Table I). Each had different treatments of dispersion, turbulence, deposition and convective mixing. An evaluation of all the differences is beyond the scope of this paper, but the models have been compared and described previously as part of the ETEX tracer experiment (Bompay, 1998; D'Amours, 1998; Ryall and Maryon, 1998; Sandu *et al.*, 2003). These differences between the models will be responsible for some variation in the models' outputs. In addition to this range of dispersion characteristics, there are many differences in the way the models are run for VAAC purposes and in the parameters that are used to initiate them. The most important of these, for ash forecasting, are the source release rates and the method for determining the boundary of the ash cloud from the modelled concentrations. The definitions of these parameters and their differences across the models are considered next.

2.1. Source definition

The location of the eruptive vent and the emission height-range are essential parameters for initiating any model in a volcanic emergency application. For Grimsvötn, the coordinates of the location where the eruptive column broke through the glacier were reported by the Icelandic Meteorological Office to the London VAAC. The lateral extent of the source is often unknown at the start of an eruption and depends on the style of eruption. The dimensions of the source may also change during the course of the eruption; this was the case at Grimsvötn, where the erupting source varied between a fissure and single vent. The spatial dimensions used for an eruption are, consequently, often a default value set by the VAAC. For example, Washington uses a vertical line source extending from the volcano summit to the top of the eruption column. London uses a similar definition in operational runs, but for this study, a 1×1 km area source was used. (Comparison work has shown that in this case, there was little difference between results from area- and line-source set-up options.) The Darwin model is initiated over a slightly larger scale, with the source defined as a cylinder with a fixed radius of 10 km. The Eulerian models are more rigid in their source definition and require emissions to be released over whole grid boxes. Toulouse uses an even release over a source definition of four grid points surrounding the volcano (equivalent to an area of 1.5° latitude ×1.5° longitude). In contrast to the other VAACs' spatially uniform releases, the horizontal distribution of the ash at the source in Montreal's model is defined by a Gaussian distribution with a standard deviation (SD) of one grid point. In a Gaussian distribution, 68% of the values are within one SD of the mean, 95% are within two SDs and about 99.7% lie within three SDs. Hence, in the Montreal approach, 68% of the mass is erupted within a circle of one grid point, 95% within two grid points, and so on. The grid is the same as that used for the output (in this case 50 km). Owing to the Gaussian distribution, a run at a higher grid resolution (e.g. 25 km) will produce an initially smaller plume at the source and a correspondingly thinner dispersion plume.

At present, no VAAC models simulate the initial eruptive phases of volcanic plume formation nor do they contain eruptive momentum or appropriate buoyancy equations. Consequently, the upper release height for ash must be set to the maximum plume height as determined from observation, satellite data or other modelling. Information on the height of the lower plume boundary is often even more scarce than that for the plume top and, as a result, the minimum height for the release is usually taken to be the surface elevation of the volcanic vent. All of the participant VAACs use a constant vertical distribution of ash from the volcano summit to the plume top as default, but from understanding of eruption momentum, dynamics (e.g. Sparks *et al.*, 1997) and observations, it is unlikely that much of the ash mass would be entrained at the lower height levels. This may cause over-predictions of ash concentrations in lower flight levels. Fallout of ash particles larger than those modelled from higher levels could, however, still make these levels as unsafe for aviation.

2.2. Release rates

The amount of ash that should be modelled, per source, for a given interval is not specified by the International Civil Aviation Organization (ICAO) and, in reality, will vary according to the specific eruption. This has resulted in very different values being used by the VAACs (Table I). Some VAACs have a fixed release rate for all eruptions (e.g. London, Washington), while others (e.g. Montreal) have a variable rate determined from the eruption magnitude.

The London release rate of 0.463×10^{-4} g s^{-1} is derived from a release of 1 g per 6 h. This rate is based on the relationship between London's ash-threshold definition (defined relative to a 1 g release, see Section 2.7) and their averaging period (6 h). The Montreal release rate is based on an estimation of the total erupted mass and the duration of release. The default erupted mass

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(1×10^{12} g) is based on the eruptions of Mount Spurr (Keith, 1995). This default is equivalent to only 10% of the total ejected mass in order to represent just the small particles that would remain in the atmosphere. Various options are available to define the 'shape' of the temporal release curve (e.g. Gaussian, constant, empirical), but a constant release is used as default. Uncertainties in the source term and the mass removal can be compensated for by adjusting the threshold values used to display the ash cloud on the maps (see Section 2.7). If more data become available during the course of the eruption, then the Montreal VAAC initiates a new run based on new estimates of mass. In this comparison, the Montreal release rate was calculated from the Sparks *et al.* (1997) equation for Plinian eruption columns (see Section 5) using the eruption duration and maximum plume height as parameters.

2.3. Meteorological data

In addition to the differences between the designs of the VAAC models, the meteorology used for each is different. For this study, the London model was run on 3-hourly reanalysis meteorology from the UK Met Office Unified Model Version 6 (Cullen, 1993) on a 0.55° latitude by 0.83° longitude grid. The Darwin model used analyses met data from the BMRC GASP model (Seaman *et al.*, 1995) with a temporal resolution of 6 h and a spatial resolution of 2.5°. The Montreal model used diagnostic data from the Meteorological Service of Canada Global Environmental Model on a 100-km resolution grid. The Washington model used 3-hourly archived met data from the NCEP Global Data Assimilation System (GDAS) on a 1° latitude–longitude grid and Toulouse used 6-hourly met data from the numerical weather prediction model ARPEGE of Meteo France on a 1.5° latitude–longitude grid.

2.4. Time average of results

The ICAO standard for VAACs is for updated advisory information to be issued at least every 6 h following the first observation of the ash cloud until such a time that no further reports or data on ash in the area are received (Annex 3–Meteorological Services for International Air Navigation). For each advisory, the height and position of the ash cloud should be given for the advisory time, together with forecasts for +6, +12 and +18 h. There is no time-averaging period specified for any model output that is used to conform to this standard. The current averaging periods used by the participating VAACs are outlined in Table I.

The current London default model time-average is 6 h and output is produced for 0000, 0600, 1200 and 1800 UTC, not every 6 h following the observation time. It has been suggested that this time average is too long, however, and that the aviation community expects forecasts to be for a specific time, rather than a long-period average. Aviation SIGMETS (SIGnificant METeorology information) for example, describe the hazard at a specified forecast time, not the average up until that time. The choice of model averaging period is complex, as there is a trade-off between supplying more instantaneous data and noisier dispersion model output over shorter time periods, but a period of 1 h may be more representative for volcanic applications.

2.5. Spatial average

The dimensions of the model output grid will influence the detail that is seen in the results, both laterally and vertically. These dimensions are usually specified at the start of a model run and are influenced by the need to have a fast run-time in an emergency. The current London default set-up calculates ash concentrations on the same horizontal grid as the met data (0.55° latitude by 0.83° longitude) for the vertical levels 'surface-FL200', 'FL200-FL350' and 'FL350-FL550', where FL indicates 'flight level' and has units of 100s of feet. A composite vertical concentration for 'surface-FL 550′ is also calculated. Similar output for each time-step is produced by Washington, which averages concentrations over a higher resolution 0.25° latitude by 0.25° longitude grid, and Darwin, which uses a 1° latitude by 1° longitude grid. Montreal output is calculated on a 50-km grid with the top output level defined as FL600 and Toulouse output is on a 1.5° latitude by 1.5° longitude grid (equivalent to the met data) with height levels defined by pressure.

2.6. Ash-particle-size distribution

The definition of volcanic ash (particle size and density) in a model will influence the dispersion results. Unfortunately, there are few measurements of in-plume ash particle size distributions, on account of the risks involved with such measurements. This means that there is no clear choice for ash parameterisation. Currently, the definition of volcanic ash varies between the VAACs, with some (e.g. Washington, London) having specific particle size distributions, but others just using a standard tracer. Even where size distributions are used, differences exist. For example, Washington's HYSPLIT has four particle size bins for ash, whilst Darwin's HYSPLIT has two particle sizes. London's NAME has five particle size bins (from 0.1–30 μm) and an ash density of 2300 kg m^{-3}.

Further complications arise in defining ash particle sizes for dispersion modelling from the fact that different types of volcanic activity produce different size distributions and different ash density. Coagulation of ash, particularly in eruption plumes with high water content, also affects the size range and may skew the distribution to larger particles. Inclusion of schemes that consider interaction of hydrometeors and ash, such as that in the eruption model ATHAM (Oberhuber *et al.*, 1998), may be one option for enhancing future VAAC models.

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2.7. Ash threshold

The ICAO specifies that the position of the 'ash cloud-mass' should be forecast, but does not define any limits for ash concentration. There is presently no clear threshold for the concentration of ash that is hazardous to aviation, so the current recommended practice is to avoid all volcanic ash (IAVWOPSG, 2005). From a geophysical standpoint, it is likely that the hazardous threshold would vary according to plume altitude, ash composition and mean particle size. From an aviation standpoint, the duration of exposure of aircraft engines to ash and their thrust settings at the time of the encounter, both have a direct influence on the hazard threshold (IAVWOPSG, 2005). The 2000 eruption of Hekla demonstrated that even very low concentrations of ash, undetectable visually or by satellite sensors, can cause substantial damage to aircraft (Rose *et al.*, 2003; Lacasse *et al.*, 2004). The terms 'visible' and 'visual' (implying detectable) ash cloud have been previously used to describe areas of volcanic ash to the aviation community. These slightly ambiguous terms should be used with care, as the ash cloud may be neither visible to the eye nor detectable by remote sensing.

There is currently no consistency in the way that the participant VAACs define the ash-cloud boundary (Table II) with thresholds depending variously on the source release rate used, availability of satellite data for comparison and forecaster judgement. The London VAAC, for example uses a visual ash-cloud look-up table to determine hazardous ash concentration as a function of the plume height. This table was originally constructed by NOAA for the VAFTAD dispersion model and was based on correspondence between an ash cloud modelled with a 1 g source and that seen on satellite imagery for real eruption scenarios. As such, it is an empirical relation and may not be appropriate for all types of eruptions.

The Washington VAAC has a variable concentration threshold for determining the ash boundary from the output of the model. The default threshold is the value in the NOAA table. The forecaster then previews output using thresholds 10, 100, and 1000 times the default and chooses the appropriate threshold based on forecaster judgement, in conjunction with satellite imagery. The higher threshold results appear to be caused by less ash in the source, hence the 'ash reduction factor' terminology in Table II. In this study, a visual ash threshold of 1.0×10^{-15} units m^{-3} was used for the first eruption, whilst a threshold of 1.0×10^{-14} units m^{-3} was used for the second eruption.

The Montreal, Toulouse and Darwin VAACs produce output images with contours of ash concentration on them rather than a single threshold. Montreal plots contours on all images at 1×10^{-5}, 1×10^{-4} and 1×10^{-3} g m^{-3}. Based on calibration with real eruptions, they have found that the 1×10^{-4} g m^{-3} contour is usually the closest estimate to the visual ash cloud, but include the 1×10^{-5} g m^{-3} contour as a safety margin.

The Toulouse procedure for determining the ash threshold is based on the total mass of ash released and the height of the plume. The threshold is calculated using Equation (1) with the coefficient determined from the plume height (Table III), but the reasons and justification for the selection of these criteria are uncertain. Real-time Toulouse forecasts are based on evaluation of the modelled threshold(s) combined with analysis of satellite imagery.

$$\text{Hazardous threshold} = \text{total mass} \times \text{coefficient} \quad (1)$$

Darwin uses an approach to ash forecasting that is heavily based on the integration of remotely sensed data with the model output. The most appropriate model ash concentration contour for defining the extent of

Table III. The coefficients used by Toulouse VAAC to calculate visible ash thresholds.

Plume height range (m)	Coefficient
>15 250	1.0×10^{-19}
9750–15 250	1.0×10^{-18}
7950–9750	1.0×10^{-17}
6700–7950	1.0×10^{-17}
<6700	1.0×10^{-17}

Table II. Concentration thresholds used by the VAACs to define volcanic ash clouds.

VAAC	Threshold	Notes
London	Variable	Values determined from NOAA look-up table based on vent height and column height
Toulouse	10×10^{-6} g m^{-3}	The threshold of visible cloud is automatically chosen from the height and duration of the eruption
Montreal	1×10^{-5}, 1×10^{-4} and 1×10^{-3} g m^{-3}	1×10^{-4} g m^{-3} contour is usually a closer estimate of the visual ash-cloud
Washington	Variable (1×10^{-14} and 1×10^{-15} units m^{-3} for this comparison)	An ash reduction threshold is applied to the NOAA look-up table to determine thresholds
Darwin	1×10^{-14}, 1×10^{-15}, 1×10^{-16}, 1×10^{-17}, 1×10^{-18} units m^{-3}	

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visual ash is determined from comparison of the model output with remotely sensed data for the ash plume. For big eruptions, conservative estimates of plume extent are made based on lower concentration model output contours. For smaller plumes, less reliance is placed on the dispersion model output. This approach is reliant on good satellite observations and so would not be appropriate for eruption scenarios like Grimsvötn where little data are available.

3. Methods

Initialising parameters were taken to be identical to those used by the London VAAC in its real-time modelling of the plume transport. These were determined according to how the eruption was reported to the VAAC at the time. The first stage of the eruption was reported as outlined in the first column in Table IV. The eruption having been reported stopped was then reported as having started again with the details in the second column in Table IV.

To facilitate comparison with the original forecast and between models, 6-h time-average output for visible/visual volcanic ash was requested at 6-h intervals (0000, 0600, 1200, 1800 UTC) from 0000 UTC, 2 November 2004 to 1800 UTC, 6 November 2004 for the flight level slices surface-FL200, FL200-FL350, FL350-FL550 and surface-FL550.

To account for the differences in the output time average, the London model run was repeated using the same initialising parameters, but with the averaging time set to 1 h for output. This is more in accordance with the ICAO specifications and more tangible for aviation hazard forecasting. To maintain consistency with the 1 g source used to create the visual ash look-up table, the release rate was increased to 1 g h^{-1}.

4. Results

Two periods are presented here for comparison of the different model results. These are 1800 on 2 November 2004, representing the vigorous phase of the eruption, and 1800 on 4 November 2004, representing the dispersion of the plumes from both of the eruption phases. Images from all the VAAC model runs are given for each time period. Only outputs for visual ash are considered (unless stated otherwise) and all flight levels are shown. One thing that becomes evident when looking at the different model outputs is that their different projections do not aid direct comparison. These varying projections reflect the different visualisation approaches favoured by different agencies. This is not of operational concern, as most VAACs do not routinely deal with the North Atlantic/European region, but it highlights the benefits of using appropriate projections and the need to harmonise model graphical outputs in future inter-comparisons.

4.1. Time 1: 1800 h, 2 Nov 2004

The locations of the plumes in the FL200–FL350 and FL350–550 altitude slices demonstrate reasonable agreement at this time-step (Figure 2, Figure 3 and Figure 4). The models all show the plume arcing across the Norwegian Sea reaching as far as Finland, although the extent

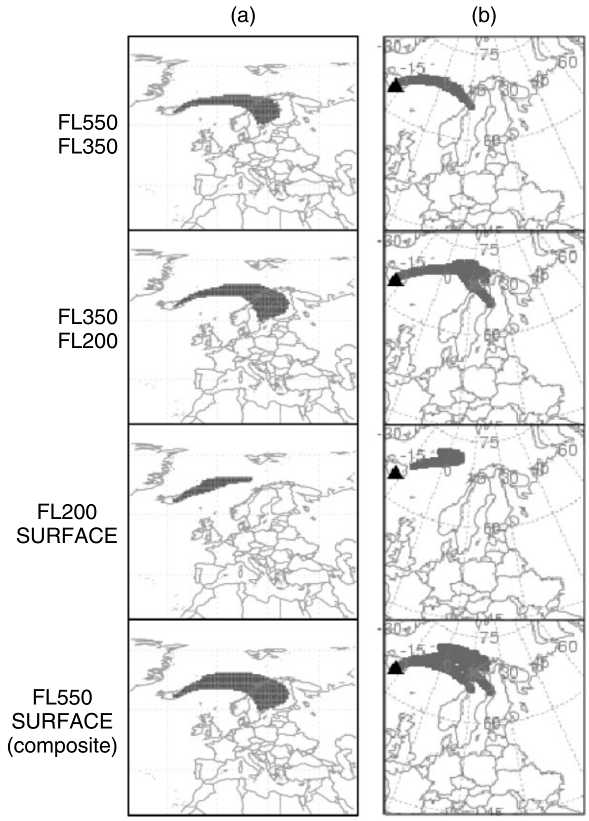

Figure 2. (a) London and (b) Washington results for 1800 h UTC, 2 November 2004.

Table IV. Parameters used to initialise the models based on information reported to the London VAAC.

Parameter	First eruptive stage	Second eruptive stage
Eruption latitude	64.26° N	64.26° N
Eruption longitude	17.26° W	17.26° W
Crater height	1725 m asl	1725 m asl
Eruption height	FL400	FL070
Start of eruption	2200 UTC, 01/11/2004	1200 UTC, 03/11/2004
End of eruption	0900 UTC, 03/11/2004	1800 UTC, 04/11/2004

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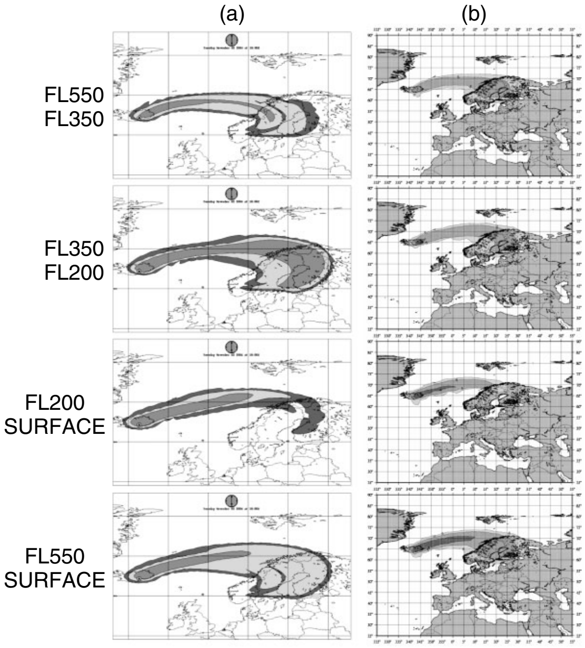

Figure 3. (a) Montreal and (b) Toulouse results for 1800 h UTC, 2 November 2004.

of cover over Norway, Sweden and Finland is variable. The Montreal and Toulouse outputs are very similar for these two vertical levels, whilst the Washington forecast is much more limited in aerial extent (this was the case in most of the model results).

In the surface-FL200 level, the extents and locations of the visual ash and high-concentration contours are broadly similar in all outputs, with ash restricted to the northeastern North Atlantic. However, the low concentration ash contours depicted on the Montreal, Toulouse and Darwin images extend much further than the visual ash areas from the other models and reach Scandinavia.

Differences between the surface-FL550 results show that the VAACs use different techniques for calculating the output at this level. The London and Washington results are composites of the outputs at the other height levels, so if visual ash is forecast in any of these levels, it also appears in the surface-FL550 level. Alternatively, Montreal, Toulouse and Darwin model the surface to FL550 as a separate fourth vertical layer.

4.2. Time 2: 1800 h, 4 Nov 2004

Differences between the modelled plumes are seen in all height levels at this time period (Figures 5, 6 and 7). The Washington output shows ash from the second eruption phase only, whereas the London, Montreal, Toulouse and Darwin outputs show ash from the first phase extending over Russia and Eastern Europe. The height levels in which the ash from the second eruption appears vary between the models. London, Washington and Darwin only depict ash in the lower vertical level and, consequently, the surface-FL550 composites, which is consistent with the low height of the eruption column. Montreal has ash at all levels except the upper level,

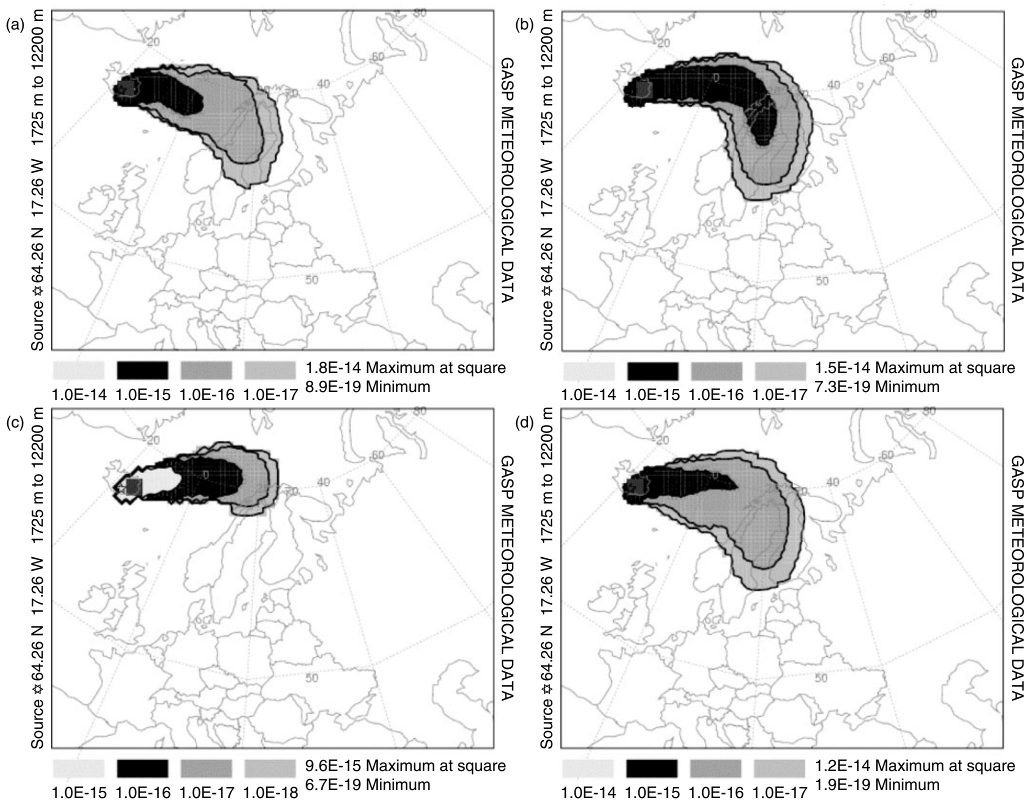

Figure 4. Darwin results for 1800 h UTC, 2 November 2004 (a) FL350-FL550, (b) FL200-FL350, (c) surface-FL200 and (d) surface-FL550. Note that the contours are not the same in each image.

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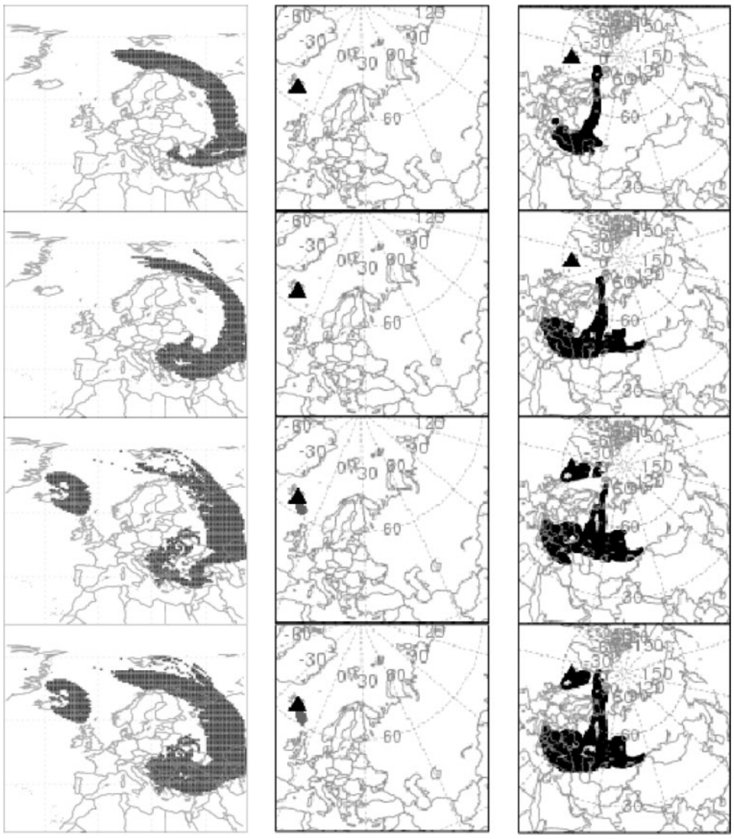

Figure 5. (a) London and (b) Washington results for visual ash for 1800 h UTC, 4 November 2004, (c) Washington results for all ash at the same time-step.

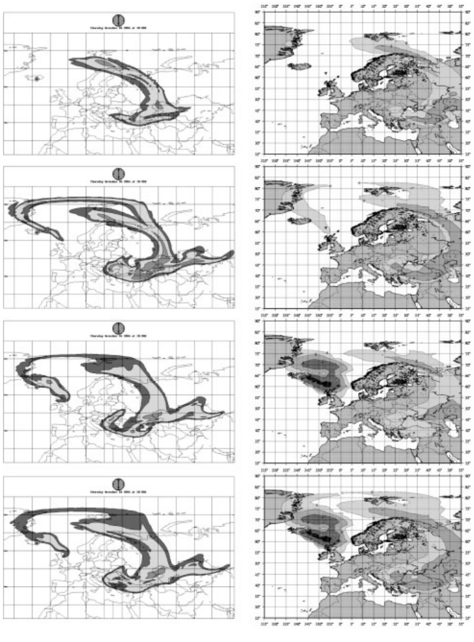

Figure 6. (a) Montreal and (b) Toulouse results for 1800 h UTC, 4 November 2004.

whilst Toulouse has ash present in all four levels. The lateral distribution of this second eruption plume is also very different, with Montreal, Toulouse and Darwin forecasting passage over Greenland, but Washington simulating only a compact plume travelling towards the UK. All the models show that the highest ash concentrations from the second eruptive phase would have been to the southeast of Iceland at this time, but varying degrees of ash to the northeast of Iceland are simulated by the different models.

Following this period, all of the models show the most concentrated part of the ash plume from the second eruption travelling over the North Sea. However, the extent of plume cover simulated over Scotland is variable, with some modelled plumes just reaching the coast, but others going as far south as the Scotland–England border. Such uncertainty in forecasting outputs has implications for airports in potentially affected regions.

The London, Montreal, Toulouse and Darwin results all forecasted that after travelling over Scandinavia, the ash plume from the first eruption circled south and then west over Eastern Europe and the Black Sea, reaching as far as the northeast Mediterranean Sea. A similar motion for the SO_2 plume from the eruption was detected by the SCIAMACHY sensor (Figure 8). There is also good agreement between the locations of modelled ash and elevated SO_2 detected by SCIAMACHY for the initial stages of the eruption.

The lack of visual-ash forecast by Washington for the second eruptive phase is considered to be more realistic

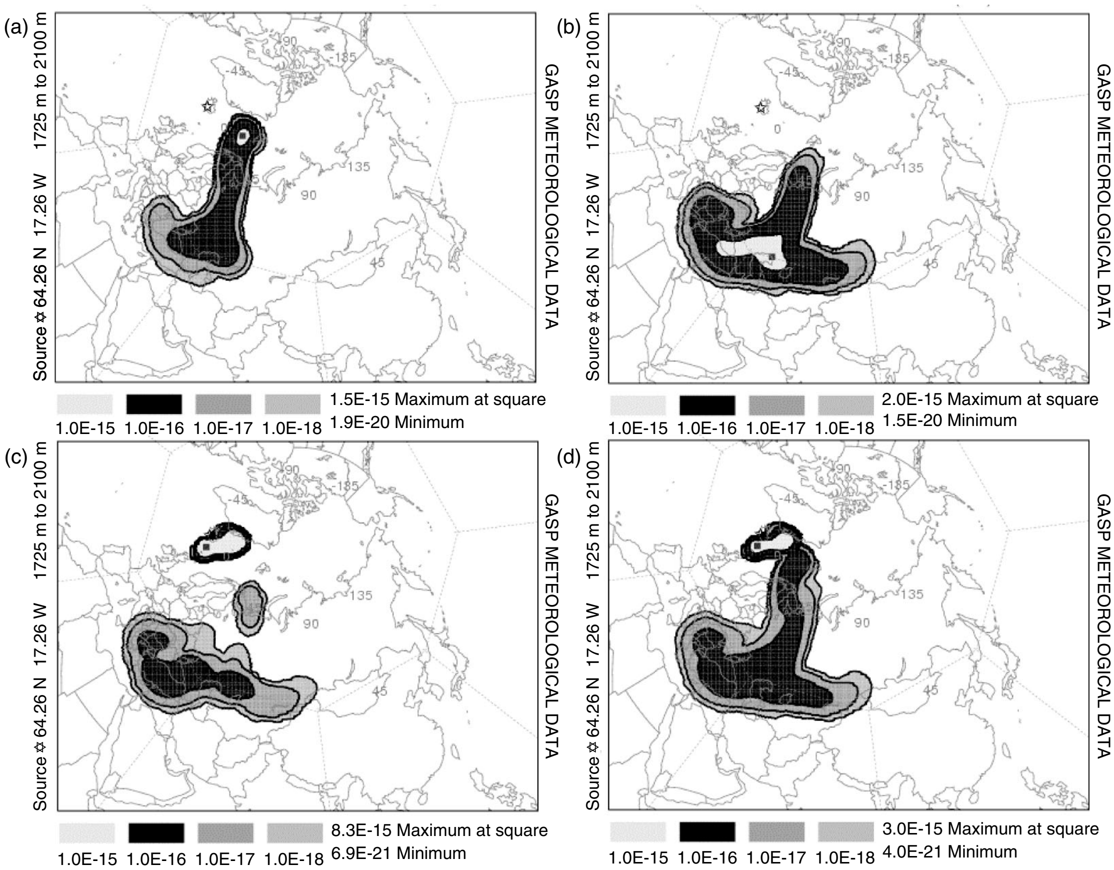

Figure 7. Darwin results for 1800 h UTC, 4 November 2004 (a) FL350-FL550, (b) FL200-FL350, (c) surface-FL200 and (d) surface-FL550.

than the simulations from the other models, as the eruption plume was very low (and, therefore, weak) by this stage. Little widespread ash would be expected from such activity and observations reveal that ashfall was constrained to the icecap at this time (Sigmundsson *et al.*, 2004a). This suggests that the Washington approach to modelling these types of small eruption plumes is better than those of the other VAACs and that there could be benefits to all VAACs from following a similar methodology in such instances.

Results from the London NAME model with 6-h and 1-h time averages demonstrated very little difference in the position and extent of the forecast visual ash plume, suggesting that the choice of averaging time is not critical.

5. Discussion

Differences in output from the models were expected owing to their different meteorological data and model physics/dynamics (for example, different treatments of horizontal and vertical turbulence), but it also appears that there were important differences in some of the initialising parameters, for example:

- ash release rates at source;
- definition of ash in the models (particle size/mass distribution);
- time averages of results;
- visual/hazardous ash threshold(s).

Given the use of these different parameters, as well as the model differences, it is reassuring that similar results were obtained from all the models for the location of visual ash. To assess fully the influence of each of the individual dispersion characteristics on the output, more model runs would be necessary (ideally on the same meteorology) to allow sensitivity testing of each parameter in turn. Such runs were beyond the scope of this work, but would be a valuable addition, and it is recommended that they be included in any future model comparisons. Although the models will remain different in the future, standardisation of the initialising parameters should be considered to ensure consistency between the VAACs. The consequences of varying some of these initialising parameters are considered in more detail below.

Current VAAC definitions of eruption sources mean that eruptions are generally initiated as a cuboid release over the entire vertical range from the ground surface to the observed top of the eruption column. The spatial dimensions of the release can range from a point located over the vent to a 50 × 50 km area. The impact of this wide range of release areas on output images will be influenced by the meteorology- and output-grid sizes. From the results presented here, it appears that there is currently little difference in output at the regional scale

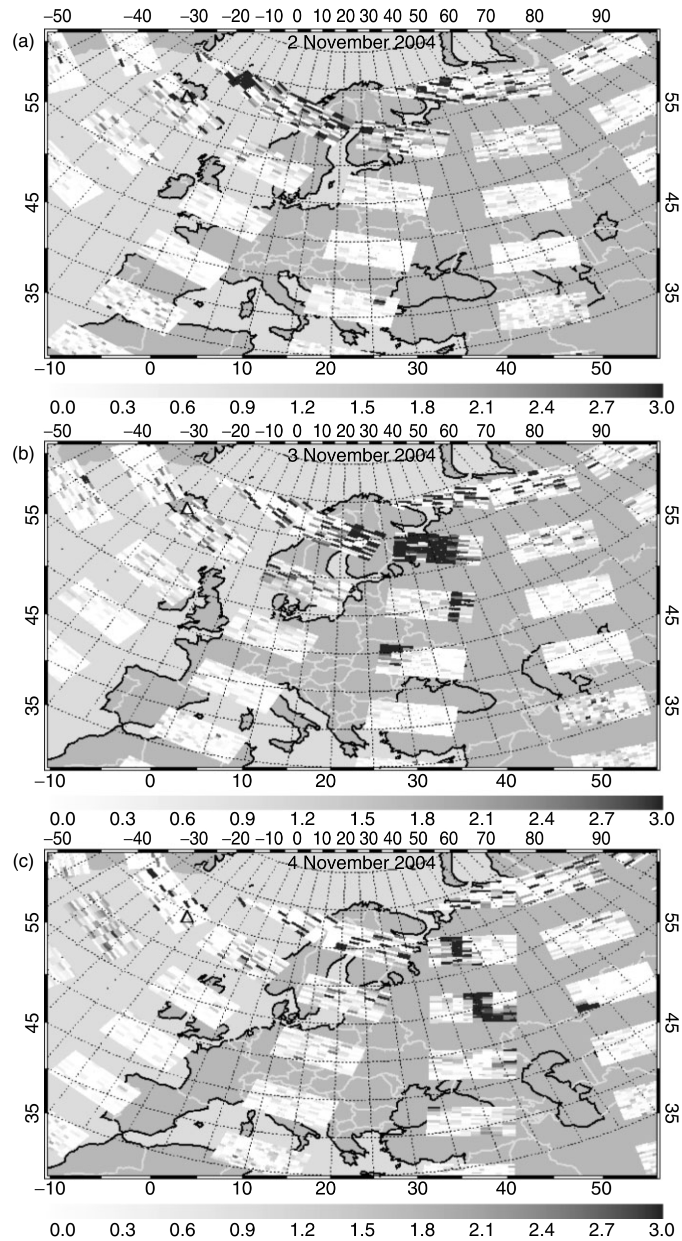

Figure 8. SO_2 slant column levels in Dobson Units observed by the SCIAMACHY sensor on (a) 2 November 2004, (b) 3 November 2004 and (c) 4 November 2004.

from using different release areas. As models move to increased grid resolutions and focus on shorter periods in the future, however, differences may become more pronounced. Work to improve source definitions, such as distribution of ash with column height and initial area of release, should be encouraged.

The two phases of the Grimsvötn eruption raise an interesting question about the validity of using the same ash emission rate for both vigorous and weak eruptions. In the Grimsvötn case, for example, it does not seem reasonable to use the same emission rate for the second, lower energy eruption. This can be explained by considering the empirically derived equation for sustained 'Plinian' eruptions (large explosive eruptions), which relates the plume rise height, H (m), to the volumetric flux of dense rock, V ($m^3\ s^{-1}$) (Sparks *et al.*, 1997):

$$H = 1670V^{0.259} \tag{2}$$

The observed decrease in the Grimsvötn plume height from 12 192 m asl to 2134 m asl is equivalent to a decrease in the actual plume height from 10 467 m to 409 m, a factor of >25. Using these values for H in the equation gives a consequent decrease in V from $\sim$1200 $m^3\ s^{-1}$ to $\sim$0.004 $m^3\ s^{-1}$, i.e. a factor of 10^5. Assuming a typical ash density of 2200 kg m^{-3} (possible range $\sim$600–2800 kg m^{-3} Pyle, 2000), this gives an emission of $\sim 9.50 \times 10^{12}$ g hr^{-1} for the larger plume, but only 3.17×10^7 g hr^{-1} for the smaller plume. Over the 35-h release period, the larger emission rate

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gives an erupted mass of 3.3×10^{11} kg and volume of 0.15 km^3. (For comparison, the 1980 Mt St Helens eruption had a total magnitude of 1.3×10^{12} kg Pyle, 2000). It is important to note that the style of the eruption was probably phreatomagmatic (involving the interaction of magma and external water, in this case melted glacial water) rather than Plinian, which diminishes the appropriateness of the Sparks *et al.* (1997) equation. Additionally, the equation is not strictly valid for the small plume. Both of these factors reduce the volumetric flux associated with the plume so a release rate definition based on the equation would be expected to over-predict the ash release. It is encouraging, in this case, that the erupted volume predicted by this equation is of a similar order of magnitude to the comparable 1983 and 1998 eruptions of Grimsvötn, where less than 0.1 km^3 of magma were erupted (Sigmundsson *et al.*, 2004a).

The results from Equation (2) prove a useful comparison in spite of the issues with differences in eruption style and demonstrate that the default release rates used by some of the VAACs (e.g. Toulouse, London) are much lower than typical eruption rates. This is irrelevant to ash cloud forecasting at the London VAAC, because the definition of the visual ash look-up table is dependent on a set release rate. Should actual ash concentration values ever be required, this would become far more important. The major drawback in the current London model is that the release rate value cannot be reduced for eruptions that are known to be small, as the definition of visual ash is dependent on this rate. The more flexible definitions of visual ash used by the other VAACs are much more advantageous, as they allow variable release rates.

Ash size distribution and release rates vary according to the type and magnitude of eruptions. The ability to alter these parameters, depending on the nature of the eruption would help refine the VAAC models. However, in an operational capacity, information on these variables may not be available initially (or at all), limiting the applicability of such options. Radar data (Figure 1) of plume heights demonstrate that, in this case, the London VAAC was reasonable in maintaining a FL400 eruption height during the first 35 h of the eruption. However, as more information became available with time about the type of eruption, ash release rates could have been reduced accordingly if this were possible.

One of the most important differences between the models used in this comparison is the technique used for defining the reported ash cloud. The results suggest that the criteria used by the London VAAC leads to a greater forecast extent of a plume than the concentration contours used by the other VAACs, whereas ash forecasts from Washington are the most constrained in aerial extent. Of note here, is that the London results are not based on a threshold chosen by an operator at the time, hence they are reproducible and errors cannot be directed to an individual. The use of one threshold, rather than contours of concentration, also clarifies the data for the forecaster. Given that the current ICAO guidance is to avoid all ash, it is unclear how a forecaster should deal with low concentration contours. The definition of ash thresholds is an area where standardisation across the VAACs would be beneficial and further investigation of the appropriateness and accuracy of the different measures for forecasting ash hazardous to aviation would be very useful. Better understanding of what ash concentrations are actually hazardous to aviation would help refine the VAAC model outputs and potentially reduce the areas declared off-limits, with consequent economic benefits.

The VAACs currently use different techniques for determining the ash concentration in the surface-FL550 level, with London and Washington producing a composite made from the other layers and Montreal, Toulouse and Darwin calculating it as a separate layer. This prevents direct comparison between these output slices and it is important that the differences are understood. It is also important that the issuers of the ash forecast understand how the results are computed. Which of these approaches is more appropriate is open to debate, but if graphical output is to be provided with forecasts in the future a decision needs be made to ensure that all VAACs are producing the same output.

This comparison has shown that all the VAAC models would have forecast ash in similar locations to that of the London VAAC based on the available data. The apparent disparity between modelled ash and detected/observed ash may have been due to high water content in the plume causing a higher plume height than that from an equivalent dry erupted mass (Sparks *et al.*, 1997) and leading to radar returns being predominantly from hydrometeors. This would have been difficult to determine at the time. The long-range transport of SO_2 from the eruption zone demonstrates that part of the eruption plume did reach as far as the models simulated, and this provides validity for the modelled dispersion.

6. Conclusion

Comparison of visual ash dispersion from the Grimsvötn eruption model using five VAAC models shows that, despite having different structures and using different meteorology, the models all produce very similar results. This is a very positive finding for the VAAC community and everyone who utilises their forecasts. Locations of the eruption plume simulated by the different models are almost identical to those predicted by the London VAAC during the eruption based on the data that was available. Modelled plume locations also agree with SCIAMACHY observations of SO_2 from the eruption. However, further observational data would have enabled better verification of model forecasts.

The results reveal that the London system, based as it is on a look-up table that requires a 1 g release, is not as flexible as other VAAC systems and cannot differentiate between different magnitudes of eruption other than by input height. This is a potential problem if small eruptions are to be modelled and may lead to over-prediction of ash concentration in these cases. The Washington system appears to be better at simulating visual ash from small eruptions.

There is considerable scope to use dynamic eruption models to better specify the height-ranges of ash injection into the atmosphere for different magnitudes of eruption and to improve VAAC model parameterisations of ash particle size distributions for different types of eruptions. However, without detailed real-time information about eruptions, any such type and/or size-specific refinements are of negligible value. The amount of data available about an eruption soon after its commencement is often limited and the presence of cloud in the eruption region is a particular hindrance to satellite observations. A reasonable default release scenario is therefore necessary to allow emergency eruption response. This is the system that was initiated at the London VAAC following notification of the Grimsvötn eruption.

The comparison has prompted valuable discussion between the participant VAACs of appropriate modelling parameters. Based on this discussion and the findings outlined in this report there appear to be a number of pertinent issues for consideration by the wider VAAC and aviation community.

1. The differences between model outputs suggest that the development of an ensemble approach to visual ash forecasting using the different international VAAC models could help forecasters with identifying areas of uncertainty in locating the ash cloud. There is potential for automating this sort of system, although response time requirements would need to be considered.
2. More realistic release rates and input height distributions, possibly derived from eruption column models, and better specification of ash could improve model forecasts. Development of a default standard and standardisation of these parameters across all VAACs would enhance consistency between models.
3. The relative merits of depicting contours of ash concentration, as opposed to areas of visual ash should be considered in more detail. An agreed definition of visual/hazardous ash threshold(s) would facilitate future comparisons between models and ensure consistency of output.

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