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A COMPARISON OF NAME MODEL PREDICTIONS AND OBSERVATIONS FROM THE 2010 EYJAFJALLAJÖKULL ERUPTION

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Abstract: During the 2010 eruption of the Icelandic volcano Eyjafjallajökull, improvements were made to the modelling procedure at the UK Met Office, enabling peak ash concentrations within the volcanic cloud to be estimated. In this paper we describe the ash concentration forecasting method and its rationale. To validate the ash concentration modelling procedure, predicted ash concentrations are compared against peak ash observations obtained from both ground based and research aircraft instrumentation. This comparison highlights the many sources of error and the uncertainties involved. Despite the challenges of predicting ash concentrations, the ash forecasting method employed here is found to give useful guidance on likely ash concentrations. Predicted peak ash concentrations are found to lie within about one and a half orders of magnitude of the observed peak concentrations. Significant improvements in the agreement between modelled and observed values are seen if a buffer zone accounting for positional errors in the predicted ash cloud is used. Sensitivity of the predicted ash concentrations to the source properties (e.g. the eruption height and the vertical distribution of ash at the source) is assessed and, in some cases, seemingly minor uncertainties in the source properties are found to have a large effect on predicted ash concentrations.

Key words: *Ash concentrations, Volcanic ash, NAME, Eyjafjallajökull, Validation.*

INTRODUCTION

The danger posed to aviation from volcanic ash is well known and has resulted, in the most serious encounters, in engine failure. The need to be able to warn the aviation community of volcanic activity and to forecast the atmospheric transport of volcanic ash clouds was recognised in the establishment of the Volcanic Ash Advisory Centres (VAACs) in the 1990s. During the 2010 eruption of the Icelandic volcano Eyjafjallajökull, restrictions on European airspace, based on the accepted guidance that volcanic ash should be completely avoided by aircraft (ICAO, 2002), were enforced over a prolonged period. The major disruption caused by this resulted in requests by the airline industry for attempts to be made to forecast peak ash concentrations in order that a revised procedure could be introduced that allowed aircraft to fly within areas of the volcanic cloud with low levels of predicted ash. Here we describe improvements to the volcanic ash forecasts introduced by the Met Office during the Eyjafjallajökull eruption enabling ash concentration predictions to be issued. The accuracy of predicted ash concentrations, modelled using a variety of approaches, is assessed against measurements from both ground-based observations and instrumentation onboard research aircraft.

METHOD

NAME (Numerical Atmospheric-dispersion Modelling Environment, Jones, A. et al., 2007) is the operational model of the London VAAC. It was developed following the Chernobyl incident to predict the dispersion of radionuclides but now has a wide range of applications including volcanic ash modelling. It is a Lagrangian model in which large numbers of model 'particles' are released into and tracked through the computational atmosphere. Each model particle represents a certain mass of dispersing material which is altered over time to represent the effects of loss processes such as wet and dry deposition and gravitational settling of heavy particles. The model particles are transported within the computational atmosphere by the resolved wind (often obtained from a numerical weather prediction model such as the Met Office's Unified Model (MetUM)) and by a random motion which represents the effects of unresolved motions such as turbulence.

In modelling volcanic ash, NAME does not attempt to model any of the complex near-source processes associated with the rising column, such as aggregation or fall-out of large particles, or with any umbrella cloud. An 'effective source' is used which aims to represent the net effect of the near-source processes in a way appropriate for estimating the long range dispersion. A particle size distribution, based on measurements from explosive eruptions of Mount Redoubt, St Augustine and Mount St Helens and presented by Hobbs, P.V. et al. (1991), is used. In keeping with the idea of an effective source, particles larger than 100 μm in diameter (either individual unaggregated grains or aggregates of grains) are assumed to fall out near to the source and are therefore not modelled. A particle density of 2300 kg m^{-3}, a value towards the low end of the possible values for rock, is assumed. A uniform vertical line source from the volcano vent (taken here to be the volcano summit) to the observed eruption height is used to represent the release of ash. Old volcanic ash is removed from NAME forecasts six days after emission, for reasons of computational efficiency which are important considerations in an operational emergency response setting. Meteorological data from the global MetUM with a temporal resolution of approximately 25 km in mid latitudes, a temporal resolution of 3 hours and a forecast out to six days was used to drive NAME during the Eyjafjallajökull eruption.

Initial modelling by the London VAAC during the 2010 Eyjafjallajökull eruption predicted regions of significant ash based on nominal emission rates and the table of 'visual ash' threshold concentrations developed by the National Oceanic and

Atmospheric Administration (NOAA) for the VAFTAD (Volcanic Ash Forecast Transport and Dispersion) model (Heffter, J.L. and B.J.B. Stunder, 1993). A nominal emission rate of 1 unit / 6 hours was used to produce forecasts based on six hourly average model concentrations over horizontal grid boxes of roughly 40 km by 40 km and over deep layers (FL000 – FL200, FL200 – FL350 and FL350 – FL550, where FL indicates the flight level which is approximately equivalent to height in hundreds of feet). The appropriate threshold concentration, based on the summit height and observed eruption height, was selected to indicate the regions of significant ash. Very soon after the high ash emissions from Eyjafjallajökull started on 14th April 2010, the approach was changed so that the emission rate varied instead of the concentration threshold in order to accommodate variations in the eruption strength.

The decision to forecast actual ash concentrations within the volcanic cloud required some modifications to the modelling procedure. Firstly, real, rather than nominal, emission rates needed to be modelled. Real emission rates were estimated from the observed eruption height using an empirical relationship between these two quantities. A number of such relationships exist within the literature (e.g. Sparks, R.S.J. et al., 1997 and Mastin, L.G. et al., 2009). Initially the emission rate was determined using a relationship based on the VAFTAD thresholds (interpreted as being inversely proportional to the emission rate) and calibrated using results of Mastin, L.G. et al. (2009). As the Eyjafjallajökull eruption progressed, this was replaced by a smooth power law fit to the VAFTAD thresholds, again calibrated using Mastin, L.G. et al. (2009). In the results presented here, the ash emission rate M (in kg s^{-1}) is determined from the eruption height H (in km above the vent height) using the relationship given by Mastin, L.G. et al. (2009),

$$M = 140.8H^{1/0.241}. \quad (1)$$

In all these relationships, emission rate is a strong function of eruption height so a 20% increase in eruption height means a doubling of the source strength. Consequently, uncertainties in the estimated eruption height, which are likely to be significant, translate into large errors in the calculated emission rate. In addition, for a given eruption height, the emission rate will vary with the type of eruption and with the meteorology. Secondly, to forecast ash concentrations in the distal field, fall out of ash near to source needs to be accounted for. Hence the effective source used in NAME should represent only the fraction of the mass emission that survives near-source fall-out processes. Estimates of this distal fine ash fraction lie between about 0.05% and 10% (Dacre, H.F. et al., 2011, Devenish, B.J. et al., 2011a, 2011b and Rose, W.I. et al., 2000). The near-source fall-out rate and the uncertainties in it are not, however, well characterised. Lastly, the aim was to forecast *peak* ash concentrations whereas the model predictions are *mean* ash concentrations over some space-time volume. In addition, the resolution of the driving meteorology, the parameterisation of sub-scale processes and the uniform representation of the source affect the model's ability to fully resolve the patchy nature and fine structure of the observed ash cloud. To account for localised regions of higher concentrations unresolved by the NAME modelling, a peak-to-mean factor is applied to the model's mean concentrations.

During the 2010 Eyjafjallajökull eruption, predicted ash concentrations were obtained over deep layers (FL000 – FL200, FL200 – FL350 and FL350 – FL550). A preliminary comparison with the available observations suggested that the localised peak observed ash concentrations were comparable to the model predicted deep layer mean concentrations when no near-source fall-out factor was applied. In other words, assuming that the emission rate is approximately correct, the near-source fall-out and peak-to-mean ratio were roughly thought to cancel each other out (or alternatively, a 5% distal fine ash fraction and a peak-to-mean factor of 20 could be assumed). Subsequently, predicting ash concentrations over thinner layers of 25FL depth has been investigated with a 5% distal fine ash fraction and a peak-to-mean factor of 10 assumed. The current operational model set-up is a hybrid scheme which uses the maximum of the 25FL sublayer model peak ash predictions within each deep layer.

COMPARISON OF PREDICTIONS WITH OBSERVATIONS

Here we compare model predictions for three model set-ups (the deep layer scheme, the 25FL layer scheme and the current operational hybrid scheme) with a range of observations obtained during the Eyjafjallajökull eruption. The dataset of observations used here (see Webster, H.N. et al., 2011) is a subset of available observations, primarily from ground-based lidars and instrumentation onboard research aircraft (DLR Falcon and FAAM BAe-146), selected on the basis that there is evidence that they represent localised peak ash concentrations. The dataset is, however, not unbiased. It is dominated by observations on 13 specific days from aircraft measurement flights which were planned with the intention of finding significant ash while avoiding regions where peak ash concentrations were predicted to be greater than 2000 μg m^{-3}. In the main, a factor of 2 uncertainty in the observations is expected. The appropriate 25FL or deep layer model value for comparing with the observation is selected based on the reported height of the observation.

Figure 1 shows scatter plots of modelled versus observed peak ash concentrations for the three model schemes. The axes are linear below 2 μg m^{-3} and logarithmic above this value (with continuous gradient at the transition) since the low values cannot be easily distinguished on a fully linear plot whereas zero values cannot be shown on a fully logarithmic plot. There is little confidence in observations of low ash concentrations since the reported values may reflect the background concentration of other aerosols or fluctuations associated with poor particle sampling statistics or poor signal-to-noise ratio. For example, the dashed vertical line at 20 μg m^{-3} denotes the value below which there is little confidence in the observations from the FAAM CAS instrument. The solid diagonal line is the 1-1 line and the horizontal dotted lines denote the boundaries between the concentration zones chosen by the aviation regulators (modelled concentrations less than 200 μg m^{-3}, 200 – 2000 μg m^{-3}, 2000 – 4000 μg m^{-3} and greater than 4000 μg m^{-3}).

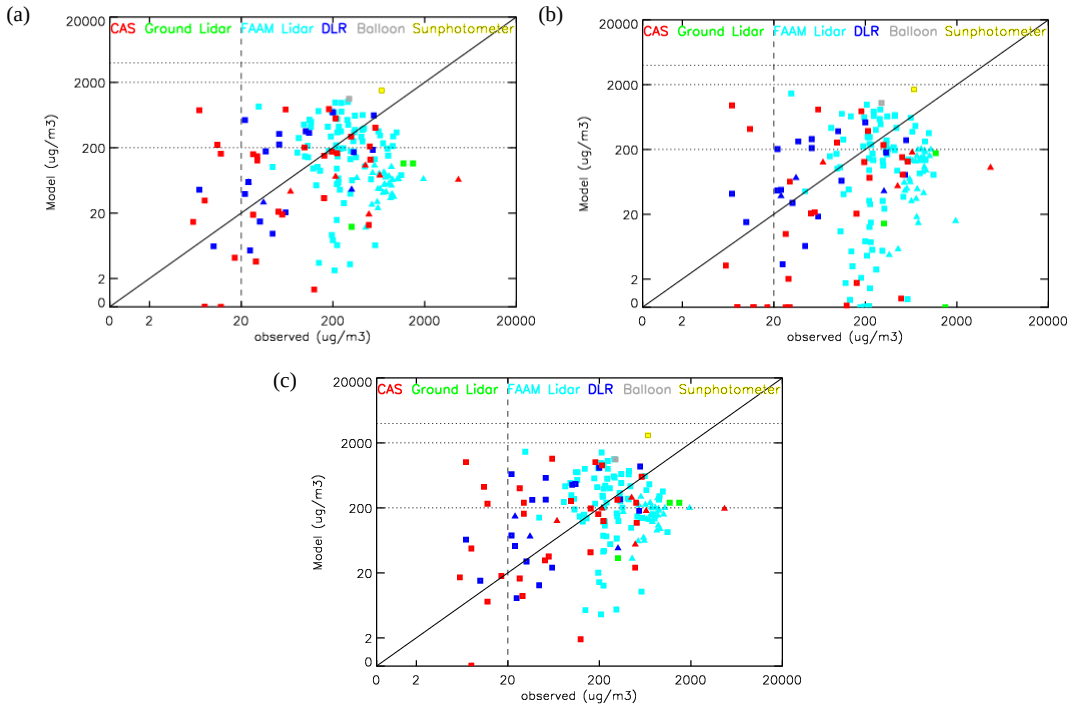

Figure 10. Modelled peak concentrations (obtained using the three model schemes: (a) the deep layer scheme, (b) the 25FL layer scheme and (c) the hybrid scheme) versus the peak observed concentrations. Squares denote observations below FL200 and triangles denote observations between FL200 and FL350. The colour denotes the observation type.

The scatter seen in Figure 1 is large as would be expected for a dispersion problem of this type where there are many possible sources of error. The general magnitude of the predicted peak ash concentrations agrees reasonably well with the observations. This indicates that the overall conversion factors, i.e. the product of the assumed distal fine ash fractions and the peak-to-mean ratios, are within the correct range. The results are comparable for the different model schemes with modelled and observed values lying within about one and a half orders of magnitude of each other, except that in the 25FL layer scheme there are a number of predictions of zero or near-zero peak ash concentrations which do not agree well with the observations. This is perhaps to be expected – the 25FL layer scheme is more sensitive to errors in the altitude of the predicted peak ash concentration and hence, when the peak concentrations are not predicted to occur at roughly the correct altitude, this scheme has a tendency to under-predict at the height of the observed peak.

Table 1 shows the percentage of modelled values over-predicting, under-predicting and in agreement with the observations for the three model schemes. Agreement is assessed in two ways. In the first, an uncertainty in the observations of a factor of 2 is assumed and the modelled and observed values are said to be in agreement if the predicted peak ash concentration lies within a factor of two of the observation. In the second, some attempt has also been made to account for potentially significant uncertainties in the modelled peak ash concentrations due to slight positional errors in the predicted ash cloud by considering the variability in the modelled concentrations over nearby model output grid-boxes. Ash cloud position errors can be caused by errors in the driving meteorology or by uncertainties in the effective ash source (e.g. eruption height, vertical distribution of ash). An ash cloud positional error of up to two grid-boxes (40 km resolution) in each horizontal direction and, for the 25FL layer scheme only, one grid-box up or down (25FL resolution) in the vertical direction has been considered. Agreement is said to occur if the uncertainty ranges for the model prediction and the observation overlap.

Table 2. A statistical comparison between model predictions and observations. * indicates agreement assessed using a factor of 2 uncertainty in the observations but no model uncertainty. † indicates agreement assessed using uncertainty in both the observations and in the model predictions. The considered uncertainty in the model predictions is due to positional errors in the ash cloud of up to two grid-boxes in the horizontal and, for the 25FL layer scheme only, one grid-box in the vertical.

Model scheme	% in agreement	% of over-predictions	% of under-predictions
Deep layer	24* 43†	25* 15†	51* 42†
25FL layer	23* 67†	17* 2†	60* 30†
Hybrid	29* 50†	29* 22†	42* 28†

When no account is taken of uncertainty in the modelled value, between 23% and 29% of modelled and observed values are found to be in agreement. The 25FL layer scheme shows a greater fraction of under-predictions with 60% of the observations under-predicted, presumably mainly due to errors in the predicted ash cloud's vertical position. For all three schemes, there is a significant improvement in the percentage of modelled and observed values in agreement when uncertainty in the modelled values (due to slight positional errors in the predicted ash cloud) is considered. This improvement is especially marked for the 25FL layer scheme and suggests that there would be significant benefit in using a 'buffer zone' with this scheme, i.e. there

would be benefit in using the maximum of the values over nearby grid-boxes in any hazard assessment. When both uncertainty in the observations and uncertainty in the predicted ash cloud are considered, the results range from 43% of values in agreement for the deep layer scheme to 67% of values in agreement for the 25FL scheme.

SENSITIVITY TO THE SOURCE PROPERTIES

It seems likely that a large proportion of the uncertainty in the predicted ash concentrations is due to uncertainty in the eruption source properties. This includes uncertainties in the eruption mass emission rate, the eruption height, the vertical distribution of the emitted ash and the particle size distribution. Sensitivity of the predicted ash concentrations to some of these source properties has been assessed and is summarised here. Further details can be found in Webster, H.N. et al. (2011).

A slightly different best-guess eruption height time profile was produced following detailed analysis of radar observations (Arason, P. et al., 2011), pilot reports (Pireps) and coastguard observations. These relatively minor changes in the eruption height time profile result, in some cases, in large differences in model predictions which cannot be explained entirely by changes in the ash emission rate per unit height. This highlights the potential for a large error in the model predictions due to uncertainties in the eruption height and suggests that an accurate representation of the eruption height is important in reducing uncertainties in ash concentration predictions.

The assumption of a uniform vertical distribution of emitted mass at the source is unlikely to be an accurate representation of the vertical distribution of the ash source. In particular, it does not capture the top-heavy weighting of ash expected. A top-heavy source term in NAME allows the peak-to-mean ratio to be reduced which suggests that the rather large peak-to-mean ratios required with a uniform vertical distribution are partly a result of the (probably overly) smoothed-out nature of the assumed uniform source profile. However, the arbitrary top-heavy weighting chosen at the source does not result in better agreement between modelled and observed ash concentrations. Consequently in the absence of accurate knowledge of the vertical distribution of ash at the source (a distribution which is likely to vary over time and between different volcanic eruptions), there seems little evidence to justify adopting a more detailed vertical distribution in preference to a uniform profile.

To obtain more accurate predictions of ash concentration, a truer representation of the source properties, namely the evolution with time of the eruption height, the emission rate, the vertical distribution of ash and the particle size distribution, is likely to be required. Stohl, A. et al. (2011) developed an inversion method to determine volcanic ash emission rates as a function of time and altitude using satellite derived total column ash amounts and a Lagrangian dispersion model. A detailed source term for the 2010 Eyjafjallajökull eruption has been obtained by Kristiansen, N.I. et al. (2011) using the inversion method of Stohl, A. et al. (2011), total ash column retrievals from SEVIRI satellite measurements (Prata, A.J., 1989 and Stohl, A. et al., 2011) and the NAME model. Comparisons of NAME predicted peak ash concentrations, using this detailed source term, with observed peak ash concentrations indicate an increase in skill, with more modelled and observed values in agreement when model uncertainty due to slight positional errors in the predicted ash cloud is not considered. However, when model uncertainty is considered, the agreement between modelled and observed concentrations is similar to that obtained using a simple uniform source. This suggests that, because of the many errors and uncertainties involved, simple source terms with the use of a buffer zone may, in an operational setting, perform as well as more complex source terms.

DISCUSSION AND CONCLUSIONS

The 2010 Eyjafjallajökull eruption was the first time that ash concentrations within the volcanic cloud have been predicted in an operational aviation-hazard context. Predicting volcanic ash concentrations accurately is an extremely difficult and challenging task. Volcanic eruptions are complex processes with substantial variations in eruption properties over time and between different eruptions. Despite these difficulties, however, the comparisons shown here between predicted and observed concentrations have demonstrated an ability to provide useful guidance on likely peak ash concentrations.

The approach described here to predict peak ash concentrations has raised a number of issues and interesting concepts which would benefit from further investigation, verification and thought. The need for clear communication is all the more paramount since there is a danger that quantitative predictions may be interpreted as implying a high degree of accuracy. The uncertainties involved in ash concentration predictions have been shown to be numerous and large. Further verification of the concentration forecasting method using data from future volcanic eruptions would improve scientific understanding. The method has been deliberately kept simple in view of the many uncertainties and limited understanding. A certain degree of tuning is advisable for each eruption (or as conditions change during an eruption). However, a number of possible improvements deserve consideration. These include methods to address ash cloud positional errors (e.g. meteorological ensembles) and representation of volcanic plume dynamics (e.g. the formation of umbrella clouds).

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