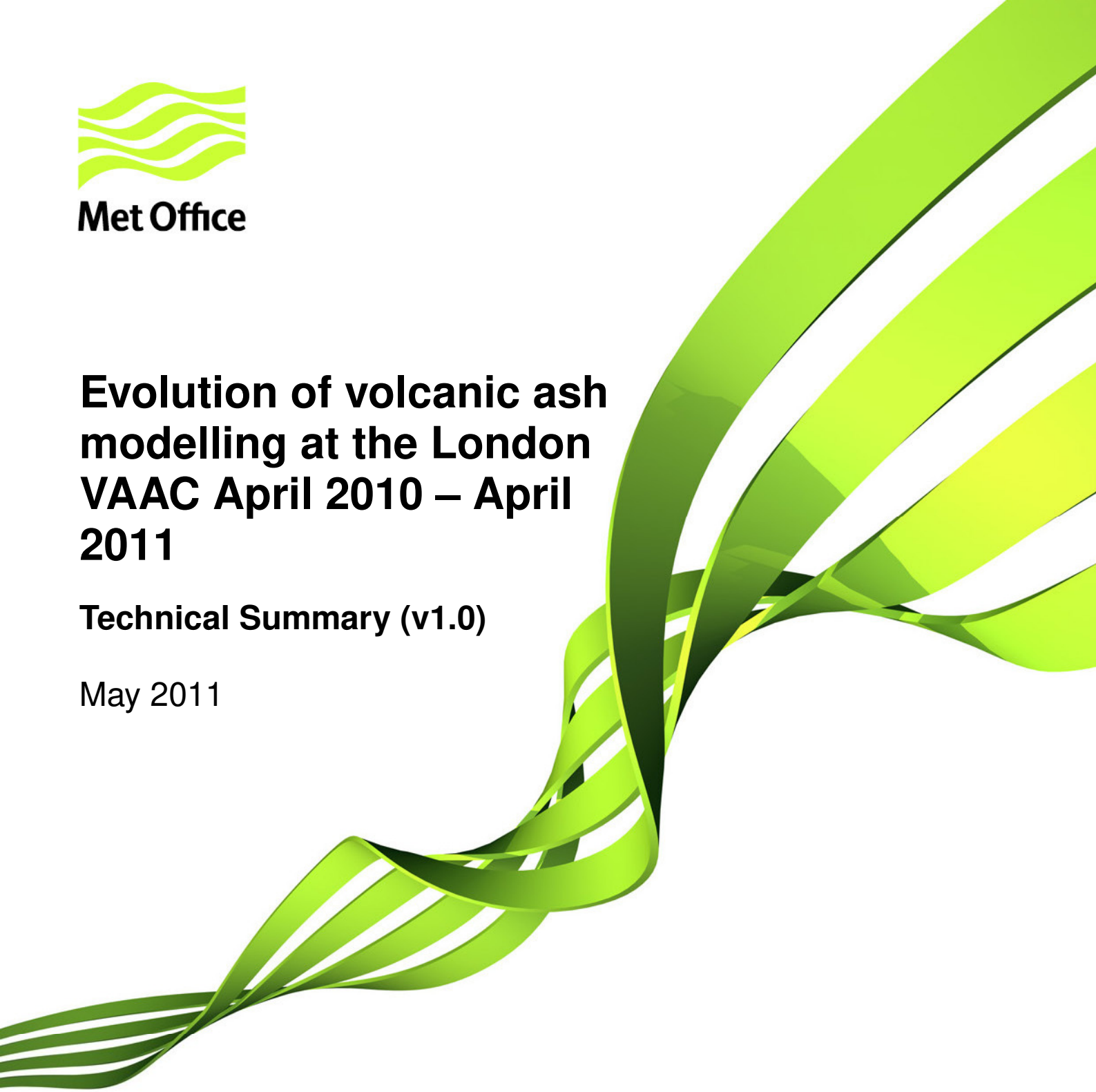

# Evolution of volcanic ash modelling at the London VAAC April 2010 – April 2011

## Technical Summary (v1.0)

May 2011

Claire Witham, Matthew Hort, David Thomson, Susan Leadbetter, Ben Devenish, Helen Webster

# 1 Introduction

The role of the London VAAC is to monitor and forecast the movement and dispersion of volcanic ash originating from volcanoes in the north-eastern part of the North Atlantic Ocean including Iceland. The London VAAC is operated by the Met Office, which is the National Meteorological Centre of the UK, and is backed up by the Toulouse VAAC run by Meteo France. Reciprocally the London VAAC back-up the Toulouse VAAC for dispersion of volcanic ash originating from volcanoes in continental Europe, western Asia and Africa.

The London VAAC and the Met Office's capability to forecast the transport and spread of volcanic ash is delivered by the NAME (Numerical Atmospheric-dispersion Modelling Environment) computer model. NAME began development following the Chernobyl accident in 1986 and since that time has been used to model a wide range of atmospheric dispersion events, including previous volcanic eruptions (Witham et al., 2007) and the Buncefield explosion in 2005 (Webster et al., 2007). In addition to its role as an emergency response guidance tool, the model is used for routine air quality forecasting and meteorological research activities. NAME provides a flexible modelling environment able to predict dispersion over distances ranging from a few kilometres to the whole globe and for time periods from minutes upwards.

This document explains how volcanic ash modelling and science have developed and evolved at the London VAAC in the year ending April 2011. It describes the changes that were implemented in response to the 2010 eruption of Eyjafjallajökull in Iceland and presents the current operational set-up.

# 2 Scientific Description of NAME

NAME is a 'Lagrangian' particle model that calculates the dispersion of pollutants by tracking model 'particles' through the modelled atmosphere. The process is initiated by the emission of model particles into the atmosphere from a user defined source. NAME has the flexibility to specify point or extended sources at any location in the atmosphere or at the surface, together with relevant source parameters such as the mass emission rate, emission velocity and temperature. Once emitted, particles move in a manner determined by the meteorology, which is input separately to the model. Operationally, NAME uses meteorological parameters derived from the main Met Office weather forecast model MetUM (the Met Office Unified Model). For volcanic ash forecasting, NAME uses meteorological data from the global MetUM, which currently has a temporal resolution of 3 hours. The most important parameters are the wind speed and direction, which vary in all three dimensions and in time. However other meteorological parameters are also used by NAME, such as the vertical temperature profile, the height of the atmospheric boundary layer, cloud liquid water, cloud ice, precipitation and surface heat and momentum fluxes. In addition to the movement of particles by the prescribed mean meteorological winds, the particle motion has a random component to represent the effects of unresolved motions including atmospheric turbulence.

## 2.1 Representation of Volcanic Ash

Each model 'particle' can have its own characteristics. For example, particles can represent different compounds or chemicals, and particles can have real particulate sizes. One of the pre-defined species in NAME is volcanic ash. Table 1 shows the particle size distribution for volcanic-ash that is used in the NAME simulations. This distribution is derived from observations made by Hobbs et al. (1991) in the plumes from explosive eruptions of Mount Redoubt, St. Augustine and Mount St. Helens. Particles

larger than 100 microns are assumed to fall out sufficiently rapidly that they do not need to be followed. Consequently, only the fine ash fraction is modelled in NAME. A default particle density of 2300 $kg/m^3$ is used for ash, which falls within observed values for erupted material (e.g. Sparks et al., 1997).

With sufficient observational information during an eruption, the particle size distribution and/or density used in NAME could be changed.

| Diameter in microns (μm) ($1\ \mu m = 10^{-6}$ m) | Cumulative mass fraction |
|---|---|
| 0.1 | 0.0 |
| 0.3 | 0.001 |
| 1.0 | 0.006 |
| 3.0 | 0.056 |
| 10.0 | 0.256 |
| 30.0 | 0.956 |
| 100.0 | 1.0 |

Table 1: The particle size distribution of volcanic ash used in NAME (Maryon et al., 1999).

## 2.2 Deposition and Aging Processes

Volcanic ash particles in NAME can be removed from the model atmosphere by several processes:

- fall out due to gravity (sedimentation)
- turbulent flux to the surface followed by impaction on roughness elements (dry deposition)
- washout where the pollutant is 'swept out' by falling precipitation (wet deposition)
- rainout where the pollutant is absorbed directly into cloud droplets as they form, prior to falling as precipitation (wet deposition)

The sedimentation parameterisation uses a fall velocity calculated using the Reynolds number dependent drag coefficient given by Maryon et al. (1999) with the Cunningham correction applied for small particle sizes (Pruppacher and Klett, 1999). Dry deposition uses a deposition velocity calculated by the resistance analogy and is combined with the sedimentation as described in Webster and Thomson (to appear) using the approach of Underwood (Underwood, 1999). Wet deposition uses scavenging coefficients and accounts for rain out and wash out by precipitation as described in Maryon et al. (1999). There is no explicit treatment of particle coagulation/aggregation at present.

Some modellers arbitrarily remove all ash which is older than a certain age (i.e. has been in the atmosphere for more than say 48 hours). In NAME this is done after a long time (6 days). Ash is not removed before this as the natural modelled processes of deposition and sedimentation are expected to control removal from the atmosphere.

# 3 Eruption Source Parameters

Eruption Source Parameters (ESP) including the volcano's location; source geometry; eruption date, time and duration; upper and lower height of the eruption plume, and vertical ash distribution can all be specified in the NAME source term. During eruptions however, not all of this information is available. No attempt is made to model the volcano dynamics or the dynamics of the rising plume, so instead material is released

between the volcano summit and the upper plume rise height (estimated from observations) with a uniform ash distribution with height.

A further key eruption source parameter is the mass erupted by the volcano. This mass is needed in order to forecast ash concentrations within the volcanic ash cloud. The following sections describe how the mass eruption rate scheme used by the London VAAC has evolved.

The eruption source parameters can be changed in NAME in accordance with varying eruption characteristics. During operational running, the model settings are primarily based on the latest observational based advice from the relevant volcano observatory (this is the Icelandic Met Office for Icelandic volcanoes), though data from satellite retrievals and other data sources are also used where available. Changes can be made to both 'current' and historical (i.e. conditions over proceeding days) settings within NAME when new observational data indicates that this is necessary. This means that different operational NAME runs can use different settings, even for output covering overlapping time periods. The purpose of this is to ensure that the most accurate forecast possible is provided at any given time.

# 4 Calculation of Mass Eruption Rate

The London VAAC used three mass eruption rate schemes during the period April 2010 to April 2011. These schemes evolved from the original VAFTAD approach; while the latest operational scheme uses the Mastin et al. (2009) plume height versus eruption rate relationship.

## 4.1 VAFTAD Table

Prior to the Eyjafjallajökull eruption in 2010, the London VAAC's standard procedure for volcanic ash eruption rates was based on the "VAFTAD table", as reported by Witham et al. (2007) and Leadbetter and Hort (2011). In this approach ash was released at a nominal emission rate E of 1 gram per 6 hours (approx 0.1667 grams per hour). To reflect the fact that emissions are known to be related to plume height, the threshold defining the area of hazard to aviation was dependent on the plume rise height. The contour defining this hazard area is referred to as indicating the extent of the 'visible' ash. The term "visual ash" was first coined by Nick Heffter (IVATF Document) who developed the VAFTAD (Volcanic Ash Forecast and Transport Dispersion) model in the early 1990's at the Air Resources Laboratory (ARL) of the National Oceanic and Atmospheric Administration (NOAA) of the United States. In comparing VAFTAD model outputs for a few cases with volcanic ash discernible by visual examination of satellite imagery at various wavelengths (visible, infrared, thermal infrared), he came up with the expression "visual ash cloud" to refer to the modelling output that corresponded spatially to the satellite detection. The meaning of the visible ash hazard threshold is not precise but it has become the basis of the ICAO VAAC service in providing guidance of avoiding all ash.

The scheme used in the US Volcanic Ash Forecast Transport and Dispersion Model (VAFTAD) was the basis for the original Met Office approach. It uses a look-up table to determine the threshold based on the plume rise height and summit height of the volcano. This table is not well documented and the methodology is only intended to give order of magnitude accuracy, with the threshold only varying in discrete factors of 10. The approach relies on the fact that concentrations are proportional to emissions and so the modelled release rate can be chosen arbitrarily provided the hazard threshold is chosen consistently. This explains why 1 gram per 6 hours can be used despite clearly

not being a realistic ash release rate. Actual release rates and threshold levels must be implicit in the VAFTAD approach but are not explicitly stated.

Using this approach, the official VAAC product was produced by forecasters showing the area of risk as the region where concentrations exceeded the VAFTAD threshold. As the 2010 Eyjafjallajökull eruption continued and the observed plume rise height varied over time, it became clear that, under this original approach, different thresholds needed to be applied to ash of different ages (and from periods with different eruption heights). This was difficult to do in a single NAME simulation so the approach was modified to use a fixed threshold ($10^{-17}$ g $m^{-3}$, grams per cubic metre) and a varying, but still nominal, ash release rate. The arbitrary release rate of 1 gram per 6 hours was used for plume rise heights corresponding to the $10^{-17}$ g $m^{-3}$ VAFTAD threshold. For plume rise heights corresponding to other thresholds under the VAFTAD look-up table, the release rate was scaled accordingly to enable the fixed $10^{-17}$ g $m^{-3}$ threshold to be used. For example, for plume rise heights corresponding to the $10^{-18}$ g $m^{-3}$ threshold, an emission rate of 10 grams per 6 hours was used with the fixed $10^{-17}$ g $m^{-3}$ threshold. This change enabled variations in the eruptive activity to be represented in a single model simulation.

Both these approaches were acceptable while the area of the ash plume was regarded as the area of risk (ICAO guidance). However, during the Eyjafjallajökull eruption, evolving guidance from the CAA (in consultation with EuroControl, airframe and engine manufacturers) meant that there was a move from an approach of just estimating the extent of the plume to making quantitative estimates of the ash concentration.

Actual ash release rates have been estimated from previous volcanic eruptions and Mastin et al. (2009) used these values to determine a relationship between the mass release rate M and the eruption height. Using the Mastin et al. results to calibrate the VAFTAD-based varying-release-rate approach described above, it was deduced that a nominal 1 gram per 6 hours release rate corresponds to a true release rate of about $10^{6}$ kg $s^{-1}$. This was used to convert the VAFTAD-based nominal released rates to true release rates and hence to provide quantitative concentration predictions (see below).

With this quantification of the release rate and various modelling assumptions for near-source fall-out and peak-mean concentration differences which are discussed in more detail in sections 5 and 6 below, it was deduced that the VAFTAD threshold used to estimate the plume extent corresponded to an estimated ash concentration of order 200 µg $m^{-3}$ (microgrammes per cubic metre). During the VAFTAD development period, the Canadian Meteorological Centre estimated, using their model CANERM, that, for the Spurr 1991 eruption, ash concentrations of about 100 µg/ $m^{3}$ corresponded to the ash cloud edge visible on satellite imagery (personal communication). Given the uncertainties in source term estimates, satellite capabilities and the models used, this is a promising level of agreement with the Met Office derived VAFTAD equivalent value of 200 µg $m^{-3}$ based on the 2010 Eyjafjallajökull eruption.

## 4.2 VAFTAD Curve

During the 2010 Eyjafjallajökull eruption a refinement was made to the way the emission rate was estimated from the plume rise height. This change involved a switch from the VAFTAD table approach described in section 4.1 (where the area at risk threshold, and later the nominal emission rate and estimated true emission rate, varied in ‘factor of 10’ steps) to a smooth function. The continuous function was designed to provide a reasonable fit to the VAFTAD values at the top of each VAFTAD height range and was also guided by the curve given by Mastin et al. (2009). The reason for fitting through the

top of each VAFTAD height range is that it is assumed that the VAFTAD approach is designed conservatively and so is appropriate for the most vigorous plumes within each of the VAFTAD height ranges. The curve fit was made by eye and was designed to fit best at the top of the $10^{17}$ and $10^{18}$ g $m^{-3}$ thresholds (Figure 1). The top of these thresholds were chosen as they are the highest threshold boundaries in the VAFTAD table and correspond to the most hazardous plumes.

The determined equation of best fit to this VAFTAD curve is:

$$H = 0.365\ M^{0.225}$$

where H is the plume rise height above the volcano summit in km and M is the true eruption rate in kg $s^{-1}$. This gives a true mass emission rate for use in NAME of:

$$M = 88.1\ H^{1/0.225}\ \text{kg s}^{-1}$$

or

$$M = 31.7 \times 10^{7}\ H^{1/0.225}\ \text{g hr}^{-1}$$

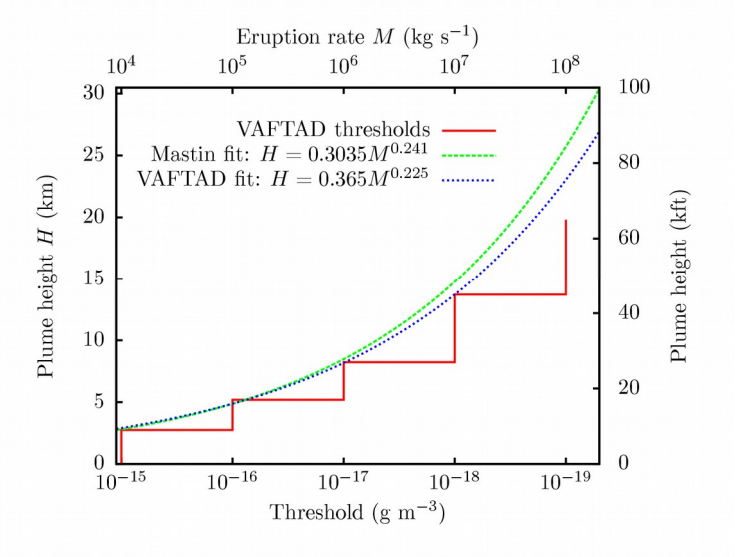


Figure 1: The original VAFTAD data, the continuous curve fitted to the VAFTAD thresholds and the Mastin curve. H is plume rise height above the volcano summit in km. The threshold values are the VAFTAD ash cloud thresholds relative to a emission rate of 1 gram per 6 hours. The VAFTAD thresholds are for a 5000 foot volcano.

## 4.3 Mastin Curve

The main weakness of the VAFTAD approach is that the original derivation of the threshold table is not well documented. Following the 2010 Eyjafjallajökull eruption, a more rigorous derivation of the mass eruption rate has been introduced. This uses the observed relationship between eruption height and eruption rate presented by Mastin et al. (2009):

$$H = 2.00\ V^{0.241}$$

Where H is the plume rise height above the summit in km and V is the volumetric flow rate in $m^3$ dense-rock equivalent per second. The volumetric flow rate V was obtained by Mastin et al. (2009) from reported mass eruption rates M (kg $s^{-1}$) using a density of 2500 kg $m^{-3}$. Hence:

$$V = M / 2500$$

and:

$$H = 0.3035\ M^{0.241}$$

This equation for H is very similar to that derived from the continuous fit to the VAFTAD thresholds (Figure 1), but gives lower eruption rates when eruption heights are high. Rearranging for M provides a true emission source rate of:

$$M = 140.84H^{1/0.241}\ kg\ s^{-1}$$

or

$$M = 50.7 \times 10^{7}\ H^{1/0.241}\ g\ hr^{-1}$$

Considerable scatter exists in the reported plume heights and eruption rates from previous volcanic eruptions that Mastin et al. (2009) used to derive this relationship. Hence, the error in the eruption rates calculated using this equation should be considered to have a 50% chance of being a factor of three or more.

# 5 Fine Ash Fraction and Unresolved Peaks

The true (or real) mass eruption rate, estimated by the continuous fit to the VAFTAD thresholds or Mastin's relationship, is the total mass erupted from the volcano. However, a significant fraction of the total eruption mass is expected to take the form of particles which are larger than those included in the NAME particle size distribution and which fall out rapidly. This is partly due to the presence of larger tephra (rock) grains, and partly due to the aggregation of individual grains. At present NAME cannot model aggregation of ash grains and does not include the larger grain sizes, hence putting all of the source mass into particles smaller than 100 microns will result in overestimates of the total amount of ash remaining in the atmosphere beyond the near field. To account for this and to represent only the fine ash fraction reaching the distal plume, it is assumed that most of the ash falls out close to the volcano. This percentage is very uncertain although a few case studies from the Eyjafjallajökull eruption (Dacre et al., 2011, Devenish et al., 2011) and previous eruptions (Rose et al., 2000) give values in the range 95% to 99.95%.

Furthermore, NAME predicted ash concentrations are mean concentrations, often over large volumes and periods of time. Localised peak concentrations, due to unresolved structures, are likely to be much higher than large (space-time) volume means. These peaks may also be enhanced by the vertical source profile being less smoothed out than the uniform profile assumed in the model.

The way the near-source fall-out and peak-mean difference was handled evolved over time and is described as part of the next section. However the aim of the approach has always been to predict the size of the likely peak concentrations that might be encountered.

# 6 Output Products

The NAME outputs are based on 6 hour time averages and quite deep (or "thick") layers (FL000 to FL200, FL200 to FL350, and FL350 to FL550, where FL is flight level in hundreds of feet).

In the approaches used during the 2010 Eyjafjallajökull eruption, thick layer mean concentrations were output. During the eruption a preliminary interpretation of the available observations suggested that the localised peak ash concentrations were comparable to the model predicted deep layer mean concentrations when no near-source fall-out was applied within the model. In other words, the two effects of accounting for the fraction of the released mass which is in the fine ash particle size range and which does not fall out near to source and accounting for the unresolved localised regions of higher concentrations were thought to roughly cancel out. Consequently the deep layer mean ash concentrations using the total mass release rates were used to estimate peak ash concentrations. This is obviously a 'high level' approximate approach and a more explicit approach would enable greater understanding and potential improvement to the numerous observational and modelling components used in the VAAC process. It is however consistent with the level of complexity used by many other VAACs (see e.g. Witham et al, 2007).

More recently, in conjunction with the Mastin curve, the Met Office also adopted a model output set-up (referred to as thin layers) aimed at more explicitly resolving the fine vertical structure of the distal ash plume. It is assumed that 95% of the released mass falls out near to source and hence, before running NAME, the mass emission rate (calculated using Mastin's relationship) is multiplied by 0.05. Observations have shown that very thin (less than 200m) layers of ash can occur whereas the NAME predicted plume is often considerably deeper (~2 km) (Devenish et al., 2011). The vertical resolution of the UK Met Office's numerical weather prediction data, the uniform representation of the released ash at the source, the fact that dispersion models present an average representation of the possible unresolved motions, and the horizontal and temporal averaging of the model output, all limit the ability of NAME to represent thin and patchy ash structures. Consequently even with high vertical resolution model output there is a need to account for unresolved peaks. This is done by multiplying the model predicted mean concentrations by a factor (known as the 'peak-to-mean factor') which accounts for peaks which the model is unable to resolve. The peak-to-mean ratio for the thinner (25FL) layer model output is taken to be a factor of 10. Webster et al. (2011) show that the model predicted concentrations, based on a 95% near-source fall-out rate and a peak-to-mean ratio of 10, agree reasonably well with observed peak concentrations for the 2010 Eyjafjallajökull eruption. To provide concise guidance and also to allow for the fact that the exact height of the ash is often not captured precisely these thin layers (25FL deep) are then combined into the thick layers (FL000 to FL200, FL200 to FL350, and FL350 to FL550) by taking the maximum value from the thin layers within each thick layer.

## 6.1 Volcanic Ash Advisories and Graphics

The official ICAO VAA and VAG products are produced by forecasters. These products are a human interpretation of the NAME modelled output and available observations. Consequently they are generally similar, but not an exact match, to the raw modelled areas. Differences between the two are due to: modifications based on interpretation of satellite and other observations, some subjective decisions associated with small areas of ash exceedences detached from the main cloud, and operational requirements such as the need for a reasonably simple area which can be defined and transmitted as a short text message.

# 7 Summary/Conclusions

- The approach to modelling volcanic ash at the London VAAC evolved during and after the 2010 Eyjafjallajökull eruption in response to requested changes in output

from the aviation industry (requirement for ash concentrations) and improvements in science.

- In March 2011 the VAAC moved to using real mass emission rates based on the Mastin et al. (2009) curve. This approach is much better documented than the previous VAFTAD approach. However there are significant variations around the Mastin et al. curve for different eruptions, and hence there remain significant uncertainties in the estimated emission rates.
- The new approach accounts explicitly for the fraction of mass that is expected to reach the distal ash plume. This fraction can be changed if observations suggest a different factor is more appropriate.
- Localised peak concentrations due to small scale structures unresolved by the modelling is accounted for by applying a peak-to-mean ratio to the model concentrations. This is currently a factor of 10.
- All VAAC output represents the peak concentration in a given layer.

# 8 References


Dacre H. F., Grant A. L. M., Hogan R. J., Belcher S. E., Thomson D. J., Devenish B. J., Marenco F., Hort M. C., Haywood J. M., Ansmann A., Mattis I., Clarisse L., 2011, Evaluating the structure and magnitude of the ash plume during the initial phase of the 2010 Eyjafjallajokull eruption using lidar observations and NAME simulations, Journal of Geophysical Research, in press.

Devenish B. J., Thomson D. J., Marenco F., Leadbetter S. J. and Ricketts H., 2011, A study of the arrival over the United Kingdom in April 2010 of the Eyjafjallajökull ash cloud using ground-based lidar and numerical simulations, Atmospheric Environment, submitted

Hobbs P. V., Radke L. F., Lyons J. H., Ferek R. J. and Coffman D. J., 1991, Airborne measurements of particle and gas emissions from the 1990 eruptions of Mount Redoubt. Journal of Geophysical Research, 96(D10), 18735-18752.

Leadbetter S. and Hort M., 2011, Volcanic ash hazard climatology for an eruption of Hekla Volcano, Iceland, Journal of Volcanology and Geothermal Research, 199, 230-241.

Maryon R.H., Ryall D.B. and Malcolm A.L., 1999, The NAME 4 Dispersion Model: Science Documentation, Turbulence and Diffusion Note No. 262, Met Office.

Mastin L. G., Guffanti M., Servranckx R., Webley P., Barsotti S., Dean K., Durant A., Ewert J. W., Neri A., Rose W. I., Schneider D., Siebert L., Stunder B., Swanson G., Tupper A., Volentik A., Waythomas C. F., 2009, A multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud transport and dispersion during eruptions. Journal of Volcanology and Geothermal Research 186, 10-21.

Pruppacher H. R. and Klett J. D., 1999, Microphysics of clouds and precipitation, 2nd edition. Kluwer, Dordrecht.

Rose W. I., Bluth G. J. S. and Ernst G. G. J., 2000, Integrating retrievals of volcanic cloud characteristics from satellite remote sensors: a summary, Phil. Trans. R. Soc. Lond. A., 358, 1585-1606.

Sparks R. S. J., Bursik M., Carey S. N., Gilbert J. S., Glaze L. S., Sigurdsson H. and Woods A. W., 1997, Volcanic Plumes. John Wiley & Sons Ltd. Chichester.

Underwood B. Y., 1999, A review of dry and wet deposition, AEAT-5382, AEA Technology plc, UK.

Webster H. N., Carroll E. B., Jones A. R., Manning A. J. and Thomson D. J., 2007, The Buncefield oil depot incident: a discussion of meteorology, Weather 62(12), 325-330.

Webster H. N. and Thomson D. J., Dry deposition modelling in a Lagrangian dispersion model, Int. J. Environ. Pollut., to appear

Webster H. N., Heard I. P. C., Johnson B. J., Thomson D. J., Turnbull K., Marenco F., Dorsey J., Minikin A., Weinzien B., Hort M. C. and Haywood J. M., 2011, A comparison of modelled and observed ash concentrations from the Eyjafjallajökull eruption, to be submitted to J. Geophys. Res.

Witham C. S., Hort M. C., Potts R., Servranckx R., Husson P. and Bonnardot F., 2007, Comparison of VAAC atmospheric dispersion models using the 1 November 2004 Grimsvötn eruption, Meteorological Applications 14, 27-38.

**Met Office**
FitzRoy Road, Exeter
Devon EX1 3PB
United Kingdom

Tel: 0870 900 0100
Fax: 0870 900 5050
enquiries@metoffice.gov.uk
www.metoffice.gov.uk