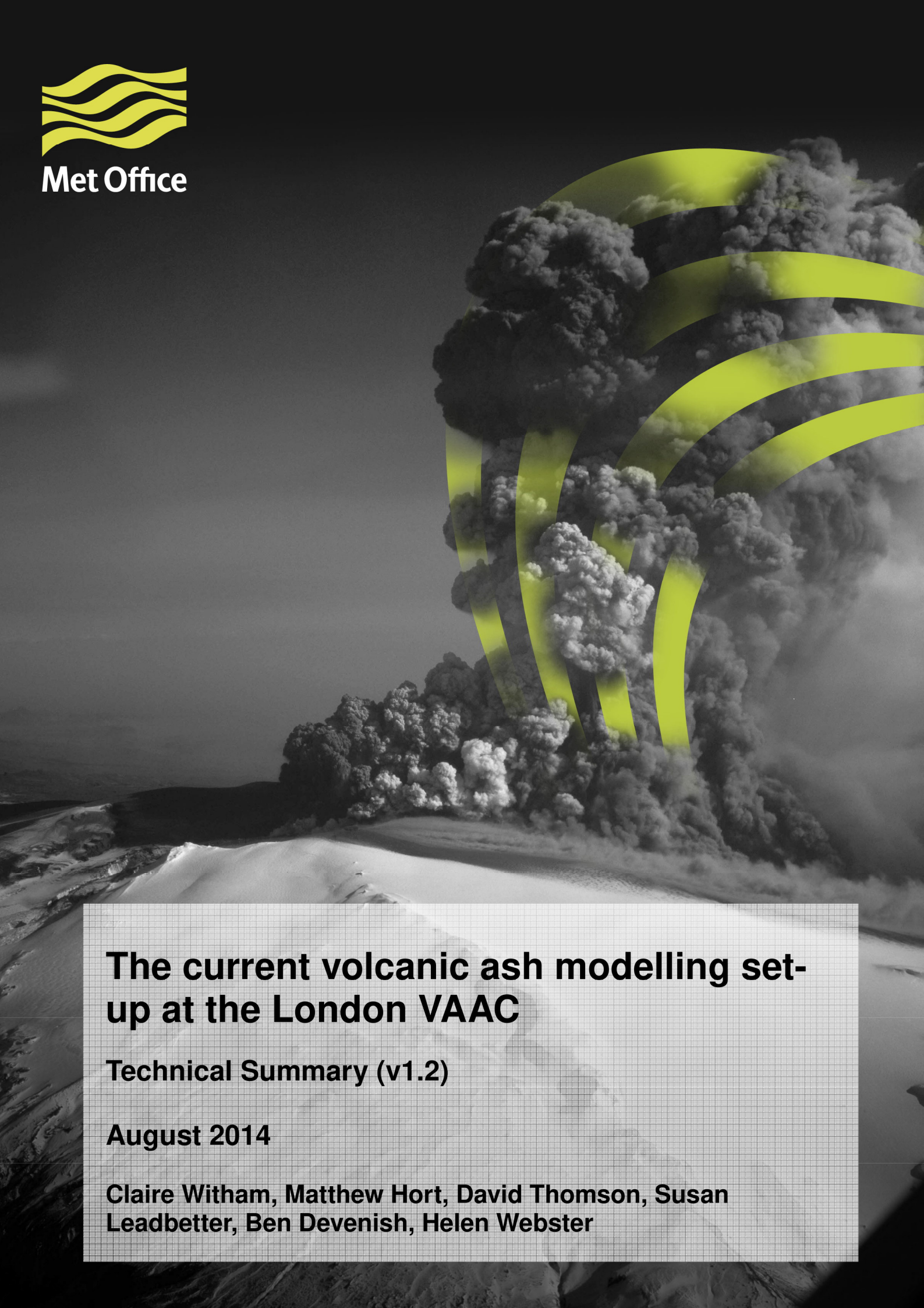

The current volcanic ash modelling set-up at the London VAAC

Technical Summary (v1.2)

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1 Introduction

The role of the London Volcanic Ash Advisory Centre (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 operated 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.

This document explains the current operational set-up (as of the date on the cover) for volcanic ash **modelling** at the London VAAC.

2 Scientific Description of Dispersion Model

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. The development of NAME began 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 (Cooke et al., 2014, Dacre et al., 2011, Devenish et al., 2011, Heard et al., 2012, Webster et al, 2012, Witham et al., 2007, Witham et al., 2012), the Buncefield oil depot explosion in 2005 (Webster et al., 2007) and the Fukushima Da-ichi nuclear power plant accident in 2011 (Leadbetter et al., 2014). In addition to its role as an emergency response guidance tool, the model is used for air quality forecasting and meteorological research activities. NAME provides a flexible modelling environment which is able to predict dispersion over distances ranging from a few kilometres to the whole globe and for time periods from minutes upwards. Using NAME it is possible to specify point or spatially extended sources at any location in the atmosphere or at the surface, together with relevant source parameters such as the mass emission rate and duration.

NAME is a Lagrangian particle model that calculates the dispersion of pollutants by tracking model 'particles' through the simulated atmosphere. The process is initiated by the release of model particles into the atmosphere from a user defined source.

Each model 'particle' can have its own characteristics. For example, particles can represent different compounds, gases or chemicals, and particles can have real particulate sizes. For particulate matter species such as volcanic ash, each model particle represents a certain mass of the actual species.

Once emitted, particles move in a manner determined by the meteorology. NAME is an offline model so the meteorology is a key input to the model.

2.1 Driving Meteorology

Operationally NAME uses meteorological parameters derived from the main Met Office weather forecast model the MetUM (the Met Office Unified Model). For volcanic ash forecasting, NAME uses meteorological data from the global MetUM, with a temporal resolution of 3 hours, a horizontal resolution of approximately 17 km and 59 vertical levels between the surface and 30 km asl. 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.

2.2 Representation of Volcanic Ash

Volcanic ash is represented in NAME by a particle size distribution and a density. Table 1 shows the particle size distribution for volcanic ash that is used as the default in operational 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 operationally in NAME. The number of particles released within each size range is proportional to the mass fraction and particles are created with diameters that are randomly distributed between the two bounding values in each range. The mass fraction released in each size range is distributed evenly across these particles.

A default particle density of 2300 kg/m ^{3} is used for all ash. This falls within observed values for erupted material (e.g. Sparks et al., 1997).

With sufficient observational information during an eruption, both the particle size distribution (the mass fraction and the diameter ranges) and the density used in NAME can be changed.

Diameter in microns (μm)	Mass fraction	Cumulative mass fraction
0.1 - 0.3	0.001	0.001
0.3 - 1.0	0.005	0.006
1.0 - 3.0	0.05	0.056
3.0 - 10.0	0.2	0.256
10.0 - 30.0	0.7	0.956
30.0 - 100.0	0.044	1.0

Table 1: The default particle size distribution for volcanic ash used in NAME (Maryon et al., 1999). 1 μm = 10^{-6} m.

2.3 Deposition and Ageing Processes

Volcanic ash 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)

There is no explicit treatment of particle coagulation/aggregation at present.

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 (2011) using the approach of Underwood (Underwood, 1999).

Wet deposition uses scavenging coefficients and accounts for both rain out and wash out by precipitation as described in Webster and Thomson (2014).

Dry and wet deposition act to reduce the mass of volcanic ash carried on each model particle. Hence deposition does not necessarily remove model particles from the atmosphere.

For computational speed it can be desirable to remove model particles (ash) completely from the model that are older than a certain age. Obviously significant care must be taken in this case so as not to remove ash that is still potentially of significance to aviation i.e. would still appear on the issued charts. 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. Where observations show that significant ash is remaining is the atmosphere for longer than 6 days this parameter can be changed.

2.4 Model Set Up

For VAAC purposes, a release rate of 15000 model particles per hour is used.

Model outputs are produced on a 40 km horizontal resolution grid. For a Lagrangian model, concentrations are determined by summing up the total mass of ash carried on model particles that are found in each grid box and dividing by the box volume.

3 Eruption Source Parameters

The following Eruption Source Parameters (ESP) can all be specified in the NAME source term:

- volcano location
- date, time and duration of each eruptive phase
- source geometry
- upper and lower height of the eruption plume
- mass eruption rate
- vertical ash distribution
- particle size distribution
- ash density

During eruptions however, not all of this information is available. Operationally 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. In the horizontal, a point source is used ($\Delta x=\Delta y=0$) so the ash is effectively released along a vertical line.

All of the eruption source parameters can be changed in NAME in accordance with varying eruption characteristics. During operational running, the model settings are based on the latest observational based advice from the relevant volcano observatory (this is the Icelandic Met Office for Icelandic volcanoes), satellite retrievals and other data sources where available. New sources can be added at any time to reflect changing eruptive activity. Changes can be made to both ‘current’ and historical (i.e. conditions over preceding days) source settings within NAME when new observational

data indicates that this is necessary. This means that different operational NAME runs can use different sources, 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. There is no limit to the number of different sources that can be used.

3.1 Calculation of Mass Eruption Rate

The default derivation of the mass eruption rate used by the London VAAC is taken from 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}. This provides a mass eruption source rate of:

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

or

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

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

3.2 Fine Ash Fraction

The mass eruption rate estimated by 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 considerable 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. The percentage that remains is very uncertain and will vary with eruption, but a few case studies from the Eyjafjallajökull eruption (Dacre et al., 2011, Devenish et al., 2011) and previous eruptions (Rose et al., 2000) give fall-out values in the range 95% to 99.95%. In the current set-up it is initially assumed that 95% of the erupted mass falls out near to source. To account for this in NAME, the mass eruption rate is multiplied by 0.05 (i.e. 5%). This percentage is deliberately conservative and can be changed for individual (or all) source terms if observations are available that suggest that this value is incorrect.

The reduction in the mass reaching the distal plume can also be used to adjust for uncertainties in the total mass emission rate introduced by the Mastin approximation, should this prove necessary during an eruption.

4 Unresolved Peak Concentrations

NAME predicted ash concentrations for the VAAC are mean concentrations for each grid box. Localised actual peak concentrations, due to unresolved structures in the atmosphere and ash plume, are likely to be much higher than model predicted volume means. These localised peaks may also be enhanced if the true vertical source profile is less smooth than the uniform profile assumed operationally.

The Met Office has 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. 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 thin layer (NAME currently outputs layers of 25 FL depth, where FL is flight level in hundreds of feet) model output is taken to be a factor of 10. Webster et al. (2012) 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 (25 FL deep) are then combined into the required thick layers (for example: FL000 to FL200, FL200 to FL350, and FL350 to FL550) by taking the maximum concentration value from the thin layers within the corresponding thick layer to be the thick layer value. It is important to note that this does not imply that the forecast concentration will occur throughout the thick layer.

5 Output Products

The NAME VAAC outputs are based on:

- 6 hour time averages (taken over the 6 hours preceding the forecast time)
- "Thick" layers: FL000 to FL200, FL200 to FL350, and FL350 to FL550
- 40 km horizontal resolution grid boxes
- Peak concentrations

Outputs are produced every 6 hours for the forecast times 00:00, 06:00, 12:00 and 18:00 UTC, and at the start of a new eruption on the nearest hour and for T+6, T+12 and T+18 after this.

The official ICAO Volcanic Ash Advisory (VAA) and Volcanic Ash Graphic (VAG) products are produced by forecasters. These products are a human interpretation of available observations and the NAME modelled output. Consequently they may not match 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 exceedances 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.

6 Summary

The London VAAC modelling approach is based on the following fundamentals:

- Total mass emission rates are calculated using the Mastin et al. (2009) equation. However there are significant variations around the Mastin et al. curve for different eruptions and hence there are significant uncertainties in the estimated emission rates. Variation in the real mass emission rate is allowed for through adjustment of the distal fine ash fraction.
- The current approach accounts explicitly for the fraction of mass that is expected to reach the distal ash plume. The default value used is 5%. 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 are accounted for by applying a peak-to-mean ratio to the model concentrations. This is currently a factor of 10.
- All VAAC concentration outputs represent the peak concentration in a given layer.

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