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Simulating atmospheric transport of the 2011 Grímsvötn ash cloud using a data insertion update scheme

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HIGHLIGHTS

- The atmospheric transport of the 2011 Grímsvötn ash cloud is simulated using NAME.
- A data insertion update scheme is implemented with different configurations.
- Simulations compare well against height, mass load and concentration observations.
- Skill scores are similar to a simpler data insertion scheme.

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ABSTRACT

Effective modelling of atmospheric volcanic ash dispersion is important to ensure aircraft safety, and has been the subject of much study since the Eyjafjallajökull ash crisis in Europe in 2010. In this paper, a novel modelling method is presented, where the atmospheric transport of the 2011 Grímsvötn ash cloud is simulated using a data insertion update scheme. Output from the volcanic ash transport and dispersion model, NAME, is updated using satellite retrievals and the results of a probabilistic ash, cloud and clear sky classification algorithm. A range of configurations of the scheme are compared with each other, in addition to a simple data insertion method presented in a previous study. Results show that simulations in which ash layer heights and depths are updated using the model output generally perform worse in relation to satellite derived ash coverage and ash column loading than simulations that use satellite-retrieved heights and an assumed layer depth of 1.0 km. Simulated ash column loading and concentration tends to be under-predicted using this update scheme, but the timing of the arrival of the ash cloud at Stockholm is well captured, as shown by comparison with lidar-derived mass concentration profiles. Most of the updated simulations in this comparison make small gains in skill on the simple data insertion scheme.

1. Introduction

1.1. The Grímsvötn eruption

Airborne volcanic ash poses a hazard to aircraft, but in restricting airspace to avoid ash, the civil aviation industry risks large economic losses, as in the case of the April and May 2010 eruption of Eyjafjallajökull, Iceland (Oxford Economics, 2010). The following year in Iceland, a sub-glacial eruption of the Grímsvötn volcano started on the evening of 21 May 2011 and continued for 7 days. The eruption quickly broke through the glacial ice cover and the basaltic magma and glacial water interaction caused explosive tephra formation. The eruption produced higher plumes (Arason et al., 2011; Petersen et al., 2012), but was shorter lived than the Eyjafjallajökull 2010 eruption, with coarser ash particles (Icelandic Met Office, 2011; Ansmann et al., 2012). During late May 2011 there were a number of low pressure weather systems which caused rainfall to the south of Iceland and variation in wind direction (Stevenson et al., 2013). The atmospheric conditions were expected to lead to rapid fall out of ash particles and a lesser impact on Europe than the 2010 Eyjafjallajökull eruption (Icelandic Met Office, 2011; Tesche et al., 2012). Air traffic was disrupted in Iceland, Greenland, northern UK and Ireland from 24 May and

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northern Germany on 25 May (Tesche et al., 2012).

1.2. Satellite measurements of ash

Volcanic Ash Advisory Centres (VAACs) provide safety advisories to civil aviation authorities informed by output from volcanic ash transport and dispersion models (VATDMs). Infrared satellite observations are valuable tools for VAACs to monitor ash clouds and validate model output. However, infrared detection of ash can be influenced by meteorological clouds, which, when overlying an ash layer, can obscure the characteristic negative brightness temperature difference (BTD; the brightness temperature at the ~11 μm channel minus the brightness temperature at the ~12 μm channel) of silicate ash (Prata, 1989). Water or ice (which normally exhibit positive BTD) within an ash cloud can decrease the magnitude of the negative BTD, and acting as condensation nuclei, the characteristic signature of ash particles can be obscured by becoming encased in ice (Rose et al., 1995).

Kylling et al. (2015) studied the effects of meteorological cloud on ash detection in simulated imagery from the Meteosat Second Generation Spinning Enhanced Visible and Infrared Imager (SEVIRI) for the Eyjafjallajökull 2010 and Grímsvötn 2011 eruptions. The authors simulated both cloudy and cloudless scenes containing ash using a radiative transfer model. Using the BTD ash detection approach, the presence of cloud led to an average 6–12% reduction in the detection of ash containing pixels, and up to 40% of those pixels in some scenes. The detection efficiency was greater for the Eyjafjallajökull ash cloud. For the Grímsvötn scenes, the study indicated that the main cause of the false negatives was the small thermal difference between the top of the ash cloud and the Earth's surface, and mixing with clouds at low altitude overlying or co-located with the ash layer (see also Kylling et al., 2013).

1.3. Data insertion

The problem of accurately predicting the transport of volcanic emissions by incorporating observations into model simulations has been approached using a range of techniques, including inversion modelling (e.g., Eckhardt et al., 2008; Kristiansen et al., 2012; Pelley et al., 2015), variational data assimilation (e.g., Schmehl et al., 2011) and others (e.g., Bursik et al., 2012; Madankan et al., 2014).

In data insertion, observations are used to create a model state from which to begin a simulation. This paper is a feasibility study that expands on previous data insertion work on the Eyjafjallajökull eruption (Wilkins et al., 2014, 2016), which includes no information on the possible location of meteorological cloud that could inhibit ash detection. (The Francis et al. (2012) retrieval used in those studies does provide an estimate of aerosol optical depth, but that information was not utilised.) In those studies, model simulations are initialised from a series of satellite retrieved ash cloud properties, and the resulting outputs are combined to form composite simulations of ash observed in all of the scenes. Here, the dispersion of the 2011 Grímsvötn ash cloud is simulated using the Met Office's Numerical Atmospheric Modelling Environment (NAME; Jones et al., 2007) forced by Met Office Unified Model (MetUM) numerical weather prediction data. Model output errors can accumulate with increasing forecast length due to errors in the meteorological forcing and removal processes (Durant, 2015). In an attempt to constrain some of the cumulative errors, simulations are updated periodically using a variation on the data insertion method. As meteorological clouds are likely to inhibit detection of parts of the Grímsvötn ash cloud in the satellite imagery, a series of satellite retrievals and the results of a probabilistic ash, cloud and clear sky classification algorithm are incorporated into the updates. Details of the scheme are given below.

2. Methods

Owing to the high temporal resolution of the SEVIRI sensor, for the update scheme both the retrieval and classification are performed using data from that instrument. In theory other instruments and measurements could be employed in a similar way. Using SEVIRI infrared channels, ash is detected at a given time and the ash cloud height and column loading are retrieved using a one dimensional variational method (1D-Var; for full details see Francis et al., 2012), assuming an andesite refractive index (Pollack et al., 1973). These data are used to initialise NAME, where only positive ash flags are inserted into the model. For later times, the retrieval data and a Bayesian atmospheric classification scheme (Mackie and Watson, 2014) are used to update the model state in a portion of the model domain.

The Bayesian scheme classifies satellite pixels by the probability of being free of meteorological cloud and ash, containing cloud or containing ash. The combined probabilities sum to unity. Specific prior information about the atmosphere within each pixel is used in the scheme, which does not include user-defined brightness temperature thresholds for ash detection. Based on the prior information and the satellite data, pixels are assigned a probability of being in each of the three states. For a complete description of the method please see Mackie and Watson (2014). The atmospheric states in the classifier are mutually exclusive. In this study, pixels are flagged as clear, cloud or ash according to which class has the highest posterior probability. Pixels are assigned as ambiguous where there is a <0.2 difference in probability between the assigned class and the next most probable.

2.1. Sequential update scheme

A step-by-step outline of the modelling methodology is given below and shown on the flow chart in Fig. 1.

1. The 1D-Var detection and retrieval scheme is run for time t_0 (0615 UTC 23 May 2011) and the output is inserted into NAME following the method outlined in Wilkins et al. (2016). Retrieved ash cloud height, ash column loading and an assumed ash layer depth are used to create a representation of the downwind ash cloud for the NAME source term. Each pixel represents a source and all sources are released into the model atmosphere. Output is obtained for time t_1 (1215 UTC 23 May 2011), forming an a priori forecast. NAME ash column loading results are output onto a 0.25°×°0.25°grid and ash concentration is output at a

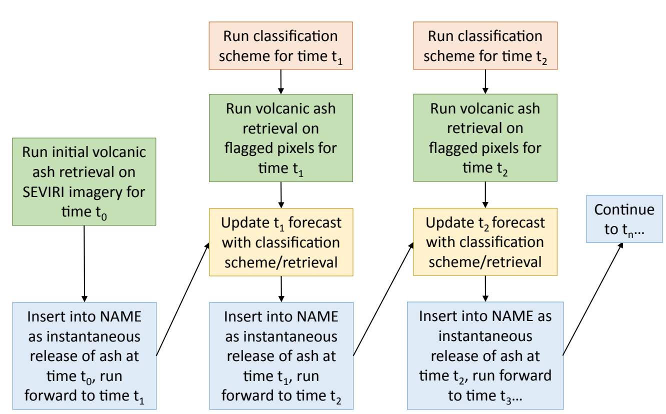

Fig. 1. Work flow for the sequential update scheme.