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Modeling the resuspension of ash deposited during the eruption of Eyjafjallajökull in spring 2010

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[1] Eyjafjallajökull, a volcano in southern Iceland, erupted explosively in April and May 2010 depositing ash over a region of more than 3000 km^2 to the east and southeast of the volcano. This deposited ash has been frequently remobilized by the wind causing concern for the health of Icelanders living in the region. An investigation was carried out to determine whether it would be possible to produce forecasts of days when high airborne ash concentrations were likely to occur. Information about the spatially varying surface characteristics of the region of deposited ash is not available so in the modeling approach adopted here ash is released from the surface at a rate proportional to the cube of the excess friction velocity (local friction velocity minus a threshold) only when the friction velocity exceeds a threshold. Movement of the resuspended ash is then modeled in a Lagrangian dispersion model. Modeled ash concentrations are compared to observed concentrations from two periods; PM$_{10}$ observations between 23 May and 2 July 2010 and airborne particle counts between 21 September 2010 and 16 February 2011. More than 66% of the resuspension episodes between May and July are captured by the model and the relative magnitudes of the modeled episodes in this period are in good agreement with the observations. 66% of episodes between October and February are also captured by the model although there is an increase in the false alarm rate which appears to be due to the influence of precipitation.

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1. Introduction

[2] Volcanic ash from the eruption of Iceland's Eyjafjallajökull volcano in April and May 2010 was deposited over a large area to the east and southeast of the volcano (Figure 1). Even before the volcano stopped erupting the ash was frequently remobilized by the wind causing concern for human health and aviation. Episodes of remobilization continued to occur into 2011 and as the eruption of Grimsvötn in May 2011 deposited ash over the eastern part of this area (to the south of Grimsvötn and between 17° and 18°W) the problem is likely to continue.

[3] Dust storms are not unknown in Iceland as the country has about 22,000 km^2 of sandy desert of volcanic origin which has been deposited during eruptions or generated through the weathering of volcanic rocks [*Arnalds et al.*, 2001]. Dust from these storms reaches Reykjavík several times a year [*Thorsteinsson et al.*, 2011]. However, following the eruption of Eyjafjallajökull in southern Iceland the area covered by dust or ash which is available for resuspension has increased and there has been a resultant increase in the frequency of the dust storms.

[4] Volcanic ash can be hazardous to human health because its fine size range means that it is respirable, and a recognized link exists between particles with a diameter less than 10 μm (PM$_{10}$) and adverse health effects [*Braga et al.*, 2001; *Dockery et al.*, 1992]. For example, there is evidence for the exacerbation of asthma in children on Montserrat following the increase in eruptive activity of Soufrière Hills volcano in July 1995 [*Forbes et al.*, 2003]. In addition to its physical hazard volcanic ash may contain potentially toxic chemicals such as crystalline silica which causes silicosis [*Baxter et al.*, 1999; *Searl et al.*, 2002]. A rapid assessment of ash from Eyjafjallajökull carried out by C. Horwell et al. (Respiratory health hazard assessment of the ash from the 2010 eruption of the Eyjafjallajökull volcano, Iceland, manuscript in preparation, 2012) has shown that the ash does not pose a chemical hazard. However, ash from the first phase of the main eruption (14 April–19 April) of Eyjafjallajökull contained a high percentage (up to 20%) of particles with a diameter of less than 10 μm [*Gislason et al.*, 2011] and as a result PM$_{10}$ concentrations in southern Iceland have frequently exceeded the European guideline of 50 μg/m^3 over 24 hours (2008/50/EG available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF) in the year since the end of the eruption.

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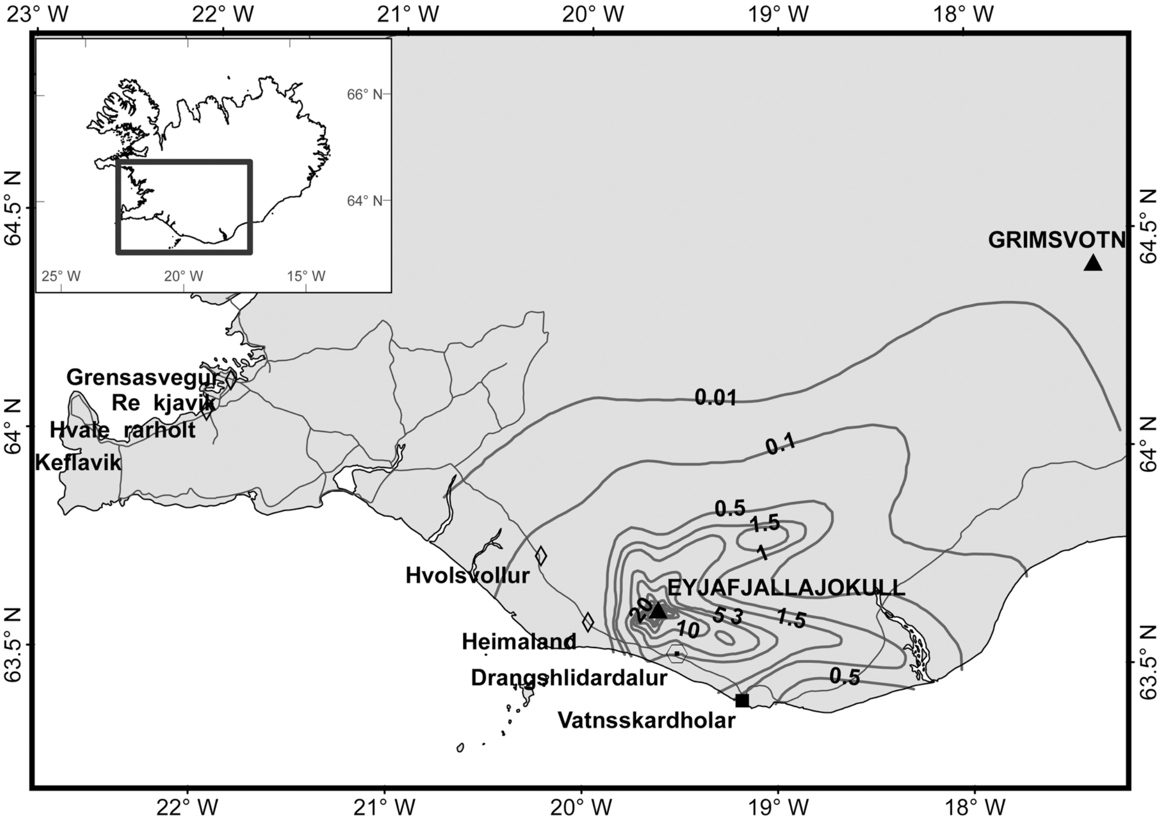


Figure 1. Map showing isopachs (in cm) of tephra deposits in southern Iceland (measured by scientists at the University of Iceland). Also shown are locations mentioned in this study (including monitoring stations).

[5] Remobilized ash can also cause problems for agriculture, suppressing plant regrowth and causing issues for grazing animals such as starvation, gastrointestinal problems, tooth abrasion and corneal abrasion. Ash from the 1991 eruption of Volcán Hudson in southern Patagonia, Chile was remobilized in 'ash storms' for many years following the eruption resulting in the loss of thousands of livestock [*Wilson et al.*, 2011].

[6] The hazards to airports caused by resuspended ash are similar to the hazards caused by ash fall during an eruption and include loss of visibility, infiltration of communications and electrical systems and damage to aircraft [*Casadevall*, 1993; *Guffanti et al.*, 2009; *Hadley et al.*, 2004]. Since Eyjafjallajökull stopped erupting, the deposited ash which has been resuspended has, on occasion, reached Keflavík and Reykjavík airports. The highest peak in ash concentration occurred on 4 June 2010 when PM_{10} concentrations exceeded 2000 $\mu g/m^3$ in the Reykjavík area. This is the same concentration as used to specify the area of medium contamination of ash for aviation in-flight as described by the European and North Atlantic region volcanic ash contingency plan (available from European and North Atlantic office of the International Civil Aviation Organization (ICAO) at http://www.paris.icao.int). There are currently no agreed contamination levels relating to near-surface concentrations of resuspended ash at airports.

[7] There have been few direct studies of the factors affecting the remobilization of volcanic ash following a volcanic eruption. Studies of the remobilization of ash deposited following the eruption of Mount St Helens in 1980 demonstrated than even modest wind speeds of a few meters per second could result in ash being lifted by the wind [*Hobbs et al.*, 1983]. In more extensive wind tunnel experiments, *Fowler and Lopushinsky* [1986] showed that the threshold wind velocity for resuspension of ash particles from the 1980 eruption of Mount St Helens on a smooth surface was 3 m/s and that this threshold decreased for rougher surfaces. *Fowler and Lopushinsky* [1986] also noted that repeated wetting and drying of the ash consolidated the ash surface making it more resistant to remobilization. However, even consolidated ash can be remobilized with sufficiently strong winds. Such an event occurred 81 years after the eruption of Katmai volcano, Alaska when, following a period of dry weather, sufficient ash was resuspended to impact aviation operations at Kodiak airport [*Hadley et al.*, 2004].

[8] Shortly after the end of the Eyjafjalljökull eruption, concern over the frequency of resuspension events in southern Iceland led the Icelandic Meteorological Office to approach the UK Met Office for assistance in producing warnings of possible ash resuspension events. This paper describes how source information provided by the Icelandic Meteorological Office and the Institute of Earth Science at the University of Iceland was used in the dispersion model NAME (Numerical Atmospheric-dispersion Modelling Environment) to investigate whether it would be possible to produce forecasts of days

when high airborne ash concentrations were likely to occur. The modeled ash concentrations were compared to observations of airborne ash concentrations made in Iceland and these comparisons are discussed in this paper.

2. Observations

[9] Observations of resuspended ash were collected during two periods. First, two PM_{10} monitors (measuring concentrations of particulate matter with a diameter of 10 μm or less) were established, one by the Environment Agency, Iceland, within the region of deposited ash at Heimaland community center and the other by the University of Applied Sciences, Düsseldorf, Germany, in the Hvolsvöllur municipality, 15 km and 34 km from the edge of the Eyjafjallajökull glacier, respectively (see Figure 1 for exact locations). Both of these monitors were located in rural areas. PM_{10} measurements from two permanent Environment Agency monitoring sites in the Reykjavík area, Grensásvegur and Hvaleyrarholt were also used in this study. The Grensásvegur monitor is located at a busy road intersection in Reykjavík and the Hvaleyrarholt monitor is located in an industrial site in the outskirts of the capital. Mean background PM_{10} concentrations at these two urban stations are of the order of 18–22 μg/m^3 which is much smaller than the PM_{10} concentrations observed during resuspension events which range from $\sim$100 μg/m^3 to $\sim$2000 μg/m^3. However, due to traffic, PM_{10} concentrations at Grensásvegur are more variable potentially masking smaller ash resuspension events. PM_{10} measurements from all four of these stations were available from the end of May until the beginning of July 2010. Concentrations were provided as hourly averages throughout the period and contained only a few gaps in measurement. No attempt has been made to fill the gaps.

[10] Second, an instrument was set up to count airborne particles at Drangshlidardalur. At this measurement site an optical particle counter (OPC: GRIMM EDM107) was used for the measurement of particles (the instrument is described in more detail by *Weber et al.* [2006]). The OPC allowed continuous measurements and was installed in weather protected housing. The measurement site was in Skogar (19.52018°W, 63.5298°N) beside a building, situated at the end of a small valley facing Eyjafjallajökull summit. This study compares model predictions of resuspended ash to data collected from this instrument between 21 September 2010 and 16 February 2011.

[11] The data consists of the number of particles per liter of air within each of 31 diameter ranges from 0.25 to 32 μm. This particle concentration was converted to a mass concentration in μg/m^3 by assuming that the particles were spheres with a density of 2300 kg/m^3 (the density value used in the modeling). The ash particles produced during the eruption of Eyjafjallajökull were generally not spherical [*Gislason et al.*, 2011] which may result in some uncertainty in the calculated mass.

3. Modeling Resuspended Ash

3.1. Dust Modeling

[12] When wind blows across a surface of loose material, such as sand, the grains will begin to move. Larger grains roll across the surface (creep), mid-sized grains bounce across the surface (saltate) and the smallest grains become airborne (are suspended) [*Bagnold*, 1941]. Studies examining the effect of the wind on desert sand and bare soil have shown that these motions only occur when the wind exceeds a threshold velocity [*Bagnold*, 1941; *Chepil*, 1945]. Studies have also shown that this threshold velocity varies in both space and time and is a function of the local atmospheric turbulence and local surface characteristics such as grain size, surface roughness, soil moisture and vegetation cover [e.g., *Fécan et al.*, 1999; *Gillette et al.*, 1982]. As it is the stress of the wind on the surface which mobilizes dust grains, numerical models generally compute the threshold friction velocity (where friction velocity characterizes the shear at the surface) at which dust grains are mobilized rather than the threshold wind velocity. Experiments have been carried out in wind tunnels to determine the threshold friction velocity for different surface characteristics. The threshold friction velocity is generally expressed as a function of grain diameter, grain density, surface roughness, soil moisture and vegetation cover [e.g., *Fécan et al.*, 1999; *Marticorena and Bergametti*, 1995].

[13] Once the threshold friction velocity has been exceeded grains may become airborne and field experiments have shown that the rate at which grains become airborne increases as a function of some power of the friction velocity. Wind tunnel experiments have shown that the dominant mechanism of resuspension is saltation. Saltating grains are lifted by the wind and then fall back to the ground. As they impact the surface their kinetic energy is transferred to surrounding grains causing them to leave the surface [*Shao et al.*, 1993]. Grains which are small enough will not fall back to the earth immediately but will remain airborne. Therefore, the rate of suspension is generally expressed as a linear function of the horizontal flux of saltating grains. The horizontal flux is typically expressed as a function of the third or fourth power of the friction velocity e.g., $Ku_*^3(1 - u_{*t}^2/u_*^2)$ suggested by *Shao et al.* [1993], $Ku_*^4(1 - u_{*t}/u_*)$, suggested by *Gillette and Passi* [1988] and 0.01 u_*^4 suggested by *Westphal et al.* [1987] where u_* is the friction velocity, u_{*t} is the threshold friction velocity, and K is a scaling parameter dependent on local surface conditions.

3.2. Modeling Resuspension Within NAME

[14] Modeling of the resuspension and subsequent advection of the ash was undertaken using NAME (the Numerical Atmospheric-dispersion Modeling Environment), the UK Met Office's Lagrangian particle dispersion model [*Jones et al.*, 2007]. Originally developed to model the spread of radionuclides from the Chernobyl disaster in 1986, NAME's capabilities have been expanded to include many physical processes on a wide range of scales. NAME is now used to model particulates and gases from a large variety of dispersion events including ash from volcanic eruptions, radionuclides from nuclear incidents, chemicals from large fires and biological agents associated with animal disease.

[15] NAME also contains a dust scheme which is based on the scheme of *Marticorena and Bergametti* [1995] and is also used in the Met Office's Numerical Weather Prediction (NWP) model [*Woodward*, 2001]. In this scheme the threshold friction velocity is calculated from grain diameter and soil moisture. Grains are then released from the surface at a rate which depends on the cube of the threshold friction

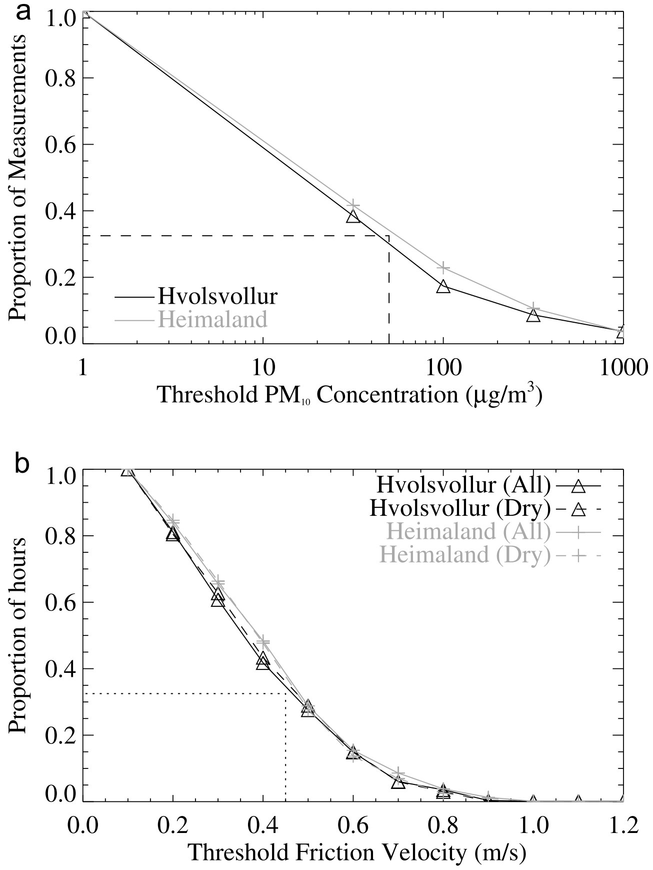


Figure 2. (a) Proportion of measurements where a PM_{10} threshold is exceeded at two locations (Heimaland, Hvolsvollur) within the area of surface lying ash. (b) Proportion of one-hour periods where the friction velocity exceeded a threshold. Calculation was carried out for all one-hour periods and one-hour periods without rain.

velocity, the proportion of bare soil and the size of grains. NAME's dust scheme was successfully used to model the transport of Saharan dust to Athens in April, 2005 [*Athanassiadou et al.*, 2006].

[16] Information about the spatially varying local surface characteristics, required by many dust suspension schemes (including the scheme in NAME), is not always available. This is particularly true for a region where volcanic ash has been recently deposited as the ash has significantly altered the surface characteristics. For instance, around Eyjafjallajökull large areas of glacier have been covered in ash, vegetation has been damaged or destroyed and new vegetation growth inhibited. Data sets of soil characteristics used for dust modeling and also used within NWP models for the computation of soil moisture are not updated frequently enough to capture fresh deposits of ash from volcanic eruptions. The current soil characteristics of this region are therefore unknown and it is not possible to use such dust schemes to model emissions of recently deposited volcanic ash.

[17] Simpler dust schemes have been used successfully to model suspension in both arid and semi-arid regions. *Escudero et al.* [2006] used a single value for the threshold friction velocity (0.28 m/s) to model mobilization of dust over northern Africa. *Draxler et al.* [2010] derived monthly values of the threshold friction velocity over North America using a four-year climatology of aerosol optical depth (AOD) from the MODIS satellite and friction velocities from the National Oceanographic and Atmospheric Administrations' National Centers for Environmental Prediction (12 km resolution) mesoscale forecast model. The threshold friction velocities were determined by equating the frequency of occurrence of aerosol optical depth (AOD) values equal to 0.75 with the friction velocity in that grid cell with the same frequency of occurrence. Values of the threshold friction velocity ranged from 0.11 to 1.1 m/s.

[18] There is insufficient data for the region of recently deposited ash in southern Iceland to derive values of threshold friction velocity using aerosol optical depths. Instead a single threshold friction velocity is derived for the whole region. A single value over the whole domain is assumed to be sufficient because all of the material was deposited from the same source and is therefore expected to have similar characteristics. The threshold friction velocity is derived by comparing the frequency of occurrence of $PM_{10} > 50\ \mu g/m^3$ to the frequency of occurrence of friction velocities at the same location extracted from the 12 km resolution limited area model of the UK Met Office's NWP model [*Davies et al.*, 2005]. This approach assumes that the presence of airborne ash at Heimaland and Hvolsvöllur is due only to ash resuspended locally at Heimaland and Hvolsvöllur (i.e., other sources of ash are ignored), and that the threshold friction velocity is a constant and does not depend on local meteorological conditions. The proportion of hours when resuspended ash is observed is expected to equal the proportion of hours when the threshold friction velocity is exceeded. Resuspended ash was assumed to have been observed during any hour when PM_{10} concentrations exceeded the European guideline (2008/50/EG) of $50\ \mu g/m^3$. PM_{10} concentrations exceeded $50\ \mu g/m^3$ 30% of the time at Hvolsvöllur and 35% of the time at Heimaland (Figure 2a). The corresponding friction velocity that was exceeded 30–35% of the time was approximately 0.45 m/s (Figure 2b). This suggests that a threshold friction velocity between 0.4 and 0.5 m/s is appropriate. Note that this threshold friction velocity is not dependent on grain size.

[19] Model runs were carried out with threshold friction velocities of both 0.4 m/s and 0.5 m/s. However, the model run using the resuspension scheme with a threshold friction velocity of 0.5 m/s missed and truncated more resuspension events than the model run using the resuspension scheme with a threshold friction velocity of 0.4 m/s. Therefore, only the run using 0.4 m/s is considered here. This is similar to the threshold friction velocity (0.42 m/s) measured in wind tunnel experiments carried out at Landeyjasandur [*Sigurjonsson et al.*, 1999]. Landeyjasandur is a region of sand/dust on the south coast of Iceland consisting of flood deposits and glacier ground material from the Markafljót river which is fed by the Mýrdalsjökull and Eyjafjallajökull glaciers.

[20] A threshold friction velocity of 0.4 m/s could be achieved in the NAME dust scheme for particles with a diameter in the range 1–10 μm if the soil moisture is around 10%. This is lower than the average soil moisture for Southern Iceland which is estimated by the NWP to be around 30% and is probably due to the poor water retention characteristics of the recently deposited volcanic ash [*Arnalds et al.*, 2001]. As

precipitation is expected to reduce the likelihood of ash resuspension, and in the absence of soil moisture information, resuspension was halted whenever precipitation rates exceeded 0.01 mm/hr. Given the apparent fast draining characteristics of the ash this would seem to be a reasonable assumption.

[21] As mentioned in the previous section the vertical flux of dust is usually expressed as a third or fourth power of the friction velocity or somewhere between the two. In this study material was released from the surface at a rate proportional to the cube of the excess friction velocity where excess friction velocity is equal to the local friction velocity minus the threshold value (1).

$$\text{Source Strength} = \begin{cases} K(u_* - u_{*t})^3 & u_* \geq u_{*t} \\ 0 & u_* < u_{*t} \end{cases} \tag{1}$$

where u_* is the friction velocity (in m/s) and u_{*t} the threshold friction velocity (in this case 0.4 m/s). K is a dimensional constant used to obtain a source strength with units of g/s. Note that in most dust schemes K is proportional to the density of the material being lifted. However, we treat this parameter as a scaling coefficient which can be adjusted to derive a source strength which is consistent with observed ash concentrations. Initially K was set to 1 to give a source strength equal to $(u_* - u_{*t})^3$. This form of the source strength equation differs from those described in section 3 and although applicable here more study would be required to determine whether it was universally applicable. NAME was run with this source strength for 23 May 2010 to 2 July 2010 and the predicted concentrations were calibrated using observations from the same period of time. Calibration of the model predictions is described in the next section.

[22] Defining the source area, the region from which ash may be lifted given favorable conditions, is a very important feature of any modeling. Here the source region is defined using an area provided by Esther Hlíðar Jensen from the Icelandic Meteorological Office and Ármann Höskuldsson and Guðrún Larsen from the Institute of Earth Science at the University of Iceland and shown in Figure 1. Measurements made shortly after the end of the eruption showed that the deepest ash deposits lay on the Eyjafjallajökull ice-cap and that deposits greater than 5 mm covered an area of approximately 3000 km^2. As the depth of material has little impact on the erodibility of the surface the ash source region used in the model was assumed to include all regions where the ash deposit depth was greater than 5 mm. The source region is approximated in NAME by a grid of rectangular sources 0.01° latitude by 0.01° longitude (approximately 1.1 km by 0.5 km). When the model is run information about the meteorological conditions in each of these grid cells is extracted from the driving meteorology and used to determine whether particles should be released. Thus, in certain weather conditions it is possible for particles to be released only from part of the source region.

[23] Lifted particles are released in the model between 0 and 10 m above the surface (the exact height that each particle is released is randomly assigned, with a uniform distribution, between these limits). This ensures that they are not immediately redeposited. Once the ash particles are lifted from the model surface they are advected by the three-dimensional model winds and dispersed using random walk techniques that take into account the ambient turbulent velocity structures. NAME was driven by meteorology from a limited area version of the UK Met Office's NWP model covering the North Atlantic and Europe at a resolution of 12 km by 12 km [*Davies et al.*, 2005]. Sensitivity tests were carried out using meteorological data from the global NWP model (which has a resolution of 0.35° longitude by 0.23° latitude; approximately 17 km by 26 km over Iceland) but the higher resolution limited area model with corresponding higher resolution surface ancillaries was found to perform better for forecasts of ash resuspension. Eyjafjallajökull is close to the southern coast of Iceland and in an area of complex topography. This topography and the location of the coastline are better represented in the limited area model and, because surface characteristics, such as roughness, are used in the calculation of friction velocity, the limited area model is a more appropriate model for resuspension forecasts in this region.

[24] Ash particles are removed from the model atmosphere by several deposition processes: (1) fall out due to gravity, (2) impaction with the surface, (3) washout where ash is 'swept out' by falling precipitation and (4) rainout where ash is absorbed directly into cloud droplets as they form. Currently no attempt is made to resuspend these deposited particles as it is assumed that the amount of ash deposited from the resuspended plume is much smaller than the amount of ash deposited during the eruption of Eyjafjallajökull. Similarly no attempt is made to deplete/augment the ash in the original supply. Clearly these assumptions may not hold over longer periods of time.

[25] To be able to compare the model predictions directly with the PM_{10} measurements, particles were released with diameters between 1 μm and 10 μm. To be able to compare the model predictions directly with the particle concentration measurements, the particle size distribution was altered so that particles with a diameter between 0.25 and 32 μm were released. Lagrangian particles were distributed uniformly with the natural log of the diameter within these ranges. The size distribution has no effect on the threshold friction velocity or the source release rate and is only used in calculations of gravitational settling once the material is airborne.

3.3. Calibration

[26] The concentrations predicted by the model were calibrated using the PM_{10} observations from four monitoring locations located at Heimaland, Hvolsvöllur, Grensásvegur and Hvaleyrarholt. First the background PM_{10} concentration was subtracted from the observations. This is because NAME was only set up to model PM_{10} from resuspended ash but the PM_{10} monitors could potentially observe PM_{10} from other sources such as traffic and industry. As only a month and a half of PM_{10} observations were available it was not possible to compute the daily and/or seasonal variations in the background PM_{10} concentrations. Instead, the background concentration was computed by taking the average of all PM_{10} observations from all stations during hours when no resuspension was simulated by NAME at the station. Background concentration values from individual stations ranged from 11 μg/m^3 to 22 μg/m^3 and were therefore much smaller than the concentration values during resuspended ash episodes which were of the order of several hundred to several thousand micrograms per meter cubed. This background value was then

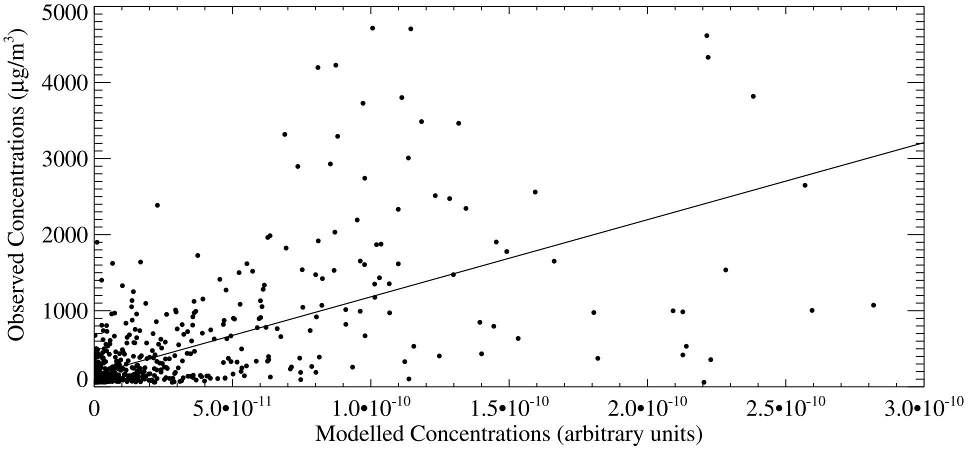
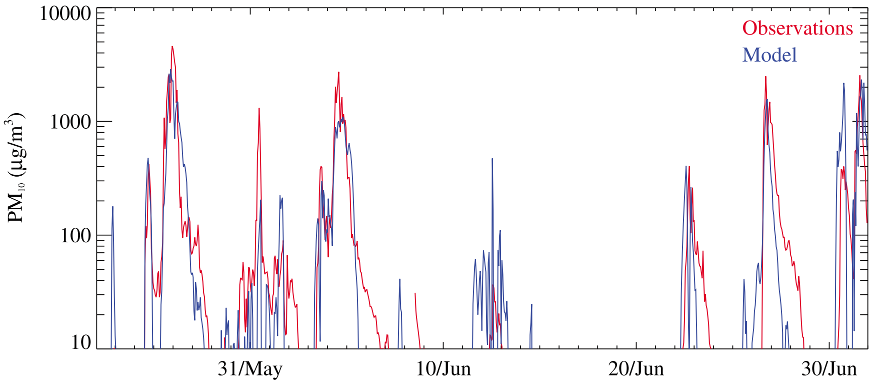


Figure 3. Comparison of simultaneous model predictions and observations from Heimaland, Hvolsvöllur, Grensásvegur and Hvaleyrarholt. Observations less than two standard deviations above the background have been removed. Note that this figure shows the model predictions before multiplying by the scaling coefficient *K* so units are arbitrary (see section 3.3). The line is a linear fit of the observations to the model predictions.

subtracted from all PM_{10} observations to give time series of observed resuspended ash.

[27] Since background concentrations varied and concentrations during ash episodes were typically much larger, the scaling coefficient *K* (see equation (1)) was computed by comparing simultaneous observations and predictions only when the observations exceeded the background value plus two standard deviations (Figure 3). The scatter is large as would be expected for a dispersion problem of this type where the exact source characteristics are unknown. The scaling coefficient *K* is taken to be the slope of a linear fit of the observations to the model predictions. Here

(a) Heimaland



(b) Hvolsvollur

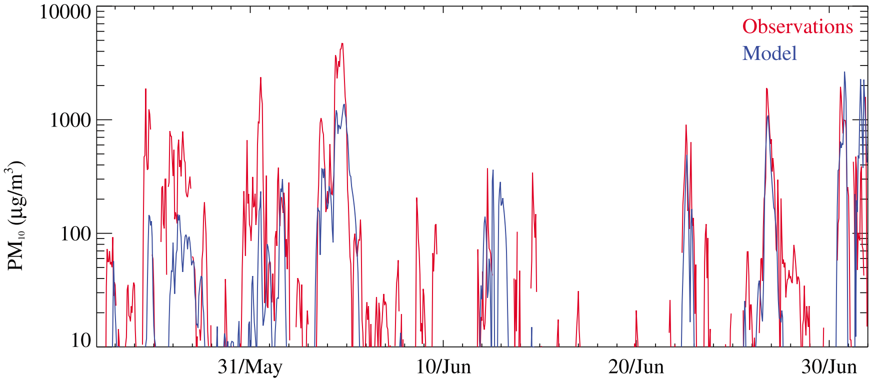


Figure 4. Comparison between PM_{10} observations at two sites in southern Iceland (red) and predicted air concentrations from NAME (blue).

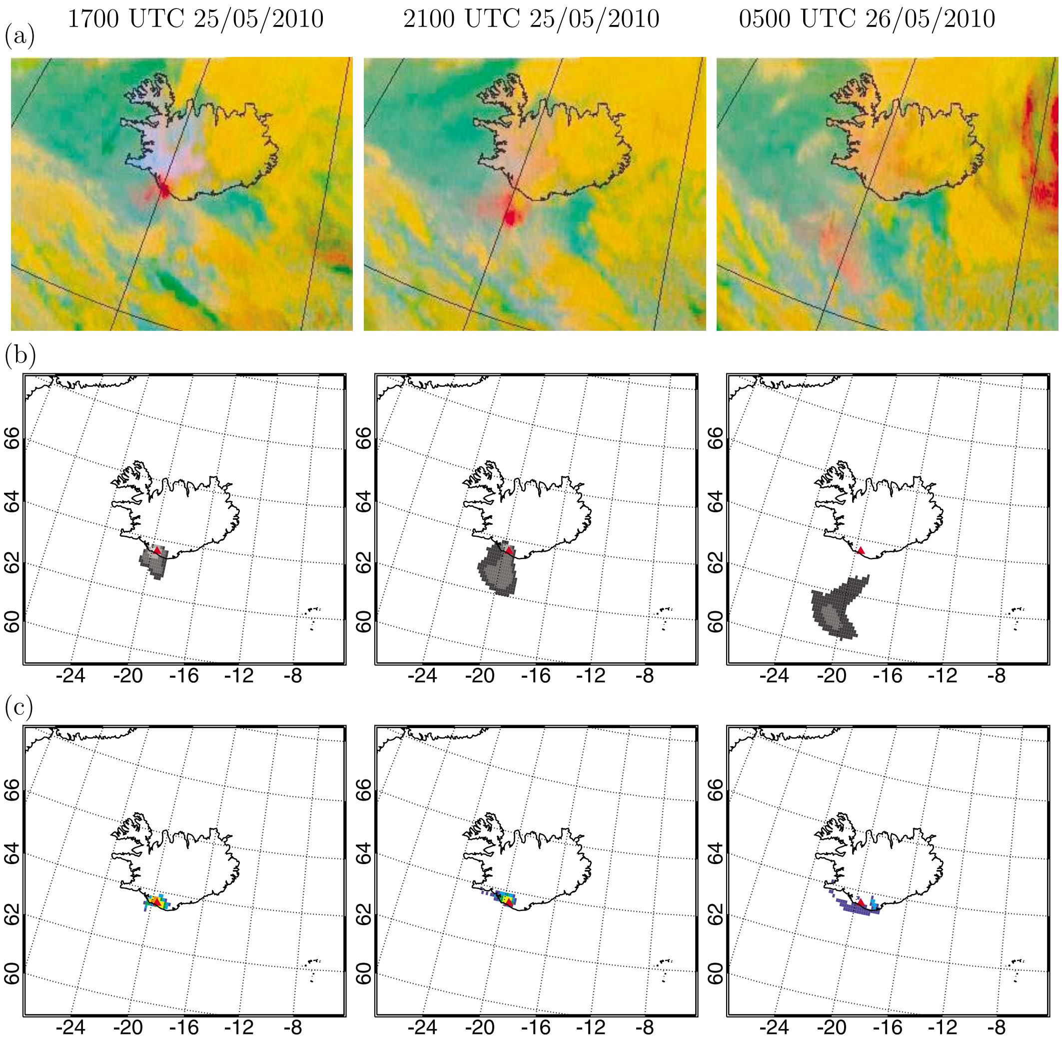

1700 UTC 25/05/2010 2100 UTC 25/05/2010 0500 UTC 26/05/2010

Figure 5. Qualitative comparison between (a) dust visible in the RGB dust product from the SEVIRI on the MSG satellite (pink-red plume), (b) one-hour average, vertically integrated concentrations of dust predicted by NAME, and (c) one-hour average, boundary layer average concentrations of dust predicted by NAME on 25 and 26 May 2010.

$K = 1.10 \times 10^{13}$ gm^{-1} (the slope of the linear fit shown in Figure 3). NAME predictions for all monitoring locations were then multiplied by K.

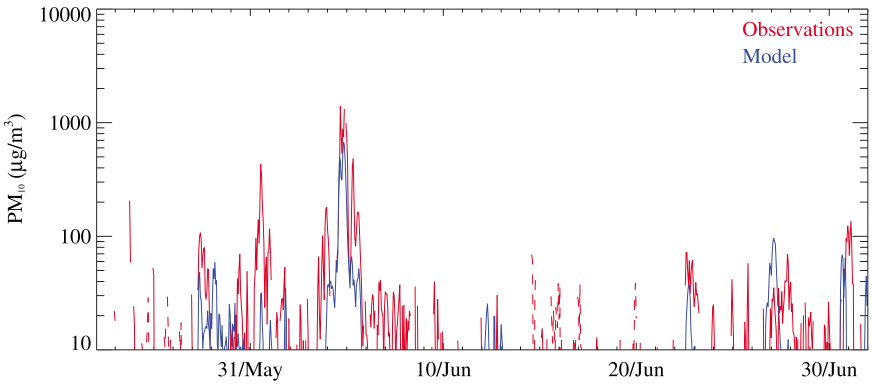
4. Results

[28] Predictions of the airborne concentration of ash were compared with observations from two periods. First, the model predictions were compared with PM_{10} observations both within the source region and in Reykjavík collected between the end of the eruption on 23 May 2010 and 2 July 2010. Second, the model predictions were compared to airborne particle counts carried out at Drangshlidardalur between 21 September 2010 and 16 February 2011. In both cases background concentrations, estimated by averaging the concentrations of all hours when NAME predicted no resuspension, were subtracted from the observations before they were compared to the model predictions. The scaling coefficient computed using the PM_{10} observations was applied to the data from both periods.

4.1. 23 May 2010 to 2 July 2010

[29] Time series of PM_{10} concentrations predicted by NAME, calibrated as described in the previous section, were output at the same four locations as the PM_{10} measurements. Heimaland and Hvolsvöllur lie within the region of deposited ash so experienced frequent episodes of high PM_{10} concentrations (>50 μg/m^3). In particular, episodes of high PM_{10} concentration were observed on 25–28 May, 31 May–2 June, 3–5 June, 12 June, 22 June, 26 June and 30 June–1 July (Figure 4). Generally NAME does a reasonable job of predicting the timing of these resuspension episodes indicating an appropriate choice of threshold friction velocity. Hit rates and false alarm rates [*Stephenson*, 2000] were computed for 24-hour rolling averages of concentration where hits were defined as those 24-hour periods when both the observations and the model recorded average concentrations above 50 μg/m^3. At Heimaland and Hvolsvöllur hit rates were 78% and 66%, respectively and false alarm rates were 7% and 14% respectively. Hvolsvöllur experienced a greater number of resuspension episodes some of which

(a) Grensasvegur



(b) Hvaleyrarholt

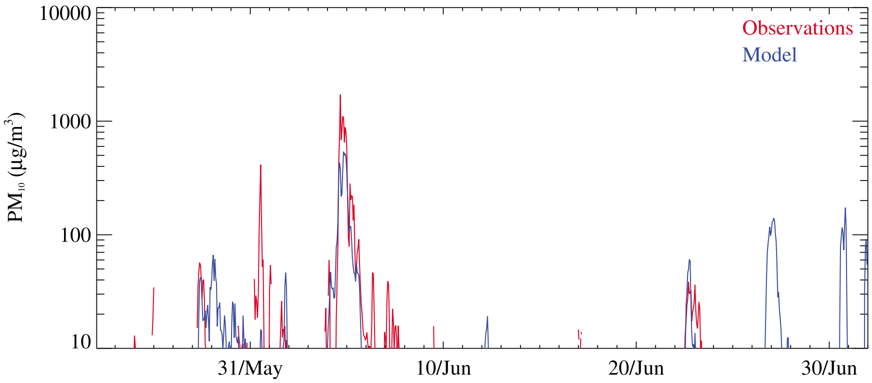
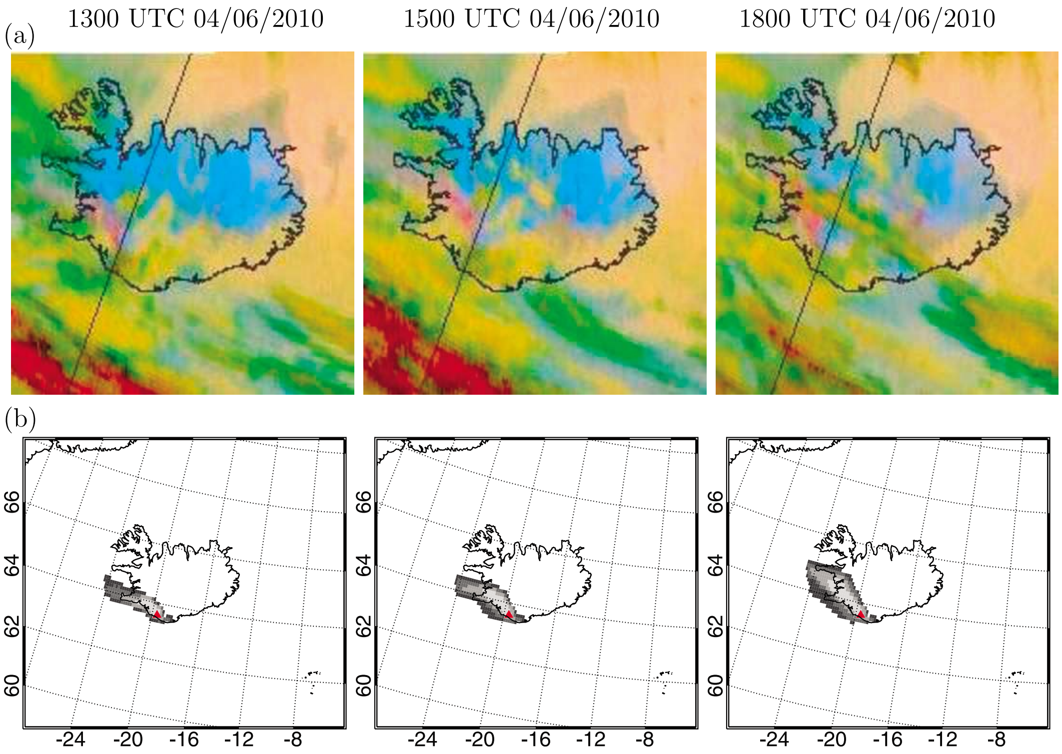


Figure 6. Comparison between PM$_{10}$ observations (red) at two sites in/close to Reykjavík, Iceland and predicted air concentrations from NAME (blue). Periods in the observations where, due to the wind direction, resuspended ash is not a possible source of PM$_{10}$ are shown dashed.

were not captured by the model predictions. This may be due to the location of the PM$_{10}$ monitor in the village where local activity such as sweeping and traffic may have resulted in ash being resuspended at lower friction velocities, leading to higher concentrations of PM$_{10}$. Additionally, the duration of some of the events (e.g., 4–5 June) is truncated in duration in the model predictions. This is probably due to the sharp cut-off of resuspension below the threshold friction velocity. In addition to the timing, the magnitudes of the ash resuspension episodes predicted by the model are in reasonable agreement with the relative magnitudes of the observed episodes of ash resuspension.

[30] In southern Iceland the largest resuspension episode occurred only a few days after the end of the eruption between 25 and 27 May. PM$_{10}$ concentrations reached 4161 μg/m^3 at Heimaland on 26 May and PM$_{10}$ concentrations at Hvolsvöllur reached 1900 μg/m^3 on 25 May. This resuspension episode was also captured in the RGB (red-green-blue) dust product from the SEVIRI (Spinning Enhanced Visible and Infra-Red Imager) on the MSG (Meteosat Second Generation) satellite (a full description of this product is given by *Millington et al.* [2012]). Ash was resuspended along the south coast of Iceland during the afternoon and evening of 25 May. The ash was then transported southwards and in the early morning of 26 May began to spread both in a northwesterly and southeasterly direction. Due to their position, satellites measure the integrated dust content of the atmosphere rather than the dust within a thin layer. So, to compare the NAME predictions with satellite images of dust, model concentrations were vertically integrated over the full depth of the atmosphere. The model shows good agreement with the observations (Figures 5a and 5b). On 25 and 26 May 2010 there was significant wind shear over southern Iceland with winds blowing from east to west at sea level and from north to south at the height of the glacier (~1500 m above sea level). Ash resuspended from the glacier is, therefore, advected southwards above the marine boundary layer while ash resuspended from ground close to sea level is advected westward within the marine boundary layer. Thus, boundary layer concentrations of ash predicted by the model (Figure 5c) are high to the west of the region of deposited ash in contrast to the total column concentrations. This demonstrates the difficulty of using satellite images to infer boundary layer concentrations of resuspended ash.

[31] At the monitoring stations at Grensásvegur and Hvaleyrarholt PM$_{10}$ concentrations reached a maximum of 1413 μg/m^3 and 1726 μg/m^3 respectively on 4 June. Both the timing and the relative magnitude of this event are well captured by the model predictions (Figure 6). High PM$_{10}$ concentrations were also observed in Reykjavík on the 4–5 June 2010 because strong winds blowing from the east-southeast caused large amounts of ash to be resuspended and blown directly toward the city. This can clearly be seen in the vertically integrated ash concentrations predicted by NAME (Figure 7). Widespread cloud cover made it more


(a) 1300 UTC 04/06/2010 1500 UTC 04/06/2010 1800 UTC 04/06/2010

(b)

Figure 7. Qualitative comparison between (a) dust visible in the RGB dust product from the SEVIRI on the MSG satellite (pink-red plume) and (b) one-hour average, vertically integrated concentrations of dust predicted by NAME on 4 June 2010.

difficult to detect wind blown dust over Iceland in the satellite dust products for 4–5 June 2010. However, a faint dust signal can be seen in the RGB dust product from SEVERI on 4 June 2010. Initially the dust is blown westward from southern Iceland and carried directly toward Reykjavík. Then between 1300 UTC and 1800 UTC the wind direction changes carrying the ash to the north of Reykjavík. This movement is captured in the model predictions.

[32] The model also predicts high PM_{10} concentrations due to volcanic ash on 29–31 May, 22 and 26 June and 1 July. At Grensásvegur there is some evidence of high PM_{10} concentrations on 26–31 May, 22 June and 1 July (Figure 6), although high background values make it difficult to conclusively link this to volcanic ash. The Grensásvegur PM_{10} monitor is located at a busy road intersection so, even in the absence of ash, higher and more variable PM_{10} values would be expected here. Data for the period 26 June to 1 July is missing from the Hvaleyrarholt observations but high PM_{10} concentrations were observed between 26–31 May and on 22 June in agreement with model predictions. Due to the low number of episodes observed at these stations hit rates and false alarm rates were not computed.

4.2. September 2010 to February 2011

[33] Mass concentrations computed from the particle concentrations measured at Drangshildardalur were compared to the mass concentration predicted by NAME for the same location. Between 19 September 2010 and 16 February 2011 there were 12 observed episodes of high airborne ash concentrations (Figure 8 and Table 1). The most severe of these episodes occurred between 16 and 22 December (Episode (8) in Table 1) when concentrations reached 1900 $\mu g/m^3$ and concentrations were almost continually greater than 50 $\mu g/m^3$ for 5 days. Very high concentrations (up to 1624 $\mu g/m^3$) were also observed during a prolonged, 54 hour, episode between 5–8 January (Episode (11) in Table 1). Both these periods were dominated by strong north to northeasterly winds. There is good agreement between the timing, duration and relative magnitude of the model predictions and the observations for episodes 1, 2, 3, 4, 5, 8, 10 and 11, but the model underpredicted episodes 6, 7, 9 and 12, although some ash was predicted during all of these periods. The model also predicted high airborne ash concentrations on several occasions when low airborne ash concentrations were observed; 28 September–6 October, 10 October, 9 November, 11 December, 1 January and 30 January to 14 February. Over the whole time period the model captured 66% of the resuspension events but had a false alarm rate of 21%. If events before 20 October 2010 and after 16 January 2011, when precipitation was recorded, are excluded the false alarm rate is reduced to 17% indicating that resuspension is inhibited for some hours following precipitation.

5. Discussion

[34] Generally, the timing, duration and relative magnitude of the resuspension events between the end of the eruption of Eyjafjallajökull and 2 July 2010 were reasonably well captured by the model. Comparisons of model predictions of two resuspension episodes on 25 and 26 May 2010 and 4 and 5 June 2010 to satellite dust imagery show that the

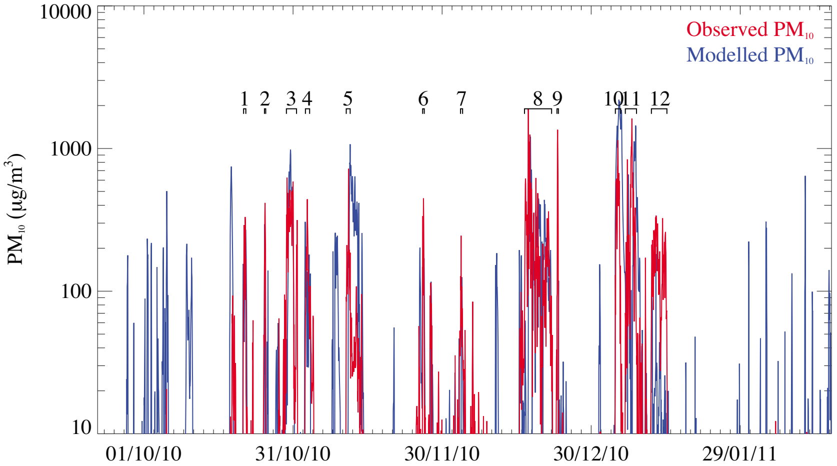


Figure 8. Comparison of observations of resuspended ash (red) with NAME predictions of resuspended ash (blue) at Drangshlidardalur. Numbers refer to resuspension episodes discussed in the text.

model also correctly predicts the spatial extent of the ash storms. These comparisons also highlight the difference between ground observations and satellite observations during periods of significant wind shear. The location of the highest dust signal in the satellite imagery is not always co-located with the peak in ash concentrations observed at ground level.

[35] Resuspension episodes during the later period, September 2010 to February 2011 were captured less well by the model than the episodes in late May/June. There are a number of model predictions on days when no ash was observed between October and February and some ash episodes are underpredicted. This may be due to a number of factors. Predictions of airborne ash in this study are made using meteorological variables (friction velocity and precipitation), however, local surface variables will also influence the likelihood of resuspension and the rate at which material is resuspended. These can be grouped into three categories which will be discussed in turn: consolidation of the surface, covering of the surface and depletion/migration of the original supply.

5.1. Consolidation

[36] The addition of moisture to the soil through precipitation increases soil cohesion making it less susceptible to suspension by the wind [*Fécan et al.*, 1999]. Also, for a freshly deposited material, such as volcanic ash, the effect of wetting may not be reversed as the material dries out. Repeated wetting and drying of ash from the 1980 eruption of Mount St Helens resulted in consolidation of the surface that, even when dry remained resistant to resuspension [*Fowler and Lopushinsky*, 1986]. Parameterizations of the ratio of wet and dry threshold friction velocity have been developed [e.g., *Fécan et al.*, 1999] but they rely on access to temporally and spatially varying soil moisture content. Soil moisture is often calculated within NWP models but because it relies on databases of soil types it is likely to be incorrect for freshly deposited ash such as that studied here. Consolidation can also be reversed by disturbances such as sweeping, vehicle movement and ploughing, activities which are difficult to include in models.

[37] Analysis shows that all of the false predictions of episodes of resuspended ash in late January and early February 2011 occur after periods of precipitation (Figure 9). This suggests that the soil becomes temporarily consolidated by the addition of moisture. Although resuspension is halted in the model during precipitation no information about precipitation which occurred in the past is retained by the model and no attempt is made to parameterize the drying out process. An extension of this study would be to include a simple parameterization of the wetting and drying out process. This would reduce the number of false predictions as the resuspension of the ash does not commence immediately precipitation stops even if the threshold friction velocity is exceeded.

5.2. Covering of the Surface

[38] Initially it was assumed that between October and March snow would first cover the ash and then consolidate it vastly reducing the likelihood of resuspension events. Snow cover inhibits the resuspension of ash from the surface so its absence from the forecast could result in false forecasts of ash suspension when snow is present. However, due to its position on the southern coast of Iceland this region typically experiences the lowest number of days with full snow cover in Iceland [*Einarsson*, 1984]. In addition surface snow cover

Table 1. Dates When High Volumes of Particulates Were Measured by the Optical Particle Counter at Drangshlidardalur

Number	Dates	Maximum 1-Hour Concentration ($\mu g/m^3$)	Approximate Duration (hours)
(1)	21 October 2010	331	13
(2)	25 October 2010	415	6
(3)	29–31 October 2010	624	36
(4)	2–3 November 2010	440	25
(5)	10–11 November 2010	721	20
(6)	26 November 2010	447	8
(7)	3–4 December 2010	245	8
(8)	16–22 December 2010	1901	130
(9)	23 December 2010	1070	7
(10)	3–4 January 2011	1141	26
(11)	5–8 January 2011	1624	54
(12)	11–14 January 2011	338	75

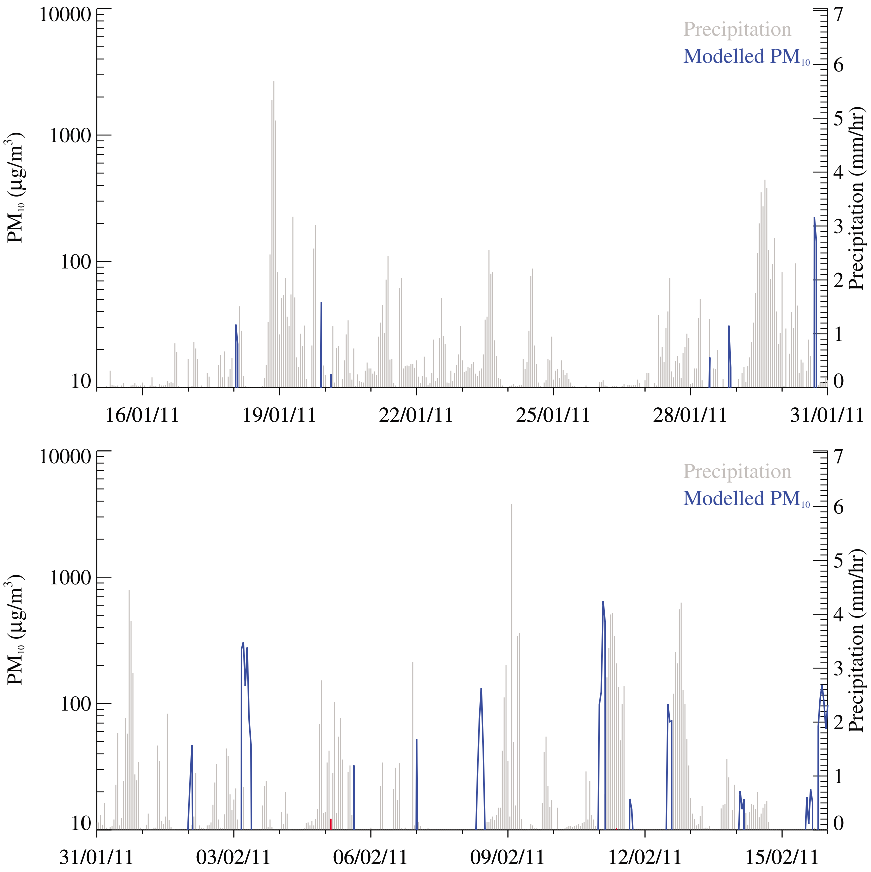


Figure 9. Comparison of NAME predictions of resuspended ash (blue) at Drangshlidardalur with precipitation (grey) at the same location between 15 January 2011 and 15 February 2011.

in the area may be inhomogeneous as the region varies in altitude.

[39] Snow fell and remained on the ground during the first week of February 2011 (meteorological observations made at Vatnsskarðhólar). This snow cover acted as a barrier to resuspension. Although snow is forecast by the NWP, and deposition due to snow is parameterized in NAME, no information about surface snow cover is retained in NAME and this could have resulted in several false predictions in early February.

5.3. Depletion/Migration of the Supply

[40] Measurements of the resuspension of radionuclides near Chernobyl showed that the ratio of the air concentration at breathing height to the initial surface deposit (termed the 'resuspension factor') was approximately 10^{-6} [*Garger et al.*, 1997] so the time-dependence of resuspension is more likely to be due to consolidation and covering of the surface than by depletion of the supply of material [*Anspaugh et al.*, 1975].

[41] The combined effect of surface consolidation and depletion/migration of the supply of resuspendable material has been investigated in relation to radionuclides. Following the explosion at Chernobyl in 1986 radionuclides were deposited around the plant and continued to be resuspended for many years. Studies of monthly averaged concentrations determined that an inverse power law best described the decrease of the resuspension factor with time [*Garger et al.*, 1999]. It is too early to determine whether a similar relationship is true for concentrations of resuspended ash.

[42] In addition to the lack of data describing the surface characteristics, time constraints and limited observations meant that it was not possible to investigate a range of parameterizations of source strength. The source strength was assumed to be proportional to the third power of the excess friction velocity. However, some studies [e.g., *Gillette and Passi*, 1988] have argued that the source strength may be better expressed as the fourth power of the friction velocity. An extension of this work would be to investigate different parameterizations of the source strength.

6. Summary and Conclusions

[43] Eyjafjallajökull, a volcano in southern Iceland, erupted explosively in April and May 2010 depositing ash over a region of more than 3000 km^2 to the west and southwest of the volcano. This deposited ash has been frequently remobilized by the wind causing a health concern for the Icelanders living in the region. On occasion the ash has also been blown as far as Reykjavík and Keflavík airports causing concern for aviation. This paper describes a study carried out to examine the feasibility of producing forecasts of ash resuspension episodes.

[44] Modeling was carried out with the UK Met Office's Lagrangian dispersion model NAME using a gridded map of the ash deposits. Particles were only released from the surface

when local friction velocities exceeded 0.4 m/s and precipitation was less than 0.01 mm/hr. Ash was then released from the surface at a rate proportional to the cube of the excess friction velocity (where the excess friction velocity is equal to the local friction velocity minus the threshold). The magnitude of airborne ash concentrations were calibrated using observations of PM_{10} taken between 23 May and 2 July. The calibrated predictions were then compared to these observations of PM_{10} as well as to concentrations derived from observations of particle numbers taken between 21 September 2010 and 16 February 2011 in southern Iceland.

[45] Generally the timing and relative magnitudes of the ash resuspension episodes in late May and June 2010 are well captured by the model predictions, although the duration of some events are truncated in duration in the model due to the sharp cut-off at the threshold friction velocity. Comparison with satellite data demonstrated that the spatial extent of ash storms is well captured by the model. However, this comparison also highlights the problems of comparing satellite data to ground based observations particularly when there is significant wind shear.

[46] The timing and duration of the resuspension episodes which occurred between September 2010 and February 2011 (not used in the calibration) are also well represented in the model but the relative magnitudes of the episodes is less well captured. There are also a number of predicted episodes when no ash was observed, probably due to recent precipitation. This study has concentrated on predicting the resuspension of ash using only wind and precipitation information. However, there are a number of other factors which will influence the likelihood of ash resuspension including consolidation of the surface, covering of the surface and (in some places) a depletion of the supply of volcanic ash. The impact of these factors on the resuspension of ash is likely to increase with time.

[47] Despite limitations this study shows that it is possible to use dispersion modeling to provide forecasts of ash resuspension episodes. Consequently, the ash resuspension model described above was set up to run on forecast meteorological data (as well as analysis meteorological data) and is run daily. The model produces time series of airborne ash concentration both for the monitoring locations in southern Iceland and for Reykjavík and Keflavík airports as well as maps showing the regions likely to be affected by resuspended ash. These times series and maps are then sent to the Icelandic Meteorological Office. When high concentrations of airborne ash are forecast by the model a text summary of the areas likely to be affected is included in the weather forecast.

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