甲D第349号証

High levels of particulate matter in Iceland due to direct ash emissions by the Eyjafjallajokull eruption and resuspension of deposited ash. J Geophys Res Solid Earth 117

ARTICLE *in* JOURNAL OF GEOPHYSICAL RESEARCH ATMOSPHERES · SEPTEMBER 2012

Impact Factor: 3.43 · DOI: 10.1029/2011JB008756

4 AUTHORS, INCLUDING:


Throstur Thorsteinsson
University of Iceland
35 PUBLICATIONS **478** CITATIONS


Nina Iren Kristiansen
Norwegian Institute for Air Research
30 PUBLICATIONS **394** CITATIONS

High levels of particulate matter in Iceland due to direct ash emissions by the Eyjafjallajökull eruption and resuspension of deposited ash

Throstur Thorsteinsson,[1] Thorsteinn Jóhannsson,[2] Andreas Stohl,[3] and Nina I. Kristiansen[3]

Received 5 August 2011; revised 7 November 2011; accepted 9 November 2011; published 10 January 2012.

[1] The dangers to people living near a volcano due to lava and pyroclastic flows, and, on glacier- or snow-covered volcanoes, jökulhlaups, are well known. The level of risk to human health due to high concentrations of ash from direct emission and resuspension from the ground is, however, not as well known. The eruption at Eyjafjallajökull, 14 April to 20 May 2010, produced abundant particulate matter due to its explosive eruption style. Even after the volcanic activity ceased, high particulate matter (PM) concentrations were still measured on several occasions, due to resuspended ash. The 24 hour mean concentration of PM_{10} in the small town of Vík, 38 km SE of the volcano, reached 1230 μg m^{-3}, which is about 25 times the health limit, on 7 May 2010, with 10 min average values over 13,000 μg m^{-3}. Even after the eruption ceased, values as high as 8000 μg m^{-3} (10 min), and 900 μg m^{-3} (24 h), were measured because of resuspension of freshly deposited fine ash. In Reykjavík, 125 km WNW of the volcano, the PM_{10} concentration reached over 2000 μg m^{-3} (10 min) during an ash storm on 4 June 2010, which should have warranted airport closure. Summarizing, our study reveals the importance of ash resuspension compared to direct volcanic ash emissions. This likely has implications for air quality but could also have detrimental effects on the quality of ash dispersion model predictions, which so far generally do not include this secondary source of volcanic ash.

Citation: Thorsteinsson, T., T. Jóhannsson, A. Stohl, and N. I. Kristiansen (2012), High levels of particulate matter in Iceland due to direct ash emissions by the Eyjafjallajökull eruption and resuspension of deposited ash, *J. Geophys. Res.*, *117*, B00C05, doi:10.1029/2011JB008756.

1. Introduction

[2] The eruption of the Eyjafjallajökull volcano system started with a relatively small eruption on Fimmvörduháls just before midnight on 20 March 2010, which lasted till 12 April [*Sigmundsson et al.*, 2010]. No significant ash plume was formed during the Fimmvörduháls eruption. The eruption at the top of Eyjafjallajökull, occurring below the peak of Eyjafjallajökull glacier at 1650 m a.s.l., started on 14 April 2010 and lasted till 20 May the same year, as defined by the last day of visible plume.

[3] The previous eruption of the Eyjafjallajökull volcanic system was a short phreato-magmatic phase in December 1821, followed by a yearlong period of intermittent magmatic/phreato-magmatic activity [*Larsen et al.*, 1999]. The explosive eruption that began on 14 April 2010 was the culmination of a long series of intermittent magmatic events observed over the past 18 years [*Sigmundsson et al.*, 2010].

[4] Ash production during the Eyjafjallajökull eruption was greatest at the beginning, between 14 and 20 April, and again toward the end, 5–18 May. In an inverse modeling study, using atmospheric ash loadings retrieved from satellite data, *Stohl et al.* [2011] found a total fine ash (diameter 2.8–28 μm) emission of 8 $\pm$ 4 Tg. On 17 April 2010 there was a northerly wind direction, and this was the day with the strongest ash fall felt by the local population (Figure 1) [*Petersen*, 2010]. Up to 4 cm of fine grained ash, properties of the ash are described by *Gíslason et al.* [2011], were deposited in the lowland south of the volcano on 17 April 2010 (G. Larsen, personal communication, 2010).

[5] Measurements of particulate matter (PM) in Vík (Figure 2) began on 22 April, and until 7 May 2010 wind direction was such that ash from the eruption had not been felt strongly in urban areas; although local farmers were hard hit south of the volcano (Figure 1). Reykjavík was never hit directly by the eruption plume, but on 4 June 2010 resuspended ash, an ash storm, reduced the visibility and the concentration of PM_{10} reached 2000 μg m^{-3}.

[6] There is mounting evidence about the adverse health effects of exposure to particulate matter. Exposure to ash from volcanoes, a source of particulate matter, during a longer time period might thus be associated with increased

[1]Environment and Natural Resources and Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland.
[2]The Environment Agency of Iceland, Reykjavík, Iceland.
[3]Norwegian Institute for Air Research, Kjeller, Norway.

0148-0227/12/2011JB008756

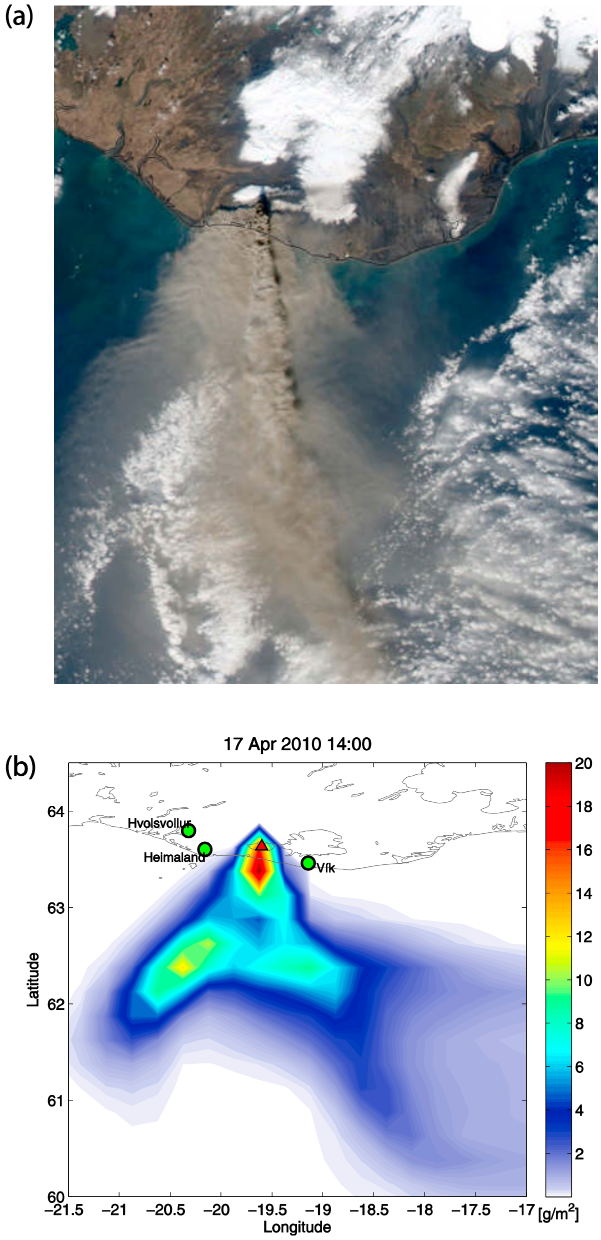

Figure 1. (a) The eruption plume from the Eyjafjallajökull volcano, and some resuspended ash, at 13:15 LT on 17 April 2010. Image from NASA Goddard Space Flight Center, MODIS Rapid Response. (b) Total ash column (g/m^2) at 14:00 LT, modeled with FLEXPART using European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological data.

prevalence of chronic bronchitis and respiratory symptoms, as well as increased respiratory infections among children [*Delfino et al.*, 2002; *Griffin and Kellogg*, 2004; *Krzyzanowski et al.*, 2005; *Perez et al.*, 2008]. Skin abrasion and eye irritation have also been reported [*Hansell et al.*, 2006]. The chemical and physical properties of volcanic ash vary substantially between eruptions and volcanoes, making it difficult to generalize findings about the toxicity of ash from individual eruptions [*Searl et al.*, 2002; *Horwell and Baxter*, 2006].

[7] The most common health limit, which is used in Iceland, for PM_{10} is 50 $\mu g\ m^{-3}$ averaged over 24 hours [*Bödvarsdóttir*, 2007; *Horwell and Baxter*, 2006; *European Parliament and Council*, 2008]. The health limit is also used as a guide to when air quality is deteriorating on shorter (hourly) timescales [*U.S. Environmental Protection Agency*, 1998]. This limit was exceeded by orders of magnitude in the vicinity of Eyjafjallajökull during and after the eruption. Therefore there was concern about the possible health effects of this high level of particulate matter pollution.

[8] In this paper we examine the concentration of particulate matter, particles smaller then 10 μm in diameter (PM_{10}), due to direct ash emissions by the volcanic eruption and resuspension of ash deposited around the volcano, both in the vicinity of the volcano and in the greater Reykjavík area, some 125 km away. Exposure levels were very high and these data provide an important basis for studies of health effects.

2. Data and Methods

[9] Measurements of particulate matter concentration were made at a couple of locations close to the volcano, Vík and

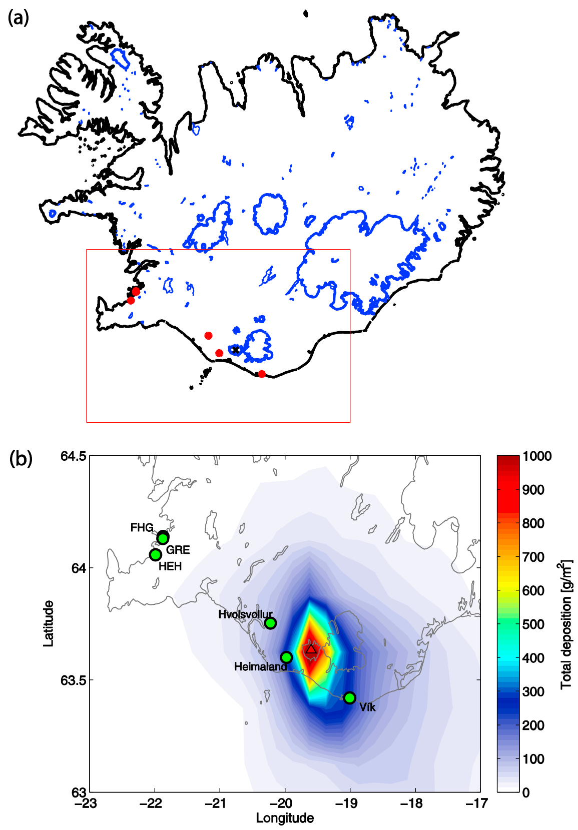

Figure 2. (a) Location of Eyjafjallajökull volcano (small black cross) and the measurement stations (red dots) in the Reykjavík area (FHG, GRE, and HEH) and at Hvolsvöllur, Heimaland, and Vík. (b) Map showing the deposition according to FLEXPART using ECMWF meteorological data.

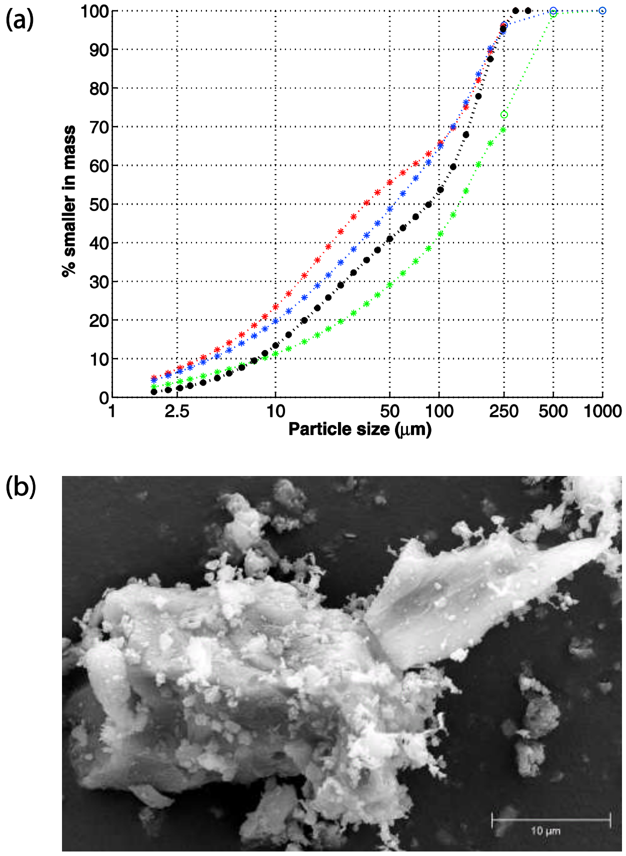

Figure 3. (a) Measured particle size of the ash. Samples from 15 April (55 km away, red dots), 17 April (20 km away, green dots), 18 April (20 km away, blue dots), and 6–7 May (38 km away, black dots). (b) A large ash grain sampled on 15 April (scale is 10 μm). Image taken using electron microscope at the Innovation Center Iceland.

Heimaland, in Reykjavík and in one location in between at Hvolsvöllur. Vík is a small village with a population of about 300 people 38 km southeast of the volcano, and Heimaland is a community center 18 km west of the volcano. Hvolsvöllur, with a population of 860 people in 2010, is 33 km west-northwest of the volcano, and Reykjavík is 125 km west-northwest of the volcano, with a population of about 201,000 people (Figure 2).

2.1. Particulate Matter

[10] The concentration of particulate matter (PM) has been measured in Reykjavík since 2002 at two fixed locations, Grensás station (GRE) and the Family and petting zoo (FHG), and with a mobile station, called FAR. The GRE and FAR stations are equipped with Thermo EMS Andersen FH 62 I-R instruments, and the station FHG is equipped with an Eberline Instrument Gmbh instrument [*Bödvarsdóttir*, 2007].

[11] The mobile station (FAR), which measures PM_{10}, was initially placed at Kirkjubæjarklaustur on 17 April 2010, but was moved to Vík on 22 April. A station from Kópavogur (HKK) was placed at Heimaland on 26 May to 30 June, a instrument from Akureyri was located at Hvolsvöllur on 12 May–23 July (Figure 2).

[12] A small portable unit, HandiLaz Mini from Particulate Measuring Systems, which measures the number of particles in the size ranges 0.3–0.5 μm, 0.5–5 μm, and >5 μm, called 0.3 μm, 0.5 μm, and 5 μm channels, was used, in particular on 4 June 2010 in Reykjavík. The HandiLaz Mini has sizing sensitivities from 0.3 μm to 5.0 μm, and simultaneously sizes and counts particles in the three fixed channels. The sample flow rate is 2.83 L min^{-1}.

2.2. Weather Stations

[13] Information about the weather conditions comes both from the PM measurements stations, measuring wind speed, wind direction, and precipitation, and from the measurement network operated by the Icelandic Met Office (IMO; http://en.vedur.is).

2.3. Satellite Data

[14] Satellite data come from the Moderate Resolution Imaging Spectroradiometer, or MODIS, which is one of four sensors carried on board NASA's first Earth Observing System (EOS) satellite TERRA, which was launched in December 1999. Another MODIS sensor was launched on the second EOS satellite AQUA in May 2002. Satellite data from the MODIS sensors aboard NASA's Terra and Aqua satellites is used for visual inspection of plume activity and ash storms.

2.4. Ash Characterization

[15] Grain size measurements of deposited ash, and electron microscopic imaging, were done at the Innovative Center of Iceland (Nýsköpunarmidstöd), using Sympatec HELOS/RODO from Sympatec GmbH SystemPartikel-Technik.

2.5. FLEXPART Calculations

[16] We used the Lagrangian particle dispersion model FLEXPART [*Stohl et al.*, 1998, 2005] to simulate the dispersion of volcanic ash in the atmosphere and its deposition onto the surface. The model simulations use the ash emissions of *Stohl et al.* [2011], which were determined by inverse modeling with FLEXPART of the total ash column loadings retrieved by satellites. We use FLEXPART simulations based on 3 hourly meteorological input data from two different weather prediction centers, the European Centre for Medium-Range Weather Forecasts (ECMWF) with a resolution of 0.18 $\times$ 0.18 degrees, and the National Center for Environmental Prediction (NCEP) Global Forecast System (GFS) with a resolution of 0.5 $\times$ 0.5 degrees. The resolution of the modeled ash concentration and deposition fields was set to 0.25 $\times$ 0.25 degree. Clearly, this resolution is not sufficient to capture the high spatiotemporal variability of measured ash concentrations in the vicinity of the volcano. Errors, and variability in the emissions not captured by the 3 hourly data of *Stohl et al.* [2011], as well as the resuspension of ash, which is not treated in the model, will cause further discrepancies between modeled and measured ash concentrations. However, the model output is suitable for examining the air quality impacts and the ash deposition on somewhat larger scales (i.e., beyond some 50–100 km from the vent).

[17] The model output consists of ash concentrations in 25 size classes from 0.25–250 μm, of which only the 11 size classes below 10 μm are used for comparison with the in situ

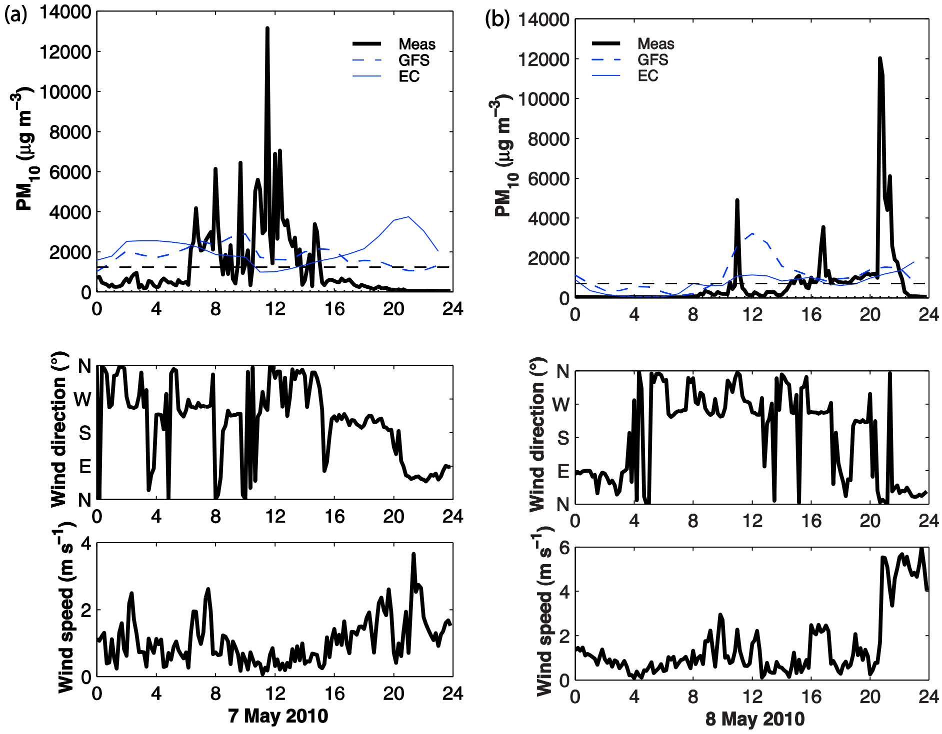

Figure 4. The measured PM_{10} concentration, wind speed, and direction (bold curves) at Vík on (a) 7 May 2010 and (b) 8 May 2010. The 24 hour average PM_{10} concentration is shown with a dashed line, and the health limit is shown with a dotted line (50 μg m^{-3}, not visible on this scale). Modeled concentration of PM_{10} due to direct volcanic emission (thin lines, top plots) using GFS and ECMWF (labeled EC) meteorological data.

aerosol measurements. This comparison used model output from the lowest model layer, extending up to 250 m above ground.

3. Results

3.1. Ash Grain Size and Properties

[18] Measurements of the grain size distribution of deposited ash were made several times during, and after the eruption. Different size distributions were observed (Figure 3), but the mass fraction of small, less than 10 μm in diameter, particles was around 20% for the fine grained ash (first 3 days of eruption), and 10% for the coarser grained ash (later phases of the eruption) [*Gislason et al.*, 2011].

[19] The ash was trachy-andesitic, with 58 mass % silica, and contained very little quartz. No cristobalite was detected, and other toxic components were almost nonexistent [*Gíslason et al.*, 2011] (see also C. J. Horwell et al., Respiratory health hazard assessment of ash from the 2010 eruption of Ejyafjallajkökull volcano, Iceland: A summary of initial findings from a multi-centre laboratory study; http://www.ivhhn.org).

3.2. Measured Particulate Matter Pollution

[20] On 7 and 8 May 2010, when the eruption activity was still high, extremely high concentration of PM_{10} was recorded in Vík (Figure 4). The 10 min average concentrations reached a maximum of 13157 μg m^{-3} on 7 May and 12028 μg m^{-3} on 8 May, with 24 hour averages of 1231 μg m^{-3} and 718 μg m^{-3}, respectively. The 24 hour health limit of 50 μg m^{-3} was thus exceeded by factors of 25 and 14, respectively.

[21] A satellite image from 12:35 on 7 May (Figure 5a) shows that the eruption plume covered Vík and the surrounding area, in agreement with total atmospheric ash column loadings from FLEXPART. However, in addition to the main plume emanating from the volcano, the satellite image also shows a broader plume of resuspended ash that is missing in the FLEXPART model simulation, but which is also responsible for the poor air quality in the area. On the following day, 8 May, there was less resuspended ash (Figure 5b), but the plume activity looked as strong as before, or even stronger [*Stohl et al.*, 2011]. Even though FLEXPART correctly simulates the ash plume traveling directly over Vík, the modeled PM_{10} concentration due to direct emission from the volcano (Figure 4; thin lines), is less than 4000 μg m^{-3} in Vík on those days. There are several possible explanations for this under-prediction. First, the ash plume is simulated mainly at higher altitudes and not enough ash may have been emitted in the model at low altitudes. Second, the distance of Vík from the volcano is only about one model grid cell and, thus, the variability of ash at the site cannot be captured by the model. Third, as also suggested by the satellite image, resuspension of previously deposited ash may be responsible for much of the ash located close to the ground, and this is not simulated by FLEXPART.

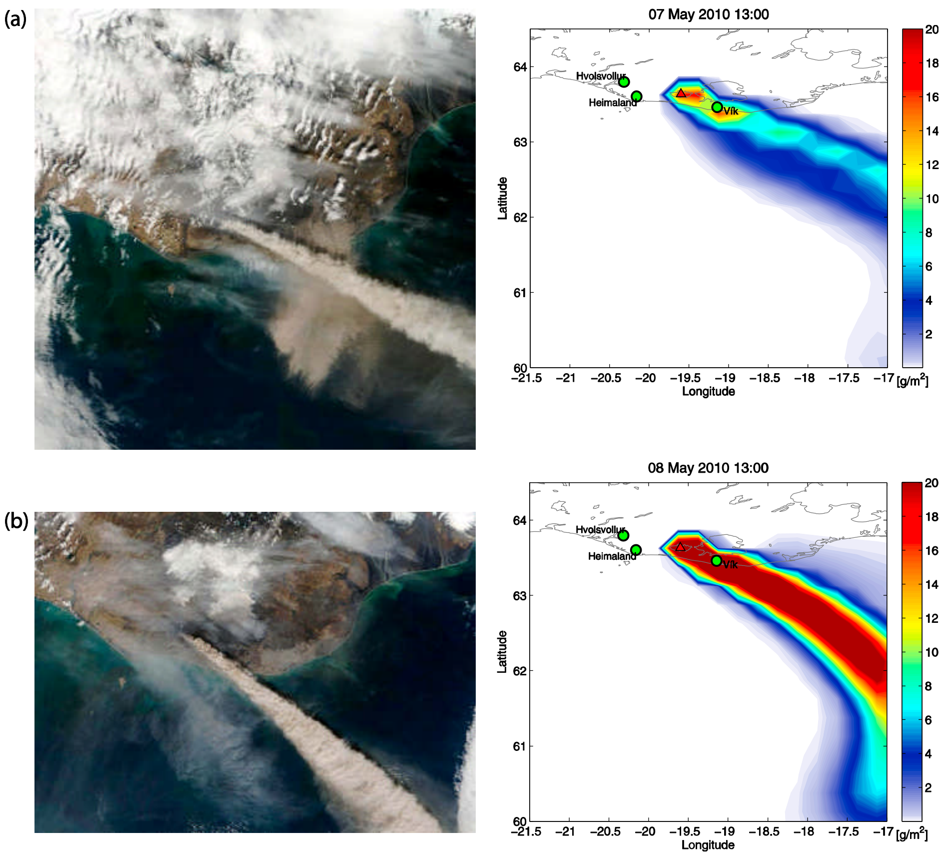

Figure 5. Satellite images showing the eruption plume and resuspended ash from Eyjafjallajökull, and FLEXPART model results for the total ash column from the eruption plume. (a) On 7 May 2010, at 12:35 LT, resuspended ash from the ground, to the east of the eruption plume, forms the wide plume underneath the eruption plume, which casts a shadow on the lower lying plume of resuspended ash. (b) Less resuspended ash than the previous day, but a very clear plume near and over Vík. Images from NASA Goddard Space Flight Center, MODIS Rapid Response.

[22] Locally high wind speed, above 8–10 m s^{-1}, results in high PM_{10} levels as ash, and even dust from sandur (and jökulhlaup (glacier outburst flood)) areas, is mobilized [*Thorsteinsson et al.*, 2011a]. However, high levels of PM_{10} often occur at low local wind speeds in Vík and Heimaland (Figure 6). Resuspended ash contributes to high concentration of PM_{10} in Vík, even when locally measured winds (10 min average) are as low as 3 m s^{-1}; since winds at higher altitude can be quite different.

[23] This can also be quite clearly seen in Figure 5a, where the wind direction at the elevation of the eruption plume is east-southeast, while the resuspended ash at the surface is being blown to the south.

[24] The daily average PM_{10} concentration for the period of 7 May to 6 June in Vík, Heimaland and Hvolsvöllur (Figure 7) exceeded the health limit 80% of the time in Vík, 75% at Heimaland, and half of the days (of valid measurements) at Hvolsvöllur [*Thorsteinsson et al.*, 2011b].

[25] The first really big effect of the eruption felt in the Reykjavík area was on 4 June 2010 (Figure 8). This was after the end of the volcanic eruption and, thus, this event was entirely due to resuspension of ash deposited during the eruption. The level of PM_{10} significantly reduced visibility, and reached over 2000 μg m^{-3} (10 min average) at HEH station, in the greater Reykjavík area. A few hours earlier, the concentration reached close to 4000 μg m^{-3} (10 min average) at Heimaland located along the pathway of the ash cloud from the volcano to Reykjavík, while in Vík the concentration remained comparatively low, even though it did reach 500 μg m^{-3} (10 min average). This is due to the easterly wind direction at the time, which is away from Vík (Figure 2). It seems thus likely that dust mobilization occurred even upwind of Vík and not only in the immediate vicinity of the volcano. Maps of modeled ash deposition show that a large area in Iceland received substantial amounts of ash, including the area east of Vík (Figure 2).

[26] Particle counts with the HandiLaz Mini showed that between 19:30 and 20:00 on 4 June 2010 the number of particles in the 0.3 μm and 0.5 μm channels was around 70×10^6 particles in cubic meter, and for the 5 μm channel there were about 4×10^6 particles per cubic meter, based on 25 measurements in 0.47 liters of air (10 s at a flow rate of 2.83 LPM). For comparison, in early July, typical values were 10×10^6, 2×10^6, and 0.02×10^6 particles in cubic meter, a factor of 7, 35 and 200 times less, for the 0.3 μm, 0.5 μm and 5.0 μm channels, respectively.

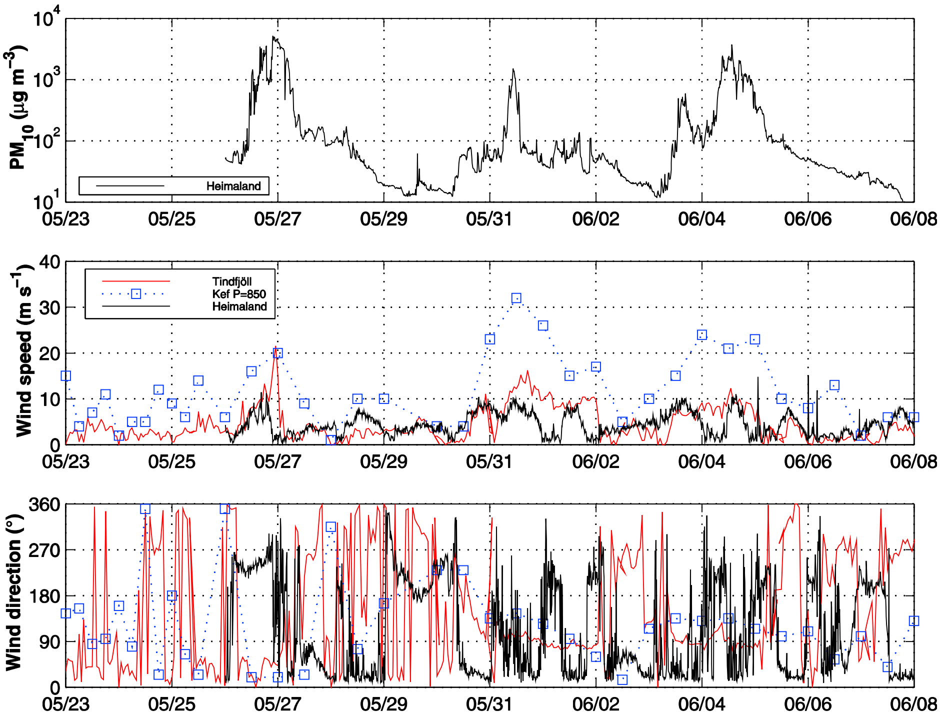

Figure 6. Measured PM_{10} concentration at Heimaland between 26 May and 7 June 2010. Also shown are measurements of wind speed and direction at Heimaland, Tindfjöll, and Keflavík (at P = 850 mbar).

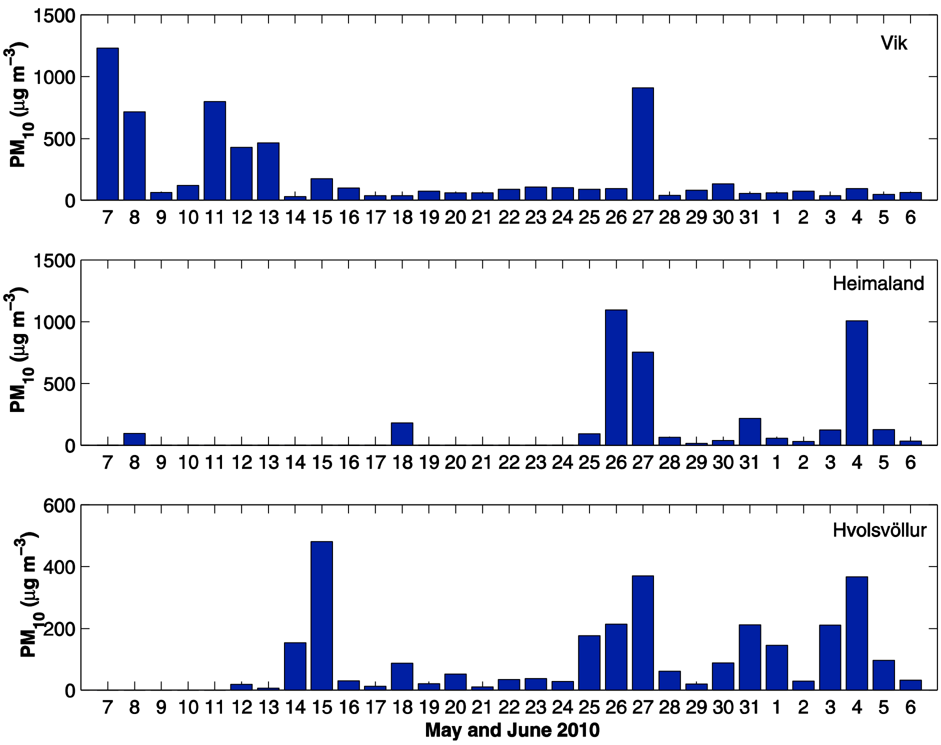

Figure 7. Daily average concentration of PM_{10} at Vík, Heimaland, and Hvolsvöllur, from 7 May to 6 June 2010. The health limit is 50 $\mu g\ m^{-3}$.

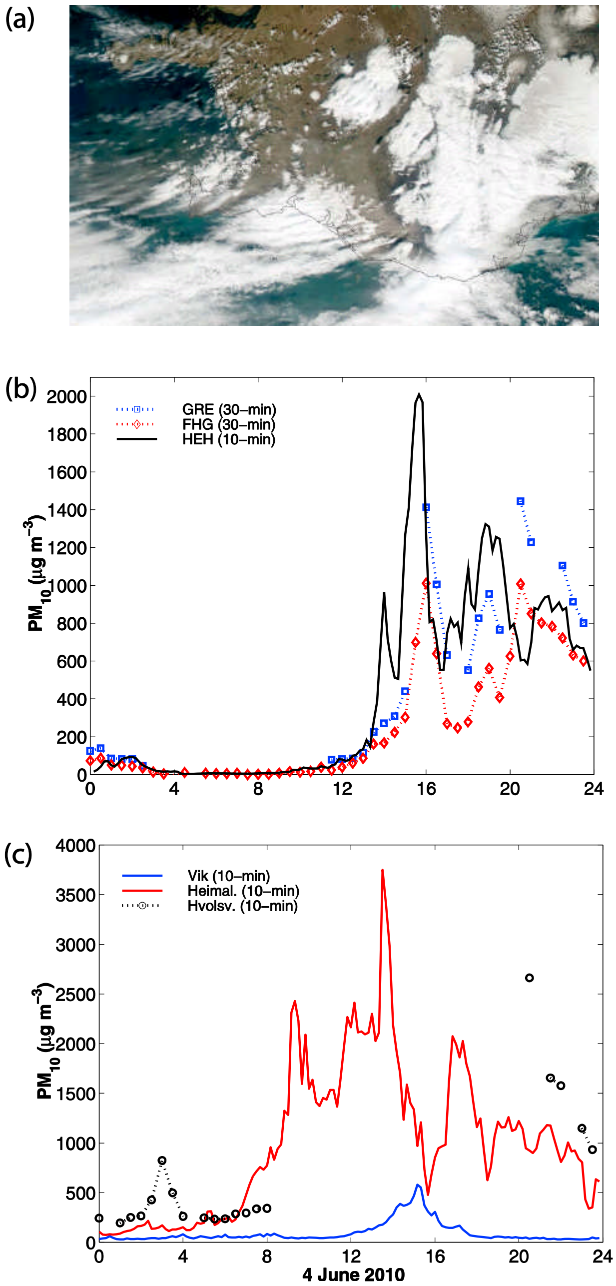

Figure 8. (a) Resuspended ash causing an ash storm on 4 June 2010. Measurements of PM_{10} concentration in (b) Reykjavík, FHG, GRE, and HEH stations and (c) Vík, Heimaland and Hvolsvöllur. Satellite image from NASA Goddard Space Flight Center, MODIS Rapid Response.

[27] A similar event occurred in Reykjavík on 7 September 2010 (Figure 9), but this time the peak value was recorded at Grensás station (GRE), 535 μg m^{-3} (30 min average). Data from $PM_{2.5}$ measurements indicate similar concentration of the fine grained material as for the PM_{10} at GRE and FHG, even though PM_{10} does include all of the $PM_{2.5}$ material. The reason for this is not well known, but at GRE and FHG the $PM_{2.5}$ values are not considered trustworthy by the station operators.

4. Discussion

[28] The health limit for particulate matter pollution (PM_{10}) in Iceland is 50 μg m^{-3}, 24 hour average, as is common in the world [*Bödvarsdóttir*, 2007; *Horwell and Baxter*, 2006]. Studies show that the crystalline silica and toxic content of the ash is negligible, so that the persistence of deposited ash in the soils and environment should not present a significant silicosis hazard. Even though the health effects of ash fall are not well known, especially when containing no, or very little, toxic material, the concentration observed in Vík and surrounding areas will clearly provide a test case for the health effects related to exposure to high concentration of PM_{10}.

[29] During periods of PM_{10} concentration over about 5000 μg m^{-3}, most residents stayed indoors, or used protective air filters and goggles when they had to go outside. A study is ongoing to examine the potential long term health effects of the volcanic eruption, including the high

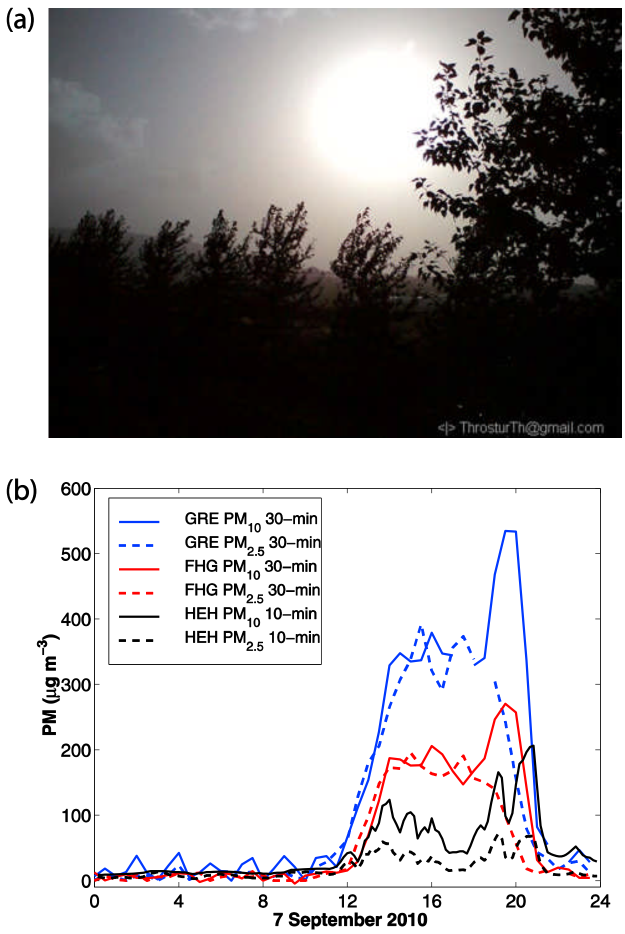

Figure 9. Resuspended ash blocked sunlight on 7 September 2010. The photograph was taken around 18:00 LT. Measurements in the greater Reykjavík area showed clearly the arrival of the ash around noon.

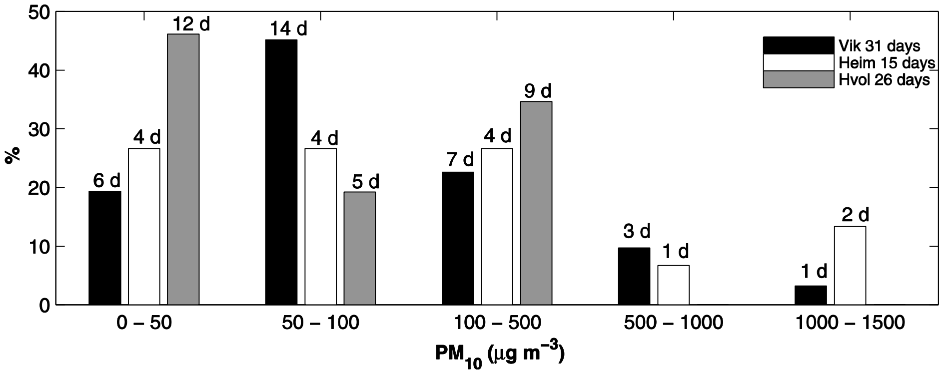

Figure 10. The occurrence of different levels of PM_{10} concentration, for the period of 7 May to 6 June 2010, shown as a ratio of total number of measurements and labeled with the corresponding number of days.

concentration of PM_{10} during and after the eruption due to resuspended ash in the area.

[30] The distribution of daily PM_{10} concentration, for the period of 7 May till 6 June 2010, shows a very different pattern for Vík, Heimaland and Hvolsvöllur (Figure 10). In Vík the concentration was above the health limit 80% (25 out of 31 days) of the time, with relatively moderate values (50–100 μg m^{-3}) accounting for 56% of those days above the health limit, and 1 day where the concentration was above 1000 μg m^{-3}. At Heimaland 27% of the days (4 out of 15) were below the health limit, and 2 days above 1000 μg m^{-3}. And in Hvolsvöllur 46% of the days (12 out of 26) were below the health limit, and none above 500 μg m^{-3}.

[31] Our air quality measurements show that near the ground resuspended ash can be as important as, or even more important than, ash emitted directly by the volcano. Satellite measurements also clearly show that, at times, ash emanates not only from the volcanic vent, but also from the surrounding areas where ash has previously been deposited. This resuspended ash may also interfere with the way satellite data and other measurements are used for inverse modeling of the source term [*Stohl et al.*, 2011] or assimilation of ash loadings into models, as most models assume that all the observed ash originates directly from the volcano. If resuspended ash contributes significantly to the measured ash, this assumption is violated. This may lead to erroneous vertical profiles of ash emissions, for example. Furthermore, the resuspended ash may also affect aviation, especially in the vicinity of an airport where aircraft are flying low. Since resuspension is not treated in any operational volcanic ash forecast model, possible aviation hazards due to resuspended ash will not be forecasted. Notice that some of the observed ash concentrations due to resuspension were above the current highest limit set by aviation regulators (4000 μg m^{-3} [*European Commission*, 2010]), even though only PM_{10} concentrations were measured and total PM concentrations were likely higher (Figure 3).

5. Conclusions

[32] We have reported several episodes during which direct ash emissions as well as resuspension of previously deposited ash have led to substantial exceedances of air quality limits for PM_{10}.

[33] The PM_{10} concentration measured in Vík, on 7 and 8 May 2010, is the highest ever measured in Iceland. During the ash storm on 4 June 2010, the concentration measured in Reykjavík, 2008 μg m^{-3} (10 min average; HEH station), exceeded all previously measured values, except for one episode during New Year's fireworks on 1 January 2006 when 2374 μg m^{-3} (30 min average) were measured. The annual concentration in Reykjavík is about 25 μg m^{-3}. Based on the current limits for aviation [*European Commission*, 2010], Reykjavík airport should have been closed on 4 June, 2 weeks after the end of the eruption.

[34] The physical process of resuspension of volcanic ash is currently not considered in volcanic ash dispersion models. However, attempts of representing resuspension by including a simple empirical remobilization model have been made by *Barsotti et al.* [2010]. They highlight the importance of resuspension and the need for more attention to this process in the future. Our results also indicate that this process may also interfere with inverse modeling and data assimilation approaches to determine the ash emissions, since the models assume that all the observed ash originates directly from the volcanic vent.

[35] Ash fall is generally not included in public emergency response plans, at least not in Iceland. Lack of knowledge of the health effects is probably the main reason. However, it is clear that when PM_{10} levels exceed the health limit by more than a factor of 20, that is 1000 μg m^{-3} for more than an hour, there is a good reason to recommend staying indoors and the use of protective wear if outdoor work is necessary.

[36] **Acknowledgments.** We wish to thank Birgir Jóhansson, at the Innovation Center Iceland, for electron microscopy images of the ash.

References

Barsotti, S., D. Andronico, A. Neri, P. D. Carlo, P. J. Baxter, W. P. Aspinall, and T. Hincks (2010), Quantitative assessment of volcanic ash hazards for health and infrastructure at Mt. Etna (Italy) by numerical simulation, *J. Volcanol. Geotherm. Res.*, *192*, 85–96.

Bödvarsdóttir, A. R. (2007), Mælingar á loftmengandi efnum í Reykjavík 2006 (Measurements of air pollution in Reykjavik 2006), *Rep. UHR-2007*, City of Reykjavík, Iceland, Reykjavík.

Delfino, R. J., R. S. Zeiger, J. M. Seltzer, D. H. Street, and C. E. McLaren (2002), Association of asthma symptoms with peak particulate air

pollution and effect modification by anti-inflammatory medication use, *Environ. Health Perspect.*, *110*(10), A607–A617.
European Commission (2010), Volcano crisis report: Report on the actions undertaken in the context of the impact of the volcanic ash cloud crisis on the air transport industry, Brussels. [Available at http://ec.europa.eu/transport/ash_cloud_crisis_en.htm.]
European Parliament and Council (2008), Directive 2008/50/EC of the European parliament and of the council of 21 May 2008 on ambient air quality and cleaner air for Europe, *Off. J. Eur. Union, L 152*, 1–44.
Gíslason, S. R., et al. (2011), Characterization of the Eyjafjallajökull volcanic ash particles and a protocol for rapid risk assessment, *Proc. Natl. Acad. Sci. U. S. A.*, *108*, 7307–7312.
Griffin, D. W., and C. A. Kellogg (2004), Dust storms and their impact on ocean and human health: Dust in earth's atmosphere, *EcoHealth*, *1*, 284–295.
Hansell, A. L., C. J. Horwell, and C. Oppenheimer (2006), The health hazards of volcanoes and geothermal areas, *Occup. Environ. Med.*, *63*, 149–156.
Horwell, C. J., and P. J. Baxter (2006), The respiratory health hazards of volcanic ash: A review for volcanic risk mitigation, *Bull. Volcanol.*, *69*, 1–24.
Krzyzanowski, M., B. Kuna-Dibbert, and J. Schneider (Eds.) (2005), *Health Effects of Transport-Related Air Pollution*, WHO Press, Copenhagen.
Larsen, G., A. J. Dougmore, and A. J. Newton (1999), Geochemistry of historical-age silicic tephras in Iceland, *Holocene*, *9*, 463–471.
Perez, L., A. Tobias, X. Querol, N. Künzli, J. Pey, A. Alastuey, M. Viana, N. Valero, M. González-Cabré, and J. Sunyer (2008), Coarse particles from Saharan dust and daily mortality, *Epidemiology*, *19*(6), 800–807, doi:10.1097/EDE.0b013e31818131cf.
Petersen, G. N. (2010), A short meteorological overview of the Eyjafjallajökull eruption 14 April–23 May 2010, *Weather*, *65*(8), 203–207.
Searl, A., A. Nicholl, and P. J. Baxter (2002), Assessment of the exposure of islanders to ash from the Soufrière Hills volcano, Montserrat, British West Indies, *Occup. Environ. Med.*, *59*(8), 523–531.
Sigmundsson, F., et al. (2010), Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption, *Nature*, *468*, 426–432.
Stohl, A., M. Hittenberger, and G. Wotawa (1998), Validation of the Lagrangian particle dispersion model FLEXPART against large scale tracer experiments, *Atmos. Environ.*, *32*, 4245–4264.
Stohl, A., C. Forster, A. Frank, P. Seibert, and G. Wotawa (2005), Technical note: The Lagrangian particle dispersion model FLEXPART version 6.2, *Atmos. Chem. Phys.*, *5*, 2461–2474.
Stohl, A., et al. (2011), Determination of time- and height-resolved volcanic ash emissions and their use for quantitative ash dispersion modeling: The 2010 Eyjafjallajökull eruption, *Atmos. Chem. Phys.*, *11*, 4333–4351, doi:10.5194/acp-11-4333-2011.
Thorsteinsson, T., G. Gísladóttir, J. Bullard, and G. McTainsh (2011a), Dust storm contributions to airborne particulate matter in Reykjavík, Iceland, *Atmos. Environ.*, *45*, 5924–5933, doi:10.1016/j.atmosenv.2011.05.023.
Thorsteinsson, T., T. Jóhannsson, and G. Pétursdóttir (2011b), High levels of particulate matter due to ash plume and ash re-suspension following the Eyjafjallajökull eruption, *Geophys. Res. Abstr.*, *13*, EGU2011-11546.
U.S. Environmental Protection Agency (1998), National air quality and emissions trends report, *1997*, Washington, D. C.

T. Jóhansson, The Environment Agency of Iceland, Sudurlandsbraut 24, 108 Reykjavík, Iceland.

N. I. Kristiansen and A. Stohl, Norwegian Institute for Air Research, Kjeller N-2027, Norway.

T. Thorsteinsson, Environment and Natural Resources, University of Iceland, Sturlugata 7, 101 Reykjavík, Iceland. (throsturth@hi.is)