Physical properties of suspended dust during moist and low wind conditions in Iceland

Pavla Dagsson-Waldhauserova,[1,2] Olafur Arnalds,[1] Haraldur Olafsson,[1,3,4] Lenka Skrabalova,[5] Gudmunda Maria Sigurdardottir,[1,3] Martin Branis,[5] Jindrich Hladil,[6] Roman Skala,[6] Tomas Navratil,[6] Leona Chadimova,[6] Sibylle von Lowis of Menar,[3] Throstur Thorsteinsson,[7] Hanne Krage Carlsen,[8] and Ingibjorg Jonsdottir[7]

[1] University of Iceland, Department of Physics, Reykjavik, Iceland
[2] Agricultural University of Iceland, Faculty of the Environment, Hvanneyri, Iceland.
e-mail: pavla@lbhi.is (corresponding author)
[3] Meteorological Office of Iceland, Reykjavik, Iceland
[4] Bergen School of Meteorology, Geophysical Institute, University of Bergen, Norway
[5] Faculty of Science, Charles University in Prague, Prague, Czech Republic
[6] Institute of Geology AS CR, v.v.i., Prague, Czech Republic
[7] University of Iceland, Institute of Earth Sciences and Environment and Natural Resources, Reykjavik, Iceland
[8] Department of Public Health and Community Medicine, University of Gothenburg, Sweden

ABSTRACT

We measured a dust event which occurred during wet and low wind/windless conditions as the result of surface heating in August 2013. Maximum particle number concentration (PM~0.3-10 μm) reached 149,954 particles cm^{-3} min^{-1} while mass concentration (PM<10 μm) was 1757 μg m^{-3} min^{-1}. The suspended dust was very fine with the highest number of particles in the size range 0.3-0.337 μm, followed by particles 1.5-5 μm in diameter. Close-to-ultrafine particle size distributions showed a significant increase in number with the severity of the measured dust event (during dust peaks). Number concentrations were well correlated with mass concentrations. The mineralogy and geochemical compositions showed that glaciogenic dust contains sharp-tipped shards with bubbles and 80 % of the particulate matter is volcanic glass rich in heavy metals. Wet dust particles were mobilized within < 4 hours. This is the first scientific study of particle size distributions in an Icelandic dust event including findings on initiation of dust suspension.

Keywords: atmospheric measurements, dust storm event, surface heating, dust aerosol, climate aspects

YFIRLIT

Eðliseiginleikar ryks við vindrof í litlum vindi rök veðurskilyrði á Íslandi

Tækjum var komið fyrir á Mælifellsandi norðan Mýrdalsjökuls til mælinga á ryki á upptakasvæði rykmengunar ágúst 2013. Við mældum einn „rykatburð“ sem átti sér stað við mjög lágan vindstyrk þegar sandurinn hitnaði í sólskyni. Hámarksstyrkur korna (PM~0,3-10 μm) náði um 150 000 kornum cm^{-3} $mínútu^{-1}$ á meðan þéttleiki (PM<10 μm) var 1757 μg m^{-3} $mínútu^{-1}$. Rykið var mjög fínkorna með flest kornin 0,3-0,337 μm en næst felst af kornastærðinni 1,5-5 μm. Hlutdeild mjög fínna korna jókst með rykmagninu. Fjöldi korna og kornastyrkur fylgdust vel að. Bergfræði og jarðefnafræði kornanna sýndi að þessi jökulættuðu rykkorn voru sum oddhvöss og blöðrótt og að 80% efnanna er gosgler með háu innihaldi af ýmsum þungmálmum. Rykkornin tókust á loft eftir að hafa þornað < 4 tíma. Þessar rannsóknir eru þær fyrstu sem sýna kornastærðir ryks á fokstað þegar rykframleiðsla á sér stað og þær fyrstu til að sýna aðstæður þegar rykmengun verður nánast í logni.

INTRODUCTION

Atmospheric dust has been measured in major desert areas of the world since the 1950s (Chepil & Woodruff 1957, Aston et al. 1973, D´Almeida 1986, Wang et al. 2008). High latitude and periglacial areas are also important sources of dust, but the number of dust studies in cold climate areas is significantly lower than reported for the major dry deserts. Dust measurements within cold region dust sources are mainly seasonal and employ measurement techniques focused mostly on the coarser silt-sized or sand-sized particles (Nickling 1978, Bullard 2013). Air particle monitoring using a range of automatic instruments is conducted far from the dust sources in the Arctic (NILU 2013).

Iceland is an active source of dust originating from glaciogenic and volcanic sediments. Volcanic sandy deserts and glacial outwash plains cover > 22% of the country (Arnalds et al. 2001). These areas are subjected to strong winds and severe wind erosion with dust deposition exceeding 500 g m^{-2} yr^{-1} in some areas (Arnalds 2010). Long-term observations of atmospheric dust show a high frequency of dust events in Iceland with > 34 dust days annually over the last 60 years (Dagsson-Waldhauserova et al. 2013a). The position of the Icelandic low determines whether dust plumes travel in a north-east or southerly direction. An annual mean of 16.4 dust days was recorded in NE Iceland and about 17.9 dust days occurred annually in southern parts of Iceland in 1949-2011 (Dagsson-Waldhauserova et al. 2013a, 2013b). These figures represent minimum values as many dust storm events occur without the dust passing the weather stations that can record the events. The frequency and the amount of dust measured in Iceland places the country among the major dust areas of the world (Mongolia, Iran, USA, China). Furthermore, Icelandic dust storms have been found to be among the most severe wind erosion events recorded on Earth (Arnalds et al. 2012, 2013).

Measurements of particle mass concentrations in Iceland have been mostly related to the Eyjafjallajökull eruption in 2010 (Leadbetter et al. 2012) or areas distal from the dust sources (Thorsteinsson et al. 2011, Blechschmidt et al. 2012). No direct measurements of dust concentrations within the major dust sources in Iceland have been made. Size segregated particle mass concentrations and number-size distributions (number of particles in defined particle size ranges) of dust aerosol can provide a better understanding of physical properties, such as textural, morphological and shape characteristics, and the possible health impacts of dust events (Harrison & Yin 2000, Morman & Plumlee 2013). Studies on number concentrations including particles < 10 µm in Iceland have not been published in the literature to date.

Icelandic dust differs from dust originating from continental dust sources, such as the Saharan and Asian dust. The dust is volcanogenic in origin, of basaltic composition, with lower SiO_2 proportions (<50%) and higher Al_2O_3, Fe_2O_3 and CaO content than crustal dust (Dagsson-Waldhauserova et al. 2013c). Volcanic dust made of glass can be very sharp and porous allowing particles as large as 50 µm to travel long distances (Navratil et al. 2013).

The main objective of this study was to provide an overview of physical properties of Icelandic dust, as exemplified by dust from Mælifellssandur, which is one of Iceland's main dust sources. Results of the first synchronized measurements of particle number and mass concentrations during a dust event directly within a dust source in Iceland are here reported. This information is combined with mineralogical and geochemical analyses of the source material to discuss the possible risk of Icelandic dust to human health.

METHODS

Location

Atmospheric Dust Measurements in Iceland (ADMI 2013) is a pioneering project launched to investigate the physical characteristics of dust aerosol *in situ* at the dust source. The

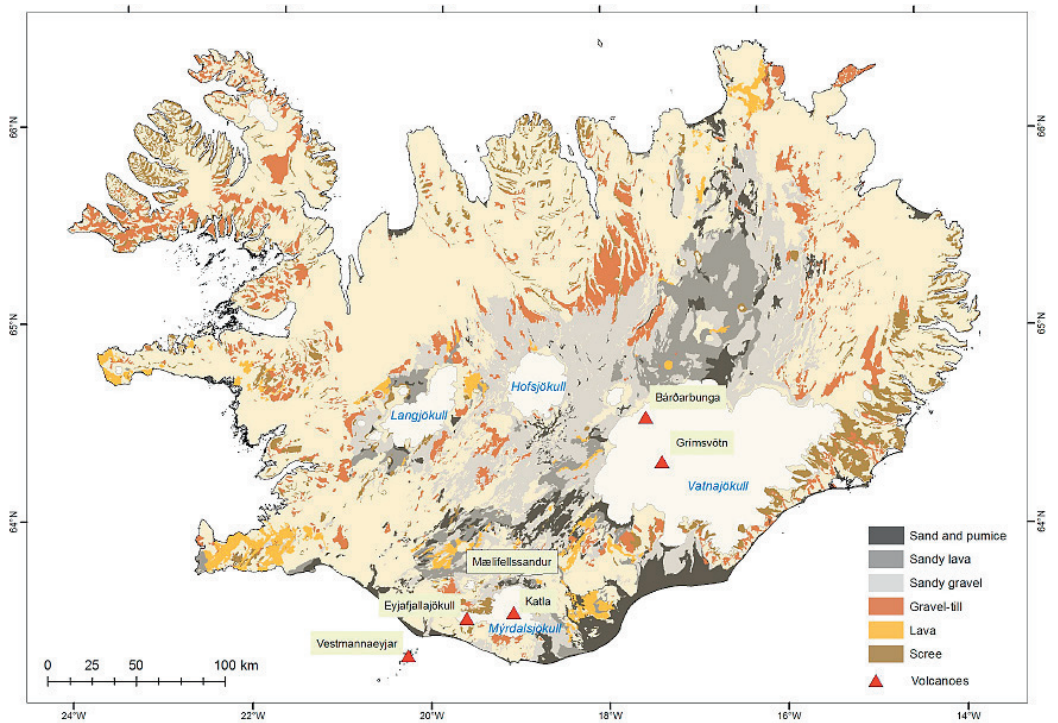

Figure 1. A map of Iceland with location of sampling site (Mælifellssandur) and active volcanoes (marked with red triangles). Based on the Agricultural University of Iceland Nytjaland and Erosion Databases, prepared by Sigmundur Helgi Brink.

ADMI 2013 took place in southern and south-western Iceland on 8-18 August 2013. It was generally a period of high precipitation and low winds when no major dust storm event was observed. Nevertheless, one short dust event was measured directly at a dust source on 12 August 2013. Instruments were placed on the dust source, the Mælifellssandur sand plain, which is located north of Mýrdalsjökull Glacier in South Iceland (Figure 1, N 63.81569 W 19.12403, 601 m above sea level, 2 km N of glacier). Mælifellssandur is a 50-60 km^2 unstable glaciofluvial plain at 550-650 m elevation. It undergoes widespread flooding during the summer melting of the glacier, leaving unstable, silty materials behind, and is considered one of the major dust sources of Iceland (Arnalds 2010). One of Iceland's most active volcanic systems, Katla, is located under the Mýrdalsjökull Glacier (Thordarson & Höskuldsson 2008), and the materials deposited on the sand plains are derived from this volcanic system. The last eruption of Katla that reached through the glacier was in 1918.

Instrumentation

Two TSI 8520 DustTrak Aerosol Monitors (DustTrak) and one TSI Optical Particle Sizer 3330 (OPS) were placed one meter above the surface on the dust source. The DustTrak is a light-scattering laser photometer that measures aerosol mass concentrations from 0.001 to 100 mg m^{-3} for particles ranging in size from 0.1 to 10 μm. Particle concentrations recorded by DustTrak instruments have been previously found as a reasonably accurate measure of dust storms in Arizona (USA) and Australia (Jayrante et al. 2011). The OPS provides particle concentration and particle size distribution measurements using single particle counting

technology, for particles with optical diameters from 0.3 to 10 µm. It employs optical scattering from single particles where particle pulses are sized and binned in up to 16 different channels.

The DustTraks were calibrated to measure Particle Mass Concentrations (PMC) of two particle diameters (PMC_{10} for particles <10 µm and $PMC_{2.5}$ for particles <2.5 µm). As result, we measured simultaneously two PMCs (PMC_{10}, $PMC_{2.5}$) and Particle Number Concentrations (PNC) from the OPS. The OPS channels that best matched the $PMC_{2.5}$ were of particle diameters 0.3-2.685 µm.

Mineralogical and geochemical analysis

We used two instrumental approaches to obtain physical and chemical characteristics of the dust particles collected from the active surface layer of the Mælifellssandur dust source right after the dust event. Firstly, semi-quantitative estimates of mineral content (Bruker D8 Discover) were determined from X-ray powder diffraction (XRD) data using the reference intensity ratio (RIR) method and, secondly, energy dispersive spectrometry EDS/(EDX), with a BRUKER silicon drift detector (SDD) on a VEGA3 XM TESCAN electron microscope (polished sections) was used for elemental characterisation of glass and minerals in the individual particles.

Using the Bruker D8 Discover, the semi-quantitative estimates of the mineral content were determined from X-ray powder diffraction data using the reference intensity ratio (RIR) method as implemented in the Bruker DIFFRAC.EVA software. To make the estimates as accurate as possible the ICDD PDF2 database entries containing experimentally determined RIR values were preferred. Such determined mineral concentrations should be correct within 10-20 rel. % range depending mainly on absolute content of the particular phase in the mixture under investigation, crystallinity of the material, diffraction geometry used to collect the database standard data, and preferred orientation of the studied specimen.

The second approach involved back-scattered-electron (BSE) detection of the size, outline and aggregation parameters of the mineral and glassy components and, subsequently, their EDS chemical element analysis. Such detailed inspection of particle populations allowed us to improve the previously obtained XRD-based estimates of mineral proportions, so that we assumed (although not exactly calculated for each of the minerals) that the possible uncertainty for the mean values was reduced to the order of a few percent.

For volcanic glass, the EDS measurements of clustered points and inspection fields were used. The composition of the volcanic glass was determined with a chemical pattern for eight main oxides which were recalculated to a total of 100 % (Na_2O, MgO, Al_2O_3, SiO_2, K_2O, CaO, TiO_2, and FeO, where the latter denote

Figure 2. Photographs showing the dust suspension event measurements. The surface was exposed to solar radiation for four hours before the event occurred (left). Surface heating resulted in cloud formation and upward air motion causing uplift of dried silt particles from the upper surface layer (middle and right).

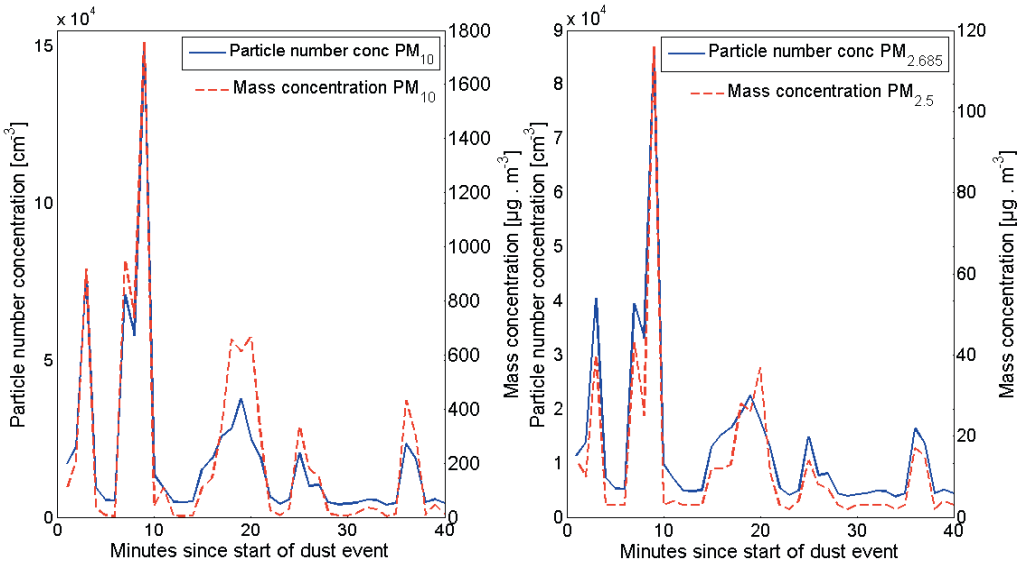

Figure 3. Particle number concentrations (blue) and mass concentrations (red) during the dust event.

FeO = FeO_{total}, ignoring the possibility of the presence of Fe^{3+} in the glass). This provides basic and practical information about these volcanic glass types.

RESULTS

The general physical properties of the dust are described in two sections: i) atmospheric dust measurements and ii) mineralogical and geochemical analyses.

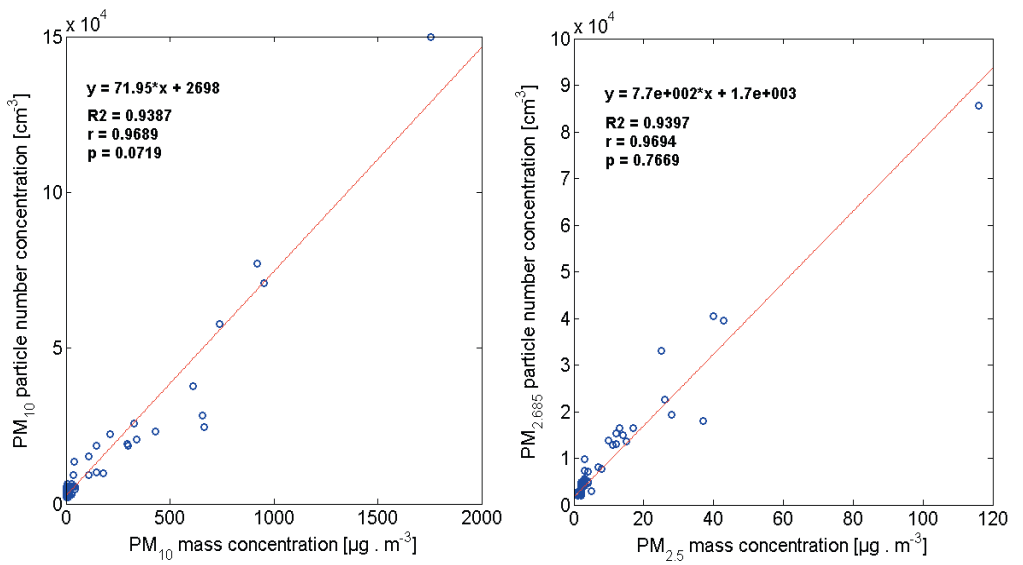

Figure 4. Correlation of particle number concentrations and mass concentrations of PM_{10} (left) and $PM_{2.5(2.685)}$ (right) during all atmospheric measurements.

Atmospheric dust measurements

The dust event was measured under unique conditions, during low wind/windless conditions when the surface was still moist after previous high precipitation. The main driver of dust suspension was direct solar radiation and consequent surface heating. The South Iceland region experienced a period of high precipitation for over a week before and during the measurements. The closest weather station equipped with a rain gauge, Laufbali, had an accumulated precipitation of > 55 mm during a period of five days, ending 14 hours before the event. High relative humidity (77-90 %) and low wind speeds (0-4 m s^{-1}) were measured at the closest weather station, the high altitude station Tindfjöll, 870 m a.s.l., during the dust event. Daily mean temperature was 6.3 °C, similar to the previous five-day mean (6.2 °C). The first dust whirls were visible after the surface was exposed to direct solar radiation for about four hours. Surface heating resulted in cloud formation and upward air motion during which dust started to be mobilized (Figure 2). Substantial dust repeatedly passed the instruments from all wind directions for about 40 minutes and the corresponding dust peaks are visible in Figure 3.

The maximum PNC_{10} (one-min average) was 149,954 particles cm^{-3} and PMC_{10} (one-min average) was 1757 µg m^{-3}. Maximum concentrations of the $PM_{2.5}$ fraction were meas-

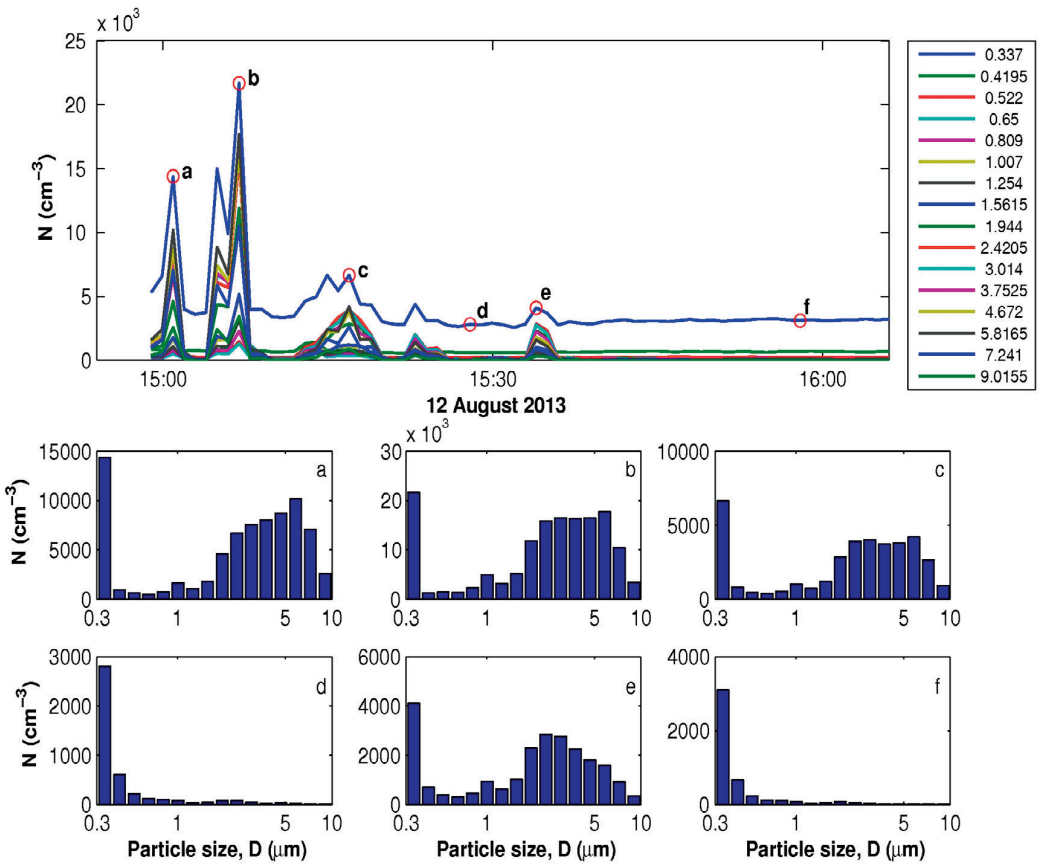

Figure 5. Size distributions of dust particles in size range 0.3 µm to 10 µm determined from the dust peaks (a, b, c, e), between the dust peaks (d) and after the dust event occurred (f). N - particle number concentration.

ured as 85,528 particles cm^{-3} in number concentration, with the mass reaching 116 μg m^{-3}. PNC were well correlated with PMC readings (R^2=0.939; Figures 3, 4). The more prominent the dust plume was, the higher the number of fine particles mobilized and, thus, the mass concentration increased accordingly. The amount of suspended particles, > 7.5 μm, was very small.

Figure 5 shows the particle size distribution in 17 size classes ranging 0.3 to 10 μm for the dust peaks (a, b, c, e), between the dust peaks (d) and after the dust event occurred (f). Very fine particles, 0.3-0.337 μm in diameter, were most abundant during all the measurements. When dust plumes passed through the instruments, the highest number of particles was found in the size range of 0.3-0.337 μm and 1.5-5 μm in diameter. The mean (median) particle diameter during the dust event was 1.69 μm (1.58 μm) with a range of 0.5–3.4 μm. Overall, the mean PMC_{10} and PNC_{10} measured directly on the dust source during the dust event were 234 μg m^{-3} and 19,024 particles cm^{-3}, respectively.

Table 1. Estimated amounts of components in the Mælifellssandur particulate matter. The semi-quantitative estimates are based on XRD analyses, but the smallest mineral contents (around XRD detection limits) also required verification of their presence by means of the chemical composition (EDX) and morphology of crystals (SEM-BSE). Note the predominance of glass (~ 80 wt. %).

MINERAL AND MATERIAL PHASES	wt %
Volcanic glass, amorphous component	78.2
Plagioclases (Na-rich anorthite + bytownite?)	12.2
Pyroxenes (augite)	4.6
Olivine + serpentine minerals (antigorite-lizardite?)	1.8
Zeolites (wairakite?)	1.1
Quartz	0.8
Magnetite + ulvospinel	0.7
Amphiboles (actinolite-tremolite?)	0.3
Undetermined phases and other components	0.3
Total	100.00

Mineralogical and geochemical analyses

The population of volcanogenic particles in the sample was homogenous, consisting mostly of extremely angular, sharp-tipped shards of largely homogeneous volcanic glass containing a small number of bubbles. These were highly polydisperse, nanometric/micrometric to coarse silt-sized (0.1–63 μm) particles. The shard faces were often curved and concave. They corresponded to spontaneous fracture patterns but, in part, also fragmentary outlines of the bubbles which originally exceeded the size of the particles. Most of these small shards resembled the volcanic glass particles which were found after the 2011 Grímsvötn eruption in Scotland (SEPA 2011) and subsequently also in the Czech Republic (unpublished data of the authors). However, this morphological similarity is incidental because of the different elemental compositions of the Mælifellssandur tephra glass (see Table 2 and Oladottir et al. 2005, 2011). According to the XRD analysis and the BSE inspection, the total amount of glass in the particulate matter reached almost 80 wt. % (Table 1).

The grains exceeding silt sizes were rare but their mass contribution was considerable. The large, sand sized clasts (0.063–0.95 mm) also consisted of glass, but mineral crystallites and phenocrysts made up a few to tens of %. In these clasts, the occurrence of Na-rich anorthite and augite was the most typical feature (Table 1, Figure 6). Olivine and antigorite occurred in significant amounts, together with ulvospinel, which typically formed tiny skeleton crystals in the glass. Other clinopyroxenes, biotite, alkali feldspars or quartz, particularly in their common sizes around 10 μm of particle equal diameter, were not found by the techniques applied and amphiboles were rare. Small amounts of zeolites (possibly wairakite based on the XRD signal) were present, mainly in the fine crystalline matrix of well packed, fine-silt lumps, and occasionally could be present with altered augitic aggregates.

The geochemical composition pattern of the

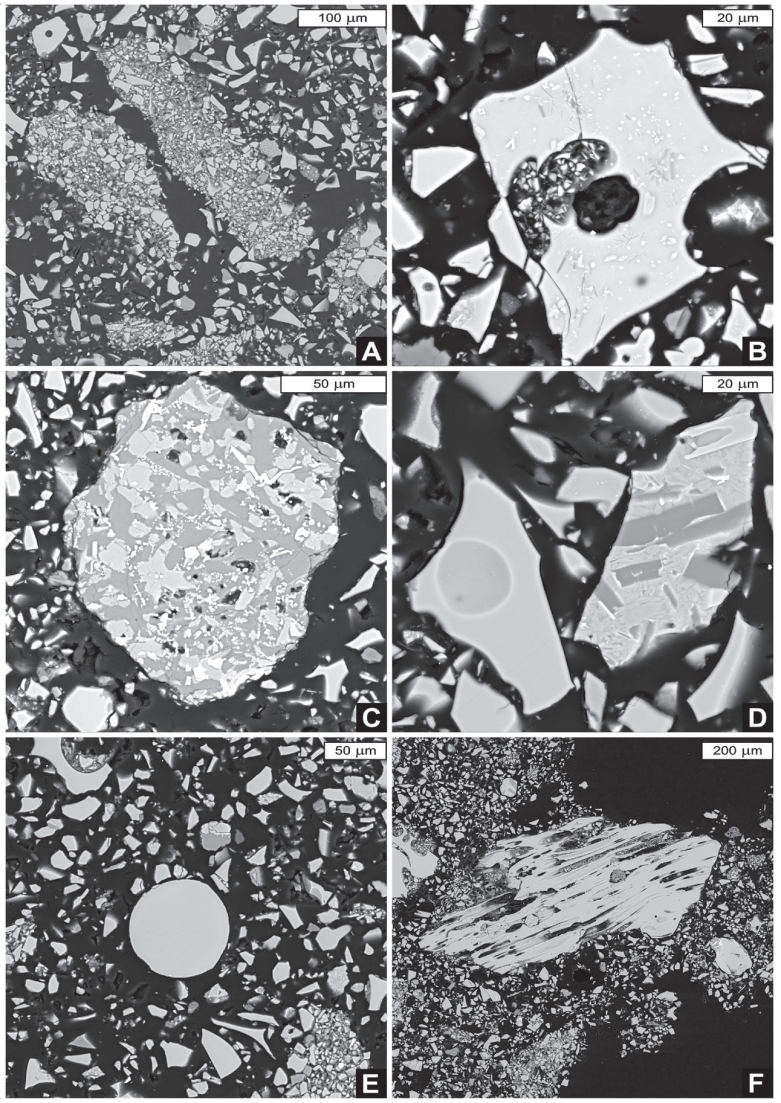

Figure 6. The BSE images of the Mælifellssandur particulate matter polished sections: Several examples of contrasting clusters of larger clasts in otherwise monotonous masses of polydisperse silt-sized (< 63 µm) shards of volcanic glass.

A – Mæli-1, occurrence of friable lumps of sub-millimetre sizes where the smallest glass particles prevailed. These were kept together due to dense packing, adhesion, and the presence of slightly developed (amorphous, crystallite dotted) meniscus and pendant cements (precipitated solutes). B – Mæli-3, a large shard of blocky glass containing small An-rich plagioclase laths (grey) and pyroxene and spinel crystals (relatively bright). The shard contains irregular voids/bubbles, selectively filled by the finest glass-silt fraction. Fractures in glass are fresh and still can expand. C – Mæli-4, a large clast with imperfectly crystallized plagioclases (grey) and pyroxenes (bright). The brightest dots are Fe- and Ti-rich minerals, particularly the skeleton crystals of ulvospinel. D – Mæli-5, pure homogeneous glass shard with a bubble (left) and a rare clast which consists of Na-rich anorthite (dark), altered augitic mass with amphiboles and zeolites (intermediate tones, structured), and an unusual hopper-shaped olivine (brighter, in upper right corner). E – Mæli-6, an uncommon spherical glass grain, with very slight initial crystallite dotting in its central part and exfoliation at the surface. F – Mæli-8, a millimeter-sized clast of fibre-like volcanic glass with long tubular bubbles.

Table 2. The chemical composition of the Mælifellssandur (M) samples based on EDX analyses of polished surfaces of individual glass particles, shown in descending order of FeO values. The eight most important oxides are used to characterize the main chemical pattern of these volcanic glasses from particulate matter recalculated to 100%-total for each set. The Eyjafjallajökull (E) and Katla (K) tephra glass (recalculated from Navratil et al. 2013 and Sigmarsson et al. 2011) are used for comparison, M/E and M/K ratios are shown. Note that M and K values are alike (the individual M/K ratios are close to 1).

GLASS. CODE	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	FeO	glass - optical appearance in BSE
Mæli-7/3	3.28	4.11	13.60	42.81	0.85	10.44	5.68	19.24	homogeneous glass between nm- to µm-sized crystallites
Mæli-9/1	1.73	5.27	13.23	42.84	0.99	11.58	6.50	17.87	pure volcanic glass with few bubbles of 15-45µm diameters
Mæli-3/4	4.08	4.09	15.29	42.00	0.85	10.51	5.56	17.62	glass closely encircled by mineral crystallites
Mæli-1/2	3.41	5.36	14.11	40.45	0.99	12.39	5.80	17.50	pure blocky glass with few spherical bubbles of 10µm d.
Mæli-5/1	3.23	5.40	13.88	42.13	0.87	11.53	6.07	16.89	pure blocky glass. few spherical bubbles of 20µm diameter
Mæli-6/1	3.21	5.40	13.89	42.10	1.02	12.18	5.47	16.72	a glass spherule of 85µm diameter
Mæli-1/1	3.41	5.59	13.62	41.55	0.89	12.22	6.16	16.55	pure blocky glass with very rare bubbles of 5µm d.
Mæli-3/1	3.42	4.93	14.49	44.58	1.03	10.89	4.20	16.45	pure blocky glass between mm-sized crystals
Mæli-8/1	3.09	5.61	13.95	42.91	0.85	11.66	5.78	16.15	pure fibrous glass. very long parallel bubbles of 5-25µm d.
Mæli-7/5	3.34	3.66	15.93	44.31	0.81	12.12	4.84	14.98	glass closely encircled by mineral crystallites
AVG.VALUES									
M, 2013 (N 10)	***3.22***	***4.94***	***14.20***	***42.57***	***0.92***	***11.55***	***5.61***	***17.00***	Mælifellssandur, this study
E, 2010 (N 15)	*3.91*	*1.43*	*17.60*	*62.58*	*1.86*	*6.02*	*0.84*	*5.74*	Eyjafjallajökull, tephra glass (Navratil et al. 2013)
K, hist. (N n/a)	*3.11*	*4.89*	*13.16*	*48.28*	*0.80*	*9.76*	*4.84*	*15.17*	Katla, historical tephras (Sigmarsson et al. 2011)
M/E ratio	*0.82*	*3.46*	*0.81*	*0.68*	*0.49*	*1.92*	*6.64*	*2.96*	
M/K ratio	*1.04*	*1.01*	*1.08*	*0.88*	*1.15*	*1.18*	*1.16*	*1.12*	

'blackish' particulate matter (PM) glass was relatively stable. Based on the pattern of eight main oxides, this volcanic glass showed a very specific composition which could be easily identified in any mixture of dust deposited at some distance from the source (Table 2) and was notably different to the glass from recent eruptions. In particular, the Mælifellssandur glass had substantially higher amounts of FeO, MgO, CaO and TiO_2 than glass from the recent eruption of Eyjafjallajökull, as shown in Table 2. The glass was more similar to historical tephra from the Katla volcano (Table 2, Boygle 1994, Sigmarsson et al. 2011) with high levels of iron and titanium (FeO~17 %, TiO_2~6 % on average for our sample and FeO~15 %, TiO_2~ 5% for the Katla tephra). The TiO_2 content was particularly high, being 6–7 times higher than the content in the Eyjafjallajökull glass and considerably higher than that reported for tephra from the active Bárðabunga and Grímsvötn volcanic systems under the Vatnajökull glacier to the east (Oladottir et al. 2011). The high concentrations of TiO_2 and FeO were accompanied by depletion of SiO_2 in the glass to about 43 wt. % (Table 2). Such concentrations were lower than that reported for the MgO- and FeO-rich Laki tephra (ca. 50 % SiO_2, Kekonen et al. 2005), for Katla basalts (46-50 %), and for the entire East Volcanic Zone, including Eldgjá and Vestmannaeyjar (Oladottir et al. 2005). Strong depletion of SiO_2 in the Mælifellssandur material was a specific feature having a great potential to characterize the suspended particulates from this main dust source.

In comparing the particle sizes of suspended dust and the surface sample of deposit taken after the dust event, the surface sample was deprived of particles < 10 μm and significantly lower in particles < 2.5 μm than the measured suspended dust. Figure 6 shows that the aggregates consisted of fine and sub-micrometer particles, but 'single' particles were often of larger sizes (> 10 μm).

DISCUSSION

The ADMI measurements showed that dust generation can be activated under specific conditions such as from wet surfaces during the high precipitation season, from low wind speeds and low temperatures. The concentrations and size distributions measured during the short dust event give a unique insight into the initiation of dust storm events. Aerosol concentrations measured during wet background conditions on the dust source were very low; PMC_{10}~1-5 μg m^{-3} and PNC_{10}~222-2550 particles cm^{-3}. A gradual, steady surface heating caused the concentrations to rise with suspension of the dust and, in about four hours of direct sun, the PNCs increased over 100 times while PMCs increased over 600 times. This event was observed during low wind/ windless condition and we assume that the time needed to initiate dust production or suspension of the drying silt on the dust source decreases with higher wind velocities.

Comparing PNCs recorded during dust events elsewhere has shown the importance of close-to-ultrafine particles (0.2-0.35 μm) in respect to the total number concentration (Jayrante et al. 2011). The particle diameter mode of 0.2-0.3 μm can contain up to hundreds of thousands particles per cm^{-3} during severe dust storms or volcanic eruptions (Jayrante et al. 2011, Vogel et al. 2012). Background condition concentrations or concentrations measured by counters designed for particle diameter >0.5 μm count up to hundreds of particles per cm^{-3} (Tittarelli et al. 2008, Jayrante et al. 2011, Zhou et al. 2012). Such high PNCs of particles 0.3-10 μm as were measured here have only been reported during a volcanic eruption (Vogel et al. 2012). This shows that glacially derived airborne sediments are very fine with the highest number of suspended particles in sizes 0.3-0.337 μm in diameter, at least during the low wind speed events described here. Therefore, such source material is easily suspended within a short time.

Despite this, the mass concentrations meas-

ured during this small event were significantly lower than those measured during severe dust storms elsewhere and further from major dust sources (Wang et al. 2008, Jayrante et al. 2011, Dagsson-Waldhauserova et al. 2013b). The wind was not strong enough to lift many of the wet particles > 5 μm. The mean PMC_{10} of 234 μg m^{-3} confirmed the long-term estimation of PMC_{10} in NE Iceland calculated from visibility observations (Dagsson-Waldhauserova et al. 2013a).

The special conditions at the dust source during this dust event made the PNC and the PMC strongly correlated (Figures 3, 4); a higher number of dust particles resulted in higher mass concentrations. Such strong relationships most likely resulted from the moist soil conditions and high humidity. The glacial floodplain was still wet and therefore only fine, dried particles were uplifted. The surface sample of deposit taken after the dust event was deprived of 'single' particles < 10 μm while the fine and sub-micrometer particles were only found in the aggregates. We suggest that the fine particles were blown away and transported further from the source. Fine mode particles are usually scavenged by larger particles during dust storms, and thus the mass concentration is estimated to increase with decreasing number of particles (Jayrante et al. 2011, Zhou et al. 2012), which is contrary to our findings. However, the highest number concentrations for submicron particles are generally attributed to wind speeds < 2 m s^{-1} (Weber et al. 2006). The most extreme wind erosion events in Iceland are characterized by limited amounts of particles <125 μm (Arnalds et al. 2013). Further research is therefore needed during the dust events of higher wind velocity to understand the opposite correlation of PNC and PMC.

Mineralogical and geochemical analyses

Considering the chemistry and morphology of the material investigated, we suggest that the Mælifellssandur dust source materials, containing mostly the recycled products of the Katla volcano and adjacent volcanic system, were the main component of dust coming from the area. There are several reasons for this assumption: i) the compositions of the glass shards had narrow ranges in composition; ii) the glass and glassy shards were marked by the raised Ti–Fe concentrations together with a scarcity of well crystallized mineral phases or aggregate rock structures; iii) the marker crystals embedded in the glass were Na-rich anorthite and very small and/or skeleton crystals of ulvospinel; and iv) the majority of the glass shards showed a very uniform morphology which corresponds to explosively and spontaneously fractured, blocky rather than intensely foamed glass. The morphology of the tiny shards resembled the glassy particle deposits from the very recent plumes of the active volcano Grímsvötn, south-west of the Vatnajökull massif. However, the tephra compositions, with markedly low SiO_2 and high TiO_2–FeO concentrations, were different. They can most likely be attributed to the Sléttujökull 'old tephra' source in the Mýrdalsjökull area, or considered as characteristic of the chemistry of the Katla volcanic system (see Larsen 2000, Oladottir et al. 2005, Sigmarsson et al. 2011). This indicates that the fresh volcanic material from recent eruptions has been removed relatively rapidly.

A strongly polydisperse mixture of glass fragments, encompassing the sub-micrometer, silt and even the lower coarse sand classes, was indicative of multiple material sources. This material must have been reworked by fluvial and glaciogenic processes that led to extremely poorly sorted parts of the outwash fans. The rarely observed, millimeter-sized clasts of specific compositions (e.g., resedimented frothy or extremely elongated tephra grains, as exemplified in Figure 6D) belonged to clasts 'floating' in the common matrix of the resedimented tephra. The light frothy clasts could have drifted drift in the top layer of streaming water, whereas the compact, heavy rock fragments were either pushed up in the granular flow (inverse grading) due to the rheological Brazil-nut effect or, more likely, rep-

resented a relict material in deflation zones (clast pavement on the surface of outwash fans, Kjær et al. 2004). Similarly, they could have been separately redeposited with snow and ice cover before their fluvial reincorporation into the sediment.

The studied PM contained few crystals or mineral phases, and zeolites with other secondary minerals were either rare or absent. The well packed to slightly cemented, friable lumps indicative of slightly hardened surfaces (or laminae formed originally close under the surface) contain a small amount of secondary minerals, but even the smallest glass shards in these lumps still have very fresh appearances (Oskarsson et al. 2012). The studied suspended particulates are considerably more uniform than the more diversified, reworked sediment units which characterize other parts of the Mælifellssandur plain and which have been reported as typical for most of the jökulhlaup outwash fans or plains in general (Maizels 1997, Krüger et al. 2010).

Climate implications and health effects

Suspended glaciogenic dust contains substantial numbers of close-to-ultrafine particles which are sharp-tipped, curved, concave, and which contain bubbles. These physical properties allow the dust to be quickly suspended. Iceland is a region with high wind velocities, large desert and ice-proximal areas, favouring dust production. The country is therefore prone to dust generation and frequent, severe dust events. As a result, Iceland is a substantial source of dust on a global level, with particles being transported distances >1000 km from the dust sources during the largest dust events (Arnalds 2010, Navratil et al. 2013). Icelandic cyclones are associated with the uplift of the surface air to the upper troposphere while the tropopause location is lower in altitude than at more southern latitudes, at about 8 km in height. This suggests that Icelandic aerosol can be transported into the stratosphere as well (Rose et al. 2006, Roesli 2008), where the residence time is prolonged up to several weeks. Due to its dark colour, the dust can act as an absorbing aerosol and become an important radiative forcing agent (Meinander et al. 2014). Rose et al. (2006) described the non-volatile portion of the 2000 Hekla eruption particulates, transported to a 10 km altitude to the 75°N latitude in the Greenland Sea, as 'heated aerosols'. Further observations are needed to estimate any direct and indirect effects of Icelandic dust aerosol on Arctic warming. A warming climate with retreating glaciers will result in larger sandy deserts in Iceland, and a warmer climate will also enhance the radiative forcing effect over these dark surfaces.

The fine mineral dust from Mælifellssandur could affect human health because it is often transported towards the capital of Iceland, Reykjavik. A high amount of bioavailable metals in respirable dust increases the inflammatory capacity of PM, which may lead to negative health effects (Morman & Plumlee 2013). Perez et al. (2008) found that the effect of $PM_{2.5-10}$ on mortality rose from 5.0% to 8.4% when an additional 10 μg m^{-3} of metal-rich Saharan dust was present in the atmosphere. Mælifellssandur dust has a 2.4 times higher content of metals than Saharan dust and the mean PMC_{10} was > 180 μg m^{-3} above the health limit of 50 μg m^{-3} (Althingi, 2002). The maximum PMC_{10} was about 30 times above the health limit at the dust source, but we need to emphasize here that this event was very short. However, the PMCs we measured at the dust source are commonly reached at the few stations that measure particulate matter in Iceland, such as in Reykjavik, where PMC_{10} often reaches >100 μg m^{-3} (Thorsteinsson et al. 2011). In vitro studies of Icelandic ash exposure on immune system biomarkers in lung cells found that biomarkers were increased (Horwell et al. 2013) and responses to bacteria were suppressed (Monick et al. 2013).

CONCLUSIONS

Here we introduced the first comprehensive study of the physical and chemical properties

of the Icelandic dust aerosol measured directly within a dust source. This suspended glaciogenic dust contained high concentrations of close-to-ultrafine particles which were sharp-tipped and contained bubbles. The material consisted mostly of volcanic glass rich in iron and titanium. Particles of such morpho-textural characteristics are prone to suspension despite meteorological conditions such as moist surface or low wind. The surface heating of a relatively dark basaltic dust source allows mobilization of moist particles within several hours. The close-to-ultrafine particles have a significant impact on the total particle number concentrations and are likely to contribute to the commonality of Icelandic dust events. PNCs during dust events are comparable to that measured during volcanic eruptions indicating that large Icelandic dust events might have similar-scale impacts on climate. High PNCs were, however, measured at the source and the proportion of smaller particles will increase travel distance from the source while particle surface characteristics may change with time and distance due to leaching. This study brings new scientific findings in the field of dust physics and cryosphere-atmosphere interactions, which should serve as a platform for climate modelling and projections of future changes in climate. We emphasize that further work on the nature of Icelandic dust sources is needed.

ACKNOWLEDGEMENTS

This study is dedicated to Professor Martin Branis (✞ 27 September 2013) from the Charles University in Prague, Czech Republic. The work was supported by the Nordic Centre of Excellence for Cryosphere-Atmosphere Interactions in a Changing Arctic Climate (CRAICC), the Eimskip Fund of The University of Iceland and the FUTUREVOLC funded by the FP7 Environment Programme of the European Commission. The Czech geological team gratefully acknowledges the support of the institute research plan RVO 67985831 and are grateful to Sarka Jonasova, Anna Kallistova and Jaroslava Jaburkova, who were of technical assistance.

REFERENCES

Althingi 2002. *Reglugerð um brennisteinsdíoxíð, köfnunarefnisdíoxíð og köfnunarefnisoxíð, bensen, kolsýring, svifryk og blý í andrúmsloftinu og upplýsingar til almennings [Regulatons on the surface concentration of SO_2, NO_2, CO_2, PM and Pb and information to the public]*. Accessed 11.02.2014 at: http://www.reglugerd.is/interpro/dkm/WebGuard.nsf/key2/251-2002. [In Icelandic]

Arnalds O 2010. Dust sources and deposition of aeolian materials in Iceland. *Icelandic Agricultural Sciences* 23, 3–21.

Arnalds O, Gisladottir FO & Sigurjonsson H 2001. Sandy Deserts of Iceland: An overview. *Journal of Arid Environments* 47, 359-371.

Arnalds O, Gisladottir FO & Orradottir B 2012. Determination of aeolian transport rates of volcanic soils in Iceland. *Geomorphology* 167-168, 4-12.

Arnalds O, Thorarinsdottir EF, Thorsson J, Dagsson-Waldhauserova P & Agustsdottir AM 2013. An extreme wind erosion event of the fresh Eyjafjallajökull volcanic ash. *Nature Scientific Reports* 3, 1257.

Aston SR, Chester R, Johnson LR & Padgham RC 1973. Eolian dust from the lower atmosphere of the eastern Atlantic and Indian Oceans, China Sea and Sea of Japan. *Marine Geology* 14, 15-28.

Blechschmidt AM, Kristjansson JE, Olafsson H, Burkhart JF & Hodnebrog Ø 2012. Aircraft-based observations and high-resolution simulations of an Icelandic dust storm. *Atmospheric Chemistry and Physics Discussion* 12, 7949-7984.

Boygle JE 1994. *Tephra in lake sediments: An unambiguous geochronological marker?* Unpublished PhD. thesis. University of Edinburgh, 227 p.

Bullard JE 2013. Contemporary glacigenic inputs to the dust cycle. *Earth Surface Processes and Landforms* 38, 71-89.

Chepil WS & Woodruff NP 1957. Sedimentary characteristics of dust storms: II. Visibility and dust concentration. *American Journal of Science* 255, 104-114.

D'Almeida GA 1986. A model for Saharan dust transport. *Journal of Climate and Applied Meteorology* 25, 903-916.

Dagsson-Waldhauserova P, Arnalds O & Olafsson H 2013a. Long-term frequency and characteristics of dust storm events in Northeast Iceland (1949-2011). *Atmospheric Environment* 77, 117-127.

Dagsson-Waldhauserova P, Arnalds O & Olafsson H 2013b. Long-term variability of dust-storms in Iceland. *Geophysical Research Abstracts* 15, EGU2013-11578-1.

Dagsson-Waldhauserova P, Arnalds O & Olafsson H 2013c. Long term dust aerosol production from natural sources in Iceland. *Journal of the Air & Waste Management Association.* DOI:10.1080/10962247.2013.805703.

Harrison RM & Yin J 2000. Particulate matter in the atmosphere: Which particle properties are important for its effects on health? *Science of the Total Environment* 249, 85–101.

Horwell CJ, Baxter PJ, Hillman SE, Calkins JA, Damby DE & Delmelle P 2013. Physicochemical and toxicological profiling of ash from the 2010 and 2011 eruptions of Eyjafjallajökull and Grímsvötn volcanoes, Iceland using a rapid respiratory hazard assessment protocol. *Environmental Research* 127, 63–73.

Jayaratne R, Johnson G, McGarry P, Cheung H-C & Morawska L 2011. Characteristics of airborne ultrafine and coarse particles during the Australian dust storm of 23 September 2009. *Atmospheric Environment* 45, 3996-4001.

Kekonen T, Moore J, Perämäki P & Martma T 2005. The Icelandic Laki volcanic tephra layer in the Lomonosovfonna ice core, Svalbard. *Polar Research* 24, 33–40.

Kjær KH, Sultan L, Krüger J & Schomacker A 2004. Architecture and sedimentation of outwash fans in front of the Mýrdalsjökull ice cap, Iceland. *Sedimentary Geology* 172, 139–163.

Krüger J, Schomacker A & Benediktsson IO 2010. Ice-marginal environments: Geomorphic and structural genesis of marginal moraines at Mýrdalsjökull. In Kjær KH, Krüger J & Schomacker A (eds.) *The Mýrdalsjökull Ice Cap, Iceland: Glacial processes, sediments and landforms on an active volcano*. Elsevier Science Publishers BV, Amsterdam, pp. 79–104.

Larsen G 2000. Holocene eruptions within the Katla volcanic system, south Iceland: Characteristics and environmental impact. *Jökull* 49, 1–28.

Leadbetter SJ, Hort MC, von Löwis S, Weber K & Witham CS 2012. Modeling the resuspension of ash deposited during the eruption of Eyjafjallajökull in spring 2010. *Journal of Geophysical Research* 117, D00U10. DOI: 10.1029/2011JD016802.

Maizels J 1997. Jökulhlaup deposits in proglacial areas. *Quaternary Science Reviews* 16, 793–819.

Meinander O, Kontu A, Virkkula A, Arola A, Backman L, Dagsson-Waldhauserova P, Jarvinen O, Manninen T, Svensson J, de Leeuw G & Lepparanta M 2014. Brief Communication: Light-absorbing impurities can reduce the density of melting snow. *The Cryosphere Discussion* 8, 259-271.

Monick MM, Baltrusaitis J, Powers LS, Borcherding JA, Caraballo JC & Mudunkotuwa I 2013. Effects of Eyjafjallajökull volcanic ash on innate immune system responses and bacterial growth in vitro. *Environmental Health Perspectives*. *Environmental Health Perspectives* 121, 691-698.

Morman SA & Plumlee GS 2013. The role of airborne mineral dusts in human disease. *Aeolian Research* 9, 203–12.

Navratil T, Hladil J, Strnad L, Koptikova L & Skala R 2013. Volcanic ash particulate matter from the 2010 Eyjafjallajokull eruption in dust deposition at Prague, central Europe. *Aeolian Research* 9, 191-202.

Nickling WG 1978. Eolian sediment transport during dust storms: Slims River Valley, Yukon Territory. *Canadian Journal of Earth Sciences* 15, 1069-1084.

NILU Norwegian Institute for Air Research 2013. *The Zeppelin observatory at Svalbard*. Accessed 21.11.2013 at http://www.nilu.no/Milj%C3%B8overv%C3%A5kning/Zeppelinobservatoriet/tabid/214/language/en-GB/Default.aspx.

Oladottir B, Larsen G, Thordarson T & Sigmarsson O, 2005. The Katla volcano S-Iceland: Holocene tephra stratigraphy and eruption frequency. *Jökull* 55, 53–74.

Oladottir B, Larsen G & Sigmarsson O, 2011. Holocene volcanic activity at Grímsvötn, Bárðarbunga and Kverkfjöll subglacial centres beneath Vatnajökull, Iceland. *Bulletin of Volcanology* 73,1187-1208.

Oskarsson BV, Riishuus MS & Arnalds O 2012. Climate-dependent chemical weathering of volcanic soils in Iceland. *Geoderma* 189, 635–651.

Perez L, Tobias A, Querol X, Künzli N, Pey J & Alastuey A 2008. Coarse particles from Saharan dust and daily mortality. *Epidemiology* 19, 800–807.

Roesli HP 2008. *Winds from ex-hurricane Ike give rise to a remarkable dust cloud over Iceland.* Accessed 19.02.2014 at http://www.eumetsat.int/website/home/Images/ImageLibrary/DAT_IL_08_09_17.html;jsessionid=D1PPTGZC3q8cQfhsYVpTLCkQYzRjktLnw948PRw83Hmp-9cGTQJRl!-521040142.

Rose W, Millard GA, Mather TA, Hunton DE, Anderson B, Oppenheimer C, Thornton BF, Gerlach TM, Viggiano AA, Kondo Y, Miller TM & Ballenthin JO 2006. Atmospheric chemistry of a 33–34 hour old volcanic cloud from Hekla Volcano (Iceland): Insights from direct sampling and the application of chemical box modeling. *Journal of Geophysical Research* 111, D20206. DOI:10.1029/2005JD006872.

SEPA Scottish Environment Protection Agency 2011. *Grímsvötn volcano (Iceland) eruption May 2011: assessing the potential consequences of ash deposition in Scotland*. Accessed 10.11.2013 at http://www.sepa.org.uk/about_us/news/other/grimsvotn_volcanic_eruption.aspx.

Sigmarsson O, Vlastelic I, Andreasen R, Bindeman I, Devidal JL, Moune S, Keiding JK, Larsen G, Höskuldsson A & Thordarson T 2011. Remobilization of silicic intrusion by mafic magmas during the 2010 Eyjafjallajökull eruption. *Solid Earth* 2, 271–281.

Thordarson Th & Hoskuldsson A 2008. Postglacial volcanism in Iceland. *Jökull* 58,197-228.

Thorsteinsson Th, Gisladottir G, Bullard J & McTainsh G 2011. Dust storm contributions to airborne particulate matter in Reykjavík, Iceland. *Atmospheric Environment* 45, 5924-5933.

Tittarelli T, Borgini A, Bertoldi M, de Saeger E, Ruprecht A, Stefanoni R, Tagliabue G, Contiero P & Crosignani P 2008. Estimation of particle mass concentration in ambient air using a particle counter. *Atmospheric Environment* 42, 8543-8548.

Vogel A, Weber K, Fischer Ch, Pohl T, von Löwis S & Moser HM 2012. Ground based stationary and mobile in situ measurements of volcanic ash particles during and after the 2011 Grímsvötn volcano eruption on Iceland. Abstract VA-3 presented at 2012 *Volcanism and the Atmosphere conference*, AGU, Selfoss, Iceland, 10-15 Jun., 71-72.

Wang YQ, Zhang XY, Gong SL, Zhou CH, Hu XQ, Liu HL, Niu T & Yang YQ 2008. Surface observation of sand and dust storm in East Asia and its application in CUACE/Dust. *Atmospheric Chemistry and Physics* 8, 545-553.

Weber S, Kuttler W Weber & K 2006. Flow characteristics and particle mass and number concentration variability within a busy urban street canyon. *Atmospheric Environment* 40, 7565-7578.

Zhou B, Zhang L, Cao X, Li X, Huang J, Shi J & Bi J 2012. Analysis of the vertical structure and size distribution of dust aerosols over the semi-arid region of the Loess Plateau in China. *Atmospheric Chemistry and Physics Discussion* 12, 6113-6143.

Manuscript received 6 December 2013
Accepted 17 March 2014