



# Snow–Dust Storm: Unique case study from Iceland, March 6–7, 2013



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## ABSTRACT

Iceland is an active dust source in the high-latitude cold region. About 50% of the annual dust events in the southern part of Iceland take place at sub-zero temperatures or in winter, when dust may be mixed with snow. We investigated one winter dust event that occurred in March 2013. It resulted in a several mm thick dark layer of dust deposited on snow. Dust was transported over 250 km causing impurities on snow in the capital of Iceland, Reykjavík. Max one-minute PM<sub>10</sub> concentration measured in Kirkjubæjarklaustur (20–50 km from the dust source) exceeded 6500 µg m<sup>-3</sup> while the mean (median) PM<sub>10</sub> concentration during 24-h storm was 1281 (1170) µg m<sup>-3</sup>. Dust concentrations during the dust deposition in Reykjavík were only about 100 µg m<sup>-3</sup>, suggesting a rapid removal of the dust particles by snow during the transport. Dust sample taken from the snow top layer in Reykjavík after the storm showed that about 75% of the dust deposit was a volcanic glass with SiO<sub>2</sub> ~45%, FeO ~14.5%, and TiO<sub>2</sub> ~3.5. A significant proportion of organic matter and diatoms was also found. This case study shows that severe dust storms are related also to meteorological conditions, such as winter snow storms, and moist conditions. Small volcanic dust particles deposited on snow tend to form larger particles (“clumping mechanism”) resulting in stronger light absorbance. This is one of the first reports on the “clumping mechanism” observed in natural conditions. The deposition of Icelandic dust on snow, glaciers and sea ice may accelerate the thaw, with the potential to increase the anthropogenic Arctic warming.

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## 1. Introduction

Dust emissions have pronounced influences on Earth’s ecosystems (Fields et al., 2010), originated from deserts occurring in a variety of climatic conditions. Cold climate regions have less extensive dust sources than warmer areas; yet cold desert dust is an important input to the dust cycle (Bullard, 2013). Cold desert areas can be found for example in Alaska (Crusius et al., 2011), Greenland (Bullard, 2013) and Patagonia (Gassó et al., 2010). However, Iceland is likely the largest and most active high-latitude dust source, where dust deposition is expected to influence an area of >500,000 km<sup>2</sup> (Arnalds et al., 2013, 2014; Dagsson-Waldhauserova et al., 2013, 2014a). Icelandic dust is of volcanic

origin with high content of iron, which has potentially marked influence on the primary productivity in oceans around Iceland and needs to be considered for nutrient budgets for the area (Prospero et al., 2012; Arnalds et al., 2014). The dust frequency of >34 dust days per year in Iceland is comparable to that found in Mongolia and Iran (Dagsson-Waldhauserova et al., 2014a). Including synoptic codes for “Visibility reduced by volcanic ashes” and “Dust haze” into the criteria for dust observations increases the frequency to >135 dust days annually, which is comparable to the major deserts of the world. Suspended dust was detected during moist and low wind conditions in Iceland in summer (Dagsson-Waldhauserova et al., 2014b). However, almost half of all dust events in southern part of Iceland occurred during winter or at sub-zero temperatures (Dagsson-Waldhauserova et al., 2014a).

Winter dust deposition on snow has been studied in Colorado and Utah, USA, where dust in snow accelerated snowmelt by direct reduction of snow albedo and indirect reduction of albedo by

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accelerating the growth of snow grain size (Painter et al., 2012; Steenburgh et al., 2012). Recently, several winter dust events caused a closure of the skiing areas in Colorado mountain areas while avalanche danger was triggered by the dust deposition (Summit County, 2014). A historical dust deposition on snow and “snow dust storm” was described in Central Europe (Czech Republic) on April 19, 1903, when the Saharan yellowish-red dust mixed with snow and rain was deposited on snow (Ankert, 1903).

Darker snow surface after dust deposition lowers snow albedo, increases melt, and can also reduce snow density (Meinander et al., 2014). Direct radiative forcing of mineral dust was calculated as negative in the IPCC report (IPCC, 2013), but indirect forcing of dust deposited on snow needs to be investigated in a greater detail. The first dust-on-snow studies showed that the average spring dust radiative forcing ranged from 45 to 75 W m<sup>-2</sup>, reducing snow cover duration by 21–51 days (Painter et al., 2012).

Icelandic dust differs from dust originating from continental dust sources, such as the Saharan, Asian or American dust. The dust is volcanogenic in origin and of basaltic composition (SiO<sub>2</sub> < 50%, high Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub> contents). Primary volcanic deposits in large areas of Iceland have been reworked by glacial processes resulting in fine glaciogenic dust (Bullard, 2013). Volcanic dust made of glass can be sharp and porous allowing particles as large as 50 µm to travel long distances (Navratil et al., 2013). Suspended glaciogenic dust can, however, contain a high number of close-to-ultrafine particles (Dagsson-Waldhauserova et al., 2014b). Such particles can affect cloud microphysics and solar radiation while the fine-grained iron containing minerals may modulate the uptake of carbon in marine ecosystems and atmospheric concentration of CO<sub>2</sub> (Min et al., 2009; Maher et al., 2010).

The purpose of this study was to investigate a special phenomenon, which we term “Snow–Dust Storm”, in a cold climate region. The Snow–Dust Storms have been observed in Iceland yearly. However, this is the first case captured by the instruments and cameras at more locations, and consequently sampled. The main characteristics of severe Snow–Dust Storm were investigated: (i) the source region and transport of the dust, (ii) suspended dust concentrations, (iii) chemical and mineralogical composition of transported material, and (iv) clumping mechanisms due to dust-on-snow deposition in natural conditions.

## 2. Methods and meteorological conditions

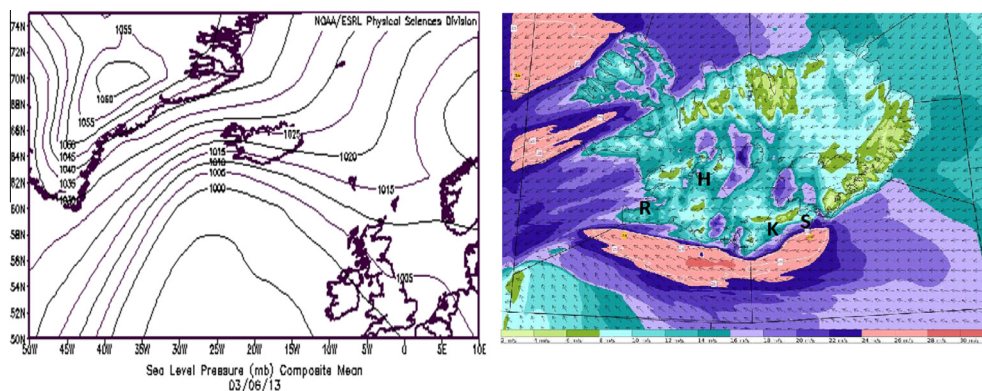
The Snow–Dust Storm (SDS) and dust deposition on snow occurred in S and SW Iceland on March 6–7 2013. The impurities on snow were visible on March 6 and 7 in Reykjavik (SW) and

Kirkjubæjarklaustur (S), which is about 200 km from Reykjavik (Figs. 1 and 3). Ambient particulate matter (PM<sub>10</sub>) mass concentration data were obtained from Reykjavik (Thermo EMS Andersen FH 62 I-R instrument) and Kirkjubæjarklaustur (Grimm EDM 365) by the Environmental Agency of Iceland. A snow sample with deposited dust (3 cm top layer) was taken in Reykjavik (Keldnaholt) on March 7 at 10:00. The compositions of the tephra glass and mineral grains were studied using backscattered electrons and quantitative X-ray analysis (EDX SEM) on samples fixed in resin and polished to planar cross-sectional surfaces. Major mineral compositions were also checked by X-ray powder diffraction (XRD).

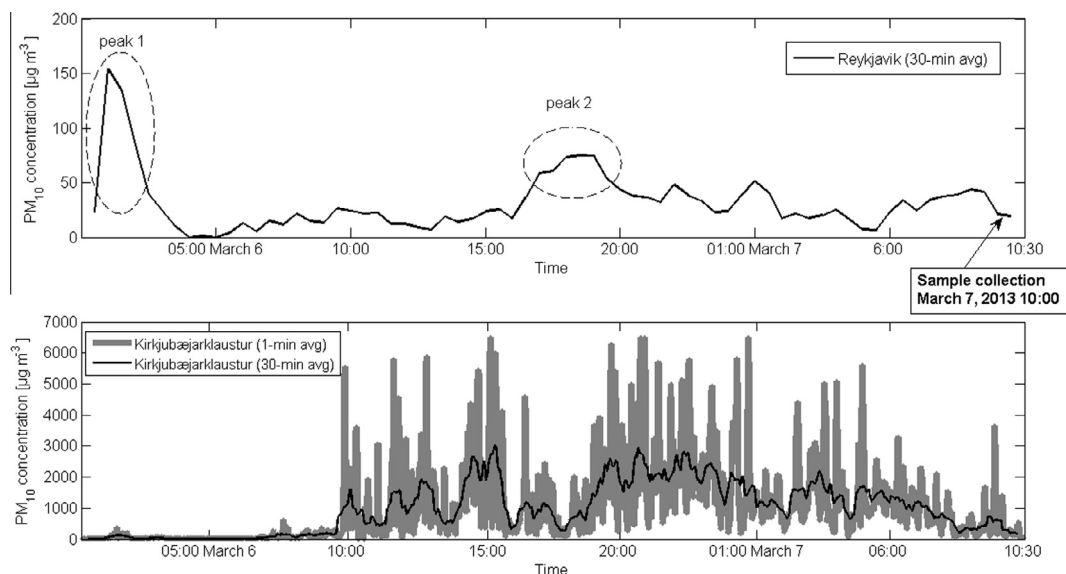
On 6–7 March 2013, there were persistent and strong winds in S-Iceland, associated with a strong pressure gradient between slowly moving and deep extratropical cyclone to the west of Ireland and a high over Greenland (Fig. 1). This quite a common weather pattern, leading to strong easterly winds over Iceland, particularly along the S/SE-coast where observed winds (U) at 10 m were about 25 ms<sup>-1</sup> on 6 March (Fig. 1). The atmosphere was conditionally unstable below ca. 850 hPa giving a Brunt–Vaisala frequency (*N*) of about 0.08 s<sup>-1</sup>. With the maximum height of the topography (*h*) in the southernmost part of Iceland being about 1500 m, the non-dimensional mountain height (*Nh/U*) is close to 0.5. At such a low value, the flow is only to a little extent diverted around the mountains. Instead, it flows rather easily over the mountain ranges between Kirkjubæjarklaustur and Reykjavik (see Fig. 1 for their location).

The first dust peak in Reykjavik lasted about 3 h (0–3 UTC) on 6 March. The SDS occurred in Kirkjubæjarklaustur from 7:00 on 6 March to 9:30 on 7 March. Subsequently, dust was observed in the air and deposited on the snow in Reykjavik for the second time at 17:00–20:00 on 6 March (second peak). The dust was transported in a few hours from either Central-Iceland (peak 1, Figs. 2 and 4) or from the Kirkjubæjarklaustur area to Reykjavik (peak 2, Figs. 2 and 4). The 24 h accumulated precipitation in Reykjavik (Kirkjubæjarklaustur) was 7.5 mm (0.5 mm) at 9 UTC on 6 March and 0.7 mm (0 mm) at 9 UTC on 7 March. These values may however not represent the true precipitation well because conventional precipitation measurements are far from accurate when precipitation is solid and there were strong winds. Synoptic observations indicate either continuous or intermittent snowfall during this period.

Backward trajectories up to 7 h were calculated, using the National Oceanic and Atmospheric Administration (NOAA) hybrid single-particle lagrangian integrated trajectory (HYSPLIT) model. The HYSPLIT model was run with the NCEP Global Data Assimilation System (GDAS) dataset. Trajectories were calculated for every hour by tracking an air parcel that is carried by the mean 3-D wind



**Fig. 1.** Left: Mean sea level pressure (hPa) around Iceland on 6 March, 2013. Based on the NCEP/NCAR reanalysis and retrieved at NOAA/ESRL. Right: Wind speed (m s<sup>-1</sup>) over Iceland at 12 UTC on 6 March 2013 as reproduced by the operational analysis of the ECMWF. R, Reykjavik; K, Kirkjubæjarklaustur; S, Skeidarsandur dust source; H, Hagavatn dust source.



**Fig. 2.** PM<sub>10</sub> concentrations during the Snow–Dust Storm in Reykjavik (upper graph) and Kirkjubæjarklaustur (lower graph) on March 6–7, 2013.



**Fig. 3.** The Icelandic Snow–Dust Storm on March 6, 2013, in Kirkjubæjarklaustur (left), caused a significant volcanic dust deposition on snow (see also the car). The impurities on snow were visible in Reykjavik, 250 km from the dust source (right) on March 6 and 7, 2013. On the snow surface, the impurities were observed to form larger particles (“clumping mechanism”) and accelerate snow melt. Such high-latitude winter and cold Icelandic dust events (>9 annually) have the potential to contribute to Arctic warming. The Icelandic dust deposition is estimated to influence an area of >500,000 km<sup>2</sup>. Left photo – courtesy of Ingvaldur Gudny Sveinsdottir from Kirkjubæjarklaustur. Right photos – ©Pavla Dagsson-Waldhauserova.

field of the meteorological model at the altitude 200 m above ground level (AGL). No cloud-free satellite images were available for this event.

### 3. Results and discussion

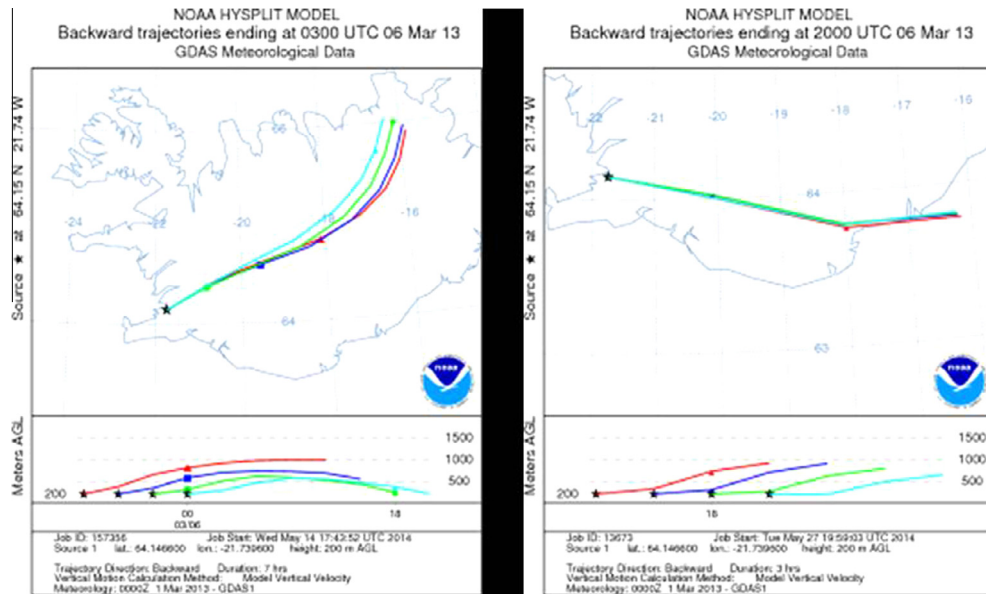
Two peaks of increased PM<sub>10</sub> concentrations of about 75–154 µg m<sup>−3</sup> (thirty-min mean) were reported in Reykjavik on March 6 (first at 0:00–3:00, second at 17:00–20:00) as depicted in Fig. 2. A severe dust storm with the PM<sub>10</sub> concentrations up to 6500 µg m<sup>−3</sup> (one-min mean) passed Kirkjubæjarklaustur on March 6–7. Mean (median) PM concentrations during the SDS in Kirkjubæjarklaustur was 1281 (1170) µg m<sup>−3</sup>. The snow was first found covered with dust on March 6 around 10:00. A new dust layer was found in Reykjavik on March 7, when the sample was taken (Fig. 3).

The HYSPLIT back trajectory analysis showed that the dust peak 1 (0:00–3:00) observed in Reykjavik consisted of dust from a NE

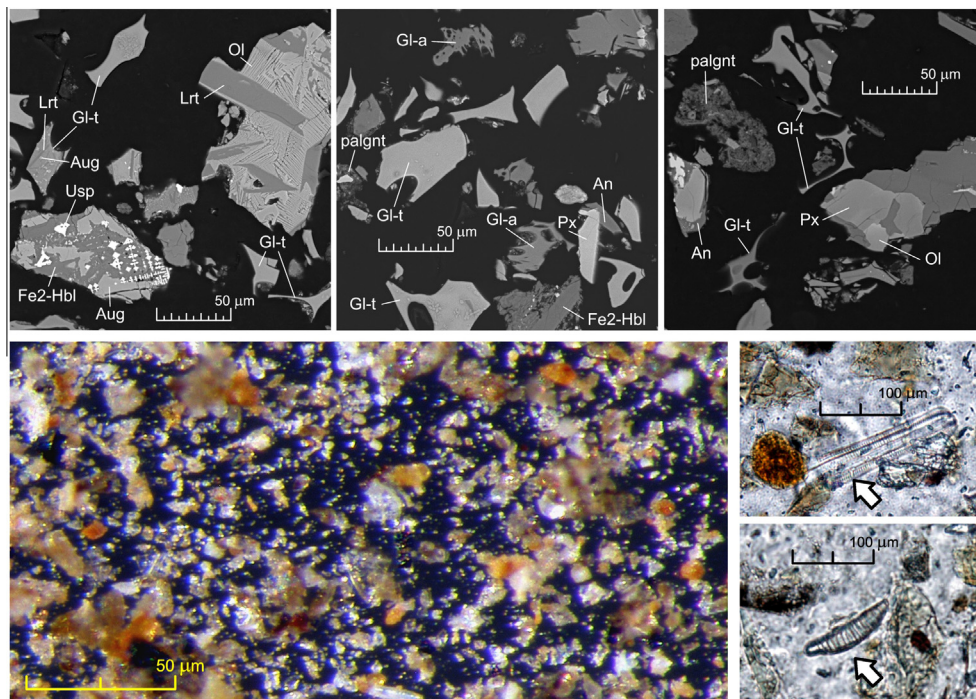
direction and the dust peak 2 (17:00–20:00) contained dust arriving from a SE direction, and is the same dust storm as observed in Kirkjubæjarklaustur (Fig. 4). The dust source Skeidararsandur is located about 20 km east of Kirkjubæjarklaustur, while Reykjavik is about 250 km downwind (WNW) of Skeidararsandur. Relatively low PM concentrations in Reykjavik during the storm are likely the result of the rapid removal of the dust particles by snow during the transport. Heavy snow fall was reported mainly from Reykjavik during the night 5–6 March (dust peak 1). Synoptic observations indicate either continuous or intermittent snowfall during the period 6–7 March for South Iceland. However, high surface wind speed cleared the snow from the flat fields of SE-Iceland and brought the dust into suspension. The strong winds and the complex terrain contribute to strong turbulence and mixing of the dust in at least the lowest 1 km of the atmosphere.

Mineralogical and geochemical composition of a dust sample, taken from the top layer of the snow in Reykjavik on March 7, was investigated to determine the source of the dust transported to Reykjavik. The XRD combined with the optical microscopy





**Fig. 4.** The HYSPLIT backward trajectories calculated for the first (left, 00:00–03:00) and the second (right, 17:00–20:00) dust peak in Reykjavik.



**Fig. 5.** Microscopic images of the dust material. *Upper row:* Examples of backscattered electron images of planar-polished sections of the dust particles; the analyzed and interpreted minerals and glasses are marked by symbols: An – andesine, Aug – augite, Fe2-Hbl – ferrohorneblende, Lrt – labradorite, Ol – olivine, Px – pyroxene, Usp – ulvospinel; Gl-t – volcanic glass of tholeiitic series, Gl-a – volcanic glass of alkalic series; palgnt – palagonitic material. *Lower row:* The fine particle distributions are illustrated in the figure on the left (optical microscope, dark field). Examples of diatoms – *Rhopalodia* sp., poss. *R. gibba* (upper), *Epithemia* sp., poss. *E. adnata* (lower).

identified about 75% of the dust deposit as a volcanic glass with grains 1–250 µm in diameter (average 17 µm). However, about 70% of the particles were <10 µm and 20% were in range 10–50 µm. High PM<sub>10</sub> mass concentrations detected during the SDS in Kirkjubæjarklaustur measured only the particles <10 µm, but about 30% of transported material found in Reykjavik was >10 µm. Including large particles would increase the suspended dust mass substantially.

Most of the volcanic glass particles (about 70%) showed chemical compositions of: SiO<sub>2</sub> ~45%, FeO ~14.5%, TiO<sub>2</sub> ~3.5%, Al<sub>2</sub>O<sub>3</sub>

~14.5%, CaO ~12%, MgO ~6.25%, and Na<sub>2</sub>O + K<sub>2</sub>O ~4%. This composition corresponds closely to the composition of the Grimsvotn tephra materials (see Oladottir et al., 2011a), suggesting the Skeidararsandur origin of the dust. Small number of glass shards corresponded to alkalic transitional tephra and materials from the alkalic Holocene eruptions of the S, SW Iceland (Oladottir et al., 2011b), which could originate from the Hagavatn dust source (northern trajectory in Fig. 4), but also, alternatively from the 2010 Eyjafjallajökull deposits (southern trajectory in Fig. 4). The Hagavatn dust analysed by Baratoux et al. (2011) also shows

similarities in major element composition with our sample. The PM<sub>10</sub> concentrations measured in Reykjavik and chemical analysis of the snow–dust sample indicate that the majority of the dust was deposited on snow during the peak 1 on March 6 (0–3 h). Consequently, volcanic glass from the Grimsvotn volcanic system was transported towards Reykjavik (dust peak 2).

The most common glass morphologies were characterized by numerous ~10–20 µm gas bubbles. Low frequency of bubbles corresponded to massive shards, while high frequency was in bubble-wall shards. Rare alkali- and silica-rich glasses showed different, very fine pipe-vesicular structures (Fig. 5, top-right). Such elongated shapes are more similar to asbestos particles or black carbon than mineral dust, and may pose health risks (Donaldson et al., 2006). The individual mineral grains and crystals embedded in the glass were mostly plagioclases (labradorite and andesine), pyroxenes (augite), olivines (fayalite) and amphiboles (ferrohornblende), whereas Na–K feldspars were rare. Titanium and iron were often concentrated to ulvospinel (Fig. 5), magnetite–titano–magnetite and ilmenite. Such mineralogical contribution along with the chemical compositions indicates that the sample was a mixture of material originating in Skeidararsandur (southern trajectory, peak 2) and Hagavatn dust (northern trajectory, dust peak 1).

Transported dust contained various clay minerals, chlorites, zeolites and many minerals revealing a wide spectrum of altered, heterogeneous tephra and primitive soils. We identified hydrated palagonites with imperfect lattices of ferrihydrite and smectites (possibly also allophane, imogolite, zeolites and carbonates) in several glass fragments. Detritus of decayed organic matter (from algae to vascular plants, ~0.25 vol.%) and scattered *Bacillariophyceae* opal frustules were also found (Fig. 5). The volume of the organic matter in the SDS is considered as relatively low compared to 8–67 wt% reported from Australia (Boon et al., 1998). It reflects both the Iceland subarctic conditions and winter state of the emitting surfaces. Presence of diatoms and organic matter in transported dust indicates that the dust originated in area of lakes or river beds. However, the identification of exact location from the 49 examined lakes and 139 diatom taxa found in Iceland is complicated (Karst-Riddoch et al., 2009). Identified diatoms are benthic and may be present in shallow pools or waters around the edges of lakes and rivers. Fig. 5 shows the *Rhopalodia* and *Epithemia* diatom species (likely epiphytic).

Recent terminology does not include a classification for the dust and deserts of volcanic origin. Volcanic dust in this paper means the material which was re-suspended/emitted from old to ancient tephra deposits, mainly glaciofluvial and by-wind-recycled tephra sediments; as in contrast with “fresh, unaltered volcanic ash”. Icelandic volcanic dust is a dust made of volcanic materials, regardless of age and mode of formation. It can be redistributed volcanic ash, lava materials, hyaloclastics and other volcanic materials becoming airborne because of aeolian processes.

Dust deposition on snow affects climate by reducing snow albedo and increasing snow-melt due to light-absorbing particles (Painter et al., 2012). The melting rates of snow influenced by Icelandic volcanic dust were similar to snow with a black carbon layer (Meinander et al., 2014). We observed the small volcanic dust particles that were deposited on snow to form larger particles (“clumping mechanism”, Fig. 3). Our observation of particle clumping in natural conditions is with high potential importance, as it may influence the absorbance of the dust in snow. Moreover, the mechanism has been considered only as an artefact occurring in artificial experiments (Brandt et al., 2011). Our finding makes new relevance to the results from any experiment using artificially deposited impurities on snow.

There are strong indications, according to our measurement data on the optical properties of the Icelandic volcanic dust, that

Icelandic dust is a positive radiative forcing agent, both directly and indirectly, which is contrary to mineral dust effects reported by the IPCC (IPCC, 2013; Meinander et al., 2014). Dust deposition on Icelandic glaciers was calculated as 4.5 million t per year with the mean deposition of 400 g<sup>−2</sup> yr<sup>−1</sup> (Arnalds et al., 2014). We suggest that Icelandic volcanic dust events not only affect Iceland but have the potential to reach the Arctic glaciers and sea ice and accelerate the Arctic warming.

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