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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, Reykjavik. Max one-minute PM_{10} concentration measured in Kirkjubæjarklaustur (20–50 km from the dust source) exceeded 6500 $\mu g\ m^{-3}$ while the mean (median) PM_{10} concentration during 24-h storm was 1281 (1170) $\mu g\ m^{-3}$. Dust concentrations during the dust deposition in Reykjavik were only about 100 $\mu g\ m^{-3}$, suggesting a rapid removal of the dust particles by snow during the transport. Dust sample taken from the snow top layer in Reykjavik after the storm showed that about 75% of the dust deposit was a volcanic glass with SiO_2 ~45%, FeO ~14.5%, and TiO_2 ~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.

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^2 (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 $W\,m^{-2}$, 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 ($SiO_2 < 50\%$, high Al_2O_3, and Fe_2O_3 contents). Primary volcanic deposits in large areas of Iceland have been reworked by glacial processes resulting in fine glacigenic 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 glacigenic 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_2 (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_{10}) 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^{-1} 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^{-1}. 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

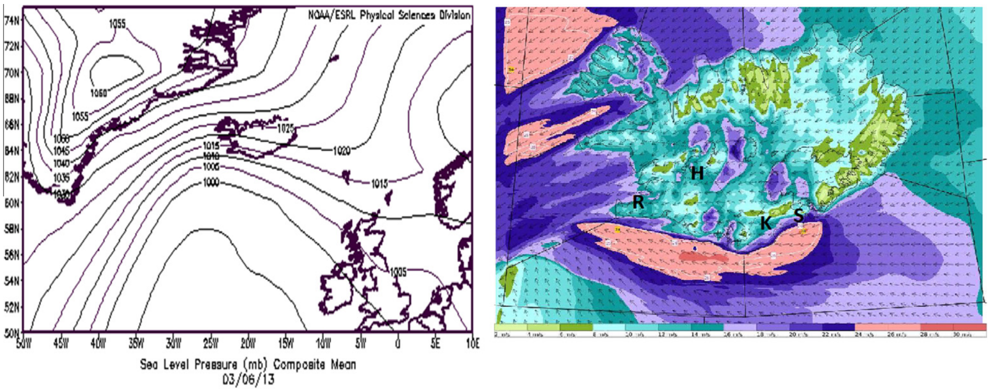

Fig. 1. *Left:* Mean sea level pressure (hPa) around Iceland on 6 March, 2013. Based on the NCEP/NCAR reanalysis and retrieved at NOAA/ESRL. *Right:* Wind speed ($m\,s^{-1}$) over Iceland at 12 UTC on 6 March 2013 as reproduced by the operational analysis of the ECMWF. R, Reykjavik; K, Kirkjubæjarklaustur;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