Review article

The Icelandic volcanic aeolian environment: Processes and impacts — A review

Olafur Arnalds [a,b,*], Pavla Dagsson-Waldhauserova [a,c,d], Haraldur Olafsson [d,e]

[a] Agricultural University of Iceland, Hvanneyri, Iceland
[b] United Nations University Land Restoration Program, Reykjavik, Iceland
[c] Faculty of Environmental Sciences, Czech University of Life Sciences, Prague, Czech Republic
[d] Faculty of Physical Sciences and Faculty of Earth Sciences, University of Iceland, Reykjavik, Iceland
[e] Icelandic Meteorological Office, Reykjavik, Iceland

A R T I C L E   I N F O

A B S T R A C T

Iceland has the largest area of volcaniclastic sandy desert on Earth or 22,000 km^2. The sand has been mostly produced by glacio-fluvial processes, leaving behind fine-grained unstable sediments which are later re-distributed by repeated aeolian events. Volcanic eruptions add to this pool of unstable sediments, often from subglacial eruptions. Icelandic desert surfaces are divided into sand fields, sandy lavas and sandy lag gravel, each with separate aeolian surface characteristics such as threshold velocities. Storms are frequent due to Iceland's location on the North Atlantic Storm track. Dry winds occur on the leeward sides of mountains and glaciers, in spite of the high moisture content of the Atlantic cyclones. Surface winds often move hundreds to more than 1000 kg m^{-1} per annum, and more than 10,000 kg m^{-1} have been measured in a single storm. Desertification occurs when aeolian processes push sand fronts and have thus destroyed many previously fully vegetated ecosystems since the time of the settlement of Iceland in the late ninth century. There are about 135 dust events per annum, ranging from minor storms to >300,000 t of dust emitted in single storms. Dust production is on the order of 30–40 million tons annually, some traveling over 1000 km and deposited on land and sea. Dust deposited on deserts tends to be re-suspended during subsequent storms. High PM$_{10}$ concentrations occur during major dust storms. They are more frequent in the wake of volcanic eruptions, such as after the Eyjafjallajökull 2010 eruption. Airborne dust affects human health, with negative effects enhanced by the tubular morphology of the grains, and the basaltic composition with its high metal content. Dust deposition on snow and glaciers intensifies melting. Moreover, the dust production probably also influences atmospheric conditions and parameters that affect climate change.

Contents

* Corresponding author at: Agricultural University of Iceland, Keldnaholt, Árleynir 22, Keldnaholt, Reykjavik 112, Iceland. Tel.: +354 843 5340.
  E-mail address: oa@lbhi.is (O. Arnalds).

1. Introduction

Iceland is one of the most active aeolian areas on Earth, despite the fact that it does not lie in an arid region. Unstable sandy surfaces are widespread and subject to frequent high-velocity winds, resulting in numerous wind erosion events and dust production. Airborne redistribution of surface materials has a dominant influence on Icelandic soils and ecosystems. It also affects such factors as human health, climate, snowmelt, Icelandic soils, and possibly ocean fertility. Icelandic desert areas comprise the largest volcaniclastic desert area in the world (Edgett and Lancaster, 1993; Arnalds et al., 2001a), which distinguishes them from other areas of intense aeolian activity. Icelandic sand-fields have served as analogs for planetary desert landscapes and processes, such as on Mars (e.g., Baratoux et al., 2011; Mangold et al., 2011).

Volcanic eruptions in Iceland occur every 3–5 years, fed by the mantle plume or hotspot under the island (Thordarson and Höskuldsson, 2008). About 11% of the country is covered by glaciers (Björnsson and Palsson, 2008) with many active volcanoes located under the ice. This enhances production of volcanic ash during "wet explosive eruptions". The glaciers also produce glacio-fluvial plains covered with sediments that might be termed "volcano-fluvial" deposits. These materials are primarily basaltic in composition, while andesite and rhyolite also occur in smaller amounts. The influence of the dust deposits on ecosystems is amplified by the volcanic nature, basaltic composition and rapid weathering of the materials.

Knowledge of aeolian activity in Iceland is of crucial importance for understanding aeolian processes in general and their impact on ecosystems and atmospheric processes. Furthermore, aeolian processes in Iceland can shed light on global loess production, large scale wind erosion and the impact of dust on both the natural environment and society. Understanding of aeolian processes in Iceland has improved substantially in recent years. The purpose of this paper is therefore to review and summarize our current knowledge of aeolian processes in Iceland.

2. Background

Iceland is a volcanic island with an area of 103,000 km^2 located just south of the Arctic Circle, lying between 63° and 66.6° north latitudes and 13–24° west longitudes (Fig. 1). The climate is relatively mild in spite of its northern position as it is influenced by the
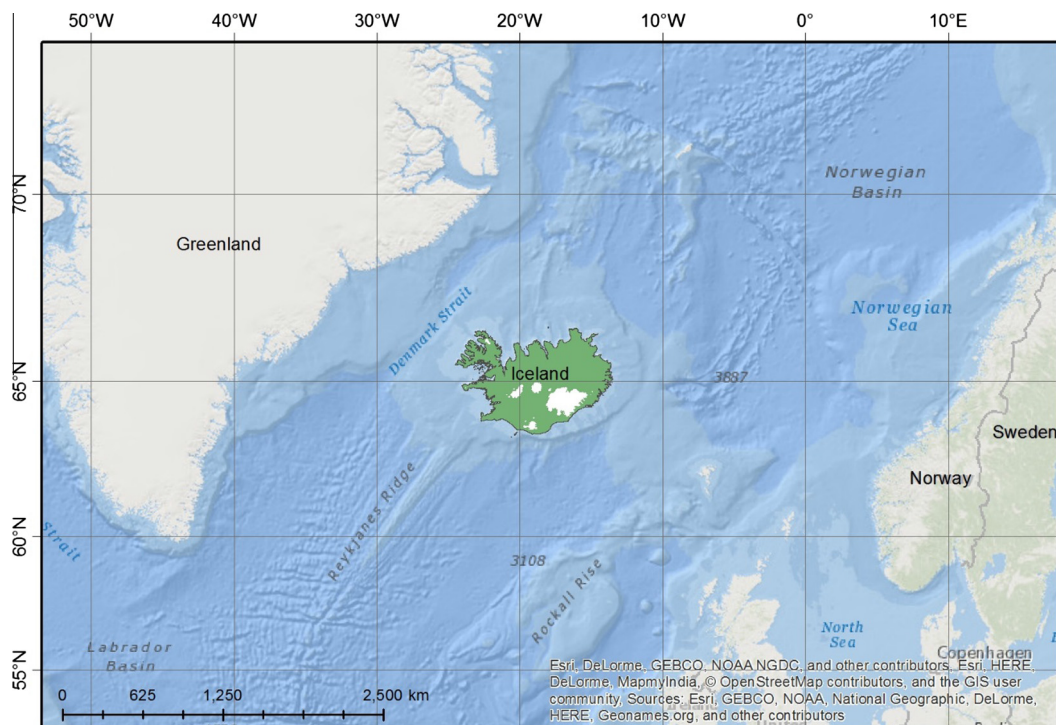

Fig. 1. Location of Iceland in the North-Atlantic Ocean.

Table 1
Deserts and other main surface types of Iceland, separated by elevation intervals, with a total of 43,388 km² of deserts. *Source:* AUI Nytjaland database (Gisladottir et al., 2014). Hay fields/cultivated land includes both drylands and drained wetlands. Drylands consist of the AUI vegetation classes 'grassland', 'heathlands' and 'shrubs and forest'. Wetlands are both 'damp wetlands' and 'saturated wetlands'. 'Deserts' consists of the AUI classes 'half vegetated' and 'barren' with various types of desert surface, including sandy deserts.

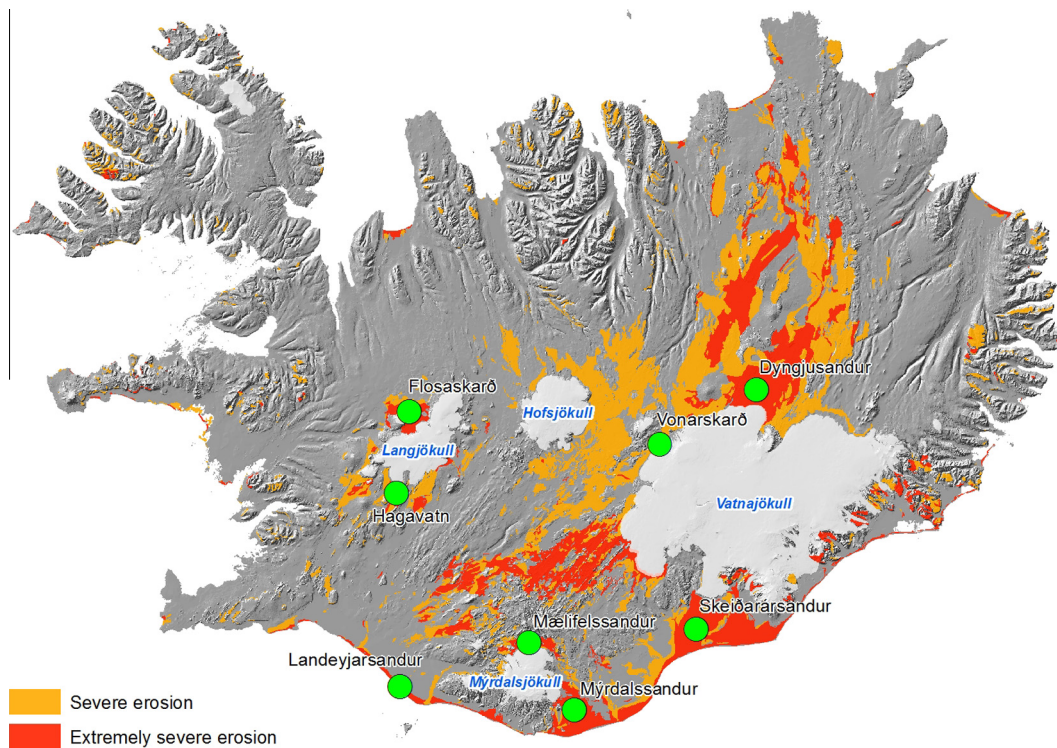|	Elevation intervals (m)					
	0–200 (km²)	200–400 (km²)	400–800 (km²)	>800 (km²)	Total (km²)	%
Hay fields/cultivated	1678	44	1	0	1723	1.7
Vegetated drylands	14,208	10,919	13,059	468	38,654	37.6
Vegetated wetlands	2704	1642	1449	2	5797	5.6
Deserts	5209	5047	24,577	8555	43,388	42.2
Water, ice, glaciers	1350	430	1795	9756	13,331	13.0
Total	25,149	18,082	40,881	18,781	102,893	100

Fig. 2. Sandy deserts in Iceland, shown with yellow and red colors, which represent erosion severity (yellow: erosion severity 4, severe erosion; red: erosion severity 5, extremely severe erosion). They cover large proportions of the south-coast and glacial margins of the active volcanic zone from Mýrdalsjökull glacier to areas northeast of Vatnajökull glacier. Several localized dust hot-spots are marked with a circle and more detailed account of these are provided in Table 3. Map: AUI Soil Erosion Database, prepared by Sigmundur Helgi Brink© SHB/OA, AUI.

powerful North Atlantic Current (Irminger Current) that brings warm waters to the southern shores of Iceland while the cold East Greenland Current affects the west and north (Einarsson, 1984; Olafsson et al., 2007). Atmospheric low pressure systems are common, sometimes referred to as the "Icelandic low," which frequently result in relatively high wind speeds. The mean annual temperatures are commonly 0 to +4 °C in the lowlands and mostly 0 to −4 °C in the highlands. Large parts of Iceland receive ample moisture to support vegetative growth with more than 600 mm annual rainfall. However, areas of low rainfall north of the Vatnajökull Glacier receive less than 400 mm rainfall annually. Humidity is usually as high as 75–90%, but can be quite low in cold dry air masses (see e.g., Einarsson, 1984). Although rainfall is common, it is typically long-lasting and of low intensity. Due to the common occurrence of low-pressure areas and the periodic occurrence of storms (cyclones) blowing from the Arctic, Iceland is generally windy (Einarsson, 1984; Olafsson et al., 2007). Wind speed can reach 30 m s⁻¹ and exceed 50 m s⁻¹ near mountains during severe storms, with wind speeds of 5–15 m s⁻¹

quite common (see Icelandic Meteorology Office web page, www.vedur.is).

Icelandic surfaces were classified by the "AUI Nytjaland" land cover database into several vegetation classes (Gisladottir et al., 2014). A simplified version is presented in Table 1, separated by elevation intervals, which shows how vegetation cover decreases with the harsher ecological conditions at higher elevations. However, a substantial proportion of the deserts was formed after the settlement of Iceland by the Norse about 1200 years ago, due to the interaction of harsh natural conditions and land use that included grazing by livestock and cutting trees for firewood, especially in the areas below 600–800 m elevation (see Arnalds, 2015, Ch. 12). Most settlements and agriculture are located below 200 m of elevation. About 43,000 km² of Iceland are desert (about 22,000 km² are sandy deserts), making it miniscule compared to the world's deserts in arid areas, but its northerly mid-ocean position on the North Atlantic Storm track has made it a focal point in terms of strong winds and dust and ash distribution.

Table 2
Active aeolian surfaces in Iceland. Erosion severity represent erosion activity with 3: considerable; 4: severe; 5: very severe. Based on "Soil Erosion in Iceland" (Arnalds et al., 2001a). The combined areas of erosion severity 4 and 5 represent the active aeolian areas (14,795 km²).

Surface type	Erosion severity			Total (km²)
	3 (km²)	4 (km²)	5 (km²)	
Sandur (sand-fields)	318	1087	2828	4233
Sandy lag-gravel	5407	6217	1286	12,910
Sandy lava	1366	1757	1620	4743
Total	7091	9061	5734	21,886
Total 4 + 5		14,795		

Fig. 3. Examples of the major desert surfaces in Iceland. A: level sand plain (sand-field) showing deflation in one year (about 30 cm); B: silty surface (aeolian hot-spot) being charged by glacial stream, which will disappear within hours; C: sandy lava surface.

3. Sandy surfaces in Iceland

There are several types of desert surfaces in Iceland, with varying degrees of aeolian activity. Following is a description based on a classification of desert surfaces made for a national survey of soil erosion in Iceland (Arnalds et al., 2001a). Subsequently, the most active dust emission areas, termed "dust hot-spots" are given a special consideration with examples of two such locations. The origins of the aeolian materials on these different surfaces are discussed in Section 4.

3.1. Desert types

Only a proportion of the 43,400 km² desert surfaces are classified as sandy deserts, or about 22,000 km². Their distribution is shown in Fig. 2. About 15,000 km² are considered to have active aeolian surfaces (Table 2). All desert surfaces were mapped during the survey of soil erosion in Iceland (Arnalds et al., 2001a), which include in addition to sandy deserts: 'scree slopes', 'lava surfaces' and 'glacial till'. The general pedological characteristics of the deserts were studied by Arnalds and Kimble (2001). Other reviews of these surfaces include those of Arnalds et al. (2001b) and Arnalds (2015, Ch. 11). The sandy deserts are separated into three main geomorphic types and examples are presented in Fig. 3. The mapping by Arnalds et al. (2001a) employed erosion severity scores from 0 (no erosion) to 5 (very severe erosion) with scores 4 and 5 used for sandy deserts, and a score of 3 for surfaces that are occasionally active. The extent of each of the sandy surface types is presented in Table 2 (from Arnalds, 2015, Ch.11), separated by erosion scores (3–5), with total area given in the last column. The main areas subjected to aeolian processes are those of erosion scores 4 and 5, which total 14,795 km² (bottom row in Table 2).

Sand fields and pumice are relatively level plains covered with sand or pumice and include some of the most active aeolian areas. The pumice areas are often rather coarse with a large fraction of >2 mm pumice; the light density contributes to their susceptibility to wind erosion. The sand fields vary considerably in size and nature, ranging from a few hectares to hundreds of square kilometers.

They tend to be silty close to glacial sediment sources (glacial margins, glacial river sediments), but sandier downwind from the sources. Examples of large sand fields include Dyngjusandur north of the Vatnajökull Glacier, Skeiðarársandur south of the Vatnajökull, Mýrdalssandur southeast of Mýrdalsjökull, and Mælifellssandur north of the Mýrdalsjökull Glacier (Fig. 2). The geomorphology and formation of some of these sand fields were discussed by Kjær (2004) for Mælifellssandur and Mýrdalssandur; Krüger (1997) and Russel et al. (2001) for Skeiðarársandur; and Mountney and Russell (2004), Baratoux et al. (2011) for Dyngjusandur; and Gisladottir et al. (2005) and Mangold et al. (2011) for the Hagavatn area. The extent of unstable sand fields (erosion scores 4 and 5) is about 4000 km², and these include some of the most active dust sources in Iceland. Dust hot-spots are covered in greater detail at the end of this Section 3.2.

Sandy lag gravel surfaces form on glacial till, raised shorelines and alluvial sediments where sand is deposited on gravelly surfaces by aeolian processes, often at the rate of 0.1–1 mm yr^{-1} (see Arnalds, 2010). This accumulation is enhanced by selective frost heaving of pebbles and rocks in winter, which gradually develops sandy subsurface horizons covered by more coarse rock fragments on the surface. Sandy lag gravel surfaces become unstable during dry high intensity winds with threshold velocities considerably higher at the sandy lag gravel than for the sand field surfaces (often 12–15 m s^{-1} vs 5–8 m s^{-1}, respectively, at 2 m height; see Arnalds et al., 2001b). The aeolian sediment losses from these surfaces during high intensity storms balance the aeolian influx, which may lead to net losses in some years and gains during other years. The total extent of sandy lag gravel is nearly 13,000 km² of which about half is subjected to aeolian processes during intense winds (about 7500 km²). These surfaces dominate many of the poorly vegetated highlands that are not covered with lavas.

Sandy lava surfaces are Holocene-age lavas covered by sandy deposits that have been blown into these surfaces. They also capture materials that result from volcanic ash deposition during eruptions. Unstable lava surfaces (erosion scores 4 and 5) are about 3400 km². Surface roughness of the lavas varies considerably, from relatively smooth pahoehoe lavas to rough aa lavas. The rougher

Table 3

The main dust hotspots in Iceland. Location (1–8) is given in Fig. 2. The area in km^2 roughly estimated from Landsat 8 images, and includes only areas of major dust production. The extent of these sandy deserts is considerably larger. Activity of these areas vary between years and are subjected to frequent changes and definition, as changes from primary dust areas to saltation areas are gradual.

Nr	Area	km^2	General characteristics
1	Dyngjusandur	140	Large glacio-fluvial plain flooding daily in summer leaving silty sediments on the surface. In part confined by the Dyngjufjöll mountains and the Jökulsá river. Dust storms often daily during summer. Area periodically subjected to jökulhlaups from the Bárðarbunga and Kverkfjöll volcanic systems. In part covered by lava during volcanic eruption in 2015 but size exceeded 200 km^2 prior to the eruption
2	Hagavatn	10	Receding glacier with glacio-fluvial plains and glacial lake with fluctuating water level. Characterized by more crystalline materials than the volcanic glass that makes up most other Icelandic dust. Sand is trapped in lavas and at Rótarsandur depression
3	Mýrdalssandur	60	Glacio-fluvial lowland plain charged by fluctuating glacial waters, some of which disappear on the surface leaving unstable silty sediments behind. Periodically disturbed by jökulhlaups from the Katla volcanic system. Subjected to dust events the year around depending on snow cover. Sand transported mainly towards the ocean
4	Mælifellsandur	40	Glacio-fluvial highland plain charged by fluctuating glacial waters, some of which disappear on the surface leaving unstable silty sediments behind. Periodically disturbed by jökulhlaups from the Katla volcanic system. Frequent dust storms in summer, but covered by snow in winter
5	Skeiðarársandur	130	Glacio-fluvial lowland plain charged by active rivers but relatively frequent jökulhlaups from the Grímsvötn volcanic system and the Grænalón glacial water lagoon. Last large-scale jökulhlaup (40–60 000 m^3 s^{-1}) in 1996 with dramatic changes and widespread loose deposits
6	Landeyjasandur	17	Large beach area, charged by the Markarfljót glacial river (sediments from the Katla volcanic system). Recently reduced area because of large scale vegetation establishment project
7	Flosaskarð	20	Isolated area where glacial melt waters disappear (resurfaces as spring water at >30 km distance), and leave loose silty materials on the surface. Rough lava surfaces reduce the distribution of the sand, but some are gradually filling up
8	Vonarskarð	15	Isolated highland plain area where glacial rivers leave loose sediments on the surface. Covered with snow much of the year. Limited sand transport from the area
9	Other areas	30	Includes Tungná and Skaftá river plains, Hálslón and Hágöngur reservoirs, Sandkluftavatn, Kreppulón, Þorlákshöfn sand plain and more

lavas can accumulate an immense amount of sand (often 500,000–1,000,000 t km^{-2}, based on Gisladottir, 2000) before becoming unstable sand fields, thus providing a temporary shelter from sand for the downwind areas. Large sandy lava fields occur in the Mt. Hekla area and the lava fields of northeast Iceland.

3.2. The dust hot-spots

Dust can be generated from all the major sandy areas of Iceland; however the amount of finer particles that become dust varies with the surfaces. There are areas that produce more dust by far

compared to the general sandy deserts; they have therefore been termed "dust plume areas" or "dust hot-spots" and were first described as such by Arnalds (2010). They are characterized by repeated charging of fine sediments with a relatively high proportion of finer (silty) materials which, upon repeated wind erosion become sorted downwind from the sources with loss of silt (dust) and an increasing saltation component (sand). The dust hot-spots are marked in Fig. 2 and listed in Table 3. Table 3 accounts for the most active dust producing areas, while sandy areas (with less dust production) are much larger at each site. More detailed descriptions of two areas (Dyngjusandur and Hagavatn) are provided below as examples.

Dyngjusandur is the most extensive dust source area in Iceland, located at the northern tip of the Vatnajökull, where Jökulsá á Fjöllum, the major river of NE Iceland, originates. The tributaries are loaded with glacial sediments and overflow widespread areas, often with daily flooding during warm temperatures and subsequent receding at night, alternating frequently between channels. Fine sediments are left on the surface after each "flooding" which are highly susceptible to wind erosion (cf. Mýrdalssandur in Fig. 4b, see also Fig. 5). More detailed accounts of the area are provided by Baratoux et al. (2011) and Mountney and Russell (2004). Several dust events can occur each day (unpublished observations from monitoring camera and field experience) during dry periods in summer, though the area receives 400 mm rainfall annually. Dyngjusandur is covered with snow much of the winter, from Sept/Oct to May/June. The sediments are primarily blown northwards, though dust directions range from SE to W depending on dry wind directions. The sediments become sorted down-wind from the sources, with an increasing proportion of saltation materials which accumulate along topographic obstacles such as the Dyngjufjöll Mountains and Vaðalda, or land in the main channels of the Jökulsá River (Fig. 5). There are several surface pathways or "rivers" of aeolian sediments that extend more than 80 km from the Dyngjusandur source (Arnalds, 1992; see also Alho, 2003). These "aeolian rivers" are clearly visible on satellite images. The dust generation from Dyngjusandur can reach over 300,000 t per storm event (see Section 8 on quantification), extending far into the Arctic regions north of Iceland (Fig. 6).

There were dramatic changes to the Dyngjusandur dust source area in the winter of 2014/2015 with the six-month Bárðabunga–Holuhraun eruption which covered about 85 km^2 with new lava (Institute of Earth Sciences, www.earthice.hi.is), thus reducing the size of the active dust source area by about half. Changes in dust event frequency and intensity as a result of the eruption are being investigated, but a substantial decrease in dust production can be expected, at least temporarily. However, further volcanic activity in the Bárðarbunga volcanic system could produce catastrophic jökulhlaups (see below), with the formation of large temporary sources of unstable sediments along the 140 km long river channel to the north coast (see e.g., Alho et al., 2005; Carrivick et al., 2013).

The Hagavatn dust plume area is located south of the Langjökull Glacier (Fig. 7). The aeolian conditions in the area were investigated by Gisladottir et al. (2005) and both physical and chemical properties of the materials by Baratoux et al. (2011) and Mangold et al. (2011). The area has undergone pronounced changes over the last century, which include the disappearance of a lake of about 10 km^2, leaving loose sediments exposed on the ground (Sigbjarnarson, 1967). This area was previously covered by the glacier, which has been retreating for more than a century. A part of the former lake bed continues to be charged with unstable fine sediments by streams draining from the glacier.

Dust is blown from the glacial river area and the lake shores over SW Iceland. Larger particles were saltated up to a 16 km distance towards the Rótarsandur depression (Fig. 8) during the peak

Fig. 4. Active dust production at Mýrdalssandur sand-field, Sept. 2015. Two distinct main source areas visible, associated with river outlets. Photo taken from a surveillance camera placed about 300 m above the plain. The plumes come from the unstable glacio-fluvial silty deposits, but other parts of the sand-field are not very active during this particular storm. Wind speed about 12 m s^{-1}.

Fig. 5. The Dyngjusandur area before the 2014/2015 volcanic event. The debris dominated margins of the Vatnajökull glacier at the bottom. The lake (black in color upper left) is the Askja caldera. Some of the most recent, but dried out glacio-fluvial deposits appear blue-gray in the figure. The Askja 1875 AD light colored rhyolitic pumice is prominent in the upper part of the figure (light color). The bluish areas in front of the glacier are the most active dust sources (one small plume can be seen), but sandy materials are salted tens of km to the northeast (toward the top-right of the image), directed by major dry winds, topographical obstacles but often trapped by major rivers. Photo: Spot (Euroimage).

years after 1940, but seemingly not this far under current conditions. Gisladottir et al. (2005) surveyed the amount of sand within the Hagavatn area from the source to the Rótarsandur depression. The amount of sand in the lava south of the source area exceeds 30

million m^3 (based on Gisladottir, 2000), showing that the total sediment yield of the source area has exceeded a hundred thousand tons per year on average, though with lower activity presently than in the latter part of the 20th century.
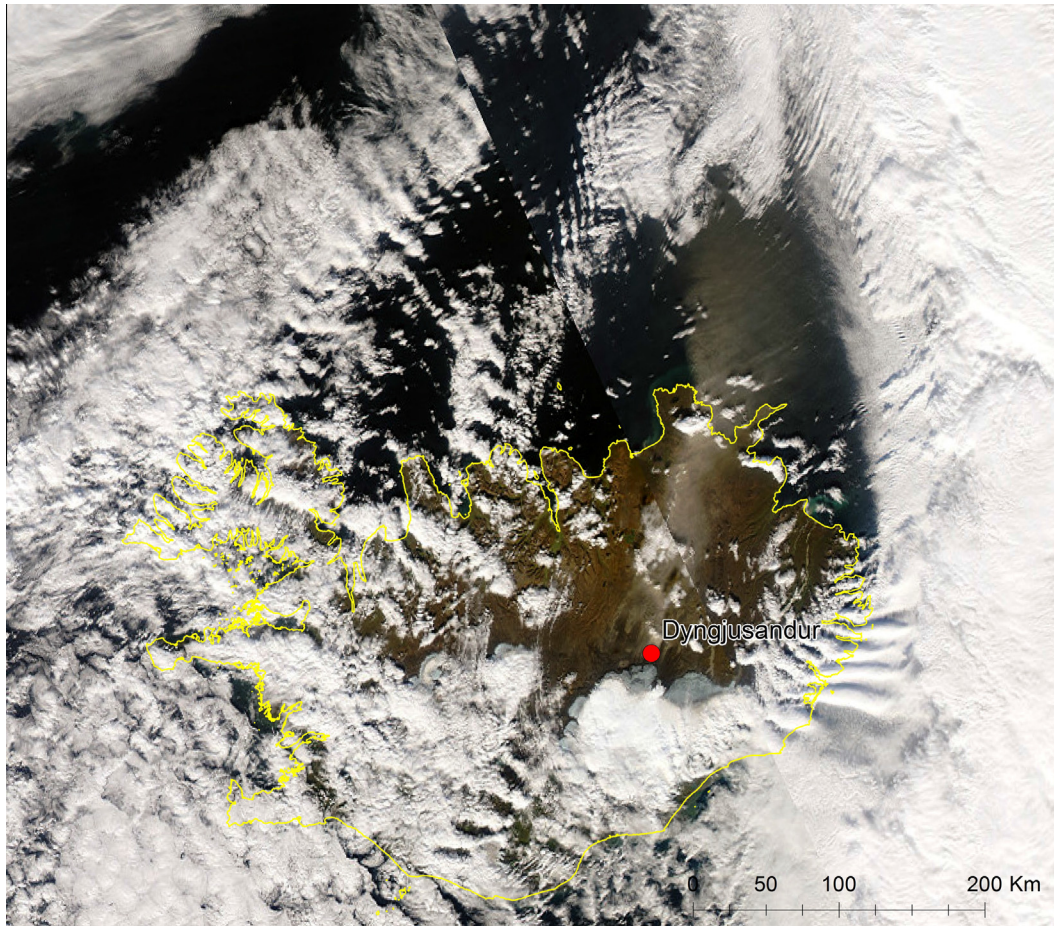
Fig. 6. Dust storm from Dyngjusandur in September 2008, extending >300 km to the north. Photo: MODIS/NASA.

Fig. 7. Conditions within the Hagavatn area. Hagavatn is the name of the lake to the right. Glacial streams feed the lake, but their channels are highly variable creating active dust sources. Much of the area to the left of the lake was a part of much larger lake prior to 1940, which, after draining, became a hyperactive dust source for some decades and still remains active.

4. Where do the aeolian materials originate?

The last section described the nature of the different aeolian surfaces in Iceland. As shown in Table 2, sandy deserts cover about 22,000 km^2, nearly 15,000 km^2 of which are unstable surfaces subject to active aeolian processes. In this section we address the question: where do all these loose sediments come from? The short answer is: from glaciers, glacio-fluvial processes and volcanoes.
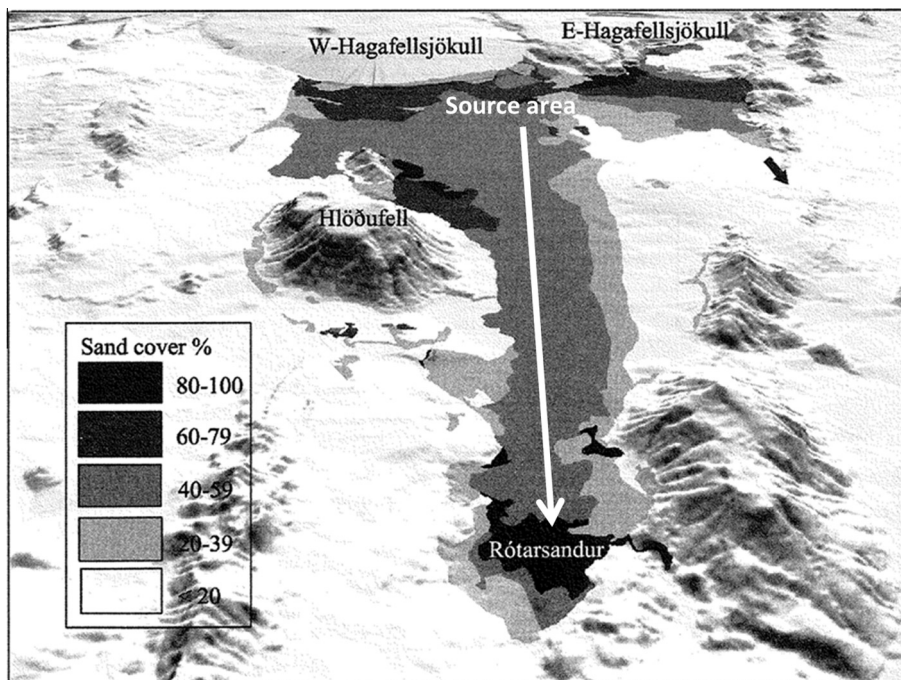
Fig. 8. Hagavatn plume area: typical sand transport southbound with dry northerly winds over 16 km from the source to the Rótarsandur depression. The aeolian activity is not as active compared to the peak years and the sand is mostly caught by the rough lavafelds south of the source areas. From Gisladottir et al. (2005).

The high sediment delivery of the glacial rivers is enhanced by the soft, poorly crystalline volcanic rocks that underlie many of the glaciers and are relatively easily eroded as the glaciers move over the surface (Gislason, 2008). Below is a short discussion about the sources of sand in Iceland. It is important to bear in mind that the sediments can be blown long distances and encroach on topographic obstacles, sometimes with destruction of fully vegetated ecosystems.

Jökulhlaups are lahars or flood events that result from the melting of ice during volcanic eruptions (Rodolfo, 2000), carrying high concentrations of volcanic materials. Thermal areas under glaciers can also cause jökulhlaups by periodic release of meltwater contained under the glacier. Jökulhlaup events can reach over 100 000 $m^3 s^{-1}$ discharge rates in Iceland, but are more often of the order of 3–15,000 $m^3 s^{-1}$ (Larsen and Eiriksson, 2008; Björnsson and Palsson, 2008; Björnsson, 2009; Eliasson et al., 2007). The jökulhlaups can flood immense areas leaving unstable glacio-fluvial deposits on the surface. Although aeolian activity as a result of jökulhlaups has been reported elsewhere, e.g. in Greenland (Bullard, 2013), their frequent and large scale occurrence in Iceland is one of the factors that place Icelandic sandy deserts apart from most other desert areas (whether Arctic or warm and dry), in addition to the volcanic and basaltic nature of the desert materials. Dyngjusandur, Skeiðarársandur, Mælifellssandur, and Mýrdalssandur (Table 3) are all periodically affected by jökulhlaups. A spike in aeolian activity occurs after jökulhlaup events; however, dust sources may "dry out" after a period of time, even decades, while surface processes (saltation) are maintained for a much longer time (hundreds or even thousands of years), often recharged by repeated flood events, periodic tephra deposition and continual aeolian deposition. Saltation abrasion, the colder northern climate, and grazing all have negative effects that often prevent vegetation succession in Iceland, in spite of the reasonable level of rainfall in many places.

A recent example of a jökulhlaup is the 1996 Skeiðará River jökulhlaup after the Gjálp eruption (Skeiðarársandur), which peaked at about 50,000 $m^3 s^{-1}$ with a total sediment transport of about 1.8×10^8 m^3 (Russell et al., 2005). The river flow subsequently changed, with the largest river (Skeiðará) moving its

course to the Gýgjukvísl River, leaving a relatively small amount of water flow under Iceland's longest bridge (about 1 km long). Dust events were frequent after the 1996 jökulhlaup (Prospero et al., 2012). The extreme jökulhlaup events in the Jökulsá á Fjöllum (outlet at Dyngjusandur) are believed to have reached 700–900,000 $m^3 s^{-1}$ at least three times during the Holocene (Alho et al., 2005; Kirkbride et al., 2006; Carrivick et al., 2013; Baynes et al., 2015). The largest jökulhlaups at Jökulsá á Fjöllum are assumed to have inundated about 1400 km^2 along the 140 km long course of the river. Smaller jökulhlaups are much more common (3000–15,000 $m^3 s^{-1}$), and are often in association with periodic volcanic activity in the Bárðarbunga and Kverkfjöll volcanic systems. Peak discharge rates from the Katla volcanic system are believed to have exceeded 400,000 $m^3 s^{-1}$ (Larsen, 2000; Gudmundsson et al., 2008). The last such extreme event occurred in 1918 with a flow down Mýrdalssandur (one of the dust hotspots) of >250,000 $m^3 s^{-1}$ (Eliasson et al., 2007). Jökulhlaups from Katla have historically swept down three major pathways, all of which affect present-day aeolian environments in Iceland: to the west by Markarfljót, SE at Mýrdalssandur, and north to Mælifellssandur.

Daily melt-water flooding and unstable glacial lakes. Many of the main active aeolian areas, the dust hot-spots in particular, are subjected to daily flooding by melt-waters. Upon receding, silty materials are left on the surface which are subjected to aeolian processes, both saltation and dust generation. The water also sometimes percolates into the very porous sand and disappears, leaving the fine sediments on the surface. The combination of silt and sand makes them very susceptible to wind erosion with threshold velocities as low as 5 $m s^{-1}$ (at 2 m height). Mýrdalssandur, Dyngjusandur and Mælifellssandur are dust hot-spots that are charged by daily melt-water flooding in summer. Glacial lakes with receding or unstable water levels tend to have the same characteristics for a period of time after the water level drops (e.g., Hagavatn in the south).

Glacial river channels. Many of the glacial rivers are subjected to periodic flooding (jökulhlaups, spring and summer melt). Level stretches along the rivers are subjected to deposition of river
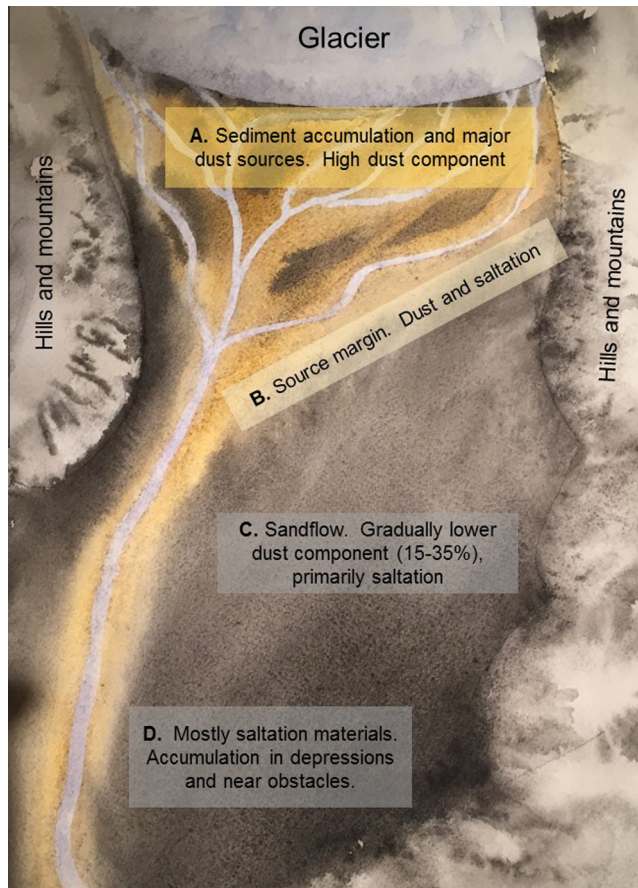
Fig. 9. Conceptual drawing of aeolian source components at a glacial margin with rivers depositing high quantities of silty materials on the surface. Area A is the dust-hotspot, but area B is also very active dust source. Areas C and D are dominated by saltation processes with varying degree of dust production. The sand can end up in lavas, depressions and even in the major river if it cuts downwind areas.

sediments that become unstable. Jökulsá á Fjöllum in the north, and Skaftá, Tungnaá and Þjórsá in the south are examples of rivers that have created sandy sources, which subsequently can be saltated over large areas away from the rivers

Sandy beaches are common along the south coast (e.g., Landeyjarsandur). The source of the sand is the many glacial river outlets, with jökulhlaups contributing a large share of the sediments. The main dry winds along the southern shores are northerly, leading to sediment transport to the sea. Occasional southerly dry storms lead to inland dust transport, especially with strong southeasterly winds which can drive dust from Landeyjasandur over south and southwest Iceland.

Volcanic ash deposition. Many of the frequent volcanic eruptions cause large scale deposition of volcanic ash. Thicknesses of tephra deposition range from traces (mm) to more than10 cm. Vegetated ecosystems can immobilize volcanic ash up to a point, depending on vegetation height and composition (see Arnalds, 2013). The materials become finer with distance from the volcanic source. Volcanic ash deposited on desert landscapes is unstable and often subjected to intense aeolian redistribution, as experienced after the 2010 Eyjafjallajökull eruption (Thorsteinsson et al., 2012; Arnalds, 2013; Arnalds et al., 2013) and the 2011 Grímsvötn eruption (Liu et al., 2014). Such redistribution of volcanic materials is common elsewhere (e.g., Wilson et al., 2011), and can even cause more severe environmental effects than events during the eruption. Surprisingly, the wide spread re-suspension of ash is often overlooked as a risk associated with volcanic eruptions (Arnalds, 2013).

Repeated aeolian deposition. Steady aeolian deposition leaves sediments that can become unstable, even after hundreds or thousands of years of accumulation. The resulting sediment layers often become 1–2 m thick (soils), with silty material dominating, with occasional tephra layers within the profile. Lacking layer silicates to provide cohesion, they are very susceptible to wind erosion. Furthermore, the sandy areas of the interior do not become depleted of aeolian materials as long as they are recharged from large sources by surface transport, repeated aeolian deposition as dust, or periodic recharge by volcanic ash during eruptions.

5. Surface area components near glacial margins

Aeolian processes in periglacial environments are important drivers for providing the loess deposits, especially during the Pleistocene glaciation (e.g., Bullard, 2013). Aeolian activity in periglacial environments is found in many areas of the world and has been subjected to recent review by Bateman (2013), and Bullard (2013) reviewed contemporary glacigenic inputs to the dust cycle. Recent papers on specific glacial areas include those of Gillies et al. (2013) and Lancaster et al. (2010) for dry valleys in Antarctica, and Crusius et al. (2011) and Hugenholtz and Wolfe (2010) for Alaska and Canada. Sandy areas in front of the glaciers are often treated as one unit, which can cause confusion when pinpointing main dust sources and explaining progression of the sand as it moves from the main sources. Here we present a conceptual model for glacio-fluvial areas in Iceland that comprises many of the most active aeolian areas in Iceland (i.e. locations 1–5 and 7–8 in Table 3). It should be noted that this model does not apply to such sandy areas as the shorelines (i.e. Landeyjarsandur). The schematic drawing presented in Fig. 9 shows the major components near active aeolian sources according to this model. The most active glacial margin areas are continually recharged by glacio-fluvial processes, as has been shown in front of other glaciogenic aeolian areas (e.g., Orwin et al., 2010; Crusius et al., 2011; Bateman, 2013). The major dry wind direction is "down" in the figure with mountains forming boundaries that contain the aeolian flow as does a river at the bottom of the figure. The area is subjected to periodic flooding that charges area A with sediments. There is a high proportion of silty materials (up to 50%), but with more coarse sediments as well. Dust is also a large component of the materials bordering the major source area (B). Areas A and B can be considered hyper-active with a low threshold velocity (e.g., 5 m s^{-1} at 2 m height) and may correspond to areas of high deposition described by Hugenholtz and Wolfe (2010) for areas in the Athabasca River Valley in the Canadian Rocky Mountains. As aeolian surface transport brings materials downwards on the figure (C to D), the sediment composition changes with finer materials lost as dust with an ever increasing saltation component. Threshold velocity often increases. This "aeolian river" continues until the sediments are trapped by landscape obstacles, in this case the lava areas south of the source and a depression (area D in the figure). Research by Gisladottir et al. (2005) showed that slopes >7% effectively halted the movement of the saltation materials in the Hagavatn area. In many cases in Iceland, aeolian flow is halted by large rivers. In some cases this model holds only temporarily, such as after jökulhlaups or volcanic ash deposition, until the major sources are depleted. Rough lavas can act as sediment traps which substantially slow the advancement of the sand for decades and even centuries.

Research is needed to quantify the relationship between the charging of a major sediment source, the sediment balance of these components, how the textural properties change as the sediments are moved away from the main source, and to quantify the changes in saltation rates and dust emissions along the way. Such
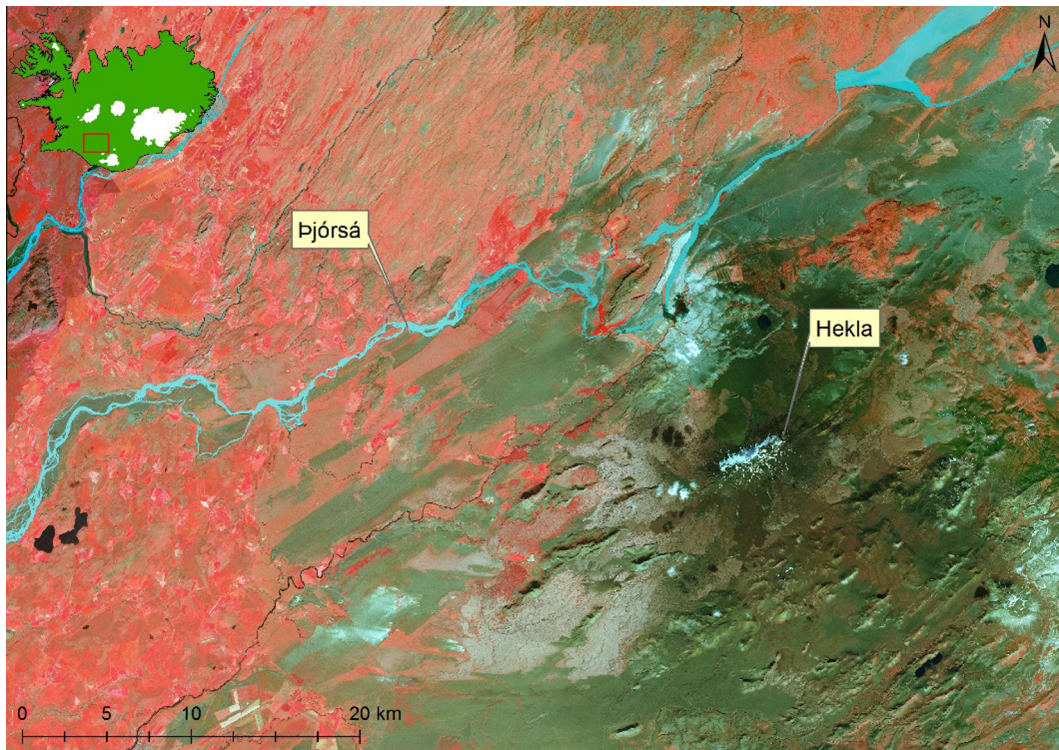
Fig. 10. Infrared satellite image (vegetation red) showing the marks of advancing sand-fronts in South Iceland (Mt. Hekla region). The activity has been halted but the consequences are still evident with tongue-shaped fronts with the linear features to the sides (long straight boundaries between vegetated areas (red) and deserts (dark blue-green). AUI/Spot Euroimage.

information is important for modeling both surface transport as well as dust generation on landscape levels.

6. Quantification of surface transport

Advancing sand has caused immense ecosystem damage in Iceland (Crofts, 2011). There has been considerable research devoted to the quantification of surface transport (saltation) by aeolian processes in Iceland. This research is important both for understanding threats caused by potential sandstorms and for casting a light on how destruction occurred in the past. Here we report some of the rates that have been published and give a short discussion of advancing sand fronts at the end of this section.

6.1. Rates

The commonly employed response value for surface transport of sandy materials in Icelandic research is kg m^{-1} over a unit time or season, which is how much sediment is blown over a 1 m wide line. The research is based on BSNE (Big Spring Number Eight) sediment traps (Fryrear, 1986; Stout and Fryrear, 1989) and Sensit wind erosion sensors (Gillette et al., 1997), often used in combination with on-site weather stations and data loggers. Measurements have been made at the Hagavatn area (Gisladottir, 2000; Gisladottir et al., 2005), in the Mt. Hekla area (Thorarinsdottir and Arnalds, 2012), on the Eyjafjallajökull volcanic ash (Arnalds et al., 2013), and at various other locations (Sigurjonsson et al., 1999; Arnalds et al., 2001b, 2012). Research in the Hekla area (Thorarinsdottir and Arnalds, 2012) attempted to study aeolian transport at the landscape level, revealing the importance of the interaction between fluvial processes recharging sediment sources (winter and spring) and aeolian processes during summer and early winter months. Models have also been employed in relation to environmental impact assessments from hydropower reservoirs

(unpublished reports), which have yielded results similar to the measured values reported here.

Measured rates on gravelly sandy surfaces generally are of the order of few hundred kg m^{-1} over one summer, such at the Geitasandur experimental area (Arnalds et al., 2012). With a higher proportion of sand on the surface, these values rise to >1000 kg m^{-1} over each season. Wind erosion, measured after the 2010 Eyjafjallajökull eruption, was one of the most violent wind erosion events ever reported, with more than 11 tons of materials blown over a 1 m wide transect in a single storm (Arnalds et al., 2013). Dust redistribution after the eruption caused severe dust problems in extensive areas (Thorsteinsson et al., 2012).

There is a need to extend research on transport rates from point measurements to landscape modeling of surface transport, as was stressed by Lancaster et al. (2010) working in Antarctica. Such modeling involves a variety of surface types with varying degrees of threshold values, where some areas with rough surfaces act, at least temporarily, as sediment traps, while threshold values remain low in other areas. Landscape features affect wind directions and steep slopes can stop surface transport of sand. Such work on landscape level could better explain the spread of sandy deserts in the past as well as identify areas where sandstorm events may threaten vegetated ecosystems. Furthermore, such modeling may help in developing strategies to minimize the negative effects from glacio-fluvial flooding and volcanic ash deposition.

6.2. Advancing sand-fronts/encroaching sand

One of the most destructive forms of land degradation in Iceland since the ninth century Norse settlement of Iceland is the encroachment of sand over vegetated areas, smothering the plant life (Arnalds et al., 2001a; Crofts, 2011). These advancing sand fronts leave barren deserts in their wake. The silty and sandy materials of the soils underneath the vegetation that is destroyed are

added to the pool of aeolian materials, thus creating a snowball effect with an ever-increasing pool of saltation materials. The marks on the land created by advancing sand fronts are tongue-shaped desert areas that extend into vegetated land. The fronts generate long linear features at the boundary between vegetated land and deserts on the sides, where sand is saltated along escarpments which often are 0.5–2 m high. The direction of the fronts reflects the dominant dry wind direction, and these features are easily identified on infrared satellite images (Fig. 10).

The Icelandic Soil Conservation Service was established in 1907, originally as the Sand Reclamation Office (Sandgræðsla ríkisins in Icelandic) to battle such sand fronts. It is one of the oldest such government soil conservation institutions in the world, reflecting the severity of this problem in Iceland. The most devastating sand storms could destroy several farms in single storms during the latter part of the 19th century, advancing many km each year (see Crofts (2011)), which is difficult to comprehend for the modern day naturalist in Iceland. However, the high rates measured by recent research in Iceland (>10 t m^{-1} in a single storm) explain the rapid advancement that can occur during the most intensive storms.

7. The frequency and climatology of dust events in Iceland

The long-term frequency of dust events in Iceland has been determined using dust observation records from 30 weather stations around Iceland for the years 1949–2011. This method has been used in major desert areas around the world (Baddock et al., 2014; Wang, 2015), such as Mongolia (Natsagdorj et al., 2003), the US (Steenburgh et al., 2012), Australia (Ekström et al., 2004), China (Qian et al., 2002), and Iran (Jamalizadeh et al., 2008). The synoptic weather codes give information about dust event observations, together with wind velocity, wind direction, and temperature, etc. Research shows over 34 dust events per year in Iceland, based on the conventional synoptic codes for the desert dust. Icelandic deserts are strongly influenced by glacial and volcanic activity, however, which requires including special synoptic codes for such observations such as "re-suspension of volcanic ashes" and "dust haze". Including these codes increases the number of dust events in Iceland fourfold, resulting in 135 dust days annually. This high number places Iceland among the dustiest areas of the world.

Visibility during dust observations is an important indicator of dust event severity, especially where no direct measurements are conducted (Baddock et al., 2014). Mean visibility during dust events in Iceland was 25 km but there were 32 "severe dust storms" with observed visibility of <500 m. In comparison, the visual range can be over 300 km in dry climates and 100 km in humid climates on clear days (Hyslop, 2009). Annually, Iceland experiences on average about 6 dust events with visibility <5 km (measured at some distance from the source). It should be stressed that meteorological observations are likely to miss many events, especially those blowing directly out to sea from the dust sources

along the southern shore, but research is under way to identify how common such un-noticed events are.

The location of the atmospheric surface-pressure field determines if dust plumes travel in northeasterly or southerly directions. The dust events in northeast Iceland are "Arctic dust events" because they are warm and occur during the summer/autumn (May–September), as described in Alaska and Greenland (Nickling, 1978; Bullard, 2013). About half of the dust events in south Iceland occur in winter or at sub-zero temperatures and can be termed "sub-Arctic dust events". These are "cold events" as have been observed in Mongolia (Natsagdorj et al., 2003). The Arctic dust events are warmer (T_{mean} = 10.5 °C) and with lower wind velocities (WS_{mean} = 10.3 m s^{-1}) than sub-Arctic dust events in south Iceland (T_{mean} = 3 °C, WS_{mean} = 13.6 m s^{-1}). However, extreme wind speeds of >40 m s^{-1} can occur. Interestingly, we have observed dust storms during wet conditions. As an example, there was a dust event measured under rainy and moist conditions when the winds were very low (0–4 m s^{-1}) and the relative humidity was 77–90%. The main driver of dust suspension in such cases is direct solar radiation and consequent surface heating of dark wet surfaces on the glacial flood plain (Dagsson-Waldhauserova et al., 2014b). Other wet dust storms occur due to extreme wind velocities (e.g., >30 m s^{-1}).

8. Quantification of dust production from Iceland

While saltation flux along the surface is relatively simple to measure in the field, quantification of dust production is a more complicated task. Large advances have been made in understanding dust generation globally, as was reviewed recently by Bryant (2013). There are, several types of information that can be drawn from in order to estimate the total dust production in Iceland. (a) The production can be estimated by the annual number of dust events in the country, classification of their severity, and estimated dust production per storm. With each of these factors comes a large degree of uncertainty, but the information still gives an order of magnitude of dust production, which is an important step beyond having no information at all. (b) Metadata for deposition rates for Iceland can be used to generate a deposition map of Iceland and the surrounding oceanic areas, which subsequently can be used to estimate total dust production in Iceland. (c) In addition, it is possible to measure and/or estimate the aerial extent of the major dust plume sources and model the deflation rates for each storm in addition to information about storm frequency. We have made efforts to use approaches a and b to arrive at dust production estimates for Iceland, and the following discussion is largely based on the publication of our first attempts (Arnalds et al., 2014).

Dagsson-Waldhauserova et al. (2013, 2014a) estimated the frequency of storms in Iceland. The storms were divided into three categories based on visibility classes of weather observations (Dagsson-Waldhauserova et al., 2013). Detailed calculations of dust amounts were made for 4 storms using weather observations (visibility), compared and confirmed by NOVA satellite images, and with atmospheric modeling (Arnalds et al., 2014), which resulted in emissions of 215–384 thousand tons per storm. These numbers were used to give average emissions per event in the previously gathered storm frequency data, with emissions of 0.1, 0.3 and 1 million tons per small medium and large events, respectively (Table 4). Combining the frequency and dust amounts results in an estimated 30 million tons per annum of dust production in Iceland.

Arnalds (2010) used soil profile metadata from published records and the Agricultural University of Iceland soil database to produce a GIS-based isopach map for average aeolian deposition

Table 4
Event based calculation of total dust emissions from Iceland. Modified from Arnalds et al. (2014).

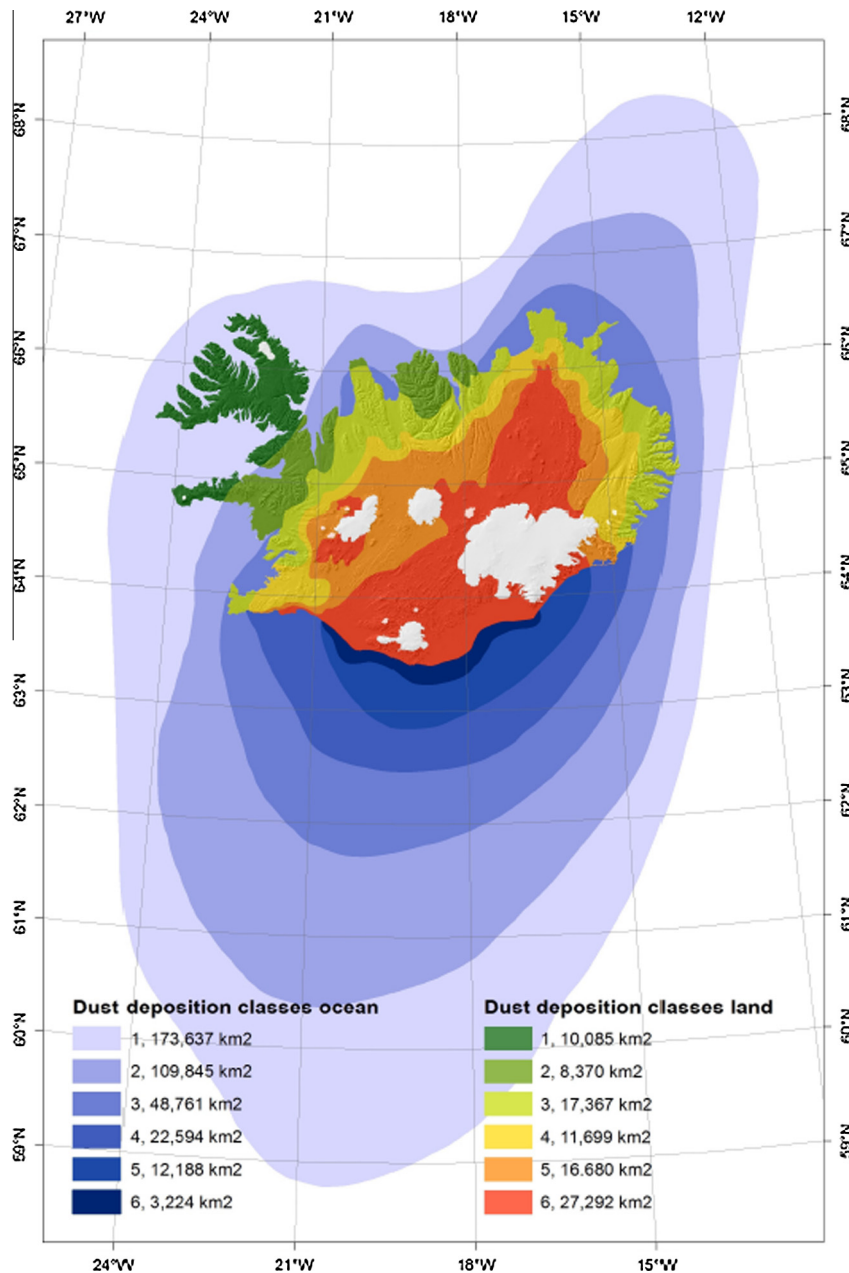| Event size	# events	Emissions per event	Total emissions
		Million tons	
Major	7.8	1	7.8
Medium	50.3	0.3	15.8
Minor	75.6	0.1	7.6
Total	135.6		30.5

Fig. 11. Deposition map based on metadata for deposition rates measured in soil profiles (Arnalds, 2010). Data extended to the oceans. Modified from Arnalds et al. (2014).

in Iceland, which was modified and extended to oceanic areas by Arnalds et al. (2014). Deposition rates varied from 1–15 g m^{-2} (lowest category) to 500–800 g m^{-2} (highest or extreme category) per annum (Fig. 11). The GIS system was used to calculate total annual dust deposition on land, glaciers and oceans (hence, total annual dust emissions), totaling about 40 million tons. This number is surprisingly close to the independently derived event based quantification of about 30 million tons. It is, however, likely to be an overestimate because of re-suspension of dust deposited on desert areas, as discussed later in the paper.

There are no comprehensive measurements of deflation rates (in mm or cm) or sediment yields per unit area (t km^{-2}), but point measurements show lowering of the surface by more than 5 cm in some places and exceeding 30 cm over a season at Mælifellssandur and Mýrdalssandur. Deflation rates at the major dust areas are confounded by alternating sedimentation and removal, both by fluvial sedimentation and aeolian processes, which makes monitoring of deflation rates in these areas unrealistic.

The high dust emission activity in Iceland of more than 30 million tons annually is an order of magnitude larger than that reported for the Arctic areas (Crusius et al., 2011; Bullard, 2013), and is comparable to figures reported for the warm desert areas of the world with a substantial contribution to the North Atlantic Ocean (5.5–14 million t yr^{-1}; see discussion in Arnalds et al., 2014).

9. Physical and chemical properties of the particulate matter

9.1. Particulate matter (PM) concentrations of dust aerosol

Measurements of particulate matter (PM) concentrations in Iceland have primarily been made in relation to the Eyjafjallajökull Glacier eruption in 2010 (Leadbetter et al., 2012), Holuhraun eruption in 2015 (Sigurdardottir et al., 2015), or areas distant from the dust sources (Thorsteinsson et al., 2011; Blechschmidt et al., 2012). Long-term measurements of dust aerosol concentrations

Table 5
The chemical composition of the Mælifellssandur and Skeiðarársandur dust event samples based on EDX analyses of polished surfaces of individual glass particles. A total of 72 glasses analyzed (Dagsson-Waldhauserova et al., 2015).

Average values (% wt)	SiO_2	FeO	Al_2O_3	CaO	TiO_2	MgO	$K_2O + Na_2O$
Mælifellssandur dust event	42.6	17.0	14.2	11.6	5.6	4.9	4.1
Skeiðarársandur dust event	45.0	14.5	14.5	12.0	3.5	6.2	4.0

in the vicinity of the deserts in Iceland are not available. There is a small network of the PM stations, mostly in Reykjavík and more than 100 km from the major dust sources. The PM_{10} (particulate matter up to 10 µm in size) pollution in Reykjavík is generally low (Thorsteinsson et al., 2011) with the annual level around 22 µg m^3 Jökulhlaups and volcanic eruptions can both contribute to dust spikes that influence air quality (Arnalds, 2010; Prospero et al., 2012). Leadbetter et al. (2012) modeled the re-suspension of ash after the 2010 Eyjafjallajökull eruption, which affected air quality at great distances (>150 km) with concentrations exceeding 1000 µg m^{-3} in widespread areas (see e.g., Thorsteinsson et al., 2011). The highest PM_{10} mass concentrations during dust storms are >7000 µg m^{-3} judging from available data, showing the high magnitude of Icelandic dust events. For example, PM_{10} mass concentrations during a dust storm in March 2013 were measured as >6500 µg m^{-3} min^{-1} while the mean (median) PM_{10} concentration during a 24-h storm was 1281 (1170) µg m^{-3} (Dagsson-Waldhauserova et al., 2015).

Suspended aerosols measured on site at the dust source are very fine and high in particle number concentrations (Dagsson-Waldhauserova et al., 2014b). The maximum particle number concentration (PM~0.3–10 µm) reached almost 150,000 particles cm^{-3} per minute for a mass concentration (PM < 10 µm) of 1757 µg m^{-3}. Maximum concentration of the $PM_{2.5}$ fraction was 85,528 particles cm^{-3} with the mass reaching 116 µg m^{-3}. Suspended glaciogenic dust is 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. Particle number concentrations were well correlated with mass concentrations. This is unusual because mass concentration generally increases with larger particles suspended, while the number of particles decreases. Such high concentrations of particles 0.3–10 µm have only been reported during a volcanic eruption (Vogel et al., 2012; Sigurdardottir et al., 2015). The highest particle number concentrations for submicron particles are generally attributed to wind speeds <2 m s^{-1} (Weber et al., 2006), which was also the case for close-to-ultrafine particles during the dust event we measured at the dust source. These "on site" measurements are limited in scope, however, and new research is being undertaken that will add data about particle dynamics at the dust sources.

Several air-borne measurements have been made in Iceland with the Light Optical Aerosols Counter (LOAC, PM~0.2–100 µm) fitted on meteorological balloons (Renard et al., 2015a,b). LOAC can provide an estimate of the main categories of aerosols (dust, black carbon, sulphuric acid, water droplets and ice). The flight conducted in Reykjavik in November 2013 after a season of dust events in a high precipitation period revealed the presence of dust particles at about a 1 km height. Dust particles were also found during aircraft measurements in south Iceland from 400 to 1900 m altitude (Blechschmidt et al., 2012). Small liquid and sea salt particles were detected by LOAC close to the surface, while background carbon particles were present at around 5 km altitude between the cloud layers. High concentrations of particles >1 µm (even tens of micrometers) occurred in the stratosphere above 12 km, showing unusual conditions. This experiment showed that dust particles can be present in the atmosphere many days after a dust event despite precipitation and wet deposition removal of the

particles. It has also shown that aerosols such as black carbon are found in the sub-Arctic atmosphere, far from their sources.

9.2. Mineralogical and geochemical compositions of the particulate matter

Mineral grains and geochemical composition of Icelandic dust varies with the major dust sources (Baratoux et al., 2011; Oladottir et al., 2011). Mineralogical and geochemical analyses were carried out for two dust event samples – one sample from the Mælifellssandur dust source during a dust event in August 2013 and the second sample from the severe snow dust storm in Reykjavik in March 2013. The origin of the second sample was likely from the Skeiðarársandur dust source. The analyses show that both samples included also traces of fresh volcanic material from the Eyjafjallajökull 2010 eruption and the Grímsvötn 2011 eruption.

The glacigenic dust contains sharp-tipped shards with bubbles, and 75–80% of the particulate matter is volcanic glass rich in heavy metals. Crystalline plagioclases and pyroxenes were also found. Major element composition shows lower SiO_2 content in Icelandic dust compared to average crustal dust with about 58% SiO_2 reported by Weast et al. (1966). Table 5 summarizes the average element composition of two dust samples with unusually high amounts of FeO and TiO_2 contents.

Dust deposited on snow (transported more than 100 km) was of variable size range (average 17 µm). About 20% of particles were in the range of 10–50 µm and 10% were >50 µm. We suggest that the PM_{10} concentration measurements can overlook a significant part of the suspended dust mass during major dust storm events in Iceland. Diatoms and organic matter are also transported during the dust events in Iceland. Diatoms transported during the March 2013 event included *Rhopalodia* and *Epithemia* (likely epiphytic), which are benthic and may be present in shallow pools or waters around the edges of lakes and rivers (Fig. 12).

10. Atmospheric processes and distribution of the dust from Iceland

Iceland is located close to the North-Atlantic Storm track and is frequently visited by extratropical cyclones during all seasons (Olafsson et al., 2007). Most cyclones travel south of Iceland, leading to easterly winds over Iceland, while several cyclones find their way between Greenland and Iceland, generating winds over Iceland from the southwest or west. On a regional scale, strong winds can be expected from any direction. However, due to the topography, local windstorms tend to occur only in winds from preferred directions. Windstorms are most frequent during winter and are rare in the summer season. (Fig. 13 and Agustsson and Olafsson (2012) for upper atmospheric levels). Almost all the cyclones are associated with a precipitation system (fronts) and deep cyclones, giving strong winds, and they tend to produce heavy and widespread rain or snow. Precipitation could therefore be expected to prevent a high number of dust storms considering the high frequency of moist or wet windstorms. However, the mountains and glaciers of Iceland are sufficiently high to generate a precipitation shadow on their leeward side. There is in fact very little and
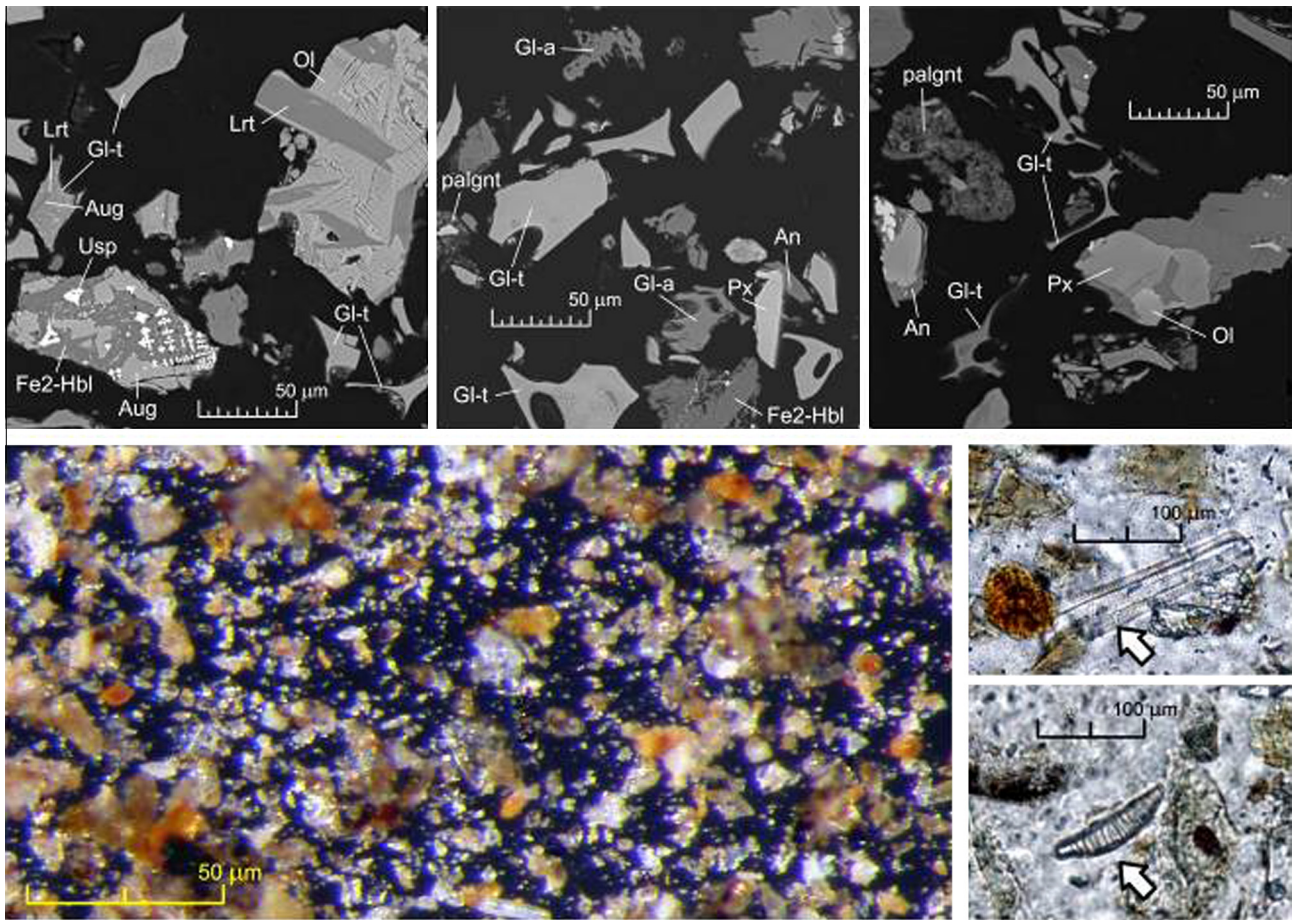
Fig. 12. Microscopic images of the dust material. Upper row: backscattered electron images of planar-polished sections of the dust particles; the analyzed and interpreted minerals and glasses are marked by symbols: An – andesine, Aug – augite, Fe2-Hbl – ferrohornblende, Lrt – labradorite, Ol – olivine, Px – pyroxene, Usp – ulvospinel; Gl-t – volcanic glass of tholeitic 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) and *Epithemia* sp., poss. *E. adnata* (lower). From Dagsson-Waldhauserova et al. (2015).
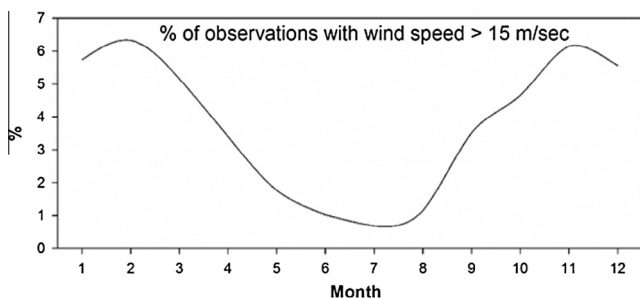

Fig. 13. Seasonal variability of windstorms in Iceland. Data from 120 automatic weather stations 2001–2010.
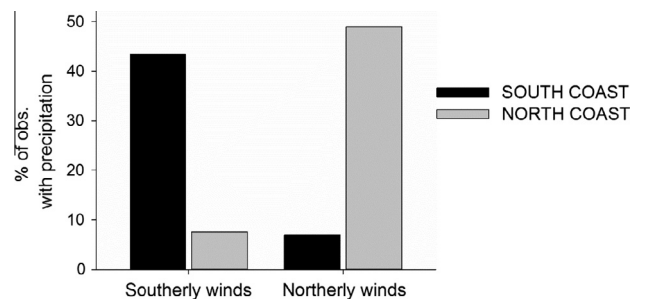

Fig. 14. Frequency of observations at 09 UTC 2001–2010 showing precipitation in southerly and northerly winds at Eyrarbakki (South coast) and Mánárbakki (North coast). Only cases with sustained wins greater than 8 m/s in the highlands (measured at 10 m height at Hveravellir weather station) are considered.

infrequent precipitation in north Iceland during southerly winds and very little and infrequent precipitation in south Iceland during northerly winds (Fig. 14).

Fig. 2 shows the main sources of dust storms in Iceland. Dust storms at all the sources except the southernmost ones are mainly associated with downslope winds, i.e. where the winds blow from a nearby mountain or ice cap. Such winds are locally enhanced by the buoyancy of the air and gravity as the air moves downwards from the mountains. Thus, the contribution of high topography to dust storms is twofold; it contributes both to dryness and to increased winds on its downstream side. The two southernmost

dust sources in Fig. 2 are associated with the topography, as the winds are enhanced locally when the airflow is deflected by the mountain range in the southernmost part of Iceland, forming so-called corner winds or barrier winds. This deflection occurs typically when the static stability of the air mass is high (e.g., Olafsson et al., 2004)

No systematic evaluation of the depth of the atmospheric boundary layer during dust storms has been made so far, but values can be expected to be typically 1–3 km (see e.g., Jonassen et al.,

2014). Strong mechanically generated turbulence, in addition to thermal instability during daytime, suggests that the dust is in general well mixed within the boundary layer.

11. Icelandic dust: Global implications and climate change

There are strong indications that Icelandic dust particles in dust plumes travel long distances: (i) a high number of satellite images confirming dust plumes extending more than 500 km (example Fig. 17); (ii) dust particles from Iceland were identified in Ireland, a 1300 km distance (Ovadnevaite et al., 2009); (iii) Icelandic dust particles were identified in ice-core samples in Central Greenland (Drab et al., 2002); and (iv) dust periods retrieved from the ice core data during the GISP2 project in Greenland (Donarummo et al., 2002) correlated with the NE Iceland dust frequency 1950–1990 (Dagsson-Waldhauserova et al., 2013). However, there is a lack of case studies identifying the long range transport of Icelandic dust and the magnitude of the impact of dust from Iceland on the atmosphere is unknown at this point. There are several ways in which the dust may have an impact on the radiation budget, both directly and indirectly. Firstly, dust deposition on snow or ice in the Arctic increases its albedo and accelerates melting in the summer season. Secondly, the dust has a direct impact on radiation. The most important part of this impact can be expected to be the reduction of short wave radiation reaching the surface of the earth. Thirdly, the dust may act as condensation nuclei, triggering cloud formation which in turn impacts the radiation budget in a complex manner, depending on parameters such as the height of the clouds and the albedo of the underlying surface. The quantification of these impacts remains to be done.

In general, numerical predictions of future climate do not indicate great changes in precipitation, mean winds or the number of windstorms in the Iceland region (e.g., Thorsteinsson and Björnsson, 2012), in spite of predicting strong warming in the Arctic in general. However, as the topographic windstorms are local, small changes in storm tracks may result in pronounced changes in wind directions and thereby the local windstorm climate. Consequently, the reliability of the evaluation of magnitude and frequency of dust storms in Iceland in the future may be even less reliable than the evaluation of more fundamental parameters of the climate, such as winds, temperature and precipitation on a larger scale.

On a decadal to centennial time scale, melting of ice will lead to lowering of the major ice caps. This may have several implications. Firstly, melting will reduce the precipitation sheltering on their downstream side. Some frontal rain may in other words reach more easily to the area downstream of the major glaciers and reduce the uptake of dust. Secondly, a complete melting of the ice caps will increase the surface roughness and surface heat fluxes, leading to poorer conditions for downslope windstorms (Jonassen et al., 2014). Thirdly, and perhaps most importantly, on a shorter time scale the retreat of the ice may open new sources of dust, as has been occurring over the last few decades.

12. Impacts of the aeolian activity and Icelandic dust

12.1. Ecosystems and aeolian history

The spread of deserts caused by aeolian surface processes has played a major role in the nearly 1200 years of human history of Iceland. Aeolian sand has devastated extensive areas, with a relatively well documented history of desertification in south Iceland (Crofts, 2011; Arnalds, 2015, Ch. 12).

Dust deposition is a major factor shaping Icelandic ecosystems. Dust, together with volcanic tephra, becomes the parent material

of the soils (and organic matter). The sedimentation causes a steady rise of the surface, often 0.01–0.5 mm yr^{-1}, providing new materials for soil formation (see Arnalds, 2015, Ch. 9). The sedimentation rate is one of the key factors for separation and classification of Icelandic Andosols, with less organic matter found in wetland soils of rapid aeolian deposition. Hence, more organic soils, including Histosols, are found furthest away from the aeolian sources (Arnalds, 2015, Ch. 6). Soils close to active aeolian sources tend to be coarse grained with a large sand component. The basaltic ash weathers relatively rapidly, providing cations that maintain soil pH. The inference is therefore that the deposition has a fertilizing effect. Birds are considered a good indication of ecosystem fertility and integrity. Research shows that the highest densities of bird nests on comparable habitats on vegetated land are found within the areas of the highest sedimentation rates in Iceland (Gunnarsson et al., 2015).

It should be noted that dust generation is not limited to the sandy deserts, as soil erosion associated with ecosystem degradation has caused massive dust generating events, especially during some parts of the Middle Ages (Arnalds, 2015, Ch. 12). Redistribution of soil materials has been a substantial part of aeolian deposition during these times. It is likely that growing sandy areas at the margins of glaciers have increased the proportion of aeolian materials of glacio-fluvial origin during the past 100 yrs. Furthermore, reduced vegetation cover due to land degradation has increased aeolian redistribution of volcanic materials after eruptions, as materials deposited on barren areas are unstable, resulting in heightened aeolian spikes after volcanic events. Similarly, steady aeolian deposition on barren land (deserts) leaves unstable materials on the surface that become re-suspended during the next storm. This leads to an increased overall deposition on vegetated areas that are able to stabilize the sediments and possible overestimation of dust generation based on soil thickening rates under vegetation.

12.2. Dust, snow and glaciers

Satellite images have shown that dust particles are transported over the Atlantic Ocean and Arctic Ocean at times for more than 1000 km (Arnalds, 2010). Globally, fine dust particles may be transported at altitudes of up to 10 km and can be carried distances greater than 10,000 km (Husar, 2004). Grousset et al. (2003) suggested that dust particles can travel over 20,000 km in two weeks. Icelandic dust is likely to contribute to Arctic or European air pollution and affect indirectly the climate via dust deposition on Arctic glaciers or sea ice. Local glaciers cover about 11% of Iceland (Björnsson and Palsson, 2008). However, the closest distance to the Greenland glacier is about 500 km from Iceland. Drab et al. (2002) identified dust particles in the Arctic glaciers with origins from Asia and Africa and including volcanic particles from Iceland.

Dust events in the southern part of Iceland often occur during winter, even at sub-zero temperatures, resulting in snow mixed or covered with dust. Darker snow reduces the albedo and accelerates snowmelt (Painter et al., 2012; Steenburgh et al., 2012). The "Soot on the Snow" (SoS-2013) experiment carried out in Sodankylä, Finland, was aimed to study the effect of black carbon (BC) and Icelandic dust on the surface albedo, snow properties and snow melt (Meinander et al., 2014; Peltoniemi et al., 2015). Two Icelandic dust samples, coarse dark volcanic sand and fine light-brown glaciogenic silt, were used in the study. The snow albedo during the time of the deposition was the highest for clean snow and slightly reduced for snow with volcanic sand. The soot reduced the snow reflectance significantly, but the fine Icelandic silt reduced the snow reflectance even more at the time of the deposition. Hadley and Kirchstetter (2012) found a 20% decrease in snow albedo (at $\lambda = 0.412$ μm) for the soot concentration $c = 1.68$ μg g^{-1}.

Fig. 15. Melting, metamorphose and diffusion processes on snow where glaciogenic silt was deposited. Left: freshly deposited. Right: several hours after dust deposition. ©Maria Gritsevich.

Fig. 16. The Icelandic Snow-Dust storm on March 6 2013, in Kirkjubæjarklaustur (left), caused an extreme volcanic dust deposition on snow. The impurities on snow in Reykjavik, 250 km from the dust source (right) were observed to form larger particles ("clumping mechanism") and accelerate snow melt. Left photo – courtesy of Ingveldur Gudny Sveinsdottir, Kirkjubæjarklaustur.
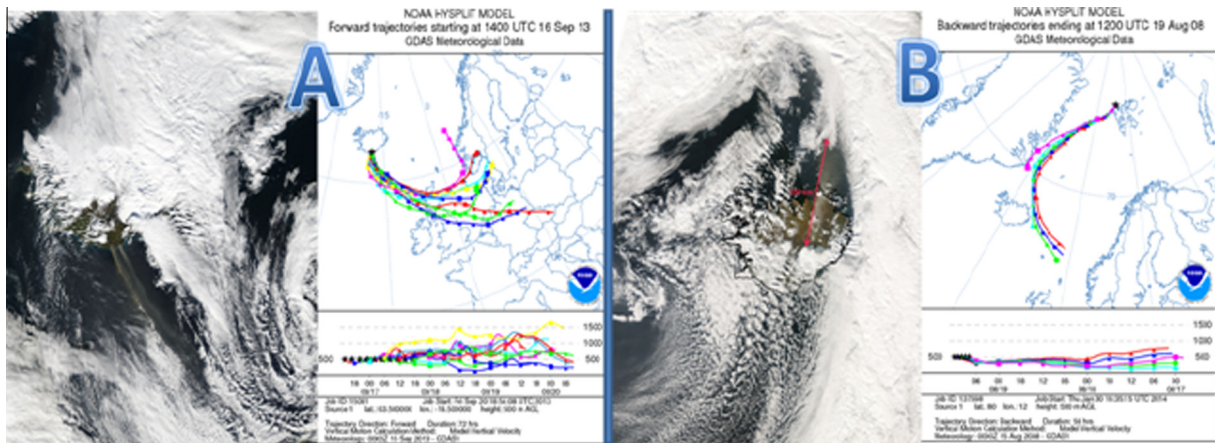

Fig. 17. MODIS Aqua satellite images of dust storms in South (A) and Northeast (B) Iceland. Calculated forward (A) and backward (B) trajectories (HYSPLIT) for the events on September 16, 2013 reaching Europe (A), and August 17–18, 2008 reaching Svalbard (B).

However, Painter et al. (2007) observed the most pronounced decrease towards the UV portion of the spectrum due to global dust deposition.

Overall, the larger volcanic sand particles reduced the reflectance more than the fine glacio-genic silt particles except that the small silt particles tended to form larger grains during several hours after deposition (Fig. 15). The Snow-Dust storm event in Iceland in March 2013 confirmed that a "clumping mechanism" occurs under natural conditions (Dagsson-Waldhauserova et al., 2015), contrary to earlier observations (Brandt et al., 2011). Fig. 16 (right) shows the formation of larger grains on snow in Reykjavik after the event under natural conditions. This dust traveled about 250 km before being deposited on snow. The layer of dust deposited on snow closer to the dust source was several centimeters thick (Fig. 17 left).

A positive instantaneous radiative forcing of the Saharan dust on snow reaches values up to $153 \, W \, m^{-2}$ (di Mauro et al., 2015). Icelandic volcanic dust is expected to cause greater radiative forcing than crustal dust due to its darker color and the clumping mechanism of fine dust. The volcanic dust deposition on the Icelandic glaciers is estimated as $400 \, g \, m^{-2} \, yr^{-1}$ (Arnalds et al., 2014). In addition, several severe dust events bring extreme amounts of dust to the glaciers and snow surfaces in Iceland each year. This indicates that volcanic dust has a strong negative impact on the snow and glaciers. The glaciogenic silt, which is a major component of the dust, was found to have lower reflectance than more coarse sand. However, Clark et al. (1990) compared 33 dust samples (none from Iceland) and reported a higher spectral reflectance for all the samples compared to results reported for Icelandic samples.

Generally, direct radiative forcing of mineral dust is calculated as negative (IPCC, 2013). In terms of climate forcing, black carbon (BC) has been found as the most powerful absorbing aerosol and the second most important human emission after carbon dioxide (Bond et al., 2013). However, research shows that the optical and thermal properties of Icelandic volcanic dust, which is largely basaltic, and BC particles are similar (Yoshida et al., in press). We therefore emphasize that Icelandic dust can possibly have climatic effects and should be considered in future climate models, as pointed out by Ovadnevaite et al. (2009).

12.3. Air quality and possible health impacts of Icelandic volcanic dust

Iceland is generally considered to have limited air pollution compared to more densely populated areas in Europe and North America. Dust emissions, however, do reduce air quality such as in the capital Reykjavik (Thorsteinsson et al., 2011). Particulate matter (PM_{10}) concentrations during dust events in Reykjavik often exceed the health limit of $50 \, \mu g \, m^{-3}$ over 24 h (WHO, 2005; UST, 2015). PM concentrations measured during dust events in the vicinity of dust sources (<30 km) exceed the health limit on an order of 10–100 times (UST, 2015). Research has shown that mortality increases with dust pollution, e.g. for about 8% per $10 \, \mu g \, m^{-3}$ in Barcelona, Spain, when Saharan dust is suspended (Perez et al., 2008). High PM_{10} levels from volcanic dust in Iceland tend to be significantly associated with emergency hospital visits; estimates range from 4.8% to 7.3% increase per day of exposure (Carlsen et al., 2015; see also Gudmundsson, 2011). The World Health Organization considers that an annual $PM_{2.5}$ concentration of $10 \, \mu g \, m^{-3}$ and estimated visibility of 67 km imply health risk, or a daily standard of $35 \, \mu g \, m^{-3}$ and visibility range of 31 km (WHO, 2005). The long-term frequency of dust events in Iceland is 34–135 dust days annually with a mean visibility of 25 km. This indicates that some areas in Iceland may be similar to heavily industrialized regions of the world in terms of PM air pollution. It should be mentioned that considerable research was devoted to air quality in relation to the 2010 Eyjafjallajökull eruption, not only in Iceland but also in Europe (e.g., Navratil et al., 2013).

Mineralogical and geochemical analyses of Icelandic samples showed that 75–80% of the particulate matter is volcanic glass rich in heavy metals, such iron and titanium. Alkali- and silica-rich glasses have often complicated pipe-vesicular structures (Fig. 12, top-right) more similar to asbestos particles or black carbon than mineral dust, and may pose health risks (Donaldson et al., 2006). Moreover, a high amount of bioavailable metals in the dust increases the inflammatory capacity of the PM, which may cause health problems (Morman and Plumlee, 2013). Few studies have addressed dust particle numbers in the close-to-ultrafine size range, but I in a study of urban particles, modes with a mean of 0.212 μm in diameter were associated with increased admissions for pediatric asthma and respiratory disease (Andersen et al., 2008). 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).

The impact of Icelandic dust on human health and air quality is poorly understood. Dust emission research should be linked with existing health records from various parts of Iceland in order to investigate possible health effects. Furthermore, more and more widely distributed dust measurements are needed to develop health risk warning systems.

13. Conclusions

Aeolian processes and dust production are a major part of the Icelandic geomorphic environment, shaping ecosystems both on land and on glaciers, and possibly influencing oceanic conditions. The processes are comparable to those reported elsewhere in the world, but with important differences. In comparison to other Arctic as well as European areas, Iceland has the largest active aeolian surfaces (about $15,000 \, km^2$, Table 2), and the fact that aeolian materials in Iceland are chiefly made of volcanic glass makes them unique in a global context. The variable density of the materials, which include some light materials (down to $1 \, g \, cm^{-3}$ in places; Thorarinsdottir and Arnalds, 2012) is likely to enhance surface transport and dust production together with other factors such as frequent high wind velocities. The amount of dust (millions of tons) exceeds by far other published numbers for emissions in the Arctic (e.g., by Crusius et al. (2011); see also Bullard (2013)). The frequency of the dust storms is also higher than reported for the Arctic and Antarctic areas, with storms occurring throughout the year, owing to the mild oceanic climate in winter. Furthermore, the size and the frequency of jökulhlaups, which create and recharge active aeolian areas, are unique to Iceland.

It can be concluded that increased vegetative cover, especially in areas of periodic volcanic ash deposition and high rates of aeolian sedimentation, can reduce the overall aeolian surface transport and dust production in Iceland. The spread of sandy deserts has been of major concern. It has, however, been halted in the most active areas. Nevertheless, active sand sources need to be monitored in order to prevent future "advancing sand events".

Icelandic ice caps and outlet glaciers generally advanced after ca. 5000–4000 years ago until the late 19th century, in response to deteriorating climate (Björnsson and Palsson, 2008; Geirsdóttir et al., 2009; Striberger et al., 2012; Hannesdottir et al., 2014). Their retreat has greatly added to the formation of extensive sand fields that are prone to dust production. The glacial retreat has also exposed barren subglacial landscapes that in many cases were fully vegetated and carrying birch forests prior to the glacial expansion (e.g., Jonsson et al., in press). The retreat of Iceland's major glaciers will undoubtedly lead to increased dust production in

the future, as has been suggested for other areas experiencing glacial retreat (e.g., Alaska; Crusius et al., 2011). The effect of retreating glaciers in Iceland is dependent on such factors as vegetation succession and on the level of human intervention by preventing grazing damage and implementing revegetation efforts.

We conclude that Icelandic dust may have a considerable impact on glaciers and atmospheric conditions in the sub-Arctic and Arctic areas, due to high emission rates, the long distance of travel, and the light adsorbing nature of the dark colored materials. Further research is needed to study these impacts. Furthermore, recent research reviewed in the paper shows that the impact of Icelandic dust on air quality is likely to be substantial and that there is therefore a need for increased research efforts.

It is important to investigate aeolian processes in Iceland in greater detail. This includes assessment of the major dust sources in Iceland and their nature such as the number and magnitude of dust events, as well as their physical and chemical characteristics. The impact of dust on the fertility of land and sea also needs further research attention. Transport of aeolian sediments over extensive areas (hundreds of km^2) needs to be quantified and modeled. Such research is important in order to understand the future impact of sand storms in order to better understand and prepare for future catastrophic events like glacial flooding, glacial retreat, and volcanic ash deposition. The influence of dust deposition on ecosystems on land and sea is likely to be great, considering the rapid weathering rates of the basaltic volcanic dust. The information is needed, among other things, for the protection of human health.

Acknowledgments

References

Agustsson, H., Olafsson, O., 2012. The bimodal downslope windstorms at Kvísker. Meteorol. Atmos. Phys. 116, 27–42.

Alho, P., 2003. Land cover characteristics in NE Iceland with special reference to jökulhlaup geomorphology. Geogr. Ann. A 85, 213–227.

Alho, P., Russell, A.J., Carrivick, J.L., Kayhkö, J., 2005. Reconstruction of the largest Holocene jökulhlaup within Jökulsá á Fjöllum, NE Iceland. Quat. Sci. Rev. 24, 2319–2334.

Andersen, Z.J., Wahlin, P., Raaschou-Nielsen, O., Ketzel, M., Scheike, T., Loft, S., 2008. Size distribution and total number concentration of ultrafine and accumulation mode particles and hospital admissions in children and the elderly in Copenhagen, Denmark. Occup. Environ. Med. 65, 458–466.

Arnalds, O., 1992. Pathways of aeolian sand-drift in Northeast Iceland (Sandleiðir á Norðausturlandi). In: Græðum Ísland (Icelandic SCS Yearbook) IV, Soil Conservation Service of Iceland, pp. 145–149 (in Icelandic).

Arnalds, O., 2010. Dust sources and deposition of aeolian materials in Iceland. Icelandic Agric. Sci. 23, 3–21.

Arnalds, O., 2013. The influence of volcanic tephra (ash) on ecosystems. Adv. Agron. 121, 331–380.

Arnalds, O., 2015. The Soils of Iceland. World Soils Book Series. Springer, Dordrecht, the Netherlands.

Arnalds, O., Kimble, J., 2001. Andisols of deserts in Iceland. Soil Sci. Soc. Am. J. 65, 1778–1786.

Arnalds, O., Thorarinsdottir, E.F., Metusalemsson, S., Jonsson, A., Gretarsson, E., Arnason, A., 2001a. Soil erosion in Iceland. Soil Conservation Service and Agricultural Research Institute, Reykjavik (original edition in Icelandic 1997).

Arnalds, O., Gisladottir, F.O., Sigurjonsson, H., 2001b. Sandy deserts of Iceland: an overview. J. Arid Environ. 47, 359–371.

Arnalds, O., Gisladottir, F.O., Orradottir, B., 2012. Determination of aeolian transport rates of volcanic soils in Iceland. Geomorphology 167–168, 4–12.

Arnalds, O., Thorarinsdottir, E.F., Thorsson, J., Dagsson-Waldhauserova, P., Agustsdottir, A.M., 2013. An extreme wind erosion event of the fresh

Eyjafjallajökull 2010 volcanic ash. Nat. Sci. Rep. 3, 1257. http://dx.doi.org/10.1038/srep01257.

Arnalds, O., Olafsson, H., Dagsson-Waldhauserova, P., 2014. Quantification of iron-rich volcanogenic dust emissions and deposition over ocean from Icelandic dust sources. Biogeosciences 11, 6623–6632. http://dx.doi.org/10.5194/bg-11-6623-2014.

Baddock, M.C., Strong, C.L., Leys, J.F., Heidenreich, S.K., Tews, E.K., McTainsh, G.H., 2014. A visibility and total suspended dust relationship. Atmos. Environ. 89, 329–336.

Baratoux, D., Mangold, N., Arnalds, O., Bardintzeff, J.-M., Platevoet, B., Gregorie, M., Pinet, P., 2011. Volcanic sands of Iceland – diverse origins of aeolian sand deposits revealed at Dyngjusandur and Lambahraun. Earth Surf. Proc. Land. 36, 1789–1808.

Bateman, M.D., 2013. Aeolian processes in periglacial environments. In: Shroder, J. R., Giardino, R., Harbor, J. (Eds.), Treatise on Geomorphology, vol. 8. Academic Press, San Diego, pp. 416–429.

Baynes, E.R., Attal, M., Niedermann, S., Kirstein, L.A., Dugmore, A.J., Naylor, M., 2015. Erosion during extreme flood events dominates Holocene canyon evolution in northeast Iceland. PNAS 112, 2335–2360.

Björnsson, H., 2009. Jöklar á Íslandi (Icelandic Glaciers). Opna, Reykjavik, Iceland, p. 479 (in Icelandic).

Björnsson, H., Palsson, F., 2008. Icelandic glaciers. Jökull 58, 365–386.

Blechschmidt, A.-M., Kristjansson, J.E., Olafsson, H., Burkhart, J.F., Hodnebrog, Ø., 2012. Aircraft-based observations and high-resolution simulations of an Icelandic dust storm. Atmos. Chem. Phys. 12, 10649–10666. http://dx.doi.org/10.5194/acp-12-10649-2012.

Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Karcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P.K., Sarofim, M.C., Schultz, M.G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S.K., Hopke, P.K., Jacobson, M.Z., Kaiser, J.W., Klimont, Z., Lohmann, U., Schwarz, J.P., Shindell, D., Storelvmo, T., Warren, S.G., Zender, C. S., 2013. Bounding the role of black carbon in the climate system: a scientific assessment. J. Geophys. Res. Atmos. 118 (11), 5380–5552. http://dx.doi.org/10.1002/jgrd.50171.

Brandt, R.E., Warren, S.G., Clarke, A.D., 2011. A controlled snowmaking experiment testing the relation between black carbon content and reduction of snow albedo. J. Geophys. Res. 116, D08109. http://dx.doi.org/10.1029/2010JD015330.

Bryant, R.G., 2013. Recent advances in our understanding of dust source emission processes. Prog. Phys. Geogr. 37, 397–421.

Bullard, J.E., 2013. Contemporary glacigenic inputs to the dust cycle. Earth Surf. Proc. Land. 38, 71–89.

Carlsen, H.K., Gislason, Th., Forsberg, B., Meister, K., Thorsteinsson, Th., Johannsson, Th., Finnbjornsdottir, R., Oudin, A., 2015. Emergency hospital visits in association with volcanic ash, dust storms and other sources of ambient particles: a time-series study in Reykjavík, Iceland. Int. J. Environ. Res. Public Health 12, 4047–4059.

Carrivick, J.L., Tweed, F.S., Carling, P., Alho, P., Marren, P.M., Staines, K., Russell, A.J., Rusmer, E.L., Duller, R., 2013. Discussion of 'Field evidence and hyrdaulic modeling of a large Holcene jökulhlaup at Jökulsá á Fjöllum channel, Iceland' by Douglas Howard, Sheryl Luzzadder-Beach and Timothy Beach, 2012. Geomorphology 201, 512–519.

Clark, R.N., King, T.V.V., Klejwa, M., Swayze, G.A., Vergo, N., 1990. High spectral resolution reflectance spectroscopy of minerals. J. Geophys. Res. 95 (B8), 12653–12680. http://dx.doi.org/10.1029/JB095iB08p12653.

Crofts, R., 2011. Healing the Land. Soil Conservation Service of Iceland, Gunnarsholt, p. 208.

Crusius, J., Schroth, A.W., Gasso, S., Moy, C.M., Levy, R.C., Gatica, M., 2011. Glacial flour dust storms in the Gulf of Alaska: hydrologic and meteorological controls and their importance as a source of bioavailable iron. Geophys. Res. Lett. 38, L06602. http://dx.doi.org/10.1029/2010GL046573.

Dagsson-Waldhauserova, P., Arnalds, O., Olafsson, H., 2013. Long-term frequency and characteristics of dust storm events in Northeastern Iceland (1949–2011). Atmos. Environ. 77, 117–127.

Dagsson-Waldhauserova, P., Arnalds, O., Olafsson, H., 2014. Long-term variability of dust events in Iceland. Atmos. Chem. Phys. 14, 13411–13422. http://dx.doi.org/10.5194/acp-14-13411-2014.

Dagsson-Waldhauserova, P., Arnalds, O., Olafsson, H., Skrabalova, L., Sigurdardottir, G.M., Branis, M., Hladil, J., Skala, R., Navratil, T., Chadimova, L., von Lowis of Menar, S., Thorsteinsson, Th., Carlsen, H.K., Jonsdottir, I., 2014. Physical properties of suspended dust during moist and low-wind conditions in Iceland. Icelandic Agric. Sci. 27, 25–39.

Dagsson-Waldhauserova, P., Arnalds, O., Olafsson, H., Hladil, J., Skala, R., Navratil, T., Chadimova, L., Meinander, O., 2015. Snow-dust storm: a case study from Iceland, March 7th 2013. Aeol. Res. 16, 69–74.

di Mauro, B., Fava, F., Ferrero, L., Garzonio, R., Baccolo, G., Delmonte, B., Colombo, R., 2015. Mineral dust impact on snow radiative properties in the European Alps combining ground, UAV and satellite observations. J. Geophys. Res. Atmospheres 120 (12), 6080–6097. http://dx.doi.org/10.1002/2015JD023287.

Donaldson, K., Stone, V., Faux, S., MacNee, W., 2006. Testing new particles. In: Ayres, J., Maynard, R., Richards, R. (Eds.), The Impact of Air Pollution on Respiratory Health. Imperial College Press, London, pp. 163–195.

Donarummo, J.J., Ram, M., Stolz, M.R., 2002. Sun/dust correlations and volcanic interference. Geophys. Res. Lett. 29 (9), 75-1–75-4.

Drab, E., Gaudichet, A., Jaffrezo, J.L., Colin, J.L., 2002. Mineral particles content in recent snow at Summit (Greenland). Atmos. Environ. 36, 5365–5376.

Edgett, K.S., Lancaster, N., 1993. Volcaniclastic aeolian dunes: terrestrial examples and application to Martian sands. J. Arid Environ. 25, 271–297.

Einarsson, M.A., 1984. Climate of Iceland. In: Loon, Van. (Ed.), World Survey of Climatology, vol. 15. Elsevier, Amsterdam, pp. 673–697.

Ekström, M., McTainsh, G.H., Chappell, A., 2004. Australian dust storms: temporal trends and relationships with synoptic pressure distributions (1960–99). Int. J. Climatol. 24, 1581–1599.

Eliasson, J., Kjaran, S.P., Holm, S.L., Gudmundsson, M.T., Larsen, G., 2007. Large hazardous floods as translatory waves. Environ. Model. Software 22, 1392–1399.

Fryrear, D.W., 1986. A field dust sampler. J. Soil Water Conserv. 41, 117-12.

Geirsdóttir, A., Miller, G.H., Axford, Y., Olafsdóttir, S., 2009. Holocene and latest Pleistocene climate and glacier fluctuations in Iceland. Quat. Sci. Rev. 28, 2107–2118.

Gillies, J.A., Nickling, W.G., Tilson, M., 2013. Frequency, magnitude, and characteristics of aeolian sediment transport: McMurdo Dry Valleys, Antarctica. J. Geophys. Res. 118, 461–479.

Gillette, D.A., Fryrear, D.W., Xiao, J.B., Stockton, P., Ono, D., Helm, D., Gill, T.E., Lay, T., 1997. Large-scale variability of wind erosion mass flux rates at Owens Lake 1. Vertical profiles of horizontal mass fluxes of wind-eroded particles with diameter greater than 50 μm. J. Geophys. Res. 102 (25), 977–987.

Gisladottir, F.O., 2000. Environmental change and eolian processes south of the Langjökull Glacier (MSc thesis). University of Iceland (in Icelandic).

Gisladottir, F.O., Arnalds, O., Gisladottir, G., 2005. The effect of landscape and retreating glaciers on wind erosion in South Iceland. Land Degrad. Dev. 16, 177–187.

Gisladottir, F.O., Brink, S, H., Arnalds, O., 2014. Nytjaland (Icelandic Farmland Database). Agricultural University of Iceland Report 54, In Icelandic, English summary.

Gislason, S., 2008. Weathering in Iceland. Jökull 58, 387–408.

Grousset, F.E., Ginoux, P., Bory, A., Biscaye, P.E., 2003. Case study of a Chinese dust plume reaching the French Alps. Geophys. Res. Lett. 30 (6), 1277.

Gudmundsson, G., 2011. Respiratory health effects of volcanic ash with special reference to Iceland. A review. Clin. Respirat. J. 2011. http://dx.doi.org/10.1111/j.1752-699X.2010.00231.x.

Gudmundsson, M.T., Larsen, G., Höskuldsson, A., Gylfason, A.G., 2008. Volcanic hazards in Iceland. Jökull 58, 251–268.

Gunnarsson, T.G., Arnalds, O., Appleton, G., Méndez, V., Gill, J.A., 2015. Ecosystem recharge by volcanic dust drives broad-scale variation in bird abundance. Ecol. Evol. 5, 2386–2396.

Hadley, O., Kirchstetter, W., 2012. Black-carbon reduction of snow albedo. Nat. Clim. Change 2, 437–440.

Hannesdottir, H., Björnsson, H., Palsson, F., Adalgeirsdottir, G., Gudmundsson, S., 2014. Variations of southeast Vatnajökull ice cap (Iceland) 1650–1900 and reconstruction of the glacier surface geometry at the Little Ice Age maximum. Geogr. Ann.: Series A Phys. Geogr. 2, 3. http://dx.doi.org/10.1111/geoa.12064, 1-28.

Horwell, C.J., Baxter, P.J., Hillman, S.E., Calkins, J.A., Damby, D.E., 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. Environ. Res. 127, 63–73.

Hugenholtz, C.H., Wolfe, S.A., 2010. Rates and environmental controls of aeolian dust accumulation, Athabasca River Valley, Canadian Rocky Mountains. Geomorphology 121, 274–282.

Husar, B.R., 2004. Transport of dust: historical and recent observational evidence. In: Barceló, D., Kostianoy, A.G. (Eds.), The Handbook of Environmental Chemistry, vol. 4. Springer, Dordrecht, pp. 277–294.

Hyslop, N.P., 2009. Impaired visibility: the air pollution people see. Atmos. Environ. 43, 182–195.

IPCC, 2013. Climate change 2013: The physical science basis. In: Working Group I Contribution to the IPCC 5th Assessment Report – Changes to the Underlying Scientific/Technical Assessment‖ (IPCC-XXVI/Doc.4). URL: http://www.ipcc.ch/report/ar5/wg1/#.UlvUNVPfShM (accessed Sep 26, 2015).

Jamalizadeh, M.R., Moghaddamnia, A., Piri, J., Arbabi, V., Homayounifar, M., Shahryari, A., 2008. Dust storm prediction using ANNs technique (a case study: Zabol city). Proc. World Acad. Sci. Eng. Technol. 33, 529–537.

Jonassen, M.O., Agustsson, H., Olafsson, H., 2014. Impact of surface characteristics on flow over a mesoscale mountain. Quart. J. Roy. Meteorol. Soc. 140, 2330–2341.

Jonsson, S.A.J., Benediktsson, I.Ö., Ingolfsson, O., Schomacke, A., Bergsdottir, H.L., Jacobson, W.R., Linderson, H., in press. Submarginal drumlin formation and late Holocene history of Fláajökull, southeast Iceland. Ann. Glaciol., in press.

Kirkbride, M.P., Dugmore, A.J., Brazier, V., 2006. Radiocarbon dating of mid-Holocene megaflood deposits in the Jökulsá á Fjöllum, Iceland. Holocene 16, 605–609.

Kjær, K.H., 2004. Architecture and sedimentation of outwash fans in front of the Mýrdalsjökull ice cap, Iceland. Sediment. Geol. 172, 139–163.

Krüger, J., 1997. Development of minor outwash fans at Kötlujökull, Iceland. Quat. Sci. Rev. 16, 649–659.

Lancaster, N., Nickling, W.G., Gillies, J.A., 2010. Sand transport by wind on complex surfaces. Field studies in the McMurdo dry valleys, Antarctica. J. Geophys. Res. 115. http://dx.doi.org/10.1029/2009JF001408.

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

Larsen, G., Eiriksson, J., 2008. Holocene tephra archives and tephrochronology in Iceland – a brief overview. Jökull 58, 229–250.

Leadbetter, S.J., Hort, M.C., von Löwis, S., Weber, K., Witham, C.S., 2012. Modeling the resuspension of ash deposited during the eruption of Eyjafjallajökull in spring 2010. J. Geophys. Res. 117, D00U10.

Liu, E.J., Cashman, K.V., Beckett, F.M., Witham, C.S., Leadbetter, S.J., Hort, M.C., Gudmundsson, S., 2014. Ash mists and brown snow: remobilization of volcanic ash from recent Icelandic eruptions. J. Geophys. Res. Atmos. 119. http://dx.doi.org/10.1002/2014JD021598.

Mangold, N., Baratoux, D., Arnalds, O., Bardintzeff, J.-M., Platevoet, B., Gregoire, M., Pinet, P., 2011. Segregation of olivine grains in volcanic sands in Iceland and implications for Mars. Earth Planet. Sci. Lett. 310, 233–243.

Meinander, O., Kontu, A., Virkkula, A., Arola, A., Backman, L., Dagsson-Waldhauserova, P., Järvinen, O., Manninen, T., Svensson, J., de Leeuw, G., Leppäranta, M., 2014. Brief communication: light-absorbing impurities can reduce the density of melting snow. Cryosphere 8, 991–995.

Monick, M.M., Baltrusaitis, J., Powers, L.S., Borcherding, J.A., Caraballo, J.C., Mudunkotuwa, I., 2013. Effects of Eyjafjallajökull volcanic ash on innate immune system responses and bacterial growth in vitro. Environ. Health Perspect. 121, 691–698.

Morman, S.A., Plumlee, G.S., 2013. The role of airborne mineral dusts in human disease. Aeol. Res. 9, 203–212.

Mountney, N.P., Russell, A.J., 2004. Sedimentalogy of cold-climate aeolian sandsheet deposits in the Askja region of northeast Iceland. Sediment. Geol. 166, 223–244.

Natsagdorj, L., Jugder, D., Chung, Y.S., 2003. Analysis of dust storms observed in Mongolia during 1937–1999. Atmos. Environ. 37, 1401–1411.

Navratil, T., Hladil, J., Strnad, L., Koplikova, L., Skala, R., 2013. Volcanic ash particulate matter from the 2010 Eyjafjallajökull eruption in dust deposition at Prague, central Europe. Aeol. Res. 9, 191–202.

Nickling, W.G., 1978. Eolian sediment transport during dust storms: Slims River Valley, Yukon Territory. Can. J. Earth Sci. 15 (7), 1069–1084.

Oladottir, B.A., Sigmarsson, O., Larsen, G., Devidal, J.-L., 2011. Provenance of basaltic tephras from Vatnajökull subglacial volcanoes, Iceland as determined by major- and trace-element analyses. Holocene 21, 1037–1048.

Olafsson, H., 2004. The dust storm weather Oktober 5th, 2004 (Sandfoksveðrið 5. október 2004). Náttúrufræðingurinn 72, 93–95, in Icelandic, English summary. z.

Olafsson, H., Bruemmer, B., Furger, M., 2007. The weather and climate of Iceland. Meteorol. Z. 16, 5–8.

Orwin, J.F., Lamoureux, S.F., Warburton, J., Beylich, A., 2010. A framework for characterizing sediment fluxes from source to sink in cold environments. Geogr. Ann. 92 A, 155–176.

Ovadnevaite, J., Ceburnis, D., Plauskaite-Sukiene, K., Modini, R., Dupuy, R., Rimselyte, I., Ramonet, R., Kvietkus, K., Ristovksi, Z., Berresheim, H., O'Dowd, C., 2009. Volcanic sulfate and arctic dust plumes over the North Atlantic Ocean. Atmos. Environ. 43, 4968–4974.

Painter, T.H., Barrett, A.P., Landry, C.C., Neff, J.C., Cassidy, M.P., Lawrence, C.R., McBride, K.E., Farmer, G.L., 2007. Impact of disturbed desert soils on duration of mountain snow cover. Geophys. Res. Lett. 34, L12502. http://dx.doi.org/10.1029/2007GL030284.

Painter, T.H., Skiles, S.M., Deems, J.S., Bryant, A.C., Landry, C., 2012. Dust radiative forcing in snow of the Upper Colorado River Basin: Part I. A 6 year record of energy balance, radiation, and dust concentrations. Water Resour. Res. 48, W07521. http://dx.doi.org/10.1029/2012WR011985.

Peltoniemi, J.I., Gritsevich, M., Hakala, T., Dagsson-Waldhauserová, P., Arnalds, Ó., Anttila, K., Hannula, H.-R., Kivekäs, N., Lihavainen, H., Meinander, O., Svensson, J., Virkkula, A., de Leeuw, G., 2015. Soot on snow experiment: bidirectional reflectance factor measurements of contaminated snow. Cryosphere 9, 1–15. http://dx.doi.org/10.5194/tc-9-1-2015.

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.

Prospero, J.M., Bullard, J.E., Hodgkins, R., 2012. High-latitude dust over the North Atlantic: inputs from Icelandic proglacial dust storms. Science 335, 1078–1082.

Qian, W.H., Quan, L., Shi, S., 2002. Variations of the dust storm in China and its climatic control. J. Clim. 15, 1216–1229.

Renard, J.-B., Dulac, F., Berthet, G., Lurton, T., Vignelles, D., Jegou, F., Tonnelier, T., Thaury, C., Jeannot, M., Couté, B., Akiki, R., Mineau, J.-L., Verdier, N., Mallet, M., Gensdarmes, F., Charpentier, P., Mesmin, S., Duverger, V., Dupont, J.-C., Elias, T., Crenn, V., Sciare, J., Giacomoni, J., Gobbi, M., Hamonou, E., Olafsson, H., Dagsson-Waldhauserova, P., Camy-Peyret, C., Mazel, C., Décamps, T., Piringer, M., Surcin, J., Daugeron, D., 2015a. LOAC: a small aerosol optical counter/sizer for ground-based and balloon measurements of the size distribution and nature of atmospheric particles – Part 1: principle of measurements and instrument evaluation. Atmos. Meas. Tech. Discuss. 8, 1203–1259. http://dx.doi.org/10.5194/amtd-8-1203-2015.

Renard, J.-B., Dulac, F., Berthet, G., Lurton, T., Vignelle, D., Jegou, F., Tonnelier, T., Thaury, C., Jeannot, M., Couté, B., Akiki, R., Mineau, J.-L., Verdier, N., Mallet, M., Gensdarmes, F., Charpentier, P., Mesmin, S., Duverger, V., Dupont, J.-C., Elias, T., Crenn, V., Sciare, J., Giacomoni, J., Gobbi, M., Hamonou, E., Olafsson, H., Dagsson-Waldhauserova, P., Camy-Peyret, C., Mazel, C., Décamps, T., Piringer, M., Surcin, J., Daugeron, D., 2015b. LOAC: a small aerosol optical counter/sizer for ground-based and balloon measurements of the size distribution and nature of atmospheric particles – Part 2: first results from balloon and unmanned aerial vehicle flights. Atmos. Meas. Tech. Discuss. 8, 10057–10096. http://dx.doi.org/10.5194/amtd-8-10057-2015.

Rodolfo, K.S., 2000. The hazards from lahars and jökulhlaups. In: Sigurdsson, H., Houghton, B., McNutt, S.R., Rymer, H., Stix, J. (Eds.), Encyclopedia of Volcanoes. Academic Press, New York, pp. 957–971.

Russel, A.J., Knight, P.G., Van Dijk, T.A.G.P., 2001. Glacier surging as a control on the development of proglacial, fluvial landforms and deposits, Skeiðarársandur, Iceland. Global Planet. Change 28, 163–174.

Russell, A.J., Roberts, M.J., Fay, H., Marren, P.M., Cassidy, M.J., Tweed, F.S., Harris, T., 2005. Icelandic jökulhlaup impacts: Implications for ice-sheet hydrology, sediment transfer and geomorphology. Geomorphology 75, 33–64.

Sigbjarnarson, G., 1967. The changing level of Hagavatn and glacial recession in this century. Jökull 17, 263–279.

Sigurdardottir, G.M., von Löwis, S., Bergson, B., Thorsteinsson, Th., Johannsson, Th., 2015. Measurements of volcanic aerosols during the Holuhraun eruption in Iceland. Geophys. Res. Abstracts 17, EGU2015-10597.

Sigurjonsson, H., Gisladottir, F., Arnalds, O., 1999. Measurements of eolian processes on sandy surfaces in Iceland. Rala Report 201, Agricultural Research Institute, Reykjavik, Iceland.

Steenburgh, W.J., Massey, J.D., Painter, T.H., 2012. Episodic dust events of Utah's Wasatch Front and adjoining region. J. Appl. Meteorol. Climatol. 51, 1654–1669.

Stout, J.E., Fryrear, D.W., 1989. Performance of a windblown-particle sampler. Trans. ASAE 32, 2041–2045.

Striberger, J., Björck, S., Holmgren, S., Hamerlik, L., 2012. The sediments of Lake Lögurinn – a unique proxy record of Holocene glacial meltwater variability in eastern Iceland. Quat. Sci. Rev. 38, 76–88.

Thorarinsdottir, E.F., Arnalds, O., 2012. Wind erosion of volcanic materials in the Hekla area, South Iceland. Aeol. Res. 4, 39–50.

Thordarson, T., Höskuldsson, A., 2008. Postglacial volcanism in Iceland. Jökull 58, 197–228.

Thorsteinsson, Tho., Björnsson, H., 2012. Climate Change and Energy Systems: Impacts, Risks and Adaptation in the Nordic and Baltic countries. Nordic Council of Ministers, Copenhagen, Denmark, p. 228.

Thorsteinsson, Thr., Gisladottir, G., Bullard, J., McTainsh, G., 2011. Dust storm contributions to airborne particulate matter in Reykjavík, Iceland. Atmos. Environ. 45, 5924–5933.

Thorsteinsson, Thr., Johannsson, T., Stohl, A., Kristiansen, N.I., 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. http://dx.doi.org/10.1029/2011JB008756.

UST, 2015. Air quality in Iceland. Umhverfisstofnun [The Environment Agency of Iceland]. URL: <http://ust.is/the-environment-agency-of-iceland/> (accessed Sep 26, 2015).

Vogel, A., Weber, K., Fischer, Ch., Pohl, T., von Löwis, S., Moser, H.M., 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., pp. 71–72.

Wang, J.X.L., 2015. Mapping the global dust storm records: review of dust data sources in supporting modeling/climate study. Curr. Pollut. Rep. 6, 1–13. http://dx.doi.org/10.1007/s40726-015-0008-y.

Weast, R.C., Selby, Hodgman, C.D., 1966. Handbook of Chemistry and Physics. Chemical Rubber Company, Cleveland, Ohio, p. 1856.

Weber, S., Kuttler, W., Weber, K., 2006. Flow characteristics and particle mass and number concentration variability within a busy urban street canyon. Atmos. Environ. 40, 7565–7578.

WHO, 2005. The World Health Organisation – Air Quality Guidelines Global Update 2005. Report on a Working Group meeting, Bonn, Germany 18–20 October 2005.

Wilson, T., Cole, J.W., Stewart, C., Cronin, S.J., Johnston, D.M., 2011. Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. Bull. Volcanol. 73, 223–239.

Yoshida, A., Moteki, M., Ohata, S., Mori, T., Tada, R., Dagsson-Waldhauserova, P., Kondo, Y., in press. Detections of light-absorbing iron oxide particles using a single-particle soot photometer. Aerosol Sci. Technol.