JOURNAL OF THE AIR & WASTE MANAGEMENT ASSOCIATION
2017, VOL. 67, NO. 2, 173–181
http://dx.doi.org/10.1080/10962247.2013.805703

TECHNICAL PAPER

Long-term dust aerosol production from natural sources in Iceland

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ABSTRACT
Iceland is a volcanic island in the North Atlantic Ocean with maritime climate. In spite of moist climate, large areas are with limited vegetation cover where >40% of Iceland is classified with considerable to very severe erosion and 21% of Iceland is volcanic sandy deserts. Not only do natural emissions from these sources influenced by strong winds affect regional air quality in Iceland ("Reykjavik haze"), but dust particles are transported over the Atlantic ocean and Arctic Ocean >1000 km at times. The aim of this paper is to place Icelandic dust production area into international perspective, present long-term frequency of dust storm events in northeast Iceland, and estimate dust aerosol concentrations during reported dust events.

Meteorological observations with dust presence codes and related visibility were used to identify the frequency and the long-term changes in dust production in northeast Iceland. There were annually 16.4 days on average with reported dust observations on weather stations within the northeastern erosion area, indicating extreme dust plume activity and erosion within the northeastern deserts, even though the area is covered with snow during the major part of winter. During the 2000s the highest occurrence of dust events in six decades was reported. We have measured saltation and Aeolian transport during dust/volcanic ash storms in Iceland, which give some of the most intense wind erosion events ever measured.

Icelandic dust affects the ecosystems over much of Iceland and causes regional haze. It is likely to affect the ecosystems of the oceans around Iceland, and it brings dust that lowers the albedo of the Icelandic glaciers, increasing melt-off due to global warming. The study indicates that Icelandic dust may contribute to the Arctic air pollution.

Implications: Long-term records of meteorological dust observations from Northeast Iceland indicate the frequency of dust events from Icelandic deserts. The research involves a 60-year period and provides a unique perspective of the dust aerosol production from natural sources in the sub-Arctic Iceland. The amounts are staggering, and with this paper, it is clear that Icelandic dust sources need to be considered among major global dust sources. This paper presents the dust events directly affecting the air quality in the Arctic region.

PAPER HISTORY
Received October 31, 2012
Revised May 9, 2013
Accepted May 9, 2013

Introduction

Iceland is a volcanic island in the North Atlantic Ocean with maritime climate, mild and moist winters, and cool summers. In spite of its moist climate, large areas are with limited vegetation cover where >40% of Iceland is classified as having considerable to very severe erosion and 21% of Iceland is volcanic sandy deserts (Arnalds et al., 2001). Not only do dust emissions from these natural sources influenced by strong winds affect regional air quality in Iceland ("Reykjavik haze"), but dust particles are transported over Atlantic Ocean more than 1000 km at times (Arnalds, 2010). Dust aerosol causes regional haze during or after dust events. Furthermore, Iceland is located in one of the main atmospheric transport pathways to the Arctic and dust pollution from natural sources is transported over northeast Iceland toward the Arctic Ocean (Rekacewicz, 2005). Globally, fine dust particles may be transported at altitudes of up to 6 km and can be carried distances of up to 6,000 km (Sivakumar, 2005). Dust is considered to contribute to the Arctic haze phenomena (Quinn et al., 2002).

The global dust belt, where most of the dust sources are located, extends from Africa, through the Middle East, into Central Asia (Formenti et al., 2011). In this study, the long-term frequency of dust events in Northeast Iceland is compared with major world arid regions such as in the United States (Steenburgh et al., 2012), Australia (Ekström, McTainsh, and Chappell, 2004), Mongolia (Natsagdorj, Jugder, and Chung, 2003), the northern part of Africa (N'TchayiMbourou et al., 1997), China (Qian, Quan, and Shi,' 2002), and Iran (Jamalizadeh et al., 2008). These papers show that

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long-term annual means of days with dust are about 150 days per year in the northern part of Africa, about 50 dust storm days in Australia, about 40 dusty days in Mongolia, up to 35 dust days in active regions of China, about 25 dusty days in Iran, and 4.3 dust events per year in Utah in the United States. Long-term dust activity was significantly greater during the 1950s and 1960s except in Africa and Mongolia. Dust observations were frequent in Mongolia, Africa, and Iran during the 1980s.

The World Health Organization presents annual a $PM_{2.5}$ concentration standard of 10 μg m^{-3} and an estimated visibility of 67 km to indicate health risk, or daily standard of 35 μg m^{-3} and visibility range of 31 km (WHO, 2005). In comparison, visual range can be more than 300 km in dry climates and 100 km in humid climates on clear days (Hyslop, 2009).

Meteorological observations in dust-source regions worldwide include continuous atmospheric dust and sand observations. Visibility is a parameter that is used as an important indicator of the severity of dust events where no in situ measurement of aerosol concentration is provided. Long-term visual observations of atmospheric dust are available in Iceland. Many of the manned weather stations are located downwind of major dust sources. These stations record conventional meteorological parameters, including visibility. Many of these stations have been in continuous operation for more than 60 years, and the data acquired at these stations are ideal for studying long-term variability in dust production and severity of historical dust events. The aim of this paper is to place Icelandic dust production areas into an international perspective, present long-term frequency of dust storm events in northeast Iceland, and estimate dust aerosol concentrations during reported dust events.

Methods

A network of eight weather stations in proximity to the dust sources for northeast Iceland was chosen for the study. Many of these stations, which are run by the Icelandic Meteorological Office, have been in continuous operation for more than 60 years. Figure 1 depicts the location of the stations at Akureyri, Egilsstaðir, Grimsstaðir, Raufarhöfn, Staðarholl, Vopnafjörður, Kollaleira, and additionally Hveravellir. Hveravellir is located on the notional border between northeast and southwest Iceland and is the only weather station in central Iceland. The data are stored at the Icelandic Meteorological Office after being submitted to strict quality control.

Meteorological observations with present weather (codes for dust observations) and related visibility were used to identify the frequency and the long-term changes in dust production in Northeast Iceland. Present weather refers to atmospheric phenomena occurring at the time of observation, or which has occurred preceding the time of

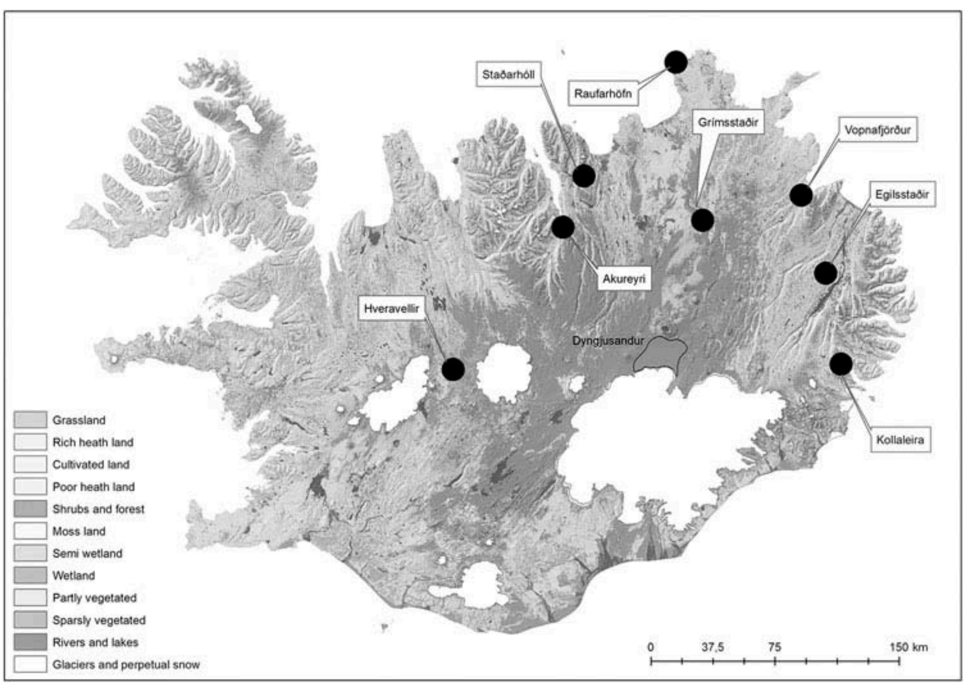

Figure 1. The locations of weather stations in northeast Iceland (Akureyri, Egilsstaðir, Grímsstaðir, Raufarhöfn, Staðarholl, Vopnafjörður, and Kollaleira) and station in central Iceland (Hveravellir). The major dust source for northeast Iceland is Dyngjusandur (marked red).

observation. In this study only atmospheric phenomena such as for "moldrok" (blowing soil/dust), "sandfok" (blowing sand/dust), "sandbylur" (extreme blowing sand/dust), and codes for dust haze, suspended dust, blowing dust, and dust whirls, are used and defined as a "dust observation." The synoptic codes (ww) for present weather that refer to dust observation are 7–9, 30–35, and 4–6 only if the codes for primary or secondary past weather (ww_1, ww_2) are 3 for blowing soil, dust, sand, and dust storm. At all stations, the weather is observed every day of the year three to eight times per day.

The initial data set was built from the occurrence of "dust observations" made at one or more weather stations. Long-term dust activity is expressed in dust days. "Dust day" is defined as a day when at least one station recorded at least one dust observation.

Unfortunately, dust aerosol measurements are not made in northeast Iceland and it is therefore necessary to estimate the concentrations based on visibility observations. Several methods have been developed to relate visibility with total suspended particle concentration. D'Almeida (1986) found a good correlation (r^2= 0.95) between horizontal visibility and PM_{10} in the 0.2 to 40 km range (shown in eq 1). This relationship was obtained during measurements with the Mainz sun photometer during Saharan sand storms in 1981–1982. In the present study, Aeolian dust concentrations were derived from eq 1 based on conversion between horizontal visibility and suspended particle concentration presented by D'Almeida (1986).

The aerosol dust concentration formula estimated from visibility and PM_{10} concentration is

$$PM_{10} = aV^{-b} + c \quad (1)$$

where PM_{10} is the particulate matter concentration in μg m^{-3}, V is the horizontal visibility in km, and a, b, and c are coefficients (a is set to 914.06, b is set to 0.73, c is 19.03).

Dust events were classified from visibility ranges (Table 1) based on criteria in Leys at al. (2011) and Wang et al. (2008). Dust events with visibility less than 500 m are often classified as "severe dust storms." This classification is used in the present study. Dust events with observed visibility above 10 km have been used in the literature to represent floating dust or suspended dust (Natsagdorj et al., 2003). In this study we classify a dust event in the visibility range 11–30 km as "suspended dust" and for the visibility range above 30 km it is called "moderate suspended dust."

Table 1. Dust event classification based on visibility categories; mean visibility of each dust class is calculated into PM_{10} concentration using the formula in D'Almeida (1986).

Dust event class	Visibility (km)	PM_{10} concentration (μg m^3)
Severe dust storm	≤0.5	19,753
Moderate dust storm	>0.5–1.0	10,062
Severe haze	>1.0–5.0	385
Moderate haze	>5.0–10.0	201
Suspended dust	>10.0–30.0	112
Moderate suspended dust	>30.0–70.0	67

Results and discussion

Frequency and temporal variability in dust production

There were annually 16.4 days on average with reported dust observations on weather stations in northeast Iceland in 1949–2011. This indicates extreme dust plume activity and erosion within the northeastern deserts, even though the area is covered with snow during the major part of the 6- to 8-month-long winter. Such an annual mean is similar to that found in Iran (Jamalizadeh et al., 2008), and more active than Utah (4.3 dust days/yr; Steenburgh et al., 2012), but much less frequent than in Africa north of the equator (up to 150 dust days/yr; N'TchayiMbourou et al., 1997).

The number of dust days for each decade from 1950 to 2010 is shown in Figure 2. The first decade of the 2000s had the highest occurrence of dust days in northeast Iceland and also in Iran (Jamalizadeh et al., 2008). Contrarily, the 1980s was the least active decade, which coincides with trends in the United States (Steenburgh et al., 2012), China (Qian et al., 2002), and Australia (Ekström et al., 2004). The most active decade, the first decade in the 2000s, has double the mean frequency compared to the least active decade, the 1980s. The occurrence of total "dust observations" is, however, the highest in the 1990s and during the first decade of the 2000s. In the long term, the most active periods were the 1950s and the period from the early 1990s until 2008. Worldwide peaks in dust production in the 1950s coincide with a period in northeast Iceland with higher temperatures and lower than average precipitation (Bjornsson and Jonsson, 2003). There was a significant drop in temperature in northeast Iceland in the late 1960s continuing through the 1970s. However, the annual temperature at inland stations reached values in the 1990s similar to those observed in the 1950s (Bjornsson and Jonsson, 2003), which correlates well with increased dust event frequency.

The mean visibility during all dust observations was 26.7 km (shown as the solid line in Figure 2). It was lowest during the 1980s, 20.8 km, and highest for dust observations during the 2000s, up to 44 km. Dust event visibility during the 1950s and the 1970s was about 22 km, 24 km in the 1960s, and 27 km in the 1990s. After the year 2000, there is the highest occurrence of dust

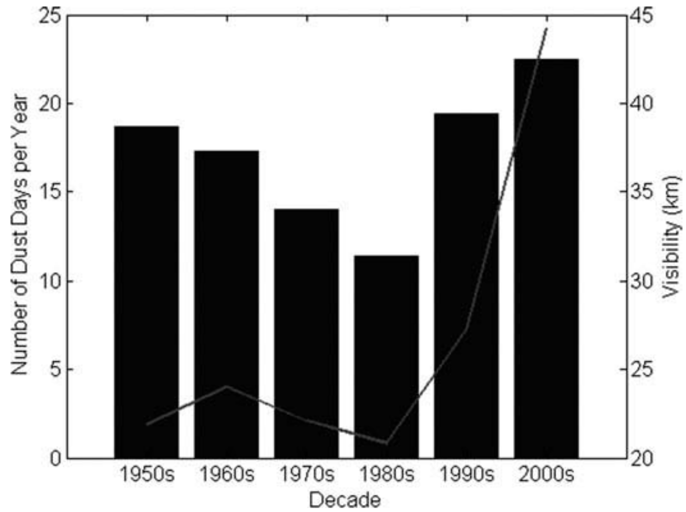

Figure 2. Total number of dust days per year in decade. Solid line represents mean visibility during the dust events.

days but reported dust event visibility is almost double compared to the other decades. Severe dust events occurred less frequently in the 2000s than during the decades 1950 to 1990 (see Figure 6, shown later).

In total, 1033 dust days were reported in Northeast Iceland during the six decades. The annual variability in the number of dust days is shown in Figure 3. The most active year was 1955, with 37 reported dust events with an average visibility of 23.2 km, about 3 km less than mean dust day visibility. The same year had also dust storm peak in the Tarim Basin, China, where 50 dust storms were recorded (Qian, Tang, and Quan, 2004). The year 1955 was calculated with the highest total dust flux in Utah in 1950–2010 by Steenburgh et al. (2012). The mean visibility during dust days varies and is notably low in 1954, 1972, 1974, and 1978. The lowest mean annual visibility during dust observations (12.8 km) was recorded in 1988 when dust events of high severity were observed. There was a severe dust event on June 18, 1988, which has been used to illustrate a severe dust storm, the so-called "June 88 storm" (Arnalds and Gisladottir, 2009). Generally, visibility during dust events increased during the first decade of the 2000s with a maximum in 2010.

Spatial variability in dust production

There is considerable variability between weather stations in the total number of dust observations recorded in northeast Iceland. The Grimsstaðir station has by far the greatest frequency of the eight weather stations, with 70% (1685 dust observations) of the total 2387observations over the 63 recorded years. Egilsstaðir counts 368 dust observations, followed by 132 observations at Hveravellir, and less than 100 observations at each of the other stations. The lowest number of dust days occurred in the 1980s but with more evenly spread observations between the weather stations. The Egilsstaðir station observed the

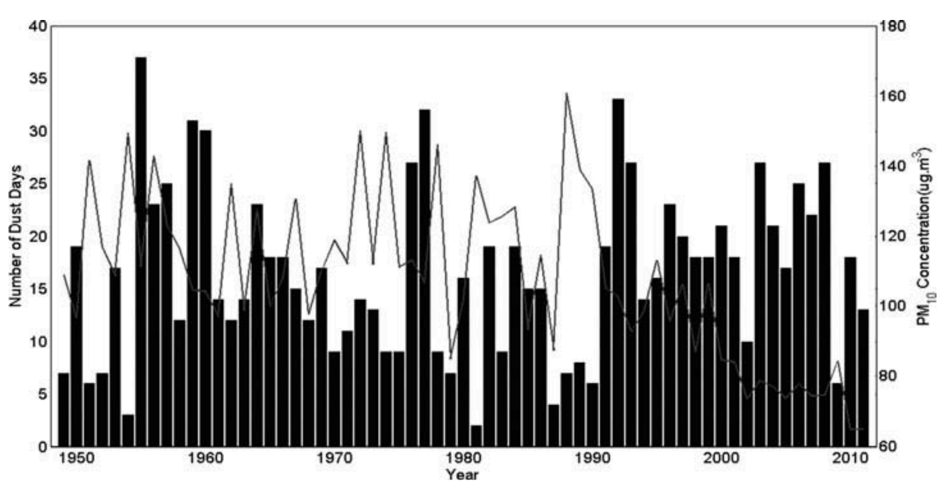

Figure 3. Number of dust days (bars) and calculated mean annual PM_{10} concentration from visibility during dust events (solid line).

most dust events in the 1980s, and the fewest events in the 1990s, but dust monitoring was discontinued there in 1998. Low occurrence of dust events in the 1980s coincides with low frequency of moderate or strong southerly winds (wind direction 100–280°). Only about 40% of all winds blew from southerly directions, which are the most frequent winds responsible for the majority of the dust events in northeast Iceland.

The highest frequency of dust observations is clearly at the inland stations, which are closer to the inland dust sources than the coastal areas. The Grimsstaðir station is the most active station, with more than 12 dust days reported annually. It is located in the vicinity of a local dust-source area and downwind from the Dyngjusandur dust plume source. The second is the Egilsstaðir station with almost 4 dust days annually. More than half of the stations observe <1 dust day annually. The average dust event visibility at these stations is about 25 km. The lowest dust event visibility was at the Raufarhöfn station. It is located at the open ocean and might be influenced by easier coagulation of dust particles and water (fog) droplets in humid areas.

Aerosol dust concentration

Aerosol dust concentration during dust events was estimated from visibility observation based on conversion between horizontal visibility and suspended particle concentration presented in a paper by D'Almeida (1986). Dust is expected to absorb weakly solar radiation, it scatters light, and it is coarse. However, Icelandic dust is of volcanic origin and the particles are darker than the Saharan dust studied by D'Almeida (1986). The optical properties of Icelandic volcanic dust correspond to stronger absorption and weaker scattering at longer wavelengths than the Saharan mineral dust (Weinzierl et al., 2012). As the optical properties of the volcanic dust in Iceland are not known and may differ considerably from properties of the Saharan dust, the present calculations of the dust loadings are associated with considerable uncertainties. Figure 3 depicts the mean annual PM_{10} dust concentrations during the dust events in northeast Iceland in 1949–2011. The maximum mean annual concentration of 160 μg $m^{-3}$was obtained in 1988 when dust events of high severity with annual mean visibility of 12.8 km were observed. Total median dust concentration of all dust events was calculated as 106 μg m^{-3} with maxima in May and September (122 μg m^{-3}). Mean dust concentration during dust events in northeast Iceland is 199 μg m^{-3}. Maximum mean with 805 μg m^{-3} is in April, the month that represents only 2% of total dust events. Highest frequency of the severe dust storms occurs also in September (37% of all severe dust storms) and May (21% of severe dust storms). Clearly, the highest median dust concentrations are confined to months with high dust event occurrence (Figure 4 and Figure 5).

Generally, visibility during dust events has doubled after 2000, and thus the calculated PM_{10} concentrations of dust events decreased (Figure 3). All the annual dust aerosol means exceeded the European guideline, which determines the limit value for health protection as 50 μg m^{-3} over 24 hr (http://ec.europa.eu/environment/air/quality/standards.htm).

Dust event classification

Most of the dust events during the study period were classified within the "suspended dust" class (46%) with

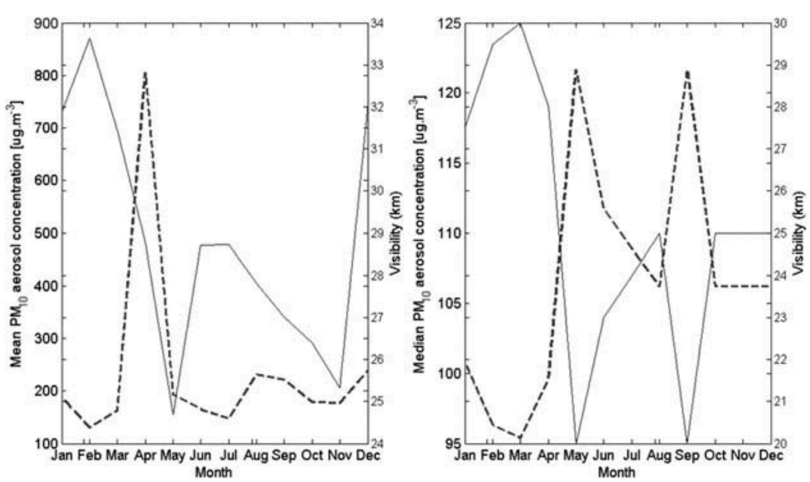

Figure 4. Mean (left) and median (right) dust concentration of dust events. Dashed line represents dust concentration and solid line shows visibility.

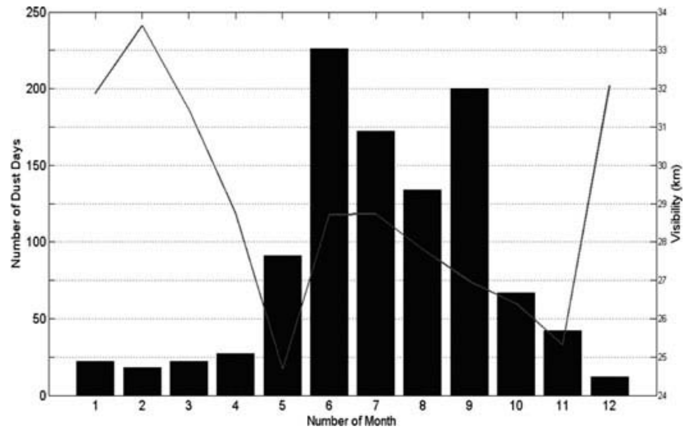

Figure 5. Number of dust days per month (bars) and monthly means of dust visibility (solid line) for the period 1949–2011.

visibility 10–30 km (Table 2). There were annually 10 events of suspended dust on average, 7 events of moderate suspended dust, and less than 3 events of higher severity (Table 2). Of all the dust events, about 13% (192 dust days) had visibility less than 5 km. The two dust storm classes (visibility 0–1 km) were most often recorded in the 1950s and the 1990s but only once observed in the 2000s (Figure 6). About 50% of dust events had visibility <10 km in the 1950s. In total, there were 14 severe dust storms from 1949 to 2011 (about 1% of dust events). Severe events are less frequent in northeast Iceland compared to Australia (20%; Ekström et al., 2004), but more often than in Utah where no severe dust storm was observed (Steenburgh et al., 2012). About 37 % of severe dust storms occurred in September, which is the month of highest median dust concentration during dust events (Figure 4).

Duration of dust events in northeast Iceland ranges from 1 day up to 7 days of continuous dust observations. About 70% of dust observations lasted 1 day or less, about 15% lasted 2 days, and 7% lasted for 3 days. More 2- and 3-day dust events were observed during the 1950s, but 7-day observations of moderately suspended dust were reported in the 2000s.

The Moderate Resolution Imaging Spectroradiometer (MODIS) flying on NASA's Terra satellite has captured many images of dust plumes blowing off the northern and northeastern coast of Iceland over the Arctic Ocean. Unfortunately, there are no clean pictures of severe or moderate dust storms without the cloud cover available. The most severe event captured by MODIS was the severe haze on September 17, 2008, which caused reduced visibility at the Grimsstaðir station for 7 days (Figure 7). The lowest visibility was observed as 1.5 km and mean wind velocity was about 19 m sec^{-1}. The visible part of the plume extended 350 km (solid line). For this event, the 3-day forward trajectory was calculated using the National Oceanic and Atmospheric Administration (NOAA) Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT), showing that air parcels originating in northeast Iceland moved northward and reached 1800 km in distance within 24 hr (NOAA, 2012). Fine dust particles could have been uplifted above the Greenland's ice sheet during the first day and travelled about 3,500 km through the Ellesmere Island to the Somerset Island within 3 days (Figure 8). Unfortunately, in situ measurements at Greenland's station Alert are not available for these dates.

Icelandic dust has been identified in ice-core samples in central Greenland (Drab et al., 2002). The prevailing winds of dust events in northeast Iceland are southerly (wind directions 130–250°). The major deposition area is over the Greenland Sea, and several trajectories of severe dust events were traced over Greenland and further into the Arctic. Dust deposition on snow or sea ice may affect the snow albedo and melting rate, while deposition over the sea may increase the ocean productivity. Chemical composition of Icelandic dust differs depending on the local dust sources. The Dyngjusandur source mainly corresponds to basaltic volcanic glasses formed below Vatnajökull glacier during subglacial eruptions (Baratoux et al., 2011). The major elements are SiO_2, Al_2O_3, Fe_2O_3, and CaO. The Dyngjusandur sediment

Table 2. Dust event classification based on visibility ranges; frequency and annual number of dust days are included.

Dust event class	Visibility (km)	Frequency (%)	Number of dust days/yr
Severe dust storm	≤0.5	<1	0.2
Moderate dust storm	>0.5–1.0	2	0.5
Severe haze	>1.0–5.0	10	2
Moderate haze	>5.0–10.0	13	3
Suspended dust	>10.0–30.0	46	10
Moderatd suspended dust	>30.0–70.0	27	7

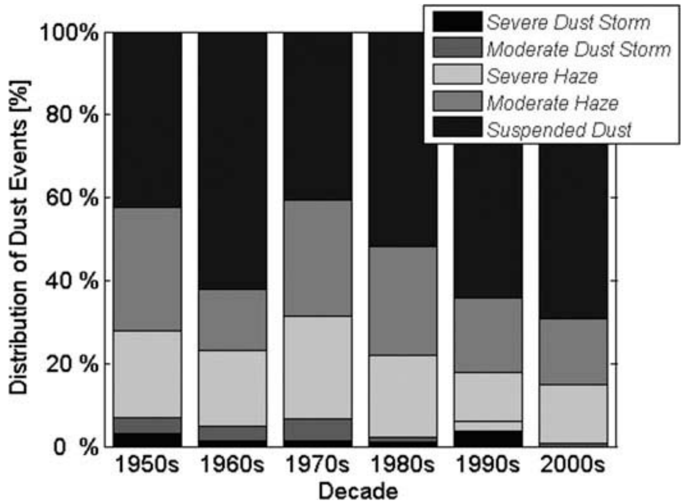

Figure 6. Distribution of dust event classes during decades in 1950–2010.

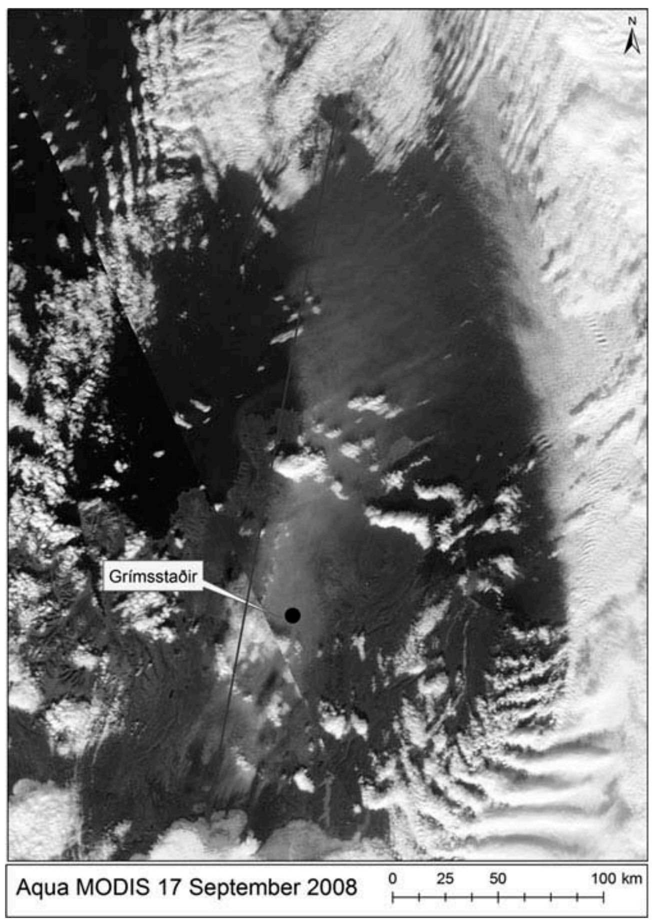

Figure 7. Severe haze blowing from Dyngjusandur and off the northern coast of Iceland over the Arctic Ocean on September 17, 2008 (NASA, 2012).

has little of quartz-rich materials but contains of more Al_2O_3, Fe_2O_3, and CaO than crustal dust. The higher iron content of the Dyngjusandur re-suspended sediments may be an essential micronutrient in marine biota in the Arctic Ocean. Frequent dust events in September may increase the ocean productivity, as the bloom ends in summer and productivity is known to be iron-limited (Prospero, Bullard, and Hodgkins, 2012).

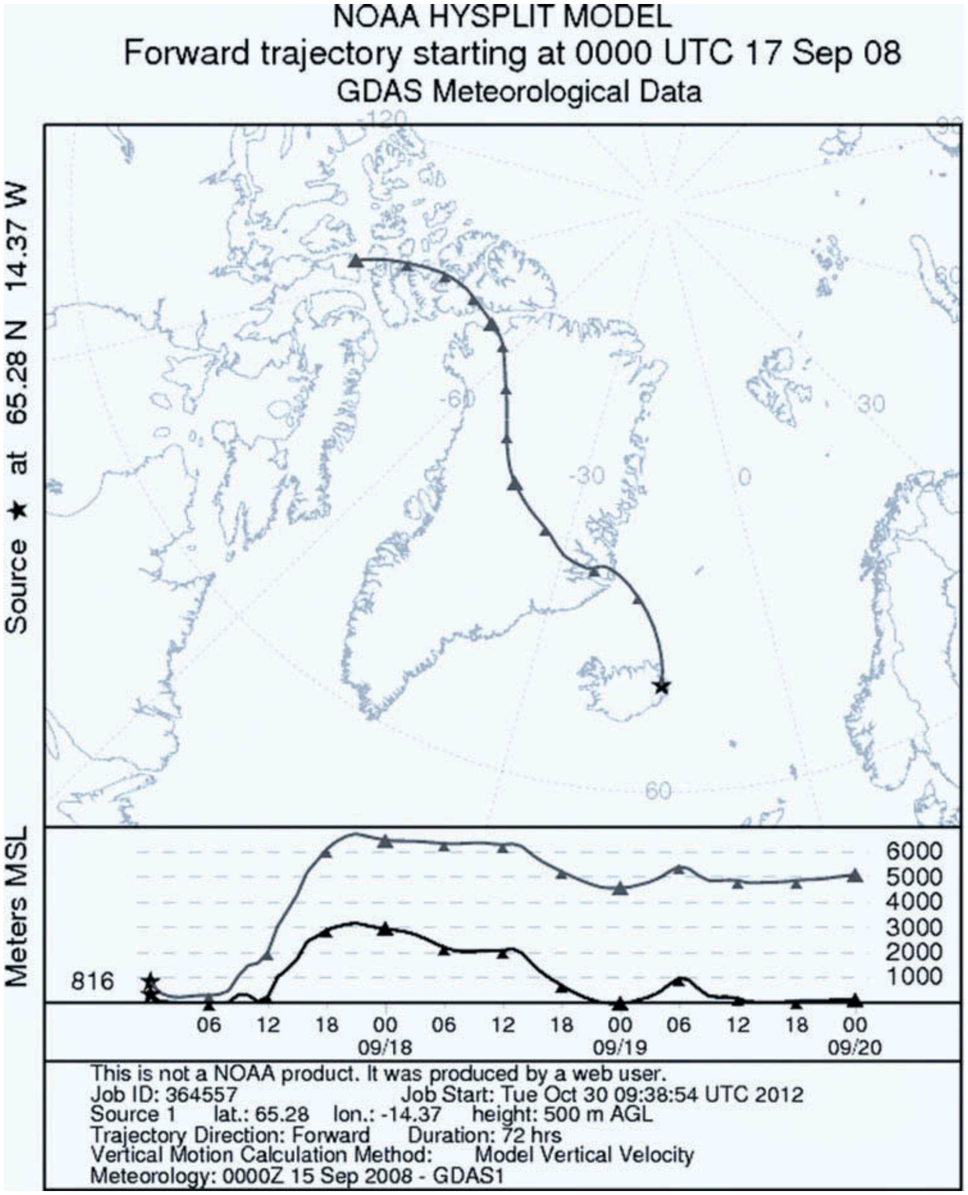

Figure 8. NOAA HYSPLIT 72-hr forward trajectory for air parcels released in northeast Icleand during the severe haze on September 17, 2008 (NOAA, 2012).

Recent changes in dust production

High severity and low visibility of dust events in the 1990s but the highest dust day frequency and high dust event visibility in the 2000s indicate changes in the environment of northeast Iceland. Such a trend could indicate that a large amount of material was transported during the 1990s but less material during the 2000s even though the frequency of dust days was higher. However, this could reflect lower availability of fine materials susceptible to dust production due to changes in the flow rate of the Jokulsa a Fjollum river in the 1990s and the 2000s, but the reason remains unclear. We found no significant correlation between high dust seasons and global climate drivers or any link to the local meteorological conditions. It is interesting to note that a volcanic ash deposited during the 2010 Eyjafjallajokull and 2011 Grimsvotn eruptions did not increase dust activity in Northeast Iceland (Figure 3). This shows that freshly deposited volcanic material is not the main source for dust mobilization in northeast Iceland during this period.

Conclusion

Dust affects the ecosystems over much of Iceland. The severity and frequency of dust events in northeast Iceland are comparable to many of the major dust areas of the world (Arnalds et al., 2013). There is great variability in the frequency of the dust events both within year and when measured by decade. The most active periods were the 1950s and the period from the early 1990s until 2008. The study indicates that Icelandic dust is not only a substantial source for regional air pollution, but may contribute to Arctic air pollution.

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