Long-term variability of dust events in Iceland (1949-2011)

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Abstract

Long-term frequency of atmospheric dust observations was investigated for the southern part of Iceland and merged with results obtained from the Northeast Iceland (Dagsson-Waldhauserova et al., 2013). In total, over 34 dust days per year on average occurred in Iceland based on conventionally used synoptic codes for dust observations. However, frequent volcanic eruptions with the re-suspension of volcanic materials and dust haze increased the number of dust events fourfold. Including such codes (04-06) into the criteria for dust observations, the frequency was 135 dust days annually. The position of the Icelandic low determined whether dust events occurred in NE (16.4 dust days annually) or in southern part of Iceland (about 18 dust days annually). The most dust-frequent decade in S Iceland was the 1960s while the most frequent decade in NE Iceland was the 2000s. A total of 32 severe dust storms (visibility < 500 m) was observed in Iceland with the highest frequency during the 2000s in S Iceland. The Arctic dust events (NE Iceland) were typically warm, occurring during summer/autumn (May–September) and during mild SW winds, while the Sub-Arctic dust events (S Iceland) were mainly cold, occurring during winter/spring (March–May) and during strong NE winds. About half of dust events in S Iceland occurred in winter or at sub-zero temperatures. A good correlation was found between PM_{10} concentrations and visibility during dust observations at the stations Vik and Storhofdi. This study shows that Iceland is among the dustiest areas of the world and dust is emitted the year-round.

1 Introduction

Frequency of dust episodes is monitored around many of the major desert areas of the world. Detailed and long-term studies on wind erosion variability can potentially explain the climatological and environmental changes in past. Periodical dust occurrences can affect ecosystem fertility and spatial and temporal distribution of animal and vegetation species similarly to climate variations (Fields et al., 2010). Oceanic ecosystems receive high amounts of nutrient rich dust spread over large areas where deserts occur near the sea (Arnalds et al., 2014). The long-term dust variability studies based on the meteorological observations present up to 90 years old records from North America, Africa, Asia and Australia (N´TchayiMbourou et al., 1997; Qian et al., 2002; Natsagdorj et al., 2003; Ekström et al., 2004; Jamalizadeh et al., 2008; Steenburgh et al., 2012). Engelstaedter et al. (2003) reported high dust activity at many weather stations located in high-latitude regions. Cold climate regions are represented by long-term dust frequency in Northeast Iceland (Dagsson-Waldhauserova et al., 2013). Dust emission intensity and deposition rates in active glacial environment have been found very high, in some cases far exceeding those in lower latitudes (Bullard, 2013). Ganopolski et al. (2009) calculated glaciogenic dust deposition > 50 $gm^{-2}yr^{-1}$ at the last glacial maximum with highest rates over the north-western Europe. Recently, the highest deposition rates of glaciogenic dust > 500 $gm^{-2}yr^{-1}$ are reported from Iceland (Arnalds, 2010, see also Bullard, 2013).

Dust events in Arctic/Sub-Arctic region have been observed in Alaska (Nickling, 1978; Crusius et al., 2011), Greenland (Bullard, 2013), Svalbard (Dornbrack et al., 2010) and Iceland (Arnalds, 2010; Prospero et al., 2012; Thorarinsdottir and Arnalds, 2012). Arctic coastal zones are considered as the windiest regions on Earth (Eldridge, 1980). Strong winds in Iceland are causing some of the most extreme wind erosion events recorded on Earth (Arnalds et al., 2013).

The highest dust emissions in Arctic regions are associated with summer and early autumn (Nickling, 1978; Bullard, 2013; Dagsson-Waldhauserova et al., 2013). Dust concentrations in Sub-Arctic regions peak in spring (April-June, Prospero et al., 2012). Cold and winter periods are, however, of higher glaciogenic dust deposition than warm periods (Ganopolski et al., 2009). Dust events are frequent during dry years (Steenburgh et al., 2012; Dagsson-Waldhauserova et al., 2013), but suspended dust has also been observed during high precipitation and low wind conditions (Dagsson-Waldhauserova et al., 2014).

Iceland is an important source of volcanic sediments that are subjected to intense aeolian activity (Arnalds, 2010; Prospero et al., 2012; Thorarinsdottir and Arnalds, 2012; Arnalds et al., 2013) and is likely the largest glaciogenic dust source area in the Arctic/Sub-Arctic region. Total emissions of dust from Icelandic dust sources are of the range 30 to 40 million tons annually with 5-14 million tons deposited annually over the Atlantic and Arctic Oceans (Arnalds et al., 2014). Seven major dust plume sources have been identified (Arnalds, 2010). These sources are all in vicinity of glaciers. The most active glacial flood plain, Dyngjusandur, covers an area of about 270 km^2 with up to 10 m thick sediments and is the main source for dust events in NE Iceland and towards Arctic (Dagsson-Waldhauserova et al., 2013). The major dust sources in South Iceland are Skeidararsandur, Myrdalssandur, Mælifellssandur, Landeyjasandur resulting in dust events south towards Europe during northerly winds, but alternatively towards Reykjavik and North America during easterly winds. The Hagavatn plume area is the source for frequent dust events passing Reykjavik and the ocean southwest of Iceland towards North America. Glaciogenic dust from the Mælifellssandur area contains fine sharp-tipped shards with bubbles and 80 % of the particulate matter is volcanic glass rich in heavy metals (Dagsson-Waldhauserova et al., 2014). Such physical properties of the particles allow rapid suspension of moist particles within only a few hours after rains. *In situ* measurements from other dust plume areas are not available.

Dust suspension is related to reduced visibility. Wang et al. (2008) found a good correlation between PM_{10} concentrations and visibility during dust observation. The visibility-dust formula can be used for dust concentration estimations where no aerosol mass concentration measurements are conducted (Dagsson-Waldhauserova et al., 2013). The relationship between dust concentration and visibility has not been investigated in Iceland.

The main objectives of this study were to explore the long-term (63 years) frequency of dust events in Iceland. Emphasis was given on determining the climatology and character of Arctic and Sub-Arctic dust events. In addition, the relationship between available dust concentrations and visibility during dust observation was investigated and the frequency of dust events placed in an international perspective.

2 Methods

2.1 Meteorological data and PM measurements

A network of 30 weather stations (15 in S Iceland, 8 in NE Iceland, and 7 in NW Iceland) operated by the Icelandic Meteorological Office was chosen for the study (Figure 1). Note the closer distance of the weather stations to the dust sources (red areas) in S Iceland than in NE Iceland. Table 1 shows the duration of station operation with majority of stations in operation since 1949. The data consist of conventional meteorological parameters such as wind velocity, wind direction, temperature and visibility, accompanied by synoptic codes of present weather. Present weather refers to atmospheric phenomena occurring at the time of observation, or which has occurred preceding the time of observation (IMO, 1981). The synoptic codes (ww) for present weather which refer to dust observation are 7-9, and 30-35. In addition, codes 4-6 are considered, but only if the codes for primary or secondary past weather (ww1, ww2) are 3 for blowing soil, dust, sand and dust storm (IMO, 1981; Dagsson-Waldhauserova et al., 2013). The weather reports on present weather (dust observation) and visibility were based on manually obtained observation by the observer at each station. Weather observations were made 3-8 times a day.

Meteorological observations (synoptic codes for dust including 04-06 and visibility) were evaluated with available particulate matter (PM) mass concentrations data provided by the Environmental Agency of Iceland (EAI). The PM_{10} data were obtained from the permanent station in Reykjavik (Grensasvegur, since 1996) and temporary stations in Vík and Kirkjubæjarklaustur (2010-2011). The Reykjavik station is equipped with Thermo EMS Andersen FH 62 I-R instrument, the Kirkjubæjarklaustur station with the Grimm EDM 365 and Thermo 5014 measured concentrations in Vik. Distance between the meteorological and EAI stations in Reykjavik and Kirkjubæjarklaustur is about one kilometer and several kilometers in Vík. Data set of dust concentrations (1997-2002, 2010) from the High-volume Filter Aerosol Sampler in Vestmannaeyjar (Westmann Islands) was used for evaluation of the dust codes and visibility at the Storhofdi station (Prospero et al., 2012). Daily dust concentrations were correlated with the minimum visibility during dust observations during the preceding 24 hours.

Most of the conventional dust studies do not include synoptic codes 04-06 for “Visibility reduced by volcanic ashes”, “Dust haze” and “Widespread dust in suspension in the air” into the criteria for dust observation (Dagsson-Waldhauserova et al., 2013). Comparing these codes with available dust concentration measurements showed that PM_{10} concentration > 41

μgm^{-3} (about a double mean concentration) was exceeded in about 80 % of the 04-06 code cases. We did not included these codes in this long-term dust day study except that the primary or secondary past weather (ww1 or ww2) was coded 3 for blowing soil, dust, sand and dust storm. We included the codes 04-06 in case of the PM_{10} concentration and visibility analysis (see Chapter 2.2).

2.2 Analysis

The initial dataset was built from the occurrence of "dust observation" made at one or more weather stations. Long-term dust activity was expressed in dust days. A "dust day" was defined as a day when at least one station recorded at least one dust observation. About 29% of the observations did not include information on the present weather and they were excluded from the dataset. Dust event (DE) refers to the dust observation.

Dust concentration measurements can be compared to the weather observations at few stations in South Iceland and for a short time period. For the stations where PM_{10} measurements were available, we applied a power regression to determine the relationship between dust concentrations and visibility during dust codes including 04-06 (methods detailed in Wang et al., 2008). Visibility during dust observation was used to classify the severity of dust events in past (Dagsson-Waldhauserova et al., 2013).

3 Results

3.1 Frequency, spatial and temporal variability in dust production

A mean of 34.4 dust days per year was observed in Iceland during the period 1949-2011. An annual mean of 16.4 dust days (total of 1033 days) was recorded in NE Iceland (Dagsson-Waldhauserova et al., 2013) and about 17.9 dust days (total of 1153 days) occurred annually in southern parts of Iceland in 1949-2011. Figure 2 shows that the most dust active decade in Iceland was the 1960s while the 1980s were the lowest in number of dust days. For the southern part of Iceland, the highest frequency of dust events was in the 1950s-1960s, whereas the 2000s was the most frequent decade in the NE Iceland. The Grimsstadir station (NE) is the dustiest weather observation location in Iceland with > 12 dust days annually. The following dusty stations with > 3 dust days annually are represented in Table 2: Hofn (S), Vatnsskardsholar (S), Egilsstadir (NE), and Hella (S). The stations with highest dust frequency in southern part of Iceland are described in Figure 2 (NE stations published in Dagsson-Waldhauserova et al., 2013a). The stations Hofn and Vatnsskardsholar reported highest number of dust days in the 1950s-1960s, the station Hella observed highest dust period in the 1960s-1970s and a new station in Hjardarland (established in 1990) was the most active in the 2000s. Dust events were less severe in the 2000s than in the 1950s-1990s reflected by increased visibility during dust observations. Mean visibility during dust observations in S Iceland was 23.3 km indicating more severe dust events in S than in the NE Iceland (mean DE visibility 26.7 km) or that weather stations in S Iceland are closer to major dust sources. Including codes 04-06 into the criteria for dust observation, the annual mean dust-day frequency was 135 dust days with 101 dust days observed in S Iceland and 34 dust days in NE Iceland.

3.1.1. Annual and seasonal dust day variability

An annual number of dust days in 1949-2011 is depicted in Figure 3. The dustiest years were 1955, 1966 and 2010, when over 55 dust days occurred annually. The least dusty period was 1987-1990 with 11-15 dust days annually. Dust events occurred more frequently in southern part of Iceland than in NE Iceland in 1949-1954, 1962-1975, 1978-1981, and 2009-2011. The NE dust events were observed more often in 1955-1961, 1976-1977, 1982-1986, and 1992-2008 (except 1994, 2003). There is a trend of having either the south or the north more active at a given time. Dust events observed in south cost of Iceland and NE Iceland usually do not occur the same dust day. The years with relatively severe dust events (and annual visibility during dust observations < 15 km) were 1949, 1966, 1975, 1996, and 1998.

The seasonal distribution of dust days in southern part of Iceland showed that about 47 % of dust events occurred in winter (Nov-March) or during sub-zero temperatures. Dust days, as shown in Figure 4, were most often in May (18 % of dust days), April (13 %) and March (11%). The lowest occurrence of dust days (< 6 %) was in January, December, August and September. Contrarily, dust events in NE Iceland occurred mainly in summer and early autumn (May-September, Dagsson-Waldhauserova et al., 2013).

3.2 Climatology of dust events

3.2.1. Long-term trends in meteorological parameters of dust events (DE, see Chapter 2.2)

The mean DE temperature in southern part of Iceland was 3°C with minimum 1.4°C in the 1960s and maximum 5°C in the 2000s (Figure 5A). There was a great variability in DE temperatures, especially during the most active dust decade, the 1960s. The DE were the coldest in NE Iceland during the 1960s as well, but the warmest DE period was the 1950s (Dagsson-Waldhauserova et al., 2013). The mean DE temperature in the NE was significantly higher than in S Iceland, about 10.5°C. The temperature differences are only related to dust observation because the mean annual temperature in South Iceland (T = 4.7°C) is higher than mean annual temperature at the North stations (T = 1.5 °C).

Dust observations in S Iceland reported high mean DE wind velocity of 13.6 ms^{-1}, where the maximum mean of 15.6 ms^{-1} was during the 1980s and the minimum of 11.9 ms^{-1} during the 2000s (Figure 5B). Extreme DE winds exceeding 30 ms^{-1} occurred mainly in the 1960s and the 1970s. The mean DE wind velocity in NE Iceland was 10.3 ms^{-1} with the maximum of 11.9 ms^{-1} during the 2000s and the minimum of 8.6 ms^{-1} in the 1980s (Dagsson-Waldhauserova et al., 2013).

The most common wind direction during dust events in S Iceland was N-NE, mainly reported from the stations Höfn, Hella, Vatnsskardsholar, Kirkjubaejarklaustur, Storhofdi, Eyrarbakki, Vik, Thingvellir, Hjardarland, Keflavik, and Reykjavik (Figure 6). Dust events were often observed from the wind direction ENE (Haell, Vatnsskardsholar), E-ESE (Storhofdi, Vatnsskardsholar, Thingvellir, Reykjavik, Keflavik), NW-NNW (Höfn), and W-WNW (Vatnsskardsholar). The DE wind directions in NE Iceland were predominantly SW-S and SSE-SE (Dagsson-Waldhauserova et al., 2013).

3.2.2. Seasonal patterns in meteorological parameters of dust events

Seasonal variability in temperature and wind velocity during dust events in S Iceland is depicted in Figure 8. The DE mean temperatures in October-May period are several degrees lower than the long-term monthly temperatures (higher in June-August period). Generally, the DE temperature in S Iceland was about 1.7°C lower than the long-term mean. Contrarily, the DE temperatures in NE Iceland were about 3°C higher than monthly long-term temperatures (Dagsson-Waldhauserova et al., 2013).

The DE wind velocities were significantly higher (5-11 ms^{-1}) than long-term monthly wind velocities (Figure 8B). The highest DE winds in S Iceland were from December to April while the lowest DE winds occurred in summer (June-September). This corresponds to the long-term monthly wind velocity trends. The mean DE wind velocity was 7.7 ms^{-1} higher than long-term mean wind velocity. The difference was most pronounced during the winter months. The predominant winds during months of frequent dust events were NE and NNE winds in March and April (Figure 7). The DE winds in May were also N and NE winds, but high proportion of E and ESE winds occurred during dust events. In NE Iceland, the DE winds were about 4-7 ms^{-1} higher than long-term means with maxima in May and September-October (Dagsson-Waldhauserova et al., 2013). Generally, the DE winds were about 3 ms^{-1} lower in NE than S Iceland.

3.2.3 Dust event classification and meteorology

Reported dust events were of different severity. Where no atmospheric dust measurements are available, visibility during dust observation is used to estimate the dust event severity. Table 2 describes the dust event classes based on the visibility ranges. The most frequent were dust observations of “Suspended” and “Moderate suspended dust” (NE 73%; S 59%) with visibility 10-70 km, “Severe” and “Moderate haze” (NE 24%; S 32%) with visibility 1-10 km, and “Severe” and “Moderate dust storm” (NE 3%; S 5%) with visibility < 1 km. There were 32 “Severe Dust Storms“ (visibility < 500 m) observed in Iceland (14 in NE mostly in the 1950s, 18 in S mostly in the 2000s).

The DE severity increased with the DE wind velocity, but the DE temperature decreased with the DE severity, except for “Moderate dust storm“ recorded mostly at the Vik station in S Iceland (Table 2). The parameters show that dust events in southern part of Iceland were observed as more severe than in NE Iceland.

Most of the dust classes in S Iceland occurred in April and May. Severe dust storms were most frequent in March and January at Vik, Hella, Kirkjubæjarklaustur, Hæll, Eyrarbakki and Vatnsskardsholar stations. The station Vik located only about 10 km from the Myrdalssandur dust source reported the mean DE visibility of 2 km indicating very severe dust events. Following stations with the lowest mean DE visibility were Raufarhofn (NE, 15 km), Höfn (18.3 km), Kirkjubæjarklaustur (20.1 km), Storhofdi (20.4 km), and Hella (21.1 km). The highest mean DE wind velocity was measured at the most windy station Storhofdi (22.6 ms^{-1}) while the lowest mean DE winds were at the station Thingvellir. Thingvellir recorded also the highest mean DE temperature (8.5°C) in S Iceland. The lowest DE temperatures were in Höfn (-2.3°C) located downwind Vatnajökull glacier.

About 18 % of dust events in S Iceland were observed at more stations in the same time (two stations: 12.5 %, three stations: 3.4%, four or more stations: 1.5%). Dust co-observations were mostly in Kirkjubæjarklaustur and Höfn, Kirkjubæjarklaustur and Vatnsskardsholar, and Kirkjubæjarklaustur with Hella. The Reykjavik station observed dust together with Hella or Thingvellir.

3.3 Relationship between PM_{10} concentrations and visibility

Hourly PM_{10} concentrations were compared with corresponding visibility data during dust observations at available stations. Higher correlation between dust concentration and visibility by power function fitting was found at the station Vik (R^2=0.73, n=13) and Vatnsskardsholar (R^2=0.48, n=219, Fig. 9A and B) than at the stations Reykjavik and Kirkjubaejarklaustur (R^2<0.3, n_{REYK}=204, n_{KIRK}=51). Weak relationship between PM_{10} concentrations and visibility during dust codes (R^2<0.3) was found at the stations Reykjavik and Kirkjubaejarklaustur. Figure 9C shows visibility of all available dust codes plotted against corresponding PM_{10} concentrations together at all stations. Power function analysis resulted in moderate correlation (R^2=0.37, p<0.01). Daily dust concentrations from the High-volume Filter Aerosol Sampler at Storhofdi during 1997-2002 and 2010 were well correlated with the 24-hour minimum visibility (R^2=0.71, Figure 9D).

4 Discussion

An annual mean of 34 dust days recorded in Iceland is comparable to dust studies from the active parts of China (35 dust days yr^{-1}, Qian et al., 2002), Mongolia (40 dust days yr^{-1}, Natsagdorj et al., 2003), and Iran (Jamalizadeh et al., 2008). The synoptic coding protocols can, however, contribute up to 15 % underestimation of annual dust day number (O´Loingsigh et al., 2010). Moreover, synoptic codes 04-06 showed a good agreement with increased PM_{10} concentrations (about 80 % of these codes matched elevated PM_{10}). Including these codes into the criteria for dust observation, the annual mean dust-day frequency would be fourfold higher than applying conventionally used dust codes for crustal deserts. This results in a total of 135 dust days per year on average for Iceland with 101 dust days observed in S Iceland and 34 dust days in NE Iceland. Such high frequency shows that active volcanic and glacial deserts, such as Iceland, differ to the crustal deserts, because of permanent input of volcanic materials, frequent re-suspension of these materials and the climatic effects of glaciers causing strong downslope winds. High numbers of dust observations presented here reflect previous studies showing high dust deposition rates in Iceland (Arnalds, 2010; Prospero et al., 2012; Thorarinsdottir and Arnalds, 2012; Bullard, 2013; Arnalds et al., 2013; Arnalds et al., 2014) and places the country among the important dust production areas of the world. Iceland is likely the most largest and active high-latitude cold dust source.

Trends in global dust emissions show high dust frequency during the 1950-1960s and low frequency during 1980s in the USA, Australia and China as well as in Iceland (Steenburgh et al., 2012; Ekström et al., 2004; Qian et al., 2002). The 2000s were reported as the most active decade in Iran and in NE Iceland (Jamalizadeh et al., 2008). Dust periods retrieved from the ice-cores data during GISP2 project in Greenland correlate with the NE Iceland dust frequency 1950-1990 (Donarummo et al., 2002).

Generally, the period 1950-1965 was warm and dry in Iceland resulting in frequent dust suspension (Hanna et al., 2004). For the NE Iceland, the dustiest year 1955 with 37 dust days, coincides with one of the warmest and driest years in NE Iceland (Hanna et al., 2004). For the southern part of Iceland, the most frequent and severe dust event period was during 1965-1968. It was a period of below-average precipitation reported at stations Reykjavik, Stykkisholmur and Vestmannaeyjar (Hanna et al., 2004) while the 1965 was the driest year in SW Iceland for the past 100 years. The 20th century warm period in Iceland (1920s-1965) ended very abruptly in 1965 with about 1°C drop in mean annual temperature (Hanna et al., 2004). The most exceptional year was, however, the year 1966 with 40 dust days reported in S Iceland. Not only was October 1966 reported as the driest October in Icelandic history, but also February 1966 in Reykjavik. Together with extremely strong maximum winds of more than 40 ms^{-1}, the meteorological conditions in February 1966 caused at least 11 days of extremely severe dust storms. Local newspaper reported several large roofs removed from the houses, ships tore away from the harbors and planes turned around (Morgunblaðið, 1966).

The seventies were cold with high precipitation, but strong winds were often observed in S Iceland bringing the dust into suspension. The 1980s and 1990s were cold and with high precipitation in S Iceland while the 1990s were warm in the NE (Hanna et al., 2004). High frequency of dust events in NE Iceland during the 2000s was associated with dry and warm Junes. High number of dust days in S Iceland in 2010 was often because of re-suspension of volcanic ash from the Eyjafjallajökull eruption during very frequent northerly winds (Petersen et al., 2012). The annual differences in dust event frequency do not correspond to trends of the global climate drivers such as the North Atlantic Oscillation (NAO), the Arctic Oscillation or prevailing ocean currents (Dagsson-Waldhauserova et al., 2013). The main driver is likely an orthogonal pattern to NAO, the dipole of Sea Level Pressure (SLP) oscillation oriented east-west (Dagsson-Waldhauserova et al., 2013).

The position of the Icelandic low determines whether dust plumes travel in a northeast or southerly direction. Strong winds in Iceland are almost always associated with extratropical cyclones with strong precipitating systems (fronts). Under such circumstances, there is, in general, only dry weather on the downstream side of the central highlands of Iceland, and this is where the dust is suspended. Higher frequency and severity of DE (low visibility and high wind speeds) in S Iceland than in NE Iceland is likely due to the close proximity of the S stations to the dust sources, higher number of major dust sources, as well as higher number of the stations in the South (Figure 1, Table 2). The Grimsstadir station (NE) is > 100 km from the Dyngjusandur source while the southerly stations are in range of tens of km from the sources. Dust deposition rates and DE severity decrease exponentially with distance from the source (Arnalds et al., 2014). This may lead to underestimation of dust events in S Iceland because the stations, located close to the sources, are not able to capture fully developed dust plume, but only the initiation part of the plume, extending several km in width. The dustiest weather station, Grimsstadir, is located at great distance downwind of the most active glacial plain in Iceland, Dyngjusandur, N of the Vatnajokull glacier, and it captures high number of dust events. On the other hand, many dust events occurring are not detected, as dust is often blown directly to sea from the sources close to the southern coastline (Myrdalssandur, Skeidararsandur). However, the most active stations are equally distributed around the areas with very high dust deposition (Arnalds, 2010) from the central NE, SE, S to SW Iceland. The land reclamation activities from the 1950s and 1970s (Crofts, 2011) resulted in decreased dust activity at the stations Hella and Höfn (Figure 2).

The local dust sources in S Iceland are also affected by milder oceanic climate during the winter while the NE highland dust sources are covered by snow for much of the winter. The DE temperatures were higher in NE Iceland than S Iceland as the events occur during summer-autumn and warm geostrophic southerly winds that cause the dust events in NE Iceland. Table 2 shows low DE temperatures in S Iceland, which point to frequent winter-spring dust occurrence and cold strong northerly winds causing dust events in S Iceland. The mean wind speeds are variable each month in S and NE Iceland. In S Iceland, the highest wind speeds were related to the winter months and April, while in the NE Iceland, the windiest months were May/June and September. All these months of high winds correlate with high dust frequency. The northerly winds, that caused dust events in S Iceland, were stronger than the winds in NE Iceland, which affects the results in Table 2.

The visibility during dust observations reflects the severity of the dust events. There is an increasing trend in DE visibility through the decades with the maxima in NE as well as S Iceland in the 2000s (Fig. 2). However, most of the severe dust storms with visibility < 500 m occurred in S Iceland in the 2000s. These severe dust storms were related to frequent re-suspension of volcanic ashes at the station Vik, located downwind the Eyjafjallajokull volcano, in 2010. The increase in dust frequency in the 2000s was coincident with dust visibility increase. The 2000s was a warmer decade in Iceland compared to the previous decades, 1970s-1990s. This may indicate less availability of fine materials susceptible to dust production determined by changes in flow rate at major glacial rivers in the 2000s, but the reason remains unclear.

The seasonal distribution of dust events in Iceland shows that the high dust period is from March to October. The NE dust events are typically warm, occurring during summer/autumn (May-September) while the S dust events are mainly cold, occurring during winter/spring (March-May). This is related to the SLP pattern which controls the warm southerly winds in NE Iceland as well as the cold northerly winds in S Iceland (Bjornsson and Jonsson, 2003). The S dust events were, however, more equally distributed during the year. The winter season is related to mild temperatures and high winds in S Iceland. Relatively high mean dust concentrations were measured during winter (Jan-March) at station Storhofdi (Prospero et al., 2012). The winter cold dust storms were frequently observed also in Mongolia (Natsagdorj et al., 2003). The highest number of dust storms occurred in March-May while the mean March-April temperatures were sub-zero. The predominant winds during dust events were NE and NNE winds in March and April, when the mean wind speeds were about 15 m s^{-1}. The DE winds in May were also frequently N and NE winds, but high proportion of E and ESE winds occurred during dust events. In May, the wind speeds were lower than in March and April, but the high dust occurrence was likely caused due to the dry conditions. May is the driest and dustiest month in Iceland while June and September are the driest months only in NE Iceland (Hanna et al., 2004; Dagsson-Waldhauserova et al., 2013). The DE wind speeds in S Iceland decreased further during the summer/autumn as well as summer months were typically with high precipitation. This trend was followed by rapid decrease in dust frequency from June to September in S Iceland (Figure 4).

The processes responsible for dust events in Iceland are several. The main drivers were strong winds during periods of low precipitation, enhanced by limited water holding capacity of the materials and rapid drying, hence the dark colour of the surfaces. Dust events in NE Iceland occur mainly during summer when the highland dust sources are snow-free, under relatively mild temperatures, while in S Iceland, the dust events occurred also during very low and sub-zero temperatures. Nevertheless, dust events can be observed also during high precipitation seasons < 4 hours after the rain (Dagsson-Waldhauserova et al., 2014). This agrees that even the highest precipitation year such 1972 can be of relatively high dust frequency. The majority of dust events reported in this long-term study were observed during strong winds.

Visibility during dust observations is an important indicator of dust event severity. To estimate the empirical relationship between visibility and dust concentration in Iceland, we compared available PM_{10} concentrations with visibility based on methods in Wang et al. (2008). We found moderate correlation (R^2=0.37, p<0.01) between dust concentrations and visibility which was likely caused due to several factors: i) visibility was observed manually and only the prevailing visibility (φ>180°) recorded; ii) generally low number of measurements, iii) the stations were located in different distance of each other, iv) time resolution between the dust and weather measurements, and v) station Reykjavik with majority of the measurements was influenced by anthropogenic aerosols. More observations are therefore needed to obtain large dataset for further quantitative analyses including estimation of extinction coefficients from the PM_{10} mass concentrations based on the mass scattering efficiencies to be investigated in detail (Hand and Malm, 2007).

The relationship between available PM_{10} concentrations and visibility during dust events showed lower PM_{10} concentrations for low visibilities (< 1 km) than expected (see calculations in Dagsson-Waldhauserova et al., 2013). Icelandic data, similarly as the Australian data from the Red Dawn dust storm (Leys et al. 2011), consist of relatively high number of PM measurements of low dust visibilities (< 500 m). Contrarily, PM measurements of such low dust visibilities are rare in the Chinese study (Wang et al., 2008). The power function calculated for the PM concentration and visibility in the Chinese study resulted in extremely high concentrations for low dust visibilities in steppe areas. The calculated PM concentrations from visibility in NE Iceland were partly estimated from these steppe areas and therefore overestimated (Dagsson-Waldhauserova et al., 2013). The first results here, based on the fit functions between the visibility and PM_{10} concentrations from Southern Iceland, were comparable to the PM concentrations during dust event conditions on Australian sand plains, sandy areas of the Taklimankan Desert and marginal parts of the Gobi Desert (Wang et al., 2008; Leys et al., 2011).

This study on long-term dust frequency showed considerably high dust day frequency in volcanic and glacial deserts of Iceland. Several dust plumes, captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) at the Terra satellite, exceeded 1000 km travelling towards Europe, North America and Arctic. Further, it was calculated that dust is deposited over 370 000 km^2 oceanic area around Iceland, carrying 6–14 million tons of dust (Arnalds et al., 2014). The dust contains high amounts of bioavailable iron. Our data showed that the majority of the dust is transported in early spring in southern parts of Iceland. Oceanic biochemical cycles and productivity might therefore be affected by local aeolian processes. We also emphasize here that high dust event frequency and long-range transport of Icelandic dust may affect the environment and climate on macro scale. Icelandic dust aerosol should be included in climate projections as well as in the European and Arctic air pollution studies.

5 Conclusions

This study of long-term dust observations in Iceland showed that dust-day frequency in Iceland can be comparable to the major desert areas in the world. It was found that dust events often occurred during winter and at sub-zero temperatures. Observed dust events were more severe in southern part of Iceland than in NE Iceland, most likely because of close proximity of the southerly weather stations to major dust sources. The highest frequency of dust events was during the 1960s in S Iceland while most of dust events in NE Iceland occurred during the 2000s. The highest number of severe dust storms (visibility < 500 m) was observed in southern part of Iceland during the 2000s. Monitoring dust frequency in active volcanic and glacial deserts requires including synoptic codes for “Visibility reduced by volcanic ashes” and “Dust haze” into the criteria for dust observation. There was a moderate correlation found between available PM_{10} concentrations and visibility during the dust observations in Iceland. More synchronised dust and weather measurements are therefore needed. Iceland can be considered as the largest and most active desert and dust source at the boundary of the Arctic and Sub-Arctic region.

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Table 1. Weather stations in Iceland reporting synoptic observations. Observation period, number of dust observations, dust days and dust days per year are included. Stations are listed in descending order from the highest number of dust days.

Station	Observation period	Dust days	Dust observations	Dust day yr^{-1}
Grimsstadir	1949-2011	791	1685	12.6
Hofn	1949-2011	243	575	3.9
Vatnsskardsholar	1949-2011	234	408	3.7
Egilsstadir	1949-1998	192	386	3.8
Hella	1958-2005	179	368	3.7
Kirkjubaejarklaustur	1931-2011	158	274	2
Storhofdi	1949-2011	118	204	1.9
Haell	1949-2011	94	132	1.5
Hveravellir	1965-2004	91	124	2.3
Eyrarbakki	1957-2011	80	120	1.5
Vik	1961-2011	76	96	1.5
Keflavik	1952-2011	68	96	1.1
Vopnafjordur	1961-2011	64	83	1.3
Thingvellir	1949-1984	56	81	1.6
Reykjavik	1949-2011	41	70	0.7
Raufarhofn	1949-2011	41	61	0.7
Hjardarland	1990-2011	38	56	1.7
Sidumuli	1949-2011	30	37	0.5
Akureyri	1949-2011	26	26	0.4
Galtarviti	1953-1994	15	16	0.4
Stadarholl	1961-2011	12	15	0.2
Stykkisholmur	1949-2011	9	13	0.1
Reykholar	1961-2004	8	9	0.2
Kollaleira	1976-2007	5	7	0.2
Blonduos	1949-2003	5	6	0.1
Natabu	1949-2004	3	4	0.1
Blafeldur	1998-2011	2	2	0.1
Bergstadir	1978-2011	2	2	0.1
Hornbjargsviti	1949-2004	1	1	0.02
Reykir i Hrutafj.	1997-2011	1	1	0.1

Table 2. Dust event classification based on visibility criteria. Frequency of dust events, mean wind velocity, mean temperature, and annual number of dust days of each dust class are included. S represents southern part and NE northeastern part of Iceland.

Dust event class	Visibility (km)	Frequency (%)		Wind velocity (ms^{-1})		Temperature (°C)		Number of dust days yr^{-1}	
		S	NE	S	NE	S	NE	S	NE
Severe dust storm	≤0.5	1.2	< 1	15.7	16.2	-1.7	8.4	0.3	0.2
Moderate dust storm	0.5-1.0	3.5	2	13.6	14.9	4.1	9.4	1.1	0.5
Severe haze	1.0-5.0	14	10	15.0	13.0	1.1	10.6	3.0	2
Moderate haze	5.0-10.0	17	13	14.7	11.3	1.7	10.9	4.1	3
Suspended dust	10.0-30.0	42	46	13.5	9.9	3.0	10.6	10	10
Moderate susp. dust	30.0-70.0	16	27	11.7	10.2	3.7	10.0	6	7

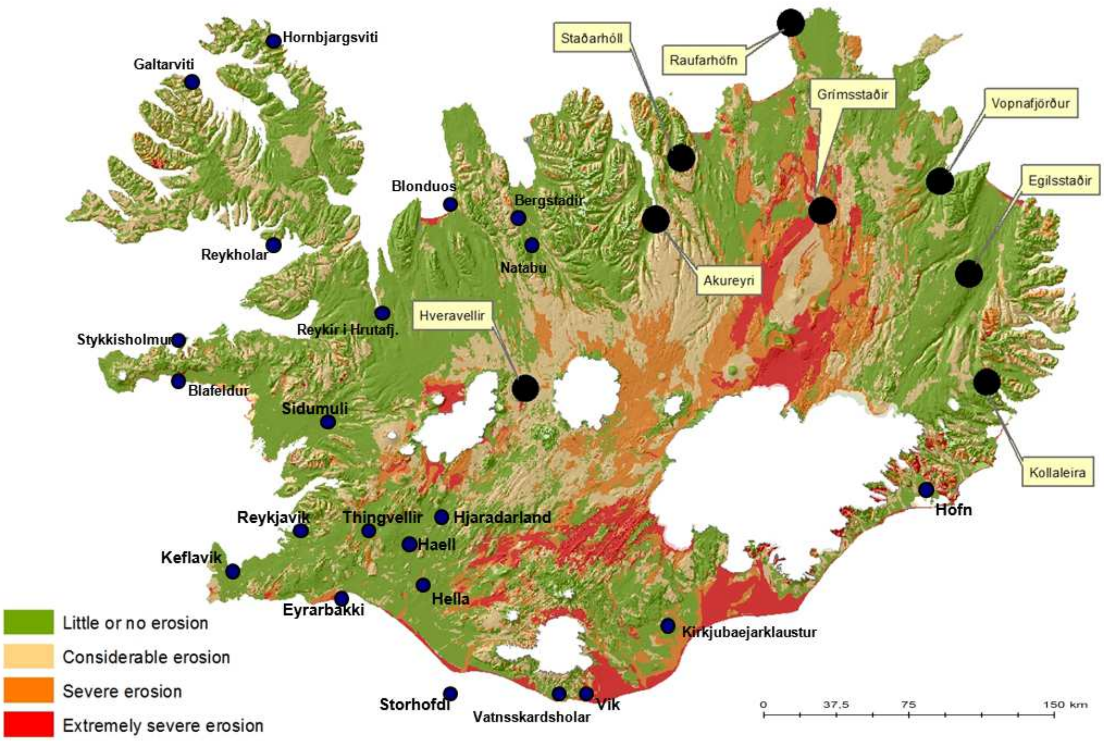

Figure 1. A map showing the locations of weather stations in Northeast and central Iceland (large black circles) and stations in the northwestern and southern part of Iceland (small circles). The red areas depict the major dust sources in Iceland. Base map from the Agricultural University of Iceland Erosion Database (Soil Erosion in Iceland).

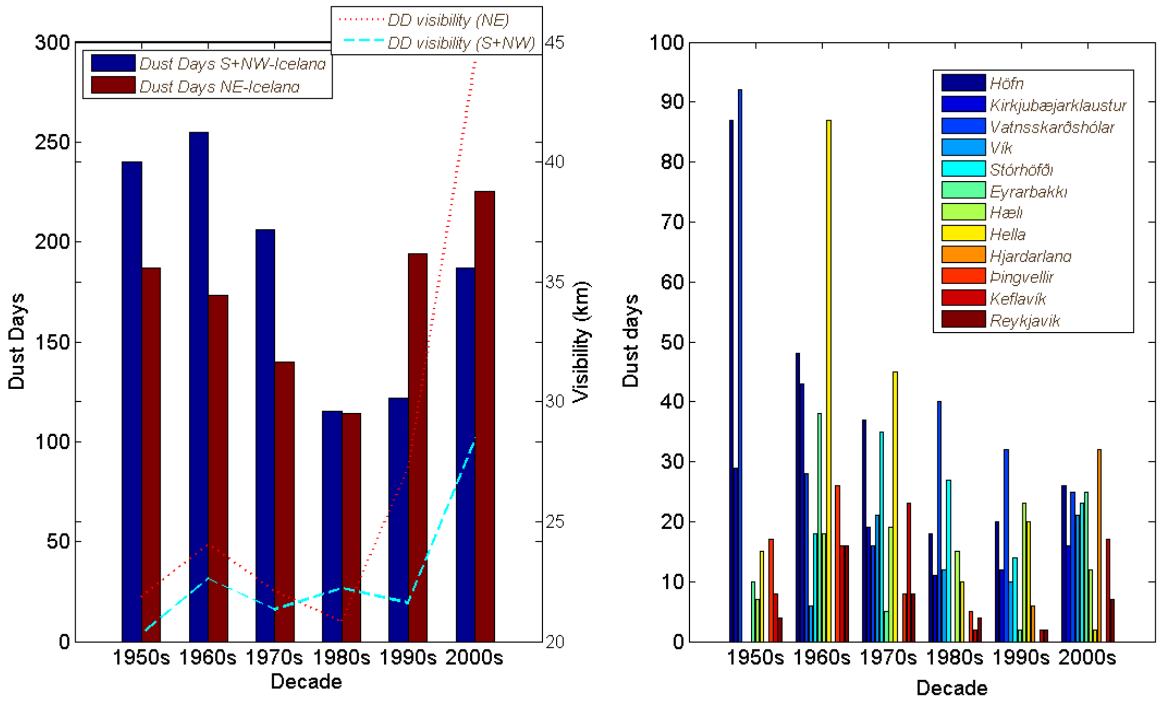

Figure 2. Total number of dust days, all stations combined to the left (blue bars for southern and northwestern part of Iceland, brown bars for Northeast Iceland). Individual stations in South Iceland sorted by decades to the right. Lines represent mean visibility (blue for S, brown for NE Iceland).

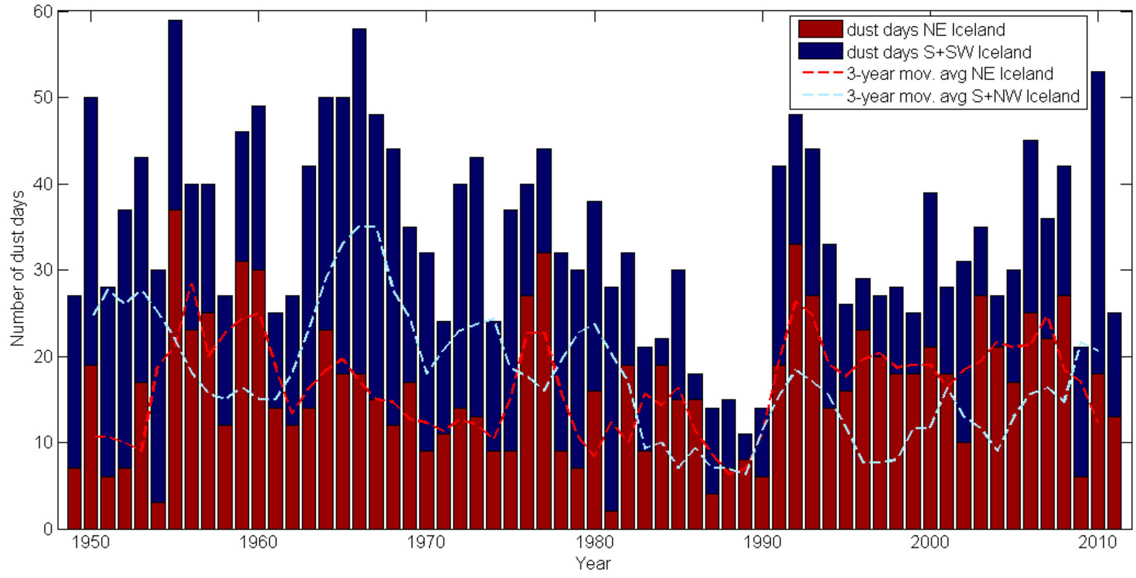

Figure 3. Number of dust days (blue bars for southern and northwestern part of Iceland, brown bars for Northeast Iceland) and 3-year moving averages of dust day frequency (red for NE, light blue for S Iceland).

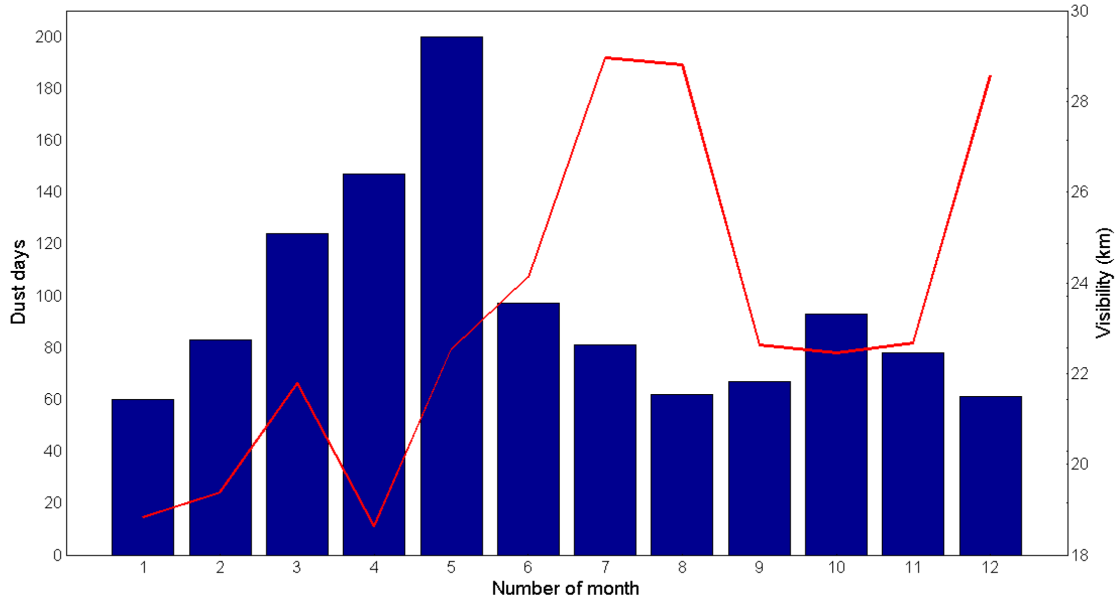

Figure 4. Number of dust days per month (bars) and monthly means of dust visibility (line) in southern part of Iceland in 1949-2011.

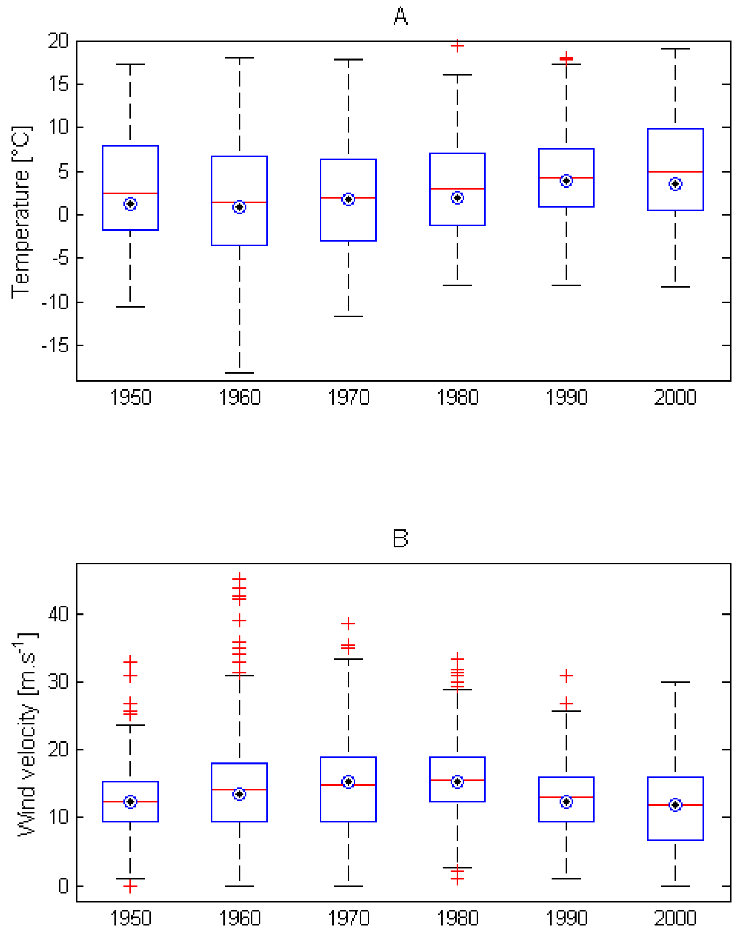

Figure 5. Temperature (A) and wind velocity (B) for dust events in southern part of Iceland in 1949-2011. The boxes demarcate the range in which half the data can be found. The red lines represent the mean and the circles the median.

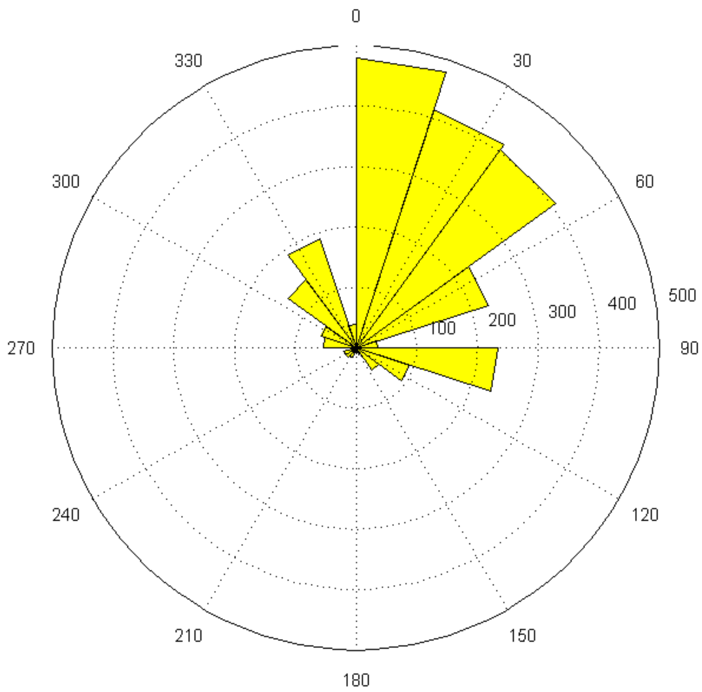

Figure 6. Wind directions (WD) during dust events in southern part of Iceland in 1949-2011. Weather stations that observed mainly WD 0-18° - Höfn, Eyrarbakki, Kirkjubaejarklaustur, Storhofdi, Thingvellir; WD 18-36°- Höfn, Vatnsskardsholar, Hjardarland, Reykjavik, Keflavik; WD 36-54°- Hella, Vatnsskardsholar, Vik; WD 54-72°- Haell, Vatnsskardsholar; WD 90-108°- Storhofdi, Vatnsskardsholar; WD 270-306° - Vatnsskardsholar; and WD 306-342°- Höfn. Dashed circles depict the number of dust observations reporting relevant WD.

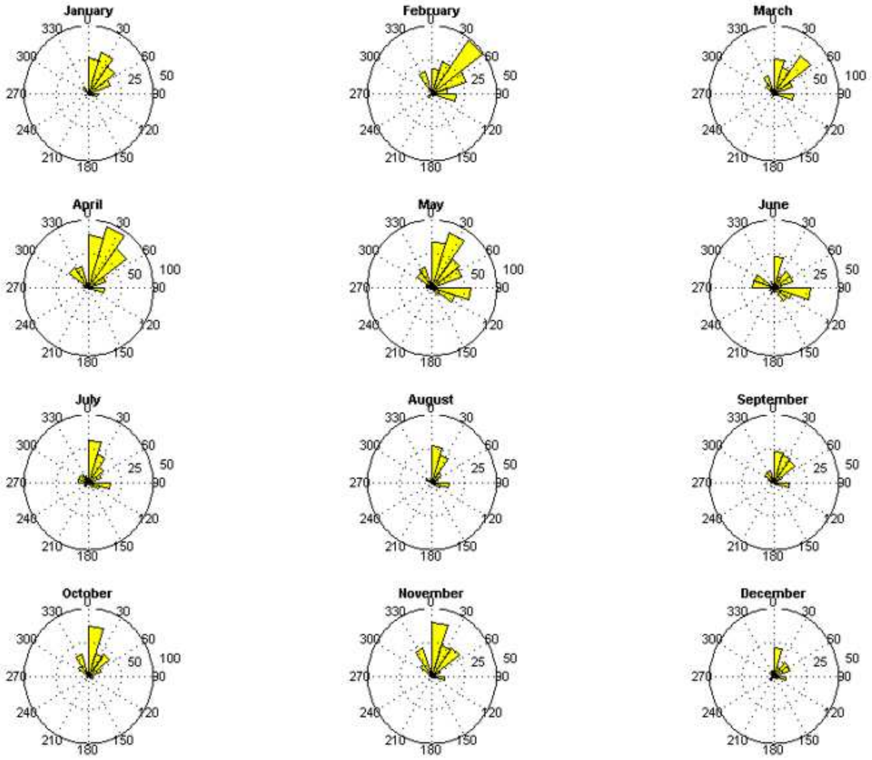

Figure 7. Monthly wind directions (WD) during dust events in southern part of Iceland in 1949-2011. Weather stations that observed mainly WD 0-18° - Höfn, Eyrarbakki, Kirkjubaejarklaustur, Storhofdi, Thingvellir; WD 18-36°- Höfn, Vatnsskardsholar, Hjardarland, Reykjavik, Keflavik; WD 36-54°- Hella, Vatnsskardsholar, Vik; WD 54-72°- Haell, Vatnsskardsholar; WD 90-108°- Storhofdi, Vatnsskardsholar; WD 270-306° - Vatnsskardsholar; and WD 306-342°- Höfn. Dashed circles depict the number of dust observations reporting relevant WD.

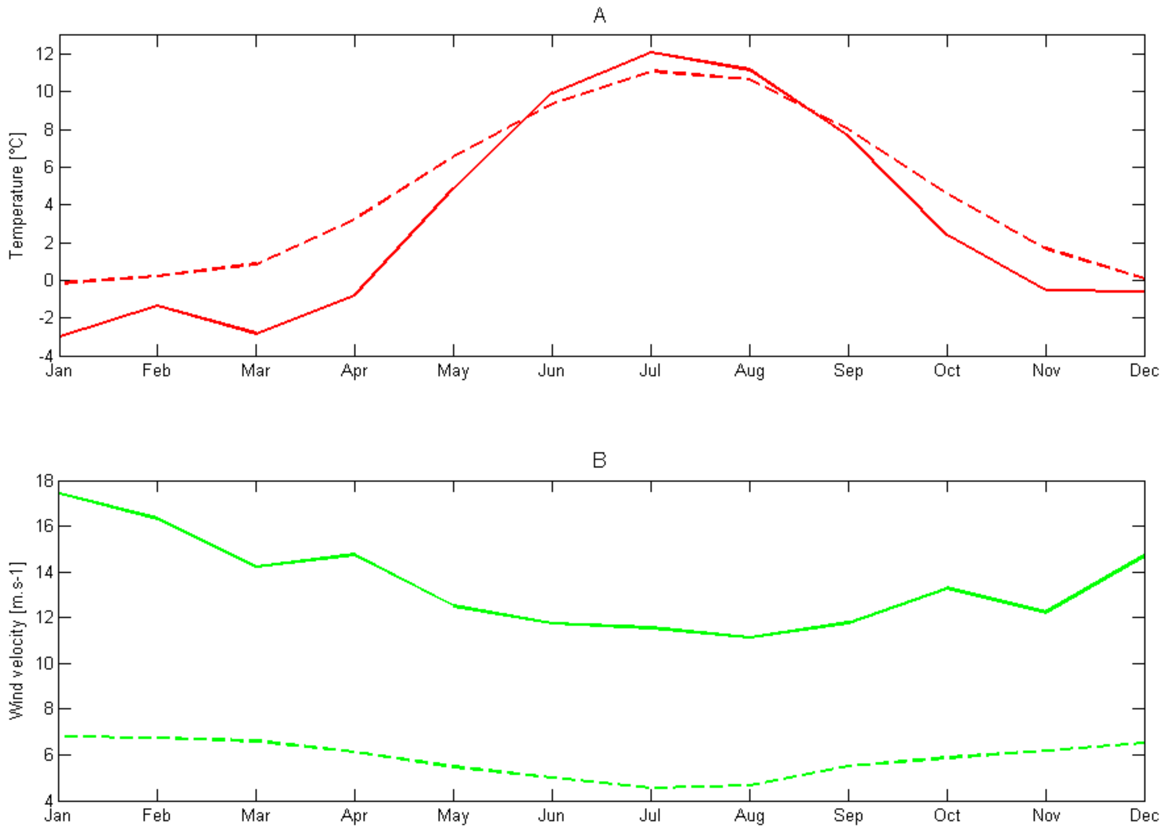

Figure 8. Monthly mean values (solid lines) of temperature (A) and wind velocity (B) during dust events in S Iceland in 1949-2011. Dashed lines represent the total mean values in 1949-2011.

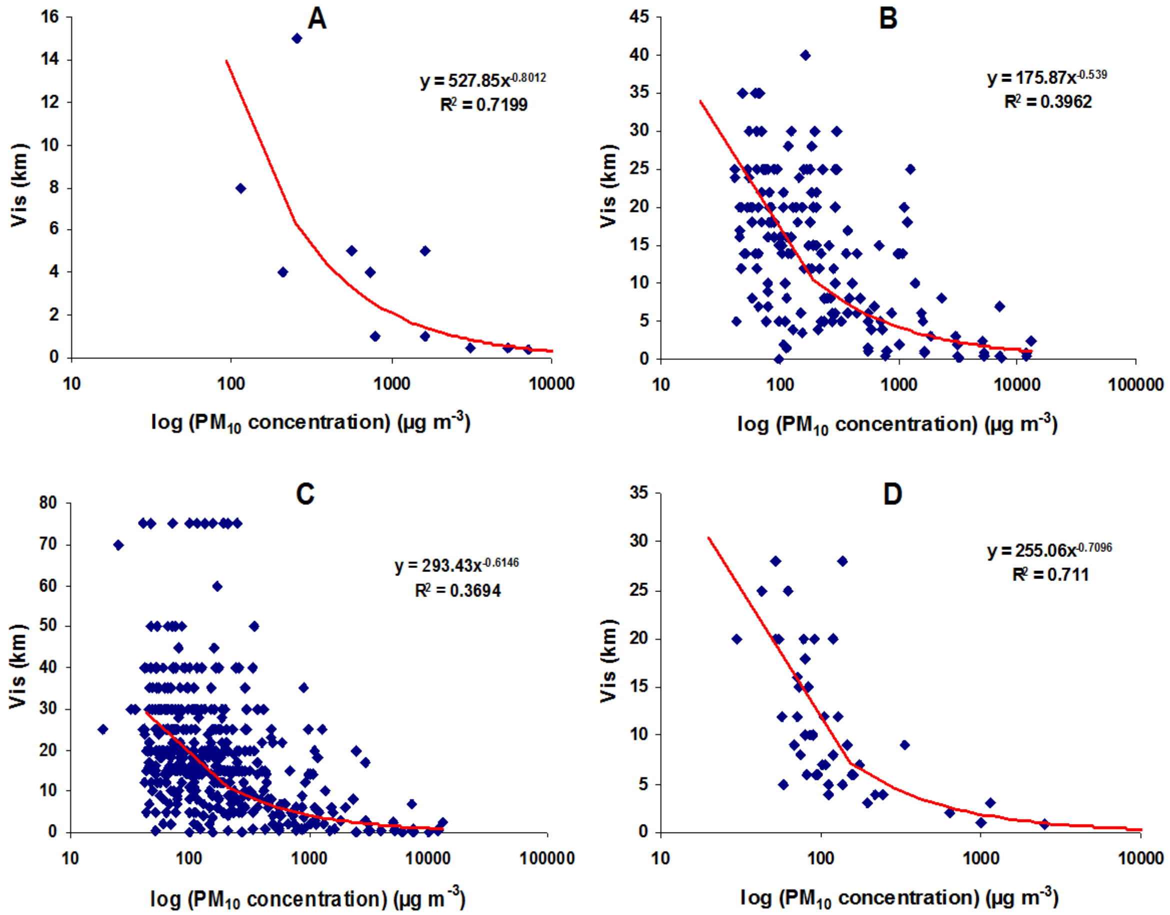

Figure 9. Hourly PM_{10} concentrations with corresponding visibility at stations: A- Vík, B- Vatnsskardsholar, and C – all stations (Reykjavik, Vik, Vatnskardssholar, and Kirkjubæjarklaustur). D represents daily PM_{10} concentrations concentrations from the High-volume Filter Aerosol Sampler with corresponding minimum 24-hour visibility.