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Long-term frequency and characteristics of dust storm events in Northeast Iceland (1949–2011)

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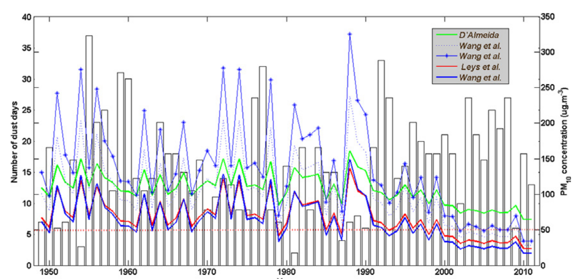
HIGHLIGHTS

- Present weather and visibility observations in Northeast Iceland.
- There were 1033 dust days in 1949–2011 with the annual mean of 16.4 dust days.
- Dust event frequency is comparable to major desert areas in the world.
- Dust production occurred during summer months, mostly June and September.
- Median concentrations were calculated as 106 μg m^{-3}.

GRAPHICAL ABSTRACT



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ABSTRACT

Long-term records of meteorological dust observations from Northeast Iceland were analysed and frequency of dust events from Icelandic deserts calculated. A total of 1033 dust days were reported during the period 1949–2011 with an annual mean of 16.4 dust days $year^{-1}$, placing the area among the dustiest areas in the world. The most active decades were the 2000s, 1990s and 1950s. Monthly dust event frequency is bimodal with primary and secondary maxima in June and September. A total of 14 severe dust storms (visibility < 500 m) occurred during the period. Median dust event concentration was calculated as 106 μg m^{-3} from the visibility observations. The frequency and severity of dust events depend on Sea Level Pressure (SLP) oscillation which controls the southerly winds in NE Iceland. The availability of fine sediments susceptible to dust production in outwash plains controlled by the flow rate of glacial river is also important. Volcanic ash from eruptions in 2010 and 2011 barely affected the dust event frequency in NE Iceland. Icelandic dust may be substantial source for large scale air pollution in the Arctic.

1. Introduction

Natural dust is emitted from many desert areas on Earth. 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). Globally, fine dust particles may be transported at altitudes of up to 10 km and can be carried distances of >10,000 km (Husar, 2004). Grousset et al. (2003) suggested that dust particles can travel over a 20,000 km in two weeks. Dust is considered to contribute to the Arctic haze phenomena (Raatz, 1984; Quinn et al., 2002).

Although dust is most often associated with dry and warm desert areas, dust is also frequently emitted in cold climate regions and at high latitudes, foremost from glacially-derived sediments of riverbeds or ice-proximal areas (Arnalds, 2010; Crusius et al., 2011;

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Prospero et al., 2012; Bullard, 2013). Glaciers produce sediments during the grinding and abrasion by ice over bedrock and meltwater transports fine particles to floodplains from which they are deflated by strong glacier-driven or katabatic winds. Eldridge (1980) considered the Arctic and Antarctic coastal zones as the windiest regions on Earth which may increase the severity of regional dust events. Furthermore, threshold wind velocities for a given particle size are lower in cold conditions than in warmer areas (Bullard, 2013). Dust emission intensity and deposition rates in glacial areas sometimes exceed those at lower latitudes (Bullard, 2013). Canada (Hugenholtz and Wolfe, 2010), Iceland (Arnalds, 2010), USA, China, and New Zealand (McGowan et al., 1996) are among areas with the highest deposition rates (Bullard, 2013). Blechschmidt et al. (2012) suggested that Icelandic deserts should be considered as major dust sources in global and regional climate models.

Iceland is an example of glaciogenic dust source area at high latitudes. In addition, Iceland is an important source of volcanic sediments that are subjected to intense aeolian processes and dust production (Arnalds et al., 2001, 2012, 2013; Arnalds, 2010; Prospero et al., 2012; Thorarinsdottir and Arnalds, 2012). Many of the major source areas for the dust have been identified (Arnalds, 2010) and the sandy deserts have been mapped (Arnalds et al., 2001). The Northeast is one of the most active aeolian areas of Iceland, with frequent dust plumes rising up from the Dyngjusandur source area and other sandy areas in the region, with dust plumes extending several hundred km from the sources (Arnalds, 2010). The Dyngjusandur active aeolian sandsheet covers an area of 270 km^2 with up to 10 m thick sediments (Mountney and Russell, 2004). Desert areas near Dyngjujokull are a result of glaciofluvial flooding, often associated with volcanic eruptions under the Vatnajokull glacier, enhanced by widespread volcanic deposition (Arnalds et al., 2001).

Atmospheric dust can reduce visibility and cause health risks. The World Health Organization considers that annual $PM_{2.5}$ concentration of 10 μg m^{-3} and estimated visibility 67 km indicates health risk, or daily standard of 35 μg m^{-3} and visibility range 31 km (WHO, 2005). In comparison, visual range can be over 300 km in dry climates and 100 km in humid climates on clear days (Hyslop, 2009). Observations of visibility during dust events are a key indicator of the severity of dust events where no aerosol measurements are conducted.

Many factors affect dust activity, such as sediment availability and climate factors. It is important to monitor changes in dust activity in time, especially in relation to climate and environmental changes. Atmospheric dust and visibility observations are available at weather stations in Iceland for more than 60 years (Arason et al., 2010). These data are ideal for studying long term variability in dust production and severity of historical dust events.

The main objectives of the study presented here were: (i) to explore the long term (63 years) variability in dust activity in NE Iceland (ii), to determine climatological characteristics of episodic dust events in a subarctic region, (iii) to place Icelandic dust production into international perspective.

2. Methods

2.1. Meteorological data

A network of eight weather stations in NE Iceland was chosen for the study. Fig. 1 depicts the location of the stations at Akureyri

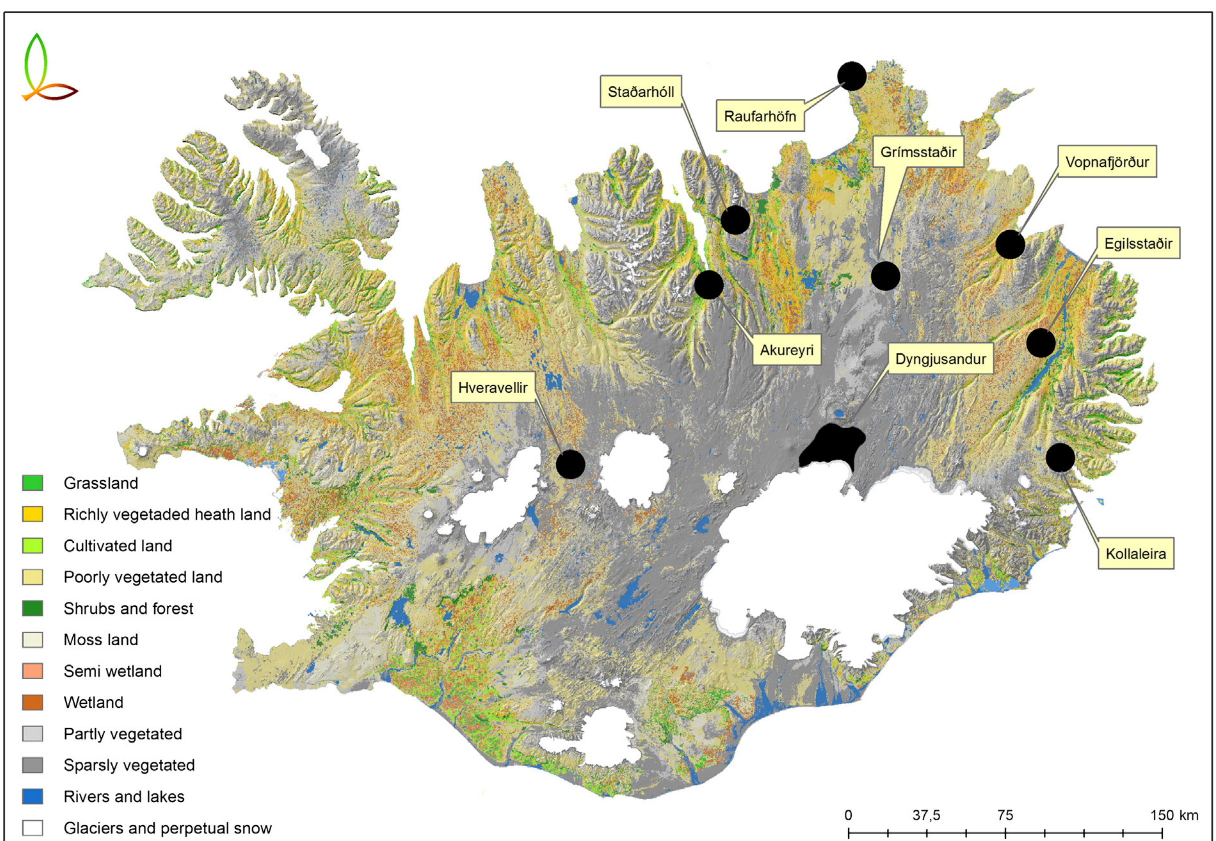

Fig. 1. A map showing the locations of weather stations in Northeast Iceland [Akureyri (AK), Egilsstadir (EG), Grimsstadir (GS), Raufarhofn (RH), Stadarholl (SH), Vopnafjordur (VO), Kollaleira (KL)] and a station in central Iceland [Hveravellir (HV)]. Base map from the Agricultural University of Iceland land use database (Nytjaland).

(AK), Egilsstadir (EG), Grimsstadir (GS), Raufarhofn (RH), Stadarholl (SH), Vopnafjordur (VO), Kollaleira (KL), and additionally Hveravellir (HV). HV is the only manned weather station located in central Iceland (Fig. 1) where dust events have been observed mostly during southerly winds and therefore affecting northern Iceland. The duration of operation varies: AK, ES, GS, and RH have been operated since 1949 (giving 63-year time series), EG 1949–1998 (50 years), SH and VO since 1961 (51 years), HV 1965–2004 (40 years), and KL from 1976 to 2007 (32 years). The weather stations are operated by the Icelandic Meteorological Office where the data are stored after strict quality control.

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 (The Icelandic Meteorological Office, 1981). 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, were used and defined as 'dust observation'. The synoptic codes (*ww*) for present weather which 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 (The Icelandic Meteorological Office, 1981). At all stations, the weather was observed every day of the year 3–8 times a day.

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 is 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 atmospheric phenomena and they were excluded from the dataset.

There are no continuous dust concentration measurements conducted in NE Iceland and therefore there are no *in situ* dust concentrations available for our dust observations. However, visibility observation during a dust event can be applied to estimate dust concentration using empirical relationships (Leys et al., 2011). Dust concentrations were derived from an equation (Table 1) based on conversion between horizontal visibility and suspended particle concentration presented in a paper by D'Almeida (1986). Additional formulas with different coefficients from Wang et al. (2008) and Leys et al. (2011) were used for comparison of mass concentrations which were measured in desert, semi-desert and loess environments (see Section 3.3.2.1).

Dust events were classified from visibility ranges (Table 2) based on criteria provided by Leys et al. (2011) and Wang et al. (2008). Dust events with visibility less than 500 m are often classified as "severe dust storms" (CMA, 1979; Tao, 2011), which is used in the present study. We classify dust event in visibility range 11–30 km as "suspended dust" and visibility range above 30 km as "moderate suspended dust". Visibility >10 km has been used in the literature to represent floating dust or suspended dust (Natsagdorj et al., 2003; Tao et al., 2002).

3. Results

3.1. Frequency, spatial and temporal variability in dust production

There was a considerable variability between weather stations in the total number of dust observations recorded over the 63 year period. The Grimsstadir station (GS) located downwind from the main dust source made 1685 dust observations (Table 3). The GS station also had by far the greatest frequency of dust days, with 65% (640 dust days) of the total 1033 dust days recorded over the 63 years. Egilsstadir (EG) counted for 15% (155 dust days), followed by 7% at HV and 5% at VO. The number of dust days per decade is shown in Fig. 2. The total number of dust days (defined in Section 2.2) is to the left, but numbers of dust days at individual stations are shown to the right. The annual mean is 16.4 dust days per year. Looking at decades separately reveals that there are frequent dust days during first decade of 21st century but also during the 1990s and the 1950s. The occurrence of total dust observations is, however, the highest in the 1990s and during the first decade of the 2000s.

The lowest number of dust days occurred in the 1980s but with a more evenly spread observations between the weather stations. EG observed most dust events in the 1980s, fewest events in the 1990s, but dust monitoring was discontinued there in 1998. The most active decade, the first decade in the 2000s has double mean frequency compared to the least active decade, the 1980s.

The mean visibility observed during all dust observations was 26.7 km (shown as the solid line in Fig. 2). It was the lowest during the 1980s, 20.8 km, and the highest for dust observations during the 2000s, up to 44 km. Occurrence of dust days was generally higher after the year 2000 but visibility during dust events (DE) was almost double compared to the rest of the decades.

Table 1
Aerosol dust concentration formulas estimated from visibility and PM_{10} concentration relation. PM_{10} is particulate matter concentration in μg m^{-3} and V is horizontal visibility in m (except D'Almeida (1986) where V is in km).

Aerosol dust concentration formulas	Surface type	Reference
$PM_{10} = 914.06V\exp(-0.73) + 19.03$	Saharan desert	D'Almeida (1986)
$PM_{10} = 1E + 08V\exp(-1.3687)$	Chinese sandy land	Wang et al. (2008)
$PM_{10} = 3E + 08V\exp(-1.4519)$	Chinese steppe area	Wang et al. (2008)
$PM_{10} = 1E + 08V\exp(-1.418)$	China – all areas	Wang et al. (2008)
$PM_{10} = 6E + 06V\exp(-1.1303)$	Australian sand plains	Leys et al. (2011)

Table 2
Dust event classification based on visibility categories. Mean visibility of each dust class is recalculated into PM_{10} concentration using the formula for steppe areas in Wang et al. (2008) and the formula from D'Almeida (1986). PM_{10} concentrations are based on an average obtained using the formulas by Wang and D'Almeida.

Dust event class	Visibility (km)	PM_{10} concentration (μg m^{-3})
Severe dust storm	≤0.5	31,027
Moderate dust storm	0.5–1.0	8209
Severe haze	1.0–5.0	1265
Moderate haze	5.0–10.0	368
Suspended dust	10.0–30.0	126
Moderate suspended dust	30.0–70.0	52

Table 3
Total dust observations, mean annual number of dust days and mean dust day visibility at all stations.

Station	Total dust observations	Dust days per year	Mean dust day visibility
GS	1685	12.5	24.8
EG	368	3.9	24.1
HV	132	2.3	38.1
VO	96	1.2	24.1
RH	61	0.7	15
AK	26	0.4	30.6
SH	13	0.24	42.7
KL	6	0.16	24.2

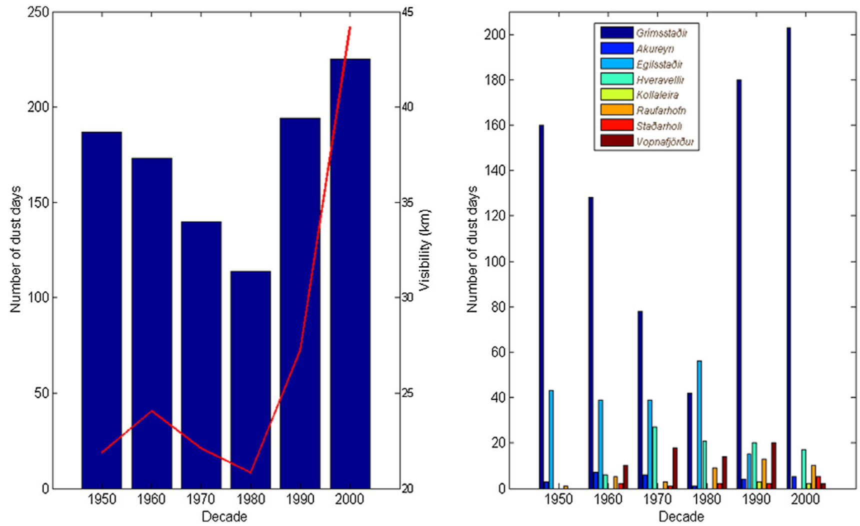

Fig. 2. Total number of days with dust observations, all stations combined to the left. Individual stations sorted by decades to the right. Solid line represents mean visibility.

3.1.1. Annual dust day variability and visibility

The annual number of dust days at all stations in NE Iceland is presented in Fig. 3. Note that 80% of reported dust days relate to the GS and the EG stations. The most active year was 1955 with 37 days of reported dust events with average visibility of 23.2 km, about 3 km less than mean dust day visibility. Other years with high occurrence of dust days in NE Iceland were 1992, 1977, 1960, and 1959. The 3-year moving average of dust day frequency (dashed line) depicts four periods of high dust activity in 1955–1960, 1976–1977, 1992–1993 and 2006–2008. The mean visibility during dust days varies and was 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 including the severe dust storm on 18 June 1988, so called '*The June 88 storm*', which has been used to illustrate a severe dust storm (Arnalds et al., 2012).

Table 3 summarizes the mean number of dust days per year and visibility at all stations. The GS station is located only about 90 km downwind from the main dust source of Dyngjusandur and was the most active station with over 12 dust days reported annually. The horizon at GS is not blocked by mountains and there are also some local dust sources. Consequently, it is of no surprise that GS provides a large majority of dust days into our database. The second was the EG station with almost 4 dust days annually, while over half of the stations observed <1 dust day annually. The RH station is located at the north-eastern shore and might be influenced by coagulation of dust particles and water (fog) droplets in marine regions, resulting in low DE visibility.

3.1.2. Seasonal patterns in dust activity and visibility

The seasonal distribution of dust events (mostly driven by the GS station) is depicted in Fig. 4. The highest occurrence was in June with almost 22% of all dust events, followed by September (19%). Low dust season started in December and ended in April. The lowest DE visibility was in May, 24.7 km. From April to November the mean visibility during dust events did not exceed 29 km.

The decadal changes in monthly distribution of dust events are shown in Fig. 5 (including only months with at least 5% of the total number of dust days). June had the highest occurrence of dust days early on and showed similar trend after 2000, while September dominated during the 1970s. August had relatively high occurrence of dust events during the 1980s and the 1990s, and May showed a contribution mainly in the 1950s. Absolute numbers of monthly dust days per decade are shown on the graph to the right. Dust events in May in the 1950s were about 2 °C warmer than in other decades. September events in the 1980s were, however, over 2 °C colder than in September during the other decades.

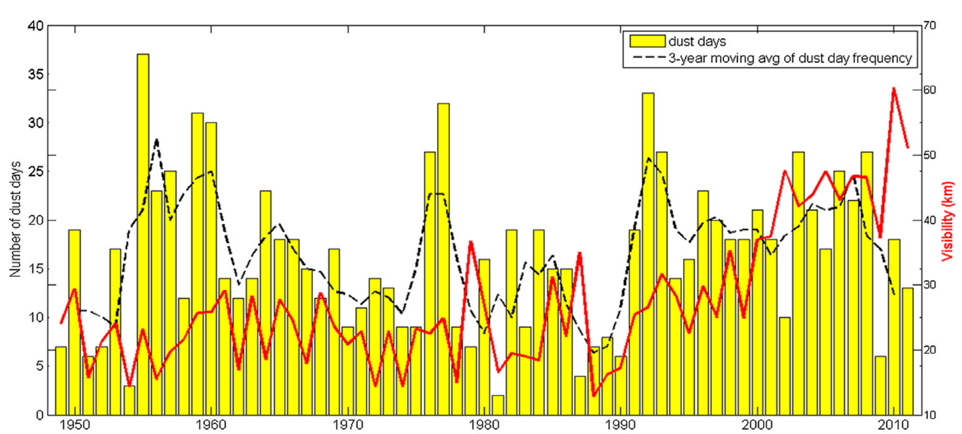

Fig. 3. Number of dust days (bars) and mean annual visibility during dust events (solid line) at all stations. Dashed line represents a 3-year moving average of dust day frequency.

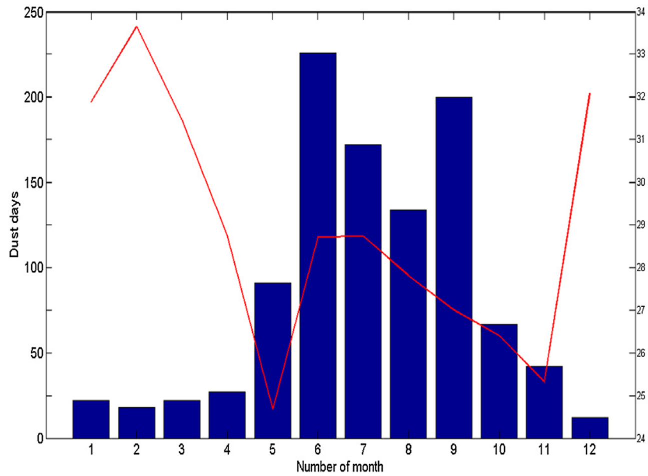

Fig. 4. Number of dust days per month (bars) and monthly means of dust visibility (solid line) for period 1949–2011.

3.2. Climatology of dust events in NE Iceland

3.2.1. Long term trends in meteorological characteristics of dust events

The mean temperature during dust events (DE) ranged from 9.6 to 11.4 °C. The DEs which occurred in the 1950s were the 'warmest' with an average DE temperature of 11.4 °C, but DE temperature dropped to 9.6 °C in the 1960s (Fig. 6A). Wind velocity correlates well with the dust event occurrence as would be expected. The fewest DE per decade were recorded in the 1980s and they occurred at the average wind velocity of 8.6 m s^{-1}. The DE wind velocities increased substantially from the 1990s (11.4 m s^{-1}) to the highest average velocity of 11.9 m s^{-1} during the 2000s (Fig. 6B). Most of the DE meteorological data in the 1950s and the 2000s were obtained at the GS station and the DE wind velocities at other stations are lower (yellow line, Fig. 6B). The RH station changed from manned to automatic station in 2005. Previous meteorological observations at this station were made more frequent than at the other stations and the data have the highest quality. The DE wind velocity at this coastal station remained similar throughout the period with a maximum in the 1990s and the lowest velocity in the 1980s (dotted line, Fig. 6B). During the dust events, the inland stations had higher wind velocities than the coastal stations.

The most common wind directions of the dust events in NE Iceland were SW–S–SE (Figs. 6C and 7). During the 1950s and the 1960s, SE storms were more frequent than in following decades. In the 1980s, dust events were mostly during winds from the SW and the first decade in the 2000s was dominated by southerly winds.

In order to gain better understanding of the frequency of the DEs, the long term variability in southerly winds was investigated in greater detail. The most active station (GS) was chosen to determine prevailing winds during dust events. GS is located in relatively flat highland area at some distance from mountains that can affect wind direction. The proportion of annual southerly air flow (winds from directions 100°–280°) on total air flow (all winds) was identified for this station. Fig. 8 depicts strong correlation between years of positive southerly air flow (>50% of winds were from directions 100°–280°, Fig. 8A) and years with high number of dust days (Fig. 8B). Low number of southerly winds in the 1980s correspond to low dust days frequency in this decade. This coincides with a drop in the frequency of southerly winds exceeding wind speed of 8 m s^{-1} during the active dust season (May–November) on total winds in the 1980s at the station RH (Fig. 8C).

3.2.2. Seasonal patterns in meteorological characteristics of dust events

Monthly mean values for temperature, wind velocity and most frequent wind direction of dust events (solid line) are shown in Fig. 9. Dashed lines depict total mean temperature and wind velocity in 1949–2011. The DE temperatures were about 3 °C higher than monthly long-term temperatures and DE wind velocities were about 4–7 m s^{-1} higher than long-term wind velocities. The major differences in temperature and wind velocity were in May, September and October. The reason is likely the occasional presence of snow within the Dyngjusandur dust source during these months and therefore the threshold wind velocity and temperature of DE are higher. The DE temperatures were warmest in June–August, with a maximum 14.4 °C in July. The highest DE wind

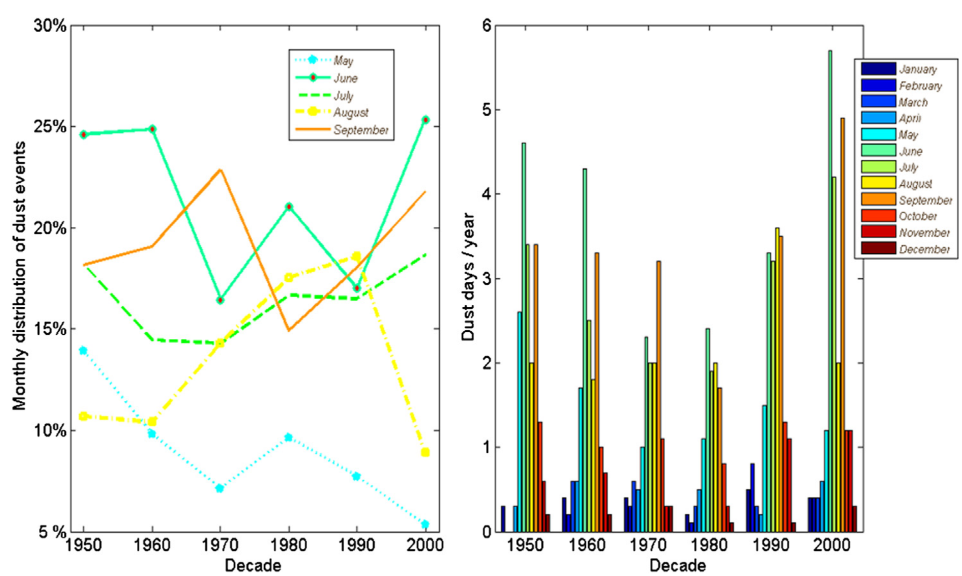

Fig. 5. Frequency of dust events during individual months of the year. The thick lines depict the fraction of June (light green) and September (orange) dust observations by decades. The dashed lines show remaining months with at least 5% of the total number of dust days. The absolute numbers of dust days each month per decade is on the right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

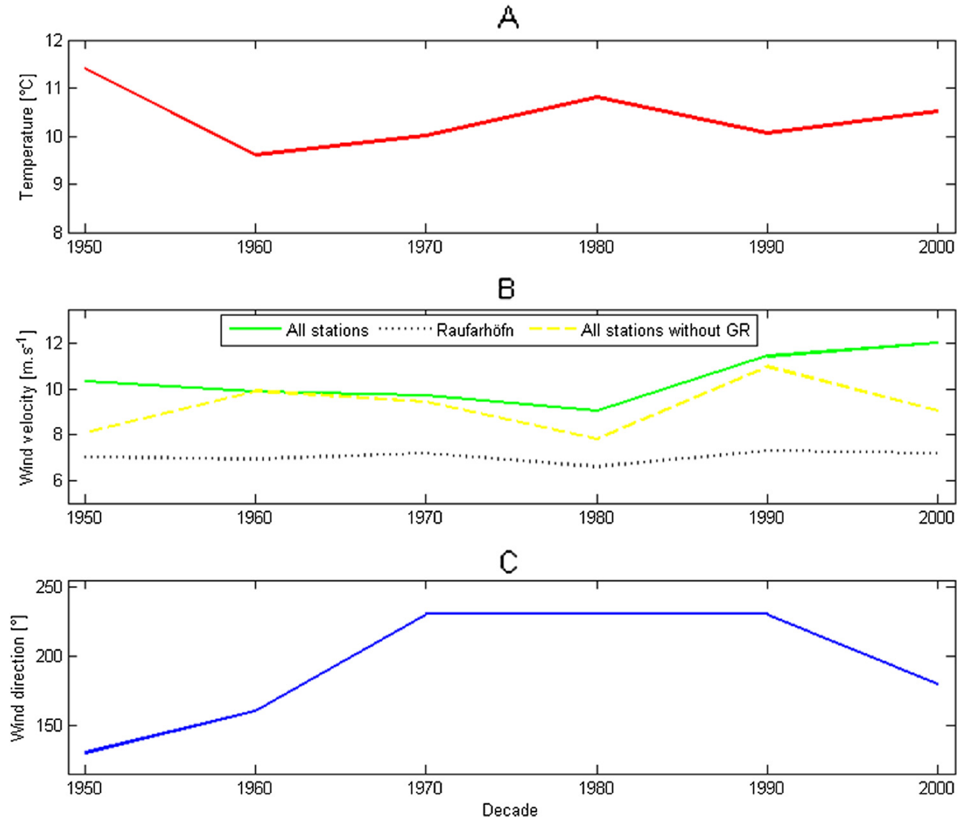

Fig. 6. Meteorological parameters for dust events 1949–2011. A-mean temperature, B-mean wind velocity, C-most frequent wind direction. Mean wind velocity during dust events at all stations is marked with a green line. Dashed yellow line shows mean wind velocities at all stations except Grimsstadir (GS, most active station) and dotted line shows mean wind velocity at the coastal station Raufarhofn (RH). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

velocities occur in September and October, 11.4–11.9 m s^{-1}, and in May (10.9 m s^{-1}). There is a characteristic decrease in wind velocities during the summer season in June–August to about 9.9 m s^{-1}. Dust events are mostly associated with S and SW winds. Such winds are dominant in the late season (July–September), while there is a considerable contribution of dust events with SE winds during the early season (May–June).

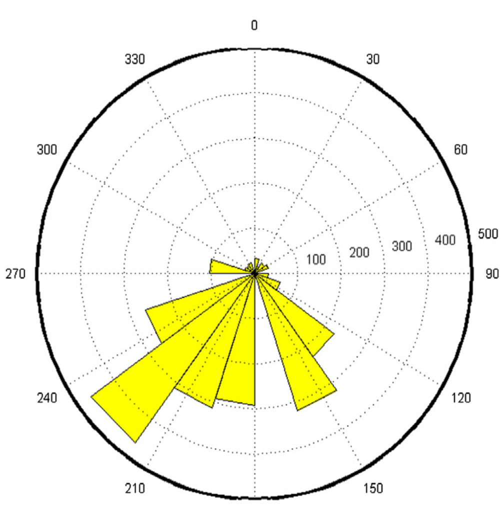

Fig. 7. Wind directions during dust events at all stations 1949–2011.

3.3. Dust event classification and aerosol dust concentrations

3.3.1. Dust event classes and climatology

Most of the dust events during the study period were classified within the 'suspended dust' class (46%) with visibility 10–30 km (Table 4). About 13% of dust events (192 dust days) had visibility <5 km. In total, we observed 14 severe dust storms with visibility less than 500 m.

The DE wind velocity generally increased with the DE severity as stated earlier. However, DE temperature was colder than average for the most severe DE classes (Table 4). The 'moderate haze' and 'suspended dust' had the highest DE temperatures because they occurred more often during the summer period (July–August).

The frequency of meteorological parameters of individual dust event classes from 1949 to 2011 is depicted in Fig. 10. Severe and moderate dust storm classes (visibility 0–1 km) were most often recorded in the 1950s and the 1990s but only once observed in the 2000s. About 50% of dust events had visibility <10 km in the 1950s. There is an increase in DE wind velocities within all classes between the 1990s and the 2000s. The DE temperatures of individual classes vary between stations during decades. The DE temperature when 'haze' classes were recorded, were warmer at the inland GS station in the 2000s compared to the 1990s but colder at the coastal RH station in the 2000s compared to the 1990s.

Duration of dust events in NE Iceland ranges from one day up to seven days of continuous dust observations. About 70% of the dust observations lasted one day or less, about 15% lasted two days and 7% for three days. More two- and three-day DEs were observed

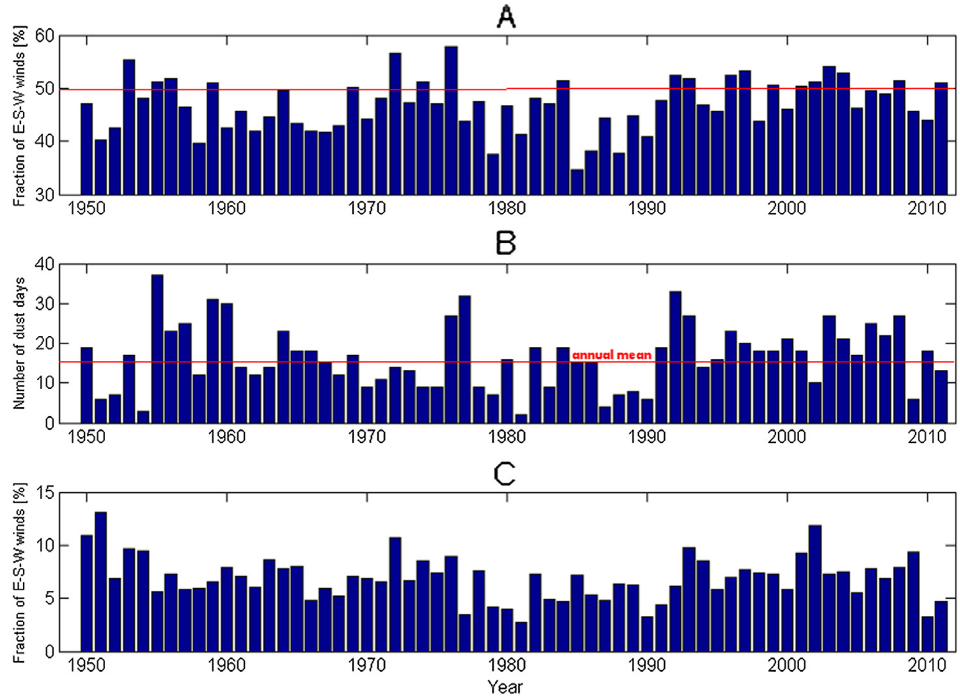

Fig. 8. Annual proportion of E–S–W (wind directions 100°–280°) winds of total winds. A-percentage of E–S–W winds of total wind observations at station GS, B-annual number of dust days, C-proportion of E–S–W winds exceeding wind speed of 8 m s^{-1} in May–November of total wind observations at station RH.

during the 1950's, but seven-day observations of moderately suspended dust were reported during 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 in NE Iceland because of cloud cover over the region. One of the most severe events captured by MODIS was the 'severe haze' on September 17, 2008 (Fig. 11), which caused reduced visibility at GS station for seven days. The lowest visibility was observed as 1.5 km and mean wind velocity was about 19 m s^{-1}. Visible part of the plume extended >350 km (red line (in the web version)).

3.3.2. Relationship between visibility and dust concentration

3.3.2.1. Aerosol dust concentration formulas. Unfortunately, dust aerosol measurements are not made in NE Iceland and it is

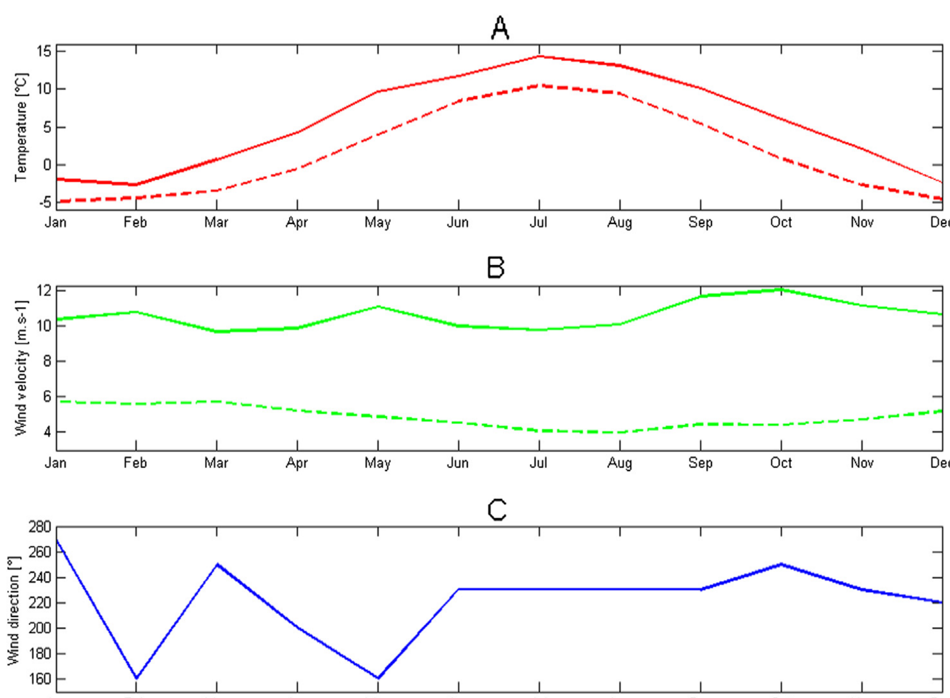

Fig. 9. Monthly mean values of meteorological parameters during dust events in 1949–2011. A-mean temperature, B-mean wind velocity, C-most frequent wind direction.

Table 4
Dust event classification based on visibility ranges, frequency of dust events in different classes and annual number of dust days. Mean wind velocity and mean temperature of each dust class are included.

Dust event class	Visibility (km)	Frequency (%)	Wind velocity ($m\ s^{-1}$)	Temperature (°C)	Number of dust days yr^{-1}
Severe dust storm	≤0.5	< 1	16.2	8.4	0.2
Moderate dust st.	0.5–1.0	2	14.9	9.4	0.5
Severe haze	1.0–5.0	10	13.0	10.6	2
Moderate haze	5.0–10.0	13	11.3	10.9	3
Suspended dust	10.0–30.0	46	9.9	10.6	10
Mod. susp. dust	30.0–70.0	27	10.2	10.0	7

therefore necessary to estimate the concentrations based on visibility observations. Several attempts have been made to relate visibility with total suspended particle concentration in the literature. D'Almeida (1986) found a good correlation ($r^2 = 0.95$) between horizontal visibility and PM_{10} during Saharan sand storms (Table 1). The green line in Fig. 12 shows calculated annual PM_{10} concentrations from DE visibility observations in NE Iceland using his formula. Wang et al. (2008) obtained formulas for visibility and PM_{10} mass concentration based on *in situ* measurements in desert, semi-desert and loess environments in Asia in 2001–2006. They obtained a strong relationship ($r^2 = 0.9$) between visibility and PM_{10} concentration. Leys et al. (2011) similarly calculated relationship for the famed 'Red Dawn' storm in Australia in 2003. Fig. 12 shows the mean annual PM_{10} dust concentrations during DE in NE Iceland using these formulas from different surfaces. The calculations suggest that the maximum mean annual concentration was obtained in 1988 when dust events caused on average concentration between 140 and 330 μg m^{-3}depending on which formula is used for the conversion. Generally the concentrations are lower in the 2000s. Concentrations calculated from DE visibility in Iceland are higher using formulas for steppe surfaces than for deserts. Using the formula derived for steppe conditions (Wang et al., 2008) resulted in the highest aerosol mass concentrations in

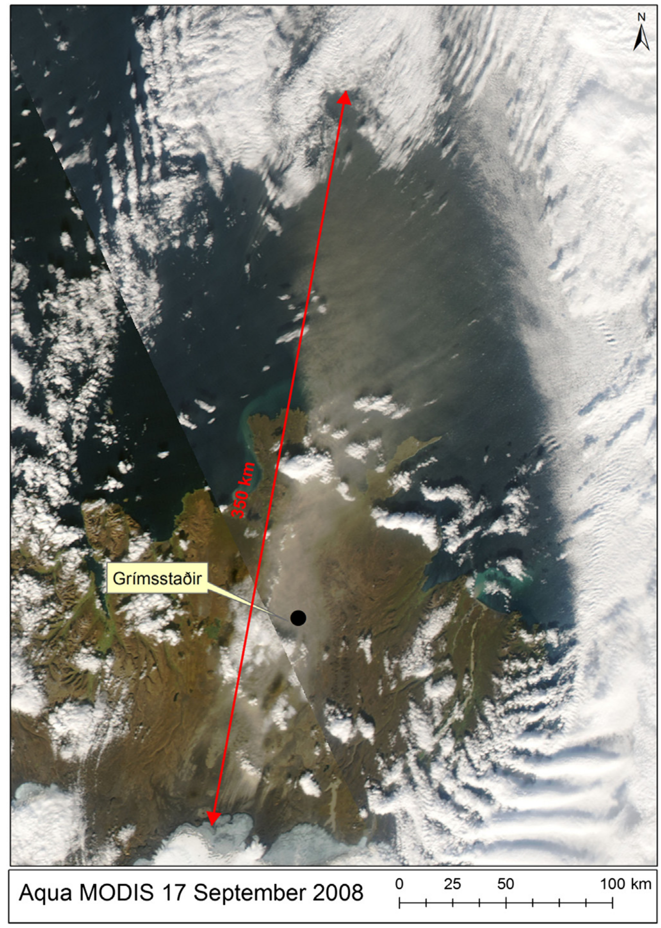

Fig. 11. Severe haze blowing off the northern coast of Iceland over the Arctic Ocean on September 17, 2008 (NASA, 2012).

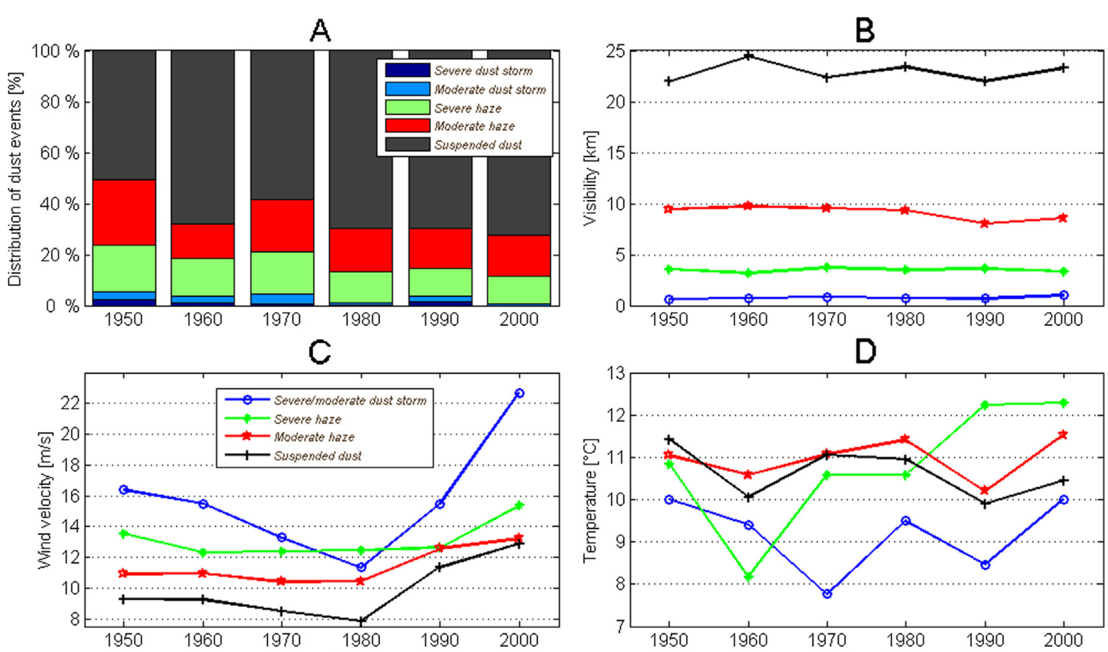

Fig. 10. Meteorological parameters of dust event classes 1949–2011. A-distribution of dust event classes; B-visibility range; C-wind velocities; D-temperature. Severe dust storm (visibility V ≤ 0.5 km), Moderate dust storm (V = 0.5–1 km), Severe haze (V = 1–5 km), Moderate haze (V = 5–10 km), Suspended dust (V = 10–30 km).

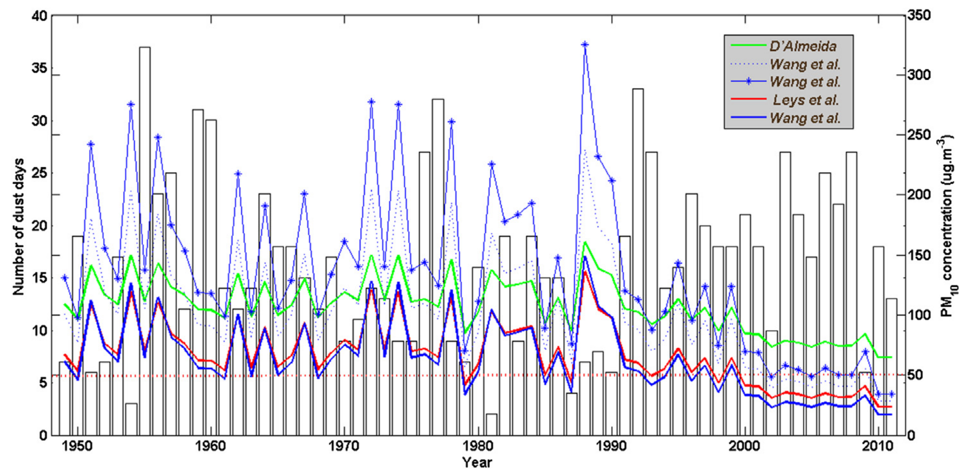

Fig. 12. Calculated mean annual PM_{10} concentration during dust events in NE Iceland based on formulas developed for different surfaces (formulas in Table 1). Bars depict number of dust days and lines indicate mean PM_{10} concentration during dust events. Blue lines are calculated values based on Asian surfaces (Wang et al., 2008), green line for African desert (D'Almeida, 1986), and red line for Australian desert (Leys et al., 2011). The European guideline determines the limit value for health protection 50 μg m^{-3} over 24 h (2008/50/EG available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

general and most likely represents Icelandic fine glaciogenic sediments.

3.3.2.2. Seasonal variability in aerosol dust concentrations. Fig. 13 shows results for the mean and the median dust concentrations calculated from visibility using the formula from D'Almeida (1986). The mean dust concentration during dust events in NE Iceland is 237 μg m^{-3} during the period 1949–2011. Maximum is in April with 805 μg m^{-3}, a month which represents only 2% of total dust events. Median dust concentration is 106 μg m^{-3}, the highest in May and September (122 μg m^{-3}), followed by June, July and August. The highest frequency of the severe dust storms is also in September (37% of all severe dust storms) and May (21% of severe dust storms). Clearly, the highest median dust concentrations occurred during months with frequent dust events.

4. Discussion

Meteorological observations around major dust source regions worldwide include continuous atmospheric dust and sand observations. Annual mean of 16.4 dust days in NE Iceland is similar to that found in Iran (Jamalizadeh et al., 2008), more active than Utah (4.3 dust days $year^{-1}$; Steenburgh et al., 2012) but less frequent than in the northern part of Africa (up to 150 dust days $year^{-1}$; N'TchayiMbourou et al., 1997), Australia (50 dust storm days $year^{-1}$; Ekström et al., 2004), Mongolia (40 dusty days $year^{-1}$; Natsagdorj et al., 2003), or in active parts of China (35 dust days $year^{-1}$; Qian et al., 2002). As for the Arctic regions, Nickling (1978) observed 15 dust storms within 59 summer days in the Yukon Territory in 1972–1973, and Bullard (2013) recorded 7 days with high dust emissions in West Greenland in summer 2007. Dust activity can also be monitored by measuring deposition rates. Iceland rates

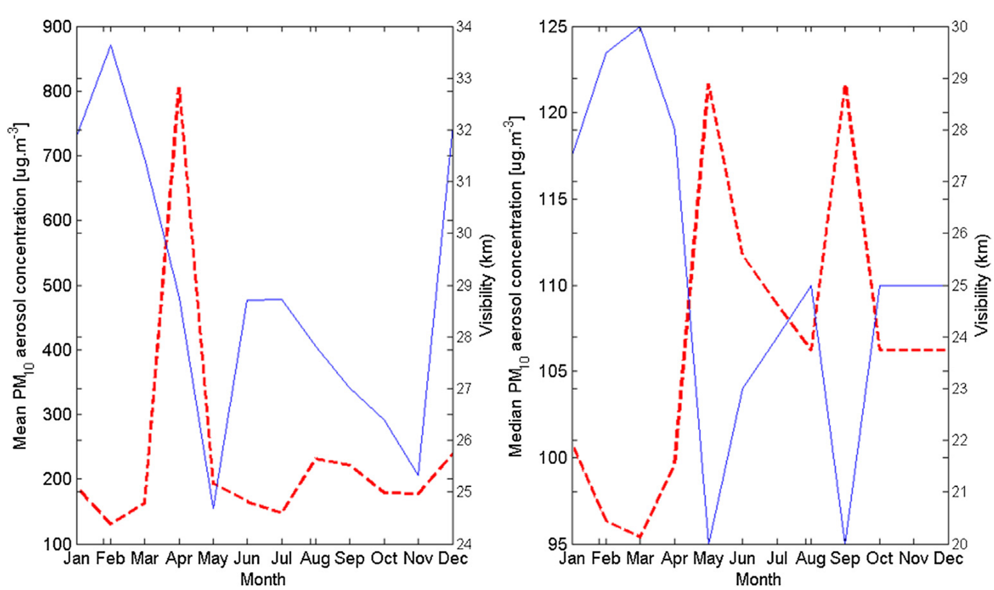

Fig. 13. Mean (left) and median (right) dust concentration of dust events. Red dashed line represents dust concentration and blue line shows visibility. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

among the highest dust deposition areas worldwide (Arnalds, 2010; Bullard, 2013), indicating that large amount of sediments are released during the dust events. The major sources have been identified as glacial floodplains (Dyngjusandur, Fig. 1) and the sandy deserts north of the Vatnajökull glacier (Arnalds, 2010).

Trends in dust emissions vary between regions over the past six decades. Generally, dust activity was relatively high in the 1950s and 1960s, and low in the 1980s in the USA (Steenburgh et al., 2012), Australia (Ekström et al., 2004) and China (Qian et al., 2002). The 2000s were reported as the most active decade in Iran (Jamalizadeh et al., 2008). Long term trend in dust production in NE Iceland correlates well with these regions. Donarummo et al. (2002) found several dust periods in ice-cores during GISP2 project in Greenland. Two periods of high (1955–1960, 1975–1978) and one period of low (the 1980s) dust concentrations correlate with Icelandic dust trend between 1950 and 1990.

The dustiest year in NE Iceland was 1955 with 37 dust days. This year was dry and warm, but the year before had high precipitation in the Northeast Iceland. Hanna et al. (2004) reports the summer of 1955 as the warmest in the 20th century at Grímsey, an island of the coast of North Iceland. The same year had also a dust storm peak in the Tarim Basin, China, where 50 dust storms were recorded (Qian et al., 2004). The year 1955 was calculated with the highest total dust flux in Utah in 1950–2010 by Steenburgh et al. (2012). In China, year 1955 was one of the four most severe drought events in 1951–2009 (Wu et al., 2011) and part of extreme drought period 1952–1956 in the USA (Nace and Pluhowski, 1965). Worldwide peaks in dust production in the 1950s coincide with NE Iceland where higher temperatures and lower than average precipitation were measured at the time (Bjornsson and Jonsson, 2003; Hanna et al., 2004). There was a significant drop in temperature in NE Iceland in the late 1960s continuing through the 1970s. However, the annual temperature at inland stations in the 1990s had reached similar values as were observed in the 1950s (Bjornsson and Jonsson, 2003), which correlates well with increased DE frequency. Increased number of dust events in June in the 2000s is associated with dry and warm months of Junes in 2000, 2004, 2006 and 2007. For the 10 dustiest years in NE Iceland, the annual temperatures were above the average. This would result in peak discharge of water to the glaciofluvial floodplains that make up the main dust source area.

Dust is primarily emitted during southerly (SW–S–SE) winds. Spring DEs are often associated with SE winds. There was a drop in frequency of SE winds in the 1970s and the 1990s, compared to high frequency in the 1950s and the 1960s. SE winds were infrequent in May of the 2000s. Low dust occurrence in the 1980s coincides with low frequency of southerly winds (wind direction 100°–280°). Only about 40% of all winds blew from southerly directions and strong May–Nov southerly winds were also low (Fig. 8C). The springs of the 1980s were cold and with long lasting snow cover.

We found no significant correlation between high dust seasons and global climate drivers such the North Atlantic Oscillation (NAO), the Arctic Oscillation or prevailing ocean currents (Olafsson, 1999). The long term temperature and precipitation trends in Iceland are often in contrast to the North Hemisphere land averages or not consistent with the global averages (Hanna et al., 2004). Although the NAO correlations were not significant, they were highly suggestive of a possible relationship (Hanna et al., 2004; Bjornsson and Jonsson, 2003; Olafsson, 1999). Hanna et al. (2004) suggest the Iceland – southern Greenland – northwestern North Atlantic region is driven by special climatic conditions. Furthermore, Iceland is near one dipole of the NAO and the NAO is driving westerly winds, and therefore weakly correlated with DEs in the NE Iceland driven by southerly winds. However, there is an orthogonal pattern to NAO, described as a dipole of sea level pressure (SLP) field that is oriented east–west (Bjornsson and Jonsson, 2003). Low SLP west of Iceland (and/or high SLP east of Iceland) will lead to warm geostrophic southerly winds and if the east–west dipole is reserved it will turn to cold geostrophic northerly winds. DEs in the NE Iceland are linked with strong southerly winds and therefore with high SLP east of Iceland.

Dust events occur most frequently in June and September which coincides with July and August having more precipitation on average than June and September at the GS station. May is the driest month but occasionally with snow covering dust sources and thus with fewer dust days than later in the season. September and May feature the greatest wind speeds during active dust season which is in harmony with the average wind speed at inland stations (Bjornsson and Jonsson, 2003). Dust storms in Canada are most frequent in May–July when rivers are at low stage exposing freshly deposited sediments (Nickling, 1978). In contrast, DEs in Alaska occur predominantly in September when low precipitation and strong winds take place (Crusius et al., 2011). Such processes cause that highest frequency of severe dust storms (visibility < 500 m) in September also in Iceland.

Dust storms (visibility < 1 km) occur during the highest wind speeds and the lowest temperatures (Fig. 10). Mean DE wind velocity of 10.3 m s^{-1} corresponds to threshold value for aeolian transport 5–10 m s^{-1} reported from glacierised regions (Bullard, 2013), but Icelandic research reports common threshold values of 6–10 m s^{-1}(Arnalds et al., 2012).

The 1990s were most frequent in 'dust observations' with the events being more severe (lower visibility) than during the 2000s. This coincides with exceptionally high frequency of south-westerly winds exceeding wind speed of 8 m s^{-1} during the May–November period (Fig. 10C). The highest number of 'dust days' was recorded in the 2000s but DE visibility doubled (about 45–50 km) indicating less severe DEs in spite of strong southerly winds. This may indicate less availability of fine materials susceptible to dust production determined by changes in flow rate at the Jokulsa a Fjollum river in the 1990s and the 2000s, but the reason remains unclear.

Volcanic ash deposited during the 2010 Eyjafjallajokull and 2011 Grimsvotn eruptions caused serious dust storms in South Iceland (Schumann et al., 2011; Leadbetter et al., 2012; Petersen et al., 2012) but no increase was recorded in dust activity in NE Iceland after these events. This shows that fresh volcanic ash is not required for high occurrence of DE in NE Iceland although ash deposited there would undoubtedly increase the frequency in the region.

The major dust emissions are towards north over NE Iceland and further into the Arctic region. Icelandic dust periods correlate with published dust concentrations from Greenland (Donarummo et al., 2002). Furthermore, Drab et al. (2002) identified Icelandic dust in ice-core samples in central Greenland. Several forward trajectories during dust events in NE Iceland confirmed that air parcels were moved to central Greenland and further north. We therefore suggest that Iceland could be a long-term source of dust into the Arctic.

5. Conclusions

The severity and frequency of dust storms events in Northeast Iceland are comparable to many of the major dust areas of the world. In the long term, the most active aeolian area in NE Iceland is inland of Grimsstadir. There is great within-year and decadal variability in the frequency of the dust storms. The most active periods were during the 1950s and the period from the early 1990s until 2008. The study indicates that Icelandic dust may be a substantial source for not only local, but also larger scale air pollution in the Arctic.

Relating visibility observations obtained from long term weather records can give a comprehensive account of dust frequency and behaviour on a regional basis. The results have relevance to a range of topics, such as on respiratory health research, aeolian deposition and ecosystem development both on land and sea, and by providing information about aerosol production on a regional scale in general.

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