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Determination of aeolian transport rates of volcanic soils in Iceland

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ABSTRACT

Sandy deserts cover >20 000 km^2 in Iceland, consisting primarily of volcanic materials with basaltic volcanic glass being the main constituent. Wind erosion is severe in the country, causing dust pollution with widespread aeolian redistribution affecting most Icelandic ecosystems and sand movement over vegetated areas in the form of advancing sand fronts. We quantified wind erosion, using BSNE field samplers and automated sensors over several years at two sites with contrasting environments. The study sites are Holsfjöll with andic soil materials in the arid northeast highlands (<400 mm annual precipitation) and Geitasandur on sandy surfaces in the humid south lowlands (>1200 mm). Both areas show similar annual aeolian transport of 120–>670 kg m^{-1} yr^{-1}. Aeolian flux in storms at the NE site was 3–43 kg m^{-1} h^{-1} on average with up to >200 kg m^{-1} h^{-1} during gusts. Multiple regression shows potential flux of >200 kg m^{-1} h^{-1} during intense storms of >20 m s^{-1} (at 2 m height). The research shows major aeolian activity in the humid South Iceland. Height distribution curves indicate considerable transport high above the surface at both sites (>60 cm). Stable height distribution curves for each location allow for measurements using single dust trap over long periods. The research explains the intense activity of advancing sand fronts in Iceland and the significance of continuously recharged sand sources for maintaining severe wind erosion in humid areas of Iceland.

1. Introduction

Iceland is a volcanic island in the North-Atlantic Ocean with cold humid oceanic boreal to arctic climate (Einarsson, 1984). About 45% of Iceland is covered by vegetation, ranging from rich ecosystems such as wetlands and birch shrublands to highland areas characterized by moss and lichens (Traustason et al., 2007). Areas with limited vegetation stretch over about 45% of Iceland, but glaciers cover about 10%. Icelandic environments are subjected to large scale dust deposition of 25–>250 g m^2 yr^{-1} in extensive areas as a result of intense aeolian activity (Arnalds, 2010), in addition to tephra deposition from frequent volcanic activity (e.g., Thordarson and Höskuldsson, 2008). Most soils of Iceland are Andosols (Arnalds, 2008), which are soils that develop in volcanic materials. Aeolian deposition is a major factor contributing to the characteristics of Icelandic soils (Arnalds and Oskarsson, 2009). Icelandic Andosols are often sandy, especially close to the active volcanic zone and near unstable glacially-fed floodplains.

Icelandic ecosystems have been subjected to large scale ecosystem degradation and destruction over the past millennia since the island was settled (Thorarinsson, 1961; Arnalds, 1987; Arnalds, 2000; Arnalds et al., 2001a; Aradottir and Arnalds, 2002). Desert-like conditions, with limited plant cover, have been created in extensive areas, where the Andosol mantle has been truncated from the surface by wind and water erosion processes. However, many of the sandy deserts in Iceland are formed by glacio-fluvial process along floodplains of glacial rivers and on outwash plains in front of glaciers, and also by deposition of volcanic materials during eruptions. The sandy deserts of Iceland occupy nearly 22 000 km^2 or about 22% of the land area (Fig. 1), and these areas are subjected to aeolian processes contributing to major redistribution of aeolian materials (Arnalds et al., 2001b). Arnalds (2010) identified two major types of dust sources in Iceland: i) plume areas of intense dust production in relatively small areas (5–30 km^2) covered with fine sediments, frequently recharged by glacio-fluvial processes (melt-water floods and fluctuating water tables); and ii) sandy deserts in general, covering extensive areas with more coarse textured materials that have been subjected to sorting in repeated wind erosion events.

The main threat associated with sandy deserts is the formation of so-called '*advancing sand fronts*', ('afoksgeirar' in Icelandic) where sand buries vegetation and kills it (Arnalds et al., 2001a,b). Subsequently, with continuous sand supply, the soil materials under the vegetation (often 1–2 m thick soils) are combined with the sandy materials, and the front continues to advance, often >10 m and even >100 m yr^{-1} (Arnalds et al., 2001a). Historical accounts (e.g., Arnason, 1958) show advancement of advancing sand fronts capable of destroying numerous farms in one major storm lasting several days, leaving sandy desert behind. These sand fronts are soil

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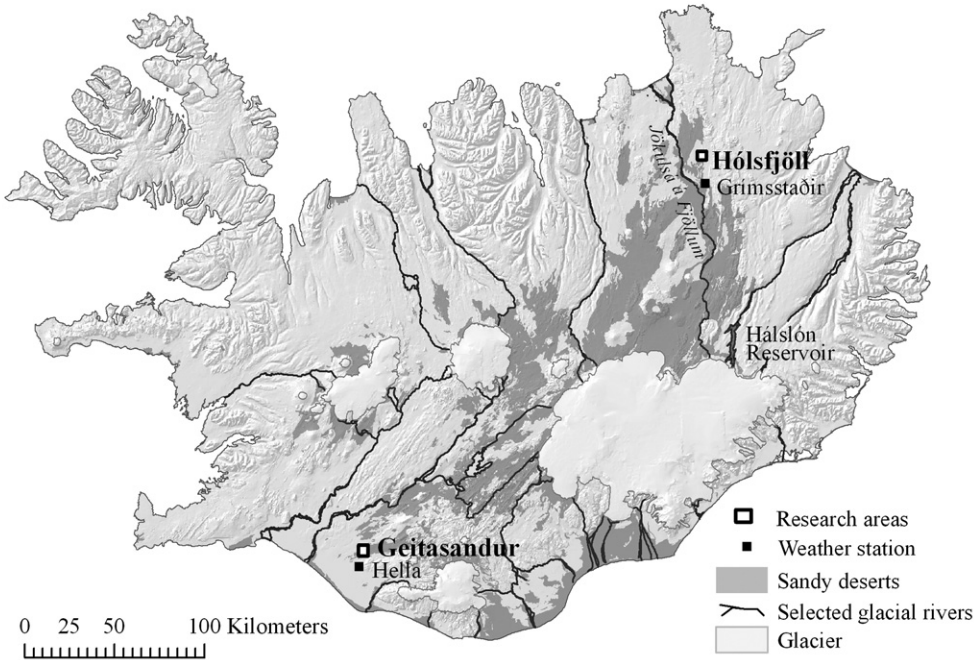

Fig. 1. Map of Iceland showing the location of the research areas at Holsfjöll and Geitasandur. The map shows the spread of sandy deserts (shaded) in Iceland, glaciers, and major rivers that have contributed to sand sources. The Halslon Reservoir is also shown, and the Grimsstadir and Hella weather stations.

stabilization priority areas, and are reclaimed with vegetation where possible. Many present day desert areas were formed because of advancing sand fronts (Arnalds, 2000; Arnalds et al., 2001a,b).

Quantification of rates of erosion/sand flux are important for understanding the aeolian behavior of the sandy systems and for developing soil conservation measures, especially where sand is moving over vegetated areas (advancing sand fronts) and/or where erosion is causing major dust production. In addition, the creation of a major hydroelectric reservoir, the Halslon Reservoir (see Fig. 1), calls for understanding of aeolian behavior of such materials to prevent environmental damage to the surrounding ecosystems. This reservoir has >50 km long shorelines which are >1 km wide in places. These shorelines are covered by loose sediments during much of summer, when water levels are low. The main purpose of the research reported herein was to develop and adopt simple methods to characterize surface transport during wind erosion under field conditions in Iceland, and to determine wind erosion transport rates on soils and sandy surfaces in Iceland. An additional impetus for the research was to obtain background information to aid in devising measures to prevent wind erosion from the shores of the Halslon Reservoir in East Iceland.

2. Materials and methods

2.1. Study sites

Two research sites were used: Holsfjöll and Geitasandur, representing two geographical areas in Iceland with contrasting climatic conditions and surface characteristics.

The Holsfjöll research location is located in Northeast Iceland (Fig. 1). The selection of the Holsfjöll site was based on: i) the existence of active advancing fronts in the area; the research location is situated within one of these fronts; ii) similarity to many major dust plume areas with substantial silt component (estimated 30–50%); and iii) similarities with the Halslon Reservoir area in environmental conditions, which includes dry climate, sandy soils and relatively high elevation (400 m a.s.l.). There has been massive soil erosion in the Holsfjöll area in general over the past centuries, partly because of sediments deposited by a nearby glacial river ('Jökulsa a Fjöllum', see Fig. 1) during catastrophic flooding, with sand moving northeast by dry SW winds, desertifying extensive areas in the path (Arnalds et al., 2001a,b). The experimental location has limited vegetation cover (Fig. 2). The materials are loose, poorly sorted silty and sandy materials with a mean grain size of 0.87 mm (dry-sieved). The area is relatively flat compared to many areas in Iceland, with no major hills or mountains closer than 10 km away.

The site is in an area with active wind erosion of Andosols as a result of an advancing front that had moved through the area, exposing about 3000 ha of soils in 1994. Most of the soils have since been blown off the area, but the experimental site was on location where soils and some vegetation cover still remained. The area is presently protected from grazing and several places in the vicinity of the site are subjected to large scale restoration efforts. The soils are a mixture of fine silt–loam and more coarse sandy–loam; being andic in nature. The soils do not contain phyllosilicate clays (layer silicates), and are therefore non-cohesive. The allophane clay present (estimated about 10% on average at the site) tends to form stable silt-sized

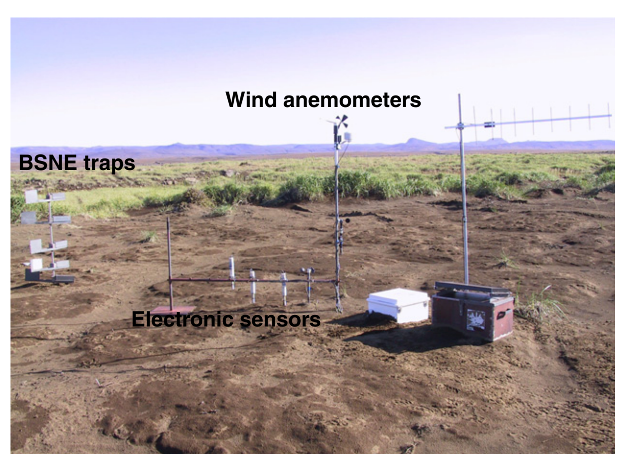

Fig. 2. The surface at the experimental site at Holsfjöll, with bare Andosol cover. Data storage module and battery inside boxes to the right, and an antenna for downloading data with a telephone.

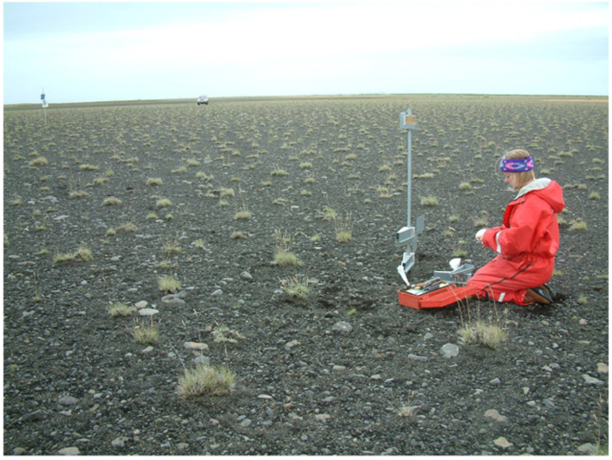

Fig. 3. Surface conditions at the Geitasandur experimental site, showing the more gravelly part of the experimental area. BSNE traps being emptied.

Table 1
Climatic conditions at weather stations near the experimental site. Data: Icelandic Met Office.

	Temperature °C			Rainfall mm		
	Annual	July	January	Annual	January	July
Holsfjöll[a]	0.7	8.9	−5	343	25	46
Geitasandur[a]	3.9	11.3	−1.5	1212	107	83

[a] Based on Grimsstadir weather station for Holsfjöll and Hella weather station for Geitasandur (1958–2005).

aggregates which are susceptible to wind erosion, as is common for Andosols (Dahlgren et al., 2004). The site is remotely located and only accessible by large all-terrain vehicles.

The second site, Geitasandur, is a restoration experiment area (Aradottir et al., 2008) in South Iceland (Fig. 1) on an unstable sandy surface (Fig. 3). There are two main sandy surface types on which aeolian sediment traps were placed: i) sandy gravel surface with 10–20% rocks >5 cm in diameter in otherwise loose coarse volcanic deposits (mostly 0.1–2 mm, with a mean grain size of 0.15–0.23 mm); and ii) sandy surface mostly without gravel cover (mostly volcanic materials 0.1–2 mm in diameter, with a mean grain size of 0.33–0.46 mm). The site has 40 restoration treatment plots, each being 1 ha in area, representing 9 treatments replicated 4 times and 4 untreated plots (control), the replications identified as A, B, G and H.

There is a marked difference in climatic characteristics between the sites (Table 1). The climate at Holsfjöll can be considered as low-arctic with annual mean temperature near 0 °C, having continental characteristics with periods in winter with temperatures <−20 °C and summer days with >20 °C. The climate of the Holsfjöll area is relatively dry compared to many other parts of Iceland, with <400 mm annual precipitation (Icelandic Met Office data). Geitasandur belongs to the humid South with >1200 mm annual rainfall and has considerably higher mean annual temperature (4 °C) which is heavily influenced by the relatively mild oceanic waters about 30 km south of the site. Frost can occur in any month at Holsfjöll, and is very common at both locations from September throughout winter.

2.2. Measurements at Holsfjöll

A variety of methods have been employed to determine aeolian sediment transport rates, such as models, wind tunnel experiments and measurements in the field with automatic sensors and traps (e.g., Zobeck et al., 2003). Measurements in the field are often problematic due to harsh environmental conditions (see e.g., Stout, 1998). Several types of aeolian sediment traps are available (see van Donk and Skidmore, 2001; Zobeck et al., 2003). The sediment traps used in the research presented here were the so-called BSNE traps (Fig. 2), also referred to as Fryrear traps (Fryrear, 1986). They are designed for minimal influence on wind flow and have proven to be quite effective in trapping saltation sand movement (Fryrear, 1986; Shao et al., 1993). The diameter of the opening facing the wind is about 10 cm^2, but trapped sediments are accumulated at the bottom of a collection tray. Each of these traps was mounted on a pole which was screwed into a specially modified car-wheel rim, which was buried into the ground.

Measurements were made at Holsfjöll over three seasons 2002–2004: i) June 10–November 26, 2002; ii) June 10–October 6, 2003; and iii) July 22–November 2, 2004. During winter the ground is mostly covered with snow, frozen or moist with relatively few sand storm events compared to the summers, given the highland location of this site.

Two methods in addition to the employment of BSNE traps were used to measure wind sediment transport at Holsfjöll: automated piezoelectric saltation sensors and sediment trapping ditch. The number of traps and sensors varied between the seasons because of initial technical problems. A backhoe was used to remove some vegetation cover at the site when the instrumentation was put in place.

A single pole was used at this site, but the number of traps used varied between the seasons: 2002 (five heights) 10, 30, 60, 100, and 150 cm; 2003 (three heights) 10, 30 and 60 cm; and 2004 (four heights) 10, 30, 60, and 100 cm height. The traps were emptied by a local farmer when sensors showed the occurrence of a dust storm, 13 times altogether (see Table 2 in results).

The automated piezoelectric saltation sensors (made by Sensit), produce an electric pulse when a sand grain bounces of piezoelectric material. The pulses are amplified and their number stored in a datalogger. We used 3 sensors in 2002 at 4, 8 and 28 cm height over the surface. During the years 2003 and 2004 one sensor was used at 8 cm height. Data were collected into a Campbell 21X datalogger in 2002 and a Campbell CR10 datalogger in 2003 and 2004. The instrumentation was solar powered. Data were obtained by a phone line, as the site is remote and inaccessible. Wind was measured at 2 m height, which is easily related to weather reports and has also been employed elsewhere (e.g., Riksen and Goossens, 2007). Humidity and air temperature at 2 m and 60 cm height were also recorded. The equipment was programmed to record parameters every 30 min, and calculating the mean and maximum wind speed for

Table 2
Wind erosion determined by BSNE traps at Holsfjöll over 13 collection periods during summer and fall seasons. Dates are presented as month/day.

Date	2002				2003					2004			
	7/20	8/19	9/9	11/26	7/15	8/3	8/28	8/29	10/6	7/28	8/7	9/9	11/2
	kg m^{-1}												
Amount	12	40	71	161	231	48	55	28	229	119	140	60	26
Total	284				591					345			

each 30 min period. In the occurrence of a wind erosion event, data was collected every 1 min, and subsequently averaged for each 10 min. There were many technical problems during the first phases of the experiment in obtaining reliable results, due to programming difficulties and electronic failures. A factor of 0.02 was used to convert Sensit pulses to kg m^{-1} based on previous Agricultural University of Iceland research (Sigurjonsson et al., 1999; Arnalds and Gisladottir, 2009). We selected kg m^{-1} as a unit because it relates well to real and practical situations working in the field with kg m^{-1} h^{-1} as flux unit.

In addition to the BSNE traps and sensors, about 1 m wide, 1 m deep and 10 m long ditch was dug in June 2002, perpendicular to the most common dry wind direction based on data from the local weather station (Grimsstadir), and communication with the local weather station personnel. Subsequently it was observed how rapidly it filled up again by aeolian materials.

2.3. Measurements at Geitasandur

One set of BSNE traps were left at four different locations at Geitasandur within barren, untreated (control) plots (A, B, G, and H replications), two (A and B) at sandy gravel sites and two (H and G) at sandy sites with low cover of gravels on the surface. Three Fryrear traps were used on each pole at 10, 30, and 120 cm heights. The traps were left in place from March 2004 to May 2007 the year around. The sites were visited every month during October–April, and every week during May–September. Traps were only emptied when about 10 g or more was present in the bottom trap. The traps were emptied 11 times during this period, after the occurrence of wind erosion events which were also monitored by local Soil Conservation Service agents in the area. The Geitasandur research area periodically receives snow, which usually melts away within days or weeks. Sand storm events can occur the year around, including winter. No electronic equipment was used to measure saltation or wind speeds, the purpose for this part of the experiment being to quantify saltation movement at this site in general to compare the results with the more detailed research at the Holsfjöll experimental site.

2.4. Determination of sediment movement using BSNE traps

The sediment movement for each collection period for the BSNE traps was calculated based on the average height distribution curve at each site (see curves in Fig. 4). The amount was determined by adding up the transport for each 10 cm height interval of the curve over 1 m wide line (10×100 cm or 1000 cm^2). A factor of 0.9 compared to transport at 10 cm height was chosen for the lowest interval based on results obtained by the automated saltation sensors. They were placed at 4 cm, 8 cm and 28 cm height in 2002, and the 8 cm sensor gave maximum movement and the 4 cm sensor gave 85–90% of the 8 cm sensor impacts. At the Geitasandur site a factor of 1 was chosen for 0–10 cm relative to movement at 10 cm based on the initial steepness of the slope and previous measurements of similar surfaces with automated instruments near the surface (Sigurjonsson et al., 1999).

In some cases, the lowest trap overfilled at both Holsfjöll (one storm in 2003) and Geitasandur (one storm in 2005) and these were excluded from determining the average height distribution, as were collection periods with low amounts of dust collected (<50 g in the lowest trap). Total sediment transport was calculated based on the amount in the 30 cm trap and the average distribution curve if the lowest trap had overfilled.

3. Results

The automated instruments at Holsfjöll recorded 11 storms during the three years the experiment lasted that could be used for further analysis. For the BSNE traps, there were a total of 13 time intervals at Holsfjöll in one sampling unit and 11 intervals at Geitasandur for four sampling units (A, B, H, and G; $4\times11=44$ sediment movement results at Geitasandur).

3.1. BSNE traps — sediment transport height curves

The height distributions of sediments collected in the BSNE traps, which is used as the basis for quantifying the sediment movement, are presented in Fig. 4a–c. Datasets obtained when traps overfilled or little was collected in the 10 cm trap (calm periods) are excluded. The curves are similar for the most part. There is a notable exception for the curve with a high 60 cm point at the Holsfjöll site (Fig. 4a), but this period was relatively calm with only 78 g in the lowest trap. The same applies for the lowest points at 60 and 100 cm (71 g in the 10 cm trap). Other data points for the Holsfjöll curve have 111–447 g in the lowest (10 cm trap) and the curves are similar. There are more curves for the 4 locations at Geitasandur and some notable differences between the 30 cm traps. However, when averaged for each of the four locations, the graphs are quite similar (Fig. 4c).

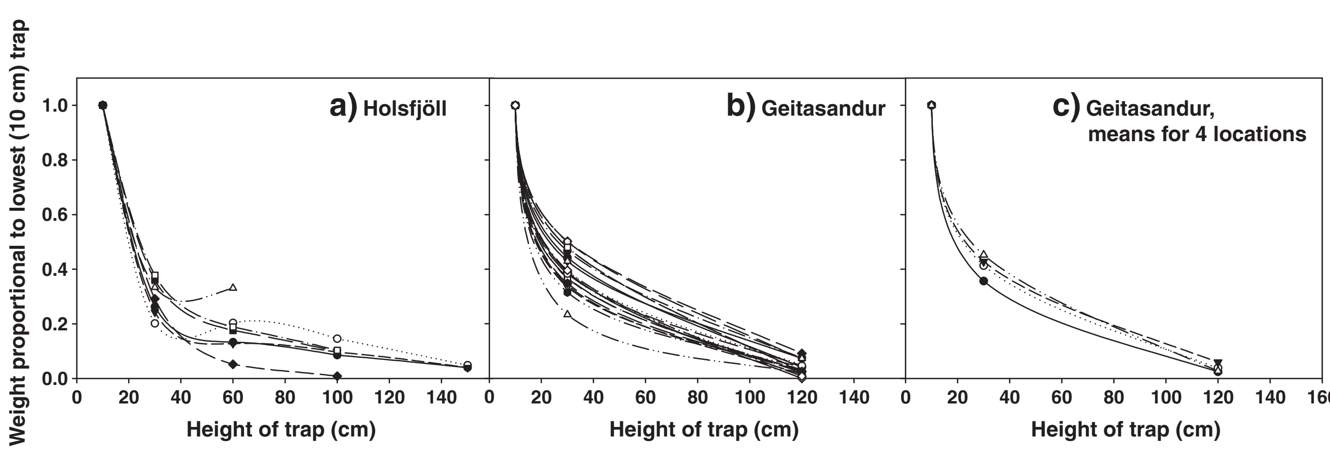

Fig. 4. Height distribution of aeolian sediment transport collected in BSNE traps at Holsfjöll (left) and Geitasandur (middle), also showing variability between the four Geitasandur sites (right).

Table 3
Wind erosion at 4 locations (A3, B9, H3 and G9) at Geitasandur determined by BSNE traps for about 3 year long period. Dates are presented as month/day.

Date	2004				2005	2006				2007	
	4/20	9/16	10/8	10/27	7/28	2/20	6/22	9/12	11/26	4/10	5/29
	kg m^{-1}										
A3	24	185	14	139	83	106	79	7	223	77	17
B9	7	78	10	38	159	71	32	4	111	29	7
H3	37	355	45	67	680	178	20	2	153	37	7
G9	43	218	28	156	658	61	27	6	154	56	10
Average yr^{-1}	360				395	308				60[a]	
Sandy gravel (A, B)	246				121	316				65[a]	
Sandur (H, G)	474				669	301				54[a]	

[a] Measurements last only to end of May.

3.2. BSNE traps — quantification sediment transport

The total transport each summer season at Holsfjöll (Table 2) was 284–591 kg m^{-1} with each collection period ranging between 12 and 231 kg m^{-1}. Early summer 2002 was relatively calm, but dust storms were common in the fall of 2002. Dust storms occurred both during early summer and in the fall of 2003, and early summer 2004. Note that aeolian sediment transport was not measured during winter at Holsfjöll.

Windblown materials were collected by BSNE traps at Geitasandur the year around (Table 3). The average transport per year ranged between 308 and 395 kg m^{-1}. Highest values were recorded for the sandy surfaces (H3 and G9) with >600 kg m^{-1} during the October 2004–July 2005 period, which contained many dust storms, mainly in the fall of 2004 (Arnalds and Metusalemsson, 2004).

3.3. Automated saltation sensors

The 11 storms recorded at Holsfjöll with the Sensit piezoelectric sensors are listed in Table 4. The storms ranged from less than an hour to almost 7 h (409 min) with a wide range of temperatures (−2.1 to +18.1 °C) and relative humidity (22–77%; data not shown in the table). Average maximum wind speeds for each minute during each storm ranged from 11.2 m s^{-1} to 15.5 m s^{-1} with gusts up to 16.5 m s^{-1}. The storms began as early as 5:00 in the morning and also in the afternoon, but one short storm initiated at midnight (storm 8).

Examples of three storms, nos. 1, 7 and 8 are presented in Fig. 5. Threshold velocities were generally between 9 and 10 m s^{-1} (measured for 1 min at 2 m height) except for storm 8, where threshold was slightly above 6 m s^{-1}. Storms 3, 4 and 9 are short storms with similar curves as storm 8 shown in Fig. 5c, while storms 1, 2, 5, 7, 10 and 11 are longer. Storm 1 has relatively narrow distribution representing similar environmental conditions throughout the storm. Storm 7 is typical for storm with changing environmental conditions, where rain begins at the last phase of the storm, shifting the data points downwards and to the right with more wind required to move the sand. Storm 8 is short, not very intense and with erratic distribution.

The transport during the storms measured by the automated instruments ranged from 5 kg m^{-1} (storm 3) to 312 kg m^{-1} (storm 7) (Table 4). The mean flux ranged from 3 to 43 kg m^{-1} h^{-1} with maximum measured flux of 206 kg m^{-1} h^{-1}. The large differences between maximum and mean flux reflect the variable flow of sand during each storm where high or maximum flow is maintained only for short periods (see also Fig. 5).

The individual storms were used to calculate a multiple regression equation using maximum 10 min average wind speed at 2 m height, relative humidity, temperature at 2 m and 60 cm heights, heat difference between 2 m and 60 cm, and time of day, using 10 minute means. The equation obtained is:

$$\textit{Sensit pulses} = \exp(-0.394 + (0.137 \times \mathtt{W}) - (0.003 \times \mathtt{R\%}) - (0.029 \times \mathtt{T}_{2m}) + (0.051 \times \mathtt{T}_{2m-60\ cm}))$$

where Sensit pulses are counted by minute, W is maximum 10 min average wind speed at 2 m height, R% is relative humidity, T_{2m} and T_{60cm} are temperatures at 2 m and 60 cm height respectively. A total of 267 10 minute means resulted in an equation with $r^2 = 0.676$, which is quite high considering the variability in the dataset exemplified by Fig. 5. Simple regressions for individual storms (wind speed vs erosion) resulted in only 5 storms having $r^2 > 0.5$. The negative T_{2m} factor can be explained by the effect of frost in lowering the threshold velocity. Using typical values for the equation parameters as well as

Table 4
Storms measured at Holsfjöll in 2003 and 2004 with automated sensors.

Storm	Date[a]	Duration	Temp range	Wind speed		Total	Flux	
				Max average[b]	Max gust[b]	Transport	Mean	Max
No	m/d/yr	Min	°C	m s^{-1}		kg m^{-1}	kg m^{-1} h^{-1}	
1	06/26/03	333	13.3–16.4	13.3	15.4	58	8	88
2	06/27/03	272	11.9–18.1	13.0	15.2	40	3	66
3	09/04/03	58	14.0–15.0	13.5	na	5	3	16
4	09/17/03	102	2.0–3.5	15.5	na	12	3	30
5	09/20/03	216	4.9–7.2	14.8	16.4	87	18	130
6	09/20/03	54	6.8–10.0	12.5	14.4	19	14	106
7	09/21/03	409	−0.7–1.3	15.0	16.5	312	43	206
8	09/22/03	70	−2.1 to −1.8	11.2	12.2	20	12	73
9	07/30/04	82	14.1–16.0	12.8	13.8	11	3	31
10	07/31/04	158	13.6–15.6	13.2	14.6	36	12	66
11	07/31/04	227	14.9–16.4	12.9	14.5	43	9	56

[a] Month/day/year.
[b] Maximum 10 min average and maximum wind speed in storm.

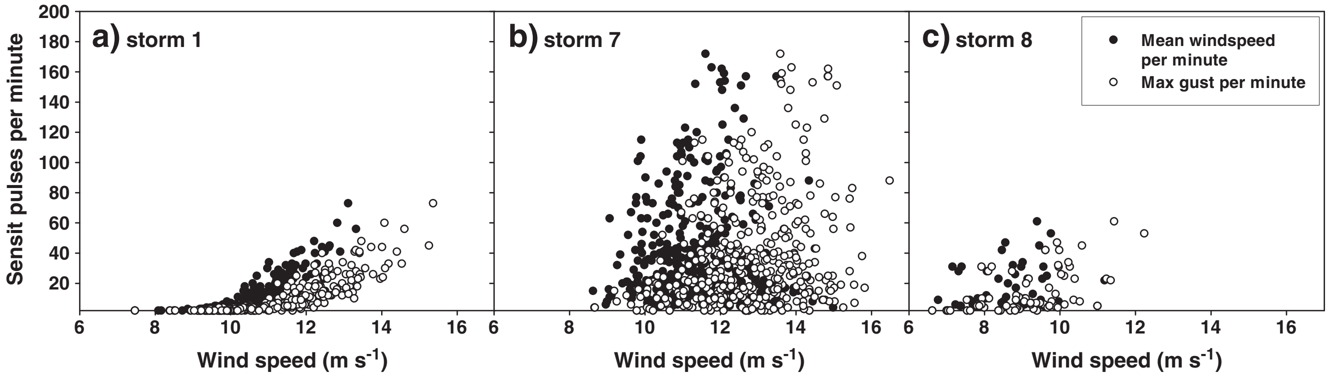

Fig. 5. Examples of three storms (1, 7 and 8) at Holsfjöll measured with automatic instruments.

extreme observed values during storms, we get a range of erosion values as a function of wind speed up to 22 m s^{-1} (Fig. 6). The results show that during a 20 m s^{-1} extreme storm, transport in the range of 50–150 kg m^{-1} h^{-1} can be expected, and a flux of >250 kg m^{-1} h^{-1} during 22 m s^{-1}.

3.4. Sediment trapping ditch

The 1 m deep sediment ditch was about half-full after one year (Fig. 7) and had accumulated what corresponds to about 500 kg m^{-1}, which is considerably more than the 284 kg m^{-1} measured by the BSNE traps over the summer season. This indicates considerable sediment transport after the BSNE traps were removed in November 2002, but could also suggest that the ditch is more efficient in trapping sediments than the BSNE traps. In July 2004, two years after the ditch was dug, it was completely full, corresponding to >1000 kg m^{-1} transport while BSNE traps showed about 875 kg m^{-1} transport over the two periods (2002 and 2003) the traps were left in place. It should be noted that the BSNE traps do not collect creep materials which the ditch does, but creep materials are commonly of the order of only 10–30% of saltation materials (Dong and Quian, 2007).

4. Discussion

4.1. Aeolian transport rates during storms

The average sediment transport during storms at the Holsfjöll area, presented in Table 4 gives a good indication of what can be expected for storm events involving dry coarse-grained Andosols in Iceland and also within major dust plume areas. These conditions are typical for the progression of advancing fronts causing the most destructive erosion events in the country. Mean storm events during moderate wind speeds (Table 4), show amounts ranging from 5 to >300 kg m^{-1}. The regression equation (Fig. 6) shows that events of >250 kg m^{-1} h^{-1} can be expected with >1000 kg m^{-1} during an extended extreme event (several hours); conditions which did not occur during the experiment at Holsfjöll.

There is a discrepancy between the Sensit and dust trap measurements, where Sensit measurements during the 2002 and 2003 storms clearly give much higher values than recorded by the traps during the corresponding, but longer periods. This discrepancy seems greater for longer storms where there are extended periods of relatively low wind speeds (9–11 m s^{-1}). The reason for this is most likely noise in the automated equipment (extra pulses), resulting in high total

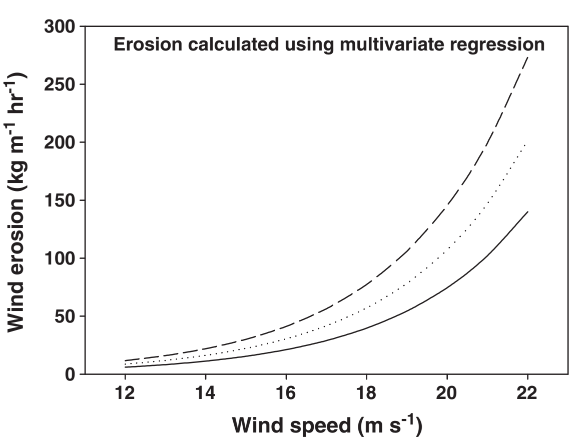

Fig. 6. Calculated range for sediment flow for Andosol surfaces in Iceland based on results from Holsfjöll, NE Iceland. Note that during storms the wind speeds vary considerably, not maintaining maximum wind speeds for extended periods.

Fig. 7. Sediment ditch at Holsfjöll after the first year. It was originally 1 m deep and it filled up in 2 yrs, indicating >1000 kg m^{-1} sediment transport during that time.

pulse values and correspondingly high total sediment transport values in longer storms. However, this noise has minimal effect during higher rates of erosion at higher wind speeds and it does therefore not affect the regression presented above. In addition, we experienced frequent problems with our apparatus, such as programs, electricity, etc., which can be expected under the severe environmental conditions in the Icelandic highlands. This shows the difficulty in using the automated equipment for quantifying erosion over extended periods, while the equipment is ideal for identifying threshold values and obtaining parameters for modeling wind erosion under these conditions. It has been noted by others that sediment traps give a good indication of overall transport while the automated instrumentation is better suited for studying individual storms (e.g., Barchyn et al., 2011).

There is a large difference between the mean and max flux ($kg\ m^{-1}\ h^{-1}$) within each storm with max flux being 4.8 to 22 times larger than the average flux. This shows that maximum wind speeds and saltation flux is only maintained over part of the storm duration. These results correspond well with results of Stout and Zobeck (1996a) who reported that saltation was only maintained 10–27% of each storm; thus the majority of soil movement and dust generation occurs for the minority of the total time.

Our results for maximum expected aeolian transport ($>1000\ kg\ m^{-1}$ for several hours, $>20\ m\ s^{-1}$ wind) are in good agreement with measured sand flow of sandy soil materials over vegetated area at the shores of the Blanda reservoir in North Iceland where 2000–3000 $kg\ m^{-1}$ were transported from the shore over a vegetated area during a major storm of $>20\ m\ s^{-1}$ (calculations based on Vilmundardottir et al., 2010). Model calculations for similar conditions as at Halslon for both long term transport and during major storm events (Kjaran et al., 2006) have generally resulted in higher values than we observe in the field.

The higher range values recorded by the automated instruments, 106–206 $kg\ m^{-1}\ h^{-1}$ and $>250\ kg\ m^{-1}\ h^{-1}$ calculated for storms $>20\ m\ s^{-1}$ are similar or higher to those reported in many other sandy areas in the world. Comparable examples include sand beaches in Indiana, USA (Bennet and Olyphant, 1998) with max flow of $>100\ kg\ m^{-1}\ h^{-1}$, sandy area in Sahel with 15–150 $kg\ m^{-1}\ h^{-1}$ flow in each storm (Sterk and Stein, 1997), but example of lower value is about 30 $kg\ m^{-1}\ h^{-1}$ reported for the Mu Us Desert in China (Fanmin et al., 2006).

4.2. Long term aeolian transport

The measuring periods for the BSNE traps at Holsfjöll and Geitasandur ranged from one day to several months, depending on weather conditions and frequency of trips to the research sites. The maximum sand flow during the sampling periods, about 230 $kg\ m^{-1}$ at Holsfjöll and 223 and 159 $kg\ m^{-1}$ at Geitasandur sandy gravel surface are rather similar, in spite of large difference between the surface types. Highest values are reported for the sandy surface at Geitasandur, $>600\ kg\ m^{-1}$ (G9 and H3 plots). Expected annual flux for sandy areas represented by the research sites are of order 100–>600 $kg\ m^{-1}$. This gives a good indication of what can be expected during average years within sand stabilization areas. This movement does affect environmental conditions in the vicinity of these surfaces, even at >100 km distance, with dust pollution and high aeolian deposition rates (Arnalds, 2010). The relatively large amount of aeolian materials transported in the humid South Iceland represented by Geitasandur is noteworthy. It shows that active aeolian processes are not confined to the arid regions of the Earth. Furthermore, these values of $>600\ kg\ m^{-1}\ yr^{-1}$ transport explain why the advancing sand fronts can be as active in the South, in spite of the humid climate, as is witnessed by the extensive desertified areas in the region.

4.3. Advancing sand fronts and stabilization considerations

Stabilization efforts on unstable surfaces in Iceland show that with seeding and fertilizing, a stable surface made of biological soil crust and vascular plants is formed, that can facilitate natural succession of these surfaces (Gretarsdottir et al., 2004). This succession can easily lead to the formation of the native birch forests in lowlands (Aradottir and Arnalds, 2002). However, the sandy surfaces, represented by the Geitasandur sandy surface, have proved to be more difficult to stabilize than the gravelly surfaces or Andosol remnants. Restoration efforts of these surfaces usually involve initial efforts to halt sand movement with lymegrass (*Leymus arenarius*), which is tolerant to sand movement and often forms small dunes. These actions are subsequently followed by measures to introduce more permanent natural vegetation (Gretarsdottir et al., 2004).

Okin et al. (2006) concluded that saltation processes are most important at patch scales at short time-scales, but they can also be important at landscape scales on longer time-scales. Advancing sand fronts in Iceland are a good example of this, with short term encroachment in single storms but large scale landscape changes with continued activity. The advancement further increases with fetch distance, enhancing the amount of material transported (Gillette et al., 1996). The advancement of encroaching sand fronts in Iceland is poorly documented but clearly visible on satellite imagery of Iceland. The advancement is often associated with few but major storm events, based on our experience and scarce literature (Arnason, 1958; Arnalds et al., 2001a,b). Based on this research, previous field experience, and literature (e.g., Sigurjonsson et al., 1999; Arnalds et al., 2001a,b; Gisladottir et al., 2005; Vilmundardottir et al., 2010), we postulate three scenarios under which these fronts advance: i) a result of direct sand advancement over vegetated areas, either from permanent or temporary sand sources; ii) soil materials from the abraded Andosols and sandy materials from external sources are combined; and iii) the blown materials are purely Andosols materials with limited external sand sources (exemplified by the Holsfjöll research site). Our results show that rapid advancement can be expected under all these scenarios, while a large external sand source (scenarios i and ii above) exemplified by the Geitasandur sandy surface is likely to maintain erosion for a longer time. Under scenario iii, the windblown materials will eventually be depleted, making restoration efforts easier, while sand can still be advancing further down the pathway of the front.

The results presented here explain why advancing sand fronts have advanced such long distances in Iceland during periods of activity, with active available sand sources and unfavorable climate. During such conditions, aeolian saltation movement of $>1000\ kg\ m^{-1}$ can be expected with dry winds $>20\ m\ s^{-1}$ lasting for many hours or days. This is much more transport than natural ecosystems can absorb on the surface, although the amount depends on the cover and height of the vegetation (Maun, 1998; Kent et al., 2001). The results presented here were used for giving scenarios for sand stabilization preparations on the shoreline of the Halslon Hydroelectric Reservoir in East Iceland (Fig. 1), which includes a 5 m wide sediment trapping ditch along the shoreline, the use of irrigation systems and soil stabilization materials.

4.4. Height distribution curves and the 'one trap method' for measuring wind erosion

The curves have a less steep gradient with more sediments transported at >20 cm height (Fig. 4) than normally is presented in the literature, where the curve has often approached minimal transport above 10–20 cm height (see e.g., Stout and Zobeck, 1996b; Zobeck et al., 2003; Ellis et al., 2009). Some of the materials collected in the higher traps (>60 cm) may be suspended particles (thus not saltation). However, the sediment trap ditch at Holsfjöll indicates similar but more transport compared to the dust trap measurements, confirming that the dust trap measurements are reasonably representative of the saltation movement alone. Our field experience during storms suggest that saltation can easily reach >100 cm height and sediments collected in the 60 and 120 cm traps can easily be >1 mm in diameter. The high proportion of materials collected at 30 cm and higher cannot be attributed to excessive wind speeds (>20 m s^{-1} at 2 m height), as that was not the case at Holsfjöll during the experiment, and the curves show similar behavior for each site independent of storm intensity. A possible explanation is the low density of both the soil and sandy materials, with the occurrence of andic aggregates in the soils (see Dahlgren et al., 2004) and a high proportion of 0.9–1.5 g cm^{-3} volcanic ash grains in both soils and the sandy materials.

In this research, we employed a simple method for calculation of total sediment transport based on the transport height curve constructed from the amount sampled in 3–5 BSNE traps at different heights. Our present and previous research shows that for a given site, this height curve tends to be relatively stable, independent of storm intensity. This suggests that after the curve has been established, a single trap could be used for measurements. As traps placed close to the surface (e.g., 10 cm height) tend to fill up rapidly on unstable surfaces, the single trap could be placed higher above the surface, for extended periods without overfilling, still giving quantitative measurement of aeolian movement with reasonable accuracy. We used the curve method for quantifying soil transport for the periods when the lowest traps overfilled by using amount of sediments trapped in the traps placed higher. Ellis et al. (2009) recommended that flux profiles should be established with traps at as many heights as possible, and we concur with his recommendation, while 3 traps seem to give reasonable approximation. With this method, a large number of single traps can be placed within an extensive research area for a better general overview of the behavior of aeolian activity. The methodology used here also has the benefit of being simple, not requiring complicated modeling or mathematical equations, allowing for general and practical use of the method by specialists in a range of scientific fields involved in soil stabilization on the ground as well as environmental research.

5. Conclusions

Much of the literature on wind erosion rates is concerned with models, but this paper focuses on measuring wind erosion under natural conditions on the ground using simple methods. The results show the magnitude of aeolian sediment transport in Iceland over extended periods (seasons/years) of 100–1000 kg m^{-1} and up to >1000 kg m^{-1} during infrequent but detrimental storm events. This magnitude shows possible scenarios for devising counter measures along the shores of hydroelectric reservoirs. It also explains why advancing sand fronts have been very detrimental in destroying Icelandic ecosystems over recent centuries. Conditions allowing for a continuously recharged sand source, such as by glacial rivers, at shorelines of lagoons, and volcanic deposition, further intensify the destructive force of the advancing sand fronts.

The intensity of aeolian sediment transport events causes saltation traps placed close to the ground to fill up quite rapidly, thus making measurements difficult. We point out that after establishing a sediment height distribution curve at a given location, only one trap is needed and could be placed high enough for preventing rapid filling. This would allow for measurements over long periods without frequent visits to field sites, and also wide distribution of traps for collecting data at a landscape scale.

The occurrence of frost and the subsequent formation of needle-ice seems to help to detach soil particles on the surface, lowering the threshold velocity from 9 to 10 m s^{-1} (2 m height) to about 7 m s^{-1} at the Holsfjöll research site (Fig. 5c). This effect of frost and needle-ice was suggested by Migala and Sobik (1984) in Spitzbergen. This explains local experience in Iceland of the occurrence of high intensity sand storms during winter, when there is no snow cover.

The Holsfjöll research site represents areas where Andosols are being eroded by wind in a semi-arid environment (<400 mm precipitation), showing very active wind erosion without an external sand source. These conditions are common in Northeast Iceland (Arnalds et al., 2001a). The Geitasandur research area has about 1200 mm annual precipitation. In spite of the humid climate, wind erosion rates are high, exceeding 600 kg m^{-1} in some years. This shows that intense wind erosion is by no means limited to the arid areas of the world, with Iceland ranking among the major dust sources on Earth (Arnalds, 2010).

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