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PLEASE CITE THE PUBLISHED VERSION

<https://doi.org/10.1002/esp.4407>

PUBLISHER

© Wiley

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

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<https://hdl.handle.net/2134/32966>.

The dynamic effects of sediment availability on the relationship between wind speed and dust concentration

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Abstract

Where sediment supply is unlimited, previous research suggests that a strong, positive relationship between wind speed and dust concentration exists at the event-scale. This relationship can break down if sediment availability is limited or changes during an event. This paper explores the dynamic effects of sediment availability on the relationship between wind speed and dust concentration using data from 9 high-latitude dust events recorded in Iceland. Of these events, 6 showed a strong positive relationship between wind speed and dust concentration. For the remainder, the relationship breaks down periodically during the event due to changing surface moisture conditions and atmospheric humidity. Results suggest a need to understand how spatial and temporal changes in humidity, surface soil moisture, soil texture and threshold velocity interact and control sediment availability for dust emissions in all environments, including at high latitudes.

Keywords

Dust storm

Dust concentration

Iceland

Soil moisture

Dust model

Introduction

Mineral dust emissions can have a substantial effect on the Earth's system through their impact on the lithosphere (Ridgwell, 2002), atmosphere (Tegen et al., 1994), biosphere (Ravi et al., 2011), hydrosphere (Crusius et al., 2011) and cryosphere (Krinner et al., 2006), and on the ways in which these components interact (Jickells et al., 2005). Dust emissions, particularly as dust storms, can also impact human health, transport and the economy (Tozer and Leys, 2013, Goudie et al., 2014).

The broad-scale global distribution of dust sources is well-understood (Prospero et al., 2002), and there is an increasing body of knowledge about regional (basin) to local (sub-basin) scale dust sources (Bullard et al., 2008). Research on dust emissions, transport and deposition takes place at a range of temporal scales from the long-term Quaternary record (Kocurek, 1998; Zhang et al., 1999), through decadal variations driven by changes in climate indices (e.g. Southern Oscillation Index) and drought (Middleton, 1985), to seasonal patterns (Reheis, 2011). There has also been a focus on very short-term, turbulence-driven dust emission processes (Stout, 2010). Although dust events have been quite well-studied with respect to identifying dust sources, they have received comparatively little attention with regards to their event-scale evolution. For example, very few studies have followed dust emission processes from the start to the end of an individual dust event. Those that have taken this approach and examined diurnal patterns of activity have elucidated useful insights in to the drivers of aeolian sediment transport (Stout, 2010, 2015).

At the event-scale, these temporal drivers include transport capacity, usually measured as surface wind speed (Gillette, 1978), and sediment supply and availability (Bullard et al., 2011). For dust events, where sediment supply is unlimited and wind speed is above threshold there should be a relationship between dust concentration and wind speed (Shao et al. 1993; Marticorena and Bergametti, 1995; Kok et al., 2012) and this is often used as the main driver of dust concentration in model predictions (Yin et al., 2005; Lu and

Shao, 2011). Where there is no relationship between wind speed and dust concentration, or the relationship is weak, other factors, such as sediment availability, are likely to be having an impact on dust emissions (Ravi and D'Odorico, 2005; Bergametti et al., 2015). The availability of sediments for entrainment can be modified by surface soil moisture (Chepil, 1956; Hugenholtz et al., 2009), humidity (McKenna Neuman, 2003), water table fluctuations (Reynolds et al., 2007), the formation of lag deposits (Nickling and McKenna Neuman, 1995; Bullard and Austin, 2011), surface crusting (Ishizuka et al., 2008; Baddock et al., 2011), and changes in vegetation density and type (Munson et al., 2011). The drivers do not operate in isolation. For example, humidity can alter the threshold wind speed required to entrain particles (McKenna Neuman, 2003).

It has been suggested that the controls on aeolian transport are similar regardless of the regional context and operate in all aeolian environments from the tropics to the poles (Bullard, 2013), however much of the work that supports this assertion has focused on the transport of sand-sized material rather than finer sediments (e.g. McKenna Neuman, 2003; 2004). The saltation of sand-sized material is an important driver of dust emissions on a variety of surfaces (Shao et al., 1993; Cahill, et al. 1996; Grini and Zender, 2004) and has been used to infer that the dust is locally-sourced rather than from a distal source (Parajuli et al. 2016). However, dust emissions can also occur without saltation (Loosemore and Hunt, 2000; Macpherson et al. 2008). Of the studies that have examined the controls on dust emissions, the majority have been conducted in the sub-tropics despite the fact that the high latitudes are increasingly recognised as an important contributor to the global dust budget (Bullard et al., 2016; Groot Zwaafink et al. 2016). The process-based research that has been focused on the high latitudes is very limited (Arnalds et al. 2016; Bullard et al. 2016). None of the studies of dust emissions carried out at the sediment source in the high latitudes has presented high resolution measurements of both wind speed and dust concentration (Nickling, 1978; Dagsson-Waldhauserova et al., 2014). Some of the factors which affect event-scale sediment availability, such as surface soil moisture, may be more persistent at high latitudes (Dai et al., 2004). For

example, whilst the Saharan dust emission zone receives $< 35 \text{ mm yr}^{-1}$ (over 32 days), dust sources in southern Iceland receive 1500 mm yr^{-1} (over 215 days) (Mitchell et al., 2004). The aim of this paper is to examine how changes in sediment availability affect the relationship between wind speed and dust concentration at a high-latitude dust source

Methods and Analysis

The aim was tested using field measurements of dust emissions and wind speed at Markarfljot ($63^{\circ}32'49.64''\text{N}$ $20^{\circ}01'30.50''\text{W}$ 8 m asl), a major dust source in southern Iceland (Arnalds et al., 2001). Markarfljot is a large glacial meltwater river which is fed by the Eyjafjallajökull and Mýrdalsjökull glacial-volcanic systems. Average winter and summer temperatures are -1°C and $+9^{\circ}\text{C}$ respectively. Average wind speeds at 10 m are 7.8 m s^{-1} in winter and 5.5 m s^{-1} in summer. Annual total rainfall is $>1500 \text{ mm}$ and average daily relative humidity is $>80\%$. Dust activity is associated with the saltation and suspension of material from palaeo-jökulhlaup deposits (Larsen, 2009) with well-sorted sediments ($200\text{--}800 \mu\text{m}$), and sediment-supply is assumed to be unlimited.

A TSI DustTrak DRX Aerosol Monitor 8533 was mounted on a tripod at 1.4 m. The DustTrak is a laser photometer and was used to measure average dust concentration over 10-second intervals. There is some uncertainty regarding the maximum particle size (over $15 \mu\text{m}$) that the DustTrak can detect (Goossens et al., 2012) and for this reason only PM_{10} values were used in this analysis. Wind speed was measured using a Vector A-100R cup anemometer at the same height and sampling interval as the DustTrak.

During this experiment, there were no instrumented measurements of saltation, however, there were strong indications that most dust particles are locally sourced. First, a modified Fryrear sediment trap (Fryrear, 1986; Shao et al., 1993) deployed at 0.3 m above the surface trapped sediments during all dust events with a modal grain size of $373 \mu\text{m}$ indicating active saltation at

source. Second, backwards air parcel trajectories calculated using HYSPLIT (Draxler and Hess, 1997, 1998) indicate that there is a very limited range of upwind sources from which the material could be transported due to the wind direction associated with each event (Figure 1). For four events, the immediate upwind trajectory travelled at least 20 km over water before reaching the source. Two events were driven by northerly winds and the remaining three by south-easterly winds where there may have been some potential for upwind entrainment and transport of material.

<<Figure 1: 12 hour backwards HYSPLIT trajectories run at 100 m start height using 0.5° GDAS daily reanalysis data for all dust events in Table 1 >>

Secondary humidity data were obtained from an Icelandic Meteorological Office weather station at Markarfljot (6 km from field site) and are considered representative of field site conditions. The nearest rainfall measurements available were from Öundurhorn (25km from field site) which is considered too distant to represent local conditions. For this reason, on-site field observations for rainfall (presence/absence) are used.

Background dust emissions were determined by deploying the DustTrak on 20 days where no dust was visible and found to be in the range $10\text{--}40\text{ }\mu\text{g m}^{-3}$. The onset of a dust event is defined here as where PM_{10} concentrations averaged over 1 hour exceed $250\text{ }\mu\text{g m}^{-3}$. Threshold wind velocity at 1.4 m is approximately 6.5 m s^{-1} .

For all events (Table 1), the relationship between wind speed and dust emission concentration was tested using the Spearman's Rank correlation coefficient. Events for which the correlation is >0.8 were combined to create a site-specific wind speed-dust emission model (Figure 2). Where points fall within the 95% confidence intervals of this model a significant relationship between dust concentration and wind speed can be inferred. Where there is no significant relationship, or where the majority of observations do not fall

within the 95% confidence limits, it is assumed that the dust concentration being observed is controlled by factors other than wind speed. For example, in locations with limited sediment supply or availability (Bullard, 2013) we may expect low dust concentrations despite the occurrence of high wind speeds (points falling above the upper confidence limit), because there is less sediment being entrained than would be predicted from the wind speed. Conversely, where dust has originated at a different source to that being monitored, there may be high dust concentrations at low wind speeds which indicate dust in transport (points lie below the lower confidence limit). These factors can be elucidated by examining the temporal variation in dust emissions and other relevant environmental drivers.

<<Table 1: Event characteristics, wind speed versus PM₁₀ concentration and Spearman correlation coefficients for all events.>>

[See end of document]

<< Figure 2: PM₁₀ concentration as a function of wind speed for three events (Events 2, 3 and 8) where wind speed and dust concentrations are strongly positively correlated a) 5 minute averaged wind speed and PM₁₀, and b) 10 second average wind speed and PM₁₀ (including 95% confidence intervals). Points inside the confidence intervals are related to wind speed fluctuations (TCL – Transport capacity limited). Points outside the lower confidence bound are assumed to be from distal sources (e.g. not local) and points outside the upper confidence bounds are supply/availability limited.>>

Results

Nine dust events were recorded during a 6-week monitoring period (23 May – 4 July 2015, Table 1). These events varied significantly in magnitude, duration and intensity. Average PM₁₀ concentrations (based on the time the source was active) ranged from 269-2654 µg m⁻³. The maximum 10-second PM₁₀ concentration recorded was 8860 µg m⁻³. Durations of events ranged

from 2 to >14 hours. This paper focuses on the relative temporal dynamics of dust events and not absolute dust emissions although maximum concentrations are the same order of magnitude as those recorded during dust events in other locations using the same type of instrument (Table 2)

<<Table 2: Maximum DustTrak concentration ($\mu\text{g m}^{-3}$) recorded during dust events in a selection of high latitude and sub-tropical regions.>>

Of the 9 events, 3 events show a significant positive relationship (> 0.8) between wind speed and dust concentration (Events 2, 3 and 8). Three events (event 4, 6 and 7) have strong positive correlations ($0.6 < p < 0.8$), however are excluded from further analysis because they lack a sufficient range of values to allow us to judge whether or not they are solely controlled by wind speed. This lack of range may also explain the slightly lower correlation values for these events.

An event specific model for events 2, 3 and 8 is presented in Figure 2. In order to determine the nature of the best-fit mathematical relationship between the two variables, 5-minute average wind speed and dust concentration were plotted. This is shown to be a cubic model. In order to determine upper and lower 95% confidence bounds, the cubic model was applied to the 10-second average data. The assumption made is that dust concentrations that fall within this envelope are controlled by wind speed. Points outside this envelope do not follow the expected relationship between wind speed and PM_{10} concentration, therefore other factors are potentially controlling emissions. The relationship between wind speed and PM_{10} concentration for all events is shown in Figure 3 where observations within the envelope are in black and outside in red/blue. Red points (above the upper 95% confidence boundary) indicate events where high wind speeds are unable to produce the PM_{10} concentration seen in positively correlated events (Figure 2) under the same wind velocities. Blue points (below the lower 95% confidence boundary) indicate low wind speeds producing exceptionally high

PM₁₀ concentrations that may be augmented by material from other sources
i.e. both local and distal (Figure 3).

<< Figure 3: Wind speed-PM₁₀ relationships for events listed in Table
1. Black dots represent points inside the confidence intervals from the
mathematical relationship in Figure 2b. Red and blue dots represent
points outside the confidence intervals (Fig 2b). See text for details.>>

For the events where there is a strong relationship between surface wind
speed and dust concentration, transport capacity and sediment supply are
assumed to be unlimited (Bullard et al. 2011). Where the relationship is weak
other factors affecting dust emissions are likely to be present. To determine
what these are, dust event evolution through time needs to be examined
(Stout, 2015).

An event that is identified as being controlled by fluctuations in surface wind
speed occurred on the 27th June 2015 (Event 8). Wind speed and PM₁₀
concentration increase and decrease in tandem reaching a sustained
maximum for 3 hours approximately 6 hours after the start of the event
(Figure 4). During the final third of the event dust emissions decrease to ~800
µg m⁻³ and this concentration is sustained for a further 6 hours at wind speeds
of approximately 8 m s⁻¹. Humidity is relatively constant (52-60%) throughout
the first half of the event, however an increase in humidity to a maximum of
81% is seen in the second half. This increase in humidity occurs at the same
time as decreases in both surface wind speed and dust concentration.

<< Figure 4: Wind speed and PM₁₀ concentration for Event 8 (27 June 2015),
Event 5 (15 June 2015), and Event 1 (30 May 2015). Arrows represent
observed precipitation at field site. Ticks on x-axis represent 2-hour intervals
for Events 1, 5 and 8. X-axis tick labels for zoomed insets are 15 minute

intervals for event 1. Hourly relative humidity (%) displayed in red dashed line.>>

For the nine events considered here, three have periods where the relationship between wind speed and dust concentration breaks down. An example is the event on 15 June 2015 (Event 5) which has a similar magnitude and duration to Event 8. Wind speed and PM_{10} increase and decrease in tandem for approximately 6 hours with emissions reaching $7500 \mu\text{g m}^{-3}$. During the second half of the event, wind speed stays consistently above the 6.5 m s^{-1} threshold at approximately 10.5 m s^{-1} but emissions slowly decline, with periods of recovery, until they fall below $500 \mu\text{g m}^{-3}$ at the end of monitoring. This final decrease in dust concentration (from $1350 \mu\text{g m}^{-3}$ to $550 \mu\text{g m}^{-3}$) is also concomitant with a sudden increase in relative humidity (from 55% to 75%).

Similarly, on 30 May 2015 (Event 1) there are periods where wind speed and dust concentration are coupled, but long periods where there is no relationship. Wind speed and PM_{10} increase and decrease in tandem during much of the record, however sharp declines in PM_{10} occur regularly whilst wind speed remains above the threshold velocity. This occurs despite constant relative humidity for the entire record (65-73%). The time the system requires to recover varies; near the beginning of the record PM_{10} is reduced to $0 \mu\text{g m}^{-3}$ for approximately 20 minutes before intermittent emissions recur prior to a full recovery of the system. In the second half of the event, dust concentration falls substantially (e.g. from $3000 \mu\text{g m}^{-3}$ to $<500 \mu\text{g m}^{-3}$) for periods of 20-40 minutes before rapidly (<20 minutes) returning to previous levels.

Discussion

The relationship between wind speed and dust concentration has been inferred in field studies from a variety of different dust emitting environments

(Nickling, 1978; Shao et al., 1993; Nickling and Gillies, 1993; Zobeck and Van Pelt, 2006; Macpherson et al., 2008). However, it has been shown here that factors other than wind speed may be important when examining dust concentrations from high latitude environments.

Field observations indicate that surface moisture affected sediment availability during events 5 and 1, but in different ways. At the onset of event 5 surface sediments were predominantly dry. However, continued deflation of the surface removed the uppermost dry sediments exposing the damp sediments beneath (Figure 5). These damp sediments are cohesive and require higher threshold velocities to be entrained (Chepil, 1956); where wind speeds remain constant, surface soil moisture limits sediment availability (Wiggs et al., 2004). Exposure of damp sediments at the surface to wind will start to dry them out making them available for transport (Cornelius and Gabriels, 2003). This does not occur uniformly across a surface as micro-topography and sediment texture can affect moisture retention and rates of desiccation (Ravi et al., 2006). As patches of sediment dry, this can cause localised resumption of dust emissions which would explain the sporadic increases in dust concentration during the second half of the dust event.

<<Figure 5: Markarfljot sandur after a) 1 hour of dust emissions and b) 14+ hour of dust emissions on 15/06/15 (Event 5). Spacing between ripples is approximately a) 20-30 cm b) 50 cm-1m. Darker-toned sediments have a higher surface moisture content than the lighter coloured material.>>

At the end of event 5 there is a sharp decrease in dust concentration concomitant with a rapid increase in relative humidity (from 55% to >75%). Much of the previous research focusing on the relationship between aeolian sediment transport and relative humidity has focused on sand-sized material rather than dust-sized particles (McKenna Neuman, 2003; Cornelius and Gabriels, 2003; Ravi et al., 2006). For example, Ravi et al. (2004) found that for loamy mixed sand, which is of similar textural composition to the material

at this site, surface soil moisture retention rates increase with relative humidity. Cornelius and Gabriels (2003) show a sharp increase in threshold shear velocity for sand particle motion with increasingly relative humidity. One of the few field studies examining the relationship between wind speed, dust concentration and relative humidity found that dust concentration in semi-arid environments increased up to 25% relative humidity before decreasing (Csavina et al. 2014). For dust events driven by saltation impact, the relationship between humidity and saltation defined at low latitudes is probably useful for high latitude environments such as described here (McKenna Neuman, 2003). However when emissions are not dependent on saltation activity (e.g. aerodynamic entrainment; McPherson et al. 2008), it is likely that the impact of humidity will be greater due an increased moisture holding capacity of finer sediments (Ravi et al., 2006). For event 5 described here, dust emissions were associated with active saltation and the increase in humidity is therefore likely to have contributed to the decrease in dust emissions. In addition, the increase in relative humidity occurred at a time when areas of exposed surface sediment were becoming unavailable (Figure 5b).

During event 1, sudden drops in dust concentration (Figure 4f) can be explained by occasional low magnitude pulses of rainfall (typically <0.3 mm) despite the wind remaining above threshold. Dust emissions are not reduced to zero during all rainfall events; for example, Ashwell and Hannell (1960) observed dust storms occurring during light rain with winds of 6 m s^{-1} in Iceland. When emissions do decrease sharply or halt altogether, concentrations within the record recover quickly, and in some cases instantly following short periods of precipitation. In high latitude regions, where wind speed is generally higher than in the sub-tropics (Mitchell et al., 2004), surface soil desiccation by high wind speeds may compensate for the lack of evaporation desiccation; this differs from sub-tropical regions, where surface sediments will dry due to high temperatures and low relative humidity (McTainsh et al., 2005).

Bergametti et al. (2016) showed the importance of rainfall in inhibiting wind erosion in the Sahel and suggest that dust emission would be halted immediately during rain events as rain droplets wash out dust particles. Data presented in this paper but for different soil and climate conditions agree with this. However, Bergametti et al. (2016) also suggest that global dust models should consider a 12h soil moisture factor, which would inhibit dust emissions from a surface where rainfall had occurred (6h for <2mm total rainfall). Our data indicate that although an increase in surface soil moisture caused by precipitation can lead to the suppression of dust emission, such emissions can recommence almost instantly following low magnitude rainfall events (<0.5mm in 6 hours) (Figure 4). This result indicates the importance of considering the role of low magnitude rainfall events in global dust models, and further work is required to constrain the relationship between surface sedimentology, wind speed and soil moisture retention as this will vary on a source by source basis.

Nine dust events were recorded in a six week period, all of which exceeded the Icelandic air quality health limit ($50 \mu\text{g m}^{-3}$ for a 24 hour average; Thorsteinsson et al., 2011). Of the larger magnitude events, 4 of these occurred during south-easterly winds and dust was transported towards the city of Reykjavík. These events increased PM_{10} concentrations in Reykjavík to $>100 \mu\text{g m}^{-3}$. This transport path is well-recognised and particularly important during spring and summer months (Baddock et al., 2017). If an increase in magnitude and/or frequency of events was to occur, for example due to an increase in suitable sediments for the aeolian system from decreasing volumes of terrestrial ice (e.g. Gisláðottir et al., 2005), this could create a major public health concern in Iceland (Carlsen et al., 2015).

Concluding remarks

The relationship between transport capacity, sediment availability and sediment supply is clearly important for dust emissions at the event scale. The results presented here indicate that it is possible to gain some insight into

the primary controls on dust emissions at the event scale, provided some conditions are met. First, high resolution measurements of wind speed and dust concentration are required to be made at the emission source. Measurements made not at source, but within dust transport pathways, are likely to be affected by variables other than emission intensity, such as plume dynamics and dispersion. Second, there needs to be a statistically-significant relationship between wind speed and PM₁₀ for transport-capacity limited events at the source. The relationship is likely to vary for different locations and should be calculated as the best mathematical fit which may be cubic, exponential or linear (Kimura and Shinoda, 2010; Martin and Kok, 2017). The type of relationship could usefully be tested for a variety of dust events occurring within a wide range of climatic conditions (from the sub-tropics to the high latitudes). In addition, different processes drive intra-event and event-to-event variations in dust emissions from a given location depending on the geomorphic and climatic setting (Bullard et al., 2011) and for this reason testing the relationships obtained over different surfaces, with varying vegetation densities, surface crusts and soil composition/texture would be valuable.

This study reinforces the conclusions of Csavina et al. (2014) highlighting the underappreciated role of relative humidity in the prediction of atmospheric dust concentrations. Wind speed is clearly the dominant driver of dust concentrations, but factors such as relative humidity and soil surface moisture are also important and need further investigation particularly in terms of their net impact on the overall timing, magnitude and persistence of dust emissions.

441 **Acknowledgements**

442 This research was funded by the British Society for Geomorphology, Royal
443 Geographical Society with the Institute of British Geographers, Dudley Stamp
444 Memorial Award, Loughborough University and The Leverhulme Trust
445 International Network grant (IN-2013-036). We thank the Icelandic
446 Meteorological Office for access to data. Data will be available from the
447 Loughborough University Data Repository after 31 December 2018.
448 <http://www.lboro.ac.uk/services/library/research/doingres/rdm/archiving/>

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Figures

Figure 1: 12 hour backwards HYSPLIT trajectories run at 100 m start height using 0.5° GDAS daily reanalysis data for all dust events in Table 1

Figure 2: PM₁₀ concentration as a function of wind speed for three events (Events 2, 3 and 8) where wind speed and dust concentrations are strongly positively correlated a) 5 minute averaged wind speed and PM₁₀, and b) 10 second average wind speed and PM₁₀ (including 95% confidence intervals). Points inside the confidence intervals are related to wind speed fluctuations (TCL – Transport capacity limited). Points outside the lower confidence bound are assumed to be from distal sources (e.g. not local) and points outside the upper confidence bounds are supply/availability limited.

Figure 3: Wind speed-PM₁₀ relationships for events listed in Table 1. Black dots represent points inside the confidence intervals from the mathematical relationship in Figure 2b. Red and blue dots represent points outside the confidence intervals (Fig 2b). See text for details.

Figure 4: Wind speed and PM₁₀ concentration for Event 8 (27 June 2015), Event 5 (15 June 2015), and Event 1 (30 May 2015). Arrows represent observed precipitation at field site. Ticks on x-axis represent 2-hour intervals for Events 1, 5 and 8. X-axis tick labels for zoomed insets are 15 minute intervals for event 1. Hourly relative humidity (%) displayed in red dashed line.

Figure 5: Markarfljot sandur after a) 1 hour of dust emissions and b) 14+ hour of dust emissions on 15/06/15 (Event 5). Spacing between ripples is approximately a) 20-30 cm b) 50 cm-1m. Darker-toned sediments have a higher surface moisture content than the lighter coloured material.

Table 1: Event characteristics, wind speed versus PM₁₀ concentration and Spearman correlation coefficients for all events.

Event	Date	Duration (hr)	Average Event Wind speed (m s ⁻¹)	Average Event PM ₁₀ (µg m ⁻³)	Maximum 10- second PM ₁₀ (µg m ⁻³)	Wind speed PM ₁₀ Correlation
1	30/05/2015	>14	11.96	2570	7330	0.2941
2	31/05/2015	3	9.43	2654	8040	0.8936
3	02/06/2015	8	7.42	787	3670	0.8323
4	06/06/2015	2	6.94	269	869	0.6783
5	15/06/2015	>14	12.6	2470	7350	0.2615
6	19/06/2015	8.5	6.42	418	1780	0.7868
7	24/06/2015	7	7.77	561	2020	0.6653
8	27/06/2015	>14	12.01	2035	8860	0.8415
9	28/06/2015	10	6.64	558	1870	0.1038

Table 2: Maximum DustTrak concentration ($\mu\text{g m}^{-3}$) recorded during dust events in a selection of high latitude and sub-tropical regions

Study	Location	Maximum event DT concentration ($\mu\text{g m}^{-3}$)
This study	Markarfljot, Iceland	8860
Dagsson-Waldhauserova et al. (2014)	Maelifsandur, Iceland	1757
Stout et al. (2015)	South Plains, USA	c. 13000
Kimura and Shinoda (2010)	Bayan Unjuul, Mongolia	c. 5000

Event 8

Event 5

Event 1

Time (hours)