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Quantification of soil erosion by dust devils in the Jordan Badia

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Study track

Geohazards and Earth Observation

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Abstract

This study aims to provide a quantitative estimate of the amount of erosion caused by dust devils in the Jordan Badia, and to find the meteorological variables that drive the formation of these dust devils. To achieve this goal a field study was done in Al-Majidyya, Jordan, on 9 days in the period of July 23rd – August 5th, 2012, during which a total of 518 dust devils were observed. Dust devils were observed between 09:09 and 17:34, were most active between 12:00 and 13:00, and were significantly more active during the first than during the second part of day. Temperature lapse rates of at least 0.76 °C/m were required for dust devil formation, and dust devils became more frequent with temperature lapse rates increasing up to a value of 1.2 °C/m. Dust devil frequency remained constant with further increases in temperature lapse rate. Dust devils were observed in the wind speed range of 0.1 – 7.5 m/s, and showed a positive relation with wind speed up to a value of 2 m/s. For values of the wind speed higher than 3 m/s, the relation became negative. A cyclic pattern was observed in the lower 2.5 m of the atmosphere during which temperature lapse rate and wind speed were highly correlated and showed a cyclic pattern of rising and falling values. This cyclic pattern was proposed to negatively influence dust devil frequency.

Annual amounts of erosion for the Jordan Badia were estimated at 9.79 kg/ha of locally and 0.03 kg/ha of regionally lost soil. These values were found to be low compared to other dust devil studies and other dust events. Compared to normal wind erosion, dust devils were found to be of low importance in this area. However, dust devils do contribute to atmospheric dust loading, which affects the atmospheric radiation balance, may pose health issues to humans and livestock, and may cause a loss of primary nutrients from the area. This study provides the only estimation of erosion by dust devils available for the Jordan Badia.

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1 Introduction

Land degradation has an adverse effect on agronomic productivity, the environment, food security and the quality of life. It is an important global issue and will remain so during the 21st century (Eswaran et al., 2001). The extent of land degradation is determined by factors such as rainfall patterns, soil morphological and pedological properties, vegetation and land use. Wind is an important cause of land degradation in areas where there is little soil surface protection by organic matter or vegetative cover (Belnap and Gilette, 1998). Wind erosion occurs when wind forces exceed soil threshold friction velocities and is of major concern worldwide (Belnap and Gilette, 1998).

Dust devils are one possible form of wind erosion. These small-scale convective vortices entrain dust and debris (Balme and Greeley, 2006), are driven by sensible heat flux (Ives, 1947; Sinclair, 1969; Balme and Greeley, 2006) and are typically observed in arid environments where the insolation causes strong vertical temperature gradients (Gilette and Sinclair, 1990). High local instability of the atmosphere leads to thermal updrafts and stretching of vortex tubes, which locally causes high wind speeds and resulting efficient vertical transport (Gillette and Sinclair, 1990). Dust devils are distinct from tornadoes since they are powered by insolation, instead of by the release of latent heat, and form under clear skies having no association with thunderstorms (Balme and Greeley, 2006).

Dust devils are common features on Earth as well as on Mars and the dustiness of the Martian atmosphere may even be caused by the dust-lifting of these dust devils (Newman et al., 2002). Dust devils on Earth are much smaller and less powerful than dust devils on Mars. Terrestrial dust devils have a typical diameter of less than 10 m and are usually not higher than 500 m (Sinclair, 1973), while dust devils on Mars can have diameters between 100 m and 1 km, with heights of over 5 km (Thomas and Gierasch, 1985; Malin et al., 1999). Although relatively small, dust devils on Earth can still be dangerous. Reports indicate that up to 10% of all accidents involving light aircrafts, sailplanes, helicopters, and balloons are related to wind gusts caused by dry convection and dust devils (Spillane and Hess, 1988).

The sheer fact that these convective vortices are visible indicates that they can carry a substantial airborne particle load and are thus presumably an effective Aeolian erosion mechanism (Metzger et al., 2011). But it is not the dust devils themselves that provide long range transport of dust, they merely entrain sediment and supply it to the atmosphere, from where it is transported by the prevailing winds. Dust devils do however threaten air quality in arid regions, since they locally enhance the concentration of airborne aerosols (Gillette and Sinclair, 1990; Mattson et al., 1993). This may pose health issues to humans (Griffin et al., 2001) and livestock (Harry, 1978), and can even have a global effect through the absorption and scattering of radiation (Myhre and Stordal, 2001; Kok and Renno, 2006) and by acting as nucleation sites for clouds or ice (DeMott et al., 2003). Dust devils are witnessed to supply large amounts of atmospheric dust in the southwestern U.S. (Deluisi et al., 1976), possibly also acting as an important source of alkaline aerosols (Gillette and Sinclair, 1990) and primary nutrients (Griffin et al., 2001).

Dust devils may be an important form of erosion in regions where these convective vortices are prone to occur. Relatively little research has however been done on the local environmental conditions controlling dust devil generation. The aim of this study was to determine the meteorological variables that influence dust devil generation, and to quantify the amount of erosion that may result due to dust devils in regions susceptible to their formation. This was achieved by using the information obtained from literature and combining this with the findings of a field experiment in the Jordan Badia, an area typical for the formation of dust devils.

The following research questions were attempted to answer:

1.) *What are the meteorological conditions of occurrence of dust devils in the Jordan Badia and how does this compare to literature?*
2.) *What is the size- and intensity-frequency distribution of dust devils in the Jordan Badia?*
3.) *What is the amount of soil erosion for each dust devil?*
4.) *What does this imply for the amount of annual soil erosion by dust devils in the Jordan Badia?*

2 Dust devil characteristics

2.1. Formation and dynamics

Dust devils frequently occur on generally flat terrain (Williams, 1948; Sinclair, 1969; Hess and Spillane, 1990; Mattson et al., 1993), near the boundary of irrigated fields (Sinclair, 1969) where opposite cold and warm air currents meet and form horizontal atmospheric vortices (Renno et al., 2004). The vortex steepens and rising warm air lifts the vortex and forces it to form a loop. The apex of the vortex then becomes thinner and weaker, eventually slows down, and breaks the vortex into two separate columns. One of the columns will often decay, thus leading to a single completed dust devil (figure 2.1).

Terrestrial dust devils are mostly short lived events which last for only a few minutes (Idso, 1974), although there have been reports of dust devils with much longer lifetimes (Ives, 1947; Mattson et al., 1993; Metzger, 1999). In general, large dust devils have longer lifetimes than small dust devils (Ives, 1947; Sinclair, 1969; Metzger, 1999). Both Sinclair (1969) and Oke et al. (2007a) found the overall frequency of dust devils during the day to show two peaks of activity, a pattern likely caused by the diurnal course of solar heating (Oke et al., 2007a).

Dust devils form as a result of vertical instability in the atmosphere, wherever there is a vertical temperature gradient, a source of vorticity, and a supply of sediment (Sinclair, 1966). Such conditions are common in hot, arid regions during the summer, but can occur throughout the year when cold air spreads over warmer ground. They are even possible in the cold, dry conditions of the sub-Arctic (Sinclair, 1966). The thermal properties and surface roughness characteristics of areas featuring minimal vegetation lead to increased dust devil size and frequency (Oke et al., 2007a). Hence, dust devils may play a more important role during periods of drought.

Meteorological variables

There is currently no clear understanding of the exact relationship between dust devils and the influence of local meteorological variables on their initiation and maintenance (Oke et al., 2007a). Oke et al. (2007a) indicate that the wind speed and vertical temperature gradient of the air close to the surface most likely drive dust devil formation. They found dust devils to occur in the wind speed range of 1.5 – 7.5 m/s, with an observed peak in dust devil frequency at wind speeds of 3 m/s. Vertical temperature gradient in the lower 2.5 m of the atmosphere ranged from 0.9 – 1.7 °C/m during dust devil occurrence, with an observed peak in dust devil frequency at a temperature lapse rate of 1.5 °C/m. Overall an increase in dust devil frequency was observed with increasing temperature lapse rate, while frequency decreased with wind speeds higher than 3 m/s (Oke et al., 2007a).

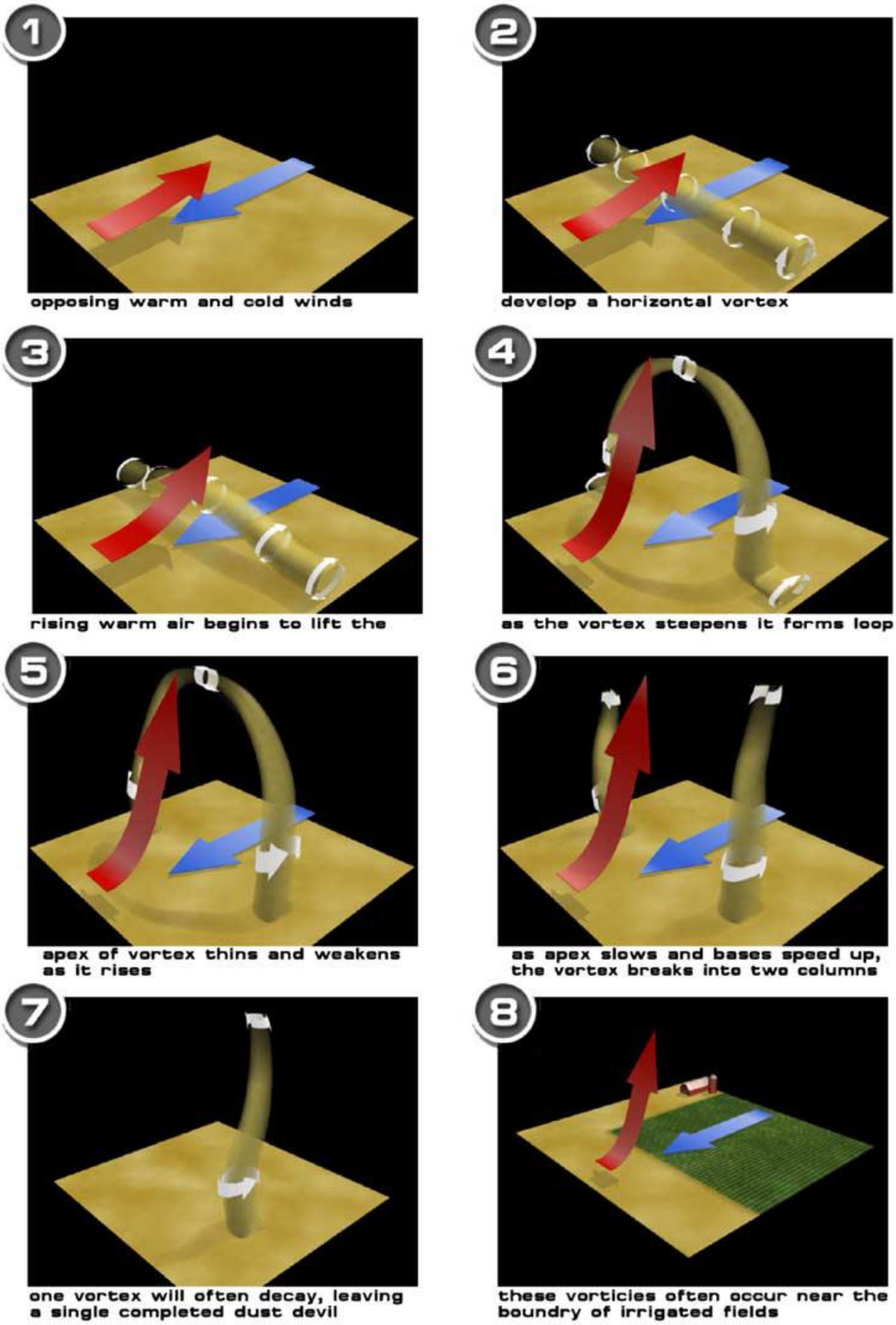

Figure 2.1. Formation of dust devils by vorticity induced by opposing cold and warm air flows (Renno et al., 2004, courtesy of University of Michigan).

2.2. Dust size-transportation

Dust devils are able to lift material by their intense swirling winds (Balme et al., 2003) and suction effects at their cores (Greeley et al., 2003; Balme and Hagermann, 2006). They have the ability to entrain particles ranging in size from clay and silt to gravel and even pebbles, however not all this material is transported into the atmosphere. An estimated 85 - 95% of the total suspended matter in dust devils features grain sizes larger than 10 µm and is thus unlikely to be transported to significant heights or distances (Metzger et al., 2011). Oke et al. (2007b) found that the total number of entrained particles in dust devils is greatest in the bottom 10 to 20 cm of the dust column, which is referred to as the 'sand skirt' and is dominated by 200 µm - 600 µm sized particles that become increasingly rare higher in the column. These finding are illustrated by figure 2.2. Figure 2.2a shows that the total number of particles carried in a dust devil decreases with height between 0 and 10 cm above the ground surface, and figure 2.2b shows that the coarser fraction of the sediment decreases rapidly with elevation between 0 and 20 cm above the ground surface.

Quantities of dust

There is an inverse relation between the amount of sediment entrained by dust devils and the amount of vegetation covering the surface (Oke et al., 2007b). Quantitative measurement of particle load in dust devils however has received little attention in literature and very few measurements of this distinctive signature of dust devils exist (Metzger et al., 2011). Sinclair (1990, in Gillette and Sinclair, 1990) made simultaneous aircraft measurements of particle concentration and vertical velocities in the updrafts of several dust devils at altitudes of 142 m and 300 m, in an arid region featuring a vegetation coverage of shrubs and needle evergreen. Means were found of experimentally determined vertical mass fluxes for dust devils categorized into four different sizes (table 2.1), and total annual vertical dust flux values were estimated.

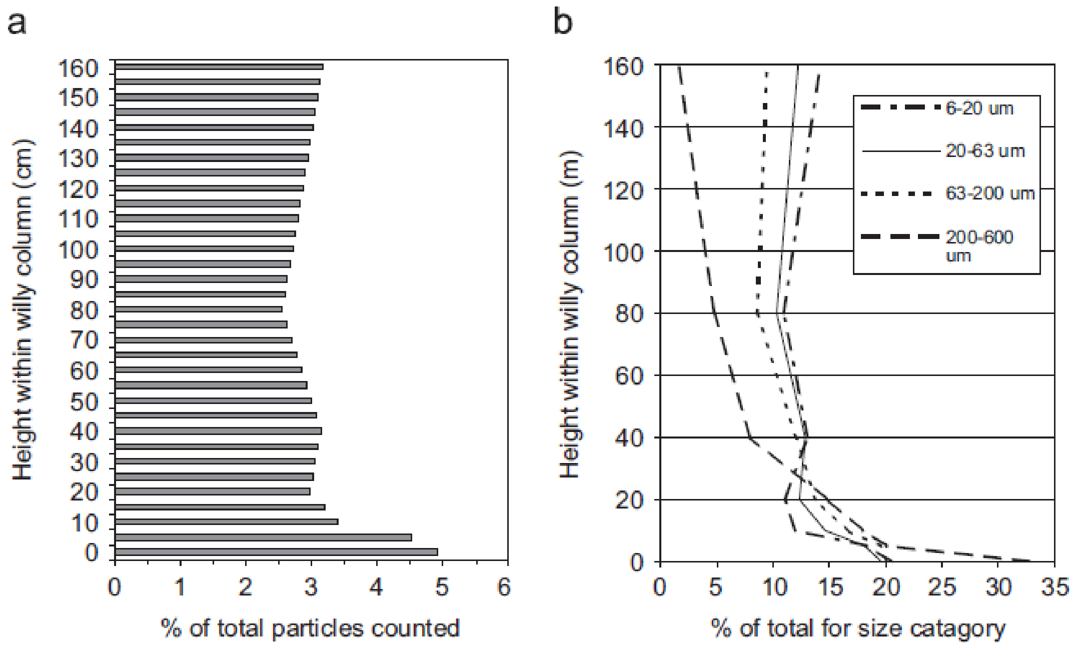

Figure 2.2. (a) Percentage of total particles counted with respect to height in the dust devil column (b) size of the particles entrained with respect to the height in the dust devil column (Oke et al., 2007b).

Table 2.1. Estimated dust devil mean vertical mass fluxes at a height of 142 m above the ground surface, and corresponding annual dust flux (After Sinclair, 1990, in Gillette and Sinclair, 1990).

Dust devil size	Estimated mean flux per dust devil	Corresponding annual dust flux
	µg/cm^2/s	g/m^2/yr
Small	2.2	4.2 x 10^{-2}
Medium	20.9	4.2
Large	198.6	52.5
X-large	297.8	50.8
Total	519.5	107.5

Details of the aircraft measurements and dust devil sizes have however never been published and thus cannot be verified. Renno et al. (2004) used LIDAR observations at 100 m above the surface in an arid and sparsely vegetated area to estimate the density of dust particles inside dust devils and measured the flux of dust in these dust devils. They found that dust fluxes in strong dust devils can be in the order of 1 g/m^2/s. Metzger et al. (2011) performed in situ sampling and analysis of over 100 dust devils in a period of 10 years, measuring total suspended particle load and suspended particle load in the 0.1 – 10 µm diameter range (PM10 measurements). They found mean dust devil PM10 flux values of 0.9 – 7.5 mg/m^2/s.

The maximum dust flux value found by Renno et al. (2004) is lower than the maximum dust flux value by Sinclair (1990, in Gillette and Sinclair, 1990), but is still in the same order of magnitude. Since particles of 200 – 600 µm end up in the sand skirt of the dust column, the mean dust fluxes as calculated by Sinclair (1990, in Gillette and Sinclair, 1990) at 142 m altitude and by Renno et al. (2004) at 100 m altitude are believed to contain particles of up to 200 µm in size only. Assuming the PM10 values by Metzger et al. (2011) are correct, a predominant part of the dust devil flux indicated by Sinclair (1990, in Gillette and Sinclair, 1990) and Renno et al. (2004) thus contains particles in size of 10 – 200 µm, which will not contribute to long range transport of sediment. However, as Sinclair (1990, in Gillette and Sinclair, 1990) measured their dust flux values at an altitude of 142 m and Renno et al. (2004) measured their dust fluxes at an altitude of 100 m, these particles do contribute to local soil loss.

3 Materials and methods

3.1. Study area

Situated in the dry region of the eastern Mediterranean Sea is the Hashemite Kingdom of Jordan, covering 89.206 km^2 of land (Karrou et al., 2011) and featuring a population of 5.5 million (FAO/WFP, 1999). The elevation ranges from a low of -411 m at the Dead Sea to a high of 1754 m at Jabal Ramm. The climate in Jordan varies from sub-humid Mediterranean in the northwestern part of the country to hyper-arid just 100 km to the east (Karrou et al., 2011). The most extensive ecosystem in Jordan is rock desert, or *Badia*, and covers approximately 81% of the country (Karrou et al., 2011). Overgrazing of shrubs has caused deterioration and degradation of the traditional rangelands of the Badia, causing the soil to be exposed to the dangers of water and wind erosion (Karrou et al., 2011).

The Jordan Badia was chosen by ICARDA as a benchmark site to develop and disseminate water harvesting approaches and techniques (Karrou et al., 2011). One of the research sites of ICARDA in the Badia is named after a small village, Al-Majidyya, and was chosen as representative for the Jordan Badia. It is located in the eastern part of the Amman district, about 45 km southeast of Amman. The research site is characterized by a Mediterranean arid climate, with an average annual rainfall of 150 mm. Rainfall occurs mainly during the rainy season from October – April, and comes usually in sporadic intense storms. Daily average temperature is 17.5 °C, with daily mean minimum of 10 °C and daily mean maximum of 24.5 °C. The absolute minimum temperature ever measured is -5 °C, while the absolute maximum temperature measured is 46 °C (Taimeh, 2003). The area features slopes that are both gentle (< 15%) and long (> 100 m), and altitude ranges from 820 – 846 m. The soils are loamy with high silt content and low organic matter. Soil crusting occurs frequently in the area, resulting in low infiltration rates. The natural vegetation in the area consists of a sparse cover of grasses and herbs. The main land use type is grazing by goat and sheep on the natural vegetation (Karrou et al., 2011).

At the Al-Majidyya research site, two study areas were chosen to conduct dust devil research (figure 3.1). It was assumed that these areas were equally efficient with respect to producing dust devils. Area 2 was outlined as a smaller area inside area 1, and would serve as a backup area should the dust devils in area 1 become too frequent to keep track of. Area 1 was about 1.16 km^2 in size, mostly covered by a sparse cover of grasses and herbs, and frequently grazed by sheep. Several plots in the area had been recently tilled, and lacked vegetation. Dry gullies ran through the area, with maximum widths of 2 m and maximum depths 1 m. At the center of the area a water harvesting test site was located, containing several water basins with levees of up to 0.5 m height. At the time of research the water basins were empty and vegetation was similar to the surrounding area. Area 2 was chosen as a 0.32 km^2 area in the most northwestern corner of area 1. This area was also characterized by a sparse cover of grasses and herbs, and frequent grazing by sheep. Part of the area had been recently tilled, and one gully of approximately 0.5 m width and 0.5 m depth ran through this plot.

Figure 3.1. Study area 1 and 2 in Al-Majidyya, Amman, Jordan. Meteorology tower marked by red cross (DigitalGlobe, 2011).

3.2. Field measurements

To measure the conditions of the atmosphere during dust devil occurrence, a meteorology tower was positioned in study area 2 (figure 3.1). This meteorology tower contained an anemometer, wind vane, temperature sensors, and incoming radiation sensor to continually measure wind speed and direction, temperature profile, and incoming radiation from July 23rd – August 5th, 2012.Temperature sensors were placed at heights of 2.5 and 0.1 m, the anemometer was placed at 2 m height, and the wind vane was placed at roughly 5 m height relative to the ground surface. A data logger (Campbell CR10) was connected to the meteorology tower. The data logger collected data from the attached measurement devices every second, then converted and stored this data into minute-averaged data.

The number of dust devils occurring in the area was determined by counting the dust devils that occurred in the study area during nine days of dust devil observations (table 3.1). Initially study area 1 was used for these observations. However, during the second observation day dust devils proved to be so frequent that it was impossible to keep track of them. Thus, starting 11:15, July 24th, study area 2 was used for further dust devil observations (table 3.1). Due to the intense heat and limited manpower, dust devil observations were not done continuously throughout the day. The days from roughly 09:00 to 18:00 were divided up into parts of 2 hours of dust devil observations, interrupted by breaks of approximately 1 hour. Next to counting their numbers, dust devil start and end time were registered to obtain data on their duration. Assumptions were that dust column diameter would be an indicator for the dust devil intensity, thus estimates of dust column diameter were made. However, during the observations dust column height proved to be a better indicator for dust devil intensity than dust column diameter. Thus, starting 13:17 on July 31st, estimates were made for both dust column diameter as well as dust column height. The diameter and height of the dust devil column was estimated by using reference objects of known width in the field, and by visually relating the dust column dimensions to these reference objects. To allow for quick registration of dust devil dimensions, pre-defined classes of dust column width and height were used. Three dust column diameter (0 – 1 m, 1 – 3 m, and 3> m) and four dust devil height (0 – 1 m, 1 – 3 m, 3 – 10 m, and 10> m) classes were used, into which each dust devil was classified on the spot.

Table 3.1. For each dust devil observation day is indicated the starting time (GMT+3), ending time (GMT+3) and total observation time (hh:mm), as well as whether study area 1 or 2 was used and whether dust column height estimates are available.

Day	Dust devil observation time			Study area	Column height
	Start	End	Total		
			hh:mm	(1/2)	(y/n)
23/07/2012	10:15	16:30	04:35	1	n
24/07/2012	9:00	11:37	01:53	1 (09:00 - 11:15) AND 2 (11:15 - 11:37)	n
30/07/2012	15:05	18:04	02:59	2	n
31/07/2012	9:16	17:00	04:44	2	y (13:17 - 17:00)
01/08/2012	10:53	18:00	04:57	2	y
02/08/2012	9:08	17:00	05:28	2	y
03/08/2012	9:00	16:00	04:53	2	y
04/08/2012	10:10	17:00	04:25	2	y
05/08/2012	8:00	10:00	02:00	2	y
Total			**35:54**		

3.3. Data analysis

Conditions of dust devil occurrence

Values of temperature and wind speed were obtained during field measurements, which were used to calculate temperature lapse rate and wind speed standard deviation. Temperature lapse rate, after Oke et al. (2007a), was calculated by subtracting the temperature in °C at 2.5 m height from the temperature in °C at 0.1 m height, and dividing by 2.4, their elevation difference in m. Thus for each minute-averaged measurement of temperature at 2.5 m and 0.1 m height, a temperature lapse rate value (°C/m) was obtained, essentially reflecting the degree of atmospheric instability of the lower 2.5 m of the atmosphere.

Wind speed standard deviation was calculated by assuming that the values of the 5 minutes preceding and the 5 minutes following a certain measurement of wind speed constitute a sample of the population. Thus, a measure of the variability of the wind speed during a 10-minute interval surrounding each minute-averaged measurement of wind speed was obtained.

To determine the conditions of dust devil occurrence, temperature lapse rate, wind speed, wind direction, wind speed standard deviation, and time of occurrence were related to dust devil frequency. To visualize these relations several graphs were made. The previously named variables were divided into suitable classes and for each class the total number of dust devils that occurred within that class was displayed. However, since some classes of a certain variable occurred more often than other classes of the same variable, this did not provide an adequate measure of the relative effectiveness of these classes in producing dust devils. To provide a better measure of the relative effectiveness, index values (after Oke et al., 2007a) were calculated for each variable class (equation 3.1).

$$C_i(x) = \frac{C_d(x)}{C_o(x)} \tag{3.1}$$

Where $C_i(x)$ is the index value (between 0 and 1) of a given class of variable *(x)*, $C_d(x)$ is the number of dust devils that occurred within a given class of variable *(x)*, and where $C_o(x)$ is the number of times that a 1-minute interval was measured during the dust devil observations with variable *(x)* attaining a value within that given variable class.

Since two different areas were used for dust devil observations, a correction factor had to be applied to the number of observed dust devils to correct for the difference in area size. The number of dust devils observed in area 1 was multiplied by 0.28, which is the surface area of area 2 divided by the surface area of area 1. It was assumed that the resulting number would have been the number of dust devils that occurred in area 2 while counting the dust devils in area 1.

To provide an additional validation of the relations found between dust devil frequency and the independent variables, a multiple linear regression model explaining dust devil frequency as a function of these independent variables was used. This model was run by using Microsoft Excel's 'data analysis' extension. To serve as model input, dust devil observation time was split up into 15-minute intervals, summing the number of dust devils that occurred during these intervals, and calculating 15-minute averages for the independent variables.

Quantifying annual dust devil erosion

Quantifying annual erosion by dust devils for the Jordan Badia involved two separate steps; (1) quantifying the amount of dust devil erosion during the study period, for the 0.32

km^2 study area, and (2) extrapolating this amount to annual dust devil erosion values valid for the entire Jordan Badia.

Step 1: dust devil erosion during study period

To quantify the amount of erosion that occurred due to dust devils in the study area, during the study period, two things needed to be known; *the dust devil intensity-frequency relation*, and *the amount of dust eroded by each dust devil of a certain intensity*.

Dust devil intensity-frequency relation: height of the visible dust column, which was obtained by field estimation, was used as an indicator for dust devil intensity. Each of the four height classes (section 3.2) were assumed to indicate the relative intensity of dust devils, with the lowest height class representing the lowest level of dust devil intensity and the highest height class representing the highest level of dust devil intensity.

Amount of dust eroded by each dust devil of certain intensity: the range of dust flux values by Sinclair (1990, in Gillette and Sinclair, 1990) in table 2.1 was used to estimate local dust devil erosion while the range of dust flux values by Metzger et al. (2011) in section 2.2 was used to estimate long range, or regional, erosion. One value for local erosion and one value for regional erosion was assigned to each dust devil of certain intensity, which was based on the dust devil height classes. The resulting emission of dust into the atmosphere by each dust devil of certain intensity was then estimated by multiplying the dust flux values of each dust devil with its duration and its diameter, as obtained during field measurements.

The resulting values of erosion per dust devil were then summed to estimate the total amount of local and regional erosion by dust devils in the 0.32 km^2 research area, during the study period.

Step 2: annual dust devil erosion for entire Jordan Badia

Estimated erosion values in step 1 are valid only for the dust devils for which both diameter as well as dust column heights were estimated. Next to that, as indicated in table 3.1, each dust devil observation day was interrupted by several breaks and the duration of observations was different for each observation day. Thus, not all dust devils that occurred during the 9 days of dust devil observations were actually registered. A number of steps were taken to estimate the annual amounts of local and regional dust devil erosion;

(a) From the estimated erosion for each of the dust devils in step 1, one average erosion value was calculated for both local and regional erosion. These values were used as estimates for the erosion of each of the dust devils for which no dust column height was estimated.

(b) By calculating the hourly average dust devil frequency, the estimated number of non-registered dust devils that occurred during observation breaks was obtained for each day. Each of these dust devils was also appointed the estimated average erosion values.

(c) The estimated average erosion values for all registered and non-registered dust devils were then summed to obtain an estimate for the amount of local and regional erosion by dust devils for the 9-day dust devil observation period.

(d) Since dust devils occur under clear skies, at times with sufficient incoming solar radiation, and in areas with little soil surface protection by vegetation, it was assumed that dust devils would only be able to occur outside the rainy season, from May to September. The annual local and regional erosion by dust devils was estimated by dividing the number of days in a dust devil season by 9, the number of dust devil observation days, and multiplying this by the amount of erosion estimated for the 9-day dust devil observation period as estimated in (c).

Since the study area was chosen as representative in surface characteristics for the entire Jordan Badia, it is here suggested that the estimated annual local and regional erosion by dust devils for the study area can be seen as representative for the Jordan Badia as a whole.

4 Results

4.1. Meteorological variables of dust devil observation days

Meteorological variables were collected between 08:00 and 18:00, during nine days of dust devil observations (table 4.1). However, due to instrument failure, no wind speed and wind direction data are available for July 23rd and August 5th. For July 24th, incoming radiation and temperature data are not available after 11:46.

Incoming radiation, temperature, and temperature lapse rate

Over the nine days of dust devil observations a minimum incoming radiation of 110 W/m^2 and a maximum of 1046 W/m^2 was registered. Variation in the daily average, daily range, and diurnal cycle (figure 4.1) between days was low (table 4.1). Since weather conditions were predominantly cloudless, incoming radiation was seen to increase and decrease with the position of the Sun relative to the Earth's surface, reaching its maximum value between 12:30 and 13:30 (figure 4.1).

Temperatures ranged from a minimum of 20.6 °C to a maximum of 35.9 °C, and varied distinctly between days (table 4.1). The daily cycle was however similar for each day, reaching a maximum between 14:00 and 16:00, after which temperatures gradually decreased again (figure 4.2).

During the dust devil observation days, temperature lapse rates of minimum 0.4 °C/m and maximum 2.2 °C/m were registered. Although temperatures between days showed distinct differences, temperature lapse rates did not (table 4.1), which indicates that temperature lapse rates were not dependent upon the absolute temperature. This illustrates the fact that temperature lapse rates of similar magnitudes would be able to form under distinctly different temperature conditions, as long as incoming radiation is high enough to heat the ground surface and indirectly invoke a temperature lapse rate.

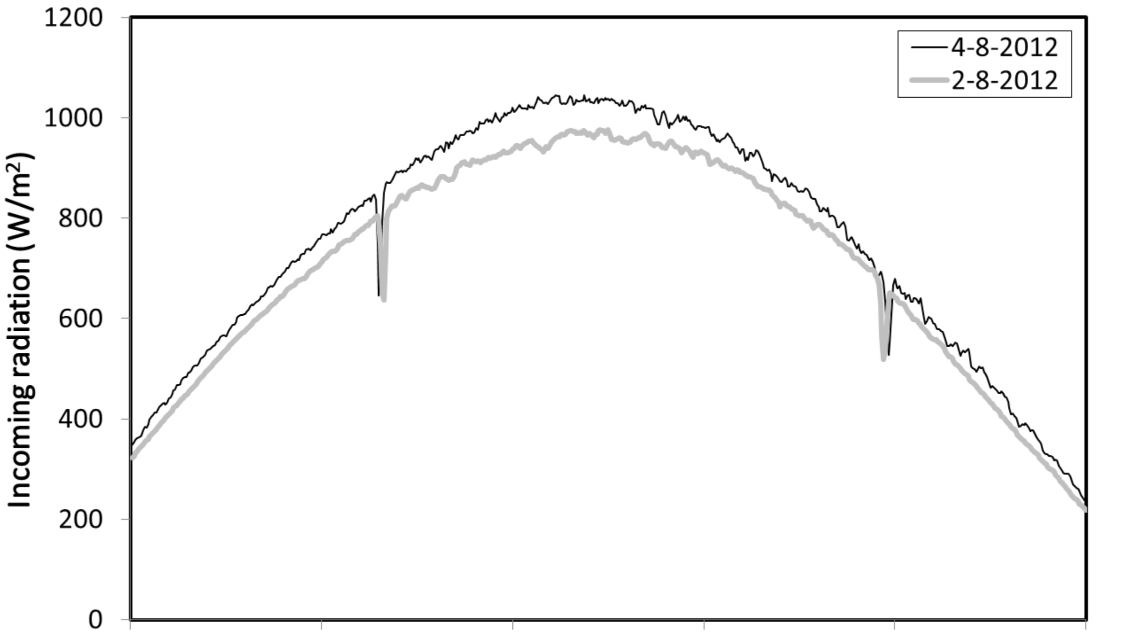

Figure 4.1. Incoming radiation (W/m^2) versus time (GMT+3) for August 2nd and August 4th, 2012, in Al-Majidyya, Jordan. Note that the features at 10:30 and 15:55 are due to shading of the cables fastening the meteorology tower.

Table 4.1. Meteorological variables of dust devil observation days, measured from 08:00 – 18:00 in Al-Majidyya, Jordan. Also indicated is the daily time spent observing dust devils, and the number of observed dust devils.

Day	Incoming Radiation		Temperature (2.5 m)		Temperature lapse rate		Wind direction	Wind speed		Observation time	Dust devils
(-)	(W/m^2)		(°C)		(°C/m)		(-)	(m/s)		(hh:mm)	(-)
	Average	*Range*	*Average*	*Range*	*Average*	*Range*	*Average*	*Average*	*Range*		
23/07/2012	758	282 - 1022	31.4	24.2 - 35.5	1.4	0.4 - 2.2	N/A[1]	N/A[1]	N/A[1]	04:35	111
24/07/2012	N/A[2]	N/A[2]	N/A[2]	N/A[2]	1.2	0.5 - 2.1	W	4.7	2.4 - 7.1	01:53	66
30/07/2012	728	175 - 1002	27.1	20.9 - 30.2	1.5	0.6 - 2.2	W	5.1	2.2 - 7.5	02:59	21
31/07/2012	735	222 - 1018	30.3	23.1 - 33.9	1.3	0.5 - 1.9	SW	5.8	0.1 - 7.4	04:44	51
01/08/2012	724	217 - 1014	32.5	27.0 - 35.1	1.3	0.4 - 2.0	SW	3.8	0.1 - 6.9	04:57	52
02/08/2012	711	219 - 977	32.9	27.4 - 35.9	1.4	0.5 - 2.2	SW	3.0	0.0 - 6.2	05:28	101
03/08/2012	721	223 - 996	30.2	23.4 - 32.7	1.4	0.6 - 2.1	W	4.9	0.0 - 7.2	04:53	81
04/08/2012	757	236 - 1046	27.0	20.6 - 30.2	1.4	0.6 - 2.1	W	5.7	0.0 - 7.2	04:25	32
05/08/2012	735	110 - 1029	26.5	20.8 - 29.8	1.4	0.6 - 2.1	N/A[1]	N/A[1]	N/A[1]	02:00	3

[1] N/A = Measurements not available due to equipment failure
[2] N/A = Measurements not available after 11:46

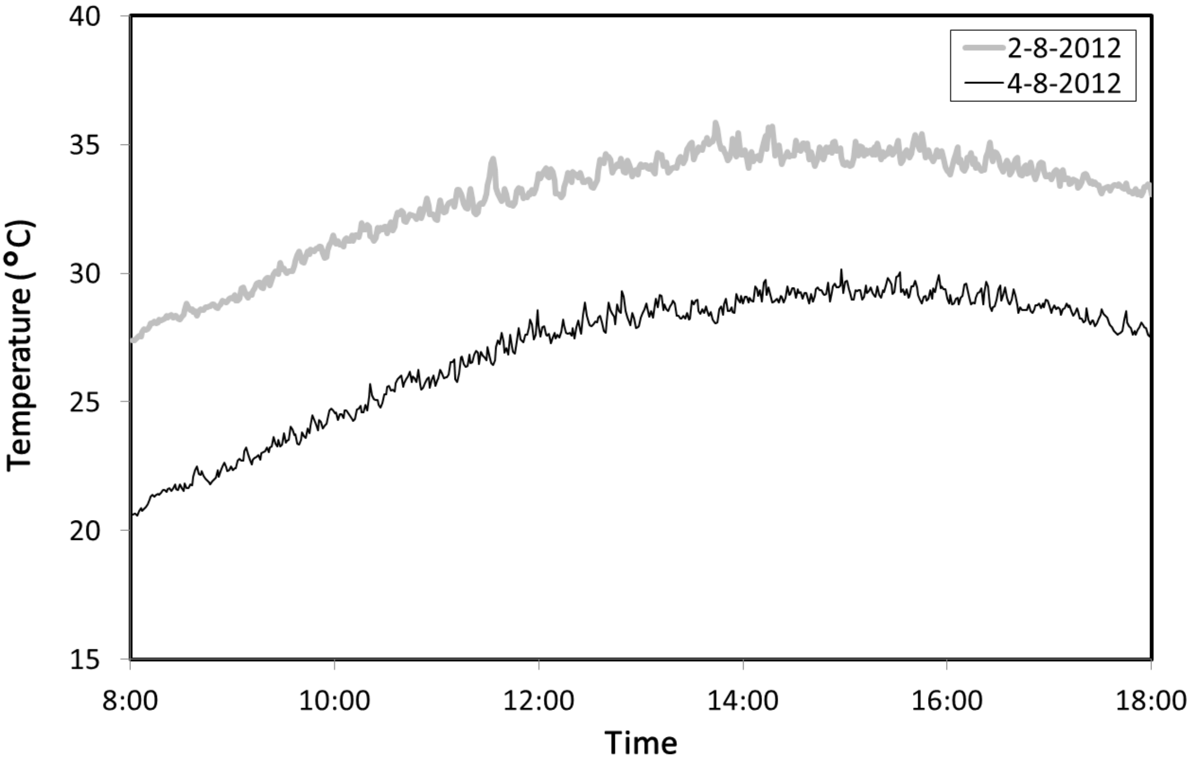

Figure 4.2. Temperature (°C) versus time (GMT+3) for August 2nd and August 4th, 2012 Al-Majidyya, Jordan.

These findings reinforce statements by Sinclair (1966), suggesting that dust devils are possible to form even in the cold, dry conditions of the sub-Arctic. The daily cycle of temperature lapse rate is indirectly driven by, and thus similar to, the daily cycle of incoming radiation, reaching its maximum between 12:30 and 13:30 (figure 4.3).

Wind direction, speed, and variability of speed

Wind directions during the dust devil observation days were relatively stable. Western winds were by far the most common, and daily average wind directions were either west or southwest (table 4.1). North and south wind directions occurred occasionally, but no easterly winds were observed (figure 4.4).

Wind speed varied in the range of 0.0 – 7.5 m/s, with significant variation of the average wind speed (table 4.1), as well as its daily cycle (figure 4.5), between days. It was assumed that high wind speeds would weaken temperature lapse rates by causing increased mixing of the atmosphere (Sinclair, 1969). This however was not the case during this study, since August 4th had considerably higher average wind speeds than August 2nd, but the temperature lapse rates were not much different. On August 2nd, temperature lapse rate even increased with wind speed around 14:30. Thus, contrary to assumptions, higher wind speeds were not seen to lower temperature lapse rates. This validates statements by Oke et al. (2007a), suggesting that the proposed mixing effect possibly only takes place higher up in the atmosphere.

In general, the variability of wind speed increased during the day, as illustrated by figure 4.5. This effect was most noticeable on days with relatively low average wind speeds, since the variability tended to be larger when average wind speeds were low. The data for August 4th (figure 4.5), however indicate that large variations in wind speed were occasionally seen to occur when average wind speeds were relatively high.

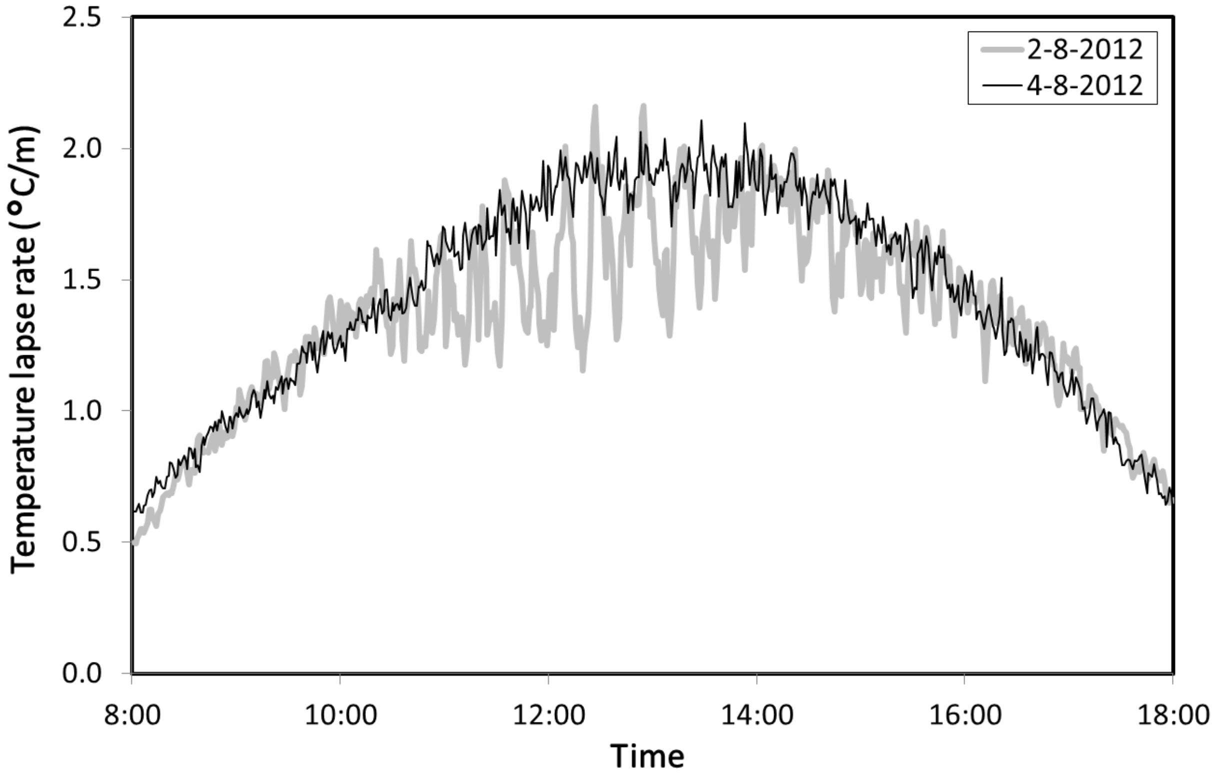

Figure 4.3. Temperature lapse rate (°C/m) versus time (GMT+3) for August 2nd and August 4th, 2012 in Al-Majidyya, Jordan.

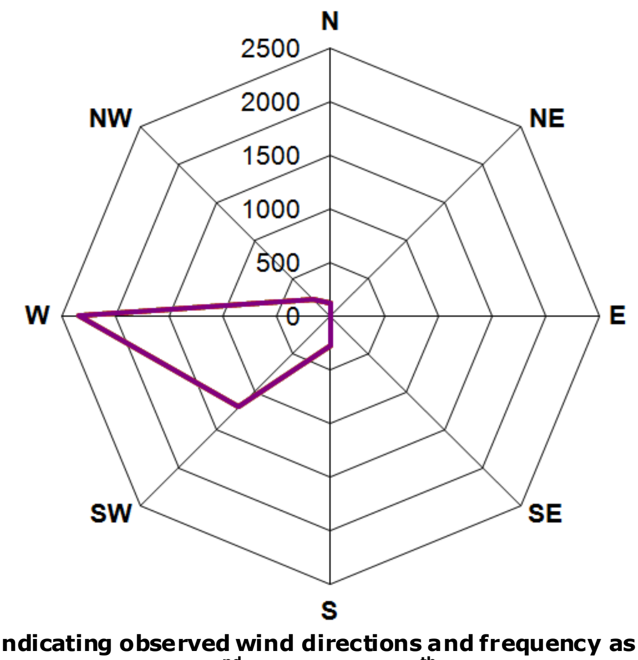

Figure 4.4. Wind rose indicating observed wind directions and frequency as measured during dust devil observation days in for August 2nd and August 4th, 2012 Al-Majidyya, Jordan.

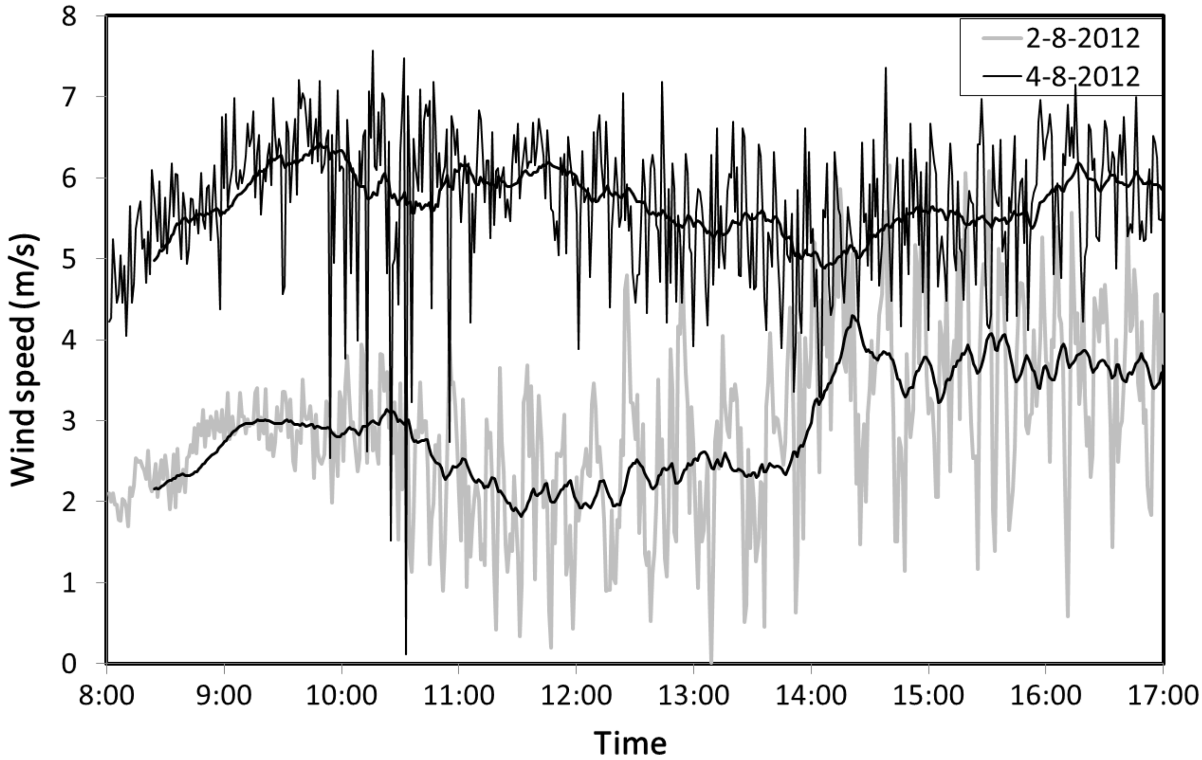

Figure 4.5. Wind speed (m/s) versus time (GMT+3) for August 2nd and August 4th, 2012 in Al-Majidyya, Jordan.

Cyclic pattern of events

When comparing the temperature lapse rate and wind speed versus time for August 2nd (figure 4.3 and 4.5), there appears to be a relation between wind speed variability on one hand, and temperature lapse rate on the other hand. This relation is most evident between 10:20 and 14:30; while wind speed variability increased, so did the variability in temperature lapse rate. A period of relatively low average wind speed occurred on August 2nd, between 12:00 and 14:00 (figure 4.6). During this period, the curves of temperature lapse rate and wind speed had strong similarities, which is supported by their correlation coefficient of 0.68, and both variables seemed to show a cyclic pattern of rising and falling values. This phenomenon was also seen to occur during other time intervals; however it seemed to occur only when average wind speeds were relatively low, and was most prominent when insolation was high enough to invoke a strong vertical temperature gradients.

Possibly the observed phenomenon was caused by the temperature lapse rate exceeding the dry adiabatic lapse rate of 10 °C/km (Schroeder and Buck, 1970). Temperature lapse rates below the dry adiabatic value of the lapse rate, for unsaturated atmospheres, are considered stable because vertical motion of air parcels is damped (Schroeder and Buck, 1970). However, when temperature lapse rate becomes greater than the dry adiabatic lapse rate, vertical motion of air parcels is favored and the atmosphere becomes unstable (Schroeder and Buck, 1970). Temperature lapse rates are then super adiabatic, and the air tends to adjust the super adiabatic condition by vertical motion and overturning, thoroughly mixing the atmosphere (Schroeder and Buck, 1970). It is proposed that the observed cyclic behavior of temperature lapse rate and wind speed (figure 4.6) was caused by the temperature lapse rate exceeding the dry adiabatic lapse rate, thus becoming super adiabatic and causing the atmosphere to become unstable. Air parcels would then be set into vertical motion, overturning the atmosphere. The overturning would cause mixing, causing temperature lapse rates to lower to values below the dry adiabatic lapse rate, thus stabilizing the atmosphere. Depending on the strength of the insolation, temperature lapse rates would then be raised again to super adiabatic values, once more causing an unstable atmosphere, thus completing the cycle.

Indeed, temperature lapse rates at the observed peaks in figure 4.6 were well above the dry adiabatic lapse rate of 10 °C/km. However, the temperature lapse rates in the observed valleys of figure 4.6 were also above the dry adiabatic lapse rate, indicating that the atmosphere must have remained unstable throughout the period. Thus, this does not explain why a cyclic pattern of events was observed, with gusts of wind following and followed by periods of relatively calm conditions. Possibly not only the conditions in the lower 2.5 m of the atmosphere drive these mixing events, but also the conditions of the atmosphere above. This hypothesis is reinforced by the observation that when average wind speeds were high, and temperature lapse rates equally so, the proposed cyclic pattern of heating and mixing was not observed. This may have been caused by the atmospheric mixing during high wind speeds that, as suggested by Oke et al. (2007a), only takes place higher up in the atmosphere, and may have lowered the temperature lapse rates in these layers of the atmosphere.

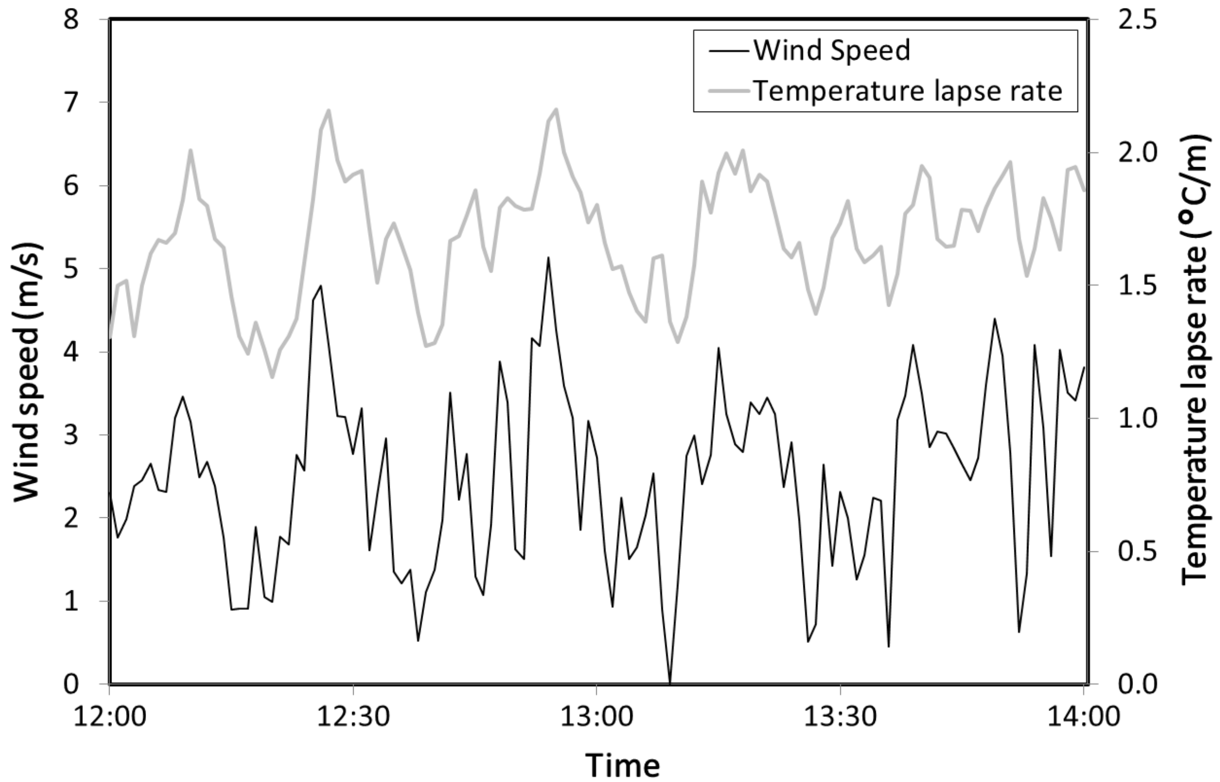

Figure 4.6. Wind speed (m/s) and temperature lapse rate (°C/m) versus time (GMT+3) between 12:00 and 14:00 for August 2nd, 2012 in Al-Majidyya, Jordan.

4.2. Generation of dust devils

Time of occurrence

During the days of dust devil observations 518 dust devils were seen to occur, which were observed between 09:09 and 17:34. Dust devil frequency, as indicated by the index value, was highest between 12:00 and 13:00, and in general was significantly higher during the first part of day than during the second (figure 4.7). There may have been factors hindering dust devil occurrence during the second part of day.

Temperature lapse rate

Dust devils were observed at temperature lapse rates of a minimum of 0.76 °C/m and a maximum of 2.15 °C/m. However, this maximum should not be seen as an upper limit of dust devil occurrence, since temperature lapse rates of a value higher than 2.15 °C/m hardly ever occurred. Dust devil frequency increased with temperature lapse rate up to a value of 1.2 °C/m (figure 4.8). A further increase in temperature lapse rate did not result in higher dust devil frequencies. Higher values of the temperature lapse rate were assumed to be more effective at producing dust devils, as they represent higher grades of atmospheric instability. The fact that the positive relation between temperature lapse rate and dust devil frequency ceased at a value of 1.2 °C/m, leads to the hypothesis that for values of the temperature lapse rate higher than 1.2 °C/m, other variables, at least for this study area, became relatively more important in controlling dust devil frequency.

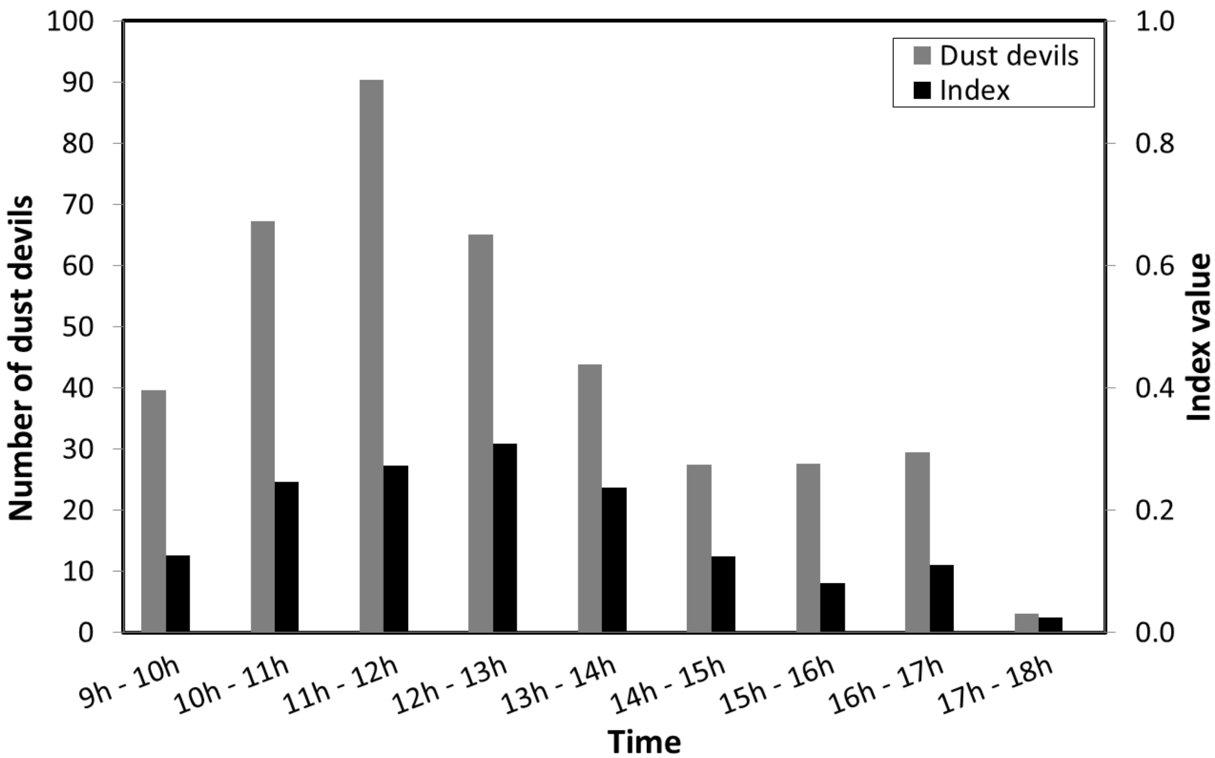

Figure 4.7. Number of dust devils and corresponding index value per time class (GMT+3) for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan.

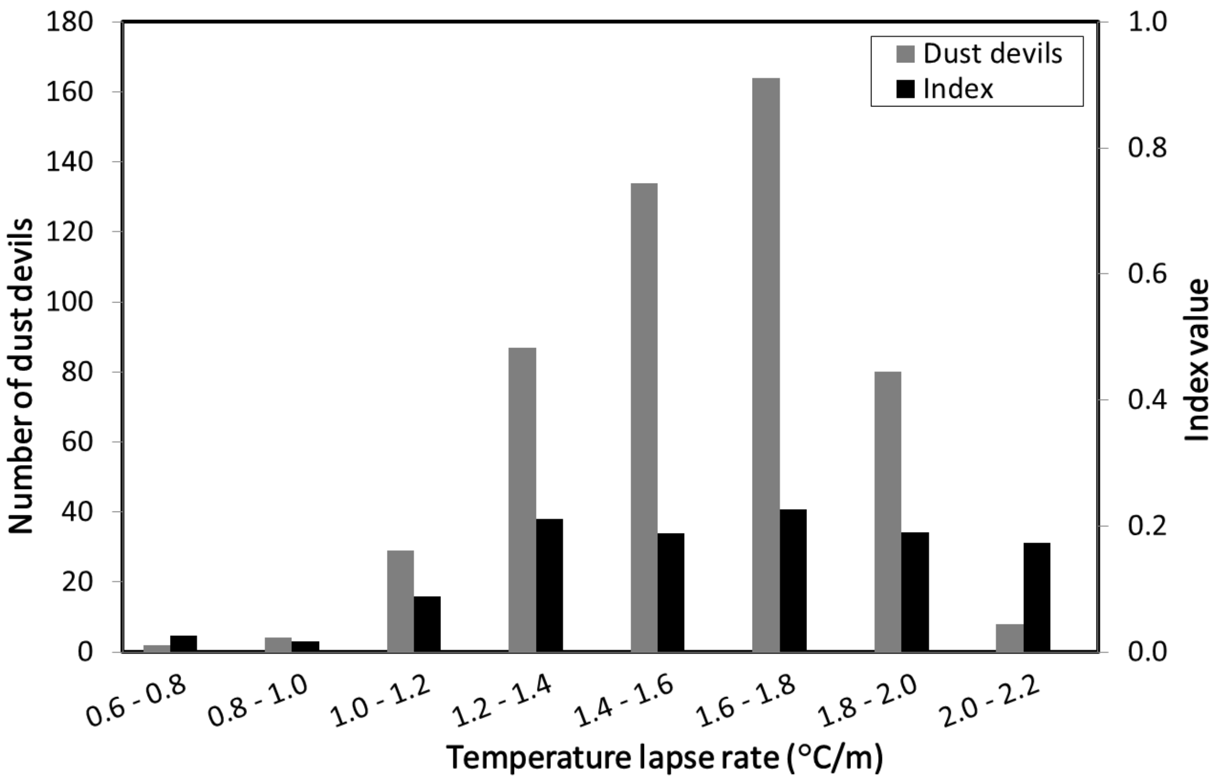

Figure 4.8. Number of dust devils and corresponding index value per temperature lapse rate class (°C/m) for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan.

Temperature lapse rate varied with the time of day, thus possibly the indicated relation between temperature lapse rate and dust devil frequency could explain why dust devils were in general much less frequent during the second part of the day, than during the first. However figure 4.3 in combination with figure 4.7 indicate that the temperature lapse cannot explain this observation. The curve of the temperature lapse rate showed a bell-shaped form and values were similar for both parts of the day.

Wind direction, speed, and variability of speed

Although western and southwestern wind directions were the dominant directions with respect to the total number of observed dust devils, southern as well as northwestern winds may have been more effective at producing dust devils (figure 4.9). The observed difference in efficiency may be a result of the topography in the area. Differences in topography can cause winds from certain directions to have a larger fetch than winds from other directions, which possibly influenced dust devil frequency.

Dust devils were observed in the wind speed range of 0.1 – 7.5 m/s. Figure 4.10 shows the number of dust devils that occurred during each wind speed class along with the corresponding index values. It should be noted that the relatively high index value of the 0 – 1 m/s wind speed class was assumed to be inaccurate, since these wind speeds only occurred during 18 minutes of dust devil observations. Most likely the relatively frequent occurrence of dust devils during these wind speeds was coincidental, and more observations of these wind speeds would possibly have lowered the efficiency of this wind speed class. Taking this into regard, a positive relation between wind speed and dust devil frequency was observed between 0 and 2 m/s, while the relation became negative for values higher than 3 m/s. One minute average wind speeds between 2 and 3 m/s seemed to produce most dust devils.

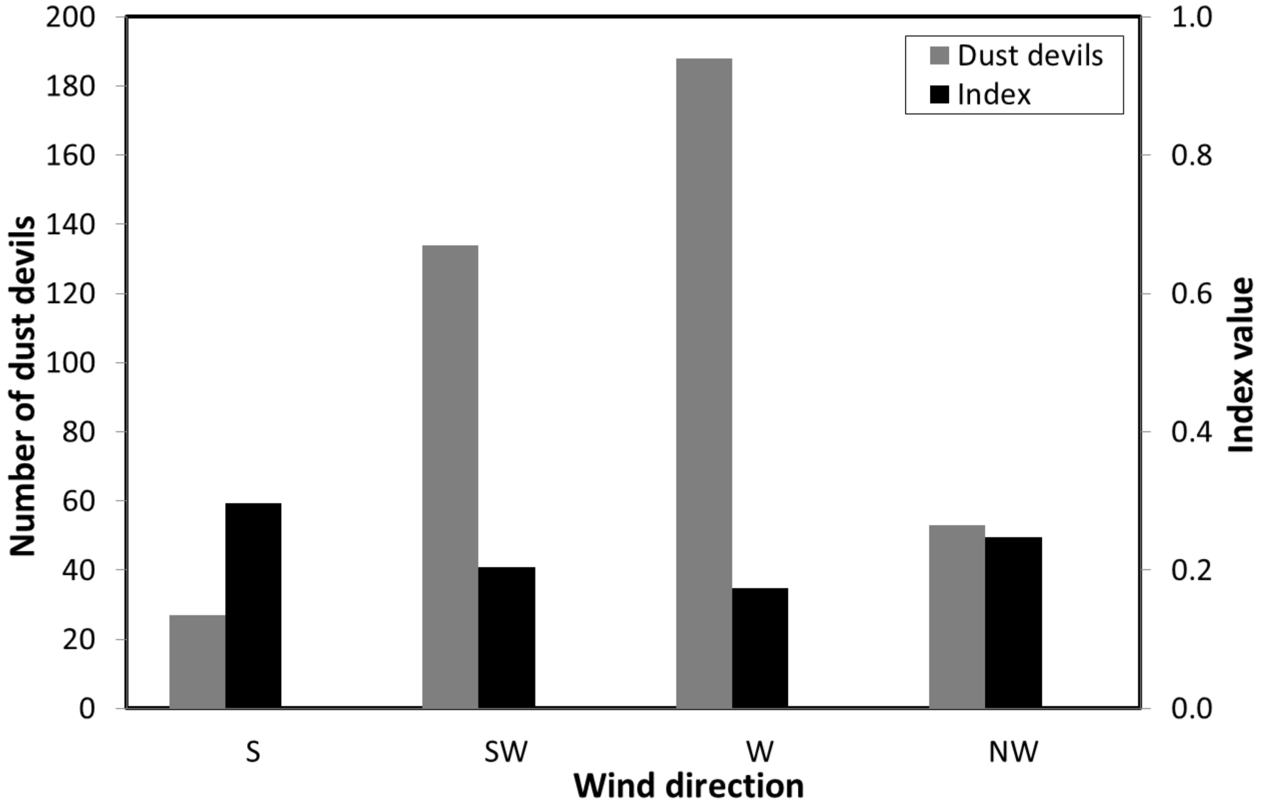

Figure 4.9.Number of dust devils and corresponding index values per wind direction for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan.

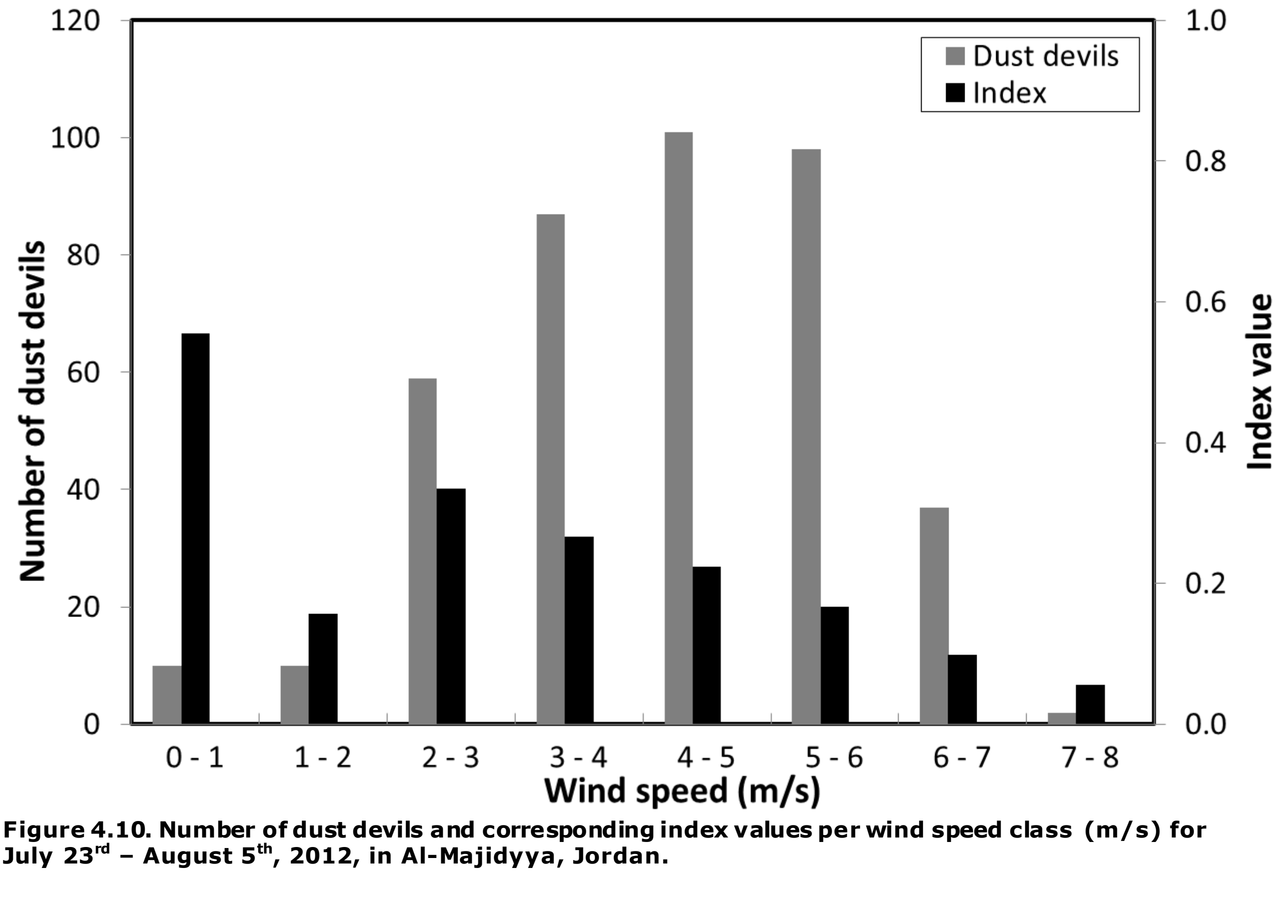

Figure 4.10. Number of dust devils and corresponding index values per wind speed class (m/s) for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan.

In section 4.1, a phenomenon was described during which temperature lapse rate and wind speed became highly correlated and showed a cyclic pattern of rising temperature lapse rates, followed by a gust of wind and mixing of the atmosphere. Field observations indicate that during these cyclic patterns, dust devils were mainly triggered by sudden gusts of wind, and in general appeared to be less frequent. Possibly this can be explained by the fact that during these cyclic patterns, wind speeds dropped to such low levels (figure 4.6, wind speeds of below 2 m/s were not uncommon) and may have been too low for dust devils to form. Whenever a gust of wind took place, wind speeds were sufficiently high, possibly leading to the observation that dust devils were mainly triggered by these sudden gusts of wind.

Whenever this cyclic pattern was present, gusts of wind would be intermitted by periods of relatively low wind speeds, thus causing wind speeds to be highly variable. Field observations indicated that dust devils were in general less frequent when these cyclic patterns were in effect. To evaluate whether this cyclic pattern had any effect on dust devil frequency, the variability of wind speed (using the standard deviation), was related to dust devil occurrence. Should there indeed be such a relationship, it may help explain why dust devils were seen to occur mainly during the first part of day. Wind speed variability tended to increase during the day (figure 4.5), thus possibly dust devil frequency was lowered by occurrence of the cyclic pattern. However, no relation between wind speed variability, and dust devil frequency was found (figure 4.11).

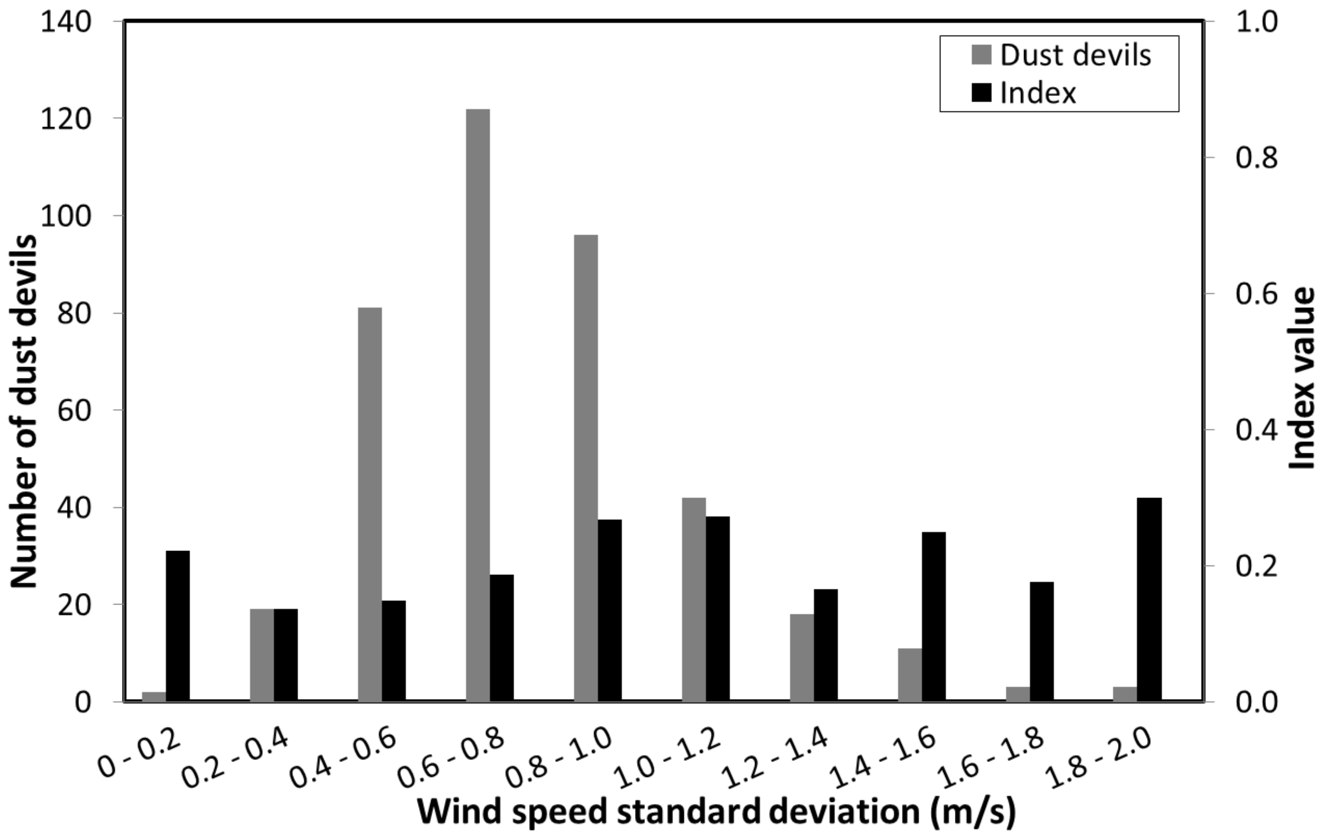

Figure 4.11. Number of dust devils and corresponding index values per wind speed standard deviation class (m/s) for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan.

Regression analysis

Results of the multiple linear regression model (table 4.3) validate the earlier findings of a positive relation between dust devil frequency and temperature lapse rate (figure 4.8). The results also underline the proposed hypothesis that this positive relation only exists up to values of the temperature lapse rate of 1.2 °C/m, since the relation between dust devil frequency and temperature lapse rate was found to be insignificant when using only values in the regression model of the temperature lapse rate above 1.2 °C/m (table 4.4). The previously stated hypothesis can thus be assumed to be correct; an increase of the temperature lapse rate above 1.2 °C/m did not necessarily lead to a higher dust devil frequency.

The relation between wind direction and dust devil frequency (figure 4.9) was found to be insignificant (table 4.3), thus it can be assumed that the formation of dust devils in the study area was not influenced by the wind direction. This indicates that the location of the study area was chosen correctly, as dust devil frequency was not biased by potential lee effects on wind speed by the area's topography.

Only two 15-minute intervals of dust devil observations were measured during which wind speed was lower than 2 m/s, thus the regression model was unable to test whether a positive relation existed between wind speeds below 2 m/s, and dust devil frequency. The negative relation between wind speeds of above 3 m/s and dust devil frequency was however confirmed (table 4.5).

To evaluate whether the observed cyclic pattern between temperature lapse rate and wind speed (section 4.1) had any effect on dust devil frequency, the variability of wind speed (using the standard deviation), was related to dust devil occurrence. No relation between this measure of wind speed variability and dust devil frequency was found (figure 4.11). However the regression model does indicate that such a relationship exists, a relation was indicated where increasing variability of wind speed would reduce dust devil frequencies (table 4.3). This concurs with field observations, as dust devil frequency appeared to be lower whenever the described cyclic pattern was in effect. However, when including only 15-minute intervals in the regression model for which wind speed was higher than 3 m/s, the relation between wind speed variability and dust devil frequency became insignificant (table 4.5). This can lead to two different conclusions; (1) these results indicate that the proposed relation is uncertain, or/and (2) these results indicate that the proposed relation is true, but only when wind speeds were below 3 m/s. Running the regression model using only the 14 intervals for which average wind speed was lower than 3 m/s, did not indicate a significant relation for any of the included variables. Possibly the total number of these intervals was too low for the regression model to accurately determine these relations. No reference to the proposed relation between the observed cyclic pattern and dust devil frequency could be found in literature.

Table 4.3. Results of multiple linear regression model explaining dust devil frequency as a function of temperature lapse rate, wind direction, wind speed, and wind speed standard deviation for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan. Includes all 15-minute intervals for which data of all 4 independent variables were available.

F = 12.62	*Sig.F = 1.69E-08*	
R^2 = 0.31	**Coefficient**	**P**
Temperature lapse rate	3.78	<0.0001
Wind speed	-1.04	<0.0001
Wind speed Std	-2.17	0.0194
Wind direction	0.02	0.1039

Table 4.4. Results of multiple linear regression model explaining dust devil frequency as a function of temperature lapse rate, wind direction, wind speed, and wind speed standard deviation for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan. Includes only data of intervals when temperature lapse rate was above 1.2 °C/m.

F = 9.75	*Sig.F = 1.41E-06*	
R^2 = 0.31	Coefficient	P
Temperature lapse rate	1.06	0.4320
Wind speed	-1.33	<0.0001
Wind speed Std	-2.84	0.0068
Wind direction	0.02	0.0520

Table 4.5. Results of multiple linear regression model explaining dust devil frequency as a function of temperature lapse rate, wind direction, wind speed, and wind speed standard deviation for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan.. Includes only 15-minute intervals for which wind speed was higher than 3 m/s.

F = 9.72	*Sig.F = 1.19E-06*	
R^2 = 0.29	Coefficient	P
Temperature lapse rate	3.48	<0.0001
Wind speed	-0.80	0.0018
Wind speed Std	-1.60	0.0814
Wind direction	0.02	0.0271

4.3. Dust devil erosion

Size- and intensity-frequency relation

Dust column diameter was estimated for all observed dust devils, but dust column height was estimated for only part of these dust devils (table 4.5). The observations indicate that the majority of observed dust devils featured dust column diameters below 1 m, and dust column heights below 10 m. Dust devils featuring dust columns larger than 3 m diameter, as well as dust columns higher than 10 m, were rarely seen to occur. Thus, in general, the observed dust devils were small in size.

Classifying dust devils into diameter and height classes was difficult at times, especially when wind speeds were high. While dust devils showed distinct dust columns under low wind speed conditions, these columns were much less clearly visible at high wind speeds. Wind caused dust stirred up by dust devils to be dispersed, causing their dust columns to become shielded in clouds of dust, making it difficult to estimate diameter and height of the dust column.

The majority of dust devils in each dust column height class had dust column diameters between 0 m and 1 m (table 4.5), which illustrates a flaw in the classification method used for the dimensions of dust devils. Field observations indicate that most dust devils featuring dust column heights of 0 – 1 m had diameters smaller than 0.2 m, while dust devils with dust column heights of over 10 m mostly had diameters closer to 1 m. Although featuring distinctly different dust column diameters, both types of dust devils were classified into the 0 – 1 m diameter class. This is a problem since the dust column diameter of each dust devil is needed to estimate dust devil erosion values. It would be unrealistic assigning equal values of the dust column diameter to all dust devils in the same dust column diameter class, thus distinctions in diameter were made based both on observations of dust column diameter as well as dust column height (table 4.6).

Field observations indicated clear differences in intensity of dust devils. While most dust devils with 0 – 1 m dust column height barely entrained any visible sediment, dust devils with dust columns higher than 10 m were mostly impossible to see through, showing a distinctly visible dust column laden with sediment. Thus, dust column height was considered indicative for the dust devil intensity, and dust flux values were assigned to each dust devil height class as such to best represent the differences in dust devil intensity as observed in the field (table 4.6)

Amount of dust devil erosion

Employing the method described in section 3.3, and using the input values given in table 4.6 and 4.7, the amount of local and regional erosion was estimated for the Jordan Badia (table 4.8). For the 285 observed dust devils for which the dust column height is available, local erosion was estimated at 0.19 kg/ha and regional erosion was estimated at 5.47×10^{-4} kg/ha. Annual erosion values were estimated at 9.79 kg/ha of local erosion and 0.03 kg/ha of regional erosion.

Table 4.5. Number of registered dust devils for which dust column height is available, with respect to diameter (m) and height (m) of visible dust column for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan.. Indicated by an asterisk are the total number of dust devils with respect to diameter for all 518 registered dust devils.

Diameter (m)	Height (m)				Total
	0 - 1	1 - 3	3 - 10	> 10	
0 - 1	195	67	10	3	**275 (452*)**
1 - 3	0	3	4	2	**9 (57*)**
> 3	0	0	0	1	**1 (9*)**
Total	**195**	**70**	**14**	**6**	**285 (518*)**

Table 4.6. Dust column diameters of dust devils assigned to each combination of dust column diameter and height class.

Diameter (m)	Height (m)			
	0 - 1	1 - 3	3 - 10	> 10
0 - 1	0.2	0.5	0.8	1
1 - 3	N/A	1	1.5	3
> 3	N/A	N/A	N/A	5

Table 4.7. Dust flux values of local and regional erosion ($mg/m^2/s$), and total duration of dust devil (s) for each dust column height class for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan.

	Height (m)			
	0 - 1	1 - 3	3 - 10	> 10
Local erosion ($mg/m^2/s$)	22	100	500	2978
Regional erosion ($mg/m^2/s$)	0.9	1.5	3	7.5
Duration (s)	5983	2511	720	316

Table 4.8. Estimated amount of local and regional erosion caused by the 285 observed dust devils for which dust column height is available, as well as estimated amount of local and regional annual erosion for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan.

	Erosion by 285 dust devils		Annual erosion	
	kg	kg/ha	kg	kg/ha
Local erosion	6.17	0.19	313.28	9.79
Regional erosion	0.02	5.47×10^{-4}	0.96	0.03

5 Discussion

5.1. Generation of dust devils

Apart from Oke et al. (2007a), no studies relating temperature lapse rate to dust devil frequency are currently available for which the temperature lapse rate was calculated over the same heights as during this study. Ryan (1972) observed dust devils occurring at temperature lapse rates as low as 0.1 °C/m, but Oke et al. (2007a) state that these low values of the temperature lapse rate may have been the result of the fact that calculations of the temperature lapse rate by Ryan (1972) did not include the more extreme change in temperature close to the surface. The lower limit of dust devil occurrence was 0.76 °C/m in this study. This is slightly different from the lower limit of 0.9 °C/m indicated by Oke et al. (2007a) for their study area.

Oke et al. (2007a), Sinclair (1969), and Ryan (1972) all found a general increase in dust devil frequency with temperature lapse rate, but the increase observed by Sinclair (1969) and Ryan (1972) was relatively weak. Both Sinclair (1969) and Ryan (1972) evaluated the temperature lapse rate over a much greater height than in this study and by Oke et al. (2007a). Oke et al. (2007a) suggested that their observed strong relationship between dust devil frequency and temperature lapse rate thus indicates that it is the temperature lapse rate of the atmosphere close to the surface that drives dust devil generation. The results of this study tend to validate that suggestion, although it is here proposed that, at least for this particular study area, a temperature lapse rate of 1.2 °C/m was the threshold after which atmospheric instability was high enough and other factors became more important in controlling dust devil occurrence.

Oke et al. (2007a) observed the lower limit of wind speed to be 1.5 m/s, and the upper limit of wind speed to be 7.5 m/s for dust devil occurrence. This study found that dust devils were able to occur at wind speeds as low as 0.1 m/s, and as high as 7.5 m/s, but failed to establish definite lower and upper limits since wind speeds below and above these values hardly ever occurred.

Other studies have also investigated the wind speed range of dust devil occurrence. Carroll and Ryan (1970) reported on dust devils occurring between wind speeds of 1.1 m/s and 5.8 m/s. They however used a sample size of just 80 dust devils, which may explain the small indicated wind speed range (Oke et al., 2007a). Hess and Spillane (1990) observed dust devils between wind speeds of 0.1 and 18 m/s. They however did not use local measurements of wind speed but calculated the likely wind speed in the area by using synoptic charts and values from the nearest meteorology station. It is thus possible that this method involved some degree of imprecision (Oke et al., 2007a). Lastly, Sinclair (1969) used wind speed classes (0.5 – 2.3 m/s and 7.4 – 9.3 m/s) to indicate his findings of the wind speed range for dust devil occurrence, which makes it difficult to compare to the results of this study since Sinclair (1969) did not supply an excact wind speed range.

All of the above named studies however did observe that low wind speeds were unfavorable for the occurrence of dust devils. This more or less concurs with the results of this study. Although such a relation could not be established by the regression model, a positive relation between wind speeds of 0 – 2 m/s and dust devil frequency was indicated by figure 4.10. The fact that this relation seems to exist suggests that the instability of the lower atmosphere alone is not enough to induce the formation of dust devils. A certain amount of wind seems to be required to create an initial source of vorticity to set the dust devil into motion, which can possibly be caused by the shear in the horizontal flow of the local wind (Carroll and Ryan, 1970).

The findings by Oke et al. (2007a) of a maximum dust devil frequency at wind speeds of approximately 2 - 3 m/s, and the findings of all the above named authors of a negative relation between wind speed and dust devil frequency above that value, concur with the results of this study. It thus seems that a wind speed between 2 – 3 m/s is ideal for initiating the required source of vorticity. Sinclair (1969) observed that dust devils forming at high wind speeds tended to be rapidly destroyed because the lower end of the dust devil would move more slowly than the upper end of the dust devil, shearing off the dust devil. Possibly this effect is larger at high wind speeds since the stronger the wind, the greater the influence of surface roughness and thus the greater the development of shear (Oke et al., 2007a). Oke et al. (2007a) observed this occurring on several occasions with high wind speeds, where the lower sections of the dust devil columns would lag behind the upper sections of the colmuns. This was also observed during this study, thus it seems that when high wind speeds occur near the surface, the vertical shear may be too large to initiate and maintain the dust devil vortex (Oke et al., 2007a).

Although the results of the regression analyses were considered significant (table 4.3 - 4.5), the R^2 values of 0.31 – 0.35 indicate that the majority of the observed variance in dust devil frequency was not explained by the independent variables. The observed imprecision in explaining the variance in dust devil frequency as a function of the variance in the measured meteorological variables may be the result of the limitations of the experimental setup. Meteorological measurements were done at a meteorology tower that was placed in the field. Thus these measurements were all done at just one point in the study area. Dust devils however occurred throughout the study area and it is thus possible that the value of the meteorological variables at the place of dust devil occurrence differed from the value of the meteorological variables at the meteorology tower. Moreover, it is possible that for multiple dust devils there was a time difference between their formation and their actual observation. These limitations may have led to a certain degree of imprecision in the observed relation between dust devils and the meteorological variables influencing their formation.

It is likely that the above named limitations of the experimental setup and the possible human error have negatively influenced the multiple linear regression model's precision to some degree. However, there has not been much research on the relationship between dust devils and their local environment, and these relations are not yet well understood (Oke et al., 2007a). Previous studies have proposed that dust devils are controlled by local meteorological conditions (Oke et al., 2007a) and the results of this study indicate that dust devils are active only in limited meteorological conditions. However, the exact factors controlling dust devil formation may be active at a much smaller scale than measured here. It is perfectly possible that if two different time intervals would have occurred during this study with measured equal meteorological variables, different values of the dust devil frequency would have been observed. This reflects the fact indicated by the low accuracy of the multiple linear regression model; accurate prediction of dust devil occurrence based on the meteorological variables measured at the spatial scale during this study is not yet possible.

5.2. Dust devil erosion

The dust flux values indicating local erosion used in this study are based on the same dust flux values Sinclair (1990, in Gillette and Sinclair, 1990) used in his study to estimate erosion by dust devils for an area near Tuscan, Arizona, United States of America. He however estimated erosion values to be more than 100 times higher than estimated here for the Jordan Badia. This could indicate that dust devils in general, or dust devils with high intensity, were markedly less frequent in the Jordan Badia than in the study area used by Sinclair (1990, in Gillette and Sinclair, 1990). Regional erosion values were based on PM10 measurements given by Metzger et al. (2011). Metzger et al. (2011) estimated that one of their observed dust devils, which lasted for more than 10 minutes and featured a 15 m diameter, was able to transport 0.8 kg of PM10 material. This is significantly more than the estimated 0.007 kg of PM10 material eroded by the largest dust devil observed in this study, which lasted for 46 seconds and measuring 5 m in diameter. Part of this difference was caused by the fact that Metzger et al. (2011) measured the entire duration of this dust devil, while the duration of dust devils observed during this study was only registered until the dust devils had crossed the border of the study area. Still, taking these different methods of observation into account, the differences in estimated amounts of regional erosion are significant and must be attributed to the difference in dust devil diameter. Metzger et al. (2011) did not provide diameters for all dust devils observed during their study, however when comparing the previously mentioned dust devil to their other observations, it proves to be one of the smaller dust devils they observed. This, in combination with results from Sinclair (1990, in Gillette and Sinclair, 1990), leads to believe that dust devils in the Jordan Badia were generally smaller, and thus less intense, than dust devils measured by Metzger et al. (2011) and Sinclair (1990, in Gillette and Sinclair, 1990).

Results of Duijts (2012), who modelled wind erosion in Al-Majidyya for January – March of the years 2002, 2003, and 2004, indicate that the amount of wind erosion in the area is much higher than the amount of dust devil erosion. Soil loss by wind erosion was modelled at 1300 kg/ha for 2002, and 900 kg/ha for 2003. For 2004 an amount of 800 kg/ha was modeled, which took place during a mere period of 5 days. Taking these results into regard it can be concluded that, in the Jordan Badia, the total amount of erosion by dust devils is substantially lower than the amount of wind erosion.

Table 4.10 displays the percentage of each combination of dust column diameter and height class with respect to the amount of local dust devil erosion estimated for the 285 dust devils for which dust column height estimates are available. The indicated relative percentages show a similar distribution for the regional erosion. These percentages suggest that dust devils with dust column heights larger than 10 m were markedly more efficient at transporting sediment than smaller dust devils. For example, 93.6% of total estimated erosion was caused by the only 6 dust devils with dust column height exceeding 10 m, while just 0.1% of total erosion was caused by 195 dust devils having dust column heights between 0 m and 1 m. Especially remarkable is the 43.9% of total dust devil erosion, amounting to 2.7kg, caused by just one dust devil which was estimated to have a diameter of 5 m and dust column height of more than 10 m. This particular dust devil was observed in the field to distinctly stand out with respect to its dimensions and intensity in comparison to other dust devils.

These percentages illustrate that the greatest part of observed dust devils were inefficient at transporting dust, it is the very few dust devils featuring large diameters and column heights that caused the major part of sediment transport. This illustrates a significant degree of uncertainty in the estimations of local as well as regional erosion; if just one more dust devil of the largest dust column diameter and height registered would have moved through the area during observations, ~2.7 kg would have been added to the total amount of estimated local erosion. Occasionally, dust devils featuring dimensions markedly larger than dust devils registered here, were observed moving through the surrounding areas.

Table 4.9. Local erosion of each dust column diameter and height class as percentage of total local erosion by 285 dust devils for July 23rd – August 5th, 2012, in Al-Majidyya, Jordan.

Diameter (m)	Height (m)				Total
	0 - 1	1 - 3	3 - 10	> 10	
0 - 1	0.1%	0.7%	2.0%	5.4%	**8.2%**
1 - 3	0.0%	0.3%	3.4%	44.3%	**47.9%**
> 3	0.0%	0.0%	0.0%	43.9%	**43.9%**
Total	**0.1%**	**1.0%**	**5.3%**	**93.6%**	**100.0%**

It is thus perfectly possible that if a similar study would have been conducted during the same time period and in the same region but on a different location, it would have yielded substantially higher values of local and regional erosion.

Next to the above described imprecision in estimations, there may also be a margin of error in the estimation of dust devil dimensions, the upscaling method used to estimate annual erosion values, and the division of dust flux values. A larger sample size, thus meaning a longer period of dust devil observations, in combination with improved methods for classifying dust devil dimensions and upscaling to annual values, could possibly lower the described uncertainty and margin of error. Despite these reservations, the presented values in table 4.8 and 4.9 are the only estimations for erosion by dust devils available for the Jordan Badia.

6 Conclusion

Dust devils were suspected to constitute an important form of erosion in the Jordan Badia, since areas like these are notorious for the frequent occurrence of dust devils, and these convective vortices may carry substantial amounts of soil particles. The aim of this study was the quantification of dust emissions into the atmosphere by dust devils for the Jordan Badia, and to relate the occurrence of these dust devils to the meteorological variables controlling their formation. To achieve this, dust load information obtained from literature was combined with a field study, which took place during 9 days in the period of July 23 – August 5h, 2012. In total 518 dust devils were observed and related to meteorological variables, which were measured during the dust devil observations.

Generation of dust devils

Dust devils were observed between 09:09 and 17:34. Dust devils were most active between 12:00 and 13:00, and were significantly more frequent during the first part, than during the second part of the day. Temperature lapse rates of at least 0.76 °C/m were required for dust devil formation. Dust devils became more frequent with rising temperature lapse rates, however this positive relation ceased when the temperature lapse rate reached a value of 1.2 °C/m. Dust devil frequency remained constant with further increases of temperature lapse rate. Thus, this value is here proposed to indicate a threshold after which atmospheric instability, at least for this study area, was high enough for efficient dust devil formation and other factors became more important in controlling dust devil frequency.

Dust devils were observed to occur in the wind speed range of 0.1 - 7.5 m/s. Wind speeds below and above these values were hardly ever observed, thus a definite lower and upper limit to wind speed could not be established. Wind speed and dust devil frequency were positively related until wind speed values of 2 m/s, after which the relation became negative. The fact that these relations exist suggests that the instability of the lower atmosphere alone is not enough to induce dust devil formation. A minimum wind speed is required to create an initial source of vorticity to set the dust devil into motion, which can possibly be caused by the shear in the horizontal flow of the local wind (Ryan and Carroll, 1970). Wind speeds of 2 – 3 m/s were seen to be most beneficial for dust devil formation, thus indicating that these wind speeds were ideal for initiating the required source of vorticity. When high wind speeds occur near the surface, vertical shear may be too large to initiate and maintain the dust devil vortex, which thus may explain the negative relation observed when wind speeds increase to values above 3 m/s.

A cyclic pattern was observed in the lower 2.5 m of the atmosphere during which temperature lapse rate and wind speed were highly correlated and showed a cyclic pattern of rising and falling values. The hypothesis is that the observed phenomenon was caused by the temperature lapse rate in the atmosphere above 2.5 m exceeding the dry adiabatic lapse rate, causing the atmosphere to become unstable. These cyclic patterns were not seen to occur when average wind speeds were high, which may be explained by the suggestion that atmospheric mixing by high wind speeds takes place above 2.5 m height in the atmosphere. The induced mixing may have lowered the temperature lapse rates in these layers of the atmosphere to values below the dry adiabatic lapse rate.

Field observations indicated that during these cyclic patterns, dust devils were mainly triggered by sudden gusts of wind, and overall appeared to be less common. Possibly this relation can be explained by the fact that during these cyclic patterns, wind speeds dropped to relatively low levels, thus wind speeds may have been too low for dust devils to form. There is thus reason to believe that a negative relation existed between the occurrence of this phenomenon and dust devil frequency. Should there indeed be such a relationship, it may help explain why dust devils were seen to occur mainly during the first part of day. Wind speed variability tended to increase during the day, thus possibly dust devil frequency was lowered by occurrence of the cyclic pattern. Evidence for this relation was however not conclusive and no references to literature concerning this relation were found.

Previous studies have proposed that dust devils are controlled by local meteorological conditions. The results of this study indicate that these local conditions are indeed of influence on dust devil occurrence, but the exact factors initiating these dust devils may be active at a much smaller spatial scale than the scale of the meteorological variables measured in this study. This reflects the fact that accurate prediction of dust devil occurrence based on the meteorological variables measured at this spatial scale is not yet possible.

Dust devil erosion

Annual amounts of erosion for the Jordan Badia were estimated at 9.79 kg/ha of locally lost soil and 0.03 kg/ha of soil lost from the region. These values of erosion were found to be very low compared to other dust devil studies, which leads to believe that dust devils in the Jordan Badia are generally smaller and less intense than dust devils in other regions. Also compared to normal wind erosion in the area, the amount of annual soil erosion by dust devils was low. This indicates that in this area, compared to wind erosion, dust devil erosion is of low importance. However, dust devils do contribute to atmospheric dust loading, which affects the atmospheric radiation balance, may pose health issues to humans and livestock, and may cause a loss of primary nutrients from the area.

The greatest part of observed dust devils were inefficient at transporting dust, it is the very few dust devils featuring large diameters and column heights that caused the major part of sediment transport. This illustrates a significant degree of uncertainty in the estimations of erosion; if just one more large dust devil would have moved through the area during observations, a significant percentage would have been added to the total amount of estimated erosion. Next to the above described imprecision in estimations, there may also be a margin of error in the estimation of dust devil dimensions, the upscaling method used to estimate annual erosion values, and the division of dust flux values. A larger sample size, thus meaning a longer period of dust devil observations, in combination with improved methods for classifying dust devil dimensions and upscaling to annual values, could possible lower the described uncertainty and margin of error. Despite these reservations, this study provides the only estimation of erosion by dust devils available for the Jordan Badia.

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