**Atmospheric
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Does the size distribution of mineral dust aerosols depend on the wind speed at emission?

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Wind speed dependence of dust size distribution

J. F. Kok

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

◄◄　　►►

◄　　►

Back　　Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

The size distribution of mineral dust aerosols greatly affects their interactions with clouds, radiation, ecosystems, and other components of the Earth system. Several theoretical dust emission models predict that the dust size distribution depends on the wind speed at emission, with larger wind speeds predicted to produce smaller aerosols. The present study investigates this prediction using a compilation of published measurements of the size-resolved vertical dust flux emitted by eroding soils. Surprisingly, these measurements indicate that the size distribution of naturally emitted dust aerosols is independent of the wind speed. This finding is consistent with the recently formulated brittle fragmentation theory of dust emission, but inconsistent with other theoretical dust emission models. The independence of the emitted dust size distribution with wind speed simplifies both the parameterization of dust emission in atmospheric circulation models as well as the interpretation of geological records of dust deposition.

1 Introduction

Mineral dust aerosols affect the Earth system through a wide range of interactions, including scattering and absorbing radiation, serving as cloud nuclei, providing nutrients to ecosystems, and lowering the reflectivity of snow and ice (e.g., Goudie and Middleton, 2006; Mahowald et al., 2010; DeMott et al., 2010; Painter et al., 2010). Since the size of dust aerosols affects many of these interactions and also determines the lifetime and transport of dust (e.g., Tegen and Lacis, 1996; Kok, 2011), a detailed understanding of the particle size distribution (PSD) is critical for simulating the myriad interactions of dust with the Earth system.

Unfortunately, large uncertainties exist in the treatment of the emitted dust PSD in atmospheric circulation models (Cakmur et al., 2006; Kok, 2011). In particular, it is unclear whether the emitted dust PSD depends on the wind speed at emission (e.g.,

Sow et al., 2009). Determining this dependence will thus facilitate more accurate simulations of dust interactions with weather, climate, and ecosystems, as well as aid the interpretation of variations in the mean diameter of deposited dust in geological records (Rea, 1994; Ruth et al., 2003).

5   Measurements of the dependence of the emitted dust PSD on wind speed have yielded contradictory results. Whereas a subset of wind tunnel studies have reported that the dust aerosol size decreases with increasing wind speed (Alfaro et al., 1997, 1998; Alfaro, 2008), other wind tunnel measurements and field studies have not found a clear dependence of the emitted dust PSD on the wind speed (Gillette et al., 1974;
10 Shao et al., 2011). Theoretical models of dust emission mirror these contradictory experimental results: whereas the models of both Shao (2001, 2004) and Alfaro and Gomes (2001) predict that the size of emitted dust aerosols decreases with wind speed, the recently formulated brittle fragmentation theory of dust emission predicts that the emitted dust PSD is independent of the wind speed (Kok, 2011). While the former
15 theories are in agreement with a subset of wind tunnel studies, the latter theory is in good agreement with field measurements (Fig. 1).

In order to, (i) help distinguish between these contrasting theoretical dust emission models, (ii) inform dust emission parameterizations in atmospheric circulation models, and, (iii) aid the interpretation of geological dust deposition records, this article for the
20 first time uses a compilation of published measurements to determine the dependence of the emitted dust PSD on the wind speed. As shown in the subsequent sections, the results indicate that the emitted dust PSD is invariant to even substantial changes in wind speed.

2   Methods

25 To investigate whether the emitted dust PSD depends on wind speed, I determine the variation of the mean dust aerosol diameter with the wind friction speed u_* (defined as the square root of the ratio of the wind stress and the air density). I do so by calculating

the mean aerosol diameters by number (D_N) and volume (D_V) for every reported value of u_* of each published data set of the size-resolved vertical dust flux emitted by an eroding soil (see Table 1). That is,

$$D_N = \int_{D_{low}}^{D_{up}} D\frac{dN}{dD}dD \Big/ \int_{D_{low}}^{D_{up}} \frac{dN}{dD}dD; \qquad D_V = \int_{D_{low}}^{D_{up}} D\frac{dV}{dD}dD \Big/ \int_{D_{low}}^{D_{up}} \frac{dV}{dD}dD, \qquad (1)$$

5 where N and V respectively denote the number and volume of emitted aerosols of a given diameter D. The limits on the integration were set according to the maximum overlap in size ranges measured by the various data sets, resulting in $D_{low} = 1.2\,\mu m$ and $D_{up} = 8.4\,\mu m$ (Table 1).

The detailed procedure for using Eq. (1) to calculate D_N, D_V, and their uncertain-
10 ties is described in the supplementary text. Briefly, data sets for which the particle bin limits do not exactly match D_{low} or D_{up} were corrected by truncating the relevant particle bin(s). Furthermore, the integration in Eq. (1) was performed by assuming that the sub-bin distribution follows the power law for $\sim$2–10 μm diameter dust reported in Gillette et al. (1974) and Kok (2011) (i.e., $dN/d\log D \sim D^{-2}$ and $dV/d\log D \sim D$). Finally,
15 the uncertainties of D_N and D_V were calculated by propagating the uncertainty in the measurements of $N(D)$ and $V(D)$, respectively.

3   Results

Results from a compilation of the six data sets of field measurements show that the trends of D_N and D_V with u_* are within the standard error, and thus statistically insignif-
20 icant (Fig. 2a, b and Table 1). Similarly, individual field data sets show opposing and mostly statistically insignificant trends of D_N and D_V with u_* (Table 1). In addition to this apparent insensitivity to u_*, D_N and D_V also appear relatively insensitive to changes in the soil characteristics. Indeed, the mean aerosol diameters of different field data sets

are mostly within one standard deviation (Table 1), despite variations in soil character-istics between the different data sets (see the relevant references and Table S1 in Kok, 2011). Note that calculating D_N and D_V with the extended size range of $D_{low} = 0.6\,\mu m$ and $D_{up} = 8.4\,\mu m$ spanned by the most recent field measurements of Sow et al. (2009) and Shao et al. (2011) yields qualitatively identical results (Supplement Fig. S1).

Although field measurements thus indicate that the PSD of naturally emitted dust is independent of u_*, the wind tunnel measurements of Alfaro et al. (1998) do show a statistically significant decrease of the mean aerosol diameter with u_* (Fig. 2a, b and Table 1). Comparable measurements by Alfaro et al. (1997) and Alfaro (2008) were not included in the present analysis because these studies did not use natural soil and measured the emitted dust PSD only up to $5\,\mu m$, respectively. However, these measurements similarly show a pronounced shift to smaller aerosol diameters with u_* (see Fig. 10 in Alfaro et al. (1997) and Fig. 2c in Alfaro, 2008). In contrast to these results by Alfaro and colleagues, the wind tunnel measurements of Gillette et al. (1974) show no clear dependence of D_N and D_V on u_* (Fig. 2a, b and Table 1).

4 Discussion

4.1 Testing the accuracy of theoretical dust emission models

The surprising result that the PSD of naturally emitted dust aerosols is independent of u_* can be used to test the accuracy of theoretical dust emission models. The brittle fragmentation theory of dust emission (Kok, 2011) correctly predicts this independence (Fig. 2c, d), whereas the dust emission theories of Alfaro and Gomes (2001) and Shao (2001, 2004) predict that larger wind speeds produce more disaggregated and hence smaller dust aerosols. These theories thus predict a decrease of the mean aerosol diameters with increasing u_* (Fig. 2c, d). However, this prediction is inconsistent with measurements (Fig. 2a, b), except for the Alfaro et al. wind tunnel experiments. A possible explanation for the puzzling discrepancy of the Alfaro et al. studies with other measurements is discussed in Sect. 4.2.

The results of the detailed field study of Sow et al. (2009) further favor the brittle fragmentation theory of dust emission. Although Sow et al. (2009) found that the emitted dust PSD is invariant to variations in u_* during a given dust event (see their Fig. 10), consistent with the findings in Table 1 and Fig. 2, they did find variations in the emitted dust PSD between dust events. Moreover, Sow et al. reported changes in the aerodynamic roughness length (table 1 in Sow et al., 2009) and the threshold u_* for dust emission between the three measured dust events, which could indicate changes in the physical state of the soil. Brittle fragmentation theory (Astrom, 2006) predicts that changes in the physical state of the brittle material (aggregates of dust particles in the soil in this case) affect the propagation distance λ of the side branches of cracks created by a fragmenting impact. For instance, precipitation between the dust emission events could have affected the cohesiveness of the soil dust aggregates (Rice et al., 1996) and thus changed the propagation distance λ. Although these changes affect the large-size cutoff, which is determined by λ and is on the order of 10–15 µm, they do not affect the emitted dust PSD in the $<\sim5$ µm size range, which is instead determined by the fully dispersed (and presumably constant) soil PSD (Kok, 2011). This "fingerprint" of brittle fragmentation theory is indeed apparent in the measurements of Sow et al. (2009), which are highly similar between the three dust emission events for the <5 µm size range, yet show variation in the >5 µm size range (see Fig. 9 in Sow et al., 2009). By adjusting the value of λ, this variation of the emitted dust PSD between the three events is reproduced by brittle fragmentation theory (Fig. 3).

4.2 Cause of discrepancy between theories and measurements

As discussed above, the theories of Alfaro and Gomes (2001) and Shao (2001, 2004) predict a shift to smaller aerosol diameters with increasing u_* (see Fig. 5 in both Shao (2001) and Alfaro and Gomes, 2001), which field measurements indicate is incorrect (Table 1 and Fig. 2a, b). This predicted shift is due to the assumption in these models that the energy with which bouncing ("saltating") sand particles impact the soil, is proportional to u_*^2 (Eq. (1) in Alfaro and Gomes (2001) and p. 20,247 in Shao, 2001).

(The breakdown of dust aggregates by the impact of these saltating particles on the soil is the main source of dust aerosols (e.g., Gillette et al., 1974).) The Alfaro and Gomes (2001) and Shao (2001, 2004) models then hypothesize that the increase of the saltator impact energy with u_* produces more disaggregated and hence smaller dust aerosols.

Although these arguments appear plausible, recent measurements, numerical models, and theories of saltation all indicate that the saltator impact speed, and thus the saltator impact energy, is independent of u_* (Fig. 4). This result is a logical consequence of the requirement that there must be exactly one particle leaving the soil bed for each particle impacting it in order for saltation to be in steady state. This condition is fulfilled at a particular mean saltator impact speed that is independent of u_* (Ungar and Haff, 1987; Andreotti, 2004; Kok and Renno, 2009; Kok, 2010a; Duran et al., 2011). Since field measurements of saltation show that the saltation flux responds to variations in wind speed on a characteristic time scale of a second (e.g., Jackson and McCloskey, 1997), saltation in most natural conditions can be assumed to be close to steady state (Duran et al., 2011). Removing the assumption that saltator impact speeds increase with u_* would thus likely improve the agreement of the Alfaro and Gomes (2001) and Shao (2001, 2004) theoretical models with field measurements (see Fig. 2c, d), as also inferred by Shao et al. (2011, p. 18) from their field measurements.

Note that the arguments above apply only to transport limited saltation, for which the amount of saltating sand is limited by the availability of wind momentum to transport the sand (Nickling and McKenna Neuman, 2009). Indeed, in the alternative case of supply limited saltation, for which the amount of saltating sand is limited by the availability of loose soil particles that can participate in saltation, the drag on the wind by saltating particles is insufficient to reduce the saltator impact speed to its wind-independent value. Consequently, the impact speed in supply limited saltation generally increases with wind speed (Houser and Nickling, 2001; Ho et al., 2011). Since none of the experimental studies of size-resolved dust emissions (see Table 1) reported supply limited conditions, it is thus possible that the PSD of dust aerosols generated during supply

limited saltation does depend on the wind speed. However, since supply limited saltation occurs due to aggregation of the soil surface or the formation of crusts, such soils usually have a higher dust emission threshold and produce less dust for a given excess shear stress, and are therefore generally less productive sources of dust aerosols (Rice et al., 1996; Lopez et al., 1998; Gomes et al., 2003; Nickling and McKenna Neuman, 2009).

The arguments above also provide a possible explanation for the puzzling result of the wind tunnel measurements of Alfaro and colleagues (Alfaro et al., 1997, 1998; Alfaro, 2008), which found a strong dependence of the emitted dust aerosol size distribution on u_*, in conflict with results from both field measurements and the wind tunnel study of Gillette et al. (1974). The cause of this discrepancy might be that Alfaro and colleagues used a wind tunnel with a working section of only 3.1 m in length (Alfaro et al., 1997). Indeed, measurements indicate that ∼10 m is required to produce steady-state saltation for natural soils (Shao and Raupach, 1992; Duran et al., 2011), although the use of carefully designed roughness elements can reduce this length (Rasmussen et al., 1996, 2009). Consequently, saltation did probably not reach steady-state in the wind tunnel used by Alfaro et al. (1997), as also noted by these authors (p. 11,243). Therefore, the steady-state requirement that there must be exactly one particle leaving the soil bed for each particle impacting it, which constrains the saltator impact speed to remain constant with u_* (see Fig. 4 and discussion above), did probably not apply. Increases in wind speed could thus have produced increases in the saltator impact speed, which in turn could have produced smaller dust aerosols (Alfaro and Gomes, 2001). This interpretation is supported by the apparent independence of the mean aerosol diameter with wind speed for the wind tunnel measurements of Gillette et al. (1974), which were performed in a wind tunnel with a longer working section of 7.2 m.

5   Summary and conclusions

The present study for the first time uses a compilation of published measurements of the size-resolved vertical dust flux emitted by eroding soils to determine the dependence of the emitted dust PSD on wind speed. The results indicate that the size distribution of naturally emitted dust aerosols is independent of the wind speed at emission (Fig. 2a, b and Table 1). This finding is important for several reasons. First, it simplifies the parameterization required to simulate dust emission in atmospheric circulation models, many of which currently account for a dependence of the emitted dust PSD on the wind speed. Second, this finding simplifies the interpretation of geological records of dust deposition. Indeed, it supports the interpretation that increases in the mean dust size in these records are not related to changes in the wind speed during emission, and instead indicate either stronger transporting winds or a reduced distance to the source (Ruth et al., 2003). And finally the independence of the emitted dust PSD with wind speed can be used to test the accuracy of theoretical dust emission models. Specifically, the models of both Alfaro and Gomes (2001) and Shao (2001, 2004) predict that larger wind speeds produce smaller dust aerosols, which is thus inconsistent with measurements. The cause of this discrepancy is probably the assumption by these models that the speed of impacting saltators is proportional to the wind friction speed, which is likely incorrect (Fig. 4). In contrast, the brittle fragmentation theory of dust emission (Kok, 2011) does correctly predict the independence of the emitted dust PSD with wind speed, and is also consistent with the variation of the coarse dust fraction ($>\sim 5\,\mu m$) with changes in the soil state observed by Sow et al. (2009) (Fig. 3).

Supplementary material related to this article is available online at: http://www.atmos-chem-phys-discuss.net/11/19995/2011/ acpd-11-19995-2011-supplement.pdf.

Wind speed dependence of dust size distribution

J. F. Kok

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

◄ | ►I

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

References

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Wind speed dependence of dust size distribution

J. F. Kok

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Back | Close

Full Screen / Esc

Table 1. Summary of published wind tunnel and field measurements of the size-resolved vertical dust flux. Listed for each data set are the number of measurements, the friction speed and dust aerosol diameter ranges spanned by those measurements, the average D_N and D_V with standard deviation of those measurements, and the trend with standard error of each data set with u_*. A compilation of all six data sets of field measurements is also listed.

Data set	Measurement type	Number of measurements	u_* range (m s^{-1})	D range (µm)	Average D_N (µm)	D_N trend (µm m^{-1} s)	Average D_V (µm)	D_V trend (µm m^{-1} s)
Gillette et al. (1974)	Wind tunnel	3	0.74–1.14	1.2–80	2.6 ± 0.2	0.1 ± 0.7	5.0 ± 0.5	2.9 ± 1.9
Alfaro et al. (1998)	Wind tunnel	4	0.35–0.66	1–100	4.6 ± 2.7	−21.2 ± 0.1	6.0 ± 1.4	−11.1 ± 0.1
Gillette et al. (1974)	Field	3	0.25–0.78	1.2–40	2.6 ± 0.5	−1.0 ± 1.0	5.4 ± 0.3	−0.1 ± 2.0
Gillette (1974), soil 1	Field	12	0.18–0.58	1.2–20	2.5 ± 0.4	−2.6 ± 1.6	5.2 ± 0.7	−2.6 ± 3.0
Gillette (1974), soil 2	Field	4	0.49–0.78	1.2–20	2.6 ± 0.2	1.7 ± 2.0	4.5 ± 0.5	3.6 ± 5.1
Gillette (1974), soil 3	Field	4	0.28–0.48	1.2–20	3.1 ± 0.4	3.8 ± 4.3	5.4 ± 0.7	3.7 ± 6.1
Sow et al. (2009)	Field	3	0.40–0.60	0.3–20	2.6 ± 0.2	−1.6 ± 2.9	5.0 ± 0.3	−2.9 ± 5.8
Shao et al. (2011)	Field	8	0.20–0.55	0.6–8.4*	2.3 ± 0.1	0.3 ± 0.6	4.4 ± 0.2	0.7 ± 1.4
All field measurements	Compilation	34	0.18–0.78	1.2–8.4	2.6 ± 0.4	0.1 ± 0.4	4.9 ± 0.6	0.5 ± 0.8

* The Shao et al. measurements actually span the size range of 0.3–8.4 µm, but the authors questioned the reliability of the 0.3–0.6 µm size bin (Shao et al., 2011, p. 13).
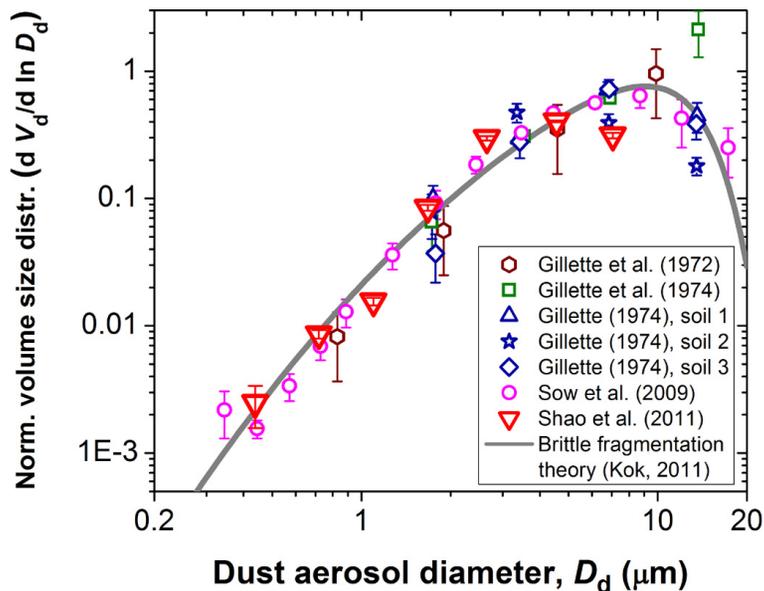
Fig. 1. Field measurements with standard error of the volume size distribution of emitted dust aerosols (assorted symbols), processed as described in Kok (2011). The brittle fragmentation theory of dust emission (solid line) (Kok, 2011) is in good agreement with these measurements, including the subsequently published Shao et al. (2011) (large triangles; note that Shao et al. (2011) questioned the reliability of their 0.3–0.6 μm particle size bin).
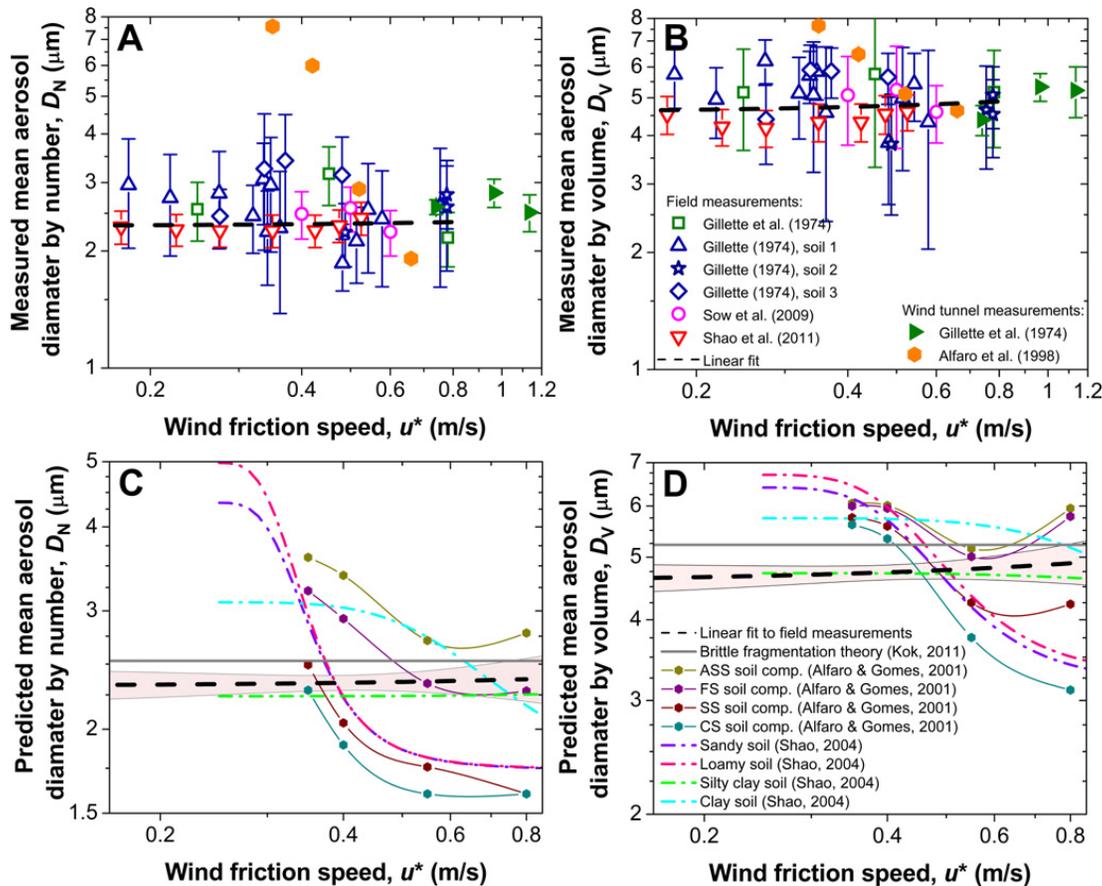
Fig. 2. Caption in next page.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Fig. 2. Dependence of the mean dust aerosol diameters by number (**a**) and volume (**b**) on the wind friction speed. Wind tunnel and field measurements are respectively denoted by filled and open symbols. Linear least-squares fits to the compilation of all field measurements (black dashed lines) show trends of the mean aerosol diameter with u_* that are within one standard error (Table 1), and are thus statistically insignificant. Linear fits to individual data sets are also reported in Table 1. Panels (**c**) and (**d**) respectively show the mean aerosol diameter by number and volume predicted by theoretical dust emission models. Plotted for comparison are the linear fits to the measurements from (**a**) and (**b**); the shading denotes the uncertainty on the fit, which is calculated as described in the supplementary text. Parameters required for the brittle fragmentation theory (solid grey line) were obtained from Kok (2011). However, the models of Alfaro and Gomes (2001) (solid lines and hexagons) and Shao (2004) (dash-dotted lines) require detailed soil size distribution information, which is not available for most of the data sets of the size-resolved vertical dust flux. Nonetheless, mean dust aerosol diameters were calculated from Eq. (1) for several "typical" arid soils, which thus do not necessarily correspond to any of the soils for which measurements of the emitted dust PSD were made. For Alfaro and Gomes (2001), D_N and D_V were calculated from the theoretical emitted dust PSD reported for four values of u_* in their table 5. The increase in D_N and D_V at $u_* = 0.80\,\mathrm{m\,s}^{-1}$ for several of the soils is inconsistent with the assumption in Alfaro and Gomes (2001) that higher wind speeds produce more disaggregated aerosols and might be due to numerical errors in the production of their table 5 (Grini et al., 2002). For Shao (2004), D_N and D_V were obtained by inserting the four soil size distributions reported in his table 1 into his Eq. (6), and using a threshold u_* for erosion of $0.25\,\mathrm{m\,s}^{-1}$, consistent with the thresholds reported in the experimental data sets used here (Table 1).
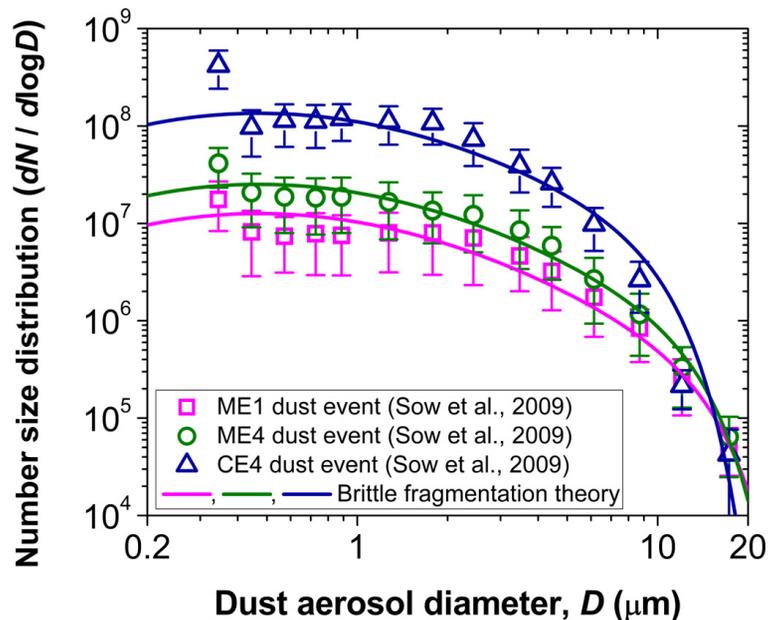
Fig. 3. Measurements by Sow et al. (2009) of the emitted dust PSD for three different dust events are reproduced by varying the side crack propagation length λ in the brittle fragmentation theory of dust emission (Kok, 2011). Values for λ of 15.1, 13.5, and 10.3 µm were obtained for respectively the ME1, ME4, and CE4 dust events by using a least-squares fitting procedure with Eq. (5) in Kok (2011). The fully-dispersed soil PSD parameters in the brittle fragmentation theory were obtained from Kok (2011).
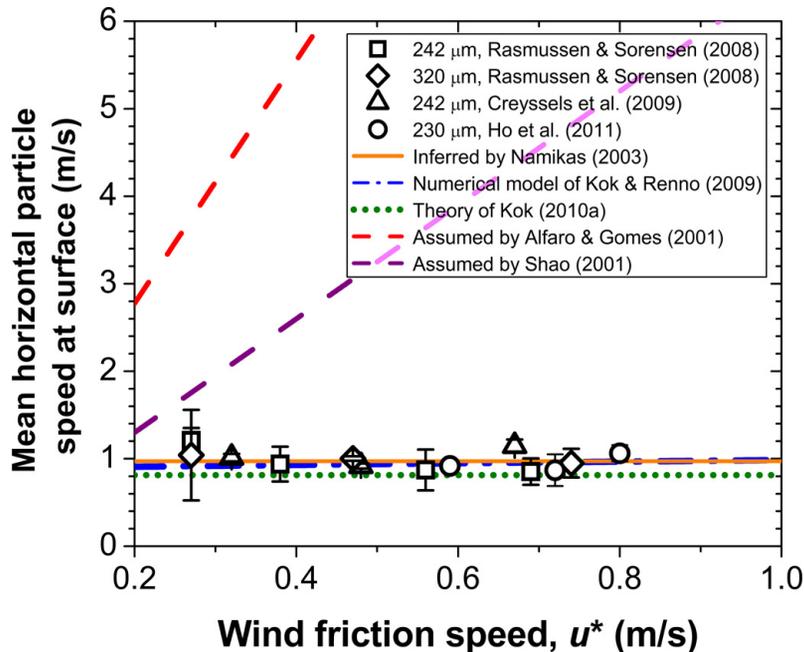
Fig. 4. Wind tunnel measurements of the speed of ~250–300 µm saltating particles report that the mean horizontal speed at the surface stays constant with u_* (symbols). Similarly, Namikas (2003) inferred from his field measurements that the speed with which saltating particles are launched from the surface is independent of u_* (solid orange line). These experimental results are supported by predictions for 250 µm sand by a recent numerical model (dash-dotted blue line; Kok and Renno, 2009) and theory (Ungar and Haff, 1987; Kok, 2010a) (dotted green line denotes Eqs. (13) and (14) of Kok, 2010a). The assumption of increasing saltator speed by Alfaro and Gomes (2001; dashed red line) and Shao (2001; dashed purple line) is thus likely incorrect. (The impact speed of $v_{imp} = 20u_*$ assumed by Alfaro and Gomes (see their Eq. 1) and the launch speed and angle of ~0.70 m s^{-1} and ~35° inferred by Namikas (2003) were converted to a mean horizontal surface speed by using that the rebound speed is ~ $v_{imp}/2$, and that the impact and launch angles are ~12° and ~35° (Kok and Renno, 2009). The wind tunnel measurements of Rasmussen and Sorensen (2008), Creyssels et al. (2009), and Ho et al. (2011) were extrapolated to the surface as detailed in Kok, 2010b.)

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Wind speed dependence of dust size distribution

J. F. Kok

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion