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## RESEARCH LETTER

10.1002/2016GL069324

## Key Points:

- Wind erosion was measured in situ under natural rains in the Sahel
- A rain event inhibits sand transport within a few minutes
- After the end of the rain, 6 to 12 h are required to restore the potential of sand transport of a sandy soil in the Sahel

## Supporting Information:

- Supporting Information S1

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## How long does precipitation inhibit wind erosion in the Sahel?

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**Abstract** Simultaneous measurements of saltation, wind speed, and rainfall performed in Niger before, during, and after 18 rain events are used to investigate how rain events affect wind erosion in the Sahel. The results show that the inhibition of saltation is rapid but progressive after the beginning of a rain event. The decrease of sand transport during the rain event is better linked to the time elapsed from the beginning of the rain event rather than to the cumulative rainfall. In the Sahel, after a rain event, less than 12 h is necessary to almost fully restore the sand transport potential. Our results suggest that assuming that no sand transport and dust emission occur during the 12 h following the end of a rain event could be a reasonable alternative to existing parameterizations of the influence of soil moisture on the wind erosion threshold, at least for the Sahelian conditions.

### 1. Introduction

Precipitation has the capability to limit wind erosion. Rain increases soil moisture and allows capillary forces to develop between soil grains, reinforcing soil cohesion, thus increasing the minimum threshold wind friction velocity required to initiate the movement of soil by wind [i.e., *Belly*, 1964].

Many experiments have been conducted to quantify the influence of soil moisture on the wind erosion threshold [Chepil, 1956; *Belly*, 1964; *Bisal and Hsieh*, 1966; *Hotta et al.*, 1984; *McKenna-Neuman and Nickling*, 1989; *Selah and Fryrear*, 1995; *Chen et al.*, 1996, among others]. These experiments encompassed a large range of soil water contents and soil types (sand, silt, loam, and clayed soils). They were always performed in wind tunnels to control the experimental conditions. For most of these experiments, soil moisture was determined in the very superficial top layer of the soils (generally the first 0.1 or 0.2 cm), i.e., the soil directly transported by wind.

Based on these measurements, *Fécan et al.* [1999] proposed a semiempirical parametrization of the ratio of wet to dry wind erosion thresholds as a function of the soil moisture and the soil texture. Briefly, this parameterization assumes that water is first adsorbed on soil grains and that the excess water filling the space between the grains is responsible for the capillary forces that increase soil cohesion and thus the wind erosion threshold. The amount of water adsorbed on the soil grains depends on soil texture, so that the minimum water amount at which an increase of the erosion threshold is detected also depends on soil texture. This parameterization was developed to be used in dust emission models and thus was only based on parameters that may be easily accessible at large scale (namely, soil moisture and soil clay content).

However, when included into dust emission models, this parameterization generally predicts an increase of the threshold wind friction velocity that appears far too high to be realistic [Zender *et al.*, 2003; *Grini et al.*, 2005]. This is mainly due to the fact that neither regional nor global models are able to provide precise soil moisture estimates for a superficial soil layer as thin as those measured in the wind tunnel experiments used to build the *Fécan et al.*'s parameterization. Indeed, as mentioned by *Darmenova et al.* [2009], dust emission models commonly use the soil moisture simulated by the land surface module of regional or global models [e.g., *Zender et al.*, 2003; *Sun et al.*, 2006; *Zhao et al.*, 2006]. However, these land surface models calculate the soil moisture in a limited number of soil layers, with a topmost layer of at least 2 to 10 cm thick. In the same way, *Xi and Sokolik* [2015] indicated that when using the Weather Research and Forecasting model-Chem-Dumo with the Noah Land Surface Model, the soil moisture derived from this model for its top layer (0–10 cm) induces a complete suppression of the dust emission.

An alternative to account for the effects of precipitation (and thus of soil moisture) on wind erosion and dust emission consists in determining the time during which wind erosion is suppressed (or at least significantly

reduced) after a rain event. Because it concerns the very thin superficial top layer of the soil, the influence of soil moisture on the wind erosion threshold should act very rapidly after the start of a rain event. For the same reason, this superficial layer probably dries rapidly after the end of rain (especially in the windy conditions required for wind erosion). If these durations are short enough and can be precisely determined, they could be used in dust emission models to inhibit and/or limit the dust emission for a given time period after a rain event.

## 2. Material and Method

### 2.1. Site and Material

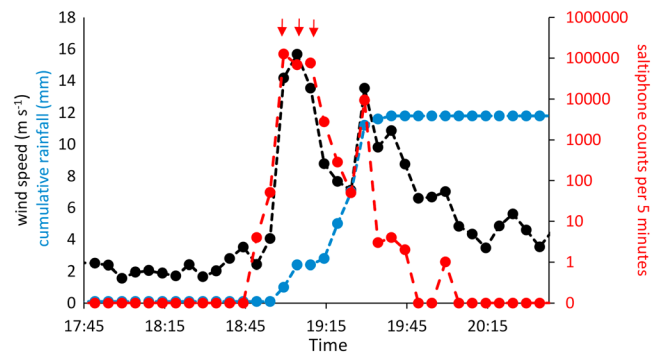
In the framework of the AMMA (African Monsoon Multidisciplinary Analysis) [Redelsperger *et al.*, 2006] program, a wind erosion/dust measuring station was implemented in 2006 close to the village of Banizoumbou (13.5217°N; 2.6291°E), a remote Sahelian location about 60 km east of Niamey (Niger). This site, mainly devoted to agricultural activities, has been used since the early 1990s, when measurements of soil erosion were performed on a cultivated field and a fallow [Rajot *et al.*, 1995; Rajot, 2001]. In addition to instruments dedicated to aerosol measurements (see for details Rajot *et al.* [2008] and Marticorena *et al.* [2011]), this station was instrumented to identify the local wind erosion events and to quantify the resulting saltation [Abdourhamane Touré *et al.*, 2011] and dust emission [Sow *et al.*, 2009].

For this study, we used the data obtained from a saltiphone (Eijkelkamp®, Giesbeek, the Netherlands) which records the number of impacts of saltating sand grains on a microphone membrane [Spaan and van den Abeele, 1991]. The saltiphone was installed at 7 cm above the soil surface and the number of impacts was cumulated over a 10 s time step. A Windsonic 2-D anemometer (Gill® Instruments Ltd.) provided the wind speed and direction averaged over a 5 min time step at 6.5 m height. Rainfall was monitored using an ARG100 aerodynamic precipitation sensor (Campbell® Scientific Instruments) working according to the principle of the “tipping bucket” mechanism. It provides a contact closure at each tipping (i.e., for each 0.2 mm of rainfall). The number of tips was cumulated over a 5 min time step, and so the beginning and the end of each rain event are known with an uncertainty range within this time interval. Data acquisition was performed using CR10X and CR200X Campbell® Scientific Instruments data loggers.

The agricultural field on which the experiment was set up is one of the largest in the area (450 × 400 m). At the time of the experiment (June to mid-July 2006), the soil surface was almost vegetation free. The soil is sandy (~95%) like about 50% of the soils in the Sahelian region [e.g., Hoogmoed and Stroosnijder [1984]]. The soil is classified as a sandy siliceous isohyperthermic psammentic Haplustalf [Biielders *et al.*, 2000]. Rajot *et al.* [2003] found that the topsoil (0–5 cm) has a low content in fine particles (clay = 2.8%; silt = 2.4%) and in organic carbon (0.21%). Crusting of this soil and its effects on wind erosion were also intensively studied by Rajot *et al.* [2003]. These authors showed that immediately after the first rain, a “sieving crust” [Valentin and Bresson, 1992] was formed on the experimental plot and that its main characteristics remained unchanged during the rainy season. The amount of loose sand grains present at the crust surface was reduced by 75%, but the proportion of the soil surface covered by this layer of loose particles remained the same after the rain event as before. At the same time, the amount of fine particles in this layer dropped from 2.5% to about 1.5%. Nevertheless, these stock reductions did not lead to any detectable decrease in the measured horizontal or vertical fluxes. Rajot *et al.* [2003] concluded that even after crusting, the sand grain layer remains thick enough to avoid saltation supply limitation and that the sandblasting process is very efficient at extracting fine particles from the soil even when its fine-particle content is as low as 1.5%.

### 2.2. Data and Method

In the Sahel, most of the rain events occurring during the rainy season are associated with regional Mesoscale Convective Systems (MCS) [e.g., Lebel and Ali, 2009]. These MCS generate violent cold pool outflows caused by moist deep convection [Houze, 1977, 2004] and have been identified as responsible for dust emission in the region [e.g., Marsham *et al.*, 2008; Williams, 2008; Marticorena *et al.*, 2010]. During the period 1 June to 17 July 2006, 18 rain events were recorded at Banizoumbou (Table S1 in the supporting information). In this study, a rain event is considered to start at the 5 min time step during which the first tipping of the rain gauge occurred and to finish at the 5 min period during which the last tipping of the rain gauge was recorded. These rain events spanned a large range of duration (from 5 min to more than 5 h) and cumulative rainfall (from 0.4 mm to more than 35 mm).



**Figure 1.** Time series of wind speed (black curve), cumulative rainfall (blue curve), and saltpHONE counts (red curve) during 1 June 2006 rain event. Red arrows indicate periods during which 10 s saltpHONE measurements were saturated.

We attempted to identify the influence of the rain events on the saltation of soil grains and to determine the delay to recover similar conditions for sand transport as those prevailing before a rain event. The methodology we used consisted in comparing how many counts were recorded by the saltpHONE before, during, and after rain for a given wind speed. In order to do this, the saltpHONE counts were summed over a 5 min period to be in perfect phasing with the wind speed and rainfall measurements. This also enabled us to obtain saltpHONE records having

a better statistical representativeness for each time period. Note that the 10 s saltpHONE counts can be saturated during periods with very intense saltation. In our data set, saturation of the saltpHONE was only observed just before the beginning or during the first 5–10 min for some rain events. In these cases, the saltpHONE counts reported for the corresponding 5 min periods are underestimated. SaltpHONE count can also be affected by rain splash. Indeed, during precipitation periods associated with high wind speed, soil particles can be lifted into the air by raindrop splash and transported by wind [e.g., *de Lima et al.*, 1992]. However, it has been shown that the contribution of wind-driven rain splash-saltation to the total saltation fluxes is much lower than that of the rainless saltation (especially for high wind speeds) until the soil moisture is sufficiently high to totally inhibit rainless saltation [e.g., *Cornelis et al.*, 2004].

### 3. Results

#### 3.1. Inhibition of Saltation During a Rain Event

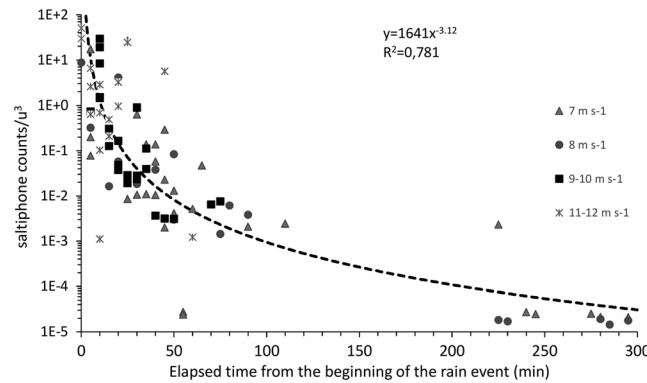
Figure 1 reports the saltpHONE counts, wind speed, and cumulative rainfall recorded during the rain event that occurred on 1 June 2006. Rain started at 18h55, and strong wind speeds, up to  $16 \text{ m s}^{-1}$ , were observed during the first 15 min following the beginning of this rain event. These high wind speeds induced intense saltation and very high saltpHONE counts (ranging from 68,000 to more than 125,000 per 5 min) were recorded during this time period.

After 15 min, wind speed decreased progressively, ranging from 8 to  $12 \text{ m s}^{-1}$ . This decrease in wind speed was accompanied by a more rapid decrease in the saltpHONE counts. Thirty minutes after the beginning of the rain event, saltation was considerably reduced since saltpHONE counts were only of the order of 10,000 and 3 per 5 min for wind speeds respectively of  $13.53$  and  $9.82 \text{ m s}^{-1}$ , i.e., 8 and 100 times lower than those recorded 15 min after the beginning of the rain event for similar wind speeds, i.e.,  $13.53$  and  $8.78 \text{ m s}^{-1}$ . During the last period of the rain event (from 19h35) and just after the end of the rain event, wind speeds ranging between 7 and  $10 \text{ m s}^{-1}$  produced saltpHONE counts never greater than 5 per 5 min.

This confirms that a rain event can strongly limit saltation and also shows that this inhibition effect is not immediately complete as suggested by the progressive reduction of the saltpHONE counts observed during the rain event.

In order to verify the generality of these observations, we analyzed all the saltpHONE, wind speed, and rainfall measurements performed during the 18 rain events. We reported the saltpHONE counts for different wind speed classes as a function (i) of the cumulative rainfall at the time of the measurements or (ii) of the time elapsed from the beginning of the rain event.

No significant link was found between the cumulative rainfall at each 5 min time step and the saltpHONE counts (see Figure S1), indicating that the amount of rainwater having reached the soil surface from the beginning of the rain was not the primary driver of the saltation decrease. In contrast, a significant decreasing relationship was observed between the saltpHONE counts and the time elapsed since the beginning of the



**Figure 2.** Decrease of the saltiphone counts per 5 min period normalized to the wind speed power 3 as a function of the elapsed time from the beginning of the rain event for the eighteen rain events. The zero saltiphone counts values are considered as 0.001 for this figure.

rain,  $t$ . Figure 2 shows that this decrease in saltiphone counts (and thus in saltation) is rapid. The data suggest that this decrease follows a power law in  $\sim t^{-3}$ . These results are in agreement with the observations performed on a sandy beach by *Jackson and Nordstrom [1998]* which indicated that “light rain of longer than 10 min duration that results in surface moisture values over 7% is not sufficient to eliminate transport, but the rate of transport during and immediately after rain is much lower than can occur on the beach a few hours after rain.”

As shown in Figures 1 and 2, our results suggest that the increase in threshold wind velocity during a rain event is progressive and that 10 to 15 min on average is necessary before the wind erosion threshold becomes high enough to totally inhibit sand transport. Thus, the contribution of the high wind speeds that occur just before or at the beginning of a rain event cannot be neglected in terms of sand transport. However, it is also very likely that the mineral dust that might be generated during these first 10 to 15 min after the beginning of a rain event would be immediately washed out by the rain droplets.

### 3.2. Frequency of Sand Transport in Dry and Wet Conditions

To determine the time period following a rain event during which the frequency of sand transport is reduced, we compared, for a given wind speed, the frequency of sand transport in dry conditions to that observed for different elapsed times after a rain event. Thus, we first assumed that the superficial layer of the soil should be dried no later than 48 h after a rain event in Sahelian conditions. Therefore, we selected all 5 min wind speed measurements and coincident saltiphone counts subsequent to the end of the previous rain by at least 48 h ( $n = 5585$ ), these selected data constituted the reference data set for sand transport occurring in dry conditions. The remaining 5 min coincident measurements of wind speed and saltiphone counts were divided in five groups corresponding, respectively, to elapsed times of 0–6 h ( $n = 1238$ ), 6–12 h ( $n = 1162$ ), 12–18 h ( $n = 1008$ ), 18–24 h ( $n = 879$ ), and 24–48 h ( $n = 2717$ ) following the end of a rain event. Finally, six different groups of data, characterized by the time elapsed since the last rain event, were constituted, including the data set for dry conditions (see Table S2 in the supporting information).

For each of these groups, we defined, for wind speed classes ranging from 0 to  $13 \text{ m s}^{-1}$  with  $0.5 \text{ m s}^{-1}$  interval,  $P_i$ , the probability of occurrence of saltation:

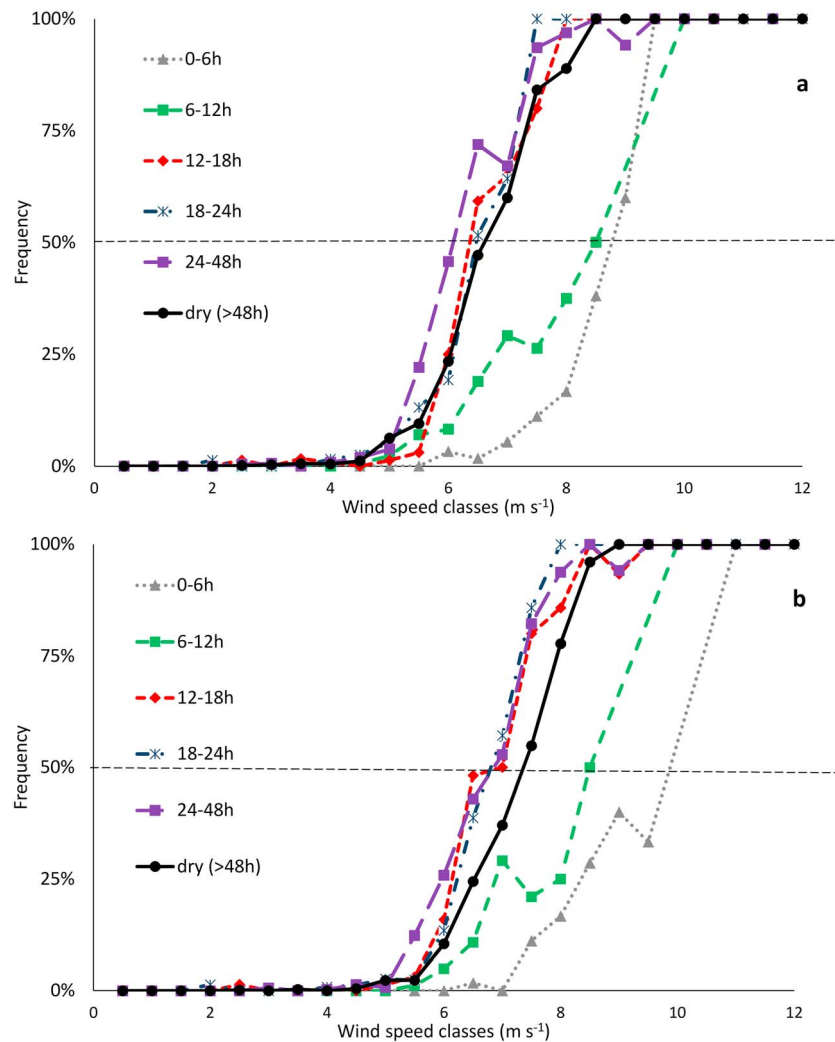
$$P_i = n_i / N_i \times 100 \tag{1}$$

where  $n_i$  is the number of 5 min periods in wind speed class “ $i$ ” during which saltation occurred and  $N_i$  is the total number of 5 min periods in class  $i$  [*Abdourhamane Touré et al., 2011*].

This probability was computed for two different thresholds in saltiphone counts: (i) more than 10 counts and (ii) more than 100 counts. We decided to use two thresholds to test the insensitivity of the analysis to the specific choice of the threshold, and these threshold values were chosen to be quite low to capture even very small saltation events.

Figure 3 shows that the groups 12–18 h, 18–24 h, and 24–48 h exhibit probability curves very similar to those obtained in dry conditions for both saltiphone counts  $\geq 10$  and  $\geq 100$ . This clearly suggests that the inhibition effect of a rain event on the frequency of sand transport has totally disappeared in about 12 h in average after a rain event in the Sahelian conditions.

The wind speed class for which the 50% probability value ( $P^{50}$ ) is reached is strongly shifted toward higher wind speeds for the 0–6 h period (i.e., the period corresponding to the moistest soils) when compared to dry conditions (Figure 3): for the 0–6 h period,  $P^{50}$  is reached for wind speeds close to  $8.5$  and  $10 \text{ m s}^{-1}$ ,



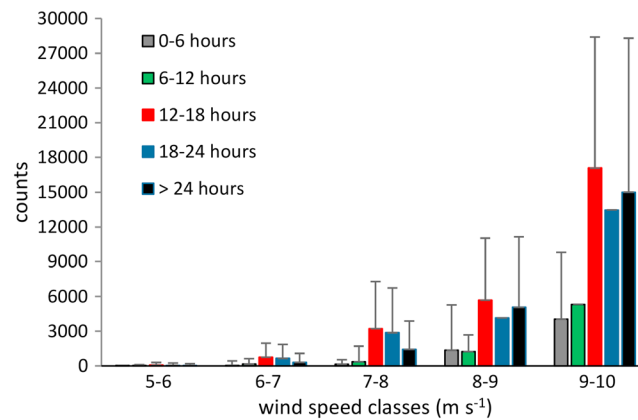
**Figure 3.** Frequency of saltation counts (a)  $\geq 10$  counts and (b)  $\geq 100$  counts as a function of the wind speed for dry conditions (i.e.,  $t$  after the last rain event  $>48$  h (black line)) and for different elapsed times (0–6 h (grey line), 6–12 h (green line), 12–18 h (red line), 18–24 h (blue dotted line), and 24–48 h (purple line)) since rainfall completion.

respectively, for saltiphone counts  $>10$  and  $>100$ , while  $P^{50}$  is observed for wind speeds of only  $6.5$  and  $7 \text{ m s}^{-1}$ , respectively, for dry conditions. More precisely, the probability of saltation is close to 100% in dry conditions for the wind speed class  $8\text{--}8.5 \text{ m s}^{-1}$  but is only about 33% during the period 0–6 h after a rain event and reaches about 50% for the 6–12 h period. Even if a rain event still has a significant effect on the probability of sand transport up to 12 h after the end of rain, this effect is progressively attenuated as time goes on.

Importantly, the role of the precipitation amount is not negligible. Indeed, the saltiphone counts  $>10$  or  $>100$  measured for 0–6 h and 6–12 h groups were recorded only for rain events having a cumulative rainfall lower than 2 mm (RE-3, RE-9, RE-13, and RE-14, see Table S1). This seems consistent with a more rapid drying of the superficial soil layer after light rain events and suggests that the events with a cumulative rainfall lower than 2 mm could have a shorter effect on the frequency of sand transport in the Sahel.

### 3.3. Intensity of Sand Transport in Dry and Wet Conditions

Rajot *et al.* [2003] showed that the saltiphone counts (when not saturated) are proportional to the horizontal flux of sand. Thus, the number of counts recorded by the saltiphone during a period of time can be used as an indicator of the intensity of sand transport. In order to check how much the sand transport is reduced after a



**Figure 4.** Saltiphone counts (per 5 min) for different wind speed classes and for different elapsed times from the end of a rain event.

the numbers of counts recorded by the saltiphone are about one third of those recorded for the groups corresponding to time periods longer than 12 h after the end of rain. This ratio is even lower (1/10) for wind speed classes  $<8 \text{ m s}^{-1}$ .

These results show that a rain event does not only reduce the frequency of sand transport but also significantly reduces the intensity of the remaining saltation flux during the 12 h that follow a rain event. This is consistent with *Hotta et al.* [1984] who showed from experiments performed in Japan that about 18 h after a rain stopped the sand volume moved by wind was almost the same as that blown off a dry sand surface.

#### 4. Conclusions

Using wind speed, saltation, and rainfall measurements performed in the Sahel during the first part of the rainy season (June to mid-July 2006), we examine how rain inhibits sand transport during a rain event and after rain stops. The results show that during a rain event, saltation is not immediately stopped but is progressively inhibited. The sand transport is strongly reduced especially during the first 10–15 min following the beginning of the rain event, and almost no significant sand transport occurs after 30 min. The progressive inhibition of sand transport by the rain seems to be linked to the time elapsed from the beginning of the rain and not to the cumulative rainfall, suggesting that whatever the rain amount, a minimum time is necessary to allow the soil moisture to be sufficient to completely inhibit sand transport.

In the Sahel, rain events are frequently associated to gust fronts induced by convective cold pools; thus, high wind speeds generally take place just before or just after the beginning of the rain event. Our results suggest that when it rains, most of the sand transport occurs during these short periods of time during which (i) wind speeds are sufficiently high to produce sand transport and (ii) the time elapsed from the beginning of the rain is not sufficiently long to allow soil moisture to totally inhibit the wind erosion.

Our results also showed that both the frequency and the intensity of sand transport are reduced during the hours that follow a rain event. However, this inhibition effect lasts no longer than 12 h after the end of the rain event, even for rain event having a cumulative rainfall of 20 mm. Moreover, a partial recovery of the frequency and intensity of the saltation can even be observed in a shorter time after rain stops (6 h or less) in the case of light rain events (less than 2 mm).

These results suggest that considering a complete inhibition of dust emission during a rain event and in the 12 h following a rain event would not generate large errors in dust emission estimates for semiarid regions having similar soil and climatic conditions to those observed in the Sahel during the rainy season (dominant sandy soils and high air temperature). Indeed, the dust resulting from saltation occurring at the beginning of a rain event should be for a large part washed out by rain droplets. Concerning the 12 h that follow rain, data show that saltation is inhibited or significantly reduced and occurs mainly for rain events with low rainfall ( $<2 \text{ mm}$ ). Even if some saltation events will not be accounted for in dust emission models by inhibiting saltation during the 12 h following a rain event, this “error” should be acceptable, these events generating

rain event, we computed the mean number of counts recorded by the saltiphone for five groups corresponding to different periods after a rain event (0–6 h, 6–12 h, 12–18 h, 18–24 h, and  $>24 \text{ h}$ ) for wind speed classes having an interval of  $1 \text{ m s}^{-1}$ . Figure 4 reports the results obtained for the wind classes ranging from 5 to  $10 \text{ m s}^{-1}$  (i.e., wind speed classes for which at least one saltiphone observation was recorded; see Table S3 in the supporting information).

We observed that for the groups corresponding to the time periods of 0–6 and 6–12 h after a rain event

only low saltation. This can constitute an efficient and pragmatic alternative to the use of more physical parameterizations of the effects of soil moisture on the wind erosion threshold which remains up to now difficult to apply in 3-D models.

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