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From Gustiness to Dustiness—The Impact of Wind Gusts on Particulate Matter Emissions in Field Experiments in La Pampa, Argentina

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Abstract: This study delivers the first empirical data-driven analysis of the impact of turbulence induced gustiness on the fine dust emissions from a measuring field. For quantification of the gust impact, a new measure, the Gust uptake Efficiency (GuE) is introduced. GuE provides a percentage of over- or under-proportional dust uptake due to gust activity during a wind event. For the three analyzed wind events, GuE values of up to 150% could be found, yet they significantly differed per particle size class with a tendency for lower values for smaller particles. In addition, a high-resolution correlation analysis among 31 particle size classes and wind speed was conducted; it revealed strong negative correlation coefficients for very small particles and positive correlations for bigger particles, where 5 µm appears to be an empirical threshold dividing both directions. We conclude with a number of suggestions for further investigations: an optimized field experiment setup, a new particle size ratio ($PM_1/PM_{0.5}$ in addition to $PM_{10}/PM_{2.5}$), as well as a comprehensive data-driven search for an optimal wind gust definition in terms of soil erosivity.

Keywords: wind gusts; wind erosion; particle uptake; dust plumes

1. Introduction

Wind erosion is a widespread problem on agricultural land around the globe. To varying degrees, all climatic zones and all farming systems are affected [1]. Associated dust emissions influence physical and chemical processes in the atmosphere, impair air quality and disturb other ecosystems far away from the source areas [2]. Dust emitted from agricultural land has a ten times higher ice nucleation efficiency compared with desert dust and can be connected to local extreme thunderstorms in north-central Argentina [3,4]. The onsite effects are losses of organic matter (OM), silt, and clay particles, resulting generally in a deterioration of the physical and chemical properties of soil [5]. Since soils susceptible to wind erosion have only small shares of OM, silt, and clay, these losses contribute over-proportionally to soil degradation and are of high relevance for sustainable agriculture [6,7].

The province of La Pampa in Argentina is particularly affected due to its semi-arid climate, soils susceptible to wind erosion, and a gradual but steady land use change from pasture to arable land, with the consequence that soil surfaces are longer and more frequently exposed to wind without protection by vegetation [8,9]. Despite quite homogeneous soil conditions in large areas, wind erosion processes have a strong spatial variability caused by little variations in other controlling parameters such as field length, landscape structure, or topography [10,11].

Wind, or moving air as the driver of wind erosion, is characterized by unsteadiness directly at the surface. This turbulent characteristic of the atmospheric boundary layer causes rapid fluctuations of the wind velocity. Historically, the consideration of wind gusts was closely connected to the development of the measuring techniques and various definitions exist. Most of them are based on a certain, absolute, or relative exceedance of an average. Wind gusts can be expressed by a gust factor G, describing the ratio of the wind speed within the gust to the average wind speed ($G = u_{max}/u$) [12]. The World Meteorological Organization (WMO) recommends defining a gust as the 3 s average of a 10 min sampling period, but gust factors have been derived for various measurement and averaging times [13,14]. Wind velocity fluctuations result in temporal variations in the transport intensities during wind erosion events. Most research is related to the saltation load or sand transport, which provides an immediate and distinct response to wind velocity or wind friction velocity fluctuations [15–19]. Wind fluctuations and saltation transport have been measured in temporal high resolution in many studies with devices for wind speed such as ultrasonic or hot wire anemometers, and for saltating grains with the Saltiphon (Eijkelkamp Soil and Water, [20]), the Sensit (Sensit Inc, [21]), or the Safire (Sabatech, [22]). The underlying measuring principle is the detection of impacts of colliding grains on a membrane. This is not applicable for dust particles, as their impacts are not strong enough, their particle number concentrations are too high, or they follow the air stream around the sensors because of their low inertia. Dust measurements are mainly based on technologies collecting or counting particles over a certain time. Thus, there are discrepancies in the possible measurement intervals of wind (5–20 Hz), saltation (~1 Hz), and dust (0.1–0.016 Hz).

Wind gusts over erodible surfaces lead to sudden occurrence of saltation streamers, which again initiate discontinuous, locally limited emissions of dust particles. The challenge for the measurement methodology here is that saltation and suspension cannot be measured together at the point of origin for technical reasons. This is only possible after separation of the two transport forms, i.e., after traveling a certain distance. As the settling velocity of dust particles is very low, they are mixed into much higher heights, and thus are not as directly affected by turbulent fluctuations of the flow as saltating particles [23]. The particles of the PM_{10} fraction remain in suspension for long times once airborne [24]. Their transport is often equated to that of momentum, as used for approximated flux calculations in turbulence-dominated boundary layers [25–27]. The long residence time of these particles in the atmosphere and the resulting long transport distances, make it clear that the dust concentrations measured at a particular location cannot be directly attributed to the surface properties below the measuring point or of the immediate surroundings. The measured quantity is rather the result of all windward located sources, called 'footprint' and representing the relative influence of all effective source areas upwind [28–32]. This is extremely difficult in a landscape such as that in La Pampa, due to the mobility of strong point sources of dust (tillage and harvest operations, traffic on unpaved roads), their distribution over large areas (cattle drives), and their discontinuity in time and space. Therefore, one strategy in measuring dust emissions on arable land is to place at least one measuring point relatively close above the surface to have a clear signal of the windward surroundings.

In field trials, all these aspects must be taken into account and brought together [33]. In this study, this micro-meteorological phenomenon is regarded from a data analytics-based perspective by quantifying the impact of peak values of dust concentrations on the overall dust uptake during wind erosion events.

The approach of this study therefore follows a hypothesis that was already brought forth by [34]: Gusts extraordinarily contribute to the gust uptake during a wind event. The statistical analyses presented here underline this hypothesis and deliver statistically robust proof.

This approach is new, because the fundamental mechanic of gusts contributing to the material uptake in wind erosion processes has historically been mentioned and suggested but never statistically quantified using field measurements.

2. Materials and Methods

2.1. Site Description

Wind, wind erosion, and dust concentrations were measured in the northeastern part of Argentina's province La Pampa at the experimental Station of the National Institute for Agricultural Technology (INTA) in Anguil (63.9885° W and 36.577° S). The topography of the site is characterized by soft hills with max elevation changes of 10 m. A measuring field was installed with a size of 1.44 ha (240 × 60 m) located within other agricultural land but surrounded by pastureland in its immediate vicinity. A direct input of saltating soil particles from the neighborhood were excluded, which was valid for the dust fraction in a limited way, whose origin may be also much more remote (Figure 1).

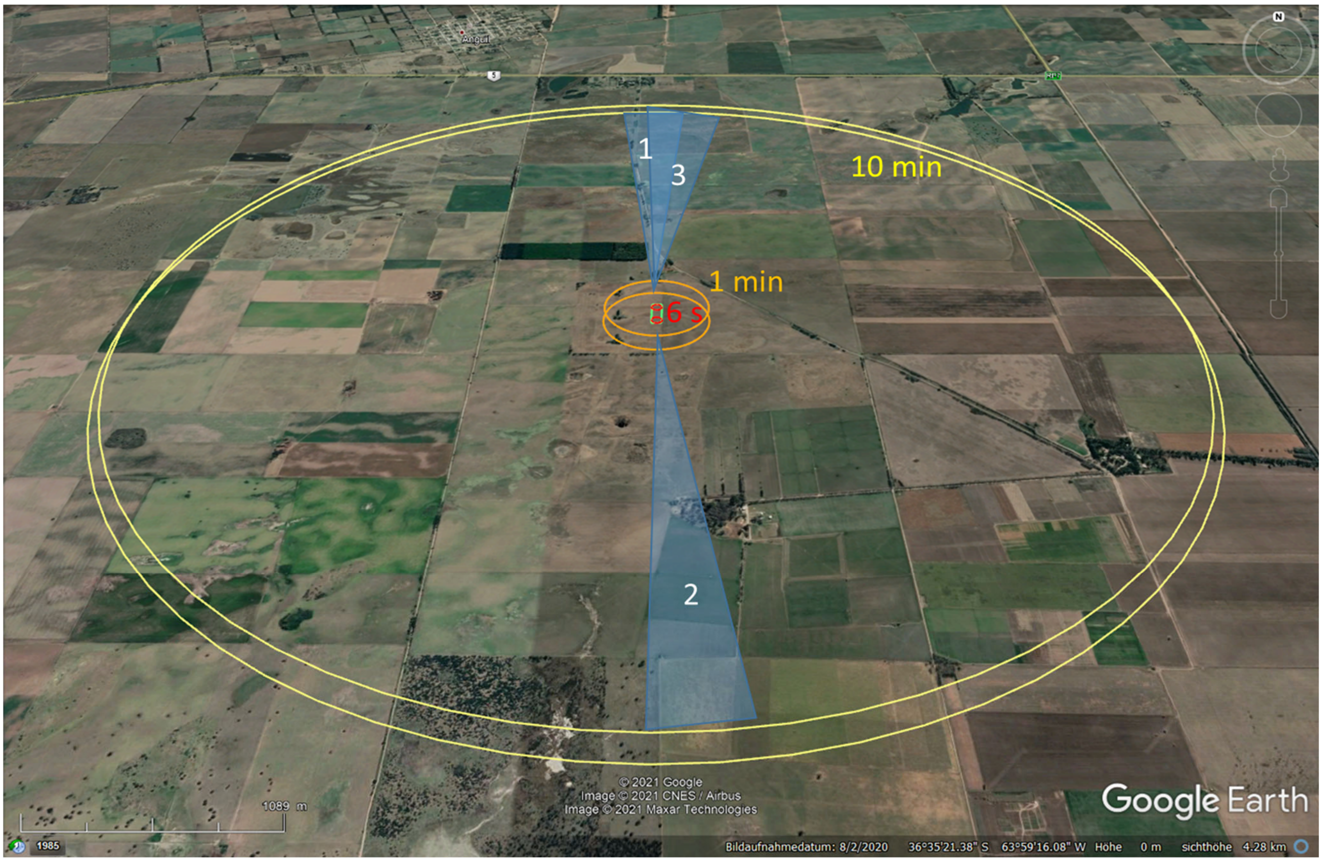

Figure 1. Location of the measuring field and travelled distance of air and particulate matter for both measuring points at the test field (green rectangle) for a wind velocity of 6 m s^{-1} and different measuring intervals (red circles: 6 s—highest temporal resolution of the EDM164; orange circles: 1 min—regular interval of the EDM164; yellow circles: 10 min—common interval of long-term meteorological measurements); blue sectors mark the wind directions of the three considered events.

The soil at the measuring field is a Typic Ustipsamment developed from aeolian deposits of Holocene origin with a sand content of 76%, a silt content of 17%, and a clay content of 7%. The texture class is loamy sand resulting in a medium to high susceptibility to wind erosion. The carbon content of the field varies between 0.5 and 1.8%, with the higher values at the higher relief positions [11].

2.2. Wind and Dust Measurements

The measurements took place between March and December 2016, of which 6 days with continuous measurements are in the focus of this study. The selection was made according to the prevailing wind direction of the day; only days were selected on which the wind came in the direction of the longitudinal orientation of the measurement field, in this case from north or south. Due to the opposite wind directions, we do not address the station "north" and "south" in the ongoing manuscript, but rather name "IN" and "OUT" instead. The measurement equipment was setup as shown in Figure 2. A comprehensive description of the study site can be found in [11].

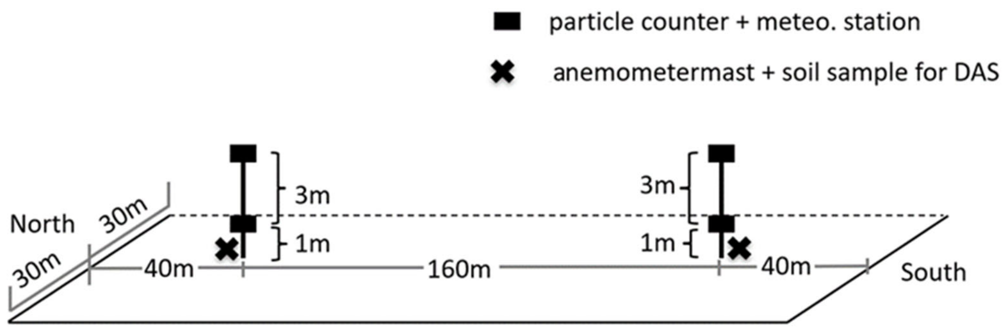

Figure 2. Experimental setup of the dust monitor, the meteorological.

Two compact all-in-one-weather stations (WS500-UMB, Lufft Mess- und Regeltechnik GmbH, Fellbach, Germany) measured temperature, air humidity, air pressure, wind velocity, and wind direction at a height of 1 m. Wind velocity and direction were measured with 2 D ultrasonic sensors. They have no moving parts and can therefore be used without concern even in dusty environmental conditions without affecting their measuring accuracy over time. Furthermore, they are not influenced by inertia and thus have a short reaction time to changes in wind velocity. The weather stations are connected to Environmental Dust Monitors of the type EDM164 (GRIMM Aerosol Technique GmbH, Ainring, Germany), where all data are stored together in one data logger. Dust concentrations were measured with four dust monitors in total, two EDM164 and two EDM107 at heights of 1 and 4 m, respectively. The relatively low height of 1 m for a dust measurement was chosen to achieve a large proportion of the measured quantities from the area of the measurement field, with 40 m to the field boundary at the "IN" position and 200 m at the "OUT" position. Both types of EDM measure mass concentrations of PM_{10}, $PM_{2.5}$, and PM_1 (in µg m^{-3}) and particle concentrations (in n dm^{-3}) for particle sizes between 0.25 and 32 µm in 31 classes.

The wind velocity (u) was used to calculate the transport capacity of the wind (W_{tc}) [35] for all wind velocities above a certain threshold (u_t) with:

$$W_{tc} = (u - u_t)\, u^2 \tag{1}$$

Additionally, wind measurements with three anemometers in the heights of 0.4, 0.8, and 1.6 m were used to derive the friction velocity u_* at the "IN" and "OUT" position from the logarithmic wind profiles as 1 h average several times per day.

$$u_* = \kappa \frac{(u_{z_2} - u_{z_1})}{(\ln z_2 - \ln z_1)} \tag{2}$$

where z_1 and z_2 are height 1 and 2; and u_{z1} and u_{z2} are the respective wind velocities at these locations.

The common measuring interval of the EDM is one minute, the shortest possible interval six seconds. The shortest interval of the connected weather station has five seconds. The smallest joint interval of both is 1 min. Therefore, the statistical measures are related to 10 values per minute for particulate matter and particles, and to 12 values per minute for wind velocity. Compared with micrometeorological measurements the measuring intervals are quite large; however, for a landscape-related approach they are sufficient [13,36].

2.3. Derivation of Gusts

Wind gusts over bare land lead to sudden occurrences of saltation streamers, which initiate dust emissions running over a certain distance and can often be observed around noon or early afternoon. For identification and quantification of the impact of such gusts, we need a clear definition of such comparatively short-term events. Historically, a wide range of definitions of wind gusts exist. Most of them (e.g., the WMO's definition) are based on a certain exceedance of a threshold. For example, a 5 m s^{-1} higher wind speed than the average of the previous 10 min. Such definitions are only applicable for events/situations with relatively stationary wind speeds without mid-term trends which is the case at all three events of this study. Moreover, they are not appropriate for the comparison between events with different levels of average wind speed.

Thus, in this study, we define a gust as a wind speed which is at least 10% higher than the average of the previous 10 measurements. In the literature, higher threshold values can sometimes be found, ranging from 30% to 50%. This is because they normally refer to higher resolution measurement data. In this study, we used 1 min averages and thus, the threshold must be comparatively low to catch the important events. The final gust definition regarding the 10 min average interval also was derived by explorative analyses, where other gust definitions were also tested (e.g., a maximum change between two points in time or visibility graphs). In the results section it is shown that the chosen threshold definition captures all the relevant wind gusts. We can write the evidence of a gust (g) at a point in time (t):

$$g_t = \theta\left[\frac{v_t}{avg(v_{t-1} : v_{t-10}) * GIC}\right] \tag{3}$$

where v_t is the wind speed at time t and θ denotes the Heaviside step function here defined as θ (x) = 0 for $(v_t - 6) <= 0$ and θ (x) = 1 for $(v_t - 6) > 0$. We define GIC as the gust intensity coefficient, where the latter was set to 1.1 (i.e., 10% higher) for the purpose of our study. GIC defines the relative exceedance of the wind velocity of a gust in comparison to the average within the regarded time interval.

It should be noted that this approach is related to, but not identical with anomaly calculation of time series. Here one would rather relate a point in time to the surrounding (i.e., previous and following) points in time. Such an approach would not be suitable for this study, because we are specifically interested in events that occur suddenly, whereas the wind speed values following the gust are not of interest.

Because the EDM collect data in one-minute averages, the actual wind speed maximums during that one-minute gust can be weighted higher than the average. For the wind transport capacity, this is a bit lower. Hence, the 10% gust definition should catch most of the gusts. To quantify the impact of the wind gusts on the aerosol uptake, we defined the Gust uptake Efficiency (GuE):

$$GuE = \frac{PM_{gust1.1}}{PM_{total}} * 100 \tag{4}$$

where $PM_{gust1.1}$ is the average particulate matter concentration during gusts (using the gust definition described above with a GIC of 1.1) and PM_{total} is the average particulate matter concentration during all other times. If the wind gusts have an over-proportional impact on particle uptake, the GuE should be above 100%.

3. Results

3.1. Influence of Measuring Intervals on Mean Wind Velocity and Transport Capacity

The standard for estimating the mean wind, set by the WMO, is the 10 min average [13]. At the beginning of our campaign, we measured three events with the highest temporal resolution of 5 s (03.03., 09.03. and 26.08. 2016). We average (upscale) these values from 5 s measuring to 1 min intervals in order to compare the results between the two setups: 5 s and 1 min averages. This analysis is used to analyze the influence of the measuring intervals on mean wind velocity. These three events cover a wide range of wind velocities and can be considered as weak, medium, and strong events. The frequency distribution of the measured wind velocities is shown in Figure 3; the frequency of each velocity class is on the left side, the summarized curves are at the right side. The wind velocity is 4 m s^{-1} (measured in a height of 1 m); the threshold shows that during the event at 03.03.2016 just 20% of all winds were above the threshold, about 70% at the 09.03.2016 and almost all wind velocities were above the threshold at the 26.08.2016 (Figure 3, right panel). It must be noted that the 4 m s^{-1} threshold is only used for illustration purposes here, the value is not used for any further statistical analyses. Taking into account earlier work from [34], the threshold is a rather variable value depending on meteorological conditions. Hence, the threshold can range between low values in winter and high values in autumn.

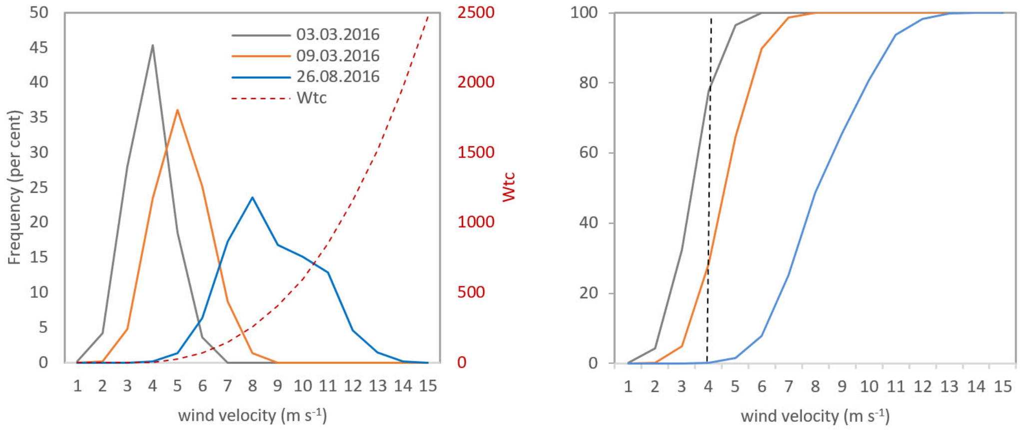

Figure 3. Frequencies of wind velocities of the three measuring campaigns; left: absolute values, W_{tc} for a threshold of 4 m s^{-1}; right: summarized values.

The relationship between the maximum wind velocity of the 5 s intervals and the 1 min averages is shown in Figure 4. In general, all events are on the same line, with a slight increasing tendency of the 5 s maxima at higher values of the 1 min averages, which is reflected in the increasing values of the slopes (m) of the regression lines. The maximum wind peaks are 18 to 24% higher than the averages, with a decreasing tendency at increasing average wind velocity. If these slopes are regarded as the gust factor, they are closer to the recommended conversion factors for open sea than for land surfaces [37].

The comparison of the transport capacity of the wind (Wtc) calculated from the 1 min averages and the mean of the 5 s intervals shows similar decreasing differences at increasing wind velocity (Figure 5). The weak event at the 03.03.2016 has a 52.2% higher transport capacity if the 5 s intervals are used for calculation, the medium event has 27.1% higher values, and the strong event comes even closer to the values of the 1 min averages, with only 8.4% higher values. This shows again that longer average time intervals cut the peaks of wind speed and therefore to a greater extent the transport capacity, which is derived from wind speed by an exponential relationship [38,39]. Lower wind speeds are more affected because individual wind peaks tend to be eliminated completely due to averaging.

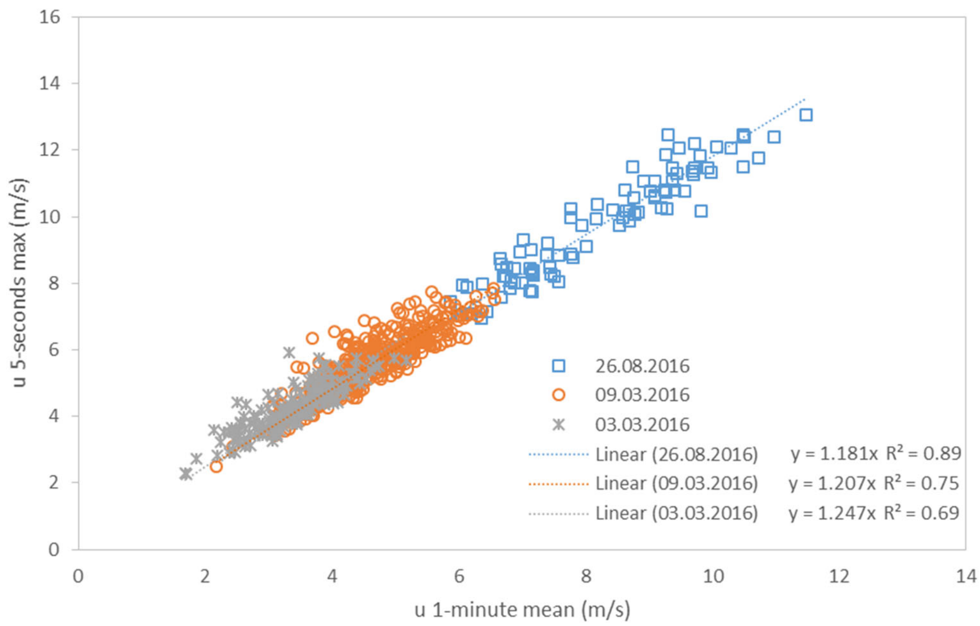

Figure 4. Comparison of the maximum wind velocity of a 5 s interval measured within a one-minute mean.

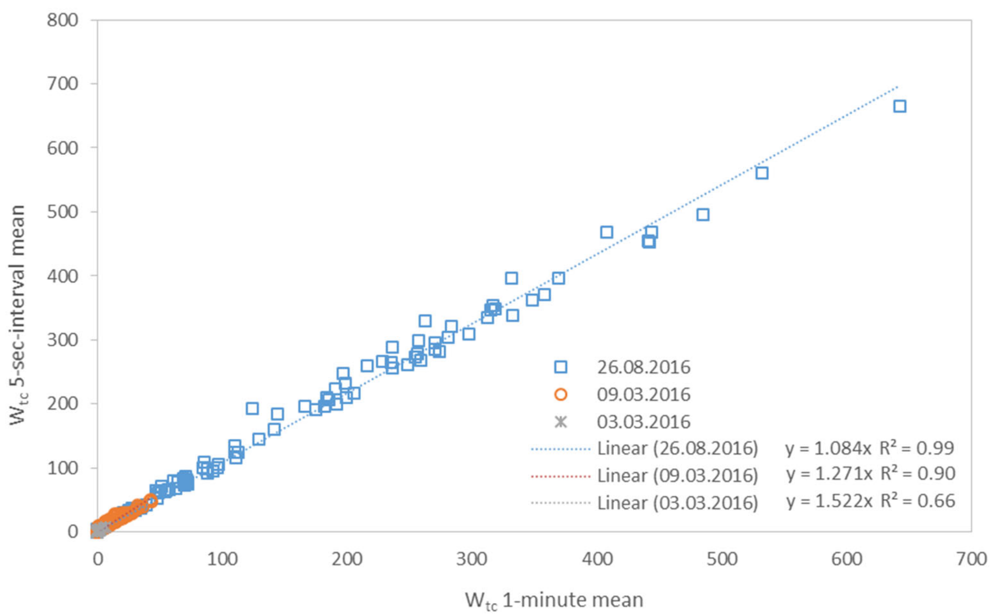

Figure 5. Comparison of the transport capacities of the wind derived from 1 min averages of wind velocity and from the 5 s intervals.

Following the analyses shown here, we conclude that a 1 min averaged measurement of wind speed and particulate matter values is an appropriate approach to quantify wind gust impacts, even though wind gusts itself can partly happen on lower temporal scales. Hence, in the following sections we use 1 min averaged data from three other wind events captured on 18 November 2016, 20 November 2016, and 4 December 2016, subsequently called Event I, Event II, and Event III, respectively (see Siegmund et al. 2022 [33]).

3.2. *Impact of Gust Activity on Particle Uptake*

Figure 6 illustrates the temporal wind speed variation and marks the gusts by the grey bars following the above definition for all three events. All events have in common that the gusts are relatively homogenously distributed over the event period and that the definition matches visible peaks. However, a shortcoming of this approach can be identified: if a strong decrease in wind speed is immediately followed by a strong increase, it is not reflected by the averaging interval. Although one would obviously define those periods as gusts/gusty, for the study of wind erosion this is not a problem; we are predominantly interested in the acceleration of wind in comparison to the previous point in time (t − 1), not so much in comparison to the following point in time (t + 1).

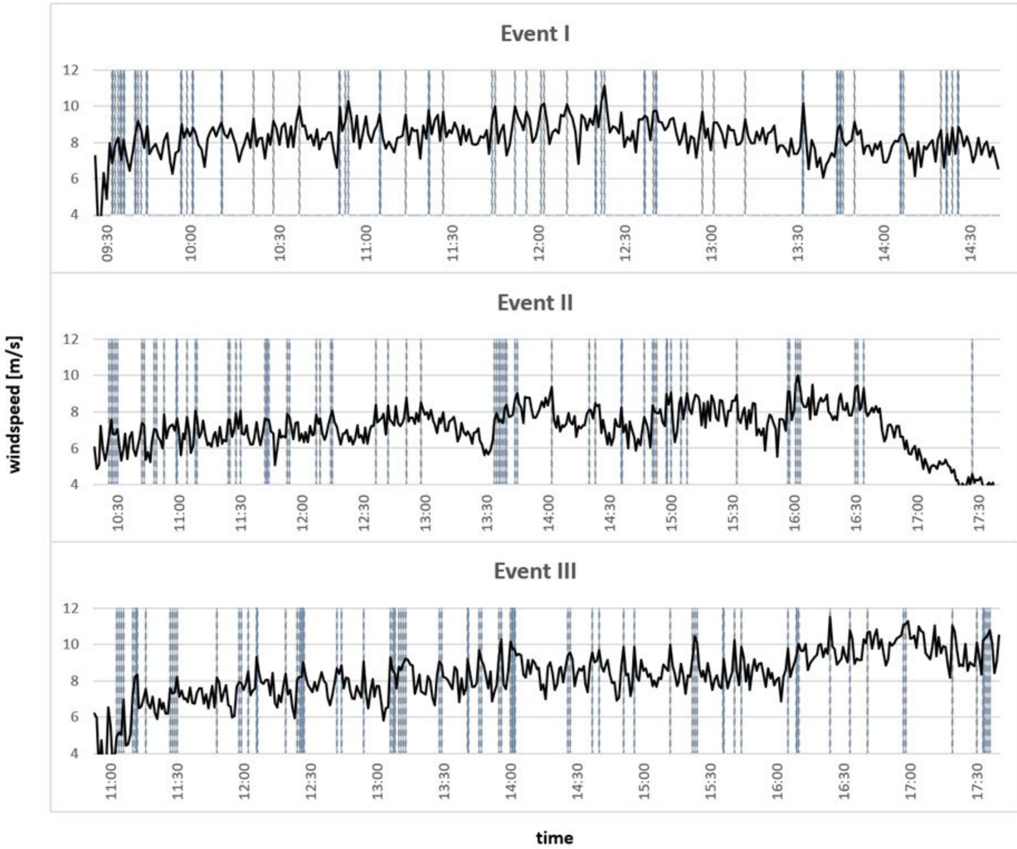

Figure 6. Wind speed during all three events. Grey bulks mark wind gusts following the gust definition described above.

This proposed definition of wind gusts has one sensitive parameter, and this is the chosen GIC value. In this study we chose a GIC value of 1.1 to make sure the events hit all the spikes in the wind time series, which can be seen as a more pragmatic approach. Moreover, this gust definition is only suitable for temporal sampling resolutions of 1 min and higher.

In Siegmund et al. (2022) [33] it was shown that the correlation strength between dust particles and wind velocity decreases with particle size. While in this former analysis only three particle size classes (PM_{10}, $PM_{2.5}$ and PM_1) were investigated, we here increase the resolution of this analysis to the whole spectrum of the EDM. Figure 7 illustrates the linear Pearson correlation coefficients between wind speed and particle concentration of all 31 particle size classes of the EDM. For this analysis, we use the linear correlation for illustration purposes only, leading into the following analyses of wind gust impact. Yet, the assumption of a linear relationship between wind speed and particle uptake cannot be used for quantitative analyses. Siegmund et al. (2022) [33] investigated particulate matter classes, representing clustered particle number concentrations; here, we work with the separated particle counts of each class. A correlation analysis can nevertheless directly be compared because both show a certain measure of dust intensity.

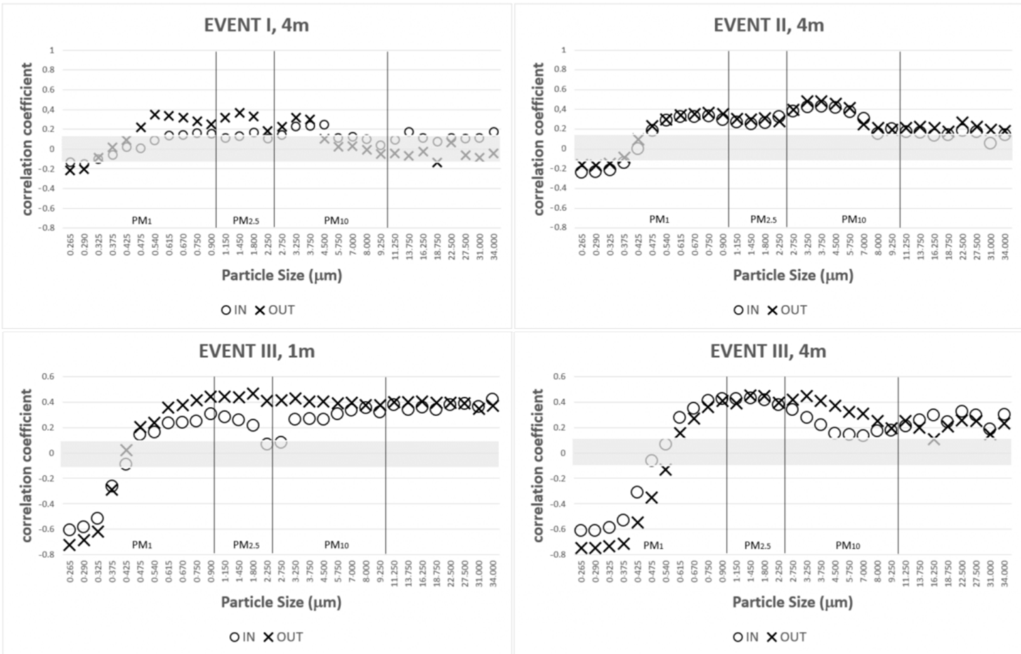

Figure 7. Linear Pearson correlation coefficients for the 1 min measurements between wind speed and particle counts for 31 particle size classes. The grey shadow indicates non-significant correlation coefficients ($\alpha = 0.05$). At Event I and II the 1 m particle count data were lost during the field campaign and cannot be shown here. For comparison reasons, the respective particulate matter classes are also displayed.

Figure 7 resembles the general findings of [33], but here for each individual particle class: bigger dust particles show a mainly strong positive correlation with wind speed; smaller particles show a lower, non-significant, or negative correlation. The detailed view on the particulate matter classes shows that particles in the PM_{10} and $PM_{2.5}$ classes have quite consistent signals. In contrast, the particles smaller than 1 µm diameter (PM_1 class) can further be subdivided into particles with positive or negative correlations, separated at the particle diameter of around 0.5 µm. Only particles smaller than 0.5 µm have non-significant or negative correlations, so that this particle diameter can be seen as a kind of threshold value. At Event III these were very strong, reaching up to −0.8. This event was the strongest of the three considered, and consequently more of the very small particles (PM_1) were already released outside of our measuring plot. These particle sizes are known to stay in suspension for very long times and are removable only by wash out by rain or if they adhere at surfaces by direct contacts. The latter also concerns larger particles in suspension together with these fine fractions, collecting them and depositing together. Because all three events were only relatively weak wind erosion events, the emission of larger particles were also low. Therefore, the very fine particle classes can accumulate along the travelled path in the atmospheric boundary layer (<10 m) even during short calming phases of the wind speed. In these times, they are still present at unchanged concentration, leading to the negative correlation shown in Figure 7. As PM_1 is almost not present in the soil as isolated particles, it needs a releasing process as wind erosion, tillage, or traffic to be dispersed in the air. However, these particles can be rapidly entrained and vertically transported out from the sampling height. There is a significant knowledge gap regarding the interplay between different releasing processes and particle composition at the landscape scale that shall be further addressed in future experiments.

Nevertheless, the correlation pattern as shown in Figure 7 can thus only be found in gusty wind conditions (i.e., high variance in wind speed), and hence, the following chapter discusses the impact of gusts on the particle uptake.

3.3. Wind Speed Variation and Its Impact on Particle Uptake

In Figure 8 the results of the calculations of the Gust uptake Efficiency (GuE) for the three particulate matter classes and for both “IN” and “OUT” stations are shown. At 1 m height, the values generally show larger differences, both between the particulate matter classes and the “IN” and “OUT” positions, whereas the values are generally more balanced in 4 m height. The GuE for all events is clearly over 100% on the 1 m height measurements (except for Event I, “IN”) and closer to, yet still over 100% on the 4 m height measurements. This clearly shows that the transports at a height of 1 m can be assigned to the processes of erosion or sedimentation of the measurement field, whereas the particles at the height of 4 m rather originate from sources outside. It is also possible that particles are carried out of the sampling space by turbulent, vertical movement, see [40]. Regarding the particle sizes, a tendency for higher values for bigger particles can be seen, specifically at Events II and III.

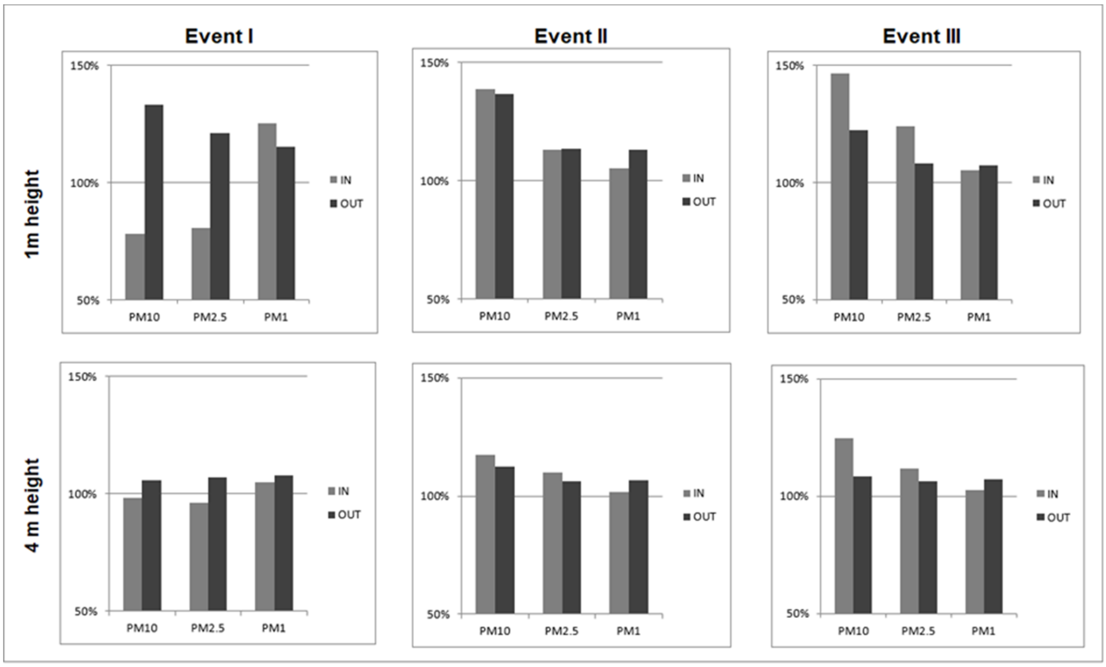

Figure 8. Gust update Efficiency (GuE) for all three events and for the heights of 1 and 4 m, calculated for the three particulate matter classes PM_{10}, $PM_{2.5}$, and PM_1.

A systematic difference between the values for “IN” and “OUT” cannot be seen, this seems to vary among the three events. Other studies such as [41] demonstrated that the total amount of saltating material transported along wind direction continuously increases with field length. In our study, station “OUT” is 160 m further along wind direction than station “IN”, being a comparable setting to the setup of sand traps described by [41]. While [41] focused on particle sizes > 62 µm, the EDM devices of this study measured much smaller particles (<32 µm). Hence, from our results we cannot conclude that this effect also propagates through smaller particle sizes, at least not at this spatial scale.

Because the results of Figure 8 are quite heterogeneous between the three events, we increased the temporal resolution of the analysis for Figure 9 and calculated the GuE for 30 min time windows. Since the events occurred over different time spans, this results in 11–15 time windows per event.

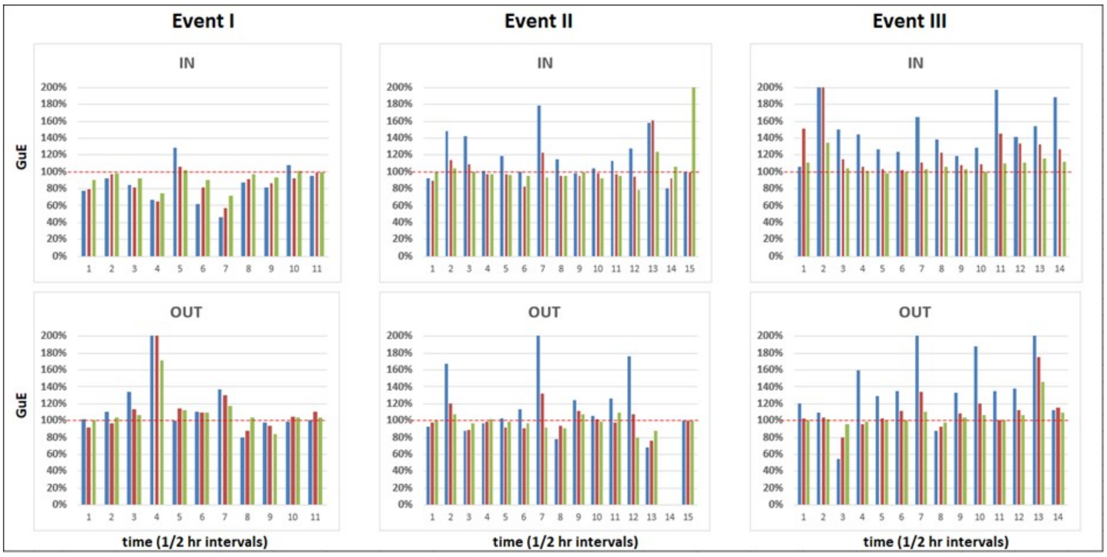

Figure 9. GuE for the three wind events at "IN" and "OUT" in 30 min temporal resolution for PM_{10} (blue), $PM_{2.5}$ (red), and PM_1 (green). The y-axis was limited to 200% for visibility purposes, resulting in sporadic overflows. This has no impact on the general interpretation of the results.

Figure 9 illustrates that the level of GuE is not constantly distributed over an event, but rather fluctuates in wave-like patterns. These wave patterns are equally expressed in the three particle classes. During periods where the GuE is generally above 100%, the coarser particles (PM_{10}) are always more affected by the gusts than the smaller particles. One feature of Figure 9 specifically points out: the dominance of PM_{10} GuE during Event, I. "OUT" ends after three hours (six half-hours intervals). Interval 7–11 PM_{10} has mainly a smaller GuE than the other particle size classes. The general periodicity of particle concentrations in all particle size classes results from the gusty wind conditions.

4. Discussion

In our analyses we found a 20% up to 50% increased particle uptake by gusts over the average emissions for PM_{10}, a 5–25% increase for $PM_{2.5}$, and an up to 10% increase for PM_1 particle concentrations at 1 m height. At the 4 m height this increased gust-induced particle uptake was less expressed. This is because dust in this height is already better sorted than in 1 m height, where saltation and suspension transports superimpose.

When determining the erodible fraction of soils, often wind tunnel experiments and rotary sieves are applied. When comparing the results of these two techniques against field experiments, Ref. [41] found good concordance in quality (positive correlation) but not in quantity. In other words, the erodible fraction was systematically higher at field experiments [42] than in laboratory settings. One reason for that can be observed in Figure 6, the gusty nature of "real" wind. Mostly, in wind tunnel experiments uniform or cascades of incrementally increasing wind speed are used [43–46]. Such approaches are more comparable to conditions with a very constant wind speed, we propose that gusty wind conditions can be considered to obtain comparable outcomes; one option would be wind tunnel experiments with gust simulation (frequently altering wind speeds).

In this study, we could not see a systematically higher dust activity at the "OUT" versus the "IN" station. A previous study [10] proved such an increasing cascade for saltating material. In our setup the distance between our two dust monitors, "IN" and "OUT" was not long enough to also capture that effect in the fine dust particles. Theoretically only emissions from the first third of the measuring field could reach the 4 m height at the "OUT" position 160 m away downwind. Topography was also previously shown to influence the spatial variability of sediment transport [11].

Also, we found the systematic change in dust uptake activity only during Event I where the wind direction is almost perfectly parallel to the plot. These findings lead to the conclusion that for future field experiments, it would be preferable to work on circular fields that have a large enough extension to be able to rotate the orientation of the measurement points according to each wind direction.

Our analyses as well as other studies such as [40] revealed different results for different particle size classes. While these differences were only slightly discussed in this manuscript, we propose to start further investigation on these systematic differences and their implications in future studies. One specific suggestion would be to analyze the proportion of big versus small particles in high resolution, i.e., in addition to the $PM_{10}/PM_{2.5}$ ratio which was suggested by [33], a $PM_1/PM_{0.5}$ ratio can be used because in this study the 0.5 μm threshold was found to separate negative from positive correlation with wind speed.

Finally, we constitute that the Gust uptake Efficiency (GuE) defined in this study is an appropriate measure to quantify the impact of wind gusts on the aerosol uptake during wind events with a high wind speed variability.

Limitations of the New Approach and Scope of Further Investigations

The variable parameter of how exactly a wind gust is defined (in our study as provided at the beginning of Section 3.2) needs to be carefully considered. The problem of a concrete event definition in continuous environmental data was comprehensively discussed in [47], where one possible approach was demonstrated to cover these uncertainties. Although possible, it is beyond the scope of this work to also perform such an extensive data approach which will be part of future investigations, possibly using the CoinCalc R package specifically designed for such purposes (see [48]).

For future studies we also recommend to further investigate how a gust can optimally be defined to best quantify the gust impact on soil erosion, how dust plumes can best be defined from time series, and to possibly apply event synchronization approached (such as, e.g., [49]) between gusts and dust plumes.

A concrete data analytics problem with the suggested approach on event definition is a scenario where the windspeed decreases abruptly and then starts accelerating again. In such a case a possibly evident wind gust directly after this pattern would not be identified as a gust. This happened a couple of times during our experiment, e.g., visible in Figure 6, Event II between 16:00 and 16:30. The same issue can be seen during tendentially decreasing wind velocities, e.g., Event III, between 13:00 and 13:30. The reason for this behavior is that the previously high wind velocities are also part of the mean calculation provided in Equation (3). In order to also capture those events, the average period (here set to $t-10$) would need to be decreased to, e.g., $t-5$. Yet for a data-driven automated approach, this cannot be performed manually and hence a mechanism must be defined to detect these events and automatically adopt the averaging period. In general, an approach making use of an auto-adoptive averaging period can be very promising. One possible approach can be classification methods screening the entire time series for clusters of specific patterns such as "decreasing tendency", "increasing tendency", "mixed", and others. Then, the averaging period for the gust definition can be adopted accordingly.

From a pure data-driven standpoint, combining the two major uncertainties of the suggested approach, the GIC value and the average period for gust definition to define a gust can comprehensively be investigated through the following setup: an analysis looping the entire sequence of analytics (event definition + GuE calculation) through a two-dimensional parameter set, using a range of GIC values and a range of average periods. This would result in a multi-dimensional GuE matrix. An interpretation of this matrix would lead to an "optimal" parameter set to defines maximal GuE. It can be assumed that this optimal set varies for changing meteorological conditions as well as for different soil types, SOM concentrations, and so on.

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