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Electrification of particles in dust storms: Field measurements during the monsoon period in Niger

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ABSTRACT

On the first fortnight of June 2010, experiments were carried out at a millet field in Niger to address the electrification of soil particles under natural conditions. The experiments were conducted during a period of high wind erosion, resulting from the passage of mesoscale convective systems (MCSs) which generate "walls" of dust passing through the Sahel. Soil particles are lifted from the ground by the stress exerted by the wind, with a threshold for emission that is particle size dependent. These particles then collide with other particles, leading to electrostatic charging of the particles. Soil samples of either positive or negative polarity were collected from the soil surface in 3 situations: 1) during "quiet" periods (far removed from a dust storm), 2) immediately after a dust storm, and 3) 12 h after a dust storm. Our results show that immediately after a dust storm, smaller particles are predominantly charged positive and larger particles are predominantly charged negative; this effect is still evident but smaller in magnitude 12 h after a dust storm. This size dependence for the charge polarity is in apparent contradiction with previous investigations; we believe this contradiction is only apparent, because the very fine particles, which we cannot measure with our technique, are expected to be negatively charged. Our results are rationalized by combining a population balance model for charged species trapped in high energy states with the wind threshold for soil particle motion.

1. Introduction

Large amounts of dust are released by wind erosion in desert and semi-arid areas. The finest dust particles (i.e., those with diameters smaller than 3 μm) can remain suspended in the air for days and be transported thousands of kilometers from their source (Pye, 1987; Reid et al., 2008). The suspended particles impact the climate by scattering solar radiation to cool the atmosphere (Kaufman et al., 2002), absorbing terrestrial IR radiation to heat the atmosphere (Sokolik and Toon, 1999) and influencing cloud formation (Levin et al., 1995), and can impact human health spreading diseases such as meningitis (Sultan, 2005; Perez et al., 2008). In semi-arid areas, the loss of dust that is often highly nutrient-enriched can hinder plant growth and lead to desertification (Bielders et al., 2002; Sterk, 2003). These issues are particularly acute in the semi-arid Sahel region of northern Africa because of its sensitive climate with frequent droughts (Brooks, 2004) and because its rapid population increase (Guengant and Banoin, 2003) has caused most of its arable lands to be under cultivation for food and thus more susceptible to wind erosion (especially when the cultivated land is dry) (Loireau et al., 2000; Moulin and Chiapello, 2006).

Wind erosion can be significant in the Sahel region in late spring, when dust storms are common and the vegetation cover is minimal (Bielders et al., 2004). From a climatic point of view, this timing corresponds to the arrival and installation of the monsoon, caused by the Inter-Tropical Convergence Zone moving north (Bielders et al., 2004). While monsoon winds occasionally reach intensities sufficient to cause some

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erosion, most erosion is caused by the wind generated from more violent fronts of convective systems. The southwest direction of the monsoon wind brings water vapor from the Atlantic Ocean to the continental atmosphere; when the water vapor concentration becomes sufficiently high in the monsoon layer, mesoscale convective systems (MCSs) with wide spatial extension form. The MCSs give rise to "squall lines" that sweep across the Sahel from east to west (almost opposite in direction to monsoon flows), with winds speeds of 60 to 70 km/h.

Dust storms take place by a combination of saltation and suspension mechanisms. In the saltation mechanism, wind stress above a threshold value causes particles and/or aggregates of particles with diameter, D, in the range 70 to 500 μm to be lifted to heights of less than 1 m and transported laterally with a ballistic trajectory; these trajectories include several rebounds off of the soil surface (Chepil and Woodruff, 1963). Fine particles ($D<20$ μm) do not take part in saltation (as individual particles) because they are agglomerated with other particles. These fine particles are released by the aggregates when the kinetic energy of saltating particles impacting the ground acts to overcome the binding energy of the dust particle (Gillette and Goodwin, 1974; Gillette and Walker, 1977; Shao et al., 1993; Alfaro et al., 1997; Shao and Lu, 2000). The freed fine particles are light enough to be pulled up to high altitudes by turbulence, and while suspended can travel thousands of kilometers before being re-deposited on the ground or in the ocean.

The wind stress thresholds for saltation can be influenced by electrical phenomena (Kok and Renno, 2006, 2008). Large dipolar electrical fields have been observed in dust storms and dust devils (Farrell et al., 2004; Schmidt et al., 1998), presumably due to triboelectric charging of the particles (tribolectric charging is the electrostatic charging that occurs when two surfaces contact). The charge on the particles, and the electric fields in the dust storms, are expected to reduce the threshold for saltation. However, previous emission models have not taken into account this effect and may underestimate dust emission in the atmosphere and thus its impact on climate change (Kok and Renno, 2006, 2008).

Despite its importance, the triboelectric charging of particles in dust storms remains poorly understood (Lacks, 2010). The presence of a dipolar electric field suggests that the sign of the charge on particles is size dependent: since smaller particles are lighter and thus lifted to higher altitudes than larger particles, a dipolar electric field will occur if the small and large particles have different polarities (we note that a different mechanism has also been proposed (Pahtz et al., 2010): for a particle cloud in a pre-existing electric field, the particles become polarized by the field, driving charge transfer systematically in one direction (vertically) to create a dipolar electrical field within the particle cloud with a opposite polarity compared to the pre-existing electric field). A number of studies have shown that the dipolar electric fields in dust storms have the positive pole near the soil surface (Farrell et al., 2004; Crozier, 1964; Ette, 1971; Williams et al., 2009). The present study addresses, for the first time, the size-dependent charge polarity of the particles themselves.

2. Experimental methods

Experiments were carried out at a cultivated millet field of 20 ha in the Sahel, near the village of Banizoumbou, Niger (13.5° N, 2.6° E; about 60 km east of Niamey, the capital of Niger). This field site has been operational since the early 1990s, when the first measurements of soil wind erosion were performed on a cultivated field (Rajot et al., 1995). More recently, this site was used for experiments of dust emission fluxes under natural conditions, as part of the African Monsoon Multidisciplinary Analysis (AMMA) international framework (Sow et al., 2009). The experiments were performed during the first two weeks of June 2010, which is the beginning of the Sahelian rainy season; wind erosion is strongest at this time because MCSs occur often and soil protection by crops is minimal (Abdourhamane Touré et al., 2011). The meteorological conditions were monitored during the experimental period. The wind direction was measured with a wind vane (W200P Vector Instrument®), and the wind velocity was measured with an anemometer (A100R Vector Instrument®); these measurements were taken 5 m above the ground. The saltation activity was recorded during the whole experimental period with a particle impact sensor (Sensit model H11B, http://www.sensit.com/), which records electrical signals when saltating particles hit it. In regard to the wind and saltation activity measurements, these results are just used qualitatively, to determine when dust activity occurs, and for this reason we do not go into more detail on the measurements.

Particles of a specific charge polarity were collected from the soil surface during quiescent conditions (before and after dust storms). A non-contact method similar to that of Forward et al. (2009) was used, in which an electrically biased (±8 kV) stainless steel disk is held approximately 1 cm above the soil surface (Fig. 1). The distance of approximately 1 cm is used because the resulting electric field (~800 kV/m) acting on charged sand particles is sufficient to lift the particles against gravity (greater distances would require larger voltages on the plates). The disk (diameter 10 cm) was covered with a polymer film (Parafilm) that acts as a dielectric spacer to prevent particles from discharging when they hit the plate (and thus falling back onto the surface soil). A positive voltage (8 kV) was placed on the disk to extract negative particles from the surface soil, and a negative voltage (−8 kV) was used to extract positive particles (as addressed in the Discussion section, induction effects could cause the plates to also pick up neutral particles). The electric bias on the disk was supplied by a high voltage source (model E101, http://www.emcohighvoltage.com) powered by a 12 V battery; the disk was attached to an insulating nylon rod that could be safely held by the collecting operator even when the disk holds a high voltage. Operators move across the field holding the high voltage disks at a distance approximately 1 cm above the ground; collections with both the positive and negative disks are carried out simulataneoulsy, in very close proximity to each other. The collection proceeds for 2 min, after which the disks are completely covered with particles.

The samples of collected particles were brought back to our laboratory. The particles were removed from the Parafilm by rinsing with deionized water in a glass vessel; after rinsing, the particles were dried in an oven and weighed. The particle size distribution was determined for each sample with an optical Coulter LS 320 Particle Analyzer. The instrument uses laser diffraction to determine the particle size distribution from 0.4 to 2000 μm, for samples of particles suspended in deionized water (no special attempts were made to disperse aggregates of fine particles). The output is a histogram of the percentage