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Evaluation of the electrical properties of dust storms by multi-parameter observations and theoretical calculations

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ABSTRACT

Dusty phenomena, such as wind-blown sand, dust devils, and dust storms, play key roles in Earth's climate and geological processes. Dust electrification considerably affects the lifting and transport of dust particles. However, the electrical properties of dust storms remain poorly understood. Here, we conducted multi-parameter measurements and theoretical calculations to investigate the electrical properties of dust storms and their application to dust storm prediction. The results show that the vertical electric field (E-field) decreases first, then increases, and finally decreases with the height above the ground, reversing its direction at two heights, ∼8–12 and ∼24 m. This suggests that the charge polarity of dust particles changes from negative to positive and back to negative again as the height increases. By carefully analyzing the E-field and dust concentration data, we further found that there is a significant positive linear relationship between the measured E-field intensity and dust concentration at the given ambient conditions. In addition, measurements and calculations demonstrate that a substantial enhancement in the vertical E-field can be observed several hours before the arrival of the external-source dust storms, indicating that the E-field can be used to provide an early warning of external-source dust storms.

1. Introduction

Dust storms frequently occur in arid and semi-arid areas and can cause serious damage to the economy, environment and human health (Shao and Dong, 2006; Akhlaq et al., 2012). Therefore, achieving a clear understanding of the physical processes involved in dust storms and high accuracy early warning of dust storms can considerably minimize these hazards. Preliminary dust storm E-field measurements have shown upward vertical E-fields with values of 5–10 kV/m (Rudge, 1913). Subsequent measurements have detected both downward and upward vertical E-fields, with values of ∼50–200 kV/m at the ground level (e.g., Demon et al., 1953; Stow, 1969; Williams et al., 2009). Recently, comprehensive three-dimensional E-field measurements recorded both the upward vertical E-field and downwind streamwise E-field (Bo and Zheng, 2013). Moreover, the magnitude of the streamwise E-field was larger than that of the vertical E-field, reaching up to ∼60 kV/m at a height of several meters above the ground. Measurements and theoretical models have suggested that the intense E-field had pronounced effects on the trajectories of saltating particles (Zheng et al., 2003; Kok and Renno, 2008), the evolution of wind-blown sand (Zheng et al., 2006), and the lifting of dust particles from the ground (Kok and Renno, 2006, 2008; Esposito et al., 2016).

To date, the vertical E-field was measured at only one height (Rudge, 1913; Kamra, 1972; Williams et al., 2009; Esposito et al., 2016) or at four heights ranging from 0.4 to 4 m (Bo and Zheng, 2013). The measured vertical E-field was upward (Rudge, 1913; Stow, 1969; Bo and Zheng, 2013) or downward (Demon et al., 1953; Esposito et al., 2016) at a near-ground height of ∼2 m. The reason for this difference in the measured E-field direction is still unclear. In addition, the measured vertical E-field decreased rapidly with height in the saltation layer (Schmidt et al., 1998), but initially increased and then decreased with height in the region of 0.4–4 m (Bo and Zheng, 2013). The entire profile of the vertical E-field in dust storms has not been completely investigated.

Existing technologies that are used for dust storm detection and early warning can be classified into two categories, namely, traditional ground-based observations and spaceborne observations. The former method is generally based on monitoring the wind speed, temperature, and dust concentration, etc. However, it is difficult to forecast upcoming dust storms because the large increases in these quantities can only be measured when the dust storms arrive. For the latter method, the position, propagation direction, and average propagation speed of dust storms are determined by analyzing the continuous monitoring of satellite images and thus can

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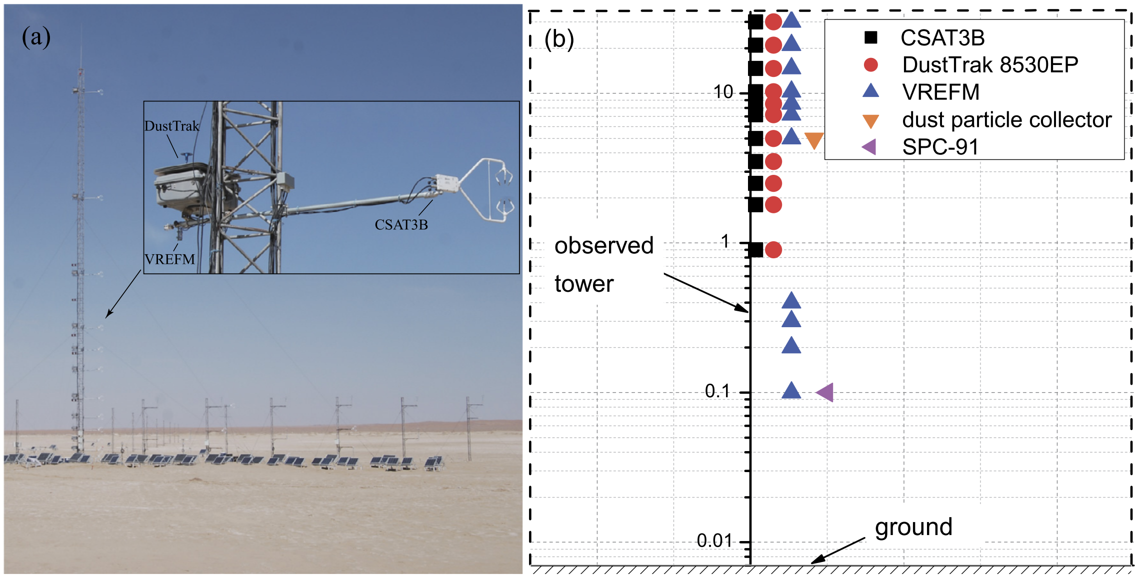

Fig. 1. (a) An overview and (b) accurate configuration of the instrument array at Minqin, Qingtu Lake, China. All instruments were mounted on an observed tower (32 m in height). The CSAT3B and DustTrak II Aerosol Monitor were mounted at heights of 0.9, 1.71, 2.5, 3.49, 5, 7.15, 8.5, 10.24, 14.65, 20.96, and 30 m above the ground. To measure the E-field in the near-ground region (<0.9 m), the VREFMs were mounted at heights of 0.1, 0.2, 0.3, 0.4, 5, 7.15, 8.5, 10.24, 14.65, 20.96, and 30 m. The SPC-91 and dust particle collector were mounted at 0.1 and 5 m, respectively.

issue an early warning to the downwind regions. Nevertheless, this method is also limited by the low spatial and temporal resolution of satellite imaging devices. For example, GOES and GERB provide data with a temporal resolution of up to ∼15 min, but the spatial resolution is as low as ∼10 km. The poor spatial resolution is insufficient to determine the accurate location of the leading edge. By contrast, Quickbird has a high spatial resolution (∼0.65 m) but low temporal resolution (revisit time is 1–3.5 days). Thus, it is ineffective at providing real-time monitoring of dust storms.

As discussed above, the existing traditional methods have some limitations. Unlike wind speed and the dust concentration, the E-field is something real that extends throughout a volume of space, and therefore the E-field can be detected at a distance between the source and measurement point. Although the existing measurements of dust storms cannot directly confirm long-distance electrical effects (e.g., Bo and Zheng, 2013), measurements in other natural granular systems, such as dust devils (e.g., Freier, 1960; Crozier, 1964) and volcanic plumes (Rakov and Uman, 2003; Mather and Harrison, 2006; Aizawa et al., 2016), are well-documented. If the exterior E-field is large enough in dust storms, detection of dust storms can be achieved by monitoring strong increases in the atmospheric E-field. However, whether this method is feasible remains unknown.

In this study, we present a series of dust storm E-field measurements up to a height of 30 m above the ground in Minqin, China. Based on the measured results, we also propose a simple E-field model. The objectives of this study are as follows: (1) reveal the vertical E-field profile; (2) obtain the relationship between the dust concentration and vertical E-field; (3) determine the charge-to-mass ratios of airborne dust particles; and (4) discuss whether the prediction method based on monitoring the E-field is feasible for a dust storm early warning system.

2. Field measurements

Measurements were taken in the flat-bottomed dry lakebed of the Qingtu Lake (longitude: 103°40′03″; latitude: 39°12′27″), approximately 90 km northeast of Minqin, Gansu, China. This field site is located between the Badain Jaran Desert and Tengger Desert, which are source areas of sand and dust particles. Measurements were performed continuously during the spring season from March to June 2015.

Measurements of the wind velocity, ambient temperature, vertical E-field, mass concentration of PM_{10} (dust particles with diameter of <10 μm), number density of saltating particles, and particle size distribution (PSD) of airborne dust particles were taken simultaneously. The accurate configuration of the instrument array is shown in Fig. 1b. The wind velocity and ambient temperature were measured by sonic anemometer (model CSAT3B, Campbell Scientific), and the PM_{10} dust concentrations were measured by DustTrak II Aerosol Monitor (Model 8530EP, TSI Incorporated). The vibrating-reed electric field mill (VREFM) developed by Lanzhou University was used to measure the E-field. The number density of saltating sand particles in the range of 36–490 μm (with 32 bin steps) was obtained using sand particle counter (SPC-91, Niigata Electric Co., Ltd.). Measurements were performed at a sampling rate of 1 Hz (expect CSAT3B with 50 Hz). In addition, the PSD of total airborne dust particles was determined by measuring the PSD of sample dust particles collected in a dust particle collector mounted at a height of 5 m above the ground.

It is worth noting that the DustTrak II Aerosol Monitor measures dust concentrations based on the principle of light scattering, and thus the measurements are highly dependent on the particle size and material properties. The 8530EP Monitor is factory calibrated to the reparable fraction of the standard ISO 12103-1 A1 ultrafine test dust, which has a nominal 0–10 micron size. In the present study, we use the factory defaults calibration factor (i.e., User Cal is 1.0) to measure the PM_{10} dust concentration in the dust events because the aerosols are very similar to ISO 12103-1 A1 test dust. Therefore, the measurement error could be considered to be negligible. Additionally, to obtain accurate measurements for other specific aerosols, such as PM_1 and $PM_{2.5}$, an additional calibration experiment is required and implemented following Morawska et al. (2003) and Zhou et al. (2016).

The working principle of VREFM is based on detecting the charge induced on the sensor electrode (Zheng, 2013). As the electrode oscillates, it charges and discharges periodically, and the electric current is linearly proportional to the electric field intensity. The VREFM is calibrated using a large (1 m square plates) parallel-plate electric field calibrator. The results of the laboratory