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Electric properties of dust devils

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ABSTRACT

Dust devils are one of the most effective phenomena able to inject dust grains into the atmosphere. On Mars, they play an important role to maintain the haze and can significantly affect the global dust loading, especially outside the dust storm season. Despite dust devils having been studied for a century and a half, many open questions regarding their physics still exist. In particular, the nature of the dust lifting mechanisms inside the vortices, the development of the induced electric field and the exact contribution to the global atmospheric dust budget are still debated topics. In this paper, we analyze the dust devil activity observed in the Moroccan Sahara desert during a 2014 field campaign. We have acquired the most comprehensive field data set presently available for the dust devils: including meteorological, atmospheric electric field and lifted dust concentration measurements. We focus our attention on the electric field induced by vortices, using this as the principal detection parameter. We present, for the first time, the statistical distribution of dust devil electric field and its relationships with the pressure drop, the horizontal and vertical vortex velocity and the total dust mass lifted. We also compare the pressure drop distribution of our sample with the ones observed on the martian surface showing the similarity of the dust devils samples and the usefulness of this study for the next martian surface missions.

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1. Introduction

Dust devils are convective vortices, stable vertical air columns in rotary motion around a low pressure core, able to entrain material from the surface. On Earth, the vortices affect the atmospheric dust concentration of desert areas, but their contribution to the global dust budget is only a few percent (Jemmett-Smith et al., 2015). On Mars, the full impact of dust devils on global dust circulation is not yet fully understood, but is generally considered to be more substantial compared to the Earth (Fenton et al., 2016). By analyzing the dust storms activity on Mars, Guzewich et al. (2015) concluded that they can only explain ∼50% of the total atmospheric lifted dust. Small scale dust lifting phenomena, in particular dust devils, seem to contribute to the global martian dust budget between 25% and 75%, sustaining the global haze and the concentration of fine aerosol into the atmosphere (Neubauer, 1966; Thomas and Gierasch, 1985; Fedorova et al., 2014).

The first evidence of their existence on Mars was given by the Viking missions (Ryan and Lucich, 1983; Thomas and Gierasch, 1985). In the following years, the presence of dust devils on the planet was largely confirmed and the NASA Mars Global Surveyor and the ESA Mars Express missions allowed the observation from the orbit of dozen dust columns and dust devils tracks (Malin and Edgett, 2001; Greeley et al., 2004; Stanzel et al., 2008). The nearly global Mars coverage of these images showed that dust devils are common and widespread in both hemispheres in every season, almost at every latitudes and elevation. The NASA Pathfinder, Phoenix and Curiosity missions have acquired the meteorological signatures for hundreds of convective vortices (Schofield et al., 1997; Murphy and Nelli, 2002; Ellehoj et al., 2010; Steakley and Murphy, 2016). This was performed by using the atmospheric pressure as principal detection parameter and performing a "phase picker" analysis in order to recognize the drops due to the passage of the vortices low pressure core ("phase picker"

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is the term used in seismology for event detection – in dust devil analyses it is typically implemented as the detection of a significant negative excursion of a short-period average pressure signal from a long-period average).

However, the pressure is not the only parameter that can easily indicate the passage of dusty vortices. On Earth, sand and dust lifting phenomena are associated with the formation of an induced electric field (E-field). Indeed, during lifting, the individual grains tend to acquire an electric charge by collisions even if the whole dust cloud remains neutral (Kunkel, 1950). On Mars, due to the lack of an adequate in situ instrumentation, the presence of an atmospheric E-field has not yet been confirmed. However, the abundance of entrained dust, the generally favorable condition for lifted grains to acquire and hold charge and laboratory experiments performed in martian like condition, suggest the existence of an atmospheric electric field, widespread across the planet and highly variable in relation to the dust lifting activity (Eden and Vonnegut, 1973; Forward et al., 2009; Barth et al., 2016). The electric field induced by lifted dust may significantly affect the composition of the martian atmosphere and the habitability of the planet, locally enhancing by up to 200 times the chemical formation of oxidants able to scavenge organic material from the surface (Atreya et al., 2006). Due to the low martian atmospheric electric breakdown field strength (∼20 kV/m) (Melnik and Parrot, 1998), the concentration of suspended charges can also lead to the formation of electric discharges that can interfere and cause damage to landed instrumentation, representing an issue for human exploration.

The exact mechanism that leads to grain electrification is still debated and not completely understood (see Harrison et al., 2016 for a review on the topic). For a heterogeneous system the charge acquired during the impacts depends primarily on the composition of colliders (McCarty and Whitesides, 2008), while in a homogeneous dust cloud the process seems to be size-dependent: smaller grains tend to charge negatively while larger ones positively (Forward et al., 2009; Lacks and Levandovsky, 2007; Duff and Lacks, 2008; Desch and Cuzzi, 2000; Melnik and Parrot, 1998). Atmospheric convective activity transports grains of different weight to different heights, producing a vertical mass stratification which leads to the charges separation and to the formation of the observed electric field.

The presence of suspended dust negatively charged over a cloud of sand of opposite sign (upward directed E-field) is consistent with the majority of field and laboratory measurements reported in literature (Bo and Zheng, 2013; Freier, 1960; Crozier, 1964, 1970; Farrell et al., 2004; Jackson and Farrell, 2006). However, there are cases where this electric configuration is not reproduced (Trigwell et al., 2003; Sowinski et al., 2010; Kunkel, 1950) and there are also reported cases where the electric field is downward directed (Demon et al., 1953; Kamra, 1972; Esposito et al., 2016). These works indicate that we are still far from a comprehensive understanding of the E-field development during dust lifting events, motivating the execution of more detailed surveys. Furthermore, few measurements (less than a tenth) of dust devil electric fields have been reported so far (Freier, 1960; Crozier, 1964, 1970; Farrell et al., 2004; Jackson and Farrell, 2006). These studies present the analysis of isolated events where the E-field is not studied in combination with the meteorological parameters and lifted dust concentration.

In this work we present the analysis of the dust devils activity observed in a field campaign performed in the Moroccan Sahara desert during the 2014 dust storm season. The campaign was carried out in the frame of the DREAMS project, the meteorological station on board of the Schiaparelli lander of the ExoMars 2016 space mission (Esposito et al., 2018). In order to study on Earth the physical processes to be likely encountered on Mars by DREAMS, we deployed a fully equipped meteorological station able also to monitor atmospheric electric field and concentration of lifted sand and dust, acquiring in this way a data set unique in literature. Here, we focus our attention on the electric field induced by the vortices passage, identifying the events using it as principal detection parameter. For the first time, we show the cumulative distribution of the dust induced E-field and we present the relationship between the E-field and the other parameters of the vortices, such as their pressure drop, horizontal and vertical wind speeds and the numeric and mass concentration of lifted dust.

Moreover, we compare the distribution of our sample to the martian dust devils surveys showing that the present terrestrial dataset could be useful for studying the dust induced E-field on Mars.

2. Methods

2.1. Equipment

In this work we have analyzed the data acquired during our 2014 field campaign performed in North-Western Sahara Desert of the Tafilalt region (Morocco, 4.110°W, 31.193°N). The site is on the edge of a Quaternary lake sediment bed that is the main source of the measured atmospheric suspended dust. The composition of the sediment (sand, silt, and clay fractions) is the result of the erosion of the regional bedrock of late Paleozoic sedimentary rocks outcropping in the area and is chiefly constituted of detrital shale, quartz, and carbonates grains (see Esposito et al., 2016 for more details).

We have monitored a total of 83 days from June 15th to September 5th, using a meteorological station equipped with soil temperature (CS thermistor) and moisture (CS616-C) sensors, three 2D sonic anemometers (Gill WindSonic) placed at 0.5, 1.41, and 4 m heights above the ground, one thermometer and humidity sensor (Vaisala HMP155) at 4.5 m and one thermometer (Campbell Sci. (CS)) placed at 2.5 m, one pressure sensor (Vaisala Barocap PTB110) at 2 m, a solar irradiance sensor (LI-COR LI-200 Pyranometer) at 4 m and an atmospheric electric field sensor (CS110) faced down at 2 m. In addition, we have monitored the saltation activity with two sand impact sensors (Sensit Inc.) and three sand catchers (BSNE) placed at different heights (12, 25 and 40 cm) and the atmospheric dust concentration with a sensor (Grimm EDM 164-E) placed at 1.5 m that analyses the dust in 31 channels in the diameter range 0.265–34 μm. From July 14th we have also added two 2D sonic anemometers (Gill WindSonic) placed at 7 and 10 m and one 3D sonic anemometer (Cambell CSAT3) placed at 4.5 m.

The station operated 24 h/day at a sampling rate of 1 Hz, only the 3D sonic anemometer has acquired measures at 20 Hz.

2.2. Dust devil structure and identification

Fig. 1 shows a dust devil photographed near the measurement site. The diameter of the dust column can remain roughly constant or increase with the height, the column can be perpendicular to the surface or slightly tilted in the direction of motion (Fig. 1).

At the center of the column there must be a low pressure core, related to the vertical convection, that induces a horizontal rotary motion of the air flow. The rotational speed is approximately in cyclostrophic balance with the magnitude of the pressure drop ΔP and it can be reasonably described using the Rankine vortex model: the speed linearly increases with the radial distance r from the center of the vortex up to its wall, where it reaches its maximum, then decreases as the reciprocal of r. The pressure has its minimum value in the center of the vortex and the magnitude of the drop decreases with the distance following a Lorentzian curve (Ellehoj et al., 2010). Inside the wall of the column the lifted grains

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