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In situ measurements of dust devil pressure drop magnitudes and vertical wind speeds

D. Reiss (1) and J. Raack (2)
(1) Institut für Planetologie, Westfälische Wilhelms-Universität, Münster, Germany, (2) School of Physical Science, STEM, The Open University, Milton Keynes, UK

1. Introduction

Dust devils are common on Earth and Mars. On Mars they significantly contribute to dust entrainment in the atmosphere. Meteorological signatures of vertical convective vortices (dust devils and dustless vortices) on the martian surface were detected with meteorological instruments on landers and rovers. The most prominent temporal signature of passing convective vortices is the reduced atmospheric surface pressure within the vortex. Such pressure drops were measured and analyzed at the Viking 2 [1], Pathfinder [2], Phoenix [3], and MSL [4, 5] landing sites. Recently, large datasets were obtained on Earth [e.g. 6, 7]. Pressure drop magnitudes are direct indicators for the intensity of dust devils and are directly related to the dust devil tangential speeds to a first approximation [e.g. 8]:

$V \approx \sqrt{\frac{RT_s \Delta p}{p_s}}$, where R is the atmospheric specific gas constant, T_s the ambient surface air temperature, Δp the pressure drop magnitude, and p_s the ambient pressure. Another important parameter is the vertical speed within dust devils, which is needed to calculate dust devil sediment fluxes on Earth and Mars [e.g. 9 – 11]. Vertical speeds within dust devils on Earth have been measured to be in the range of 0.1 – 10 ms^{-1} [e.g. 9, 12]. On Mars, vertical speeds were so far only estimated at the MER-A (Spirit) landing site tracking dust clods within individual dust devils from time-lapse imagery [10]. The estimated median vertical speeds are 1 ms^{-1} (season 2 and 3) and 1.6 ms^{-1} (season 1) [10]. However, no direct measurements of vertical speeds within dust devils on Mars are available to date. Based on terrestrial measurements of vertical and tangential speeds in dust devils by [12], [13] proposed that the vertical speed is about a quarter of the value of the maximum tangential speed. Establishing correlations between pressure drop magnitudes and vertical speeds in dust devils can help to improve dust devil sediment flux calculations on Earth and Mars where often only limited parameters can be measured (e.g., atmospheric pressure). For example, such relationships in combination with estimated or measured dust loads would enable the use of numerous pressure drop magnitude measurements for the calculation of dust devil sediment flux estimates at several landing sites on Mars.

2. Field site and Instrumentation

In 2016, we performed in situ dust devil measurements near Merzouga in southern Morocco. Amongst other parameters, we measured atmospheric pressure and vertical wind speed at heights of 0.15 m above the surface. We used 5 fixed meteorological stations spaced by 5 m and logging at a sampling rate of 20Hz. Figure 1 shows an example of a dust devil directly crossing one station as well as an example of measured atmospheric pressure and vertical wind speed during a passage of a dust devil. The high time sampling resolution at 20 Hz enables us to detect even small (~1m in diameter) and fast moving dust devils. Atmospheric pressure was measured with a Bosch BMP280 digital pressure sensor set to ultra-high resolution mode (pressure oversampling = 16, temperature oversampling = 2, $t_{standby}$ = 0.5 ms, IRR filter = off) which results in a pressure resolution of 0.16 Pa, a relative accuracy of 12 Pa, and a measurement time of 40 ± ~3ms. The vertical wind speed was measured with low-cost Modern Device Rev. P hot-wire anemometers with a accuracy of ±0.5 ms^{-1} [14]. We also tested the hot-wire anemometers against an industrial cup anemometer at different sampling frequencies (1, 10, and 20 Hz) showing accurate measurements within the accuracy of ±0.5 ms^{-1}. Each anemometer was mounted within a pipe (5 × 10 cm in dimensions) to minimize noise from horizontal winds. All data were directly logged onto a SD-card using an Arduino Leonardo microprocessor with a data logger shield. In addition, the meteorological stations were monitored with a GoPro3 at a sampling rate of 1 Hz to document and constrain the path of dust devils in relation to the fixed stations.

3. Results

Figure 2A shows our measured peak pressure drop magnitudes versus peak vertical speeds of 13 dust devils which directly crossed one of the meteorological stations. Our study indicates that the vertical speed is about 0.06×ΔP. For comparison with other studies we calculated the peak tangential speeds from our peak pressure drop magnitudes (see equation above). Figure 2B shows the tangential speeds versus vertical speeds of our study in 2016 in comparison with other studies. Our study indicates that the vertical speed is about half the tangential speed and in good agreement with studies by [15], [16], and [17]. The reason for the discrepancy of our study with early studies by [12] and [18] indicates that the vertical speed is about one fifth of the tangential speed is unclear but might be, for example, due to differences in instrumentations or sampling rates. We are currently planning another field campaign using fixed as well as mobile stations to measure pressure drop magnitudes and vertical speeds at different heights to obtain a statistically more robust dataset.

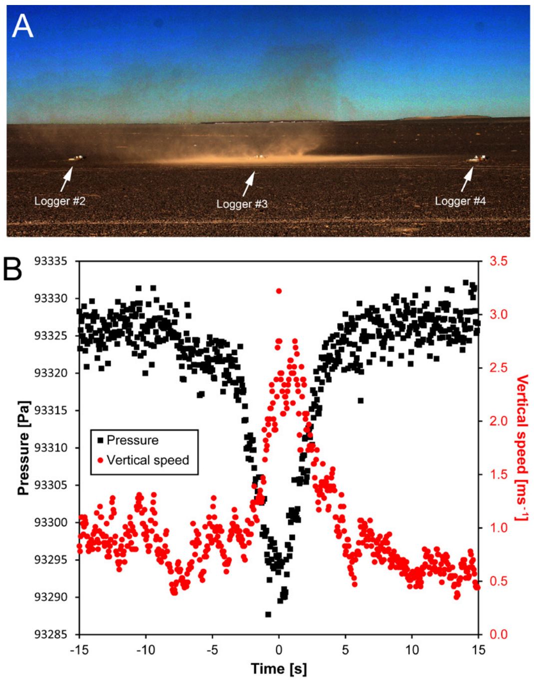

Figure 1: (A) Example of a dust devil directly passing over one of the fixed meteorological station. (B) Example of measured atmospheric pressure and vertical speed during a passage of a dust devil directly crossing one of the fixed meteorological station.

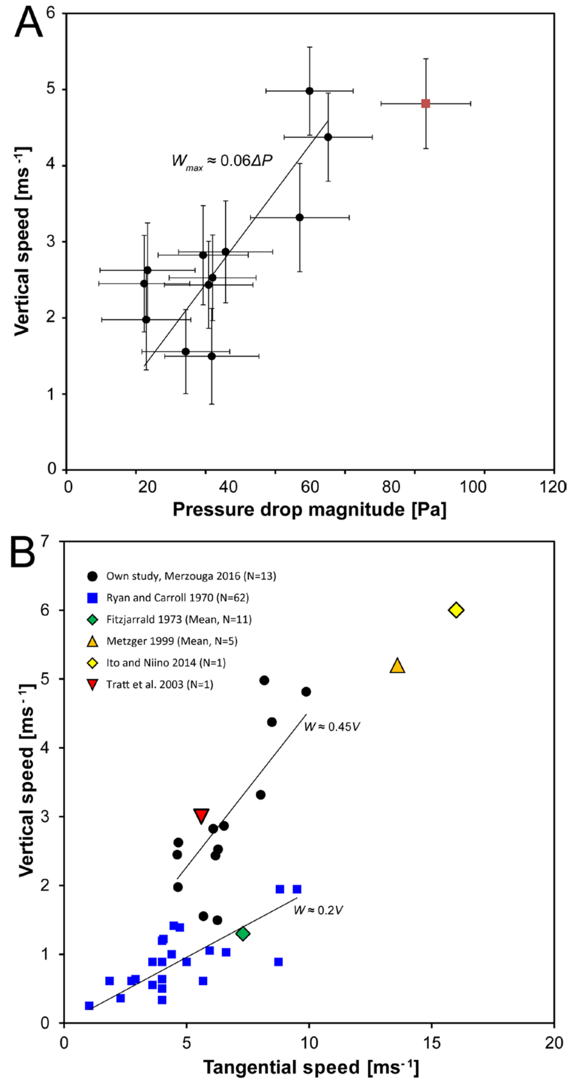

Figure 2: Relationships between dust devil vertical speeds to pressure drop magnitudes and tangential speeds. (A) Pressure drop magnitudes versus peak vertical speeds derived from dust devil cores passing directly over the sensors of fixed meteorological stations in 2016 near Merzouga (Morocco). The red square data point indicates recalculated pressure drop magnitude because the pressure sensor malfunctioned during the passage of the dust devil before the minimum pressure was reached. Indicated errors are combined instrument accuracy and peak value fitting uncertainties. (B) Comparison of our dust devil calculated peak tangential speeds versus measured peak vertical speeds with other studies.

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