Particle Image Velocimetry of a Dust Devil Observed in a Desert

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Abstract

Dust devils are small-scale atmospheric vortices that are often observed on deserts or bare land during daytime in a fine day. Dust particles lifted by strong winds and updrafts in the vortices visualize themselves. Gusty winds associated with them often prevent outdoor activities, and occasionally cause damage to weak structures such as tents and resulting injuries.

On the other hand, an increasing number of numerical studies have been presented recently. However, most numerical studies suffer from underestimates of wind speeds even if very high resolution is used (e.g. Kanak 2005; Raasch and Franke 2011; Ito et al. 2013). The reason for the underestimate is still uncertain, and further observations of the wind speeds and turbulence characteristics in dust devils are desired.

Observations by cameras along with image processing may be a useful method to systematically investigate a number of dust devils. Stanzel et al. (2006, 2008) have obtained translational speeds of dust devils on the Mars. Balme et al. (2012) implies correlations between translational speeds of dust devils and ambient winds based on terrestrial field observations. Thus, prevailing wind speeds on the Mars may be estimated from a translational motion of a dust devil. These studies, however, did not focus on the flows in dust devils.

Particle Image Velocimetry (PIV) is a method which looks for the best matching of distributions of pixel patterns in two successive frames to obtain two-dimensional velocities (e.g. Raffel et al. 1998). In a video of a dust devil (Supplemental movie S1) which is downsampled from original; Fig. 1) around 14 LST on 19 July, 2013 in a desert in the north of Tucson, Arizona, the United States. Several previous observations were conducted near the location (Sinclair 1969; Balme et al. 2012). Tens of dust devils were observed in an hour, but only one occurred in a short distance from the camera. Soil particles at the location were relatively coarse. Thus, dust suspension into the atmosphere was mostly caused by dust devils but rarely by other sporadic winds. This was also convenient for a video camera because one did not need to care about a dust protection. However, bushes on the ground are annoying since they prevent from observing flows very close to the surface.

A consumer video camera (JVC, GC-PX1; hereafter referred to as Camera A) is settled on a tripod, although such a reasonable position for PIV. Its frame rate is 60 fps (frames per second) and each frame has a resolution of 1920 pixel (px) for horizontal (x-) and 1080 px for vertical (z-) directions.

The dust devil moved leftward while increasing its height. The video is separated into 1300 sequential 24 bits RGB bitmaps at every 1/60 s. PIV is performed between time $t = 0$ and $t = 21.7$ s, but the analysis in Section 4 to obtain flows is conducted only for $0 \leq t \leq 13.3$ s. An image at $t = 66.6$ s when the dust devil has gone is used as a background (Fig. 1f).

A deviation from the background brightness $D(x,z,t) \equiv (R(x,z,t) - R_b(x,z))^2 + (G(x,z,t) - G_b(x,z))^2 + (B(x,z,t) - B_b(x,z))^2$ is computed, where $R$, $G$, and $B$ denote red, green, and blue 8 bits color values in bitmap, respectively, and the subscript $b$ means the background. To reduce the computational cost, pixels having $D \geq 300$ for a rectangular region given by $570 \leq px \leq 1800$ px and $440 \leq px \leq 740$ px (dashed square in Fig. 1) are used in the present PIV analysis. Wind vectors $\langle v(x,z,t) \rangle = \langle w(x,z,t) \rangle \equiv (dx(x,z,t)/dt, dz(x,z,t)/dt)$ are estimated by examining differences between 5 px x 5 px templates of $D$ at two different times: $\bar{v}$ is determined so as to minimize the total difference in the templates $F(dx, dz, dt) \equiv \sum_{-2 \leq t \leq 2} (D(x + x', z + z', t) - D(x + x' + dx, z + z' + dz, t + dt))^2$ in the range of $-40 \leq dx < dx < 40$, where $-2 \leq x' \leq 2$ and $-2 \leq z' \leq 2$ denote position in each PIV template. Selected wind vectors $\langle v(x,z,t) \rangle$ that satisfy both of the conditions (1) $\langle v(x,z,t) \rangle_{\delta = 0.4} \geq \langle v(x,z,t) \rangle_{\delta = 1.5}$ for the selected condition $0.5 > 0$ and $0.5 > 0.5$ are utilized in the following analysis. These procedures exclude wind vectors whose variation is so large that they seems unphysical. Note that the aforementioned criteria in the PIV are determined after considerable trial-and-error-type efforts. An objective way to determine these criteria is desired.

The resulting wind vectors are presented in Fig. 1a, b, c, d, e.
As seen in Fig. 1e, JI approached the dust devil to take a close-up movie with another handy video camera (Kodak, PLAYSPORT; hereafter referred to as Camera B; the movie is presented in the lower right window in Supplemental movie S1). The movie turned out to give useful information to estimate length scale in the PIV analysis.

3. Estimation of a length scale

In order to obtain actual wind speeds in unit of m s\(^{-1}\), a physical length scale corresponding to 1 px needs to be determined. Due to a lack of any measure of a length scale in the video, one needs to make an indirect estimate of the length scale.

Here we will estimate the physical length of a pixel near the dust devil in the following way: Camera A recorded the image of JI who stopped while following the dust devil (Fig. 1e) with Camera B and took an image of the dust devil. Figures 2a, b show simultaneous images taken by Cameras A and B, respectively. If the ratio of the diameters of the dust devil (the solid line with arrows) to the horizontal size of the characteristic pattern in background clouds in far distance (dashed line) in Fig. 2a is denoted by \(a\) (~ 1) and that in Fig. 2b by \(b\) (~ 1/2), a simple geometric calculation gives that the ratio of \(a\) to \(b\) is equal to the ratio of the distance between Camera A and the dust devil to that between Camera B and the dust devil, under an approximation that the distance between Cameras A and B is much smaller than that between the cameras and the background clouds. Thus, the distance from Camera A to the dust devil is about twice as large as that from Camera B to the dust devil.
that from JI. This means that physical length of a pixel of Camera A near the dust devil is twice as large as that near JI. Since 14 pixels of Camera A correspond to the seating height of JI, a physical length of a pixel near JI is estimated to be 6.5 cm. This means that the physical length of a pixel of Camera A near the dust devil is $6.5 \times 2 \approx 13$ cm. Based on this estimate, an environmental wind speed and various characteristics of the dust devil can be obtained from Camera A.

A weighted average of horizontal coordinate $x_d \equiv \sum_{t=0}^t xD(x,z,t)\sum_{t=0}^t D(x,z,t)$ with weighting function $D$ gives an objective estimate for a horizontal position of the dust devil for each $t$. Note that only the values of $D$ at pixels where the selected wind vector $\mathbf{v}$ exists are employed in the summations. $x_d$ turns out to decrease nearly linearly with time (Fig. 3), suggesting that the translational speed of the dust devil in the $x$-direction is nearly constant and is approximately $-20$ px s$^{-1}$ $\approx 2.6$ m s$^{-1}$. The translational speed of the dust devil remained nearly constant suggests its motion in the direction perpendicular to the frame is small.

The translational speed may be nearly equal to the environmental wind, which is believed to be associated with convection cells having larger spatial and temporal scales than those of dust devils, as seen in previous numerical studies on dust devil (e.g. Ito et al. 2013). The estimated environmental wind speed $U \approx 2.6$ m s$^{-1}$ seems reasonable: dust devils are known to favor such a weak environmental winds (Sinclair 1969; Ito et al. 2010; Raasch and Franke 2011).

Also plotted in Fig. 3 are horizontal positions of the upper and lower parts of the dust devil. The upper part precedes the lower part from $t = 0$ to 15 s in accordance with previous observations (e.g. Kaimal and Businger 1970). After $t = 15$ s, however, the tilt of the vortex axis appears to be rapidly reduced, although the reason for the change is not clear.

The diameter and height of the visualized column are estimated to be about 18 m and several tens meters, respectively. The distance between Camera A and the dust devil is estimated to be approximately 80 m based on the width of the road whose width can be seen in a satellite image on the site.

4. Wind vectors in the dust devil

In the present analysis, the wind vectors $\mathbf{v} = (u,v)$ are obtained only in the range of $x_d - 25 \leq x \leq x_d + 25$ (px) where the tangential winds of the dust devil nearly align with the plane of the paper. All wind vectors obtained by PIV at each time step are overlaid in Figs. 1a, b, c, d, e. Since instantaneous wind vectors have large fluctuations, our discussion will be based on an ensemble of wind vectors weighted by $D$ during the 13.3 s. In the following, the description will be based on actual length using the relation between the pixel size and the actual length (1 px $\approx 13$ cm).

Figure 4a shows occurrence frequency of horizontal velocity $u$ for four successive periods A, B, C, and D each of which lasts 3.3 s. The negative bias of $u$ indicates a clockwise rotation of the dust devil. The occurrence frequency increases from Period A to D as the dust devil collects dust particles. For all of the periods except for A, there is a maxima at around $-19$ m s$^{-1}$. If the horizontal translation speed of the vortex of $-2.6$ m s$^{-1}$ is subtracted, $u \approx -16$ m s$^{-1}$ may be regarded as a representative tangential wind speed. Another maxima is found at $u = 0$ m s$^{-1}$ for all of the periods. They are considered to correspond to clouds in the background.

Figure 5 shows the weighted frequency of $u$ for three different height intervals. The maximum near $-19$ m s$^{-1}$ is found for the low and middle heights, but not near the top of the dust devil. For the lower heights, a region with large $D$ may be associated with stronger tangential wind that picks up a large amount of dust particles from the ground. On the other hand, large $D$ near the top is likely to be caused by dust particles thrown out from the central core by the centrifugal force (Gu et al. 2006), resulting in the slower rotational speeds.

Vertical winds $w$ are estimated from $\mathbf{v}$ that satisfies $-24 < w < -12$ m s$^{-1}$ in order to focus on the flows near the core. The resulting weighted frequency has a positive bias (Fig. 4b). Periods B, C, and D have a distinct peak near $w \approx 6.2$ m s$^{-1}$. Vertical velocity may not be uniform in the dust devil (e.g. Gu et al. 2006) so that it is natural that the peak of $w$ becomes very broad. Height of the dust column also increases at a rate of approximately 5.9 m s$^{-1}$ (Fig. 1). Therefore, $w \approx 6$ m s$^{-1}$ is considered to be a representative speed of the updraft in the dust devil.
Vertical vorticity is estimated by means of the tangential wind \( u \) and diameter \( D \) as \( 2 \times (u - (\bar{u})/D \sim 3.6 \text{ s}^{-1} \). This value is comparable with typical values for stronger dust devils in a previous observation (Sinclair 1973). The dust devil investigated in this paper was not remarkably strong among those observed in the same day. This suggests that dust devils in the real atmosphere have much faster tangential and vertical velocities than those reproduced in numerical simulations (e.g. Kanak 2005; Gheymani and Taylor 2010; Raasch and Franke 2011; Ito et al. 2013) except for an experiment in which ambient rotation is forced at the lateral boundary (Gu et al. 2006).

5. Concluding remarks

Taking advantage that a dust devil seeds particles by itself, the present study used PIV to obtain velocity information of the dust devil videotaped by ordinary consumer cameras, where the observation was made by one of the present authors (JJ) alone. In spite of such a simple observational method, tangential and vertical velocities of the dust devil are estimated.

As mobile phones, smartphones and digital cameras with video-recording function become widely used, a number of videos of infrequent extreme atmospheric phenomena such as dust devils, tornadoes, and others started to be taken by chance and to be shared on the internet. PIV is used to extract precious meteorological information about these phenomena even if no meteorological instruments are available. The present approach still has many points to be improved. To increase accuracy of wind vector estimates, a video camera having a higher resolution rather than a higher frame rate is desirable. Stereoscopic PIV may also enables to determine the length scale and even capture some of three-dimensional features of the flows (c.f. Murai et al. 2008). However, it seems difficult to configure multiple video cameras in proper positions around a dust devil whose occurrences are almost unpredictable. An attempt to combine PIV with other observational methods is promising.

Acknowledgment

Authors thank to Prof. J. T. Snow of the University of Oklahoma for suggesting the observation of dust devils in the site, and Dr. H. Mouri of Meteorological Research Institute of JMA for advice on PIV techniques. This work is partially supported by Japan Society for the Promotion of Science’s Institutional Program for Young Researcher Overseas Visits and JSPS KAKENHI Grant Number 26800244.

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Manuscript received 9 April 2014, accepted 18 June 2014.
SOLA: https://www.jstage.jst.go.jp/browse/sola/