On the Conditions for a Dustdevil Genesis in a Large Eddy Simulation

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ABSTRACT: A large eddy simulation model is used to study the conditions favorable for a dustdevil formation. Dustdevils are found to favor weak general wind and strong surface heat flux. The vertical vorticity of the dustdevils appears to be generated through a tilting of the horizontal vorticity of a convective cell by an updraft of the cell itself. The simulated dustdevils occur from the late morning to afternoon when the convective mixed layer grows to a significant height. The vertical vorticity $\zeta$ of the dustdevils has a strong correlation with the convective velocity scale $w^*$, which is a monotonously increasing function of both the mixed layer depth and the surface heat flux. It is found that $\zeta$ exceeds $0.1 s^{-1}$ when $w^*$ is larger than $1.7 m/s$. The simulated dustdevils have no preferred direction of the rotation, and can have either one-cell or two-cell structure.

KEYWORDS: Dustdevil, vortex, convection, mixed layer, boundary layer, large eddy simulation.

1 INTRODUCTION

In the afternoon of a calm sunny day, small-scale vortices called dustdevils often occur over a desert [1,2]. These vortices are visualized by small dust particles picked up by the strong rotational wind and the central updraft. A genesis of a dustsdevil requires buoyancy and a vertical vorticity source. It is clear that the buoyancy is given by the surface heating. Several hypotheses for the vertical vorticity source have been proposed [3-5]. However, the process for the vertical vorticity generation and the reason for the frequent occurrence in the early afternoon have not been understood clearly. The present study addresses these subjects by numerical experiments using a large eddy simulation model.

2 MODEL

The large eddy simulation (LES) code used here is same as [6] except that water is excluded. The Smagorinsky-Lilly model [7,8] is used for parameterizing the subgrid-scale turbulent fluxes, where the eddy kinematic viscosity $\nu_t$ and the subgrid-scale turbulence energy $e$ are given by

$$v_t = (C_S L)^2 (2S_{ij} S_{ij} - 2 \frac{\partial \theta}{\partial z} \frac{\partial \theta}{\partial z})^{1/2}$$ and $$e = (v_t / C_k L)^2,$$

respectively. The constants $C_S$ and $C_k$ are set to 0.18 and 0.10, respectively [9]. $S_{ij}$ is the resolved-scale stress tensor and $L=(\Delta x \Delta y \Delta z)^{1/3}$ the turbulence length scale, where $\Delta x$, $\Delta y$ and $\Delta z$ are grid sizes in the $x$-, $y$- and $z$-directions, respectively. The turbulent Prandtl number $Pr$ is assumed to be a monotonously increasing function of Richardson number for stable stratification [10] and is fixed to 1/3 for unstable and neutral stratification.
The momentum fluxes at the surface are given by the bulk method with a roughness length of 0.5cm and a stability-dependent bulk coefficient. The surface heat flux between 7 and 18 LT (local time) is varied as $Q_{\text{max}} \sin[\pi(t-1)/11]$, where $Q_{\text{max}}$ is the maximum heat flux and $t$ is time in LT. Side boundary conditions are periodic. The upper boundary is free-slip. Rayleigh damping is imposed in the upper 10 layers to prevent reflections of gravity waves from the upper boundary.

Two sets of experiments are made: In the first set, the environment suitable for the genesis of dustdevils is studied by varying general wind speed $U$ and maximum heat flux $Q_{\text{max}}$ (Table 1). The calculation domain size is $4.5\text{km} \times 4.5\text{km} \times 3\text{km}$ and the grid size is 50m. In the second set (hereafter referred to as Exp. C), an attempt to reproduce an intense dustdevil with a grid size of 20m and the domain size of $4.0\text{km} \times 4.0\text{km} \times 2.6\text{km}$ is made for $U=0.5\text{m/s}$ and $Q_{\text{max}}=0.24\text{K m/s}$.

The potential temperature has initially a uniform vertical gradient of $4\text{K/km}$ with its surface value of $304\text{K}$. Adams-Bashforth scheme with a time step of 0.2s is used for the time integration.

### Table 1. Experimental setting for the first set of the experiments.

<table>
<thead>
<tr>
<th>Wind speed $U$</th>
<th>$Q_{\text{max}}$ (K m/s)</th>
</tr>
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<tbody>
<tr>
<td>0.5m/s</td>
<td>0.24</td>
</tr>
<tr>
<td>5.0m/s</td>
<td>0.05</td>
</tr>
<tr>
<td>15.0m/s</td>
<td>A1</td>
</tr>
<tr>
<td></td>
<td>B1</td>
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<td></td>
<td>A2</td>
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<td></td>
<td>A3</td>
</tr>
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<td></td>
<td>B3</td>
</tr>
</tbody>
</table>

## 3 MODEL

### 3.1 Dependence of dustdevil occurrence on the heat flux and general wind

The vertical distributions of the heat flux $<w'\theta'>$, vertical velocity variance $<w'^2>$ and vertical velocity skewness $<w'^3>/<w'^2>^{3/2}$ for Exps. A1-A3 and B1, when scaled by the surface heat flux $Q$, mixed layer depth $h$ and the convection velocity scale $w^*=[(g/\theta_0)Qh]^{1/3}$, are found to be in good agreement with previous studies [11-13] on convective mixed layers (not shown), confirming the reliability of the present LES code, where the bracket denotes a horizontal average.

Figure 1 shows the time evolution of the maximum vertical vorticity at each height level for Exp. A1. The layer with large vertical vorticity grows with the convective mixed layer. After 11 LT, a region of vertical vorticity larger than $0.1\text{s}^{-1}$ emerges near the surface. The region consists of thin columns of concentrated vertical vorticity that extend to 1km height and lasts for several minutes. These correspond to dustdevil events. A similar figure for each of Exps. A2-A3 and B1-B3 (not shown) reveals that the vertical vorticity is largest for Exp. A1 in which the surface heat flux is large and the general wind is weakest.

Figure 2a shows the maximum vertical vorticity $\zeta_{\text{max}}$ at $z=50\text{m}$ as a function of the convective
velocity $w^*$ for Exp. A1. The vertical vorticity is found to have a good correlation with $w^*$: It becomes larger than 0.1s$^{-1}$ when $w^*$ is larger than 1.7m/s. The time evolution of $w^*$ (Figure 2b) further shows that $w^*$ is larger than 1.7m/s between 10 and 16 LT, which is consistent with the frequent occurrence of strong vertical vorticity during this period (Figure 1). Note that $w^*$ is proportional to $(\Omega h)^{1/3}$, so that the mixed layer depth $h$ has to become large to make $w^*$ large. This explains why dustdevils are frequently observed in the early afternoon. The results of the present experiments that a weak wind condition and a large value of $w^*$ are most favorable for a dustdevil occurrence suggest that the source for the vertical vorticity is the horizontal vorticity of thermal convection.

3.2 Structure of a realistic dustdevil

A realistic dustdevil having a diameter of 250m, a vertical scale of 1km and vertical vorticity larger than 0.3s$^{-1}$ was successfully reproduced in Exp. C. Figure 3 shows the vertical velocity and vertical vorticity at $z=200$m. A strong cyclonic vortex having the vertical vorticity of 0.3s$^{-1}$ exists at around $x=800$m and $y=150$m (Figure 3b). Two smaller anti-cyclonic vortices are also found at $x=300$m and 1000m at around $y=200$m. The cyclonic vortex is characterized by a spiral-shaped updraft (Figure 3a) with a weak downdraft at the center, indicating a two-cell structure which has been observed by a portable Doppler radar [14]. The vortex is also accompanied by a warm temperature anomaly of 1.5K and a pressure decrease of 40Pa (not shown).

Figure 4 shows the vertical cross-section through the vortex center (along the dashed line in

Figure 3. (a) Vertical velocity and (b) vertical vorticity at $z=200$m at 1309 LST for Exp. C.
Figure 3a). A pair of positive and negative $y$-component velocities corresponding to the vortex flow exists between the surface and 1km height. The maximum tangential wind is about 5m/s.

4 CONCLUSIONS

A realistic dustdevil having the vertical vorticity of $0.3s^{-1}$ was reproduced in a large eddy simulation model. A weak general wind and strong surface heat flux, especially the growth of the convective mixed layer and the resulting increase of the convective velocity, are shown to be important for a dustdevil genesis

5 REFERENCES

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