Large Eddy Simulation of Dust Devils in a Diurnally-Evolving Convective Mixed Layer

Junshi ITO, Ryo TANAKA, Hiroshi NIINO

Ocean Research Institute, The University of Tokyo, Tokyo, Japan

and

Mikio NAKANISHI

National Defense Academy, Yokosuka, Japan

(Manuscript received 9 March 2009, in final form 28 October 2009)

Abstract

Formation of dust devils in diurnally-evolving convective mixed layers is studied by means of a large eddy simulation. It is found that a weaker general wind and a stronger surface heat flux for which cellular convection rather than roll convection prevails are favorable for the formation of dust devils. The simulation results show that when the general wind is weak, the maximum vertical vorticity in the convective mixed layer is a monotonically increasing function of $w/C_3$, where $w$ is the convective velocity scale for a convective mixed layer. Therefore, dust devils occur most frequently in the early afternoon when the heat flux is large and the convective mixed layer grows to a significant height.

The simulated dust devils are found to have a horizontal length scale comparable with observed larger dust devils. They have either one-celled or two-celled structure. Some of them have a one-celled structure initially, but later evolve into a two-celled structure.

1. Introduction

Dust devils are small-scale vortices that often occur in deserts and bare land during early afternoon in fine weather conditions. When the ground surface is heated by insolation, the stratification adjacent to the surface becomes unstable, and thermal convection is initiated. This leads to a formation of a convective mixed layer. If there exists some source of vertical vorticity near the surface, stretching by convective updrafts associated with the thermal convection would easily amplify the vertical vorticity. Strong near-surface winds in the vortex pick up dust particles from the ground, and its updraft lifts them to make itself visible.

Dust devils are known to exist not only on the earth but also on Mars. Since the Martian atmosphere is thin, daytime solar heating can produce a convective mixed layer of 10 km depth. Recent observations with the Mars Orbiter Camera show numerous ground marks that are believed to be clawed by dust devils, as well as dust devils themselves with their shade on the ground, from which their height is estimated to be as high as 8 km (Leovy 2003; Cantor et al. 2006; Drake et al. 2006). Thus, dust devils are considered to be a universal phenomenon in convective mixed layers which are formed when a stably stratified planetary atmosphere is heated from below (Fiedler and Kanak 2001; Greeley et al. 2003; Kanak 2006; Balme and Greeley 2006).

To what degree dust devils contribute to exchanges of heat and moisture between the ground and the atmosphere has not been estimated yet. They may also play an important role in picking
up dust particles from the ground into the convective mixed layer, and help synoptic-scale disturbance transport them over a long distance. Therefore to clarify the formation mechanism, frequency, and structures of dust devils and their contribution to turbulent transport would lead to a greater understanding of the convective mixed layer.

The first detailed study on terrestrial dust devils was made by Williams (1948). This was followed by detailed observational studies by Sinclair (1966, 1969, 1973). These studies found that the core region of the dust devils has high temperature and low pressure. Diameters of the dust devils range from several to a few tens of meters, and the height of dust devil columns is typically on the order of several tens of meters. Typical wind speed associated with the dust devils is 10 m s\(^{-1}\), and temperature deviation ranges from 4 K to 8 K. However, huge dust devils, whose height is comparable to the depth of the convective mixed layer, do occur occasionally. They also found that dust devils occur most frequently in the early afternoon.

The environmental conditions favorable for the dust devils have also been studied. Hess et al. (1988) and Hess and Spillane (1990) found that dust devils tend to occur frequently when the lapse rate in the surface layer is super-adiabatic and general wind is weak (5 m s\(^{-1}\) or less).

Formation of dust devils obviously requires a source of vertical vorticity and an updraft that stretches it vertically. It is clear that the updraft is caused by the air with large buoyancy originating from the surface layer with a super-adiabatic lapse rate. However, the source of the vertical vorticity has been somewhat controversial: several mechanisms for the origin of the vertical vorticity have been proposed. Williams (1948) and Barcilon and Drazin (1972) suggested that the vertical vorticity is caused by a topography or even by a small animal. Maxworthy (1973) suggested that tilting of horizontal vorticity, associated with vertical shear of the general wind, by the updraft of the dust devil is the source of the vertical vorticity. Willis and Deardorff (1979), Hess et al. (1988), and Kanak et al. (2000) suggested that tilting of horizontal vorticity, associated with a convective cell in the convective mixed layer, by the updraft of the convective cell is the source of the vertical vorticity. Carroll and Ryan (1970), Courtese and Balachandar (1993), and Kanak (2005) suggested that non-uniform convergence of convection cells and associated horizontal shear near the ground is the source of the vertical vorticity.

Using a large eddy simulation (LES) model with a horizontal grid size of 35 m, Kanak et al. (2000) succeeded in simulating dust devil-like vortices in a convective mixed layer. The simulated “dust devil” had a diameter about 250 m, height of about 1 km, and vertical vorticity of about 0.12 s\(^{-1}\). Toigo et al. (2003) simulated Martian dust devils by a LES model with a horizontal grid size of 100 m. The simulated vortex had a diameter of about 1 km, height of about 4 km, and vertical vorticity of about 0.06 s\(^{-1}\). Using a LES model with a horizontal grid size of 2 m, Kanak (2005) reproduced dust devils whose scale is more realistic: the simulated dust devils had diameters of the order of 10 m and vertical vorticity of the order of 1 s\(^{-1}\), though horizontal domain size of the convective mixed layer in her model is somewhat small for simulating a convective cell in a well-developed convective mixed layer. There are also several studies that focus on the detailed structure of a dust devil using a high-resolution cylindrical coordinate system (Zhao et al. 2004; Gu et al. 2008b). Some of them examined the manner in which dust particles are lifted by a dust devil (Gu et al. 2006, 2008a).

These studies using LESs have demonstrated that large vertical vorticity associated with dust devils is commonly formed in convective mixed layers. However, which environmental parameter determines the magnitude of the vertical vorticity and why dust devils are most frequently observed in the early afternoon (Sinclair 1969) have not been clarified except for Toigo et al. (2003) who showed that the vertical vorticity is larger when the general wind is either absent or larger.

In this paper, we use a LES to simulate diurnally-varying convective mixed layers for various combinations of general wind and surface heat flux and investigate what is a favorable condition for a dust devil formation and why diurnally variation of the dust devil occurs. First, the environment favorable for a formation of dust devils is studied with a coarse resolution model. Second, detailed structures of the simulated dust devils are examined with a finer resolution. Section 2 describes the LES model used for the present simulation. The environment favorable for a dust devil formation is examined in Section 3, and structures of the simulated dust devils are described in Section 4. Conclusions and future perspectives are given in Section 5.
2. LES model

The LES model used in the present study is the same as Nakanishi (2000) except in that moisture is not considered. Only the primary features of the model are briefly described in the following.

2.1 Basic equations

The resolved-scale momentum equation, the thermodynamic equation, and the continuity equation under the Boussinesq approximation are written as follows:

\[
\frac{\partial \bar{u}}{\partial t} + \frac{\partial \bar{u}\bar{u}}{\partial x_j} = -\frac{1}{\rho_0} \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \frac{g}{\theta_0} (\theta - \theta_0) \delta_{ij} \tag{1}
\]

\[
\frac{\partial \bar{\theta}}{\partial t} + \frac{\partial \bar{u}\bar{\theta}}{\partial x_j} = -\frac{\partial \tau_{ij}}{\partial x_j} \tag{2}
\]

\[
\frac{\partial \bar{p}}{\partial x_i} = 0 \tag{3}
\]

where the overbars denote resolved-scale variables, \( u_i \) (\( i = 1, 2, 3 \)) the velocity components (\( u, v \), and \( w \)) in \( x-, y-, \) and \( z\)-directions, respectively, \( p \) is perturbation pressure, \( \tau_{ij} \) stress tensor due to sub-grid scale motions, \( g \) the gravitational acceleration, \( \theta \) the potential temperature, \( \theta_0 \) the basic potential temperature, \( \rho_0 \) the air density, and \( \tau_{ij} \) subgrid-scale heat flux. The Coriolis force is not considered. Subgrid-scale fluxes \( \tau_{ij} \) and \( \tau_{ij} \) in Eqs. (1) and (2) are modeled as described in Appendix.

2.2 Boundary conditions

At the ground surface, \( w \) is set to be equal to 0. The surface momentum flux is calculated by the bulk method:

\[
\tau_{13, 1} = -C_D U_1 \bar{m}, \tag{4}
\]

where the subscript 1 for \( \tau_{13, 1}, U_1 \), and \( \bar{m} \) denotes the value at the lowest grid level, \( U_1 = (m_1^2 + v_1^2)^{1/2} \) the horizontal wind speed at the lowest level, and \( C_D \) the bulk coefficient derived from the Monin-Obukhov similarity theory (Businger et al. 1971). Although the bulk method is typically applied to physical variables averaged over 10 minutes, here we have applied Eq. (4) with an instantaneous wind speed \( U_1 \) to express the effect of a rotating boundary layer below the vortices. The surface roughness length for momentum is assumed to be 0.005 m after the observation in Eldorado Valley (Nevada, USA) (Balme et al. 2003). Surface heat flux \( \dot{Q} (\equiv \tau_{13, 1}) \), on the other hand, is prescribed by a sinusoidal function \( \dot{Q} = Q_{\max} \sin \left( \frac{\pi (t - T)}{T} \right) \) as shown in Fig. 1, where \( t \) is the local standard time (LST) in hours.

Lateral boundaries are cyclic, and the upper boundary conditions are \( w = 0 \), free-slip for \( u, v \), and adiabatic for \( \theta \).

2.3 Numerical procedure

Spatial derivatives are approximated by second-order centered differences on a staggered grid system. Time integration is performed by the second-order Adams-Bashforth scheme with a time step of 0.2 s. A predictor-corrector scheme is used for the momentum equations to ensure incompressibility. The Poisson equation for pressure is solved by applying the Fourier transformation in the horizon-

Fig. 1. Temporal variation of the surface heat flux for Exps. A1–A3 (solid line) and for Exps. B1–B3 (dashed line).
tal directions and finite-differencing in the vertical direction. In order to avoid reflections of gravity waves from the upper boundary, a Rayleigh-friction term is added to all the prognostic equations in the upper 10 layers.

2.4 Design of the experiments

The experiments are performed with two different horizontal resolutions. In the experiment with a coarse resolution, the surface heat flux and the general wind are varied to explore what kind of environment is favorable for occurrence of dust devils. The experiments with a finer resolution is made to reproduce more realistic dust devils and to examine their structures. Detailed design of each experiment is described in the following.

a. Experiments on the environment for dust devils (coarse-resolution experiment)

The computational domain for these experiments has a horizontal area of 4.5 km × 4.5 km and a depth of 3 km. This domain is divided into 90 × 90 × 60 grid boxes with homogeneous spacing of 50 m in all directions. The initial potential temperature increases linearly with height at a constant rate of 4.0 K km⁻¹ from 299 K at the surface to the top of the computational domain. In order to study how dust devil occurrence depends on the general wind and surface heat flux, we have made six experiments named A1–A3 and B1–B3 as listed in Table 1: Three kinds of general wind speed (0.5 m s⁻¹, 5.0 m s⁻¹, and 15 m s⁻¹), and in the two kinds of surface heat flux (Q_{max} = 0.24 K m s⁻¹ and 0.05 K m s⁻¹) are considered. The general wind is assumed to be westerly and is initially uniform both in the horizontal and vertical directions. Time integration is started at 0700 LST and is continued until 1800 LST.

b. Experiment to reproduce realistic dust devils (fine-resolution experiment)

A computational domain for this experiment has a horizontal area of 4.2 km × 4.2 km and a depth of 2.6 km. The domain is divided into 210 × 210 × 130 grid boxes with a homogenous spacing of 20 m in all directions. The design of this experiment, which will be hereafter called Exp. C, is the same as Exp. A1 except for the grid size and the domain size.

3. Environment of dust devil occurrences

3.1 Structure of the convective mixed layer

The present LES is found to well reproduce the structure of the convective mixed layer including mean quantities and turbulent statistics (not shown), which are previously studied by observations (e.g., Caughey and Palmer 1979), laboratory experiments (e.g., Willis and Deardorff 1974), and LESs (e.g., Schmidt and Schumann 1989).

Characteristics of the convective mixed layer are known to depend strongly on the surface heat flux, the initial stratification, and the general wind. Deardorff (1978) showed that a nondimensional parameter \(-h/\bar{L}\) determines the characteristics of the convective mixed layer, where \(h\) is the instantaneous height of the convective mixed layer which is determined from the minimum of the horizontally-averaged vertical heat flux and \(\bar{L}\) is the horizontally-averaged Monin-Obukhov length \(L\) defined by

\[
L = \frac{u_s^3}{k(g/\theta_0)Q},
\]

where \(u_s\) is the local frictional velocity that is defined as \(\sqrt{(\tau_{w3.1}^2 + \tau_{z3.1}^2)^{1/2}/\rho_0}\) and \(k = 0.4\) the von Karman constant. Hess et al. (1988) suggested that cellular convection occurs when \(-h/\bar{L}\) > 50 and this is also a necessary condition for occurrence of dust devils. On the other hand, Sykes and Henn (1988) suggested that roll convection occurs when \(-h/\bar{L}\) < 9.3.

Figure 2 shows time series of \(-h/\bar{L}\) in each experiment. In Exps. A1 and B1 for which the general wind is 0.5 m s⁻¹, cellular convection is expected to occur from the early morning. In Exps. A2 and B2 for which the general wind is 5 m s⁻¹, roll convection is expected to occur in the early morning, but to give way to cellular convection later. In Exp. A3, roll convection is expected to occur in the early morning, but a transient state to cellular convection would occur later. In Exp. B3, only roll convection would prevail throughout a day. The planform of the convection in the present LES is found to be consistent with that expected from Hess et al. (1988) and Sykes and Henn (1988) (not shown).
3.2 Vertical vorticity

Figure 3 shows time series of maximum vertical vorticity $\zeta = \frac{\partial u}{\partial z} - \frac{\partial v}{\partial z}$ at each height. Although one cannot completely discern individual vortices only from these figures, several vertical lines of large vorticity that extends from the surface to the upper part of the convective mixed layer do indicate existence of organized vortices, which are likely to correspond to dust devils. Because of lack of spatial resolution, however, these vortices have somewhat smaller vertical vorticity than that of observed dust devils. We will hereafter call vortices, which have vertical vorticity larger than 0.1 s$^{-1}$ (85% of the largest vertical vorticity in Exp. A1), Dust Devil-like Vortices (DDV).

Figure 3a suggests that a typical duration of a DDV is a few minutes, its height is about 500 m to 1000 m, and its maximum vorticity is one-tenth of observed intense dust devils. Simulated DDVs are formed most frequently between 1200 and 1600 LST. Experiment A2 has a less number of DDVs than Exp. A1 (Figs. 3a, b). Although a region of high vorticity exists near the surface for Exp. A3 (Fig. 3c), it is caused by a tilting of horizontal vorticity associated with strong vertical shear of the general wind. A typical height of the region with high vertical vorticity for Exp. A3 is less than that for Exp. A1, and the number of tall DDVs is also smaller than that for Exp. A1.

While Exp. B1 generates vertical vortices that extend from the surface to the upper part of the convective mixed layer as frequently as Exp. A1 does, the maximum magnitude of vertical vorticity in Exp. B1 is one-third of that in Exp. A1 (Fig. 3d). For Exp. B2 (Fig. 3e), only such a few vertical vortices appear. Experiment B3 gives a quite different result from other experiment (Fig. 3f). Two peaks of vertical vorticity appear near the ground and near the upper part of the convective mixed layer. Tilting of horizontal vorticity associated with the general wind seems to cause the two peaks. However, the vertical vorticity in Exp. B3 is much less than that in Exp. A1.

While Fig. 3a shows a time-height cross section of maximum vertical vorticity for Exp. A1, Fig. 4 presents that of minimum vertical vorticity for the
same experiment. Little differences in the number of DDVs and the absolute value of vertical vorticity are found between Fig. 3a and Fig. 4. Thus no preferred sign of vertical vorticity exists in the simulated DDVs, which is similar to Kanak et al. (2000).

Plotted every one minute in Fig. 5 is instantaneous maximum values $\zeta_{\text{max}}$ of vertical vorticity at the lowest model level against the convective velocity scale $w_* = (gQh/\theta_0)^{1/2}$ for Exp. A1. These quantities are positively correlated. Note that large deviations from the relation between $\zeta_{\text{max}}$ and $w_*$, are obtained after 1600 LST when the convective mixed layer is decaying (the data points after 1600 LST are plotted by open circles in Fig. 5). These
large deviations may have occurred because resid-
ual cellular convection contributes to form vertical
vorticity even if $w_c$ decreases rapidly. Figure 5 sug-
gests that $w_c \gtrsim 2.2$ m s$^{-1}$ is required for a DDV,
which has vertical vorticity larger than 0.1 s$^{-1}$, to
develop. It is also noted that no significant vertical
vorticity is formed for $w_c < 0.6$ m s$^{-1}$. This seems
to suggest that some kind of an instability or a re-
gime change occurs to generate vertical vorticity
for $w_c > 0.6$ m s$^{-1}$ for this particular resolution.

Figure 6 shows $w_c$ as a function of time. It shows
that the condition $w_c \gtrsim 2.2$ m s$^{-1}$ is satisfied be-
tween 1200 and 1530 LST. This period agrees well
with previous observational findings that dust dev-
ils occur frequently in the early afternoon and also
with Fig. 3. Since $w_c$ is a monotonically increasing
function of $h$ and $Q$, both deepening of the convective
mixed layer and increase of $Q$ make the early
afternoon favorable for a DDV formation.

In order to investigate the generation process of
vertical vorticity in DDV, plotted in Figs. 7a, b are
horizontal distributions of vertical vorticity and
vertical velocity at $z = 200$ m for Exps. A1 and
B3, respectively. For Exp. A1, for which cellular
convection prevails, DDVs occur most frequently.
DDVs of either positive or negative vorticity, or
both are located near regions of intense updrafts
which constitute a part of polygonal convection
cells. For Exp. B3, on the other hand, both the up-
drafts and the region of high vorticity are elongated
in the direction of the mean flow.

In Exp. B3 (Fig. 7b) for which the roll convec-
tion prevails, a number of pairs of negative and
positive pair vortices are formed on the north and
south of the elongated updrafts. These vortices are
caused by tilting of horizontal vorticity associated
with the vertical shear of the general wind (Max-
worthy 1973). The magnitude of the vertical vortic-
ity, however, is not as large as that of DDVs in

3.3 Discussion

Three different regimes of convection are found
to occur in the convective mixed layer for the range
of $-h/L$ in the present experiments: a cellular con-
vection regime, a roll convection regime, and a
transient regime between the two convection re-
gimes. DDVs are shown to occur not only in the
cellular convection regime but also in the transient
regime (Fig. 3e), which does not necessarily satisfy
the necessary condition $-h/L > 50$ (Hess and Spill-
ane 1990) for appearance of dust devils. According
to the mechanism proposed by Kanak et al. (2000)
or Kanak (2005), however, DDVs could be formed
even in a transient regime.

The vertical vorticity is also generated in a roll
convection regime through tilting of horizontal vor-
ticity associated with the vertical shear of the gen-
eral wind. However, the magnitude of the vertical
vorticity is considerably smaller than the case in
which the cellular convection prevails.

The frequency of DDV occurrence in the
diurnally-evolving convective mixed layer is
strongly correlated with the time evolution of $w_c$
under a weak general wind condition. According
to the mechanism proposed by Kanak et al.
(2000), the horizontal vorticity associated with cel-
lular convection is tilted up by the updraft of the convection, and is then stretched to form a dust devil. The horizontal vorticity associated with the cellular convection would be proportional to $w/C^3$.

Tilting of horizontal vorticity and stretching of vertical vorticity, respectively, would also be proportional to $w/C^3$. Thus, one would reasonably expect that the vertical vorticity is a monotonically increasing function of $w/C^3 = (gQh/\theta_0)^{1/3}$. A similar estimation may also be obtained for a mechanism, suggested by Kanak (2005), in which vertical vorticity associated with a horizontal shear flow at the cell boundary is stretched by the updraft. The occurrence of dust devils is therefore more favorable for a larger surface heat flux $Q$, and a larger mixed layer depth $h$.

4. Reproduction of realistic dust devils

In this section, an experiment with 20 m grid interval (Exp. C) is performed to reproduce more realistic dust devils. Initial and boundary conditions for Exp. C is the same as those for Exp. A1 (i.e., the general wind speed is 0.5 m s$^{-1}$ and the surface heat flux is 0.24 K m s$^{-1}$) for which DDVs occur most frequently.

4.1 Results

Figure 8 shows time evolutions of maximum vorticity and absolute value of minimum vorticity on...
a horizontal plane at each height level. The evolutions of the vorticity are qualitatively similar to those for Exp. A1 (cf. Figs. 3, 4). The absolute value of the vertical vorticity for Exp. C, however, is about three times as large as that for A1.

Figure 9 shows a horizontal distribution of the vertical velocity at $z = 200$ m at 1457 LST. One can clearly see that cellular convection is formed and several cells exist in the horizontal domain. At the lower center of Fig. 9 a concentric updraft pattern corresponding to a large clockwise vortex, hereafter called Vortex P, exists in the rectangular area indicated by the black dashed lines.

Now, we examine the evolution of Vortex P between 1457 and 1514 LST. Figure 10a shows horizontal distribution of vertical vorticity and horizontal velocity vectors for the rectangular area at $z = 200$ m at 1457 LST. It is seen that Vortex P having large negative vorticity is located at around $x = 2060$ m and $y = 700$ m near the intersection of band-shaped updrafts (also see Fig. 9). Its vertical vorticity approaches $-0.18$ s$^{-1}$ with a typical tangential velocity of about 5 m s$^{-1}$, and its diameter is about 150 m at $z = 200$ m. The pressure depression at its center is 21 Pa and potential temperature is 3 K higher than the environment. The vertical cross section of the vertical vorticity through the center of Vortex P is shown in Fig. 10b. The height of Vortex P reaches 1600 m. Vertical velocity on the same vertical cross section is also shown in Fig. 10c. Vortex P is located in an updraft region, showing that Vortex P at this time has a one-celled structure. The core of the vertical velocity appears to coincide with the region of the maximum vertical vorticity and reaches 4 m s$^{-1}$ at $z = 600$ m.

Vortex P intensifies with time and moves to around $x = 2250$ m and $y = 560$ m at 1503 LST (Fig. 11a). Its moving direction is nearly eastward in the direction of the general wind, but its speed is somewhat larger than the environmental wind. Vertical vorticity decreases from $-0.18$ s$^{-1}$ to $-0.20$ s$^{-1}$, and pressure depression reaches 30 Pa. The diameter of the vortex expands to about 200 m. Vertical vorticity and vertical velocity in the $x$-$z$ cross section through the vortex center are presented in Figs. 11b, c. Figure 11b suggests that the height of Vortex P reaches at least about 800 m. The core region of Vortex P is in a downdraft region (Fig. 11c), showing that Vortex P now has a two-celled structure.

After 1503 LST, Vortex P starts to dissipate (Fig. 12). Pressure depression at the core of the vortex decreases to 14 Pa. Velocity vectors show that Vortex P does not have an axisymmetric velocity distribution any more. The behavior of Vortex P at the dissipation stage is rather chaotic, so that its consistent description is not possible.

Rather surprisingly, Vortex P re-intensifies after 1510 LST and becomes more energetic than it is at 1503 LST (not shown). At 1514 LST, potential temperature is 3.2 K higher than the environment and pressure depression at its center is now 46 Pa, which is the largest observed value in this experiment. Minimum vertical vorticity is $-0.3$ s$^{-1}$ and a typical tangential velocity is 8 m s$^{-1}$ at $z = 200$ m. Figure 13 shows three-dimensional streamlines that go through regular grid points on the horizontal plane at $z = 5$ m around Vortex P and regions where vertical velocity is less than $-0.2$ m s$^{-1}$. Updrafts are located at an outer rim of Vortex P, while the vortex core is occupied by a downdraft; it has a typical two-celled structure. Vortex P thereafter starts to dissipate again and finally disappears at 1530 LST.

4.2 Discussion

In Exp. C, we obtained vortices whose radius is of the order of 100 m, which is similar to the size of large dust devils often observed in an arid area. Thus we think that realistic dust devils are reproduced by our LES with a grid interval of 20 m.
The simulated dust devils are shown to have two distinct morphologies: one-celled and two-celled structures. Smith and Leslie (1976), Mullen and Maxworthy (1977), and Bluestein et al. (2004) suggested that the structures of dust devils depend on their environmental conditions.

Figure 14 shows time series of pressure depression for one-celled vortices (Fig. 14a) and two-celled vortices (Fig. 14b), where one-celled and two-celled vortices are defined as those having an updraft and downdraft, respectively, at the vortex center at the lowest model level. Note that a vortex center is identified as a pressure minimum below −10 Pa near the surface. The pressure depression in Fig. 14 is plotted every one minute for all detected vortex centers in the domain. It is found that one-celled vortices are much more common than two-celled vortices.

Figure 14 also shows that the number of the one-celled vortices changes more frequently than that of the two-celled vortices.
of the two-celled vortices. This suggests that two-celled vortices are likely to have longer lifetimes than those of one-celled vortices. In fact, we find several long-lived two-celled vortices including Vortex P which lasted for more than 20 minutes.

An average pressure depression of the two-celled vortices is larger than that of one-celled vortices in any periods as shown in Fig. 14. It is consistent with Zhao et al. (2004) who suggested that a transition from a one-celled to a two-celled structure occurs as the vortex intensifies due to development of a downdraft driven by a non-hydrostatic pressure gradient force near the surface.

Since most of the vortices in the present experiment are located at the vertices of convective cells, their vertical vorticity is likely to come from tilting of horizontal vorticity associated with a convective cell by the updraft of the convective cell itself (Kanak et al. 2000). This appears to be in contrast to the formation of vertical vorticity due to stretching of vertical vorticity associated with a horizontal shear at the cell boundary, which occurs along the branches of the convection cell (Kanak 2005).

For some vortices, interactions with other vortices can be significant. These interactions add further complexity to the behavior of dust devils such...
as their motion, dissipation, and transition between a one-celled and a two-celled structure. Vortex P did exhibit a full complexity of these processes.

Vorticity, tangential velocity, and structure of Vortex P are similar to those of an observed dust devil whose radius was 130 m (Bluestein et al. 2004). Although the observed dust devil exhibited vertical vorticity maximum at around the outer rim of its central core, and its vertical vorticity decreased with approaching the center of the core, the simulated dust devils had a vorticity maximum at their center. The cause of this difference is not clear at the moment. One of the possibilities, however, is that the sub-grid parameterization of the present

Fig. 12. Vertical vorticity and horizontal wind vectors on a horizontal section at $z = 200$ m in Exp. C at 1510 LST.

Fig. 13. Streamlines around Vortex P at 1514 LST. The shaded regions show where vertical velocity is less than $-0.2$ m s$^{-1}$.

Fig. 14. Time series of pressure depression at the center of (a) one-celled and (b) two-celled vortices. The thick line in each panel shows an average for every one hour.
LES cannot correctly express a possible suppression of turbulence as well as anisotropy due to strong rotation in the vortex. This problem, however, is left for a future study.

Although the vortices reproduced in Exp. C with 20 m spacing are similar to observed larger dust devils, those having a diameter of the order of meter or a few tens of meter are more frequently observed in the atmosphere. A simulation with a finer spacing may be able to reproduce not only vortices with a diameter of a few meters (e.g., Kanak 2005), but also the near-surface layer with super-adiabatic temperature lapse rate more realistically. According to Hess and Spillane (1990), the depth of near-surface layer with super-adiabatic temperature lapse rate is 1 percent of the depth of the convective mixed layer. The latter in Exp. C is at most 2000 m (Fig. 8), so that the former is about 20 m. Thus, even the grid interval of 20 m adopted in Exp. C may not be sufficient to resolve the super-adiabatic layer, which is considered to have a critical role in generating buoyancy in a dust devil. A further experiment with a higher resolution such as the one adopted by Kanak (2005) but with a sufficient domain size is desired. These improvements would affect intensity and structures of vortices.

The boundary conditions at the ground surface may also have an important effect. In the present simulation, we have used the bulk method as given by Eq. (4). Since the bulk coefficient in Eq. (4) is originally determined for 10 minutes-averaged wind and temperature, it may not be appropriate to use the same value for an instantaneous wind and temperature that vary rapidly in response to dust devils. The boundary condition for heat, which is horizontally uniform in the present study, may not be realistic either. The feedback that a stronger vortex can have a stronger supply of heat flux from the surface would modify the strength and structure of the vortex, and need to be examined.

5. Conclusions

LESs have been performed to examine occurrence of dust devils in a realistic convective mixed layer with diurnal variation. Cellular convection, roll convection, or the transient state between them, is formed depending on \(-h/L\). Formation of vertical vortices similar to dust devils does occur in the cellular convection or in the transient state. The formation of strong vertical vortices is more frequent and their vorticity is larger for weaker general wind and stronger surface heat flux. Our result shows that the magnitude of vertical vorticity is a monotonically increasing function of \(w_*/\gamma\), which is larger in early afternoon when the heat flux becomes large and the convective mixed layer becomes deep. The present result seems to be supportive of the formation mechanism of dust devils proposed by Kanak et al. (2000): the fact that most of the vortices develop at the vertices of the convective cells appears to be favorable for the mechanism that horizontal vorticity generated by the convection is tilted and then stretched by an updraft.

Our LES with finer resolution reproduces dust devils having vertical vorticity of \(-0.3 \text{ s}^{-1}\). They have a diameter of about 100 m, and may correspond to large dust devils which are occasionally observed. The vortices have two distinct structures: one is a one-celled vortex and the other a two-celled vortex. The pressure depression due to two-celled structures is generally larger than that due to one-celled structures. We have also found a case in which a one-celled vortex changes into a two-celled one, which is found in the simulation of Zhao et al. (2004).

In order to simulate smaller dust devils that are more frequently observed, one would need to perform a LES having a resolution of a few meters. However, this kind of resolution would require more careful consideration on the fluxes at the surface: one needs to consider how the bulk coefficient should be determined for a rapidly-changing instantaneous wind and temperature. To perform a LES with such a very-high resolution is therefore left for a future study.

Acknowledgments

Preliminary results of a similar study to the present one were published in Japanese in Tanaka et al. (Meteorological Research Note, vol. 219, pp. 117–139, 2008). This work was partly supported by Grant-in-Aids for Scientific Research(B)(2) No. 21340134, the Japan Society for the Promotion of Science.

Appendix

Subgrid-scale model

Subgrid-scale fluxes \(\tau_{ij}\) and \(\tau_{ik}\) in Eqs. (1) and (2) are modeled as in Smagorinsky (1963) and Lilly (1966):

\[
\tau_{ij} = -2\nu_s \delta_{ij} + \frac{2}{3} \rho \delta_{ij},
\]  

(A1)
\[ \tau_{ij} = -\frac{v_i}{Pr} \frac{\partial \tilde{q}}{\partial x_j}, \]  

(A2)

where \( v_i \) is the eddy viscosity coefficient, \( e \) subgrid-scale turbulent kinetic energy, \( Pr \) turbulent Prandtl number, and \( S_y \) resolved-scale strain tensor defined by

\[ S_y = \frac{1}{2} \left( \frac{\partial \tilde{u}}{\partial x_j} + \frac{\partial \tilde{v}}{\partial x_j} \right). \]  

(A3)

\( v_i \) and \( e \) are determined diagnostically from the following equations,

\[ v_i = (C_s l)^2 \left( 2S_yS_y - \frac{1}{Pr} \frac{\partial \tilde{q}}{\partial z} \right)^{1/2} \]  

and

\[ e = \left( \frac{v_i}{C_s l} \right)^2, \]  

(A5)

where \( C_s \) and \( C_l \) are the Smagorinsky constants and \( l \) is the turbulent length scale. Following Sullivan et al. (1994), we set \( C_s = 0.18 \), \( C_l = 0.10 \), and \( l = (\Delta x \Delta y \Delta z)^{1/3} \), where \( \Delta x, \Delta y, \) and \( \Delta z \) are grid intervals in \( x, y, \) and \( z \)-directions, respectively. \( Pr \) is assumed to be \( 1/3 \) for unstable or neutral stratification and \( 1 \) for stable stratification above the critical Richardson number \( Ri = 0.25 \). It increases monotonically from \( 1/3 \) to \( 1 \) as \( Ri \) is increased from 0 to 0.25 (Nakanishi 2000).

References


Gu, Z. L., J. Qiu, Y. Z. Zhao, and X. P. Hou, 2008a: Analysis on dust devil containing loess dusts of different sizes. Aerosol and Air Quality Res., 8, 65.


