Effects of Ambient Rotation on Dust Devils

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Abstract

A previous Doppler-lidar observation near a sea-breeze front revealed that small-scale vertical vortices, similar to dust devils, have a preferred direction of rotation, which suggests that their rotation was affected by meso-scale vertical vorticity associated with the front. In contrast, planetary vorticity is believed to have a negligible effect on dust devils. This paper investigates the effects of ambient rotation on dust devils by means of a large eddy simulation, which yielded the following findings: when the ambient rotation is as small as the earth’s rotation, only a tiny asymmetry is found in the occurrences of vortices of different signs; as the ambient rotation is increased, it significantly affects the rotation direction of the vortices, and the magnitude of their vertical vorticity attains a maximum for an ambient vorticity of about \(10^{-3}\) s\(^{-1}\); a further increase in the ambient rotation changes the structure of convection in the convective mixed layer and suppresses horizontal convergence, so that vertical vorticity of the vortices is reduced.

1. Introduction

Dust devils are strong, small-scale vertical vortices that commonly occur in the atmosphere over deserts and bare lands under fair weather conditions. As they are visualized by lifted dust particles, many observational studies have examined their structure and characteristics (e.g., Sinclair 1969; Hess and Spillane 1990; Snow and McClelland 1990; Bluestein et al. 2004; Oke et al. 2007), revealing that dust devils usually have no preferred direction of rotation and implying that the earth’s rotation has a negligible effect on the vortex dynamics (Sinclair 1965; Carroll and Ryan 1970). In the past decade, dust devils have been also studied by means of large eddy simulations (LESs) (Kanak et al. 2000; Toigo et al. 2003; Kanak 2005; Ito et al. 2010; Ohno and Takemi 2010a; Ohno and Takemi 2010b; Gheynani and Taylor 2010). These numerical studies have shown that turbulent convective motions in a convective mixed layer, without the earth’s rotation, produce dust devils with no preferred direction of rotation, consistent with the observations.

Recently, observations using a Doppler lidar have shown that strong vertical vortices with horizontal and vertical scales comparable to those of dust devils occur in a convective mixed layer near a sea-breeze front over urban regions, although they are not visualized in the absence of dust particles (Fujiiwara et al. 2009; Fujiiwara et al. 2010). These vortices are found to have a cyclonic rotation, which is in the same direction of rotation as the vorticity associated with the sea-breeze front. Note that typical vertical vorticity associated with meso-scale disturbances such as a sea-breeze front can be 10 times as large as the planetary vorticity.

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2. LES model

The three-dimensional LES model used in the present study is the same as that described by Ito et al. (2010), who studied dust devils in a diurnally-evolving convective mixed layer, except that the Coriolis force due to ambient rotation is considered here. The model has a uniform grid size of 50 m in all directions. The horizontal size of the calculation domain is 6 km \(\times\) 6 km, and its height is 4.5 km. The top boundary is free-slip and adiabatic, and the lateral boundaries are cyclic. Initially, no general wind is imposed. The initial potential temperature increases upward at a constant rate of 4.0 K km\(^{-1}\) from the surface value of 299 K. Surface heat flux \(Q\) is prescribed by a sinusoidal function \(Q = Q_{\text{max}} \sin (\pi (t - 7)/11)\), where \(t\) is the local standard time (LST) in hours and \(Q_{\text{max}}\) is set to 0.24 K m s\(^{-1}\), which is a typical value at mid-latitudes. The surface drag is calculated by the bulk method, which considers the Monin-Obukhov similarity law with roughness length of 0.05 m. White noises of tiny amplitude with a random phase are added to the whole calculation domain to initiate convection. Time integration is started at 0700 LST and is continued until 1600 LST with a time step of 0.2 s. Numerical experiments are performed for nine different values of the Coriolis parameter: \(f = 0, f_\text{e}, 2f_\text{e}, 5f_\text{e}, 10f_\text{e}, 15f_\text{e}, 20f_\text{e}, 50f_\text{e}\), and \(100f_\text{e}\), where \(f_\text{e} = 7.292 \times 10^{-5}\) s\(^{-1}\) is the planetary vorticity at 30°N.

Note that we examine the effects of the rotation only by varying \(f\) for simplicity, which means that the ground rotates at the same rate as the atmosphere. This situation does not strictly correspond to the environment of a typical meso-scale disturbance for which the ground is rotating at \(f = f_\text{e}\). Our preliminary calculation with free-slip condition at the surface indicates, however, that vorticity of dust devils is little affected by the surface boundary condition. The Ekman pumping associated with the meso-scale disturbance may affect the characteristics of the convective mixed layer. To study this effect, however, is outside the scope of the present study.

3. Results

We have obtained the maximum of positive vertical vorticity, \(\zeta^+\), and the maximum absolute value of negative vertical vorticity, \(\zeta^-\), at the lowest model level (\(z = 25\) m), where \(\zeta^+\) and \(\zeta^-\) are likely to correspond to strong vertical cyclonic and anticyclonic vortices of dust devils, respectively. Since their instantaneous values show large temporal variations, we will present the maxima of \(\zeta^+\) and \(\zeta^-\) during each 10-minute period, as denoted by \(\zeta^+_\text{max}\) and \(\zeta^-\text{max}\), respectively. Likewise, we also examine the minima of \(\zeta^+\) and \(\zeta^-\) during each 10-minute period, as denoted by \(\zeta^+_\text{min}\) and \(\zeta^-\text{min}\), respectively. Figure 1 shows temporal variations of \(\zeta^+_\text{max}\), \(\zeta^-\text{max}\), \(\zeta^+_\text{min}\) and \(\zeta^-\text{min}\).
five different values of \( f \). As described in Ito et al. (2010), the magnitude of vertical vorticity in each panel increases as the convective mixed layer grows. It continues to increase until the early afternoon, but gradually decreases as the convection weakens after 1500 LST. The experiment without rotation (Fig. 1a) shows that no statistically significant difference exists between the positive and negative vertical vorticity, which agrees with the results of previous numerical studies (e.g., Kanak et al. 2000; Toigo et al. 2003; Ito et al. 2010).

When \( f = f_c \) (Fig. 1b), a slight difference is found between \( \zeta_{\text{max}} \) and \( \zeta_{\text{min}} \) after 1400 LST, suggesting that the earth’s rotation has a small but non-vanishing effect on the vertical vorticity generated in the convective mixed layer. In contrast, there is no significant difference between \( \zeta_{\text{min}} \) and \( \zeta_{\text{max}} \) when \( f = 2f_c \) (Fig. 1c), \( \zeta_{\text{min}} \) becomes significantly larger than \( \zeta_{\text{max}} \); in addition, \( \zeta_{\text{min}} \) is commonly larger than \( \zeta_{\text{max}} \).

When the ambient rotation is further increased, the temporal variations in \( \zeta^+ \) and \( \zeta^- \) show a distinct asymmetry. For \( f = 10f_c \) (Fig. 1d), the difference between \( \zeta_{\text{min}} \) and \( \zeta_{\text{max}} \) and that between \( \zeta^+_{\text{max}} \) and \( \zeta^-_{\text{max}} \) reach 0.05 \( s^{-1} \). Furthermore, the magnitude of \( \zeta^- \) increases, while that of \( \zeta^+ \) decreases. When \( f \) is further increased to 100\( f_c \) (Fig. 1e), the differences between positive and negative vorticity remain similar. However, the magnitudes of \( \zeta^- \) and \( \zeta^+ \) are now smaller than those for \( f = 10f_c \).

Figure 2 shows time-averaged \( \zeta_{\text{min}} \) between 1200 and 1600 LST for various values of \( f \). The vertical vorticity shows a rapid increase with increasing ambient rotation, attains a maximum at around \( f = 15 \sim 20f_c \), and then starts to decrease with a further increase in ambient rotation.

4. Discussion

4.1 Effects of the earth’s rotation on dust devils

Within the possible range of \( f \) that prevails on the earth, only a slight difference between \( \zeta_{\text{min}} \) and \( \zeta_{\text{max}} \) is observed (Figs. 1b and 1c). The small difference between \( \zeta^+ \) and \( \zeta^- \) is consistent with the observations in the mid-latitude by Sinclair (1965) who found no difference in the number of cyclonic and anticyclonic dust devils.

To improve the statistical reliability of the present results, we have performed seven identical LES runs with slightly different initial perturbations. Ensemble averages of \( \zeta^- \) and \( \zeta^+ \) for 10-minute periods are shown in Fig. 3 for \( f = 0 \) and \( f_c \). When the ambient rotation is absent, no systematic difference is found between \( \zeta^- \) and \( \zeta^+ \) (Fig. 3a). When \( f = f_c \), however, there exists a subtle but systematic difference, on the order of \( 10^{-2} \) \( s^{-1} \), between \( \zeta^- \) and \( \zeta^+ \), indicating that the earth’s rotation does have a weak effect on the vertical vorticity (Fig. 3b).

Figure 3 shows that an addition of ambient rotation, on the order of the earth’s rotation (\( \sim 10^{-2} \) \( s^{-1} \)), causes a difference of about \( 10^{-2} \) \( s^{-1} \) between \( \zeta^- \) and \( \zeta^+ \). Suppose that turbulent convection without ambient rotation generates angular momentum \( M_c \).

![Fig. 1](image1)

![Fig. 2](image2)
inside convective cells, the initial angular momentum $M$ with ambient rotation $M_a$ may be then written as

$$M = M_c + M_a = (\zeta_c + f) r^2/2,$$

where $\zeta_c$ is the vertical vorticity corresponding to the angular momentum $M_c$ produced by the turbulent convection, and $r$ the radial distance from the center of the rotation. When a ring of air converges to the center of an updraft, the angular momentum would be nearly conserved if turbulent diffusion is neglected. During the convergence, the vorticity of the ring increases, but the relative contributions of $\zeta_c$ and $f$ to the total vorticity remain the same. The fact that an addition of the planetary vorticity of $10^{-4}$ s$^{-1}$ causes a difference of $10^{-2}$ s$^{-1}$ between $\zeta_c$ and $\zeta_a$ suggests that the vertical vorticity is amplified by 100 times during the convergence. The values of $\zeta_c$ and $\zeta_a$ in Figs. 1a and 1b are both about 0.15 s$^{-1}$. If this value also results from the amplification during convergence, it is suggested that the vertical vorticity caused by the turbulent convection is on the order of $1.5 \times 10^{-3}$ s$^{-1}$, which is approximately 15 times larger than $f_m$.

The present argument suggests that when $f = 10f_m$, the vertical vorticity of dust devils would be significantly affected by the ambient rotation, and $\zeta_c$ and $\zeta_a$ would be distinctly different. These deductions are confirmed in Fig. 1d.

### 4.2 Effects of ambient rotation on the structure of the convective mixed layer

Figure 2 shows that the vertical vorticity has a rapid increase with increase $f$ for $f \leq 15f_m$ but starts to decrease for $f > 15f_m$. Since the ambient rotation $f$ always contributes to a linear increase in $M$, the decrease in $\zeta_c$ with increasing $f$ for $f > 10f_m$ suggests that the ability of the convection to form large vertical vorticity is diminished by the strong ambient rotation.

Figure 4 shows the structures of cellular convection together with regions of large vorticity for $f = f_m$, $10f_m$, and $100f_m$. For $f = f_m$ and $10f_m$ (Fig. 4a and Fig. 4b, respectively), the horizontal size and structure of the cellular convection seem to be similar to those in the case without rotation (not shown). Several strong vertical vortices that correspond to dust devils are found at updraft regions, in the same manner as that in the simulation without ambient rotation (e.g., Ito et al. 2010).

If the ambient rotation is further increased ($f > 10f_m$), the magnitudes of both cyclonic and anticyclonic vertical vorticity are decreased (Fig. 1e). This result appears to reflect changes in the structures and strength of the convective cells: the horizontal scale of the convection cells becomes much smaller than that for the weaker rotation (Fig. 4c). Strong ambient rotation tends to inhibit

![Fig. 3. Temporal variations in the ensemble-averaged 10-minute-mean $\zeta_c$ (solid lines) and $\zeta_a$ (dotted lines) for (a) $f = 0$ and (b) $f = f_m$. Error bars indicate one standard deviation for the seven ensemble runs.](image1)

![Fig. 4. Vertical velocity at the lowest model level (color shading) and isosurface of vertical vorticity for (a) $f = f_m$, (b) $f = 10f_m$, and (c) $f = 100f_m$ at 1400 LST. Purple denotes the surface of vertical vorticity greater than 0.04 s$^{-1}$ and grey that less than $-0.04$ s$^{-1}$. The lower 1 km of the calculation domain is shown and the vertical scale is doubled.](image2)
horizontal displacement in convective motion, as reported in many previous studies (e.g., Bubnov and Golitsyn 1986; Maxworthy and Narimousa 1994; Sakai 1997).

Convective motions without ambient rotation obtain their kinetic energy of motion in the radial-vertical plane through conversion from available potential energy associated with buoyancy. Those with ambient rotation, however, spend a part of the potential energy for generating kinetic energy of tangential wind, so that both the radial and vertical velocities are reduced.

Both the reduction of the horizontal size of convection cells and that of radial velocities for larger ambient rotation are likely to result in reduced vertical vorticity, so that the number of stronger vortices is reduced. On the other hand, the former is equivalent to an increase in the number of convection cells, which results in a larger number of weak and moderate cyclonic vertical vortices (Fig. 4c).

5. Conclusions

We have studied the effects of ambient rotation on dust devils by means of a LES. The planetary vorticity, which was previously believed to have little effect on dust devils, has no noticeable effect on their rotational direction, but causes a tiny difference in the magnitudes of cyclonic and anticyclonic vorticity. As the ambient vertical vorticity is increased from the planetary value, the vertical vorticity of dust devils attains a maximum at $f \sim 10^{-3}$ s$^{-1}$, which is close to vertical vorticity of a typical meso-scale disturbance in the terrestrial atmosphere. Furthermore, cyclonic vortices become dominant over anticyclonic ones, although the structure of the convective cells remains similar to that without ambient rotation. In fact, Fujiwara et al. (2009) found that a majority of dust devils occurring near a sea-breeze front was cyclonic. When the ambient rotation is further increased from $10^{-3}$ s$^{-1}$ to $10^{-2}$ s$^{-1}$, the structure of the convective motions starts to be significantly affected by the ambient rotation: the size of the convective cells is reduced, and the radial and vertical velocities of the convective motions are suppressed, resulting in weakening of the vertical vorticity of dust devils. Then, horizontal convergence is suppressed, thereby weakening the dust devils.

This study has considered the development of the convective mixed layer on the earth with realistic terrestrial surface heat flux and stratification, so that the ambient rotation that maximizes the vertical vorticity of dust devils then, horizontal convergence is suppressed, thereby weakening the dust devils.

Our future subject is to survey systematically the value of f$\ast$ for various intensity of convection and obtain a universal expression for it.

Acknowledgments

This work was supported in part by a Grant-in-Aid for Scientific Research (B)(2) No.21340134 from the Japan Society for the Promotion of Science, and Strategic Program for High Performance Computing Infrastructure of the MEXT of the Japanese Government. The computation was carried out using the computer facilities at the Atmosphere and Ocean Research Institute, The University of Tokyo, and at the Research Institute of Information Technology, Kyushu University.

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Manuscript received 9 June 2011, accepted 12 October 2011 SOLA: http://www.jstage.jst.go.jp/browse/sola